GEOLOGICAL SURVEY OF CANADA

DEPARTMENT OF ENERGY, MINES AND RESOURCES

BULLETIN 227

THE BENNETT LAKE CAULDRON SUBSIDENCE COMPLEX, BRITISH COLUMBIA AND YUKON TERRITORY

M. B. Lambert

Ottawa
Canada
1974

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By

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PREFACE

As part of a study designed to contribute to the understanding of volcanic processes in the Cordilleran region, mapping of the Bennett Lake complex at a scale of 1:25,000 was carried out in 1967 and 1968.

The complex, of Eocene age and composed mainly of rhyolite to dacite ash-flow tuffs and breccias, was deposited on granitic rocks of the Coast Mountains Complex. It consists of two nested cauldrons and underwent two resurgent-cauldron cycles. At least 420 cubic kilometres of volcanic and sedimentary material are preserved within the complex.

Detailed studies such as those presented in this report are designed to give a better understanding of how volcanic rocks are formed. Certain types of mineral deposits are closely associated with volcanic rocks and it is by means of studies such as that carried out by Dr. Lambert that the Geological Survey of Canada attains one of its objectives, namely, to estimate the potential abundance and probable distribution of the mineral resources available to Canada and to provide an information base for the location of such resources.

D.J. McLaren,
Director.

Ottawa, October 15, 1973

Plate I. View of the Partridge Lake valley looking southwest from the head of West Arm. Cleft Mountain is in the left foreground.

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ABSTRACT

The complex, of Eocene age, is elliptical in plan, 30 by 19 kilometres. It is part of the Sloko volcanic province, which in the study area consists mainly of rhyolite to dacite ash-flow tuffs and breccias with subordinate rhyolite, dacite and andesite lavas. It was deposited on granitic rocks of the Coast Plutonic Complex. The extrusive rocks are intercalated with epiclastic conglomerates, breccias, wackes and siltstones. The volcanic and sedimentary rocks constitute seven formations and two informal units.

The structure consists of two nested cauldrons, a central dome, concentric and radial fracture systems and a subelliptical rhyolite ring dyke which partly surrounds the entire complex. Eruptive centres lie along ring-fracture systems related to both the inner and outer cauldrons. Granitic rocks are shattered and brecciated along cauldron margins, in narrow linear and arcuate belts adjacent to dykes and faults and around some eruptive centres.

The complex underwent two resurgent-cauldron cycles. During both cycles a central block subsided essentially intact whereas the margins settled in a series of arcuate steps. The cauldron block was probably only slightly arched at the end of the first cycle whereas pronounced resurgent doming followed the second cycle.

Each cycle began with early cataclysmic eruptions after which the volume of erupted pyroclastic material decreased sharply. Although avalanching from caldera walls began intermittently during the early stages of caldera collapse, the bulk of epiclastic caldera fill was deposited after caldron subsidence. The total volume of volcanic and sedimentary material preserved within the complex is about 420 cubic kilometres (100 cubic miles). It is not known how much material was deposited outside of the complex.

A gradual change of eruptive products from salic to mafic with time, during the each eruptive cycle, is interpreted as the successive tapping of a vertically zoned magma chamber.

Potassium-argon dates of volcanic rocks indicate that the complex is 50 m.y. old and that the two resurgent-cauldron cycles may have taken place within a time span of less than one million years.

RÉSUMÉ

Le complexe géologique, d'âge éocène, est de forme elliptique vu en plan et mesure 30 kilomètres sur 19. Il fait partie de la province volcanique de Sloko, laquelle, dans la région à l'étude, est composée surtout de tufs volcaniques et de brèches à rhyolite et à dacite avec en moindie quantité des laves à rhyolite, à dacite et à andésite. Le complexe a été mis en place sur des roches granitiques du Complexe plutonique côtier. Les roches extrusives sont intercalées de conglomérats épiclastiques, de brèches, de wackes et de grès. Les roches volcaniques et sédimentaires constituent sept formations réparties en deux unités.

La structure consiste en deux chaudrons emboîtés, un dôme central, des systèmes de fractures concentriques et rayonnantes et un dyke subelliptique à rhyolite qui entoure presque tout le complexe. Les centres éruptifs se trouvent le long des systèmes de fractures circulaires qui appartiennent aux deux chaudrons, l'intérieur et l'extérieur.

Le complexe a connu deux cycles de résurgence des chaudrons. Au cours des deux cycles un bloc central s'est affaissé essentiellement intact tandis que les bords s'effondraient en une série de gradins arqués. Le bloc effondré n'était probablement que peu arqué à la fin du premier cycle alors que le second cycle a été suivi de phénomènes prononcés d'intumescence.

Chaque cycle a commencé d'abrod par des éruptions cataclysmiques après quoi le volume de matériel pyroclastique éjecté a diminué très rapidement. Quoique les avalanches à partir des murs des calderas aient commencé de façon intermittente au cours des premières phases d'effondrement, le gros du matériel épiclastique des calderas a été déposé après la formation du chaudron. Le volume total du matériel volcanique et sédimentaire préservé dans le complexe est d'environ 420 kilomètres cubes (100 milles cubes). On ne connâit par la quantité de materiel déposé hors du complexe.

Un changement graduel, dans le temps, des produits éruptifs de silico-alumineux à ferromagnésiens au cours de chaque cycle éruptif serait le résultat d'une alimentation successive provenant d'une chambre de magma verticalement zonée.

Les datations au potassium-argon des roches volcaniques indiquent que le complexe remonte à 50 millions d'années et que les deux cycles de résurgence des chaudrons peuvent s'être produits en moins d'un million d'année.

CHAPTER I

INTRODUCTION

LOCATION AND ACCESS

The map-area straddles the British Columbia-Yukon border 50 miles (80 km) south of Whitehorse, Yukon Territory (Fig. 1). Most parts of it can be reached using light fixed-wing aircraft on floats and helicopter, both of which are available for charter at Whitehorse, Y.T. and Atlin, B.C.

The northern edge of the map-area is 20 miles (32 km) by boat along Bennett Lake from Carcross, Y.T. The stream connecting Bennett Lake with Partridge Lake, however, is not navigable. The White Pass and Yukon Railway comes within 16 miles (25 km) of the map-area at Bennett, B.C. From here, the area can be reached by horse or on foot via the Homan Lake valley. There are no trails within the area except for a poor trail that links Partridge Lake with the head of the West Arm of Bennett Lake. Horse travel is difficult in the lower valleys because of the rugged terrain, very dense vegetation and general lack of trails. Almost all of the area can be traversed on foot. Several precipitous peaks, ridges, and cliff scarps along the walls of Partridge Lake valley and along the east wall of MacAuley Creek valley are negotiable only with difficulty by roped parties using advanced mountaineering techniques.

PHYSIOGRAPHY, DRAINAGE AND GLACIATION

PHYSIOGRAPHY

Physical features of this area are typical of the Coast Mountains at this latitude, with high relief, deeply incised, youthful, glacially scoured valleys, and rugged glacially sculptured alpine terrain.

Elevations range from 2,150 feet (655 m) at the head of West Arm of Bennett Lake (Fig. 2, in pocket) to 7,525 feet (2,300 m) on a peak on the south side of Jones Creek. Maximum local relief is 5,050 feet (1,550 m) in the Partridge Lake valley, and average relief of tributary valleys is about 3,500 feet (1,050 m).

The south slopes of east-west trending ridges are smooth and moderately steep, fluted by shallow V-shaped intermittent stream gullies. These slopes terminate in serrated, knife-edge ridges. North slopes are characterized by closely spaced cirques that coalesce to form jagged arêtes and horn peaks. The east-west ridges are thus reduced to a series of branching, lateral spurs on the north sides. Glaciers (generally covering an area of less than one square mile) are virtually restricted to north-facing cirques.

DRAINAGE

The area is drained by two major river systems: Partridge River which flows northeast and empties into the West Arm of Bennett Lake, and Boudette Creek which flows north-northwest from the west side of the map-area. Three large tributaries of the Partridge River system (Jones Creek, Crozier Creek, and Lemieux Creek) occupy deep valleys which form two broad arcuate patterns: an arc formed by Lemieux Creek and Crozier Creek

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which extends from Tom Thumb Mountain in the east to the Boudette Creek valley in the west; and an arc formed by Jones Creek and Boudette Creek valleys.

A water divide occurs near the centre of the map-area where Jones Creek flows east, MacAuley Creek flows north and Boudette Creek flows west.

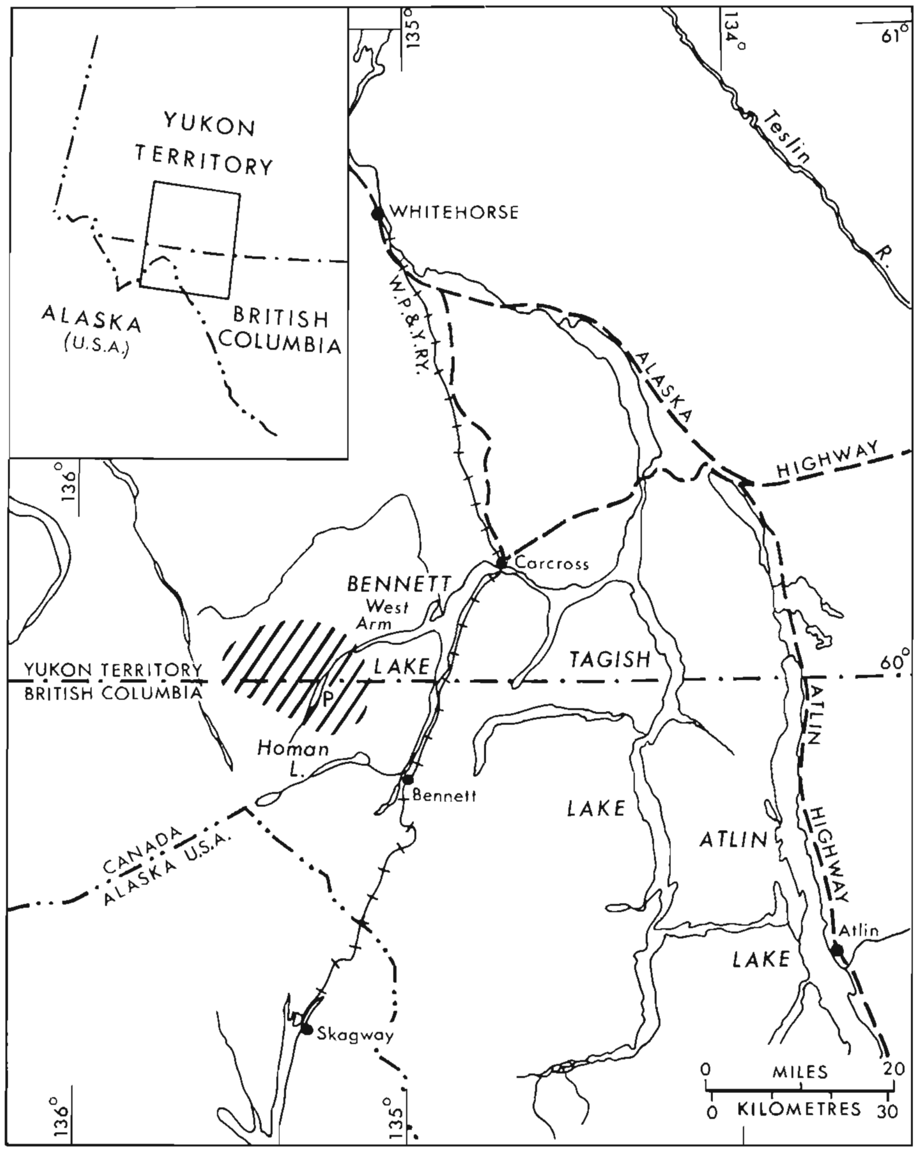

Figure 1. Index map showing location of Bennett Lake cauldron subsidence complex (lined pattern).

P indicates Partridge Lake

GLACIATION, GLACIAL DEPOSITS AND ALLUVIUM

The last major advance of the Cordilleran ice-sheet has obliterated any trace of previous advances (Wheeler, 1961, p. 9). This was a mountain ice-sheet, which reached an elevation of 6,000 to 6,500 feet above sea level, out of which higher peaks rose as nunataks. This sheet probably retreated to the south.

Glacial features within the map-area indicate conditions of valley and alpine glaciation. U-shaped valleys, cirques and hanging valleys with alpine moraines and small glaciers, morainal drift, and terraces record deglaciation in the area.

Alluvium and colluvium deposited mainly by postglacial streams and by mass wasting includes deltas, alluvial fans, landslide deposits, and steep aprons and cones of scree and talus.

PREVIOUS INVESTIGATIONS

Previous geological work in this map-area was carried out during reconnaissance mapping at a scale of one inch to four miles by the Geological Survey of Canada: J.O. Wheeler mapped the complex on the north side of the British Columbia - Yukon border as part of the Whitehorse map-area during the field seasons of 1948 to 1951, and R.L. Christie mapped the complex south of the border as part of the Bennett map-area during the field seasons of 1949 to 1953.

Wheeler (1961, p. 84) suggested that this complex may be a cauldron subsidence, ring-dyke structure; his general interpretation is correct. The following excerpts from his report (op. cit., p. 83-84) suggest mechanisms that played a major role in the evolution of the complex:

> "The Skukum group accumulated principally in response to intermittent explosive volcanism and subordinately from the extrusive of lava . . . . Explosive volcanism was also particularly effective in disturbing, and to some degree in mobilizing the underlying rocks . . .
>
> It is suggested that, in the MacAuley Creek area, volcanism began locally with the rapid passage of hot gases through granodiorite containing inclusions of metamorphic rocks, the whole being at or near the surface. The sudden release of hot gases through the granodiorite to the surface may have partly shattered the rock. Material plucked from the walls of fissures was carried upwards by the uprushing gases and then expelled at the surface to form agglomerate composed almost entirely of granitic fragments, some of which were rounded from attrition during their ascent through the fissures . . .
>
> Subsequently, magma rose through fissures in the granodiorite and was extruded as lava from vents and volcanic piles . . .
>
> . . . .
>
> . . . subsidence of the inner part along ring-fractures may well have formed one or more calderas, which received and preserved from subsequent erosion much of the material forming the Skukum group."

Christie's work (1958, p. 130-144) is concerned mainly with the shattered and brecciated granitic rocks that underlie the Skukum Group. In his interpretation he states (p. 141):

> "The shattering of the granodiorite and the angular nature of the breccias may be due to explosive volcanic action . . . Volcanic material and granitic fragments plucked from the walls of fissures by the up-rushing gases and lava were perhaps both injected in overlying strata as sills and expelled at the surface as fluid granitic agglomerate."

He also concluded (p. 143, 144) that plutonic bodies in the vicinity of Partridge Lake represent multiple intrusion that took place in mid-Cretaceous and late Cretaceous time; that the youngest plutonic bodies were shallow intrusions; and that the granodiorite near Partridge Lake was emplaced and exposed to erosion during a period that lasted at longest from early to late Cretaceous time.

PRESENT INVESTIGATION

PURPOSE

This project is part of a continuing study of volcanism in the Western Canadian Cordillera by the Geological Survey of Canada. The extreme topographic relief and deeply incised valleys, provide excellent exposures through a thick succession of pyroclastic rocks and an opportunity for detailed investigation of stratigraphic and structural relations in three dimensions. It was expected that study of the Bennett Lake complex could be an important contribution to the understanding of cauldron subsidence structures and volcanic processes in the late geological history of the Cordillera.

The main purposes of this study were threefold: (1) to map the volcanic complex, and by means of detailed stratigraphic and structural studies to prove or disprove the hypothesis of previous workers that it is a cauldron subsidence complex; (2) to determine the precise age and sequence of volcanic, sedimentary and tectonic events which took place during the evolution of the complex; and (3) to provide data on the stratigraphy, petrography, petrochemistry, mode of eruption and environment of deposition of ignimbrites, concerning which there is little information in the literature of volcanic rocks in Canada.

FIELD AND PETROGRAPHIC METHODS

The complex was mapped at a scale of 1:25,000 during the 1967 and 1968 field seasons. Field work was carried out by two-man back-packing parties with helicopter support for base camp moves, setting out food caches and retrieving specimens at the end of field seasons.

Modal analyses of medium- and coarse-grained granitic rocks were carried out on stained slices cut from hand specimens, which were point counted under a binocular microscope using a 2 mm grid. Fine-grained matrix material and fine-grained specimens were point counted in thin section using 1,500 to 2,500 points per slide.

Modal analyses of coarse boulder conglomerates and breccias were carried out by point counting black-and-white and colour photographs projected on to a grid so that 1,000 to 2,000 points per photograph were counted. Matrix material was counted using the same thin section and hand specimen methods used for granitic rocks.

Lapilli (less than 4 mm) of volcanic rocks were point counted under binocular microscope whereas ash was counted in thin section. The amounts of the various constituents in ash were found to be constant (within 2 per cent) for several thin sections of the same specimen. The relative proportions of constituents in ash correspond closely with the proportions of lapilli determined from hand specimen and estimated in outcrop.

Identification of feldspar and quartz phenocrysts is difficult in tuffs containing abundant granitic and metamorphic fragments and crystal fragments derived from them. Criteria used to distinguish crystal fragments of phenocrystic origin are (1) euhedral crystal faces, (2) resorption, (3) lack of perthitic intergrowths (potassic feldspars from granitic rocks are almost always perthitic), (4) optics of sanidine and high temperature modifications of plagioclase, (5) inclusion in pumice (this is a rare occurrence of accidental fragments), and (6) degree of alteration (locally granitic fragments have turbid alteration in contrast to clear, unaltered phenocrystic feldspars).

Compositions and structural states of feldspars were determined optically using a four-axis universal stage and by X-ray diffraction methods of Wright (1968).

PRESENTATION

Granitic and metamorphic rocks predating the Skukum Group are referred to as the basement complex and described in Chapter III.

The map-area is divided into three subareas in which seven volcanic and sedimentary formations are distinguished. Stratigraphy of each formation is described first (Chapter IV) followed by a description of the structural patterns of the complex as a whole (Chapter V). A preliminary chemical study of the major volcanic formations is discussed in Chapter VI. After a discussion of the chronology of the complex (Chapter VII) the stratigraphic, structural and chemical data are brought together in a synthesis of the magmatic and structural evolution of the complex (Chapter VIII).

ACKNOWLEDGMENTS

Grateful appreciation is expressed to Dr. J.M. Moore, Jr. who provided many hours of valuable discussion and constructive criticism while supervising the author's doctoral thesis at Carleton University. Drs. R.W. Yole (Carleton University) and W.R.A. Baragar (G.S.C.) critically reviewed the preliminary thesis manuscript.

Dr. J.G. Souther, as G.S.C. supervisor of the project, suggested the problem, visited the field area and provided valuable counsel and encouragement. Competent assistance in the field was given in 1967 by Mr. A.J.M. Elliot, and in 1968 by Mr. P.H. Thompson. The generous co-operation of many residents of Carcross, Y.T. facilitated the work; particular thanks are due to Mr. and Mrs. M. Watson. Chemical analyses were performed by the Geological Survey of Canada and by Mr. C. Murray at Carleton University. Mr. L. Williams (Carleton University) assisted with the drafting of figures.

CHAPTER II

GEOLOGICAL SETTING

TECTONIC EVOLUTION OF THE WESTERN CORDILLERA

The major tectonic elements of the Cordillera of western Canada and adjacent Alaska during Mesozoic time were, from east to west, the Rocky Mountain miogeosyncline, Cassiar-Columbia geanticline, Whitehorse-Nechako trough, Coast geanticline, and the Pacific trough (Fig. 4).

Details of the tectonic evolution of the western Canadian Cordillera are described by Souther (1966, 1967). The following account summarizes his conclusions from Mesozoic to the Recent time.

The major plutonic and volcanic evolution in the Cordillera followed a period of tectonic quiescence during Permian to Early Triassic time. This quiescence was broken in Middle Triassic time by the Stikine orogeny in the Coast and Cassiar crystalline geanticlines. During Late Triassic time there was sinking in the Pacific trough and effusion of much sodic basalt. Andesitic flows and pyroclastic rocks accumulated in the Whitehorse-Nechako trough. Volcanic activity declined by the end of the Triassic period.

During the Early Jurassic there was uplift of the two crystalline geanticlines and subsidence of the two troughs. Andesitic pyroclastic rocks were deposited in the Pacific trough and in the southwestern part of the Nechako trough. Local uplift and segmentation of the Whitehorse-Nechako trough took place during the Middle Jurassic. During Late Jurassic and Cretaceous there was intense deformation and plutonism in the crystalline geanticlines. By Late Cretaceous time the entire western Cordillera was uplifted in a broad arch.

The Early Tertiary was a time of widespread deformation: folding and thrusting in the miogeosyncline and block faulting, tilting and local folding in the central part. "This was also a time of granitic intrusion, during which large bodies of quartz monzonite were emplaced in both the Cassiar and Coast crystalline belts, particularly along the eastern margin of the Coast Mountains" (Souther, 1966, p. 180). In central British Columbia, there was widespread eruption of pyroclastic material in three volcanic provinces: Sloko, Ootsa Lake, and Kamloops-Midway (Fig. 5). The Bennett Lake complex is part of the Skukum Group of the Sloko volcanic province. Rocks of the Sloko and Ootsa Lake provinces are mainly of rhyolitic and dacitic composition. This was the first widespread salic volcanism in the Phanerozoic history of the western Cordillera. The Kamloops-Midway volcanics are mainly of andesitic and basaltic composition. Effusions of basaltic lava and minor rhyolite took place in the Pacific belt.

The late Tertiary was a time of effusion of extensive flood basalts in central British Columbia. Periodic eruptions of basaltic and andesitic magma are recorded during Pleistocene and Recent time.

REGIONAL GEOLOGY

The oldest rocks in the region are predominately quartzites and mica-feldspar-quartz schists and gneisses of the Yukon Group, consisting of discontinuous masses distributed in a northwesterly-trending belt mainly enclosed by granitic rocks (Fig. 6). These rocks are probably of early Paleozoic age (Wheeler, 1961, p. 21).

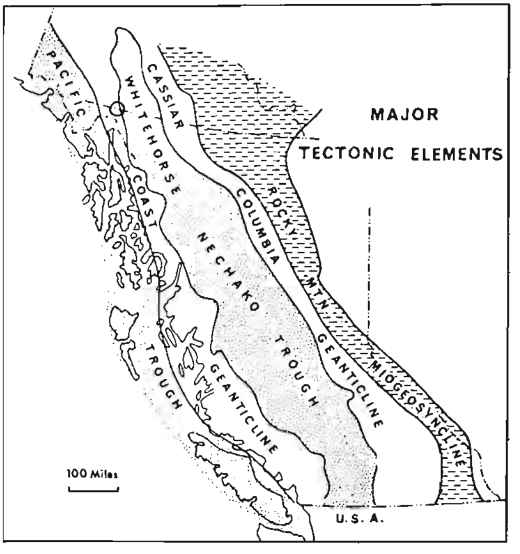

Figure 4.

Major tectonic elements of the Cordillera of western Canada and adjacent Alaska (after Souther, 1967, p. 162). Circle indicates location of Bennett Lake complex.

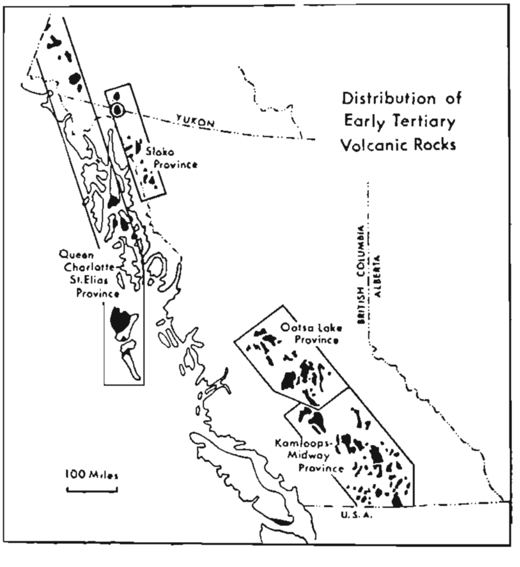

Figure 5.

Distribution of early Tertiary volcanic rocks in British Columbia, southwestern Yukon, and southeastern Alaska (after Souther, 1967, p. 164). Circle indicates location of Bennett Lake complex.

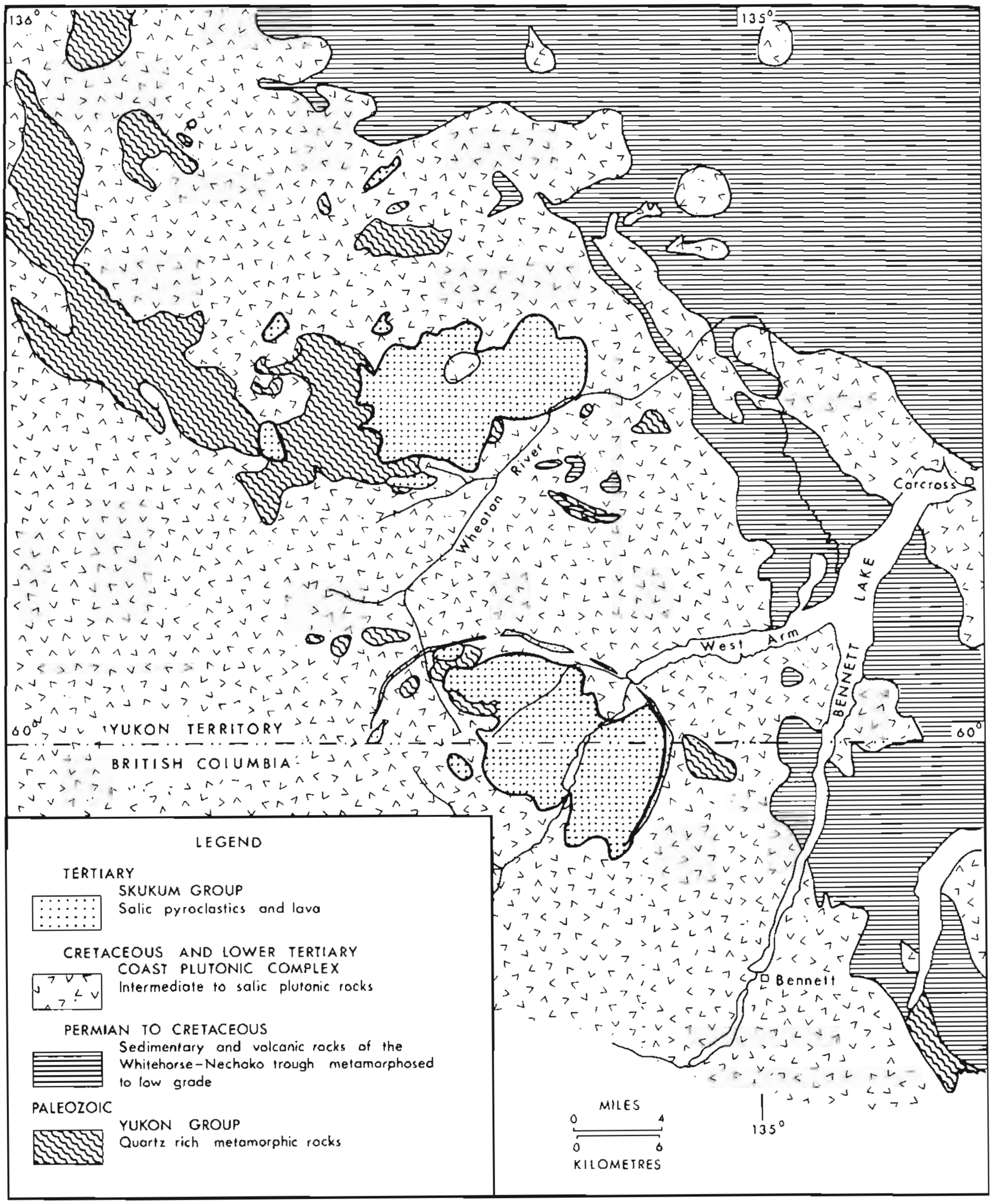

Figure 6. Regional geology in the vicinity of Bennett Lake, British Columbia and Yukon Territory. Geology modified after Christie (1957) and Wheeler (1961).

Low grade metamorphic and moderately deformed Paleozoic and Mesozoic rocks of the Whitehorse-Nechako trough are not subdivided in Figure 6, but include the Taku Group (chert, greenstone, limestone metavolcanics, serpentine), the Lewes River Group (greywacke, siltstone, conglomerate, argillite, limestone and mafic volcanics) the Labarge Group (greywacke, arkose, siltstone, quartzite, conglomerate and argillite), the Tantalus Formation (arkose, siltstone, conglomerate, argillite and coal) and the Hutshi Group (basalt, andesite rhyolite flows, tuffs and breccias) (Wheeler, 1961).

The Coast Plutonic Complex (Douglas et al., 1970, p. 367) comprises granodiorite, quartz diorite, quartz monzonite and granite of Cretaceous to early Tertiary age.

Lower Tertiary salic pyroclastic and flow rocks of the Skukum Group unconformably overlie the Yukon Group and granitic rocks near the eastern margin of the Coast Plutonic Complex. The Skukum Group outcrops in two isolated areas which are the northernmost parts of the Sloko volcanic province (see Fig. 5).

The Bennett Lake complex, of Eocene age, is the more southerly of the two outcrop areas of the Skukum Group. In the Bennett Lake area, the Skukum Group consists mainly of rhyolite to dacite ash-flow tuffs and breccias with subordinate rhyolite, dacite and andesite lavas. The volcanic rocks are partly circumscribed by a large rhyolite ring dyke. The predominance of pyroclastic rocks, the abundance of shattered and brecciated granitic rocks around the complex and evidence that the Skukum Group lies in a depression that is roughly circular in plan, and partly surrounded by a ring dyke, led Wheeler to conclude that the Skukum Group accumulated principally in response to explosive volcanism and that subsidence along ring fractures formed one or more calderas. The present study (Chapter V) supports Wheeler's conclusions and demonstrates that the complex consists of two nested calderas, an eroded structural dome and a thick succession of pyroclastic and epiclastic rocks related to eruption, subsidence and filling of the cauldrons. The complex is completely surrounded by granitic rocks containing isolated pendants or large xenoliths of the Yukon Group. Rocks of the Whitehorse-Nechako Trough are absent from the present map-area. The Table of Formations (Table I) applies only to the area mapped during this study.

TABLE I

TABLE OF FORMATIONS IN THE MAP AREA

Era	Period or Epoch	Group	Formation (Thickness in metres)	Member	Principal Lithology
Cenozoic	Pleistocene and Recent				Glacial drift, alluvium
		Unconformity	Unconformity	Unconformity	Unconformity
Cenozoic	Eocene				Porphyritic rhyolite and dacite, dykes and sills
Cenozoic	Eocene	Intrusive Contact	Intrusive Contact	Intrusive Contact	Intrusive Contact
Cenozoic	Eocene	Skukum Group (3955+)	Boudette Creek Formation (550+)		Ignimbrite
Cenozoic	Eocene	Skukum Group (3955+)	Jones Creek Formation (220+)		Basalt and rhyolite lavas; tuff, sandstone
Cenozoic	Eocene	Skukum Group (3955+)	[Crozier Tuffs and Lavas (850+)][1]		Tuff, ignimbrite, rhyolite lavas
Cenozoic	Eocene	Skukum Group (3955+)	Lemieux Creek Formation (550)		Granitic boulder conglomerate and breccia
Cenozoic	Eocene	Skukum Group (3955+)	[Crozier Breccias (450+)][1]		Volcanic and granitic fragment breccia, conglomerate and sandstone; siltstone
Cenozoic	Eocene	Skukum Group (3955+)	MacAuley Creek Formation (710)	B	Ignimbrite, densely welded
				A	Ignimbrite, partly welded
Cenozoic	Eocene	Skukum Group (3955+)	Gault Formation (225)		Granitic boulder conglomerate
Cenozoic	Eocene	Skukum Group (3955+)	Cleft Mountain Formation (710)	E	Sandstone, tuff
				D	Ignimbrite
				C	Andesite lavas
				B	Dacite lavas
				A	Ignimbrite
Cenozoic	Eocene	Skukum Group (3955+)	Partridge Lake Formation (1010+)	C	Ignimbrite, non- to partly-welded
				B	Ignimbrite, partly welded
				A	Ignimbrite, non-welded
		Unconformity	Unconformity	Unconformity	Unconformity
Cenozoic and Cretaceous	Tertiary and Cretaceous		Coast Plutonic Complex		Leucocratic granite
					Quartz monzonite
					Granodiorite
		Intrusive Contact	Intrusive Contact	Intrusive Contact	Intrusive Contact
Pre-Mesozoic			Yukon Group		Quartzite, mica-quartz-schist gneiss; marble

[1] Possible lateral equivalent

CHAPTER III

BASEMENT COMPLEX

METAMORPHIC ROCKS

Three large masses of metamorphic rocks outcrop in the northwestern part of the map-area and five smaller isolated masses along its eastern and southern periphery. They comprise laminated and massive quartzite, mica-quartz schists, mica (or hornblende)-quartz-feldspar gneisses, and altered to gneissic meta-quartz diorite. Mapping of these rocks is not sufficiently detailed to permit proper interpretation of stratigraphy and structure.

Quartzites are light- to dark-grey, fine-grained rocks that are finely laminated (0.05 to 2 cm thick) to thick bedded. Light layers consist of 99 per cent granoblastic quartz (averaging 0.3 mm), with irregular, interlocking boundaries and accessory opaque minerals, chlorite, white mica, zircon and feldspar. Dark layers owe their colour to the fine grain size of quartz (0.15 mm) and to fine disseminations and discontinuous seams of fine-grained opaque minerals and chlorite.

Schists are dark to light silvery grey (rusty brown weathering) rocks consisting mainly of quartz and muscovite with minor chlorite, feldspar (less than 1 per cent) and accessory magnetite, hematite and zircon. The dark colour of some schists is due to opaque minerals finely disseminated in layers or in thin seams parallel to the foliation, as well as to the fine grain size of the rock. Average grain size of quartz in the dark bands is about one half that in the light bands. Quartz is commonly elongate to granoblastic and has dimensional or optical orientation parallel to well developed mica schistosity. Near the head of West Arm, dark greenish grey muscovite-chlorite-quartz schist consists of alternating laminae of quartzite and intergrown muscovite and chlorite. Near the headwaters of Boudette Creek, quartzite has a schistose fabric shown by dark layers composed of lepidoblastic biotite (30 to 60 per cent) and quartz (40 to 50 per cent).

Gneisses are generally light- to dark-grey, fine- to medium-grained rocks with layering averaging 0.2 to 3 cm, but locally up to 10 cm. They consist mainly of quartz and andesine, brown biotite (partly altered to chlorite) and accessory apatite, sphene, zircon and epidote. In thin section, the only distinction between the light and dark bands is the higher concentration of lepidoblastic biotite in the darker bands. Anhedral slightly elongate quartz, has preferred dimensional orientation parallel to the layering.

Dark grey to greenish grey meta-quartz diorite is generally medium grained and massive, but is locally foliated showing weak preferred orientation of mafic minerals and lenses of mafic minerals. In some places it contains amphibolite layers. Generally it is composed of quartz (5 to 15 per cent), plagioclase, biotite, minor amounts of microperthite and myrmekite. Accessory minerals include apatite, epidote, zircon, sphene, leucoxene, calcite, magnetite, hematite and pyrite. Mafic minerals, which are almost completely altered to chlorite, make up to 40 per cent of the rock. Subhedral to anhedral andesine (An_{35-43}) has weak normal and locally complex oscillatory zoning. It is commonly altered to white mica that forms minute flecks throughout the crystals. In thin section all rocks show abundant evidence of cataclasis and some recrystallization, namely: stress twinned, bent and fractured plagioclase; thin zones of granulation, commonly healed by chlorite; granulation around the margins of feldspars, which in some specimens is accompanied by fine granoblastic mosaics of untwinned feldspar forming the area between larger feldspars. Amphibolite bands are composed mainly of green hornblende, andesine, quartz, about 2 per cent sphene, and accessory apatite, hematite, zircon, leucoxene and calcite. Hornblende has strong preferred orientation and sphene forms elongate grains or trains of grains that are parallel to the hornblende.

STRUCTURAL RELATIONS

The metamorphic rocks are isolated masses almost completely surrounded by granitic rocks. Intrusive relationships are clearly exposed at several localities, whereas elsewhere the contact is a fault.

Schistosity and gneissosity, where observed, were everywhere parallel to bedding. In one locality, near the head of Crozier Creek, schistosity is deformed into crenulations which form a prominent lineation. According to Wheeler (1961, p. 27) folds in the Yukon Group are overturned both to the northeast and southwest.

At the west edge of the northernmost mass of metamorphic rocks in the area, an apophysis of quartz monzonite has clearly intruded quartz-biotite schist. There are inclusions of schist in the granitic rocks near the contact. Several small dykes extend from the apex of the apophysis. Similar intrusive contacts, with abundant rotated blocks of metamorphic rocks included in granitic rocks near the contact, are well documented in outcrops east of West Arm and north of Crozier Creek. In the latter outcrop, many dykes of granitic rocks, one to three feet wide, interfinger along schistosity and locally cut across it.

West of Boudette Creek a broad contact zone, 150 to 200 metres wide, between granitic and gneissic rocks contains a profusion of granitic dykes and pegmatitic veins. Intrusive contacts in some places are parallel to the steeply dipping foliation in the gneiss.

Dykes of porphyritic rhyolite, tuff and tuff breccia have intruded along the western and northern contacts between granitic and metamorphic rocks in the vicinity of Crozier Creek, and along the east contact of the mass south of Jones Creek.

The contact is a fault at one locality north of Crozier Creek and at the small mass in the Partridge Lake valley. These contacts are marked by prominent topographic lineaments, zones 7 to 15 metres wide, of brecciated gneiss and quartz monzonite, and planar slickensided outcrop faces parallel to the fault zone.

Diagnostic contact relations between meta-quartz diorite and gneisses and schists, near the headwaters of Boudette Creek, were not observed in the field. From intermittent outcrop in one locality, it appears that the gneisses grade into foliated quartz diorite with lenses of amphibolite. All rock types are shattered and brecciated in this area.

The Yukon Group is overlain with angular unconformity by the Skukum Group. Its relationship is clearly exposed northwest of Munroe Peak where metamorphic rocks are unconformably overlain by volcanic breccias and tuff breccias, and both are intruded by a large andesite body.

Near the headwaters of Boudette Creek, the unconformity is very irregular. Metamorphic rocks are overlain by breccias consisting of granite, gneiss, quartzite and volcanic fragments, boulder tuff, and tuff.

In a cirque southwest of Crozier Creek, the undulatory contact between steeply dipping schist and quartzite is overlain by a bed, less than 1.5 metres thick, of gneiss- and quartzite-fragment breccia and grit. Pale green tuff overlies the breccia in this locality, but at other places in this vicinity, the tuff lies directly on the metamorphic rocks.

INTERPRETATION, AGE AND CORRELATION

The quartz-rich composition of the gneisses, schists and quartzites, and their occurrence as pendants and large xenoliths within a northwesterly-trending belt (Fig. 6) suggest that these rocks are part of the Yukon Group.

Fine laminations in quartzite, variation among layers in any one locality (for example interlayered massive quartzite, finely laminated quartzite, and mica schists), and high-silica composition suggest that the metamorphic rocks were derived from quartz-rich sedimentary rocks. Gneissic rocks, bearing considerable amounts of feldspar, may have been derived from quartz-feldspar arenites.

The sediments were involved in at least two periods of deformation. The earlier stage was isoclinal folding, suggested by foliation parallel to bedding. The later stage is represented by crenulation of the earlier schistosity.

Metasediments were intruded by quartz diorite which has undergone deformation and metamorphism since its emplacement.

According to Wheeler (pers. comm.) the Yukon Group is probably lower Paleozoic. The deformed quartz diorite, which intrudes the metasediments, may represent earliest Jurassic or older granitic rocks deformed by mid-Cretaceous folding.

GRANITIC ROCKS

Six distinct varieties of granitic rocks are distinguished: leucocratic granite[1]; hornblende-biotite quartz monzonite; pink quartz monzonite; fine-grained biotite quartz monzonite; hornblende granodiorite; and biotite granodiorite (Fig. 7). Only the distinctive characteristics and structural relations of each type are described in the text. Modal composition, chemical composition, and other petrographic details are shown in Figures 8 and 9, and Appendices I and II.

Generally the granitic rocks were mapped in less detail than the volcanic rocks. Only a few sharp contacts between units were observed directly in the field. Contacts shown as 'approximate' on the map are drawn from abrupt changes in lithology, presence of inclusions of one type in another, and presence of fine-grained marginal rocks. Assumed contacts were inferred after mapping was completed by studying the distribution of distinctive rock types from hand specimens.

Generally these rocks are internally structureless, although planar fabric is seen near some contacts. Zones of shattering and brecciation are characteristic of these rocks immediately adjacent to the volcanic rocks, along fault zones and along margins of later dykes and vents.

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[1] Nomenclature of granitic rocks follows the classification of Moorhouse, 1959.

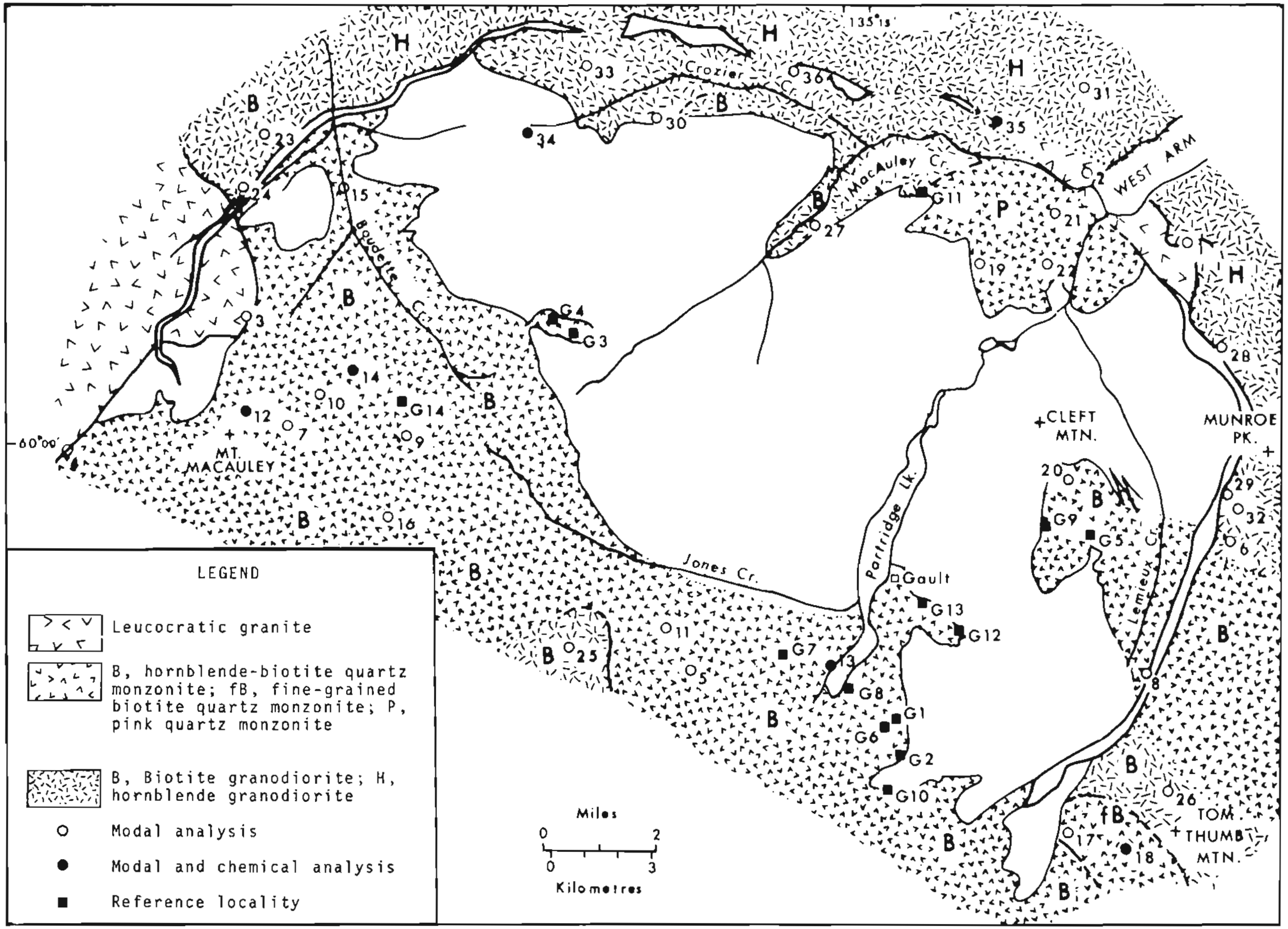


Figure 7. Distribution of granitic rocks; reference localities; and location of specimens selected for modal and chemical analysis.

HORNBLENDE GRANODIORITE

Fine- to medium-grained hornblende or biotite-hornblende granodiorite occupies the north and northeast periphery of the volcanic rocks. These fresh, medium- to dark-grey speckled rocks have colour indices ranging from 15 to 27. Small areas of quartz diorite and hornblende porphyry that occur north of MacAuley Creek are also included with this unit.

North of MacAuley Creek and on the east side of West Arm, the granodiorite is intruded by leucocratic granite and porphyritic rhyolite dykes. The granodiorite is shattered and brecciated adjacent to the rhyolite ring-dyke contact.

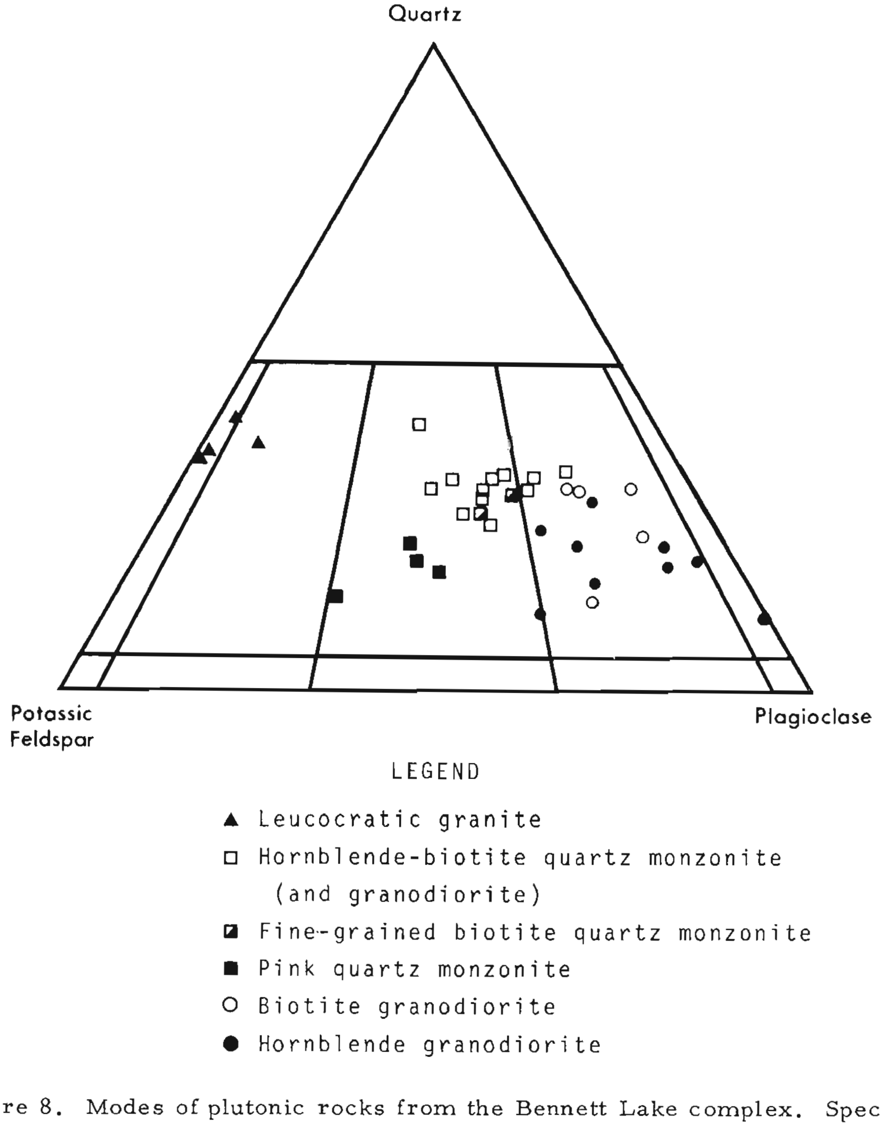
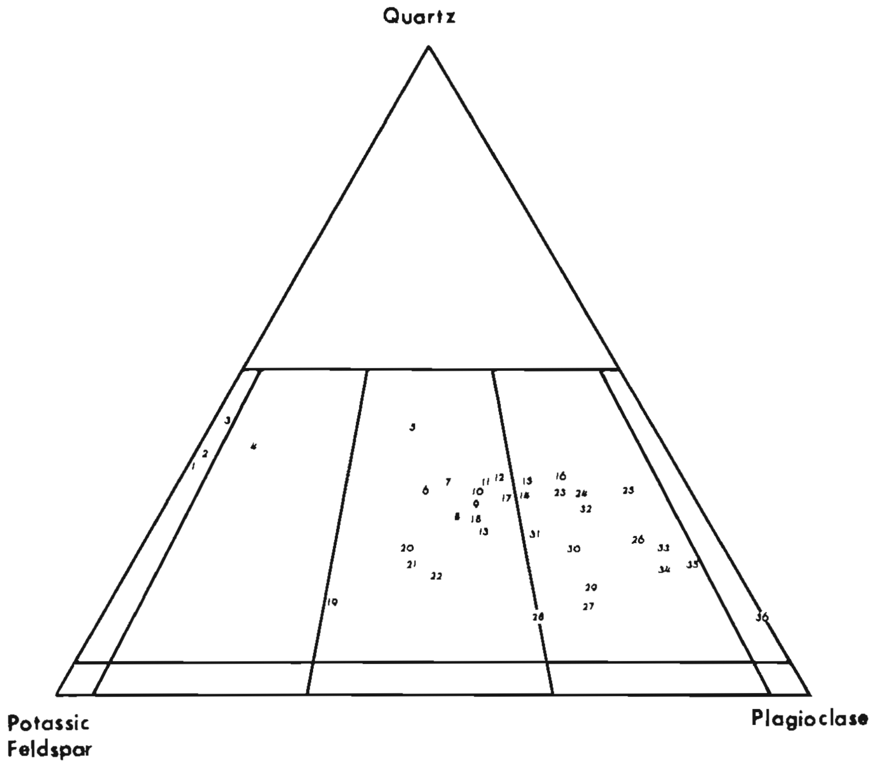


Figure 8. Modes of plutonic rocks from the Bennett Lake complex. Specimen numbers and localities are shown in Figures 7 and 9.

In the vicinity of Munroe Peak, granodiorite, near the contact with metamorphic rocks, is fine grained and has well developed planar orientation of feldspars and mafic minerals.

BIOTITE GRANODIORITE

Biotite granodiorite and hornblende-biotite granodiorite occur in the northwest corner of the map-area; along Crozier and MacAuley Creek; south of Jones Creek; and near Tom Thumb Mountain. East of Tom Thumb Mountain, the rock is a very fine grained porphyritic granodiorite in which



LEGEND

1 - 4	Leucocratic granite
5 - 16	Hornblende-biotite quartz monzonite
17 - 18	Fine-grained biotite quartz monzonite
19 - 22	Pink quartz monzonite
23 - 27	Biotite granodiorite
28 - 36	Hornblende granodiorite

Figure 9. Key to Figure 8.

the amounts of hornblende and biotite are subequal. In all other areas the rock is medium-grained hornblende-biotite granodiorite with colour indices ranging from 10 to 18.

The contact where medium-grained granodiorite has intruded fine-grained granodiorite is clearly exposed on the east side of Tom Thumb Mountain. Abundant inclusions of fine-grained granodiorite are enclosed in the medium-grained granodiorite. The size and abundance of inclusions increases toward the contact. At the contact blocks of fine-grained granodiorite make up to 80 per cent of the rock, separated by small dyke-like seams of medium-grained granodiorite. From a distance this contact zone has a spotted appearance. At the top of Tom Thumb Mountain, both types of granodiorite have been intruded by andesite and by a breccia pipe.

On the south side of Jones Creek, the intrusive nature of granodiorite into metamorphic rocks is clearly indicated by abundant blocks and cigar-shaped inclusions of biotite-feldspar gneiss in the granodiorite.

West of Boudette Creek, the granodiorite is intruded by leucocratic granite.

HORNBLENDE-BIOTITE QUARTZ MONZONITE

Grey weathering hornblende-biotite quartz monzonite forms most of the granitic rocks near Boudette Creek, south of Jones Creek, and in the vicinity of Lemieux Creek. Dominance of biotite over hornblende (totalling 5 to 10 per cent), abundance of smoky-grey quartz (25 to 35 per cent) and medium- to coarse-grain size characterize this rock. This unit contains local areas of granodiorite which were not recognized as distinct bodies in the field.

On the east side of the ring dyke, in the vicinity of Lemieux Creek, the quartz monzonite contains about 25 per cent pink potassic feldspar phenocrysts, averaging one to two cm, and a lesser amount of plagioclase phenocrysts of the same size. Locally the phenocrysts have a crude preferred orientation.

The quartz monzonite is intruded by the leucocratic granite mass and by dykes of the leucogranite in the western part of the map-area, and by fine-grained biotite quartz monzonite south of Tom Thumb Mountain.

A potassium-argon age determined from biotite in one specimen is 57 ± 3 m.y. (M. Shafiqullah, pers. comm., 1969).

PINK QUARTZ MONZONITE

Pink quartz monzonite forms an area between volcanic rocks and granodiorite near the head of West Arm. These non-foliated, medium-grained rocks are characteristically pinkish grey due to alteration of the feldspars; potassic feldspar alters pink and plagioclase alters grey to greenish grey.

A body of quartz monzonite, 300 metres across, and 950 metres south of the head of West Arm, is distinct from the pink quartz monzonite in that it has a much higher colour index, higher specific gravity, and its plagioclase alters grey-green. This body is included with the pink quartz monzonite because of its spatial relation and composition, but the two types are not necessarily related. All rocks in this vicinity are shattered and locally brecciated.

The relation of these quartz monzonites to the surrounding granodiorite is not known. Possibly the pink quartz monzonite represents an altered marginal variant of the large mass of quartz monzonite to the south.

FINE-GRAINED BIOTITE QUARTZ MONZONITE

Fine-grained biotite quartz monzonite forms a small body, about 1,200 metres by at least 2,400 metres in the southeast corner of the map-area. This equigranular, nonfoliated, light-grey rock is characterized by fine grain size, presence of biotite as the sole mafic mineral, and very fresh appearance.

In the vicinity of contacts, the fine-grained biotite quartz monzonite contains inclusions of medium-grained granodiorite and quartz monzonite. None of the contacts were seen directly in the field.

LEUCOCRATIC GRANITE

Leucocratic granite forms a large body west of Boudette Creek, a large dyke-like intrusion up to 275 metres wide and at least 5 kilometres long at the head of West Arm, and several small dykes cutting hornblende granodiorite in the vicinity of the ring dyke north of Crozier Creek.

These rocks are easily recognizable from a distance by their distinctive buff to rusty tan weathering and by a very prominent widely spaced joint pattern. The deeply weathered rock has a rough surface that locally has disintegrated into a coarse grit.

This coarse-grained, equigranular rock is composed almost entirely of creamy pink microperthite and smoky-grey quartz. Quartz is generally anhedral, but locally displays euhedral or embayed hexagonal outlines. Mafic minerals make up less than 2 per cent of the rock. The body west of Boudette Creek has a margin, about 300 metres wide, of fine- to medium-grained granite composed almost entirely of quartz and graphic granite; with miarolitic cavities that are commonly lined with crystals of dipyramidal quartz, and locally with violet, cubic and octahedral fluorite.

Leucocratic granite intrudes quartz monzonite and metamorphic rocks west of Boudette Creek. The contact is nearly vertical and in most places sharp. Locally it is confused by a maze of leucogranite dykes and small apophyses that slash through the quartz monzonite and metamorphic rocks in a zone up to 150 metres wide. At the head of West Arm the leucogranite contact is vertical to steeply dipping northward.

AGE AND CORRELATION

Structural relations indicate that the relative ages of granitic rocks, from youngest to oldest are: leucocratic granite, fine-grained biotite quartz monzonite, hornblende quartz monzonite. Precise structural relations of the pink quartz monzonite and of the granodiorites are not known.

Radiometric age of hornblende-biotite quartz monzonite from east of Mount MacAuley (G14, Fig. 7) is 57±3 m.y.; that of the matrix of the ring dyke, which is the youngest intrusive phase, is 51+3 m.y. (M. Shafiqullah, pers. comm., 1969). Lowdon et al. (1963, p. 23; 1961, p. 15-16) reports radiometric ages ranging from 65 to 68 m.y. from massive biotite granodiorite specimens collected 10 to 15 kilometres southeast of Tom Thumb Mountain. These rocks are believed to be equivalent to the biotite granodiorite of the present map-area. The structural relations and radiometric dates indicate a trend from intermediate to salic compositions with time. This is in agreement with Christie's conclusions (1958, p. 177) that there is a progressive increase in potassium and silica in the granitic rocks of the Bennett area with time.

It is thus concluded that the sequence of emplacement of granitic rocks in the present area, from oldest to youngest, is hornblende granodiorite, biotite granodiorite, (?) pink quartz monzonite, hornblende-biotite quartz monzonite, fine-grained quartz monzonite and leucocratic granite.

The massive, uniform, and locally porphyritic character of the granitic rocks suggest that they are epizonal or mesozonal intrusions (Buddington, 1959). The leucocratic granite, by virtue of its euhedral quartz, miarolitic cavities, complex intrusive relationships, and occurrence in part as an arcuate body, is best considered to be an epizonal intrusion related to the cauldron subsidence complex.

CHAPTER IV

SKUKUM GROUP

Wheeler (1961, p. 18) informally subdivided the Skukum Group into a basal division of mixed but mainly andesitic rocks, a middle division mainly of felsic rocks and an upper division mainly of basaltic rocks. This generalized subdivision is insufficient for description of the complicated stratigraphy in the Bennett Lake complex. Therefore, stratigraphic subdivision of each of three subareas: Lemieux, Partridge and Crozier subareas is here proposed (Fig. 10). Boundaries of the subareas are roughly defined by the distribution of formations. The thickest succession is exposed in the Partridge subarea, where the Skukum Group is divided into six formations: the Partridge Lake, Cleft Mountain, Gault, MacAuley Creek, Lemieux Creek and Jones Creek Formations (Fig. 11). The Partridge Lake and Cleft Mountain Formations mainly occupy the Partridge subarea but overlap, in part, into the Crozier subarea. These formations and the Gault Formation are absent from the Lemieux subarea. The MacAuley Creek Formation is common to all three subareas whereas the Lemieux Creek and Jones Creek Formations are present only in the Partridge and Lemieux subareas. In the Crozier subarea, rocks that overlie the MacAuley Creek Formation are divided into three formations: two of these are informally designated the 'Crozier Breccias' and the 'Crozier Tuffs and Lavas'; the third, and youngest stratigraphic unit, is the Boudette Creek Formation.

TERMINOLOGY OF ASH-FLOW UNITS

In the description of pyroclastic rocks to follow, most of the terms accord with the usage of Smith (1960a) and Ross and Smith (1961) as explained by Peterson (1970, p. 67).

> Ash flow: a turbulent mixture of gas and pyroclastic material, predominately ash, that moves rapidly across the ground surface; the individual depositional unit of an ash-flow accumulation corresponding to the deposit resulting from the passage of one *nuée ardente*.
>
> Ash-flow sheet: any sheetlike unit or group of units considered to be of ash-flow origin.
>
> Cooling unit: a single or multiple ash-flow deposit that has undergone continuous cooling; that is, no one part of the deposit had cooled completely before another part was emplaced upon it.
>
> > Simple cooling unit: a cooling unit that has had an essentially uninterrupted cooling history.
> >
> > Compound cooling unit: a group of ash flows that have had much the same cooling history except that minor interruptions in cooling can be recognized in deviation from the zonal welding and crystallization patterns of a simple cooling unit.
>
> Composite sheet: an ash-flow sheet that grades laterally from one cooling unit into two or more.

In this study, the term *ignimbrite* is used as the rock formed by the deposition and consolidation of ash flows. The term *ignimbritic* refers to rocks having the aspect of ignimbrites but not necessarily of ash-flow origin. The term *eutaxitic* describes the fabric of a tuff imparted by the ordered arrangement of streaks and lenses of pumice or glass or their devitrified

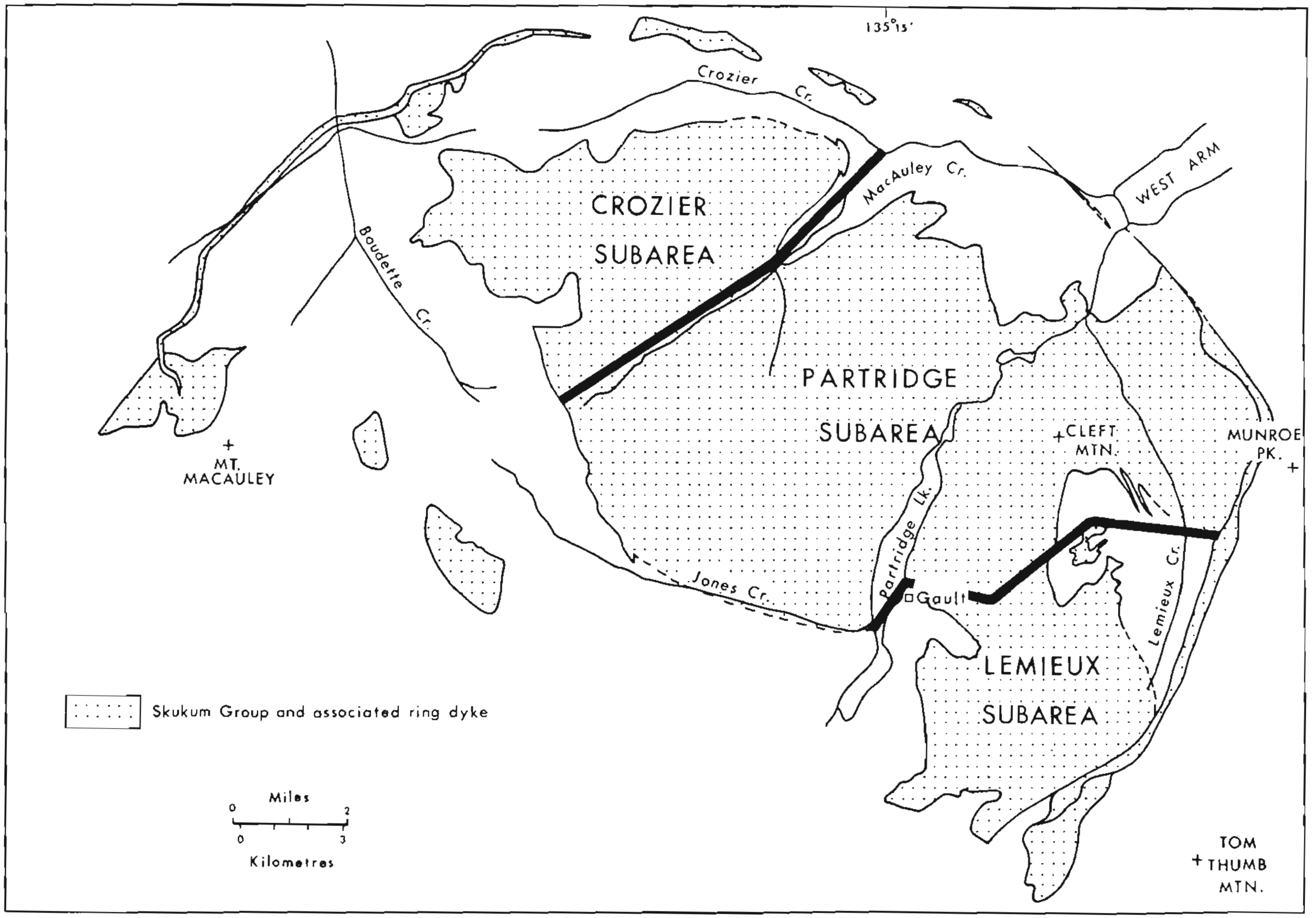


Figure 10. Subdivision of the Bennett Lake complex into the Crozier, Partridge and Lemieux subareas.

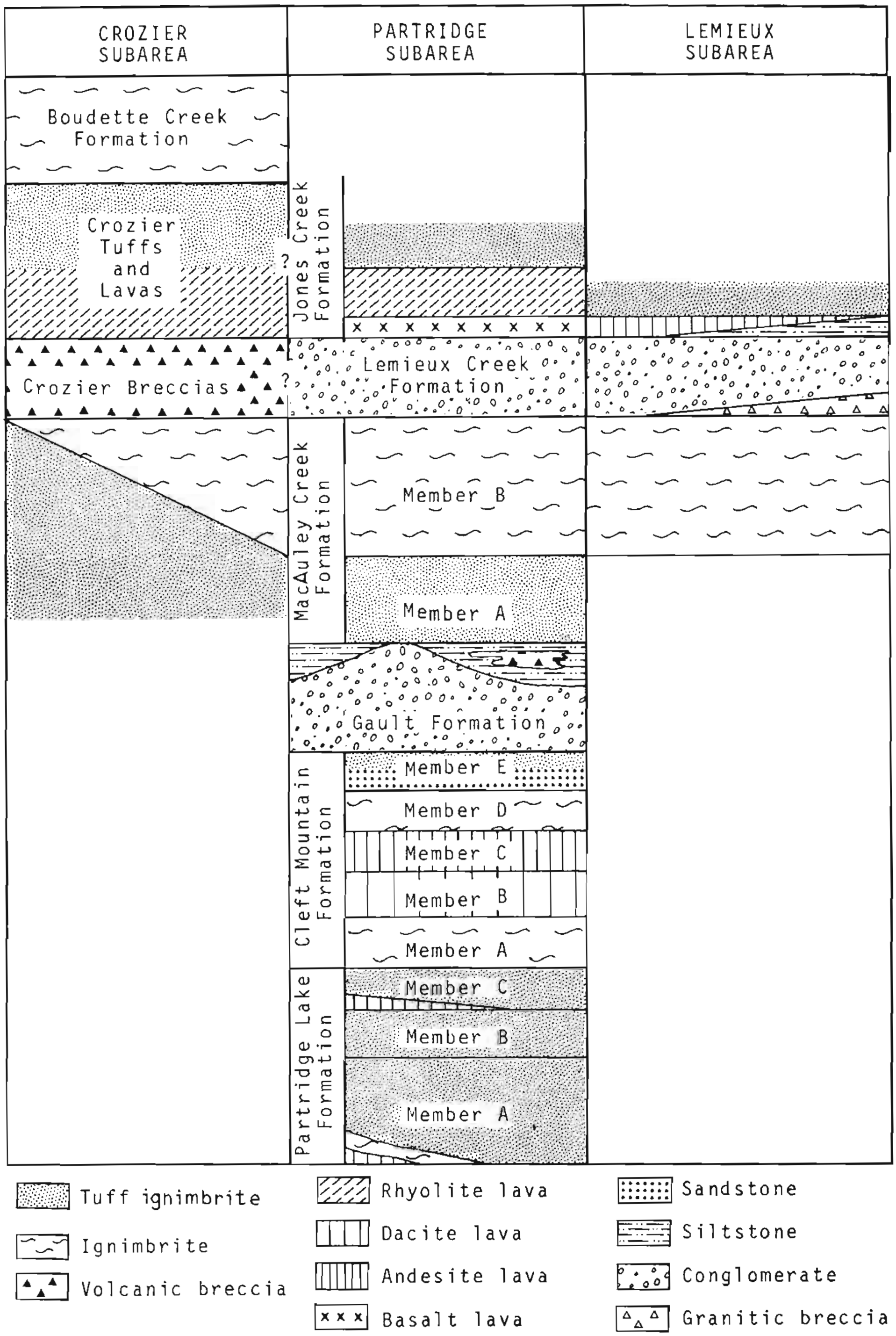


Figure 11. Correlation chart of the Skukum Group within the Bennett Lake complex (correlation of Crozier Tuffs and Lavas and Crozier Breccias is conjectural).

counterparts. The term fiamme refers to glassy lenticles (or their crystallized counterparts) which have a cross-section shaped like tongues of flame.

TEXTURES

The following sections describe welding and crystallization features common to most tuffs and ignimbrites of the Skukum Group.

Welding Textures

Welding may be defined as the cohesion, and deformation of vitric particles in a tuff by reason of having been hot and viscous at the time of their emplacement. The incipient stages of welding in fresh ash flows is marked by the cohesion of glassy fragments at their points of contact (Smith, 1960a, p. 823). This sticking results in the breaking of the rock through the pumice lumps rather than around them as in nonwelded tuffs. In rocks that are completely crystallized, however, criteria for welding depend mainly on the visible deformation of pumice fragments and shards.

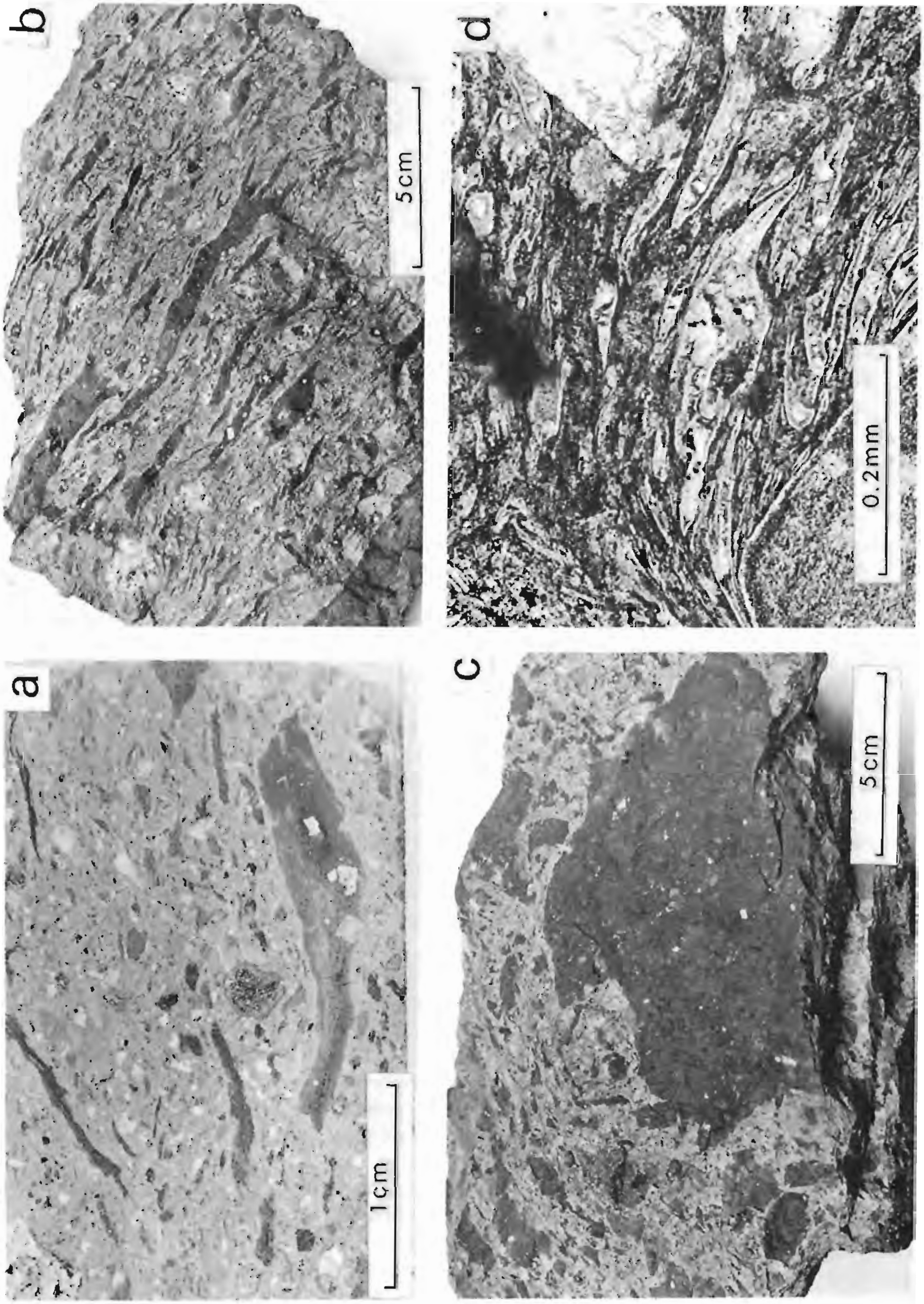
In this map-area, the degrees of welding are described as nonwelded, partly welded, moderately welded, and densely welded, and are defined on the basis of visible deformation of pumice and shards. Nonwelded tuffs show no indication of deformation of pumice or shards in hand specimen or in thin section. These rocks lack eutaxitic structure and generally lack any preferred orientation of shards and pumice.

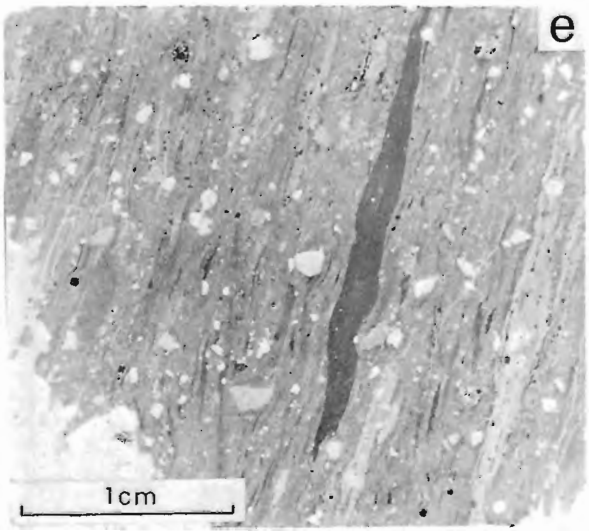
In partly welded tuffs, some of the pumice shows evidence of deformation. Large pumice fragments are partly collapsed and display intricate flame structure at the ends. Small pumice and platy shards are generally bent and have preferred orientation adjacent to lithic or crystal fragments. Away from rigid fragments, however, they display undeformed delicate features. These rocks have poorly developed eutaxitic structures shown by preferred orientation of some deformed pumice fragments. Pumice and some shards in these rocks are partly replaced by green chlorite, whereas shards and dust are very slightly altered. This selective replacement of pumice enhances the visibility of eutaxitic structure in hand specimen.

In moderately welded tuffs all pumice and shards are clearly deformed. Pumice fragments are lens-shaped with intricate digitations at their ends. Vesicles are almost completely collapsed so that internal pumice structure is not obvious. Length to thickness ratios of pumice range from 2 to 25 and average 7 to 10. Pumice and shards are molded around lithic and crystal fragments (Pl. II). In hand specimen, these rocks vary from medium grey-green to dark grey, and show very well developed eutaxitic structure. Large pumice fragments are generally darker colours (green to dark brown) than finer pumice and shards of the matrix (medium grey-green to dark grey).

Densely welded tuffs (Pl. II) have a higher degree of distortion of pumice and shards than in moderately welded tuffs: length to thickness ratios commonly reach 60:1 and average 20:1. Pumice is completely collapsed leaving very little evidence of vesicular structure. Original pore space in the rock has been completely obliterated. Pumice parallel to foliation appears as long thin strands that are molded around lithic and crystal fragments and taper out into fine sinuous, branching tails. Shards are commonly

PLATE II





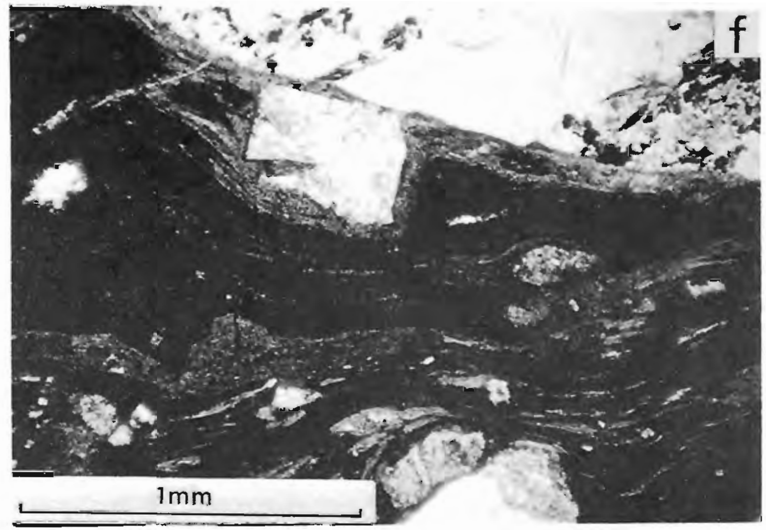


Plate II. Welding textures of tuffs from the Bennett Lake Complex (See also Plate V for non- and partly-welded tuffs).

(a) Thin section of moderately welded tuff from the MacAuley Creek Formation, showing weak eutaxitic foliation and elongate deformed pumice. Unpolarized light.

(b) Moderately welded tuff from the MacAuley Creek Formation broken perpendicular to prominent eutaxitic foliation, showing delicate fiamme structure in flattened pumice (center).

(c) Moderately welded tuff from the MacAuley Creek Formation broken parallel to the eutaxitic foliation, showing flattened pumice.

(d) Photomicrograph of moderately welded tuff from the Cleft Mountain Formation showing deformation of shards around lithic and crystal fragments. Plane-polarized light.

(e) Thin section of densely welded tuff from the MacAuley Creek Formation showing pronounced flattening of pumice and shards.

(f) Photomicrograph of densely welded tuff from the MacAuley Creek Formation showing pumice molded around lithic and crystal fragments. Plane-polarized light.

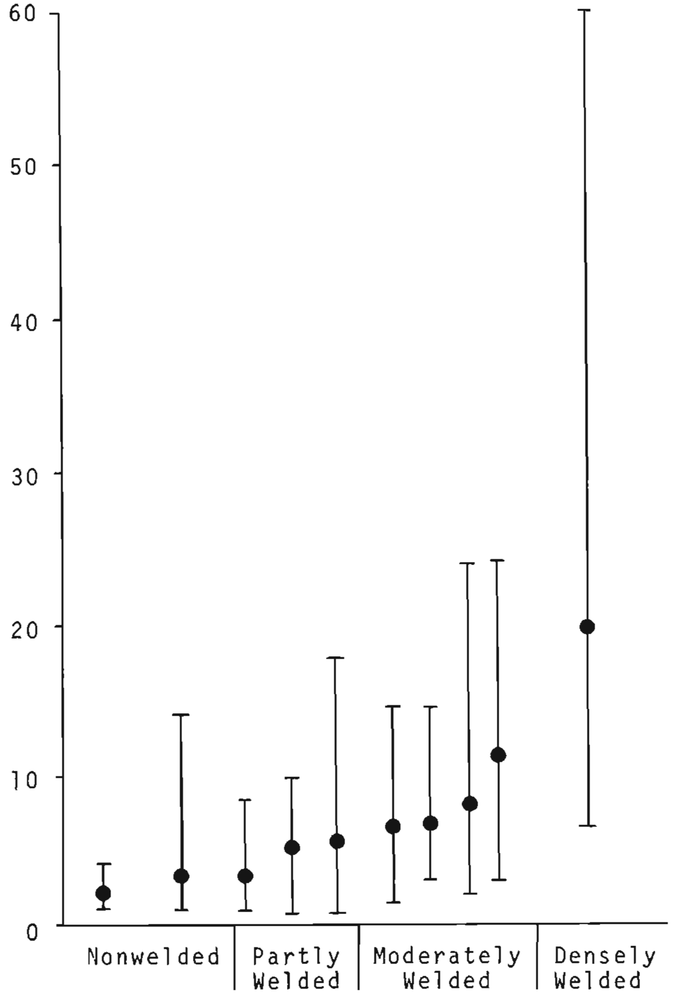


Figure 12.

Relation of length to thickness ratios (L/T) of pumice fragments to apparent degrees of welding. Upper and lower bars indicate the range of values; dot indicates average values.

thin streaks or extremely flattened Y-shapes; boundaries are almost obliterated. Hand specimens of these rocks are very dark charcoal grey, very brittle, locally with subvitreous lustre and subconchoidal fracture. Eutaxitic structure, although very well developed, is not as obvious as in the moderately welded tuffs because both fiamme and shards are the same colour. The ultimate end product of the welding process, in which there has been complete homogenization of the original glass (Smith, 1960a, p. 823) was not identified in any formation in this map-area.

Figure 12 and Table II show length to thickness ratios of pumice and shards representing all the degrees of welding defined above. Twenty to forty ratios were measured perpendicular to foliation in both hand specimen and in thin section, for each specimen. Measurements in orthogonal planes perpendicular to foliation yielded approximately the same values. The range and average values of the ratios increase with degree of welding. In a section parallel to foliation of one moderately welded specimen, there was virtually no preferred orientation of elongated fragments and the ratios have

TABLE II

Summary of length and thickness measurements of deformed pumice (data are plotted in Fig. 12).

	Length (mm)		Thickness (mm)		Length: Thickness		Number of Specimens Measured
	Range	Average	Range	Average	Range	Average	
Nonwelded	1.5 - 10.0	2.0	.17 - 6.0	1.0	1 - 14	2.7	2
Partially welded	0.5 - 14.0	2.3	.17 - 4.0	0.65	1 - 18	4.8	3
Moderately welded	0.7 - 16.0	4.4	0.1 - 2.0	0.6	2 - 24	8.2	4
Densely welded	3.0 - 56.0	10.3	0.15 - 3.5	0.7	7 - 60	19.5	1

PLATE III

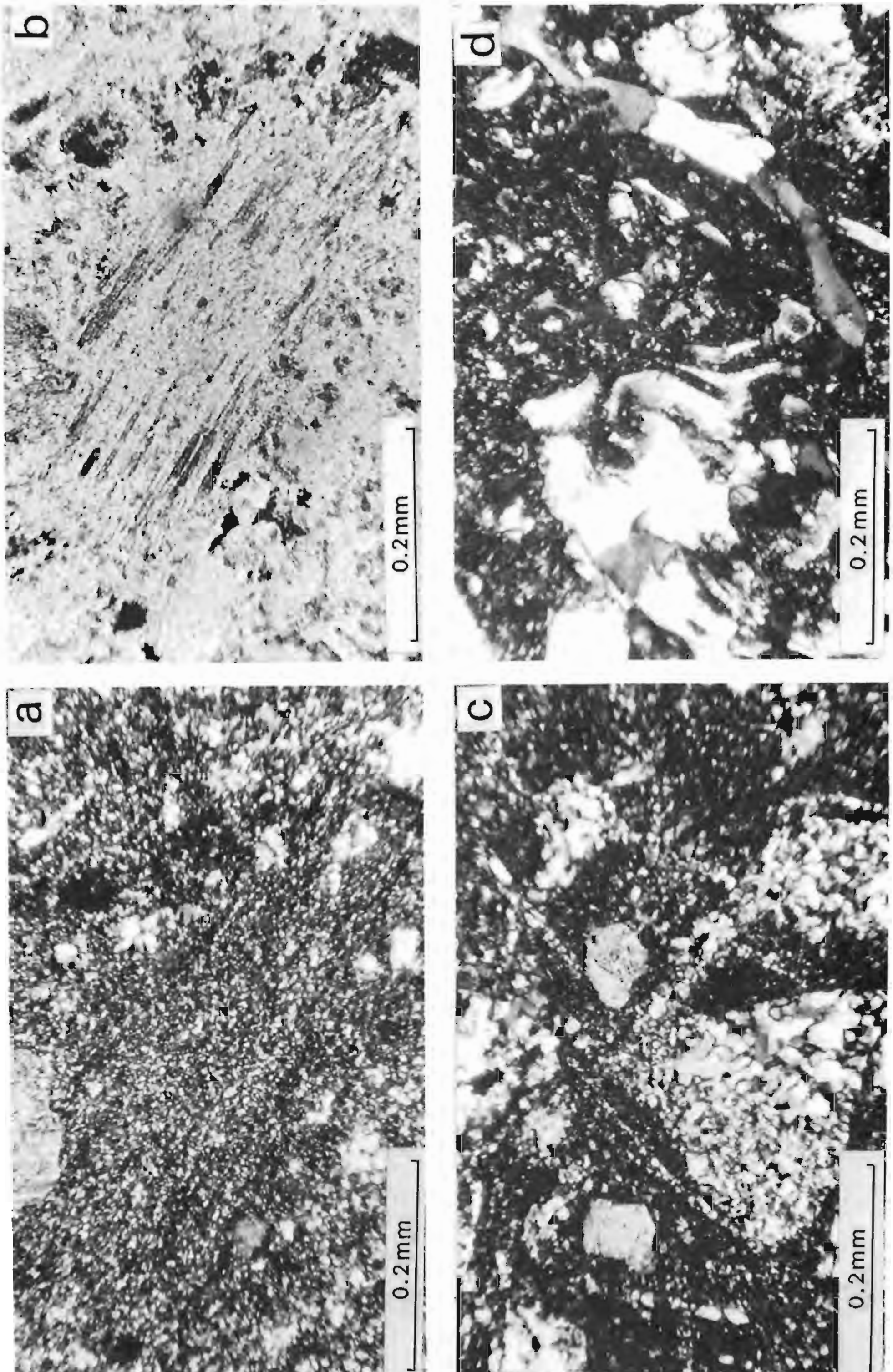


Plate III. Photomicrographs of crystallization features in tuffs from the Bennett Lake Complex.

(a) Fine-granular devitrification of tuff from the Partridge Lake Formation. Cross-polarized light.
(b) Same view as Plate IIIa, in plane-polarized light, showing pumice fragment.
(c) Medium-granular devitrification in pumice from the Partridge Lake Formation. Cross-polarized light.
(d) Coarse-granular crystallization of shards in tuff from the Partridge Lake Formation. Each shard is replaced by a few grains of quartz. Cross-polarized light.

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(e) Axiolitic crystallization of shard in tuff from the Partridge Lake Formation. Cross-polarized light.
(f) Subaxiolitic crystallization of shard in tuff from the Partridge Lake Formation. Cross-polarized light.
(g) Spherulitic crystallization of pumice in tuff from the MacAuley Creek Formation. Cross-polarized light.
(h) Subspherulitic crystallization in pumice fragment from the MacAuley Creek Formation. Spherulites are replaced by four to six sectors of quartz and feldspar. Cross-polarized light.

PLATE III

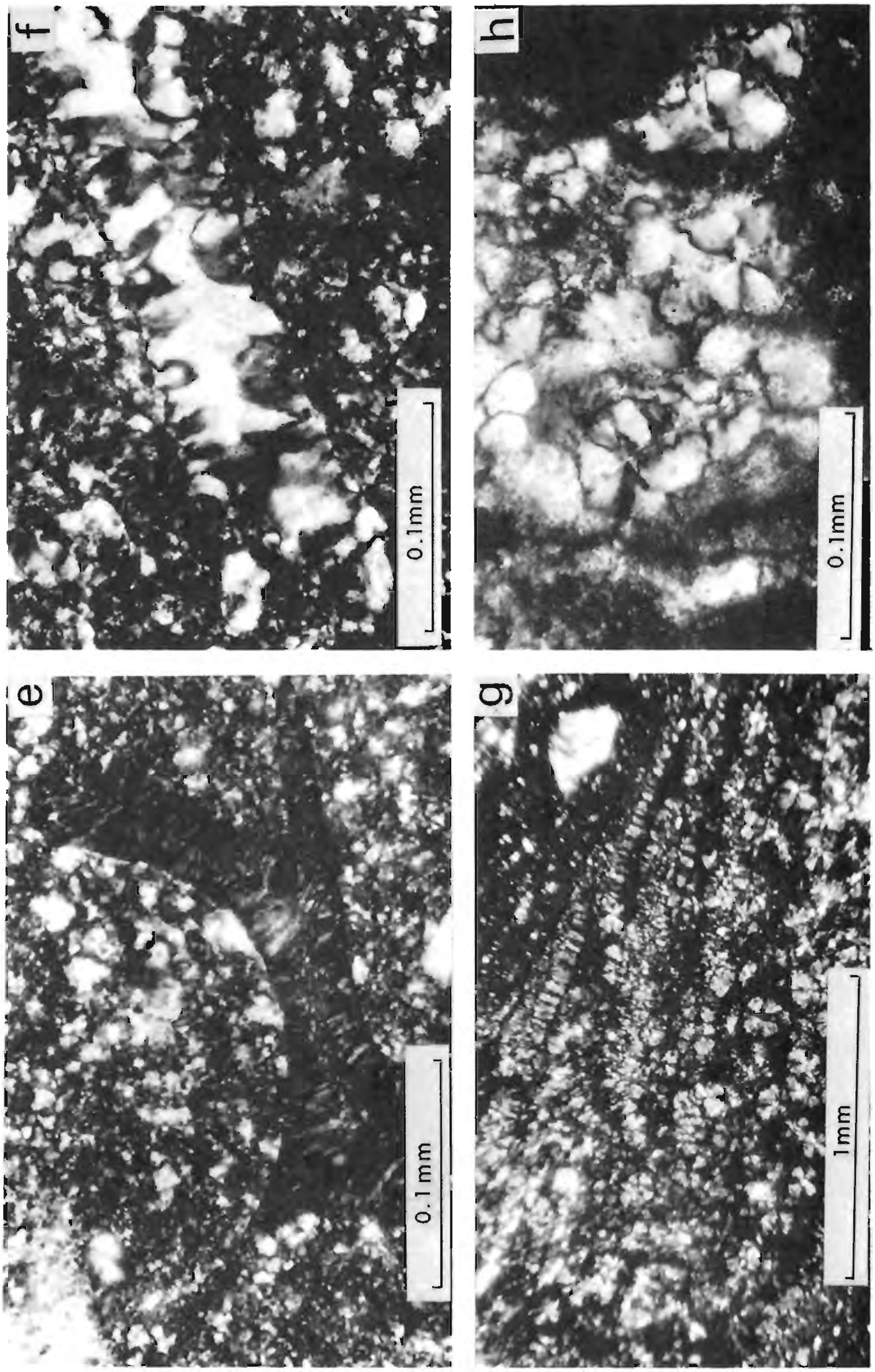

TABLE III

Devitrification textures distinguished in the tuffs and ignimbrites of the Bennett Lake complex.

Texture	Description	Reference
Spherulitic	Replacement of pumice by spherulitic growth i.e. radiating concentric array of crystalline fibres that have an over-all spherical or spheroidal form. In this study the spherulites are generally confined to within the boundaries of the fragment, but they may grow across the boundaries. The spherulites may impinge upon one another so that a completely spherical form is not attained.	Plate IIIg
Axiolitic	Fibres of feldspar and cristobalite that have grown normal to the outline of a shard and meet at a central zone of discontinuity that commonly forms a dark line. The axiolitic growth is confined to within the boundaries of the shard which it replaces.	Ross et al. (1961, p. 37) Plate IIIe
Fine-granular	Aggregates of equant to irregular intergrown grains less than 15 microns across. Individual grains commonly extinguish in an undulose wave.	Plate IIIa
Medium-granular	Aggregates of generally equant grains ranging from 15 to 50 microns across. Commonly the internal pumice structure is completely destroyed by this type of crystallization and coarser types.	Plate IIIc
Coarse-granular	Aggregates of grains generally ranging from 50 to 130 microns across or more. Grains may be equant or irregular, to micropoikilitic and granophyric intergrowths. Internal pumice structure is generally completely obliterated. Shards and small pumice are pseudomorphically replaced by one or more grains of quartz.	Plate IIId
Micropoikilitic	Single crystals of quartz enclose feldspar either microlites, spherulites or fine crystals.	Haworth (1888) Plate IVc
Granophyric	Irregular intergrowths blebs, patches and threads of quartz in a base of feldspar. The term is also used by Lofgren to describe quartz intergrowths in a base of feldspar spherulites. Smith used the term to include coarse quartz-feldspar intergrowths.	A.G.I. (1960) Lofgren (1971, p. 112) Smith (1960b, p. 152) Plate IVb

PLATE IV

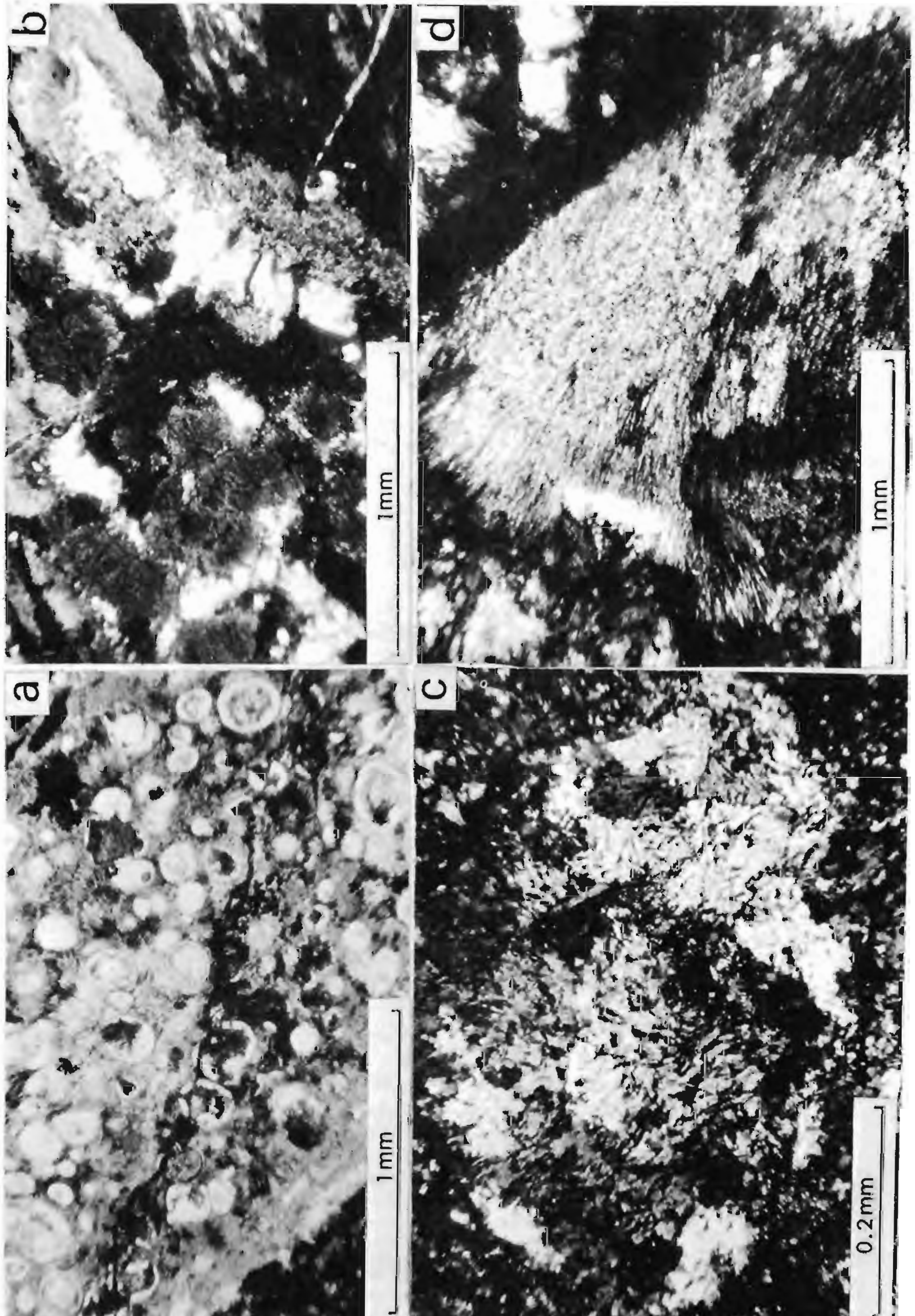

PLATE IV

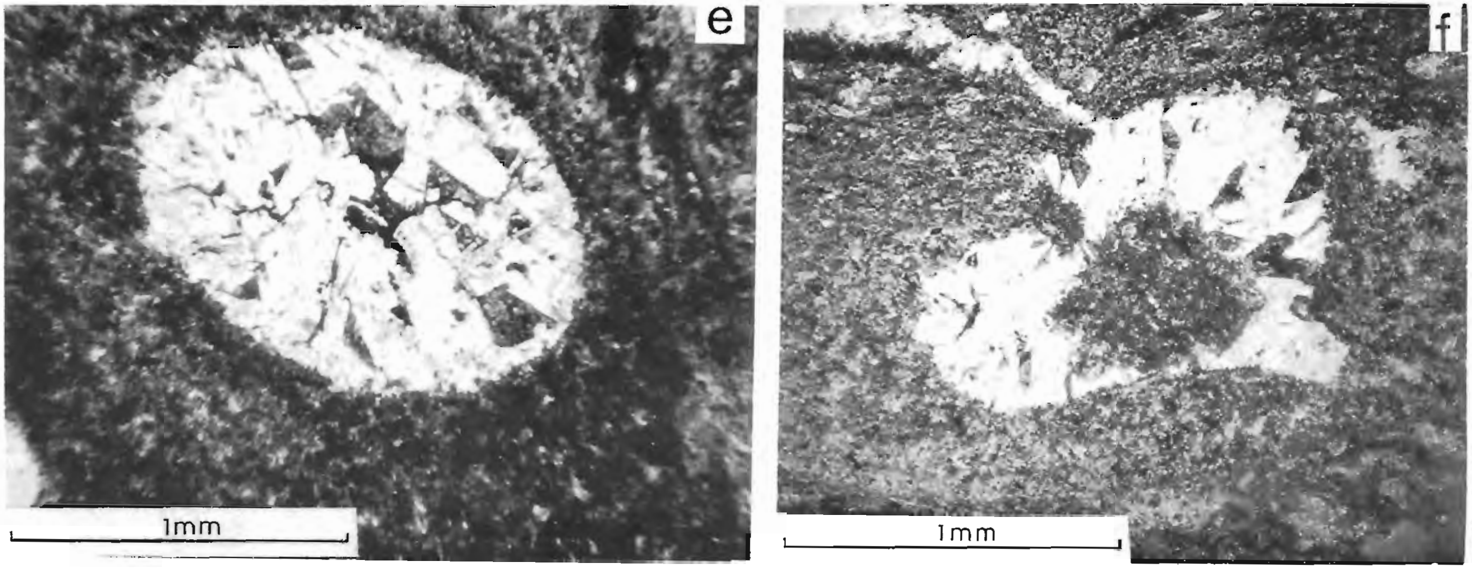

Plate IV. Photomicrographs of crystallization features in tuffs from the Bennett Lake Complex.

(a) Spherules in pumice from the Partridge Lake Formation. Cross-polarized light.

(b) Granophyric crystallization in pumice from the MacAuley Creek Formation. Intergrowth of quartz (white) and feldspar (shades of grey). Cross-polarized light.

(c) Micropoikilitic crystallization in pumice from the Partridge Lake Formation. Pumice is replaced by single crystals of quartz enclosing fine feldspar. Cross-polarized light.

(d) 'Snowflake' texture in pumice from the MacAuley Creek Formation. Fine grains of quartz and feldspar have parallel optical orientation so that broad patches have similar birefringence. Cross-polarized light.

(e) Vapour phase crystallization in vesicle of ignimbrite from the Cleft Mountain Formation. Note the prismatic form of quartz. Cross-polarized light.

(f) Vapour phase crystallization in a (?) vesicle in ignimbrite from the Cleft Mountain Formation. Prismatic quartz fills the area around a fragment. A fine stringer of quartz runs across and parallel to foliation. Cross-polarized light.

ranges similar to nonwelded tuffs. The variation in ratios parallel to foliation was thus interpreted as related to flattening of pumice with variable shapes rather than to stretching during flow. No systematic relation was found between length to thickness ratios and length of deformed fragments. This suggests either that the amount of deformation is independent of original size of fragments, or that original shapes were quite variable within the size ranges considered.

Devitrification Textures

All pumice, shards, and dust are devitrified to aggregates of quartz and feldspars. Terms describing devitrification textures are defined in Table III and illustrated in Plate III. The terms fine-, medium- and coarse-granular are introduced in this study for convenience of description.

No glass was found. Some thin sections appear isotropic under low magnification, but under high magnification and intense illumination are seen to be very weakly birefringent and made up of cryptocrystalline to fine-granular devitrification products, with abundant fine chlorite and very finely disseminated hematite. Hand specimens of such rocks are dark grey to black, have conchoidal fracture and subvitreous to resinous lustres. Such rocks are referred to as the subvitreous ignimbrites.

The progressive development of the devitrification process in shards and pumice is illustrated by the sequence spherulitic and axiolitic, fine- to medium-granular, coarse-granular, micropoikilitic and granophyric textures. There is a complete gradation from one type of crystallization to another, and in many places the distinction is arbitrary. In the transition from spherulitic to granular stage shards have a subaxiolitic structure shown by a crude preferred orientation of the granules along the edges of axiolites (Pl. IIIf); spherulites have recrystallized to a subspherulitic texture defined by four to six undulatory sectors of quartz (Pl. IIIh). The recrystallization process apparently continues until pumice fragments are replaced by coarse-granular aggregates of quartz and feldspar. In some pumice fragments, individual spherulites may be partly or completely replaced by single quartz spherules (Pl. IVa). The internal pumice structure is generally completely destroyed by medium- and coarse-grained devitrification and the pumice fragments are recognized only by the general over-all form of the aggregates or by remanent fiamme which may be preserved by fine-granular devitrification along margins. Shards are pseudomorphically replaced by one to three grains of quartz (Pl. IIId). In micropoikilitic texture the common "wave" of undulose extinction over broad patches suggests that they have been derived from spherulitic aggregates. This texture is similar to the "snow flake" texture described by Anderson (1969). Potassic feldspar is distributed in streaks and very fine pockets within the quartz.

True granophyric texture, where blebs of quartz are enclosed by a feldspar base, is rarely seen. Quartz blebs and spherules within a feldspar base or coarse quartz grains surrounded by feldspar along pumice margins are very common (Pl. IVb).

Vapour Phase Textures

Smith (1960a, p. 152; 1960b, p. 828) and Ross and Smith (1961, p. 27) have discussed criteria for identification of material deposited from a vapour phase. In this study, features attributed to crystallization from a vapour phase include (1) cavity fillings of quartz and fluorite; (2) irregular aggregates of coarse feldspar in intershard material that does not appear to be replacing any particular feature; (3) fine- to medium-granular rims on shards and pumice that are otherwise completely replaced by chlorite. Cavity fillings commonly have thin rims of medium-granular quartz and fillings of one or more of the above minerals. Commonly vesicles in pumice contain over-all lath and wedge forms that are internally composed of medium- to coarse-granular aggregates of quartz. These forms are interpreted as relict tridymite that has inverted to quartz (Pl. IVe, f).

Zonal Welding and Crystallization

Welding and crystallization features of ash-flow deposits, including those of the Skukum Group, commonly demonstrate a zonal distribution. In the Bennett Lake complex several types of devitrification consistently occur in particular zones of welding or positions within cooling units. Spherulitic and granophyric crystallization are common in zones of very dense welding, and intense alteration in the centres of cooling units. Basal and upper non- to partly-welded zones have fine- to medium-granular and sometimes axiolitic crystallization. Vapour phase crystallization occurs near tops and bottoms of cooling units and is commonly associated with coarse-granular, granophyric and micropoikilitic crystallization. Only the densest zones of welding contain 'subvitreous' ignimbrite.

Detailed studies (Smith, 1960b) of welding and crystallization zones in Recent ash-flow deposits suggest that these features may indicate the temperature of emplacement, rate of heat loss and the direction of the source of the ash flows. Ash flows emplaced at high temperatures result in ignimbrite units which are densely welded throughout, except for thin basal and upper zones of partial to moderate welding. Conversely, thick cooling units which are non- to partly-welded, indicate low temperature deposition. Crystallization zones may indicate rates of heat loss of the cooling units. The centres of densely welded, high temperature ash flows, where the rate of heat loss is low, are characterized by spherulitic crystallization. Conversely, in zones of rapid heat loss, zones such as the upper, lower and distal parts of ash flows, tuffs are vitric, and show no crystallization. Zones of high heat loss within high temperature ash flows thicken away from the source.

In ignimbrites of the Bennett Lake complex, zones indicating high heat loss (little welded, upper, lower and distal parts of units) exhibit only fine- to medium-granular devitrification, without spherulitic and vapour phase crystallization took place only in low heat loss zones, during cooling of the glass. Most granular types of crystallization formed after the glass had cooled. The remaining glass crystallized directly to a fine-granular mass, and spherulites and axiolites of previously devitrified glass were replaced by fine- to medium-granular masses.

In the Bennett Lake complex, ash flows with low emplacement temperature are characteristic of the early eruptions of each cycle whereas those with high emplacement temperature, resulting in thick low heat loss zones and thin high heat loss zones, are characteristic of the bulk of later eruptions.

STRATIGRAPHY

PARTRIDGE AND LEMIEUX SUBAREAS

Partridge Lake Formation

Definition, Distribution and Thickness

The Partridge Lake Formation consists mainly of non- to partly-welded tuffs that form monotonous, pale greenish grey weathering bluffs along the lower sides of the Partridge Lake and MacAuley Creek valleys and in the northern parts of the Lemieux Creek valley (Fig. 13). In the Partridge Lake valley, it is divided into three members: pale grey to pale green non-welded tuff (member A); dark grey to greenish grey, partly welded tuff (member B); and pale green to pale grey generally nonwelded tuff, lapilli tuff and tuff breccia (member C).

Tuffs of members A and B are altered to dark grey or mauve rocks adjacent to lavas, rhyolite dykes and sills, and in proximity to fault zones. A zone up to 18 metres wide, for example, surrounds the rhyolite sill near reference locality P_1 (Fig. 13). Lavas and ignimbrites locally mark the boundary between the middle and upper members and form the lowest exposed units of the formation on the east side of Partridge Lake. .The type section is on the lower north side of Cleft Mountain (Figs. 13 and 14*).

In parts of the MacAuley Creek valley and in the northern part of Lemieux Creek valley, the succession is complicated by the lack of the marker units and distinct zones of welding and alterations (used to distinguish the three members in the Partridge Lake valley) and by local lava flows, volcanic breccias, epiclastic breccias and conglomerates. Furthermore, the succession in these areas possibly contains some tuffs of the MacAuley Creek Formation which are lithologically very similar to tuffs of the Partridge Lake Formation. In these areas all mainly pale green tuffs and tuff breccias are grouped together and tentatively correlated with the Partridge Lake Formation (Fig. 13).

Exposed thicknesses are at least 1,170 metres at Cleft Mountain (type section), 610 to 700 metres on the southwest side of Partridge Lake, and 520 metres on the west side of Partridge Lake. Across the MacAuley Creek valley thicknesses decrease from 400 metres on the northeast side to 150 metres on the northwest side of MacAuley Creek.

Contact Relations

The lower contact of this formation is not exposed in the base of the Partridge Lake valley, but it is seen in several places on the sides of MacAuley Creek valley, and on ridges between MacAuley Creek and Partridge Lake. At P_2 (Fig. 13), a reddish brown weathering, granitic boulder

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*All rock sample numbers are abbreviated from field numbers by omission of common terms. For example, field number LQO10867 is 01087 in text.

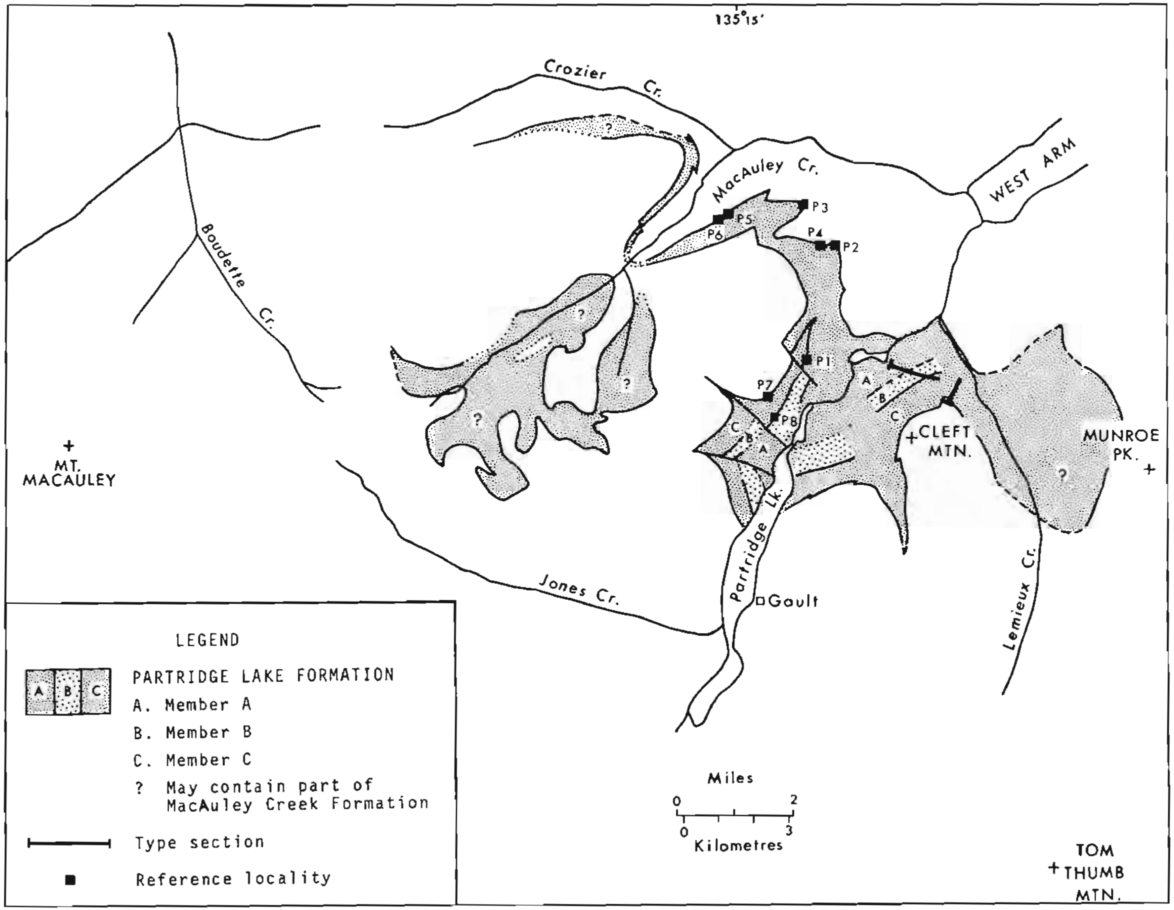


Figure 13. Distribution of the Partridge Lake Formation, location of the type section, and reference localities.

conglomerate bed lies between pale green lapilli tuff of the Partridge Lake Formation and shattered to brecciated pink quartz monzonite. The conglomerate bed is 5 metres thick on the east side of the ridge and tapers out westward. The conglomerate-quartz monzonite contact dips 10 degrees toward the southwest.

At P_3, where pale green lapilli tuff unconformably overlies shattered and brecciated quartz monzonite, the contact is approximately horizontal. Local variations of these contact relations include the following: (1) tuff overlying a series of small faults in the granite terrain of the order of 10 to 25 metres displacement (at P_4); (2) lavas and avalanche breccias at G11 (see Fig. 7 and section on epiclastic breccias); (3) a thick wedge of volcanic-metamorphic-granitic fragment conglomerate 36 metres thick at P_5; and (4) lapilli tuff overlying a regolith of the granitic terrain at P_6.

On the northwest side of MacAuley Creek, tuff overlies deeply weathered granodiorite and in some places granodiorite breccia.

The formation is overlain conformably by the Gault Formation on the southeast and southwest sides of Partridge Lake. North of "Gault" the Partridge Lake Formation grades upward, over 15 to 30 metres, from pale green tuff, through granitic boulder rich tuff, to granitic boulder conglomerate of the Gault Formation. At P_7, the Partridge Lake Formation is overlain by the basal ignimbrites of the Cleft Mountain Formation. The dark brown ignimbrite grades downward through dark to pale green tuff within 6 metres.

Foliation, Layering and Joints

In the type section (Fig. 14), units 4, 9, and 10 have an indistinct foliation formed by the preferred orientation of elongate lithic fragments and of partially flattened pumice. Unit 3 has an ill formed foliation suggested by preferred orientation of lithic fragments.

Gross layering within the formation is defined by the three massive tuff members and locally by intermember lavas and ignimbrite units. The contact between members B and C is locally marked by a lava flow on the east and west sides of Partridge Lake. At P_8, where the lava flow is absent, the contact appears to be gradational. No evidence of an erosion surface was found between the lava and the underlying tuff at these localities.

Vague layering within member C, in the type section, is evidenced by the lapilli rich zones and by the zones of coarse-granular crystallization in unit 10.

On the northeast side of MacAuley Creek, the formation locally includes medium bedded ash-flow and air-fall tuffs with sharp contacts.

On the southwest side of Cleft Mountain, the upper units of this formation have prominent, steeply dipping joints, spaced 1 to 3 metres apart, that give the outcrops a slabby appearance. These joints become more closely spaced and more blocky as they pass upward into the moderately welded ignimbrite of the overlying Cleft Mountain Formation.

Lithology

Tuffs: All the tuffs are composed of a great variety of volcanic, granitic and crystal fragments surrounded by devitrified pumice, shards and volcanic dust. The constituents do not vary significantly throughout the formation. The main lithologic variations are the degree of welding; the intensity of alteration and hence the colour of the fresh rock; and the size and abundance of accessory and accidental fragments (Fig. 14).

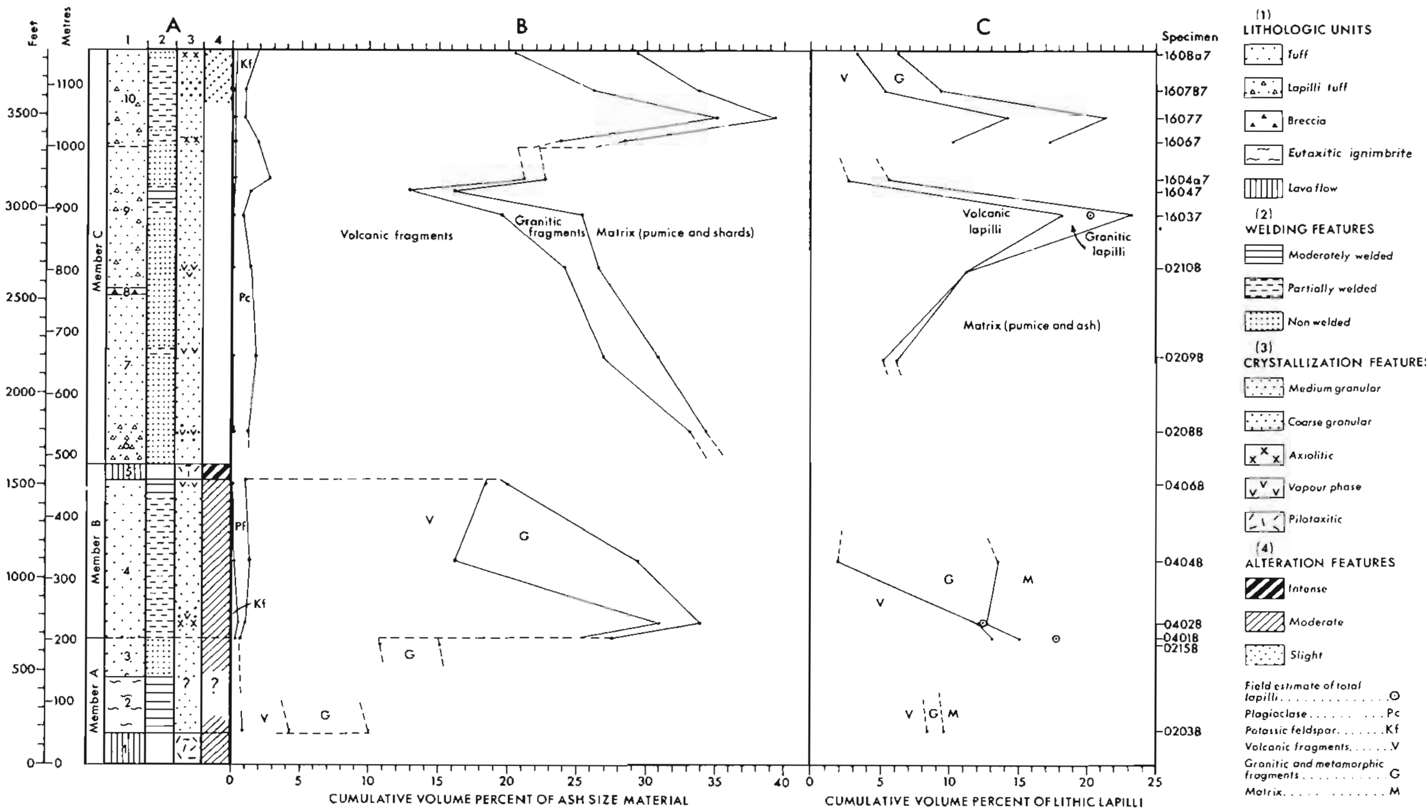


Figure 14. Type section of the Partridge Lake Formation: A, lithologic features; B, modal content of ash size material; C, modal content of lapilli.

PLATE V

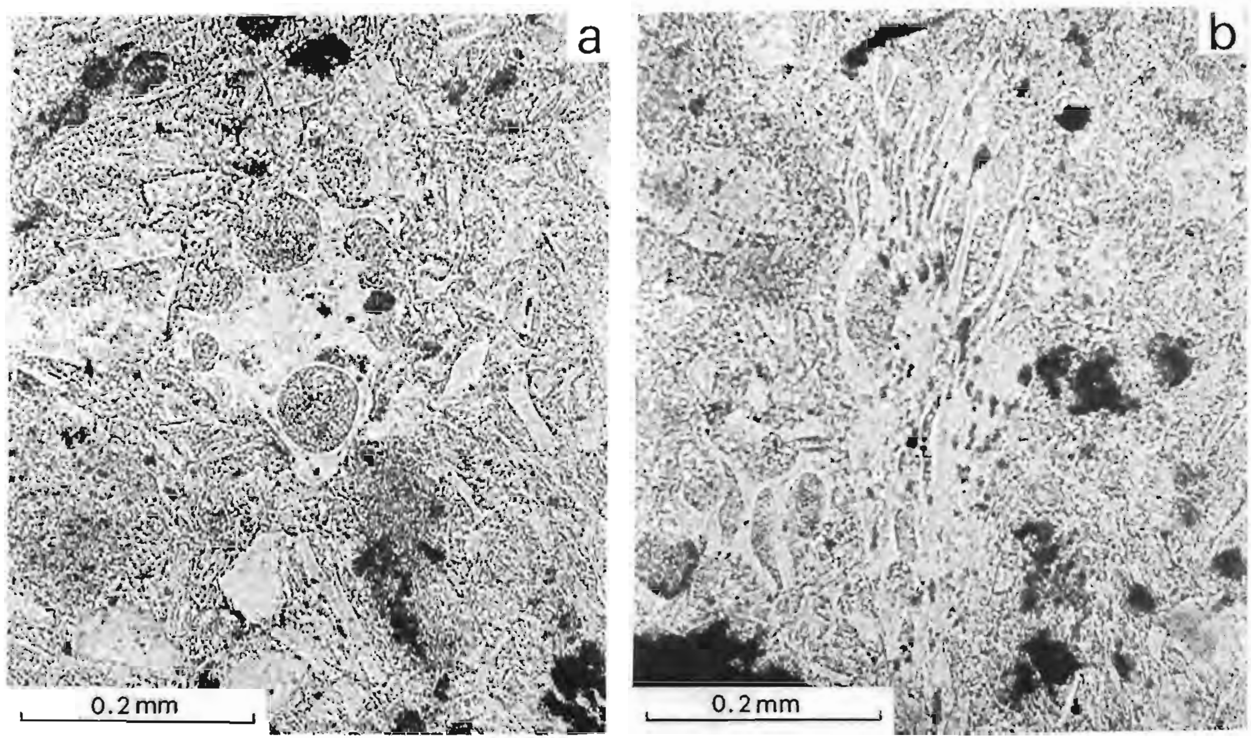


Plate V. Photomicrographs of pumice and shards in tuffs from the Partridge Lake Formation.

(a) Pumice with round vesicles in partly welded tuff. No distortion of pumice or shards is evident in this microphotograph. Plane-polarized light.

(b) Elongate tube pumice in partly welded tuff. Plane-polarized light.

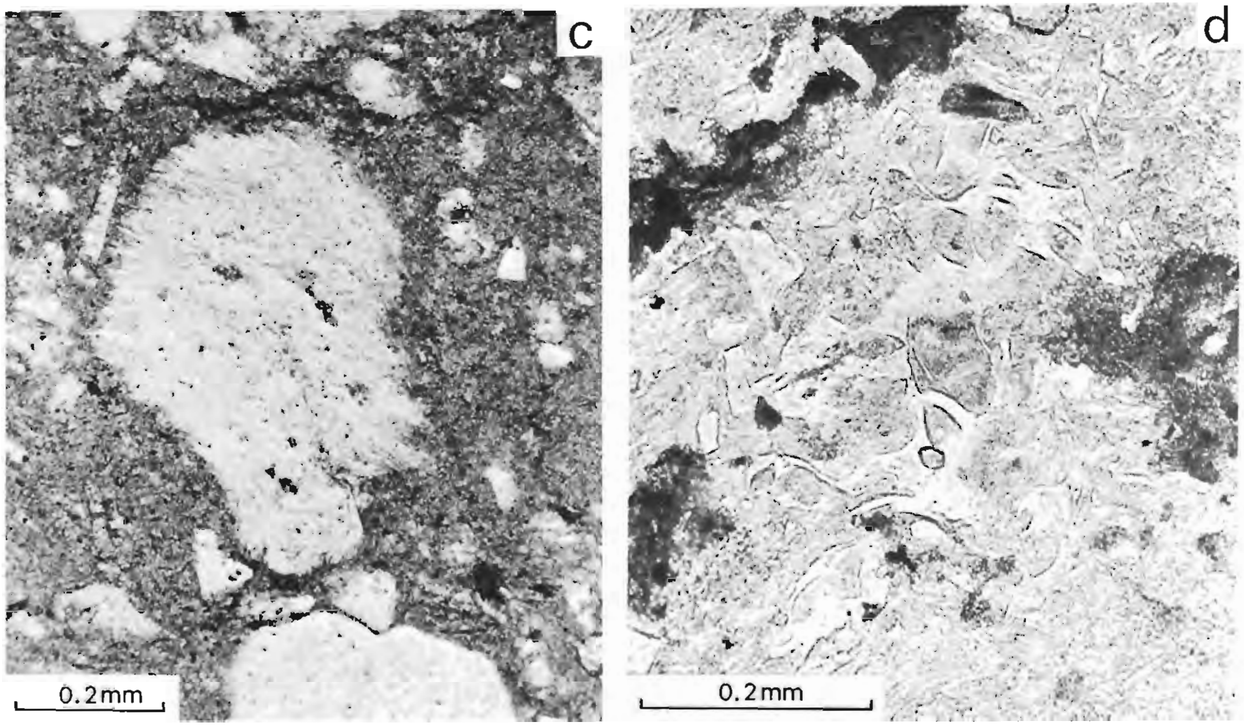


Plate V continued

(c) Rounded pumice with wispy margins. Plane-polarized light.
(d) Vesicular shards in non-welded pumice. Plane-polarized light.

PLATE V

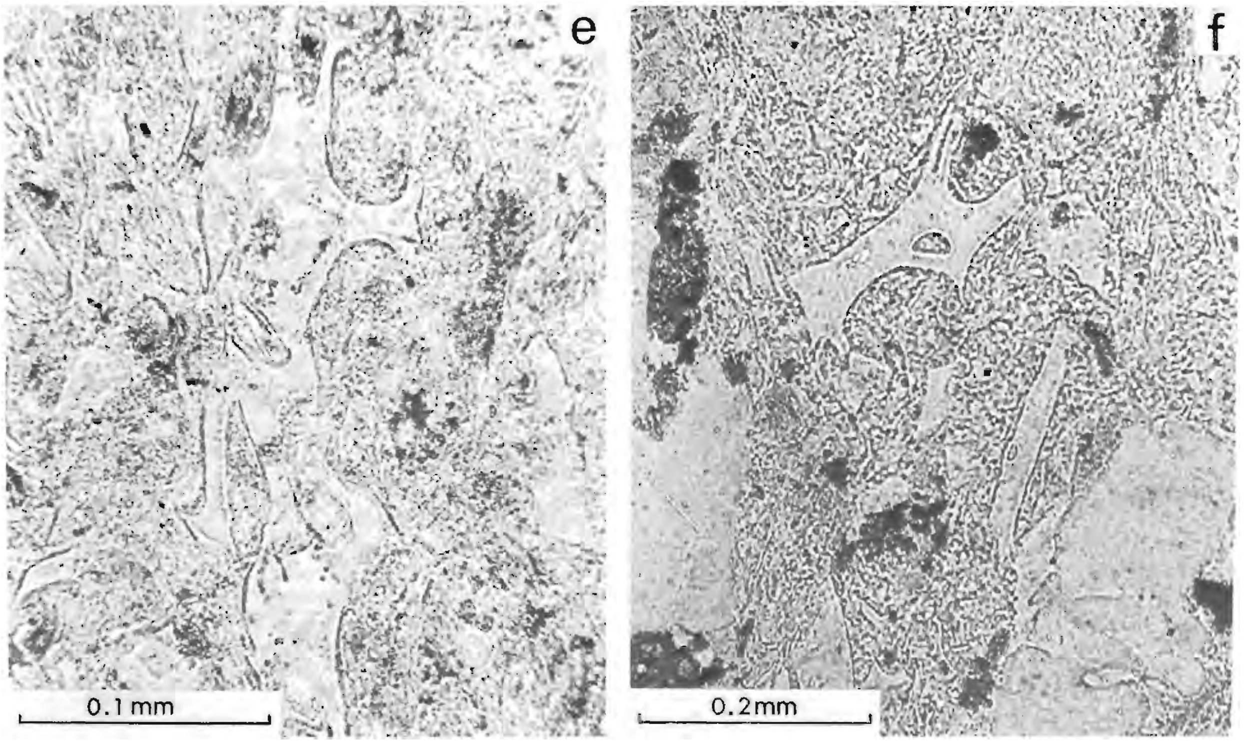


Plate V continued

(e) Elongate arborescent shard in non-welded tuff. Plane-polarized light.
(f) Platy and vesicular shards in partly welded tuff. Plane-polarized light.

Cognate Constituents: Cognate constituents include devitrified pumice, shards and volcanic dust, and feldspar phenocrysts. Pumice and shards are difficult to identify in most hand specimens because of the similar colour of all the devitrified constituents. They have a wide variety of forms including elongate, lensoid, oval to bulbous, or irregular arborescent (Pl. V). Elongate types vary from over-all platy or lath-shaped, to long curved plates that are commonly bulbous at one end and taper out into long thin tails at the other. Lensoid and oval types generally have rounded terminations. The over-all smooth boundaries, however, are minutely irregular and display wispy ragged margins or fine cuspate protrusions. This type does not have abundant vesicles within the fragments. Perhaps some of this material is devitrified glassy lenticles rather than expanded pumice fragments. Irregular, arborescent types have many protruding cusps and semicircular to deep elongate embayments. Internally this type of pumice preserves very fine, delicate, lacy vesicle walls. Where vesicles are dominately elongate tubules the pumice is referred to as long tube type in contrast to the dominately spherical bubble type. Size of pumice ranges from 0.2 to 25 mm. The largest fragments generally have elongate or rounded forms, whereas the smaller fragments are arborescent types.

Shards range from 0.05 to 1 mm and have platy, vesicular (retains an unbroken bubble) juncture (three or more pronged shard) and elongate juncture forms (Pl. V).

Most tuffs contain almost all varieties of pumice and shards. In unit 10 elongate tube type pumice predominates in the upper part of the unit whereas spherical bubble type predominates in the lower part. Platy shards appear to be most common near the top of the unit.

Phenocrysts (0.3 to 1.0 mm) are almost entirely plagioclase, rarely sanidine and (?) quartz. Plagioclase composition varies from An_{32-33} in member A, An_{34} in member B and An_{34-37} in member C. Generally it has very thin normally zoned rims. Plagioclase is deeply embayed in member B and euhedral to subhedral, slightly rounded, but not embayed, in the other members.

Potassic feldspar phenocrysts are rare throughout the formation. They are apparently most abundant in member B, where they make up as much as 0.4 per cent of the rock. They are identified optically as orthoclase ($2V_x$:48°-59°; optic plane ⊥ (010)). Crystals are euhedral to embayed and are locally replaced by epidote.

Although quartz phenocrysts were not positively identified in any thin section, possible phenocrystic quartz in the upper member is suggested by rounded to subhexagonal forms.

Accessory and Accidental Constituents: Accessory and accidental constituents include pink and grey quartz monzonite, granodiorite and quartz, plagioclase and potassic feldspar crystal fragments derived from them; finely laminated and spherulitic rhyolite; tuff; and a variety of aphanitic volcanic fragments in various shades of grey, greenish grey, cream, mauve, green and black. Accessory fragments range from fine ash to 50 mm across. In member A, lapilli average 5 to 10 mm and make up to 10 to 20 per cent of the rock. In member B, lapilli average 3 to 10 mm and make up from 5 to 15 per cent of the rock: no distinct pattern of lithic fragment distribution was determined vertically or laterally within this member. On Cleft Mountain, member C is divided into 5 units on the basis of size and abundance of lapilli:

lapilli tuffs commonly contain 10 to 20 per cent fragments up to 5 cm; unit 8 is composed of 90 per cent lapilli up to 10 cm. Unit 10 is distinguished from the underlying lapilli tuff by the abrupt increase of lithic fragments near the base, and the partly welded character.

Estimates of roundness and sphericity of lapilli (made visually from the chart in Powers, 1953, p. 118) made from 26 representative specimens indicate that large lapilli tend to be better rounded than smaller lapilli and ash size fragments; granitic lapilli tend to be more rounded than volcanic lapilli; and sphericity is essentially the same for granitic and volcanic fragments. Virtually all specimens and outcrops studied were poorly sorted. There is no apparent difference in sphericity and roundness of fragments in tuffs that bear abundant- as compared to sparse-amounts of lapilli.

Textures: Members A and C are mainly nonwelded except for partial welding in parts of units 9 and 10. Member B is partly welded throughout. Minor deformation of some of the large pumice fragments in these units is indicated by undulation of their boundaries where they meet or bend around lithic or crystal fragments. Although no evidence of deformation was found in small pumice fragments and shards, some thin sections show local preferred orientation of shards.

Most of the larger sized pumice through member B has fine-granular devitrification, whereas smaller sized pumice and shards generally have medium-granular devitrification. At the base of the member pumice is medium-granular and shards have axiolitic texture.

Members A and C have medium-granular devitrification with coarse-granular near the bottom and top of the upper member. Shards near the top and bottom of unit 10 bear axiolitic crystallization. The coarse granular devitrification gives tuffs of unit 10 a fine-grained holocrystalline appearance in hand specimen in contrast to the aphanitic matrix of most other tuffs. This is a very distinctive zone on both sides of Cleft Mountain.

Vapour phase crystallization appears at the base of units 7 and 9 and in the middle of unit 7.

The most distinctive feature of member B is that most cognate constituents are intensely altered to a micro- to crypto-crystalline mass mainly of chlorite with some white mica and opaque material. Some shards are completely replaced by this propylitic alteration except for a thin rim of medium-granular quartz. Generally the most altered rocks are the darkest coloured and bear the most strongly deformed pumice.

Intermember Lavas and Ignimbrites: Lava flows, 15 to 25 metres thick, occur between members B and C of the Partridge Lake Formation. On Cleft Mountain this unit is a sparsely porphyritic andesite composed of 3 to 5 per cent andesine (An_{40-45}) (in one crystal the core is An_{65} and the rim is An_{44}) phenocrysts, less than 1 mm long, set in a dark grey pilotaxitic to trachytic matrix made up dominantly of andesine (An_{32-35}) microlites. Pervasive alteration of the matrix is very fine epidote, chlorite and calcite. Amygdales, ranging from 0.4 to 10 mm, are filled with quartz and epidote. On the southwest side of Partridge Lake the lava is a massive dark grey, aphanitic rock consisting of about 1 per cent altered plagioclase phenocrysts, less than 1 mm long, set in an intensely altered, cryptocrystalline matrix (resembling very fine granular devitrification) in which remanent skeletal crystals and microlite forms can be subtly distinguished. This rock may be a devitrified glass flow. Although these rocks are found at the same stratigraphic position at several localities within the Partridge Lake Formation, slight lithologic differences, such as in amounts of phenocrysts, size and texture of matrix microlites, and alteration products and vesicle fillings, suggest that they are probably not the same lava flow. They probably represent several isolated outpourings of lava which took place at about the same time.

On the northeast side at the bottom of Partridge Lake valley, the lowest units exposed below the lower tuff member include an ignimbrite unit 90 metres thick and underlying lavas about 55 metres thick. Both units appear to be of local occurrence. The lavas are dark grey and consist of euhedral to subhedral plagioclase and high sanidine phenocrysts, and abundant granitic and sparsely porphyritic volcanic clasts, set in an extremely fine felty matrix made up of skeletal crystals with crude preferred orientation. Lithic fragments are altered to carbonate, epidote and chlorite. Ignimbrite units contain about 9 per cent lapilli composed of quartz, feldspars, granitic and spherulitic volcanic fragments set in a dark grey moderately welded matrix. The eutaxitic matrix consists of devitrified pumice (averaging 2 to 6 mm long) and shards.

Interpretation: The Partridge Lake Formation was deposited mainly as pyroclastic flows with intermittent lava outpourings. The three members are interpreted to indicate three major episodes of eruption. At least seven ash-flow units are present and possibly many more that have not been recognized. No distinct divisions, for example, were recognized in member B, nor in other thick units (namely 7, 9, and 10). It is conceivable that huge single depositional units, could form very close to a vent. Zones of vapour phase crystallization, however, suggest possible boundaries between depositional units.

That these were relatively low temperature ash-flow eruptions is suggested by the general lack of welding in the very thick sequence (Smith, 1960a, p. 831). On the criteria of welding, member B and units 2 and 10 were probably higher temperature eruptions than the rest of the formation.

The gradational contact between the Gault conglomerate and the Partridge Lake tuff north of Gault is interpreted to indicate deposition of a fluidized rock fall avalanche on top of an ash flow during eruption, resulting in mixing of the two turbulent fluidized units at their contact.

The gradational contact between the Partridge Lake and Cleft Mountain Formations at P_7 may represent an alteration zone formed by heat and vapours emitted during deposition of the high temperature ash flows of the overlying Cleft Mountain Formation.

Fluctuating conditions within the magma chamber during this eruptive series is suggested by the restriction of resorbed phenocrysts to member B. This phenomenon may be explained by the following sequence of events: (1) early explosive eruptions (represented by member A) caused a sudden lowering of the pressure in the upper part of the magma chamber, which in turn effected partial remelting of crystals; (2) eruption of the magma containing resorbed crystals formed member B; (3) quiet effusion of lavas (unit 5); followed by (4) another series of ash-flow eruptions formed member C.

Thinning of the formation westward and southward from the vicinity of Cleft Mountain suggests that the vent(s) for these eruptions lay to the north or northeast of Cleft Mountain. A thick pile of chaotic volcanic breccias on the north side of Lemieux Creek probably mark the general area of venting (see section on eruptive centres).

An estimate of the minimum volume of this formation is 85 cubic kilometres (20 cubic miles).

Cleft Mountain Formation

Definition, Distribution and Thickness

The Cleft Mountain Formation outcrops as dark brown to dark grey weathering, massive, precipitous cliffs along the upper northern sides of Partridge Lake valley and the northeast side and bottom of the MacAuley Creek valley. It is divided into five members: A, ignimbrite; B, dacite lavas; C, andesite lavas; D, ignimbrite; and E, arenites and tuffs. Five reference sections (CMI to CMV) were measured in the vicinity of Cleft Mountain and west of Partridge Lake (Fig. 15); two of these are detailed in Figures 16 and 17.

The formation is 710 metres thick in CMV, the only location where a complete sequence is exposed; it is at least 610 metres thick on Cleft Mountain, and pinches out about 3 kilometres east of Cleft Mountain. It is interpreted to thin westward between Partridge Lake and MacAuley Creek.

Contact Relations

All units within the formation are conformable and there is no evidence of erosion between them. Members within the formation have approximately the same attitude in any one reference section.

The lower contact of this formation grades over 10 metres into member C of the Partridge Lake Formation near section CMIII. Within this transition zone the colour changes from pale green to dark grey, the degree of welding and hence development of foliation increases upward, and granitic fragments, up to 5 cm, make an appearance. The blocky columnar jointing in the underlying tuff continues through the transition zone and halfway up into the ignimbrite member.

This formation is overlain by conglomerate of the Gault Formation in CMV. On the east side of MacAuley Creek, however, the member D ignimbrite is overlain by ignimbrite of the MacAuley Creek Formation.

On the west side of Partridge Lake valley and the east side of MacAuley Creek valley, the Cleft Mountain Formation ends abruptly against the south wall of a large graben in the Partridge Lake Formation (Fig. 3, sections E-F-G-H). On the east side of Partridge Lake, the valley south of Cleft Mountain marks the position of a large fault that forms the south wall of the graben.

The formation was deposited around shattered granitic cliffs east of Cleft Mountain.

Foliation and Joints

Eutaxitic foliation is well developed throughout the ignimbrite members. It is essentially parallel to bedding near the tops and bottoms of the ash-flow units.

In CMIII there is a systematic change in fracture pattern from bottom to top of member A ignimbrite. The lower half has blocky columns that

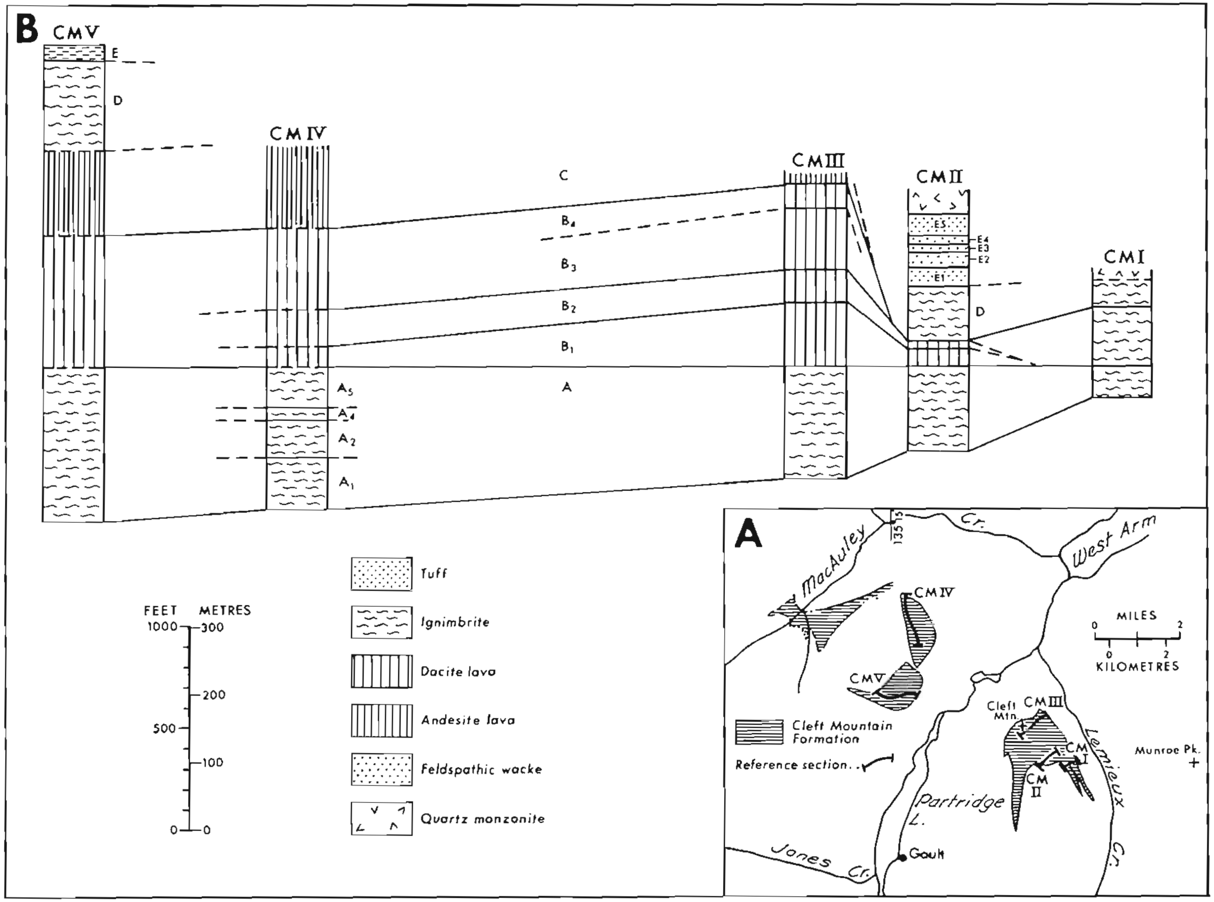


Figure 15. A - Distribution of the Cleft Mountain Formation (shaded areas) and location of reference sections.
B - Correlation of reference sections of the Cleft Mountain Formation.

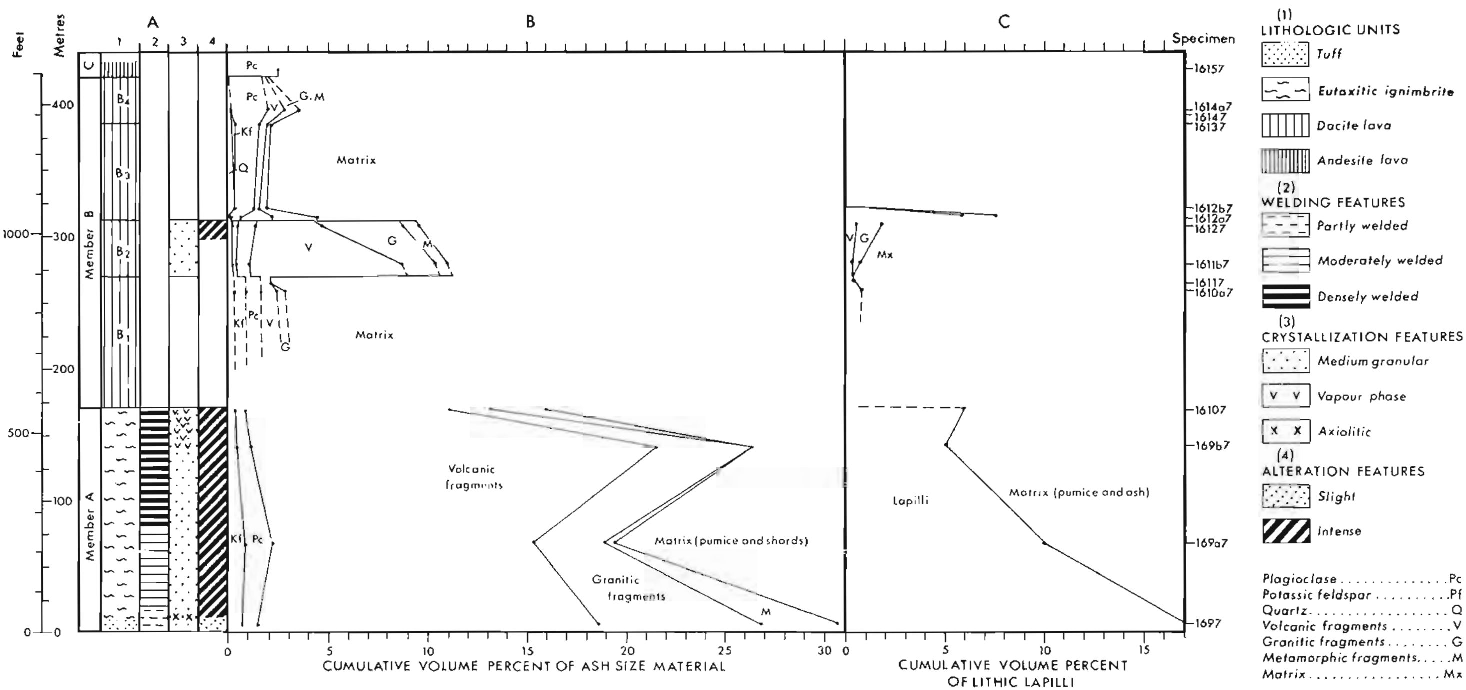


Figure 16. Reference section CMIII of the Cleft Mountain Formation: A, lithologic features; B, modal content of ash size material; C, modal content of lapilli.

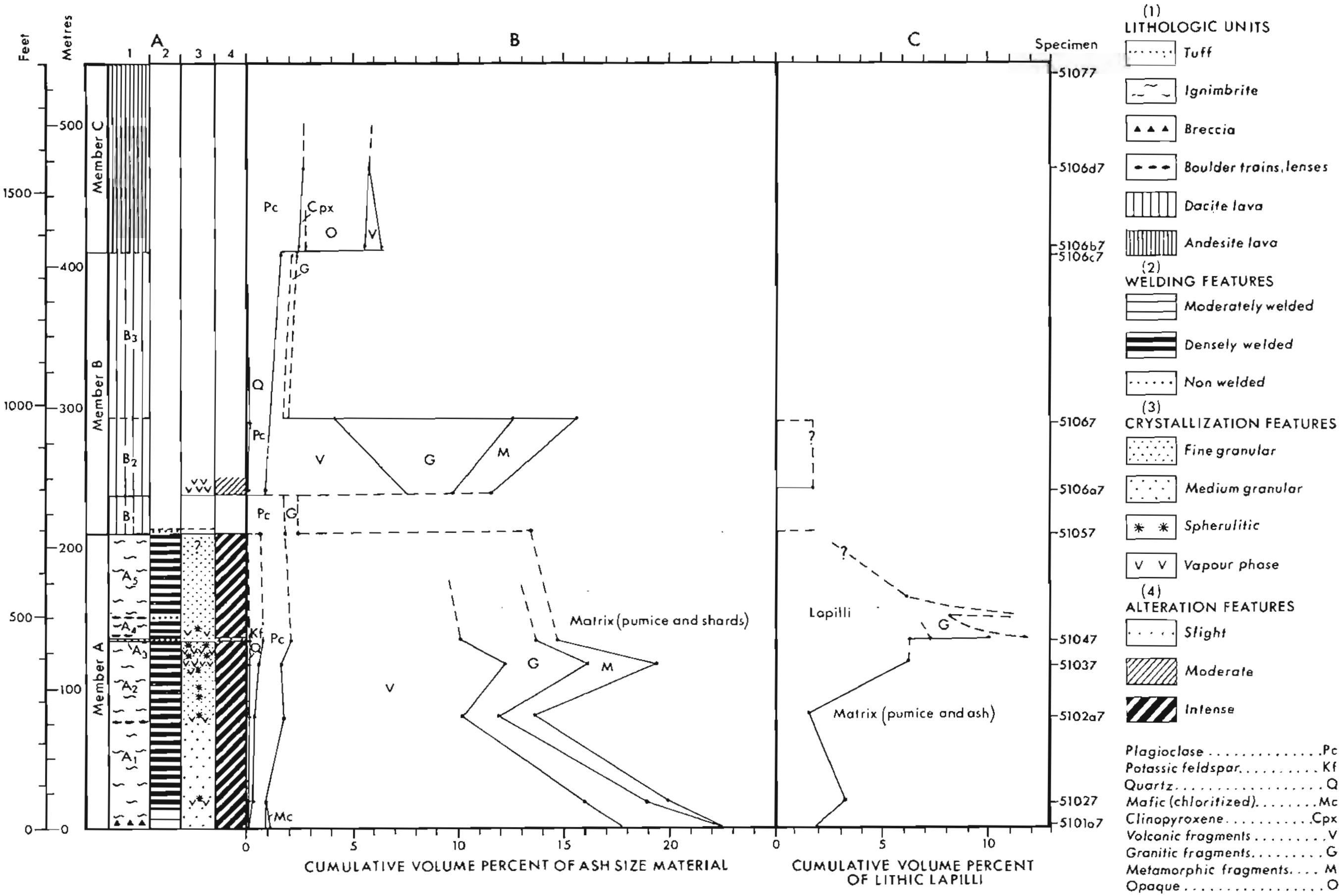


Figure 17. Reference section CMIV of the Cleft Mountain Formation: A, lithologic features; B, modal content of ash size material; C, modal content of lapilli.

PLATE VI

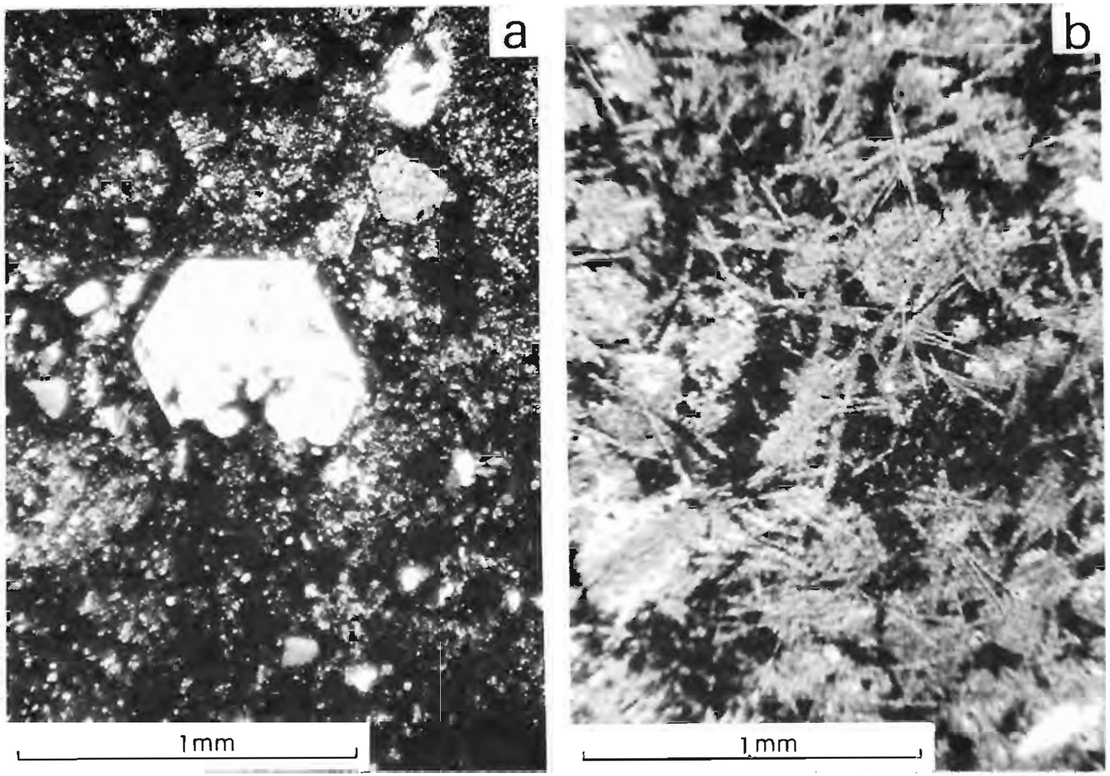


Plate VI. Photomicrographs of tectures from the Cleft Mountain Formation.

(a) Resorbed plagioclase phenocryst in ignimbrite of member A. Cross-polarized light.

(b) Relict spherulites and crystallites in felsophyric lava. The crystallites are replaced by very fine granular crystallization. Plane-polarized light.

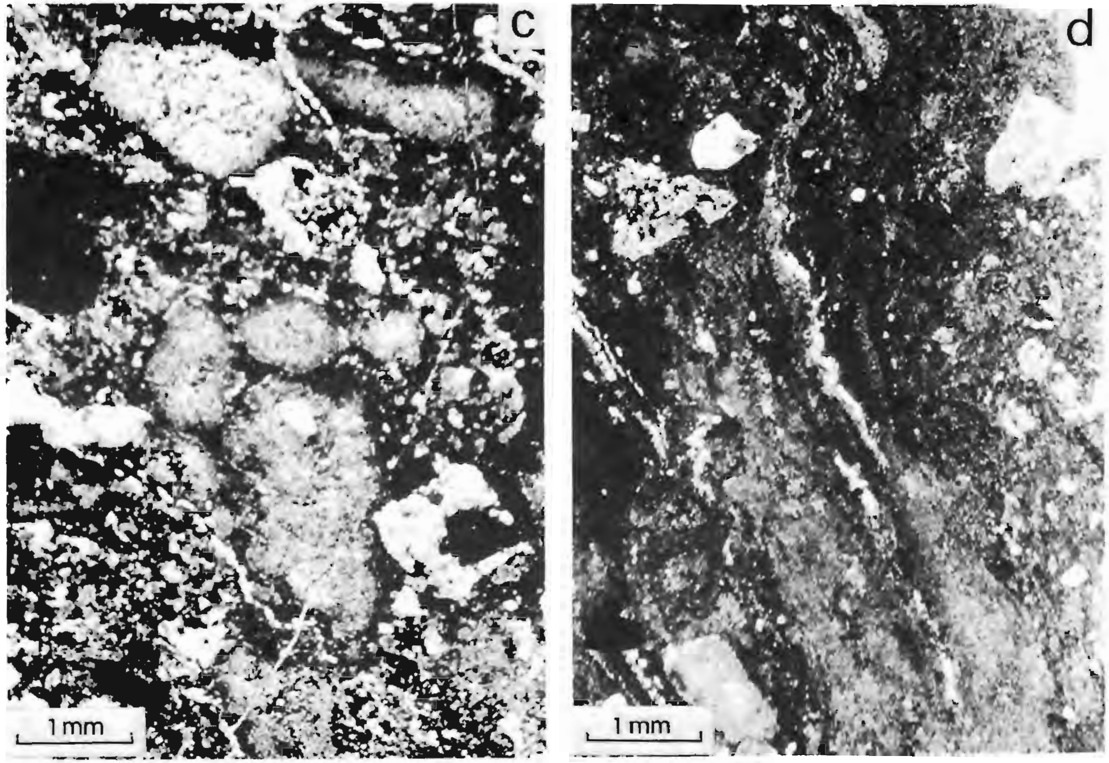


Plate VI continued

(c) Rounded cognate fragment in dacite. Plane-polarized light.
(d) Welded pumice-like digitation on lenticle at top of dacite flow (unit B_2). Plane-polarized light.

grade upward into a closely spaced irregular rubbly fracture in the upper half of the member. This recessive weathering rubbly fracture zone continues upward into the overlying dacite lava, tending to obscure the sharp contact between the two members.

Lithology

Ignimbrites (members A and D): The fresh colour of the ignimbrite (A) varies from pale greyish green with dark green lenticles, through dark grey to charcoal. Charcoal coloured rocks are very brittle, have a subvitreous lustre, and are extremely densely welded, but the eutaxitic structure is difficult to identify in hand specimen. Member D consists of very uniform, dark grey, densely welded ignimbrites.

All ignimbrite units are composed of volcanic, granitic, and metamorphic lapilli (generally less than 15 per cent) in a matrix of devitrified pumice, shards and dust, and ash-size lithic and crystal fragments. Pumice and shards in non- or partly-welded ignimbrites have essentially the same variety of forms and dimensions as those in the Partridge Lake Formation.

Phenocrysts, 0.5 to 20 mm across, include plagioclase, orthoclase, sanidine, quartz, chloritized mafic minerals and opaque oxides. They make up less than 3 per cent of the rock and plagioclase is the most abundant species (Figs. 16 and 17). No distinct pattern of variation of total phenocryst content or of the proportions of phenocryst species is evident in the sections studied in detail.

In member A, euhedral to subhedral oligoclase and andesine (An_{29-35}) phenocrysts, and broken fragments of phenocrysts, bear rounded and embayed crystal faces (Pl. VIa). Their composition is very similar throughout this member. Crystals have weak normal zoning only on very thin margins. $2V_x$ ranges from 76° to 85° indicating that the plagioclase is of the high temperature structural state (Smith, J.R., 1958, p. 1188).

Euhedral orthoclase phenocrysts ($2V_x$: 48°-60°) are perthitic, unzoned and rarely resorbed. Phenocrysts with the highest optic angles are at the base of the formation. Rare low sanidine phenocrysts were identified optically ($2V_x$: 20°) in member A.

Less than 0.1 per cent rounded quartz phenocrysts were identified in member A.

Mafic minerals are generally completely replaced by chlorite.

Accessory and accidental constituents include approximately the same variety of volcanic, plutonic and metamorphic material as described in the Partridge Lake Formation. Size ranges from fine ash to 15 mm. Larger sizes tend to be concentrated in basal parts of some depositional units, where the fragments make up to 30 per cent of the ash-size material (Figs. 16 and 17). In all sections the proportion of volcanic fragments is much greater than the sum of granitic and metamorphic fragments, and granitic fragments are generally more abundant than metamorphic fragments.

Ignimbrite (D) is densely welded throughout. On the southwest side of Cleft Mountain, plagioclase phenocrysts are embayed in the upper parts but not in the lower parts, and vapour phase crystallization is abundant in the upper parts. Although no distinct contacts were identified within this member, in CMII, three cliff forming zones, each 10 to 20 metres high, may be an indication of the number of depositional units present.

Vertical zoning within ignimbrite (A) is described by reference to CMIII and CMIV in the following sections.

Section CMIII: Member A can be divided into three vertical zones on the basis of degree of welding, colour and intensity of alteration (Fig. 16): zonal boundaries are completely gradational.

A basal, partly welded, pale green tuff zone grades upward into medium green, moderately welded tuff with 10 metres. This zone is slightly altered mainly to very fine chlorite.

The middle zone is a moderately welded, very dark charcoal grey, ignimbrite about 65 metres thick. Pumice is intensely altered to a deep brown cryptocrystalline micaceous mass with abundant finely disseminated opaque minerals. Shards are generally moderately altered whereas accessory tuff fragments are only slightly altered. The charcoal colour of hand specimens is related to the finely disseminated opaque material.

The upper zone is densely welded to the very top. It is dark grey, intensely altered to a brown to green cryptocrystalline micaceous mass, and contains much less disseminated opaque than the middle zone. On the south side of Cleft Mountain, however, ignimbrite at the top of the unit is a medium-green weathering, partly welded tuff that grades downward into the densely welded ignimbrite. Pumice and shards have fine- to medium-granular devitrification but the texture is generally masked by the intense alteration. Shards show axiolitic crystallization in the basal zone, medium-granular with very thin subaxiolitic rims in the middle zone, and medium- to coarse-granular in the upper zone. Generally shards have coarser devitrification than pumice. Vapour phase crystallization, observed only near the top quarter of this member, is evinced by round to oval vesicles, 1 mm across, filled with coarse quartz (?) plus some carbonate and hematite specks, and by pockets and streaks of coarse crystallization in the matrix.

Section CMIV: In this section member A is divided into 5 units (Fig. 17). Units A1 and A2 are dark grey, densely welded ignimbrite with subvitreous lustre that has a basal moderately welded tuff-breccia about 8 metres thick. A vapour phase zone at the top of unit A2 is at least 15 metres thick. Contact between units A1 and A2 is marked by a large pod of nonwelded tuff. The ignimbrite above and below this pod shows no apparent lithologic change.

An undulatory buff weathering, nonwelded tuff layer (unit A3), 1 to 3 metres thick, marks the contact between units A2 and A3. Units A4 and A5 are dull grey, densely welded ignimbrites, separated by a series of lenses of buff tuff, and by green weathering brecciated tuff which forms a recession on the cliff face. The base of unit A4 bears abundant granitic fragments.

Dacite Lavas (member B): This member is divided into a lower felsophyric lava flow (B1); middle unit (B2) with features similar to both felsophyric lava and ignimbrite; and upper felsophyric flows (B3, B4). Chemical analysis (see Appendix II, Fig. 45) shows the lavas to be dacites. Because the upper and lower parts are lithologically identical, only the thick lowermost unit will be described in detail. This unit forms dark grey to dark brown weathering cliffs having blocky columnar joints (averaging 10 to 25 cm in cross-section and 30 to 90 cm long). Near the upper one half to two thirds of the unit, closely spaced irregular hackly fracture gives outcrops a knobby, rubbly aspect. The unit has upper and lower zones of autobrecciation. These rocks are dark grey (almost black), massive, sparsely porphyritic felsophyres. Phenocrysts are less than 1 mm across and make up less than 2 per cent of the rock. They include euhedral to subhedral, locally embayed, normally zoned andesine (An_{41-46} in cores to An_{36} on rims), rounded quartz and chloritized mafic minerals. The matrix is a mass of relict microlites (0.005 to 0.1 mm long) and relict (?) skeletal crystallites less than 0.005 mm, surrounded by a cryptocrystalline mass. Relict microlites consist of extremely fine granular crystalline aggregates that have crude over-all lath forms. In some places they form relict spherulites (Pl. VIb). The area between relict microlites is intensely altered to very fine carbonate and micaceous material, and is speckled with very fine opaque minerals. A subtle microscopic layering is defined by discontinuous, subparallel concentrations of relict crystallites. Sparse, oval amygdales 0.3 to 1 mm across, contain carbonate and chlorite. Fragments of granitic and trachytic material make up less than 2 per cent of the rock.

Unit B2 contains abundant oval, lenticular, and elongate cognate fragments that lack the minute marginal digitations that are characteristic of pumice (Pl. VIc). The devitrified (fine- to medium-granular) fragments are warped around lithic and crystal fragments. Some of the cognate fragments near the top of this unit have digitations at their ends similar to welded pumice (Pl. VId). No shards were identified. The fragments are more strongly deformed than in the middle parts of the unit. Andesine (An_{30-36}) phenocrysts are strongly embayed. Lithic fragments and crystals are present in amounts and proportions essentially the same as in the ignimbrite members. Oval and rounded amygdules with quartz rims are filled with chlorite. The matrix between devitrified lenticles is an impalpable, intensely altered mass very similar to the matrix of the felsophyric lavas.

Andesite Lava (member C): This member consists of a series of medium grey weathering andesite lavas that form a series of recessive benches, above the dark grey dacite cliffs below. They are medium greenish grey, sparsely porphyritic rocks consisting of euhedral to subhedral plagioclase phenocrysts (less than 2 mm) in an aphanitic matrix.

In the lowest unit in CMIII, normal oscillatory zoned plagioclase phenocrysts have a considerable variation in composition from one phenocryst to the next. Composition ranges from An_{32} to An_{65}, but rarely shows more than 15 per cent variation in anorthite content within a single phenocryst. The matrix consists of normal oscillatory zoned andesine (An_{32-46}) microlites; anhedral augite ($2V_z$: 38°; $Z \wedge C$: 41°); and interstitial green to brownish green areas of chlorite and carbonate, shot through with fine opaque needles. Accessories include apatite, sphene and opaques.

In the middle and upper parts of this member at CMV andesine microlites (An_{32-35}) are not oscillatory zoned. In some units, plagioclase phenocrysts have strongly resorbed interiors. Mafic phenocrysts in the upper flows have been completely altered to chlorite.

Arenites and Tuffs (member E): This member comprises a single feldspathic wacke, about 15 metres thick in CMV, and a sequence of wackes and tuffs at least 110 metres thick in CMII.

In CMII, the member is divided into 5 units, designated E_1, to E_5 in Figure 15.

Unit (E_1) is a dark greenish grey, massive, partly welded tuff that is very similar to the middle member of the Partridge Lake Formation. This tuff is conformably overlain by dark brown to mauve-grey lithic feldspathic wackes (unit E_2) that are essentially the same as unit E_4 and the wackes at the top of CMV. The wackes are composed of deep reddish brown (due to intense hematite alteration) angular to subangular microporphyritic volcanic fragments; sparse fragments of undeformed pumice; potassic feldspar, quartz, and intensely altered mica crystal fragments; and granitic fragments. The matrix is a very poorly sorted, intensely altered mass (50-55 per cent of the rock). Bedding is defined by preferred orientation of elongate lithic, crystal, and pumice fragments.

The pale green to pale grey, well bedded, feldspathic wacke of unit E_3 has essentially the same constituents as the dark brown wackes except that clasts make up 65 to 75 per cent of the rock, feldspars and pale green tuff make up a considerable proportion of the fragments, the matrix is not as intensely altered, and it lacks pumice. All bedding is defined by alternating fine- and coarse-grained layers 1 to 3 cm thick. All beds are poorly sorted.

Fine-grained buff tuff of unit E_5 is composed mainly of ash with very few lithic fragments.

Interpretation

A gradual transition from partly welded at the bottom to densely welded at the top, the restriction of the vapour phase zone to the top, and the lack of internal contacts suggests that the ignimbrite of member A in CMIII is a single, compound cooling unit. Distinction of several ash-flow units, deposited in rapid succession at very high emplacement temperatures, may be impossible because their boundaries can merge and be obliterated during welding. Dense welding of ignimbrites to the very top of most units and the paucity of phenocrysts indicate that these were high temperature ash flows. The gradual upward increase in density of welding of member A suggests an upward increase of emplacement temperature of the ash flows.

In CMIV at least four depositional units are distinguished and all are densely welded throughout. The sequence has cooled as two compound cooling units (units A_1-A_2 and units A_4-A_5) that are separated by a thin, nonwelded air-fall tuff bed (unit A_3).

Thinning of member A, both eastward and southward from Cleft Mountain, suggests that the vents were north of Cleft Mountain. The change in welding of the upper unit, from densely welded in CMIII to partly welded on the south side of Cleft Mountain, suggests that the direction of decreasing temperature in the ash-flow unit was from north to south. This change is further evidence that the vent lies to the north. Apparent thinning of this member from the west to east sides of Partridge Lake valley, can be interpreted as indicating: (1) the source is northwest of Partridge Lake valley; or (2) the source is north of Partridge Lake but erupted in several directions, forming thicker deposits in the west than in the east; or (3) the source consisted of several vents to the north. The author favours the second interpretation.

The dacite lavas of member B are devitrified vitrophyric flows as evidenced by the upper and lower zones of autobrecciation, relict spherulitic crystallization, relict crystallites in a devitrified glass base, and microscopic layering. The lavas were less viscous than the magma which formed the preceding ignimbrites. That they contained a much smaller amount of volatiles is suggested by the paucity of vesicles and the general lack of pyroclastic disruption of the lava. The strong resorption of phenocrysts indicates that the flows erupted in a superheated condition. The magma partly crystallized upon extrusion; the vitric matrix later devitrified to a cryptocrystalline mass and crystallites recrystallized to fine-granular aggregates. These lavas

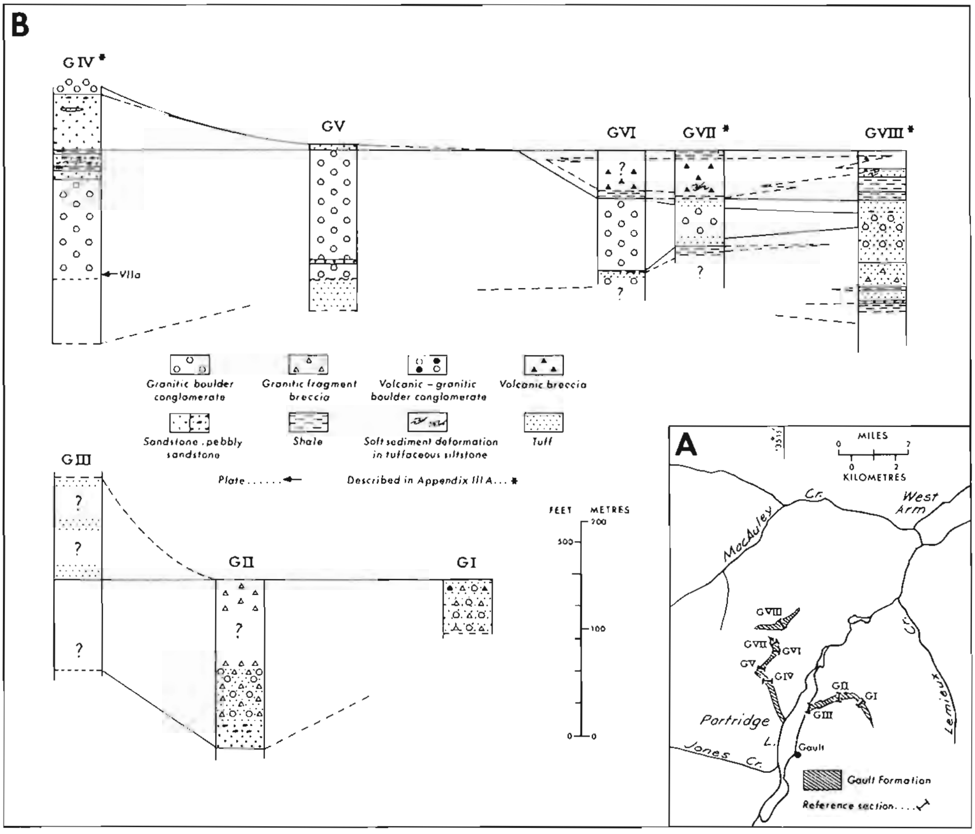


Figure 18. A - Distribution of the Gault Formation and location of reference sections.
B - Correlation of reference sections of the Gault Formation.

possibly represent that part of the magma chamber that was undersaturated with volatiles. A sudden release of pressure by breaching of the roof rocks and eruption of the overlying magma resulted in the production of superheat. Unit B_2 represents part of the magma that was richer in alkalis, silica and probably volatiles (see chemical data; Figure 45) than the previously erupted dacite magma. During effusion this relatively viscous magma became disrupted partly by vigorous vesiculation at the top of the flow and partly by autobrecciation. Cognate fragments thus formed were hot enough to deform plastically and become flattened by the weight of the ensuing overlying lava flows.

The well bedded and poorly sorted character, dominance of lithic fragments and general lack of pumice and shards suggest that the arenites overlying the partly welded tuff of member E represent subaqueous deposition of material mainly derived from the underlying volcanic terrain and from the granitic cliffs against which the beds abut. The buff weathering tuff at the top of the sequence near Cleft Mountain is air-fall pyroclastic dust.

In summary, this formation records the following sequence of events: (1) explosive eruption of high temperature rhyolitic to dacitic ash-flows;

(2) quiet effusion of vitric dacite lavas followed by andesitic lavas; (3) eruption of another sequence of ash flows; and (4) the beginning of a period of relative quiescence during which streams eroded the volcanic and granitic terrain. The whole succession was deposited in a graben in the Partridge Lake Formation. The volume of this formation is about 17 cubic kilometres (4 cubic miles), about half of which is lavas.

Gault Formation

Definition, Distribution, Thickness and Contact Relations

The Gault Formation is named after the abandoned settlement of Gault on the east side of Partridge Lake. It consists mainly of granitic boulder conglomerate and sandstone with subordinate amounts of siltstone, shale and volcanic breccia. Stratigraphy of the formation is described with reference to eight measured sections, designated GI to GVIII in Figure 18, four of which are described in detail in Appendix IIIA.

The formation is well exposed on both sides of Partridge Lake valley. It thins from south (225 m in GIV) to north (145 m in GVIII) on the west side of Partridge Lake, and it thins eastward (185 m in GIII to less than 50 m in GI) and slightly from south to north on the east side of Partridge Lake. Because of complicated faulting and incomplete exposures on the lower east side of the lake thicknesses here are accurate only to within 30 metres.

The Gault Formation conformably overlies the Cleft Mountain and Partridge Lake Formations. On the west side of Partridge Lake, it overlaps the south side of the graben which contains the Cleft Mountain Formation.

The Gault Formation is conformably overlain by tuff of the MacAuley Creek Formation.

Lithology

Granitic boulder conglomerate and breccia typically consists of rounded to angular biotite quartz monzonite or hornblende biotite quartz monzonite boulders in a green arkosic grit matrix composed of quartz, feldspars and biotite (Pl. VIIa). Granitic fragments range from fine sand size to boulders up to about 1 metre across. Cobbles and boulders that average 15 to 30 cm across commonly make up 30 to 45 per cent of the rock. Conglomerate units are massive, very poorly sorted, with essentially no indication of bedding except for rare coarse sandstone lenses and beds. Generally the boulder framework is not intact. At GI the matrix of the conglomerate is a tuffaceous wacke.

On the west side of Partridge Lake, the general trend within the conglomerate unit from south to north is thinning of the massive bed from 150 metres to GIV to 30 metres in GVII, and 15 metres in GVIII; decrease of maximum size and abundance of large angular granitic boulders; increasing proportion of well rounded boulders. On the east side of Partridge Lake these trends are not so obvious; angular granitic blocks are smaller (cobble size) in GI than in other sections, but no trend is evident between GII and GIII; angularity of the fragments is about the same in all sections. A higher proportion of boulders tends to be angular on the east side of Partridge Lake than on the west side. A small amount of volcanic fragments are present in the breccia at GI.

Plate VII.

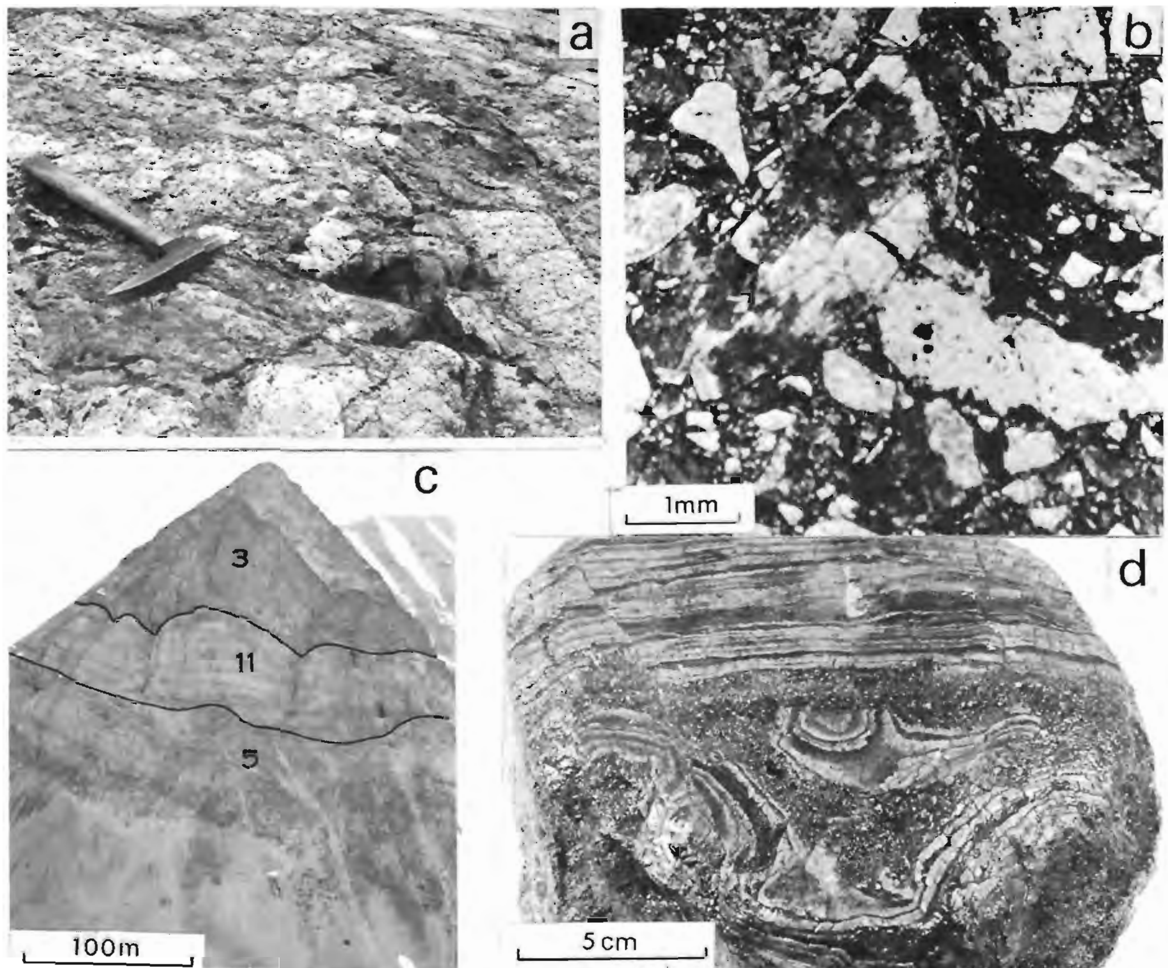
Stratigraphic and lithologic features of the Partridge Lake, Gault, MacAuley Creek, Lemieux and Jones Creek Formations and of the Crozier Breccias.

(a) Granitic boulder conglomerate of the Gault Formation near the base of reference section GIV (Fig. 18).

(b) Photomicrograph of arkosic grit matrix of the conglomerate in Plate VIIa. Plane-polarized light.

(c) Partridge Lake Formation (5) and Crozier Breccias(11) deposited around a steep sided peak in massive and shattered granites (3) at section CRII (see Fig. 25).

(d) Ball and pillow structure and disrupted bedding in tuffaceous siltstone of the Jones Creek Formation.



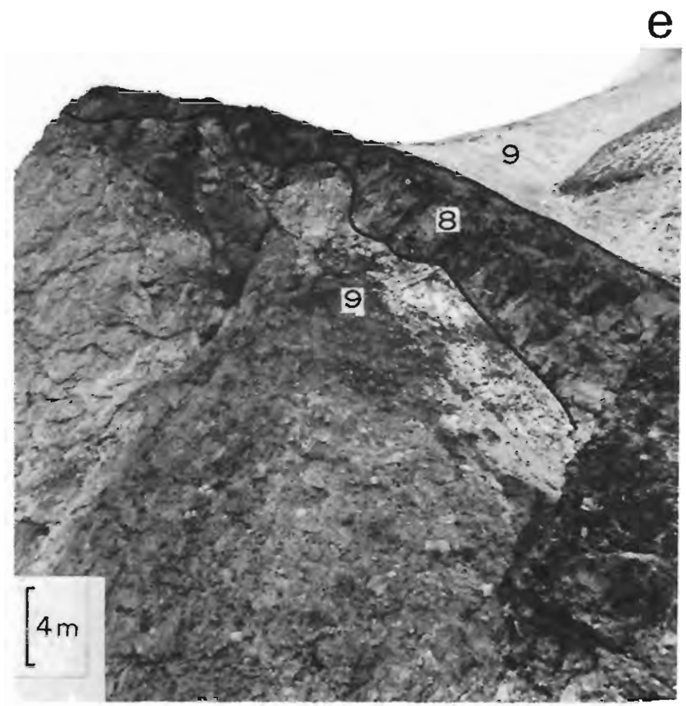


Plate VII continued.

(e) Thin, moderately welded ignimbrite unit of the MacAuley Creek Formation (8) with irregular lower contact and nearly flat upper contact. Ignimbrite is overlain and underlain by granitic boulder conglomerate of the Lemieux Formation (9).

(f) Thin to medium bedded sandstone and conglomerate lying conformably above thick, massive conglomerate of the Lemieux Creek Formation at reference locality L6 (see Plates IXb, Xc and Fig. 24).

PLATE VII

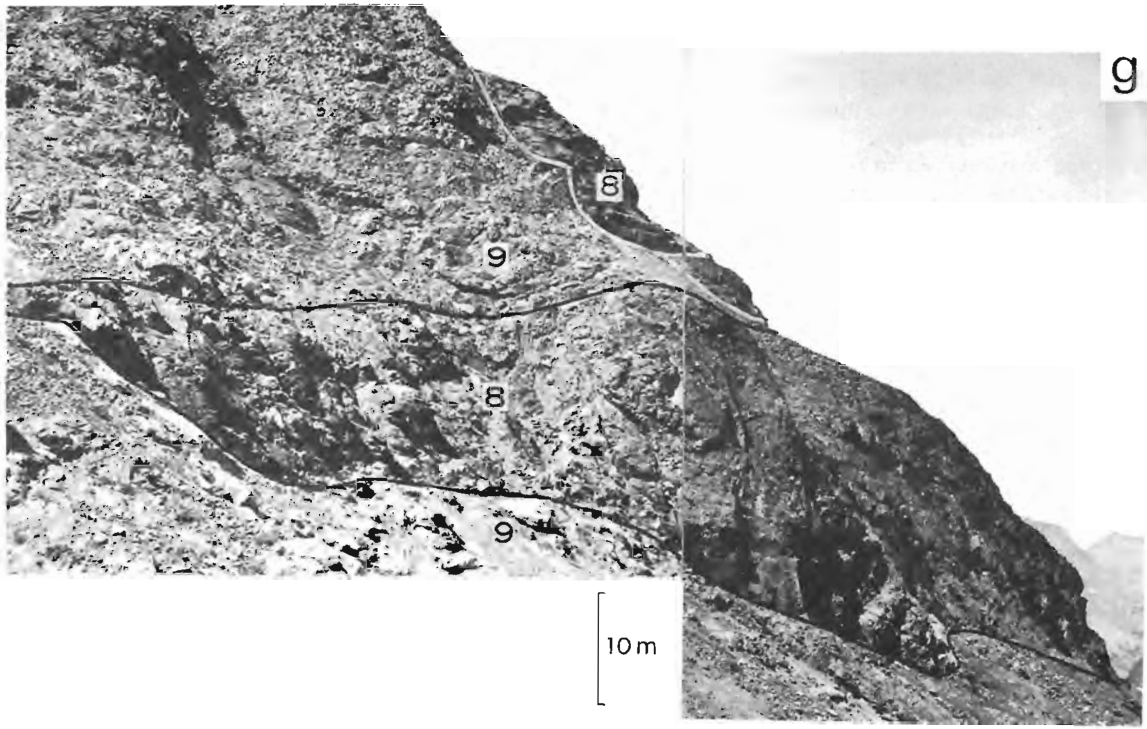


Plate VII continued

(g) Tapering out of some ignimbrite units of the MacAuley Creek Formation (8) at reference locality M5 (Fig. 19). The ignimbrite interfingers with conglomerate of the Lemieux Creek Formation (9).

Sandstone forms a wedge above the conglomerate unit that is as much as 80 metres thick in the southernmost sections (GIII, GIV), and tapers out northward within 3 kilometres of the southernmost exposure of the formation. Sandstones have sharp contacts with the conglomerate in the southern parts of the area, but have broad gradational contacts in GVIII. Sandstones are greenish grey to green, medium- to coarse-grained, poorly sorted, arkosic to feldspathic wackes and grits that are very similar to the matrix of the conglomerate units. In the southern sections they are massive or have poorly developed bedding. In GVIII bedding is generally better developed: in massive units, it is indicated by preferred orientation of elongate fragments, and locally it is thin bedded or contains lenses and partings of shale, and of sandstone of different grain size than the enclosing sandstones. These sandstones are typically arkosic and have abundant fine chlorite and carbonate, interstitial to the quartz and feldspar grains.

Siltstone and shale form partings within the base of the sandstone units, thin bedded units near the bottom of the formation in GVIII, and a series of units 6 to 18 metres thick at the top of the formation in GVIII. In GVIII, basal shale beds are typically dark grey, calcareous, finely laminated and fissile, whereas shale and siltstone near the top of the formation are dark grey-green to green, less fissile, and commonly pumiceous. The upper, dominantly shale-siltstone sequence, is interbedded with volcanic breccia containing a variety of volcanic, granitic and metamorphic fragments as well as pumice and shards. The matrix of these brightly coloured breccias is tuffaceous wacke or siltstone. These units bear abundant evidence of soft sediment deformation such as minor faults, rolled bedding, intrastratal microfolds and faults. The interbedded tuffaceous siltstones, wackes and volcanic breccias taper out near GVI just south of the graben filled by the underlying Cleft Mountain Formation.

Interpretation

The source of the conglomerates and sandstone lies south or southeast of the present exposure of the formation. This conclusion is supported by the thinning of the conglomerate northward; the decrease in size, abundance and angularity of granitic fragments from south and southeast to north; and the tapering out of the sandstone wedge northward. Quartz monzonite boulders in the conglomerate are similar to the granitic terrain to the south and southeast of the complex; granitic rocks to the north are dominantly granodiorite. The high proportion of large angular blocks and boulders that form an open framework throughout the conglomerate, the scarcity of bedding features, the lack of sorting, and the high angularity of pebble and smaller sized fragments, are all compatible with deposition of the conglomerate units by rockslide avalanches. The gradational contacts between conglomerate and sandstone in GVIII, however, suggest local subaqueous deposition. Siltstone beds in the lower parts of the formation within the massive conglomerate, suggest that lakes were filled in by the conglomerates. Sandstone units underlying the conglomerate may be stream deltaic deposits at the edges of lakes. Streams issuing from the southern highlands deposited the wedge of sandstone and grit.

The presence of siltstones, shales and well bedded sandstones indicates that most of the section in GVIII and at least the upper parts of the section in GVI and GVII were deposited in a subaqueous environment. Massive, unsorted granitic boulder conglomerate and volcanic-granitic boulder conglomerate suggest episodes of subareal deposition or possibly very rapid subaqueous deposition. Some of the landslides may have been water-soaked and thus were deposited as mudflows instead of dry rockfall avalanches. Pumice and shards in the tuffaceous siltstones and breccias at the top of the sequence may be air-fall ash deposited in a shallow basin, or tephra that was carried into the basin by streams that flowed at the time of eruption. Volcanic breccias with a tuffaceous matrix, and tuffaceous siltstones with an abundance of soft-sediment deformation structures at the top of sections GVI and GVII, are interpreted as the result of slumping in water-soaked pumiceous muds and sands during rapid deposition of the volcanic blocks. Possibly the slumping and deposition of breccias was triggered by tectonic disturbance during formation of a fault scarp near the south side of the lake.

In summary, the lithology and distribution of much of the Gault Formation may be interpreted as resulting from the erosion of steep fault scarps. Such scarps are thought to have formed the southern wall of a large caldera (Chapter V). The explosive volcanic eruptions that deposited the Partridge Lake and Cleft Mountain Formations were followed by a period of volcanic quiescence during which scattered lakes, fed by streams issuing from the caldera walls to the south, formed at the bottom of the caldera. Muds and deltaic stream deposits began to accumulate in them. In the southern parts of the area these lakes were rapidly filled by thick accumulations of landslide debris and possibly mudflows which avalanched from steep granitic caldera walls to the south. In the northern parts, silt and sand were accumulating in a lake, the southern limit of which was just beyond the southern lip of an east-west trending graben in the Partridge Lake Formation. Some of the avalanches reached this lake basin and dumped coarse granitic rubble into it. Ash and volcanic dust from volcanic eruptions, at the beginning of a new eruptive cycle, fell into the lake or were carried into it by streams. Minor tectonic disturbances, possibly related to ensuing volcanic activity or to minor fault movements, caused slumping and soft-sediment deformation of water-soaked pumiceous siltstone, and local deposition of volcanic rubble at the southern edge of this basin Meanwhile streams issuing from a highland in the vicinity of the caldera walls to the south deposited fans in the southern parts of the area.

MacAuley Creek Formation

Definition, Distribution and Thickness

The MacAuley Creek Formation outcrops as massive, grey to dark brown weathering precipitous cliffs along the upper half of Partridge Lake valley, on ridges between Partridge Lake and MacAuley Creek valleys and east of Gault, in the Lemieux subarea (Fig. 19). In the Partridge subarea, the formation is divided into two members on the basis of zones of welding: member A is a partly welded tuff, and member B is a sequence mainly of densely welded ignimbrites with minor lavas. The formation is there described with reference to two measured sections, MCI (Fig. 20) and MCII (Fig. 21) which are correlated with several other more generalized sections in Figure 19. In the Lemieux subarea (section MCVII, Fig. 22), the formation is divided into 10 units which are not to be correlated with those of the Partridge subarea. In Figures 19 to 22, member B is divided on the basis of boulder zones, various lithologic changes and interlayered lavas.

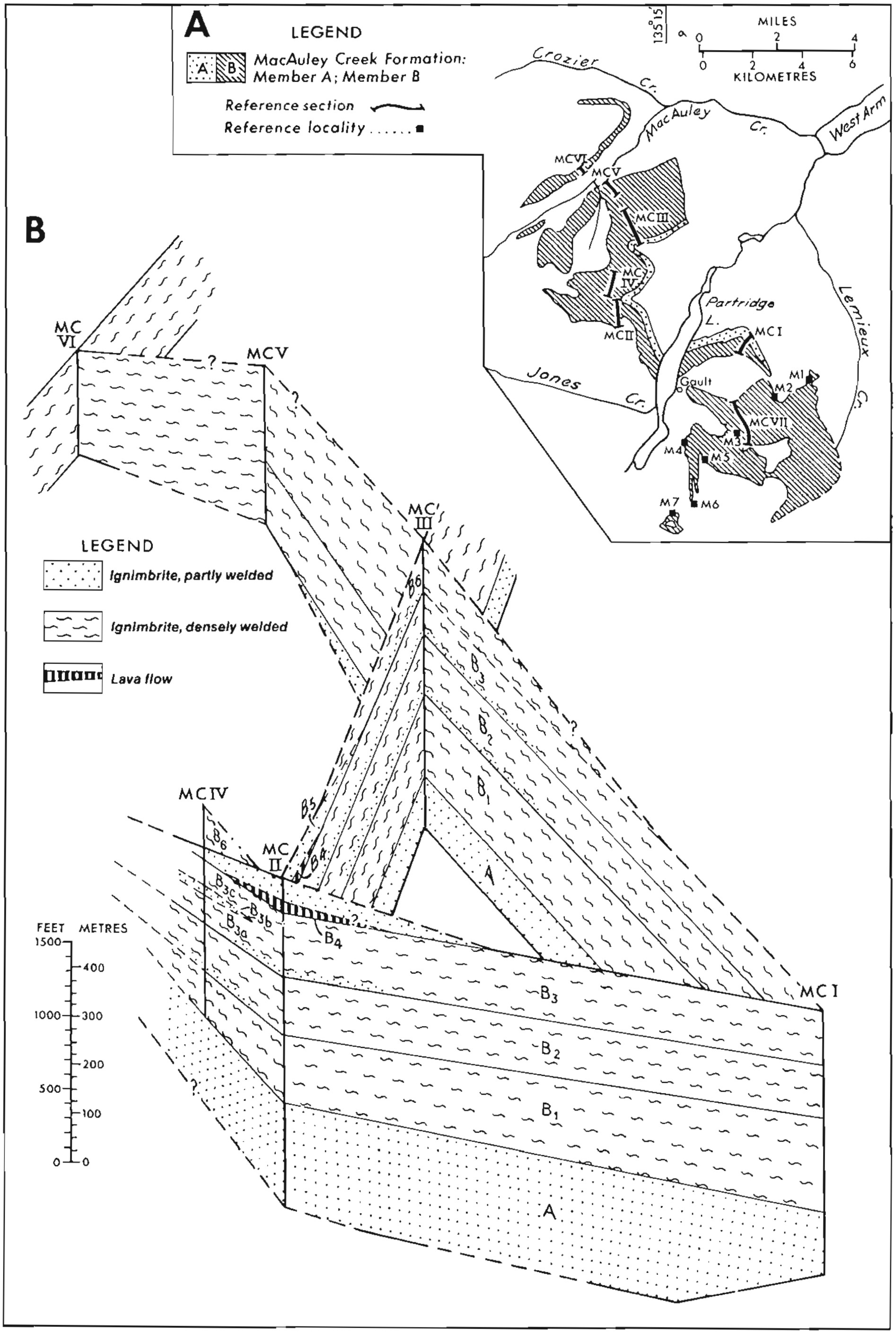


Figure 19. A - Distribution of the MacAuley Creek Formation and location of reference sections and reference localities.
B - Fence diagram of the MacAuley Creek Formation.

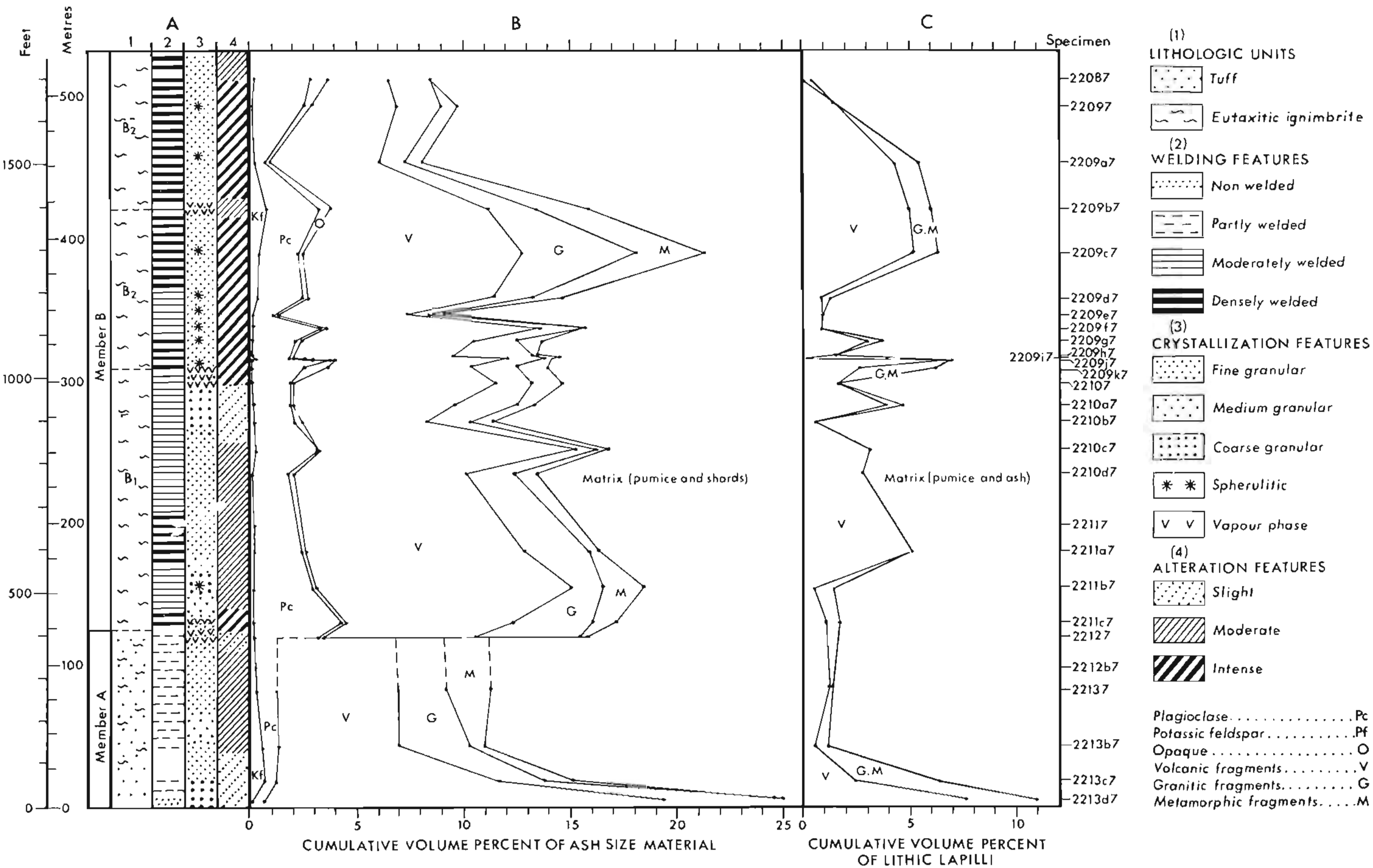


Figure 20. Reference section MCI of the MacAuley Creek Formation: A, lithologic features; B, modal content of ash-size material; C, modal content of lapilli.

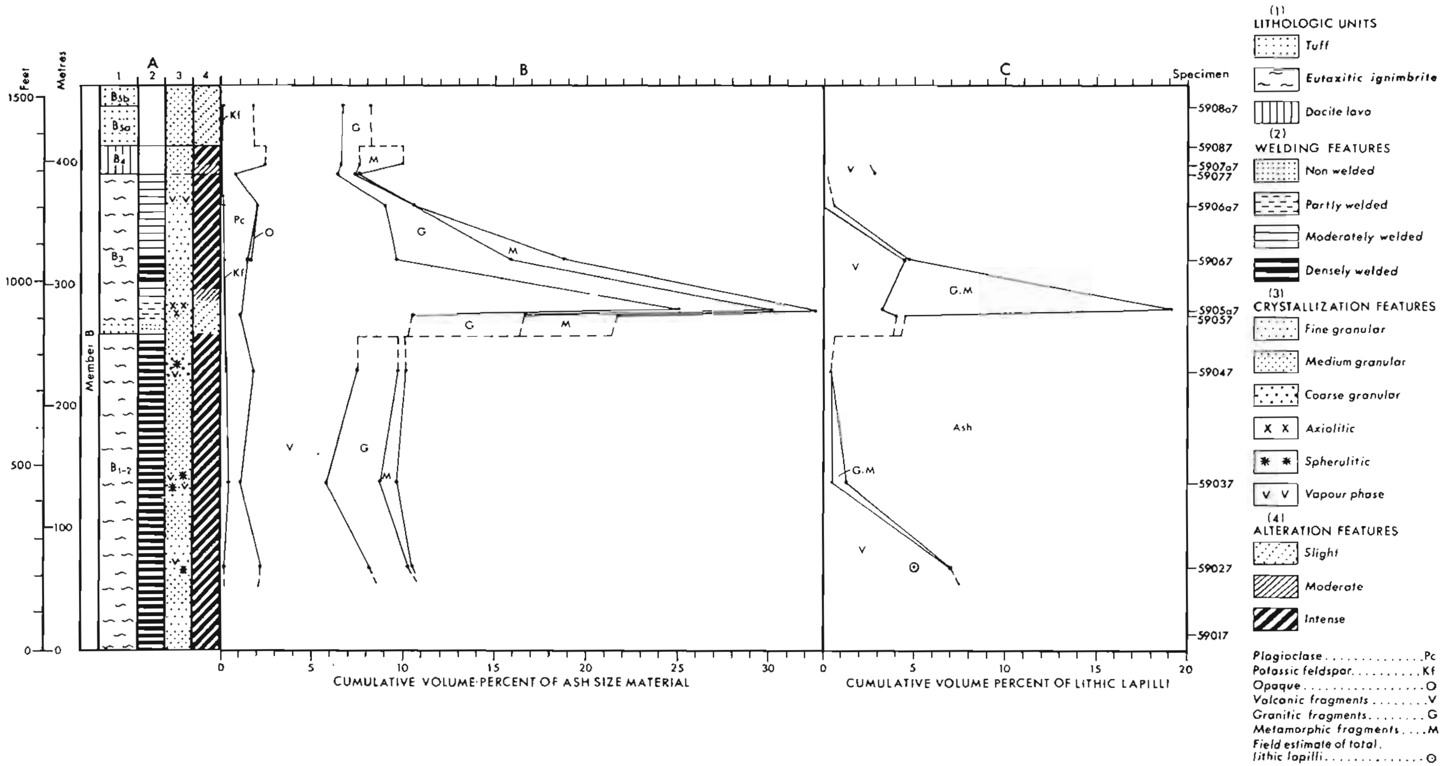


Figure 21. Reference section MCII of the MacAuley Creek Formation: A, lithologic features; B, modal content of ash-size material; C, modal content of lapilli.

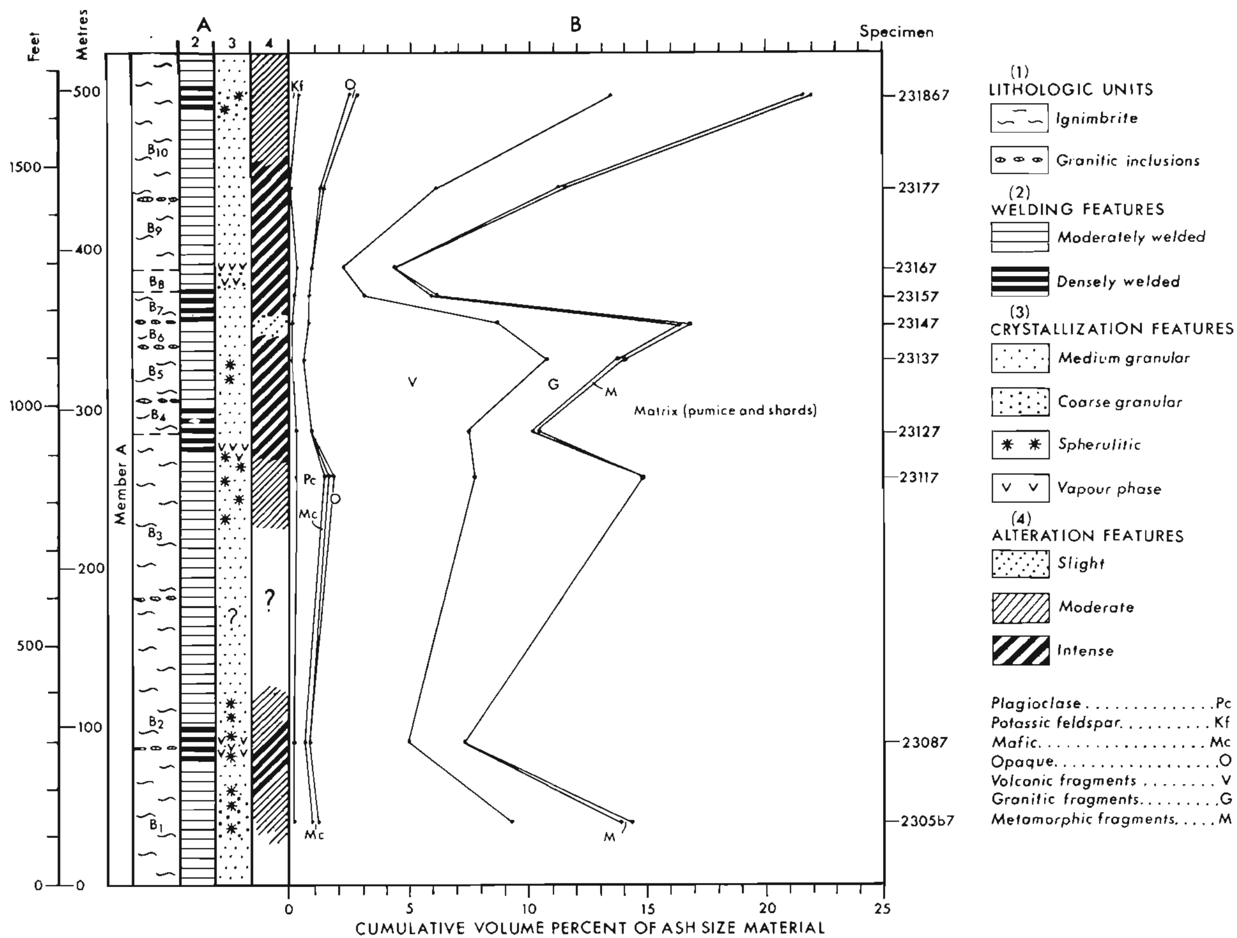


Figure 22. Reference section MCVII of the MacAuley Creek Formation: A, lithologic features; B, modal content of ash-size material.

In the Partridge subarea, the formation as a whole is thickest in the southern exposures (about 700 m in MCII), thins toward the northwest (about 360 m in MCVI) and thins out west of MacAuley Creek. Member A is 230 to 250 metres thick in the southern exposures and thins toward the northwest, apparently pinching out between MCIII and MCV. Member B is subdivided at various localities into three to eight sub-units (designated B1, B2, B3a etc. in Fig. 19). Sub-units B1, B2, B3 thin northward and westward, sub-units B4 and B5 apparently are local units in vicinity of MCII and are interpreted to thin out to the northeast and westward whereas sub-unit B6 apparently thins southeastward.

In the Lemieux subarea, the formation is thickest (500 m) in MCVII. South of "Gault" it thins abruptly southward and fingers out into four thin ignimbrite units, with aggregate thickness of about 60 metres that are interbedded with granitic boulder conglomerate of the Lemieux Creek Formation (Pl. VIII). The formation also thins southward between MCVII and the head of Lemieux Creek. Except for thin units near reference localities M1 and M2, member A is absent in this subarea.

Contact Relations

Formational Contacts: The MacAuley Creek Formation conformably overlies the Gault conglomerate in most of the Partridge Lake subarea, except on the east side of the MacAuley Creek valley where ignimbrite of member B lies directly on ignimbrite of the Cleft Mountain Formation. This contact is marked by a sharp crease in the otherwise massive ignimbrite cliffs. Above "Gault" a spherulitic rhyolite flow lies between the Gault conglomerate and the MacAuley Creek Formation.

In the Lemieux Creek subarea this formation lies nonconformably on shattered and brecciated granitic rocks. The lower contact is exposed continuously for about 3 kilometres along the southeast walls of the Partridge Lake valley; for about one kilometre on both sides of the ridge south of reference locality M1; and at the base of measured section MCVII and several isolated areas in the Lemieux Creek valley.

On the ridge near M1, several outcrops of granitic breccia (15 to 50 m across) are isolated within the ignimbrite. Some of the smaller outcrops may be large blocks rafted by the ash flows, but the larger bodies (some of which are several hundred metres above the base of the formation) are interpreted as remnant pinnacles of the very irregular granitic topography.

A huge block of ignimbrite immediately east of "Gault" has been faulted into the granitic breccia and rotated by a series of small north-south and east-west trending faults. Steeply dipping foliation in the ignimbrite changes abruptly on different sides of the north-trending faults. From a distance the steep contacts of this block with granitic breccia give the illusion that the ignimbrite body is intrusive into the granitic breccia: known faults and attitudes of foliation, however, are not compatible with this interpretation.

Near M4, the ignimbrite has filled in a very irregular block-faulted surface of the shattered and brecciated granitic terrain with a relief of 150 to 350 metres.

On the southeast side of Partridge Lake valley, the formation forms a thick ignimbrite wedge that fingers out southward into at least 5 units that are interbedded with granitic boulder conglomerate and breccia. These thin, moderately to densely welded units have undulatory lower contacts where the

PLATE VIII

Plate VIII. Stratigraphic relations of the MacAuley Creek Formation.

(a) Ignimbrite of the MacAuley Creek Formation (8) thinning southward on the southeast side of the Partridge Lake valley. The ignimbrite overlies massive and brecciated quartz monzonite (3) and is overlain by conglomerate of the Lemieux Creek Formation (9). Relief is about 4,500 feet (1,400 m).

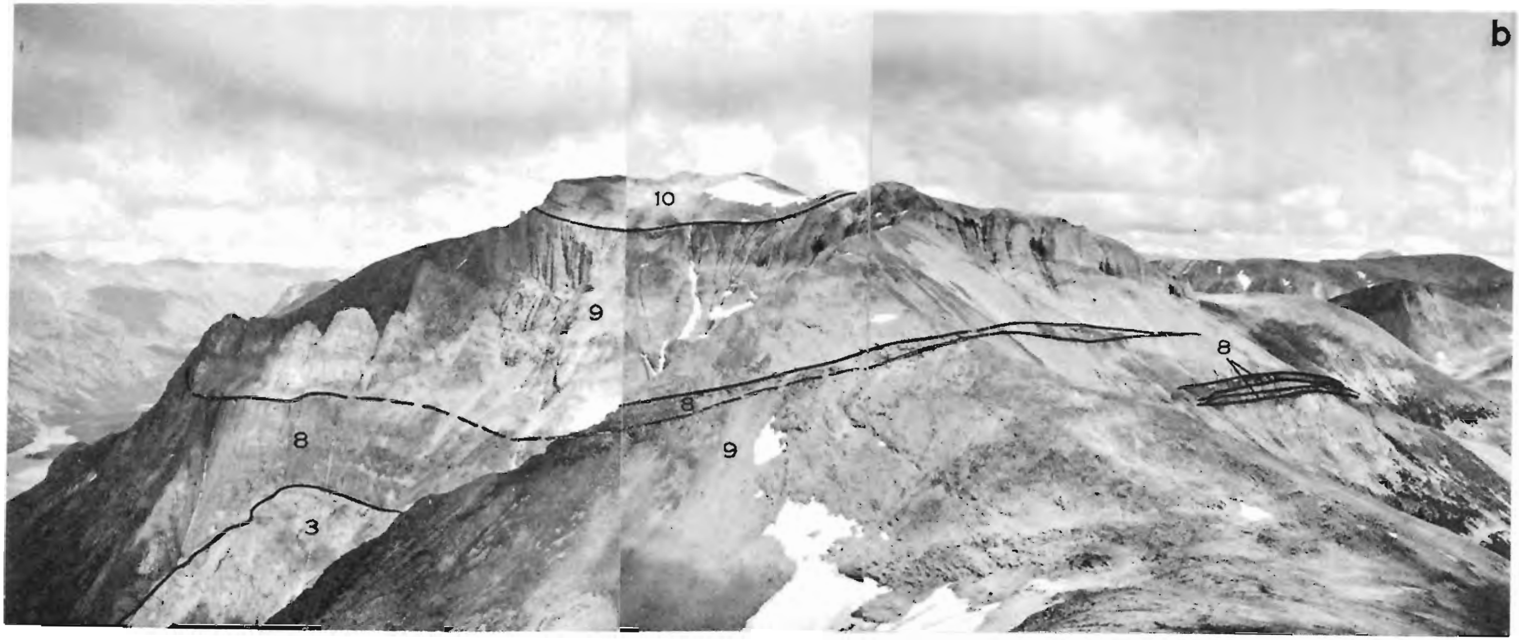


Plate VIII continued

(b) View looking northward at the south end of the ridge in Plate VIIIa. Ignimbrite (8) thins and is interbedded with conglomerate (9). Sandstones and tuffs of the Jones Creek Formation (10) conformably overlie the Lemieux Creek Formation (9).

ignimbrite is molded around irregularities on the surface of the granitic boulder conglomerate. The upper surfaces of these units are nearly planar Pl. VIIe). The fingering out of some of the upper units in the formation is shown in Plate VIIg and VIII.

At M7, the base of the ignimbrite has incorporated so much fine and coarse granitic material that the pale green ignimbrite is superficially almost identical to the underlying granitic breccia. The contact is very sharp, however, and the ignimbrite can be distinguished, in hand specimen, by the tiny green chloritized pumice lenticles.

The formation is overlain conformably by granitic boulder conglomerate of the Lemieux Creek Formation in the Partridge and Lemieux subareas, and by the Crozier Breccias in the Crozier subarea. On the southeast side of Partridge Lake valley, the upper contact is a planar surface in contrast to the highly undulatory lower contact (Pl. VIIIa).

Internal Contacts: Contacts are gradational between all units in MCI and between member A and member B in all localities. In MCI, the boundary between units B1 and B2 grades over 10 to 15 metres. In MCII, units B1 and B2 were not distinguished in the field and the boundary between the two units is drawn at a vapour phase zone and on the basis of stratigraphic position in MCIV and MCI. Contacts between units B2 and B3 can be defined within about 30 metres in MCI. In MCII, the sharp contact between the two major ignimbrite units (B1-2 and B3) is clearly marked by abundance of accessory and accidental lapilli at the base of B3, and the abrupt change in alteration and welding features. Correlation of member B units across Partridge Lake valley, and between Partridge Lake and Lemieux Creek subareas, is based on the resorption of plagioclase phenocrysts in sub-units B1 and B2, but not in the upper sub-units.

The gradational boundary between member A and member B is drawn at the top of the partly welded zone where the amount of accessory and accidental fragments of ash size increase abruptly. The contact zone is 1.5 to 6 metres thick, through which the rocks grade completely from pale green partly welded, slightly altered tuff, into dark grey, densely welded, intensely altered, prominently foliated ignimbrite. Locally a crease in the topography marks the change from the slightly recessive weathering member A tuff to the precipitous cliffs of member B ignimbrite.

In MCVII, seven of the units are distinguished by basal zones rich in granitic breccia and massive granite blocks, boulders and pebbles; and three units within the ignimbrite are distinguished on the basis of cliff forming zones which have intensely fractured, deeply weathered, recessive tops (these contacts are shown as dashed lines in Fig. 22). Blocks of massive granite and granitic breccia commonly range from 1 to 5 metres across (one inclusion between units B4 and B5 is 2.4 by 12 m and lies parallel to the eutaxitic foliation in the ignimbrite). In many places, the contacts could not be distinguished were it not for the presence of these trains of granitic blocks within the homogeneous, densely welded ignimbrites. In the vicinity of reference locality M3 units B9 and B10 are separated by a 1.5- to 3-metre layer of granitic fragment breccia.

Foliation and Layering

Eutaxitic foliation defined by preferred orientation of pumice fiamme and shards is very well developed throughout member B. Foliation is absent or very indistinct at the base of member A, becoming increasingly better developed upward to where it grades into the densely welded ignimbrite of member B. Generally, the darker the colour of the rocks, the more densely welded and the better the development of the foliation. In partly welded tuffs in the basal tuff member, preferred orientation of platy shards where they "stream" around lithic fragments defines a microscopic foliation.

Gross layering within the formation is defined by the massive members and units within the formation. A cryptic layering is defined by zones of varying types of crystallization, welding, alteration and phenocryst resorption. When the formation is viewed from a distance the layering is defined by subtle changes in weathering colour and intermittent, slightly recessive zones in the cliffs.

Bedding symbols shown in ignimbrites on Figure 2 generally indicate the attitude of eutaxitic foliation. In most places the foliation is parallel to layering defined by contacts of the massive units.

Joints

In MCI, joints near the base of B2 form nearly equant blocks, whereas joints in B3 form elongate columns spaced 0.2 to 1.2 metres apart and up to 5 metres long. In MCII, blocky rectangular columns, 0.3 to 2 metres apart persist steeply upward throughout the base of unit B1-2. Joints bounding these columns may be partly related to a regional fracture system in this vicinity rather than to true columnar jointing produced by cooling. In MCVII joints form massive columns in the lower units changing to blocky rectangular, closely spaced columns in middle units, and to hackly, rubbly jointing with intense fracturing throughout in the upper units.

Lithology

Member A: Member A is a pale greenish grey weathering, cliff forming to slightly recessive member composed of volcanic, granitic and crystal lapilli in a matrix of ash-size volcanic and granitic fragments, crystal fragments, devitrified pumice, shards and dust. In MCI, colour of the fresh rock varies from pale grey at the base to medium greyish green near the top. Pumice and shards have the same variety of forms as seen in the Partridge Lake Formation. Deformation of pumice is most obvious near the upper parts of the member where the tuff grades into the overlying ignimbrite.

Phenocrysts make up less than 2 per cent of the tuff. The ratio of orthoclase to andesine ranges from 1:1 to 1:3. Euhedral to subhedral andesine (An_{30} to $_{33}$) is strongly resorbed and weakly zoned on margins. Devitrification is mainly fine- to medium-granular except for coarse-granular zones near the bottom and vapour phase crystallization at the top of the member.

Accessory and accidental constituents include essentially the same variety of multicoloured volcanic, granitic and crystal fragments that are in the Partridge Lake Formation. Sizes range from very fine ash to lapilli up to 25 mm. In MCI lapilli are largest and most abundant at the base of the unit where they average 5 to 10 mm and make up 10 to 15 per cent of the rock. In the middle and upper parts of the member lapilli make up 2 to 5 per cent of the rock.

Member B: This member comprises a series of dark to medium greenish grey moderately- to densely-welded ignimbrites that are locally capped by lavas and air-fall tuffs. A graphic description of the welding, crystallization and alteration features, as well as modal analyses of this member in MCI, MCII and MCVII are given in Figures 20, 21 and 22. The ignimbrites are composed of sparse (less than 5 per cent) plagioclase, orthoclase and sanidine phenocrysts, and granitic, metamorphic and volcanic accidentals, enclosed in a matrix of devitrified pumice, shards and dust. Textures of these rocks are very similar to those described in member A of the Cleft Mountain Formation. Phenocrysts range from 2 to 4 per cent of the rock. The ratio of potassic feldspar to plagioclase ranges from 1:6 to 1:20 (rarely as low as 1:3). Andesine phenocrysts vary from An_{30} at the bottom to An_{37} near the top of the member. They are strongly resorbed in sub-units B1 and B2 but not resorbed in B3.

Euhedral to partly rounded weakly zoned, potassic feldspar phenocrysts are most commonly orthoclase ($2V_x$: 45°-55°; optic plane $\perp$ 010). High sanidine ($2V_x$: 35°-40°) was identified near the 'contact' between B_1 and B_2 and near the base of B_2 in MCI.

Measurements of ($\bar{2}$01) and (060) X-ray reflections from powder diffraction patterns of feldspars, by the method of Wright (1968), indicate structural states ranging from the high sanidine series to the orthoclase series (Fig. 23).

Opaque crystals (0.3 to 0.7 mm), include pyrite, magnetite, and (?) ilmenite. These minerals form euhedral (pyrite) to slightly rounded grains, around which pumice and shards are deformed. Except for the crystals within pumice, they could also be derived from granitic material.

Relative proportions of volcanic to granitic and metamorphic fragments, and of phenocryst types are approximately the same as in ignimbrites of the Cleft Mountain Formation. The total of accessory and accidental fragments, however, is generally lower in this formation than in pyroclastic formations lower in the stratigraphic section.

Zonal welding, crystallization and alteration features are the most striking vertical and lateral variations within the formation. These variations when considered together provide a basis for subdivision of this member. In the following sections attention is focused on the distinctive features of measured sections MCI, MCII and MCVII.

Section MCI: Member B is divided into three units on the basis of zones of welding, crystallization and alteration and weathering colour (Fig. 19). Unit B, is medium to light brownish grey weathering, moderately altered except for about 15 metres of intense alteration at the base, and 40 metres of very slight alteration at the top. This variation in alteration corresponds to a zone of very fine-granular devitrification (subvitreous) at the base, and coarse-granular devitrification near the top. Zones of vapour phase crystallization are at the top and bottom of this unit. The unit is densely welded in the lower central parts and moderately densely welded elsewhere.

Units B2 and B3 weather dark brownish grey. They are mainly very densely welded, very dark grey, sparsely porphyritic, subvitreous ignimbrites. In thin section, subvitreous zones are brown to reddish brown, have spherulitic and fine-granular crystallization and contain abundant finely disseminated opaque minerals. These units are intensely altered except for moderate alteration at the base and top. The moderately altered zones correspond with zones of moderately dense welding, and very fine-granular devitrification and vapour phase crystallization. Total accessory and accidental fragments show no general trend within unit B1; increase from base to upper parts of B2; and decrease from base to top of unit B3.

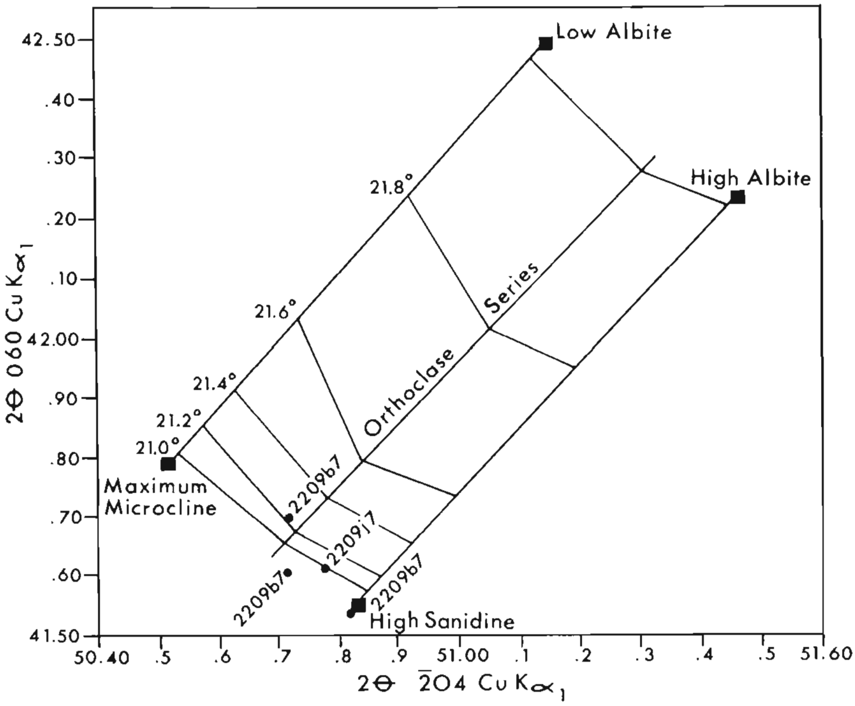


Figure 23. Structural state of four potassic feldspar crystals from the MacAuley Creek Formation, shown on a plot of 2Θ ($\bar{2}04$) against 2Θ (060) after Wright (1968, p. 92). Solid squares define the approximate maximum high and low structural states. Solid circles are feldspars from the MacAuley Creek Formation (see Fig. 20 for localities).

Approximate boundaries between these units are gradational and are drawn about 170 metres and 300 metres from the base of member B where the ignimbrite is moderately densely welded, moderately altered and contains abundant vapour phase crystallization.

Section MCII: In this section the ignimbrite units are capped by a lava flow and two nonwelded tuff units. Only two densely welded ignimbrite units can be distinguished (B1-2 and B3). The lower 260 metres consist of very dark grey, sparsely porphyritic, subvitreous ignimbrite with subconchoidal fracture. Except for the top metre, the unit is megascopically uniform and massive with no apparent lithologic variation. It is densely welded throughout and shows no apparent difference in degree of alteration. Shards and pumice are devitrified to spherulitic and fine-granular aggregates. Zones of abundant vapour phase mineralization are about 140 metres from the bottom and within the upper 30 metres of the unit. Unit B3 has a basal nonwelded greyish green tuff zone about 15 metres thick which grades upward over about 12 metres into partly welded tuff, then into densely welded dark grey, subvitreous ignimbrite, which persists to within about 30 metres of the top. The unwelded base bears up to 20 per cent lithic lapilli; 32 per cent of ash-size material consists of accessory and accidental material. Axiolitic texture is preserved in shards at the base of the unit.

Phenocrysts are the same variety and composition as in MCI. Plagioclase is strongly resorbed in the unit B1-2, but not in B3.

Unit B3 is conformably overlain by dark grey, sparsely porphyritic, felsophyric lava (B4), 23 metres thick. This unit has a light greenish grey, basal autobrecciated zone 3 metres thick. Sparse plagioclase phenocrysts comprise euhedral, continuously zoned crystals and strongly resorbed crystals. The matrix has a very fine felty texture defined by relict needle-like microlites and crystallites that are recrystallized to very fine granular aggregates set in a cryptocrystalline base. These relict microlites have a crude preferred orientation.

The lava is conformably overlain by a pale green tuff bed about 30 cm thick, which marks the base of a light grey to rusty grey weathering nonwelded tuff unit 30 metres thick (B5a). This unit is overlain by bedded pale green tuff (B5b) that has a basal unit at least 15 cm thick bearing accretionary lapilli. These range from fine rounded forms, less than 1 mm across, to flat ellipsoids up to 8 by 20 mm, and consist of very fine ash-size material that is identical to the surrounding matrix. They have light grey rims, less than 0.5 mm thick, in which particles have very vague preferred orientation. The flattened lapilli have preferred orientation with long axes parallel to bedding. Lapilli are loosely packed and rarely in contact with each other. These lapilli are almost identical to those described by Oertel (1970).

Section MCVII: In this section member B comprises at least 10 dark grey to brownish grey ignimbrite units that are almost lighologically identical. Seven of these units are divided by granitic block horizons. All units are moderately to densely welded: there are at least 4 reversals in density of welding. At reference locality M1 (Fig. 19A), the lower 100 metres of the formation contains abundant large flattened pumice fragments up to 15 cm in diameter.

Although the several reversals of intensity of alteration do not correspond exactly with the degree of welding, densely welded zones tend to be most intensely altered (very fine chlorite, yellowish brown mica, hematite and carbonate) whereas medium welded zones tend to be only moderately altered. The only zone of slight alteration is in the vicinity of the contact between units B6 and B7.

Most units show spherulitic crystallization of pumice along with fine- to medium-granular devitrification of shards and dust. The three vapour phase zones, near the tops of units B1, B3, and between B7 and B8, have some coarse-granular and micropoikilitic crystallization, and quartz spherules (that give the pumice a spongy appearance in thin section).

Phenocryst content is approximately the same as in the other sections of this formation. The most distinctive feature is the strong resorption of almost all phenocrysts in units B1 and B2, and lack of resorption (except for rare very large crystals) in the other units. The basal accumulations of granitic blocks, present in seven of the units, are not obviously reflected in the modal lithic fragments of ash-size material.

Interpretation

The MacAuley Creek Formation records a series of ash flows that were deposited in rapid succession. That the early eruptions were of relatively low temperature ash flows is suggested by the partly welded basal tuffs of member A. The following eruptions were at relatively high temperature suggested by moderate to dense welding in almost all parts of member B to the very top of the units and even in the thin units where they finger out. The rapid succession of ash-flow emplacement in member B is indicated by very thick compound cooling units, which lack distinct internal boundaries and by the lack of evidence of erosion within the formation.

Zones of welding suggest that the formation cooled as at least two compound cooling units in MCI; four cooling units in MCII; at least five units in MCIII; at least seven units in MCIV; and one compound cooling unit in MCVII.

Moderate to dense welding throughout the ignimbrite units in member B, except for thin basal and upper zones of partial welding, indicate that the ash flows were emplaced at high temperatures. Conversely, non- to partly-welded thick cooling units of members A are low temperature deposits.

In member B, high heat loss zones (with non- to partial-welding and granular crystallization) are absent or thin in MCI and MCII whereas they provide prominent markers of cooling units in MCIII and MCIV. The apparent splitting of B3 into 3 units between MCII and MCIV (Fig. 19B) probably represents the loss of heat distally from the vent so that the several ash flows no longer cooled as a single unit. Member B therefore, is a composite ash-flow sheet. The increasing distinction of member B sub-units northward (by virtue of welding and crystallization features), the gradual westward change of member B from 1 to 5 cooling units, and the thinning of member B northward and slightly westward, indicate the source of the eruptions lies to the south or southeast of the present exposures. Similarly the thinning of member A toward the northwest, and slight thinning eastward and westward in the southern part of the area, suggest the source area for these eruptions lies to the south of Partridge Lake valley.

Units B4 and B5 (which thin northward, eastward and westward from MCII) represent local, relatively small eruptions whose source may have been south of or near MCII. Similarly member B6, which apparently thins toward the southeast was probably erupted from one or more vents to the northwest of the present exposures.

It is concluded, therefore, that in the Partridge Lake subarea the MacAuley Creek Formation is a series of complex composite ash-flow sheets that issued from a major vent (or vents) south of the present exposures during most of the eruptive history and from local vents to the northwest and southwest during the later parts of the eruptive cycle.

PLATE IX

Plate IX. Cliff sections through the Lemieux Creek Formation.

(a) East-west (left to right) section through conglomerate of the Lemieux Creek Formation (9) southeast of Partridge Lake (reference section LCX, Figure 29). The conglomerate overlies ignimbrite of the MacAuley Creek Formation (8) and is overlain by sandstone, tuff and lavas of the Jones Creek Formation (10). Detail of the basal granitic breccia unit (9c) is shown in Plate Xe and f. The succession is 1,800 feet (550 m) high.

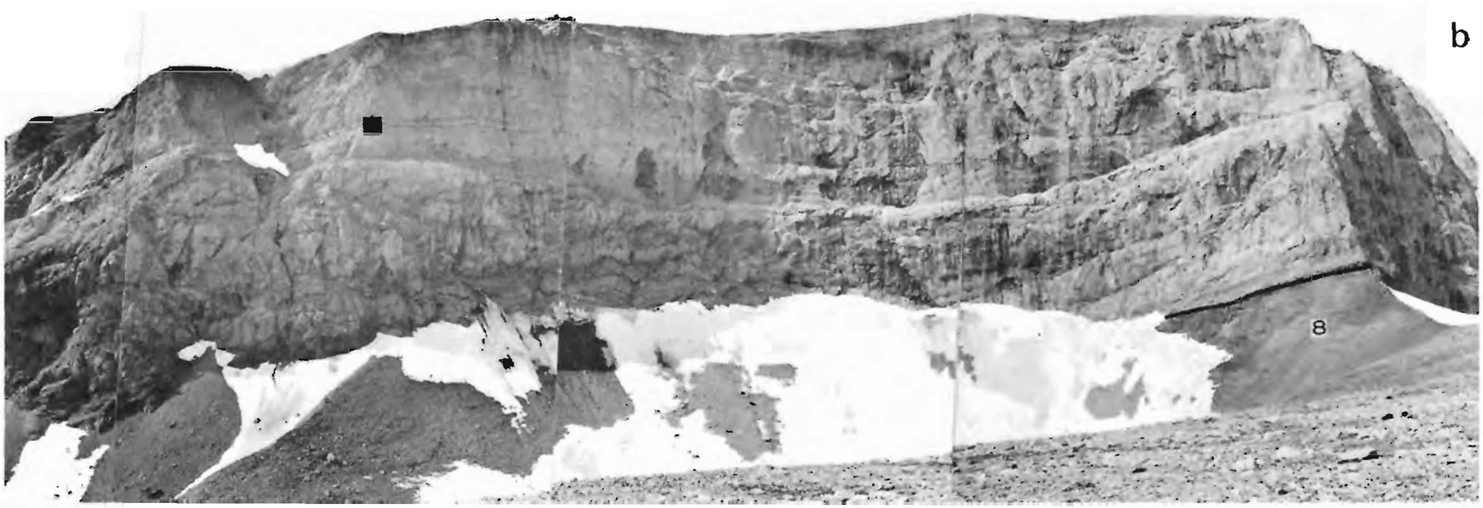


Plate IX continued

(b) East end of the section in Plate IXa showing thick massive beds in the conglomerate. The square shows the location of the thin bedded succession shown in Plate VIIf (see also Plate Xc).

In Lemieux subarea, the high temperature characteristics (dense welding and spherulitic crystallization in most units) and the abundance of granitic blocks near the base of most units, suggests that these flows must be near the source of eruption. The thinning of the formation southeastward and southward in the southern part of the subarea suggest that the vent(s) were to the north or northwest.

The opposing directions of thinning of this formation in the southern parts of the Partridge and Lemieux subareas suggest that at least one of the vent areas lies along the fault zone that separates the two subareas near the south end of Partridge Lake.

The volume of pyroclastic material represented by this formation and preserved within the complex is about 50 cubic kilometres (12 cubic miles).

Lemieux Creek Formation

Definition, Distribution and Thickness

This formation consists predominantly of massive granitic boulder conglomerate with minor sandstone, tuff and ignimbrite. It is exposed in magnificent precipitous cliffs near the headwaters of Lemieux Creek (Pl. IX), continuously along the southern sides of Partridge Lake valley, along the main tributary valley north of Jones Creek, and on the ridge north of Jones Creek. In Lemieux subarea, the formation is restricted to areas west of the ring dyke. Stratigraphy of the formation is described by reference to twelve measured sections (designated LCI to LCXII in Fig. 24), seven of which are described in Appendix IIIB.

In the Lemieux subarea, the formation is thickest (550 m) in LCXII and thins northward. Similarly, in the Partridge subarea, the formation is thickest (430 m) in the southern exposures (LCIV) but thins abruptly northward to about 185 metres at reference locality L1 and to about 15 metres at L2. It also thins eastward and westward from the Partridge Lake valley, pinching out west of LCVIII and east of LCI.

Contact Relations

The formation conformably overlies the MacAuley Creek Formation. The contact is seen at the base of sections LCII, LCIV, LCVI, and LCVII. The formation is overlain conformably by units of the Jones Creek Formation: pale green tuff above LCI, LCII, and LCIII; lavas above LCVI; and ignimbrite above LCVII.

At reference localities L1, L2 and L3, the lower part of the formation makes a fault contact with the underlying MacAuley Creek Formation. The top of the formation, however, is not displaced by this fault at L1 and L2, suggesting that the upper part of the formation was deposited against a fault scarp in these areas.

Near L8 and northeast of L6 the formation overlies shattered quartz monzonite, which in some places is almost indistinguishable from the base of this formation. The formation is truncated by a major fault on the east side of Partridge Lake.

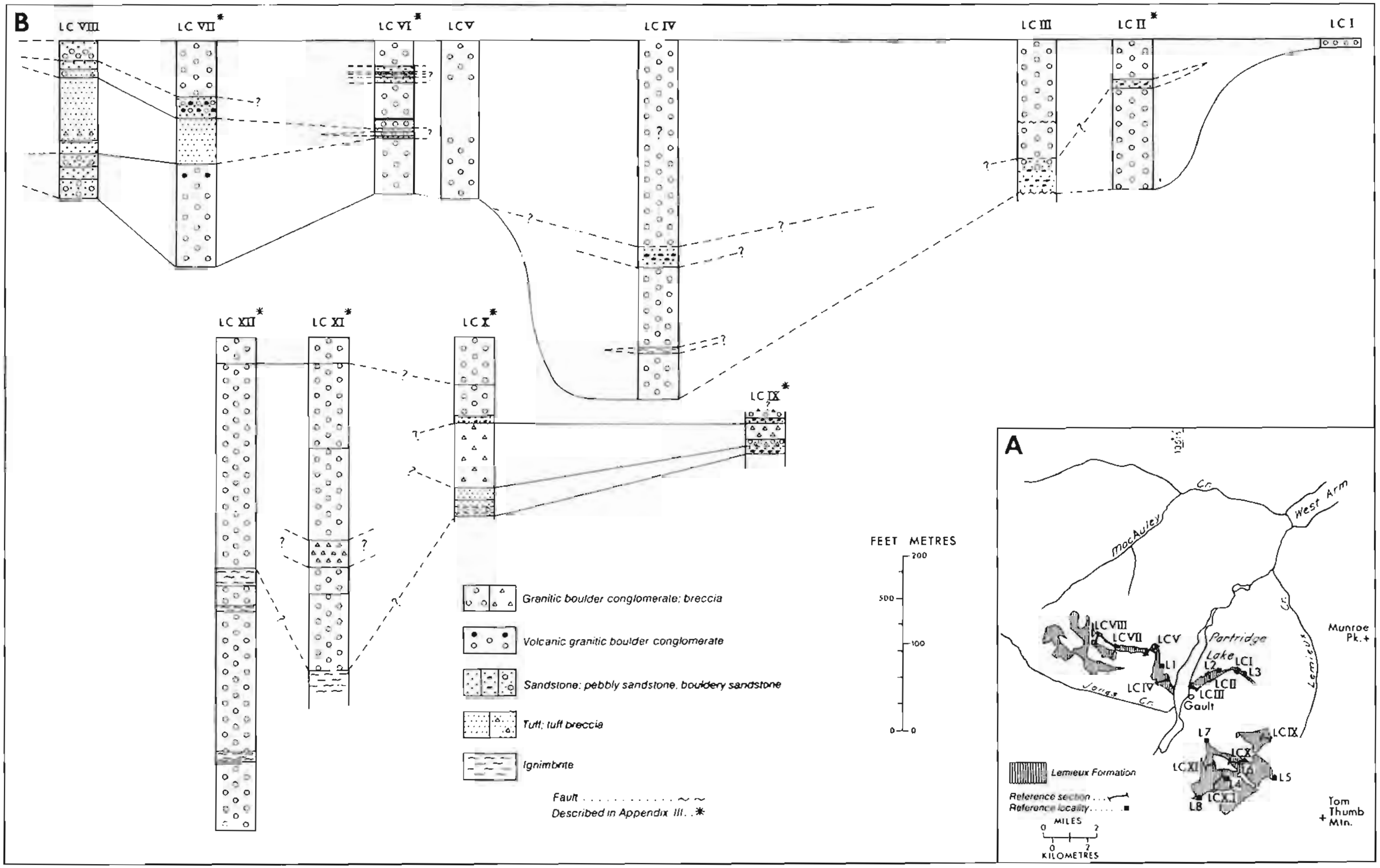


Figure 24. A - Distribution of the Lemieux Creek Formation and location of reference sections and reference localities.

B - Correlation of reference sections of the Lemieux Creek Formation.

PLATE X

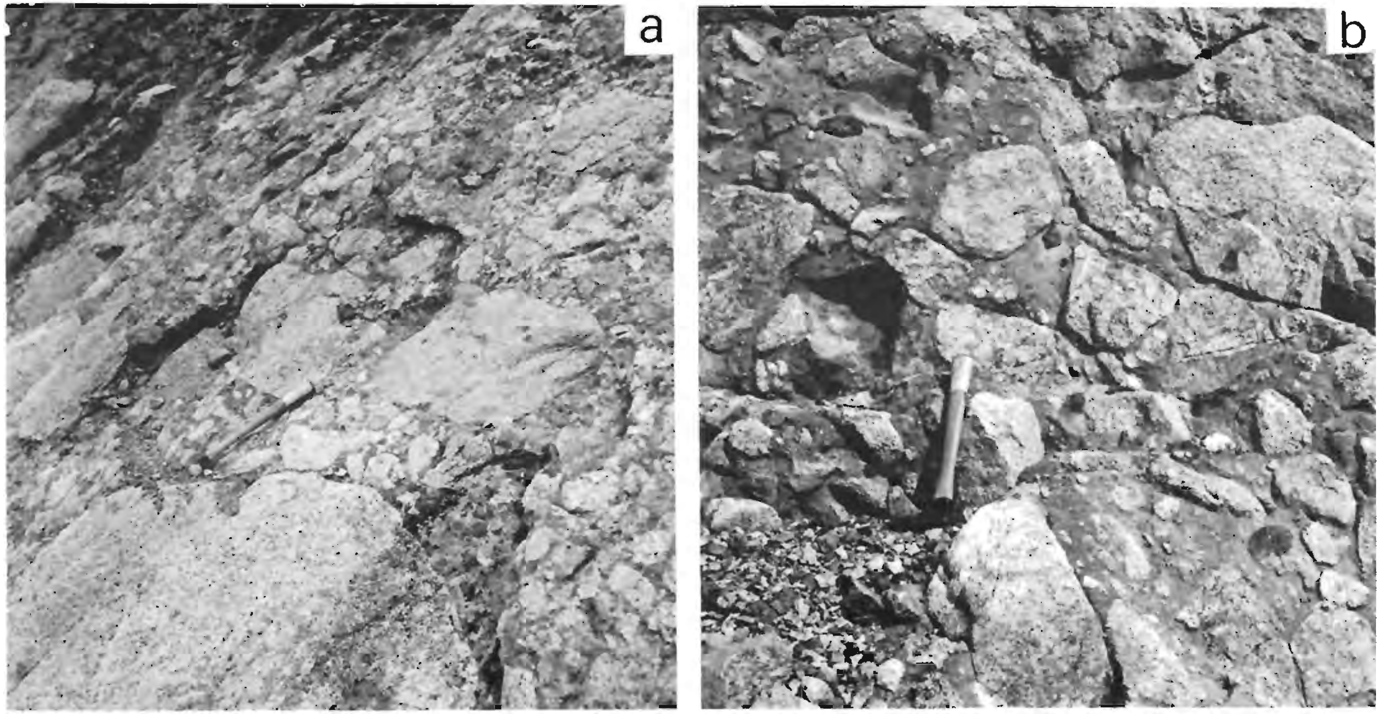


Plate X. Granitic boulder conglomerate of the Lemieux Creek Formation.

(a) Conglomerate at reference locality L4 (Fig. 24). The boulder at the lower left corner is about 3 metres across.

(b) Conglomerate at reference locality L5.

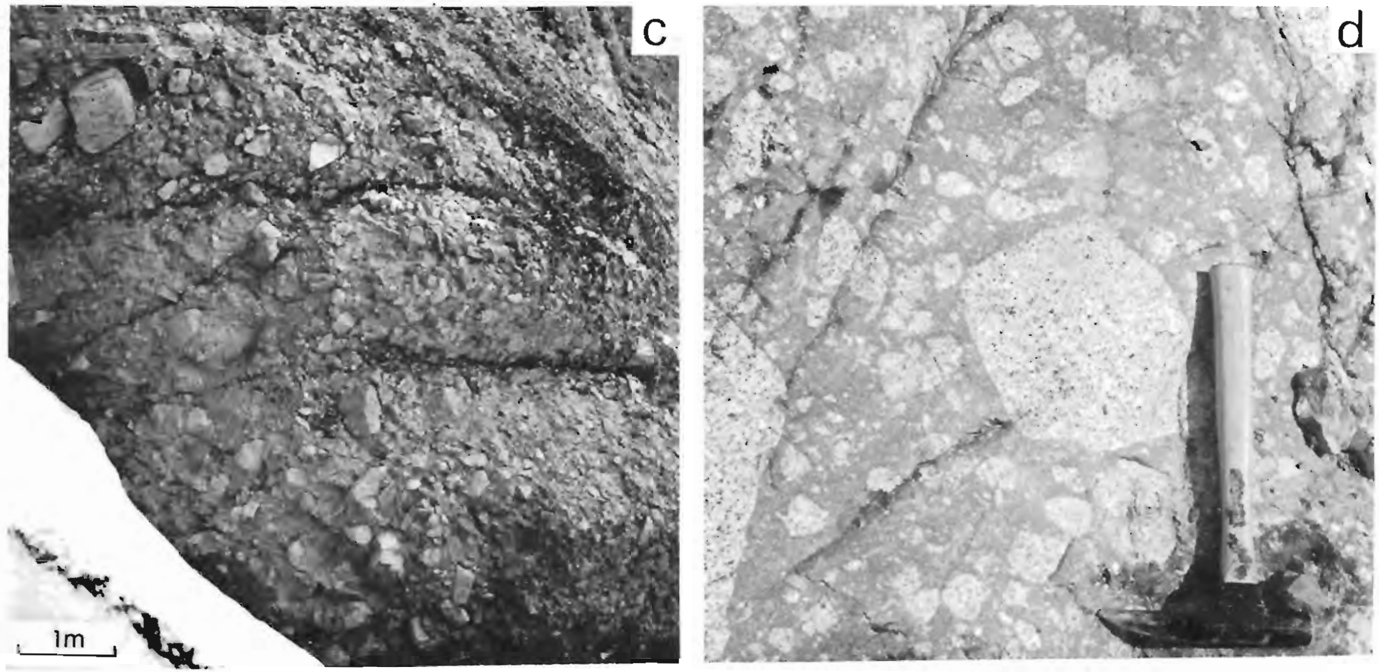


Plate X continued

(c) Conglomerate at reference locality L6. This is the massive unit underlying the thin bedded succession in Plates VIIf and IXb.

(d) Conglomerate in reference Section LCII (Fig. 24).

PLATE X

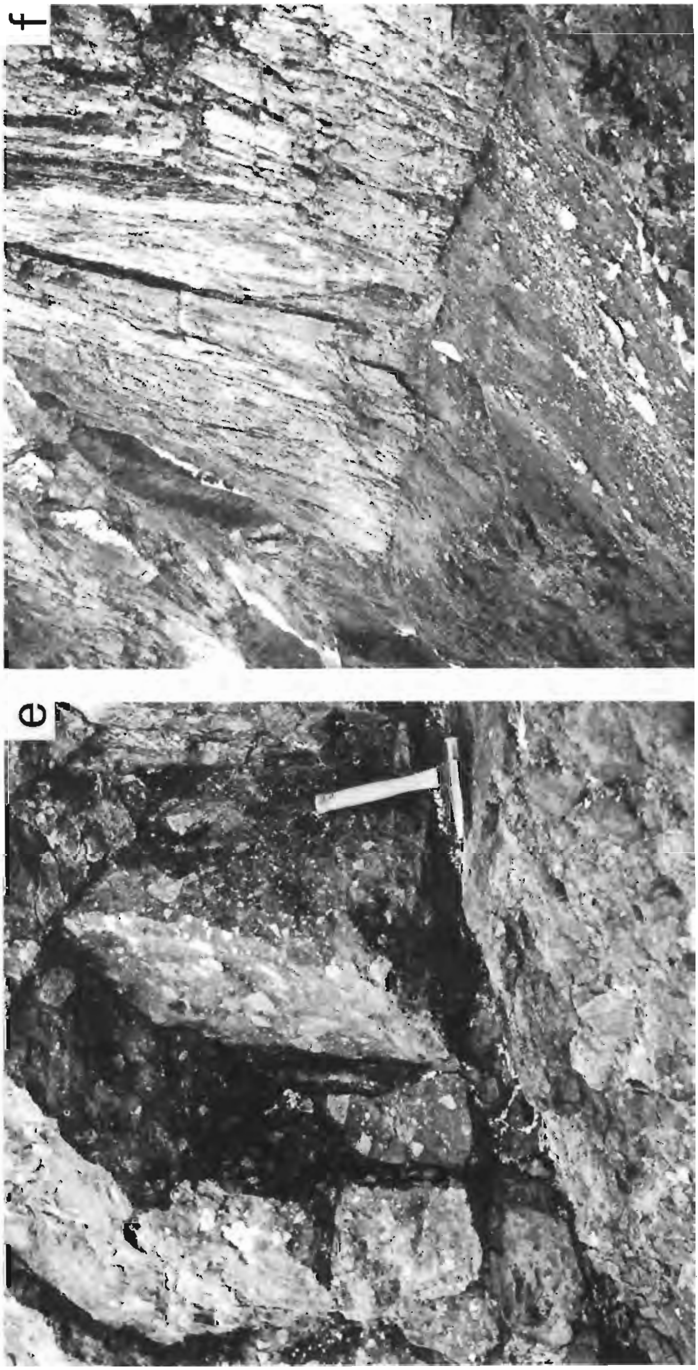


Plate X continued

(e) Granitic breccia at the base of the Lemieux Creek Formation, at reference locality L7 (unit 9c, Pl. IX).
(f) Sharp lower contact of the breccia in Plate Xe.

Lithology

The conglomerate is composed of rounded to angular pebbles, cobbles and boulders of hornblende-biotite or biotite quartz monzonite set in a medium green, medium- to coarse-grained, arkosic matrix. Rock fragments are exclusively quartz monzonite except in LCI and LCVII where volcanic boulders locally are just as abundant as granitic boulders. Almost all clasts in the matrix are derived from granitic material except for rare volcanic (lavas and tuff) fragments. Silt and clay-size material displays intense chlorite alteration, which accounts for the green colour in hand specimen. The matrix in all units is very poorly sorted and shows essentially no indication of bedding.

The size and abundance of boulders generally decreases northward within each subarea: boulders range up to 3 metres and make up from 20 to 65 per cent of the rock. This trend in the Lemieux Creek subarea is illustrated in Plate X. A similar northward trend is present in the Partridge Lake subarea. In LCX the maximum size of boulders decreases upward within the section: 60 cm at the bottom to less than 30 cm at the top. Generally, the larger boulders are subrounded to well rounded; the smaller boulders, cobbles and pebbles are subrounded to angular; and sand and smaller sized particles are very angular.

In section LCX the units are very massive (range from 40 to 85 m thick) completely unsorted in the basal and middle conglomerate units, but show crude thick layering at the top of the section. The layering in LCX is shown in Plate IX.

The most distinctive features of the conglomerate are: (1) complete lack of sorting, (2) great range in size of fragments, (3) random arrangement of fragments of all sizes, (4) massive character (lack of bedding features or preferred orientation even in the finest matrix), (5) presence of both well rounded and angular blocks, and (6) uniformity of fragment composition.

At the base of the formation, at reference locality L7, the lowermost unit is a massive breccia unit (50 m thick but tapering out at about 600 m southeast of this locality). It is different from the overlying conglomerate in that it has a much smaller amount (20 per cent) of coarse fragments (pebble and boulder size), suspended in a fine matrix (Pl. Xe). Fragments are of hornblende quartz monzonite ranging from one to 90 cm. Most are angular, but some are well rounded. The unsorted matrix is a pale green, fine-grained aggregate of angular to subangular crystal fragments (derived from quartz monzonite) which fall in size ranges 0.05 to 0.1 mm and 0.4 to 0.6 mm. Paucity of chlorite alteration accounts for the pale green colour of the matrix in contrast to medium and dark green of other breccias and conglomerates of this formation. The lower contact of this unit is very sharp and essentially planar (Pl. Xf). Only very rarely do fragments in the breccia touch this contact.

In LCIX, a unique pink, massive breccia unit near the base of the formation is composed almost entirely of angular granitic fragments with a matrix of closely packed, coarse angular crystal fragments. The amount of chloritized dust-size material is very sparse, and the rock takes its pink colour from altered feldspars.

In the Partridge subarea, sandstones occur at the base of the conglomerate sequence in sections LCIII and as beds in conglomerate of almost all sections. Sandstone beds are pale grey-green to medium green, medium-to coarse-grained, poorly sorted arkose. They are commonly pebbly and grade into granitic boulder conglomerates. Grains are angular to subangular. Bedding is massive to poorly developed and indicated by differences in size and amount of pebbles where they grade into granite boulder conglomerates, or by weak preferred orientation of some elongate fragments.

In the LCX a sequence of thin to medium bedded conglomerate, pebbly sandstone and arkose separate the thick, massive conglomerate units above and below (Pl. VIIf).

Tuff units are most common where the conglomerate bifurcates near LCVII and LCVIII. Medium green nonwelded, crystal-lithic tuff forms a thick wedge that thins eastward and interfingers with conglomerate units in LCVI. Lithic fragments are mainly granitic but include pumice lapilli and rare felty textured, microporphyritic volcanic rocks. Quartz and feldspar fragments are mainly derived from granitic material but some are plagioclase phenocrysts. All pumice, shards and dust are completely devitrified to fine- to medium-granular aggregates, and locally replaced by chlorite. Although the rocks are generally massive, preferred orientation of elongate lithic and crystal fragments suggests the plane of bedding.

Interpretation

This unique conglomerate represents landslide debris that avalanched from unstable granitic walls of a large structural depression. The composition of the boulders, the general northward decrease in maximum size of fragments and the thinning of the formation in east and west directions from the Partridge Lake valley, as well as northward, indicate that the source is from the south.

The extreme size range, lack of sorting, and angularity of fragments in the breccia at L7, as well as the thinness of this unit relative to its lateral extent, are compatible with emplacement as a fluidized mass of coarse blocks, suspended in a turbulent medium of air and sand size material. This fluidized system could originate as (1) fluidized rock fall avalanches similar to those that have occurred at Little Tahoma peak on Mount Rainier (Crandell and Fahnestock, 1965), or (2) fluidized granitic breccia dykes that have reached the surface. The author prefers the former interpretation because of the abundant evidence of landsliding in this area.

Streams issuing from the highlands in the vicinity of southern caldera walls deposited local alluvial fans between and after the avalanche episodes. Interbeds of tuff and local ignimbrite units indicate that some explosive volcanism was taking place during deposition of the conglomerate.

The fault bounding the thickest portion of the formation in Partridge Lake valley suggests that a graben formed after deposition of the MacAuley Creek Formation and before the deposition of most of the Lemieux Conglomerate. Tectonic movements that formed this graben may have initiated the avalanches which formed the conglomerate.

The shattered granite upon which the formation lies below L6 is a topographic high in the terrain around which the conglomerate was deposited.

Jones Creek Formation

Definition, Distribution and Thickness

The Jones Creek Formation consists of a mixture of ash-flow, air-fall, and waterlaid tuffs, lava flows and sandstones. It outcrops in three localities: along the ridge tops north of Jones Creek, east of "Gault" and south of "Gault". North of Jones Creek the formation consists of a basal series of basalt flows (290 m thick) overlain by two autobrecciated rhyolite flows separated by a nonwelded ash-flow tuff (totalling 250 m). These in turn are overlain by a partly welded ash-flow tuff at least 30 metres thick. The basal basalt flows thin to a single unit 1.5 metres thick near the east side of the exposure where a granitic boulder conglomerate bed, 3 metres thick, separates the basalt lavas from the overlying rhyolite. East and south of "Gault" the succession is mainly tuff with minor sandstone, siltstone and basalt flows (Appendix IIIC).

The formation conformably overlies the Lemieux Creek Formation and is the youngest formation in the Partridge and Lemieux subareas. It is at least 570 metres thick north of Jones Creek, 550 metres east of "Gault", and 200 metres south of "Gault", the upper parts of the formation having been removed by erosion.

Lithology

The dark grey, sparsely porphyritic basalt lavas contain glomeroporphyritic clusters of euhedral to deeply embayed plagioclase, less than 3 mm, and augite phenocrysts almost completely replaced by chlorite. Large plagioclase phenocrysts have broad cores (An_{76-78}) and normal oscillatory zoned margins (An_{60-66}): small phenocrysts and microlites range from An_{60-70}. The matrix is a fine mass of trachytic microlites and crystallites with scattered granules of relict pyroxene. Irregular amygdales are filled with chlorite, quartz and calcite in a complicated series of subconcentric shells. The matrix has abundant very fine chlorite and carbonate alteration.

The lower rhyolite flow is made up of thick, pale green to maroon zones of autobrecciation in its upper and lower parts and a central zone of flow banded and spherulitic rhyolite. Banding is formed by alternating layers of fine crystallites and coarse spherulitic crystallization. Phenocrysts, including low sanidine and plagioclase, make up 1 to 2 per cent of the rock. The upper rhyolite unit is entirely of autobrecciated lava along the east side of the outcrop but mainly flow banded rhyolite about 30 metres to the west. The size of rhyolite fragments in the breccia increases upwards, to about 15 cm across.

A single unit of pale green, partly welded ash-flow tuff, which caps the sequence north of Jones Creek, is composed of sparse sanidine phenocrysts, granitic fragments and rhyolite fragments (similar to the underlying rhyolite flows) in a matrix of devitrified pumice, shards and dust.

East of "Gault" the basalt and rhyolite lava flows are absent, and the formation is composed entirely of pale green to buff weathering, non- to partly-welded ash-flow tuffs. This section was not studied in detail.

South of "Gault", the formation, from bottom to top of the exposure, consists of arkose, partly welded ash-flow tuff, basalt lava flow, waterlain tuff, laminated siltstone, waterlain tuff and possibly some air-fall tuff (Appendix IIIC). Along the south side of this locality much of the lower half of the exposure is pale green coarse-grained arkose (Williams et al., 1958, p. 293). Along the north side, however, sandstones are more tuffaceous, and are accompanied by finely laminated siltstones and tuffs. Some beds have graded bedding and scour and fill structures. Others have abundant soft sediment deformation features such as convolute bedding, flow folds, ball and pillow structures and disrupted bedding (Pl. VIId). Some sandstones near the top of this section contain poorly preserved and fragmentary macroplant remains but are devoid of microfossils. No suggestion as to age is possible with any of the samples from this locality (W.S. Hopkins, pers. comm., April, 1969).

South of "Gault", the formation occupies a basin. In this exposure the sequence has been tilted as indicated by steep dips (up to 30 degrees) of graded bedding in waterlaid tuffs.

Interpretation

This formation represents quiet effusion of lavas with intermittent eruptions of ash flows, probably along the peripheral ring fracture system; and accumulation of silt, sand, and air-fall ash in a lake (or lakes) along the southeastern margins of a caldera. The various volcanic and sedimentary events were probably taking place independently and penecontemporaneously in several localities.

CROZIER SUBAREA

In this subarea, the Crozier Breccias and the Crozier Tuffs and Lavas are of uncertain age, but tentatively correlated with the Lemieux Creek and Jones Creek Formations respectively. The Boudette Creek Formation, a distinctive sequence of ignimbrites overlying both the Crozier Breccias and Crozier Tuffs and Lavas, is thus considered to be the youngest stratigraphic unit in the complex. Figure 25 shows the distribution of these formations and generalized columnar sections through them; Appendix III-D gives detailed lithology of some of these sections; and Figure 11 shows the apparent stratigraphic position of these formations with respect to formations of the Partridge subarea.

Crozier Breccias

Definition and Contact Relations

This formation consists mainly of very coarse epiclastic breccias and conglomerates with minor sandstone, siltstone and tuff. It outcrops in three isolated localities, each having a different stratigraphy and many lateral changes in lithology. The generalized stratigraphic sequence in each locality is illustrated by reference sections CRI, CRII and CRIII (Fig. 25).

In general, the Crozier Breccias conformably overlie older tuffs and locally rest on basement topography. They are mainly overlain by the Crozier Tuffs and Lavas but locally interfinger with them. In section CRI, the formation conformably overlies the MacAuley Creek Formation. In the vicinity of CRII the formation lies on undifferentiated tuffs of either Partridge Lake

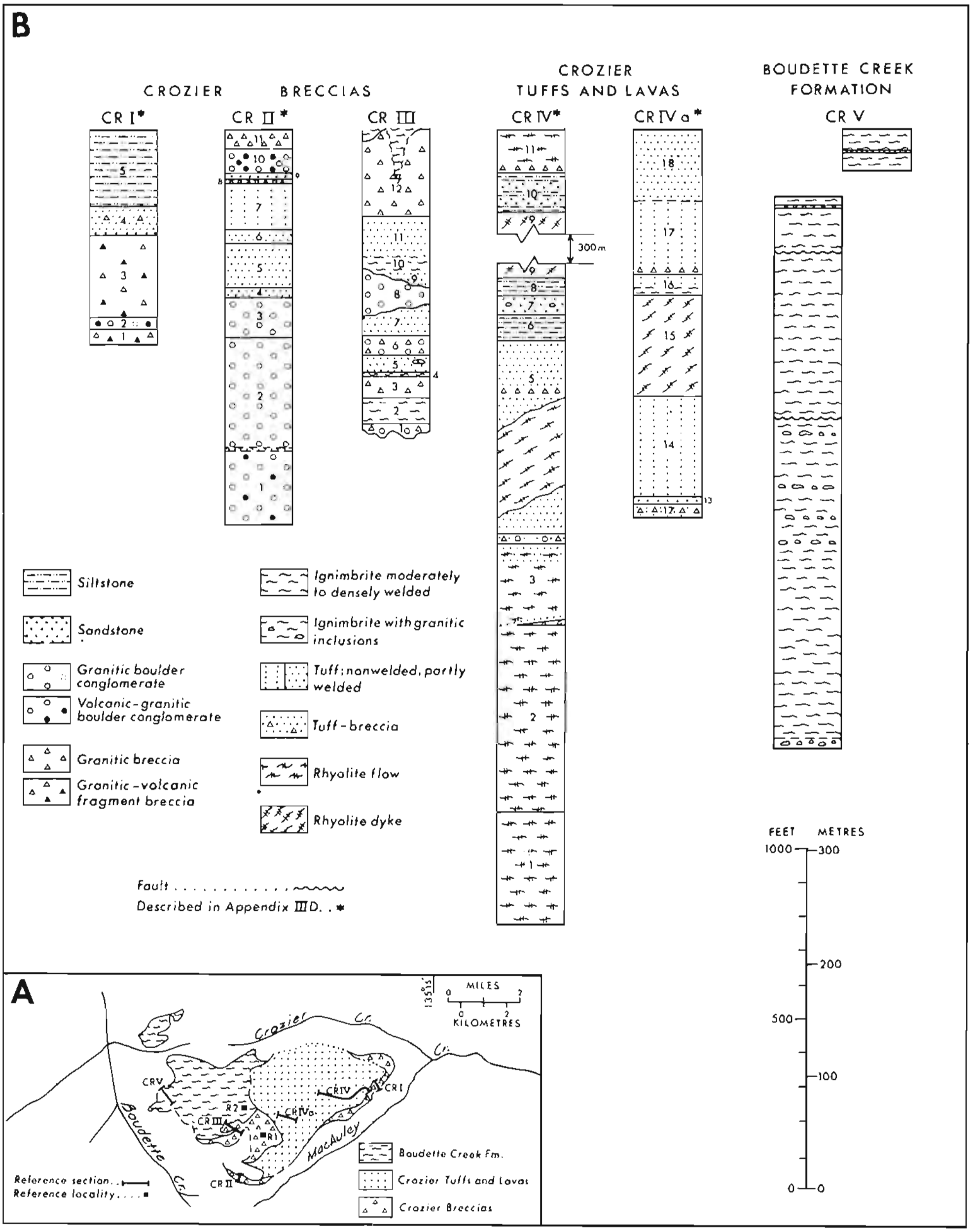


Figure 25. A - Distribution of the Crozier Breccias, Crozier Tuffs and Lavas, and Boudette Creek Formation; location of reference sections and reference localities.

B - Reference sections through formations in the Crozier sub-area.

or MacAuley Creek Formations, and both rest against a steepsided peak in the old granitic topography (Pl. VIIc). Section CRIII rests nonconformably on metadiorite of the Yukon Group. CRI and CRII are conformably overlain by the Crozier Tuffs and Lavas; CRIII is succeeded by the Boudette Creek Formation. Tuff layers in CRIII and near the top of CRII are correlated with the Crozier Tuffs and Lavas.

Lithology

Section CRI: This is a typical columnar section through an elongated wedge (3.6 km north-south by about 1.5 km wide) along the west side of MacAuley Creek valley. The formation is 125 metres thick in CRI and tapers out southward and westward.

The lower two thirds of the section is a thick succession of coarse granitic-volcanic fragment breccias that gradually become finer grained and grade into coarse grit near the south end of the exposure. These breccias interfinger with tuff-breccia and partly welded tuff near the north end of the exposure. Where the formation thins out, west of the north end of the exposure, it has much more granitic than volcanic fragments.

Units 1 to 3 are very brightly coloured, granitic-volcanic fragment breccias and conglomerates composed of andesite, rhyolite, tuff and granitic fragments in many shades of green, grey, maroon, purple, and pink, in a dark green rusty buff weathering chloritized grit matrix. The fragments, which range from sand size to blocks 60 cm across are all angular to subangular in units 1 and 3, whereas in unit 2 the large clasts are well rounded. Coarse fragments make up to 50 per cent of the rock and the ratio of volcanic to granitic fragments ranges from 3:1 to 10:1. These essentially unsorted, massive, cliff-forming units locally have crude bedding indicated by preferred orientation of elongated fragments.

Unit 4 is a dark grey weathering, massive tuff breccia that has a basal thin bedded sequence of brightly coloured grits composed of the same variety of fragments as unit 3.

Unit 5 is mainly of thin to medium bedded, dark green siltstones that lie conformably above the breccia units for about 4.5 kilometres along the west side of MacAuley Creek valley. The unit is thickest (about 75 m) near CRI and thins out gradually southward.

Toward the south end of the exposure the succession is interbedded tuff, pumiceous grit, and finely laminated dark bluish grey siltstone. In the southern exposures, where siltstone has been recrystallized to fine albite, quartz and chlorite, it is in contact with a large rhyolite sill. The siltstone is an aphanitic brittle rock that resembles devitrified obsidian, except for relict bedding features.

Section CRII: In this locality the formation consists dominantly of granitic and volcanic-granitic conglomerates and breccias, and subordinately of ash-flow and air-fall tuffs, and tuffaceous grits. CRII is the thickest section (450 m) exposed.

Units 1, 2 and 3 are massive, unsorted, conglomerates composed almost entirely of granitic fragments in a coarse unsorted grit matrix. Units 4 to 7 are mainly ash-flow tuffs with some air-fall tuff beds in unit 7. Grits, conglomerates and breccias of units 8 to 11 contain both volcanic and granitic clasts.

Near the northeast end of the exposure, finely bedded shales and siltstones comprise the uppermost units of the section.

Section CRIII: Near this section, the formation consists of extremely variable sequence of breccias with interbedded tuffs, conglomerates and ignimbrites, 275 metres thick.

Units 1 and 3 are massive, completely unsorted, coarse breccias: fragments in unit 1 are mainly volcanic whereas fragments in unit 3 are mainly gneissic and granitic with minor volcanic material. These breccias are separated by moderately welded ignimbrite of unit 2. Unit 3 is overlain by ignimbrite of unit 4. Units 5 and 7 are medium green, partly welded ash-flow tuffs. Unit 5 contains large inclusions of shattered granitic material. Unit 8 is an unsorted granitic boulder conglomerate that undulates and thins abruptly east of this section. Units 9, 10 and 11 are dark green to maroon deeply weathered ash-flow units. Units 9 and 11 are mainly non- to partly-welded tuffs, whereas unit 10 is a moderately welded ignimbrite with platy cleavage parallel to the eutaxitic foliation. The uppermost unit is massive granitic breccia which grades laterally into shattered granite. The breccia is probably granite rubble deposited against an irregular granite terrain.

The conglomerate and breccia units have variable thickness; in two dimensions some are seen to be lens-shaped bodies. Although there is extreme lateral variations, the general sequence - lower chaotic breccias, middle interbedded pyroclastic rocks, conglomerate and breccia, and upper granitic breccias - is the same throughout this locality. Breccias are all very poorly sorted, coarse massive units with angular to subangular blocks, only the largest ones being well rounded.

Near reference locality R1 the sequence is composed almost entirely of very coarse, completely unsorted breccias that have been deposited above and against nobs and cliffs of the very irregular basement topography: pyroclastic rocks are absent. The general sequence from bottom to top of the exposure consists of the following: granitic and aplite pebble breccias with lenses of tuffaceous grits scattered throughout; lenses of granitic and metamorphic fragment breccias with local grit; gneissic breccia; gneissic and granitic boulder conglomerates. Lithology of the breccia fragments changes abruptly from place to place along with the change in lithology of the basement rocks.

Interpretation

Coarse, unsorted breccias and conglomerates in all localities are interpreted as rubble, scree and talus debris deposited by avalanches, rock-falls possibly mud flows and general processes of rapid mass-wasting.

The presence of volcanic fragments as a dominant constituent in the lowermost breccia and grit units in each locality suggests that the first material was eroded from a volcanic terrain. Near CRI the elongated wedge of coarse volcanic breccias is interpreted as a broad apron of landslide rubble that was deposited at the base of a long fault scarp. The westward direction of thinning and the composition of blocks indicates that the source lies to the east of the present exposure.

Thick beds and wedges of granitic and metamorphic breccias and conglomerates represent rubble that accumulated in local depressions in the rugged basement terrain. The steep escarpments, at the base of which the rubble was deposited, are still partly preserved in the vicinity of CRII and CRIII. That the topography was probably more irregular and of higher relief in this vicinity is suggested by the many thick local wedges of breccia and the presence of coarse breccia throughout most of the succession (some of which are deposited against visible escarpments), whereas breccias only occur in the lower parts of the formation in CRI and the upper part is a thick sequence of siltstone.

Well-bedded siltstones and tuffs which interfinger with grits and tuffs near CRI represent quiet deposition in a lake while coarse sands accumulated along the lake margins or were deposited by streams flowing into the lake. The extent of the siltstone unit suggests the lake was elongated north-south, and about 4.5 kilometres long by 1 kilometre wide.

Outcrops of this formation fall within a broad zone 1.5 to 4.5 kilometres wide west of MacAuley Creek valley that is approximately along the margin of the inner cauldron (see Chapter V). The basement rocks in this zone are typically brecciated and shattered, or contain abundant narrow zones of brecciation within massive rocks. The rugged topography was probably formed by block faulting along the rim of the inner cauldron as it collapsed. Landslides from the unstable peaks and escarpments thus formed produced thick wedges of rubble. Intermittent explosive volcanic eruptions deposited ash flows and air-fall ash which filled depressions in this irregular rubbly terrain. Shocks during these eruptions may have initiated some of the landslides. While coarse rubble continued to accumulate in the high rugged area near CRII and CRIII silt and sand accumulated in a long narrow lake along the east side of the subarea.

The volcanic eruptions, landslides and subaqueous accumulation of silt and sand were taking place simultaneously in several localities. Different types of country rocks and different relief in each locality caused different rates of epiclastic deposition and the extreme stratigraphic variation.

Crozier Tuffs and Lavas

This succession of interbedded lavas, tuffs, and minor epiclastic units is restricted to the northeast part of Crozier subarea. Composite columnar section CRIV (Fig. 25) shows the general sequence of units in this formation. Its precise thickness has not been established because of complicated faulting and intrusion of large dykes and sills. In CRIV the section is at least 850 metres thick excluding the rhyolite intrusions.

At the base of CRIV and at the top of CRII the formation conformably overlies the Crozier Breccias. In one place along Crozier Creek, it rests nonconformably on granodiorite. Near the top of the exposures, near CRII and on the ridge to the north, the tuffs are interlayered with granitic boulder conglomerate considered to be part of the Crozier Breccias. Near R2 the Crozier Tuffs and Lavas are conformably overlain by the Boudette Creek Formation.

Three rhyolite lava flows (with a total thickness of about 430 m) conformably overlie the Crozier Breccias northwest of MacAuley Creek. They thin out near the south end of the exposure. Near the southern exposures of the formation, the lowermost units are green tuff with minor interbeds of finely laminated siltstone.

The middle part of the succession is interbedded tuff, siltstone, and volcanic grit. Very thick sills and dykes of white rhyolite obscure the precise sequence of beds.

The upper parts of the succession consists of coarse, pale to medium green, non- to partly-welded ash-flow tuffs. Depositional units are locally separated by beds and lenses of granitic-volcanic conglomerate and breccia.

Tuff units in the lower part of the succession are massive, unsorted ash flows, whereas in other parts they are thin to medium bedded. Thin bedded tuffs, composed of pumice fragments in dominantly lithic grit, are interpreted as waterlain tuffs or combination of waterlain and air-fall tuffs.

Units are generally thick, massive and continuous in the northern exposures whereas in the southern exposures there are many abrupt local variations such as small valley-filling ignimbrites and accumulations of granitic-volcanic breccia as well as several small faults.

Interpretation

This formation records the early effusion of rhyolite lavas followed by the eruption of ash flows. Silt and sand accumulated in one or more lakes during a period of quiescence in the midst of the eruptive series. Toward the west, the tuffs were deposited against steep peaks in the granitic terrain from which rubble tumbled down intermittently between eruptions.

Boudette Creek Formation

The Boudette Creek Formation is a succession of densely welded ignimbrites that outcrop on dark brown precipitous cliffs in the central-west side of the Crozier subarea (Fig. 25). It is at least 550 metres thick in reference section CRV. Thicknesses estimated in this section are only approximate because of complicated faulting with rotation of fault blocks.

The lower contact of the formation is visible in many localities. Above CRIII, basal dark brown ignimbrites and partly welded tuffs have filled small depressions in the granitic breccias and have lapped up and thinned out against 'peaks' in the breccia topography. In one place, wedges and slivers of ignimbrite are faulted into the granitic breccia unit.

On the west side of the ridge near CRIII, lenses of ignimbrite and irregular ignimbrite sheets drape over the steep walls of a depression in the irregular basement topography.

On the northeast side of the ridge near CRIII, ignimbrite overlies a tuff-conglomerate succession. The ignimbrite has incorporated rounded boulders and lapilli of tuff from the underlying unit. The succession occupies a depression in the granitic topography that is at least 250 to 300 metres deep. The south margin of this depression is intruded by rhyolite and ignimbrite dykes (see Eruptive Centre IX, Fig. 33).

Near CRIII the basal ignimbrite unit has incorporated large, well rounded granitic boulders and cobbles from the underlying conglomerate formation. The pale grey, partly welded ignimbrite grades upward within 3 metres into a dark brown densely welded rock. The rest of the succession is a very uniform, moderately to densely welded, massive ignimbrite with little variation except locally where the colour varies from dark green to dark brown.

At least eight ash-flow units can be distinguished. Their contacts are marked by basal zones rich in granitic and metamorphic inclusions (some are up to 7 m across); zones of unusually large pumice fiamme (welded lump pumice); thin beds or a series of lenses of granitic boulder conglomerate; ash beds; and abrupt change in joint pattern. In many cases contacts are recognizable only by the zone of abundant granitic inclusions. The upper two units have well-developed columnar jointing, averaging 20 to 25 cm in cross-section. Both units are very dark grey (almost black), densely welded ignimbrites with a subvitreous lustre. The contact between these units is marked by a thin bed (less than 0.3 m) of poorly indurated yellow ash.

Near R2 the formation has been broken up and disoriented by many faults which are clearly marked by zones of shattered and brecciated ignimbrite (in pieces 0.5 - 3 cm); orange-weathering zones of intense iron oxide alteration and abrupt change in attitude of eutaxitic foliation (in some places from nearly horizontal to nearly vertical). West of R2 the mass is less affected by faulting, and most dips range from horizontal to 20 degrees. Some of these dips may approximate the original attitudes of the ash flows.

Interpretation

This ignimbrite succession represents at least 8 depositional units, and probably many more that have not been identified. Dense welding throughout the sequence indicates a high temperature for the ash flows. The closely spaced columnar joints, unique to the upper units, possibly indicate an upward increase in temperature of the depositional units. The sequence cooled as a single, huge, compound cooling unit. Ash-flow eruptions of small volume began intermittently during accumulation of tuffs and breccias on the basement topography. This fact is indicated by lenses of ignimbrite within the breccia - tuff sequence exposed near CRIII. High temperature ash flows first filled deep valleys in the basement and then built up thick massive piles of ignimbrites. Faulting, disruption and jostling within the mass shattered parts of the ignimbrite, rotated large areas so that their foliations are nearly vertical, and incorporated slivers of ignimbrite into the underlying granitic breccia.

The Boudette Creek ignimbrite is the latest record of ash-flow eruption in the complex.

ERUPTIVE CENTRES

Eruptive centres within the map-area are inferred by the presence of one or more of the following features: (1) thick localized piles of coarse pyroclastic rocks and lavas, usually slashed through by dykes of many different lithologies; (2) breccia pipes within granitic rocks; (3) intrusive tuffs and ignimbrite bodies; and (4) necks and dykes of igneous rocks usually associated with pyroclastic dykes. Only a few of these centres contain single conduits; most are complex areas resulting from venting of magma along many different conduits at different times.

The ten centres described in the following sections lie along the periphery and west-central parts of the complex (Fig. 26).

The ring dyke and the swarm of dykes along the southern part of the map-area, although they probably represent feeders to surface eruptions, are discussed in a later section.

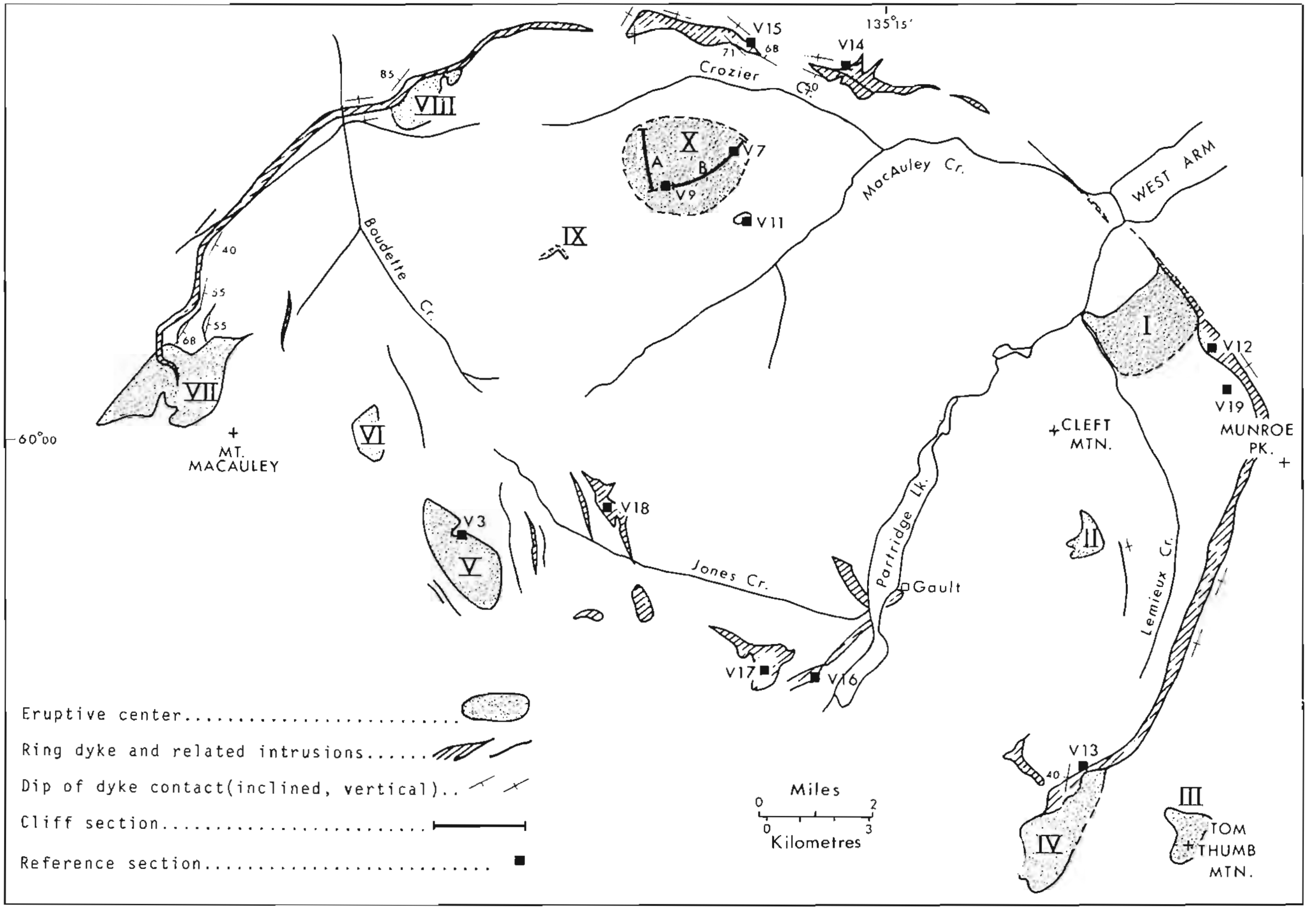


Figure 26. Location of eruptive centres and distribution and attitude of the ring dyke and related ring-fracture intrusions.

ERUPTIVE CENTRE I

In this centre an ignimbritic body about 500 metres across cuts a chaotic mass of volcanic breccias and tuffs. The tuff-breccia mass comprises a mixture of pale green non- to partly-welded tuffs, coarse volcanic fragment tuff-breccias, and dacite, rhyolite and andesite (?) lava flows and dykes. The pale green tuffs and breccias, which make up most of the exposure, form massive unsorted units. Although there is a great variety of lithologies, there is little or no lateral continuity of individual units. Breccias at the base of this mass lie nonconformably on shattered and brecciated granodiorite. The mass is cut by a system of east- to southeast-trending faults, subparallel to the ring dyke which bounds the north side. A fault with at least 1 kilometre-displacement (along which the ring dyke lies) separates the downdropped tuff-breccia mass from granitic rocks to the north.

The ignimbritic body is mainly dark brown and densely welded with lithologic features essentially the same as those of welded ash flows. Near the southeastern contact this ignimbrite grades into pale green moderately to partly welded ignimbrite, which forms large pods within the dark brown ignimbrite. Eutaxitic foliation dips steeply westward (45-60 degrees) over a vertical distance of about 250 metres along the eastern side of the body, but has shallow (15-25 degrees) westward dips in the lower, western side of the body. The steeply dipping foliation is parallel to the eastern contact of the ignimbrite with tuff-breccias. Parts of this body make fault contact with the chaotic pile of tuffs and breccias to the north.

Interpretation

Tuffs and breccias of the chaotic pile are lithologically similar to tuffs of the Partridge Lake and MacAuley Creek Formations. The pile differs from these formations only by nature of the coarseness of the pyroclastic rocks, the many local lithologic variations, and lack of continuity of units. All pale green tuffs lying directly on granitic rocks in this vicinity belong to the Partridge Lake Formation. Furthermore, the apparent thickening of the Partridge Lake Formation towards the northeast corner of the map-area points to a source near this mass. This chaotic pile, therefore, is interpreted as a remnant of a pyroclastic cone that was built along the ring-fracture system above the vents from which ash flows of the Partridge Lake Formation erupted.

The steeply dipping eastern contact of the large ignimbritic body and the parallelism of the foliation to this contact, are strongly suggestive that this may be an intrusive ignimbrite unit. An alternative explanation is that this is a huge ignimbrite block that is faulted into the tuff-breccias. Although not enough data are available to discount this hypothesis, at least some of the faults can be shown to post-date emplacement of the ignimbrite body.

The volcanic history in this locality began with explosive eruption of ash, lapilli, blocks and ash flows from a (?) fissure along the ring-fracture system. Voluminous ash flows directed south and southwestward formed part or possibly most of the Partridge Lake Formation. Post-eruptive subsidence along the outer ring fracture system dropped this pile of tuffs and breccias at least 1 kilometre, and probably partly destroyed the pyroclastic cone that built above the ring fracture system. During ring-fracture volcanism after subsidence, ignimbrite magma intruded along one of the faults to produce the large ignimbrite mass, and erupted ash flows which probably contributed to the emplacement of the Cleft Mountain Formation. Isolated ignimbrite bodies in the floor of the north end of Partridge Lake valley may be related to this eruption.

ERUPTIVE CENTRE II

This centre consists of a large ignimbrite body, about 450 metres long and at most 240 metres wide, and many small ignimbrite, tuff and felsite dykes, that intrude shattered and brecciated granitic rocks. Figure 27 shows the generalized relationships in a longitudinal section of this centre.

Structural Relations

The north and south contacts of the large ignimbrite body are clearly exposed on the crest of the ridge, whereas the precise extent and nature of the east and west boundaries of the body are obscured by talus slopes. Near contacts with granitic rocks this body has included angular to well-rounded blocks of granitic breccia, up to a metre across. There are well-rounded blocks within the ignimbrite 175 metres from the northern contact.

Vertical eutaxitic foliation in the ignimbrite mass has an extremely consistent northeast trend throughout. The foliation is parallel to the steeply dipping northern and southern contacts, and wraps around large granitic inclusions within the body.

Granitic rocks are shattered and brecciated on all sides for several hundred metres away from the body; beyond they grade into massive granite. Some of the granitic breccia, however, which contains well-rounded granitic boulders, is essentially identical to landslide conglomerates of the Lemieux Creek Formation.

On the north side of the centre, granitic breccias are intruded by several large and small tuff, ignimbrite and felsite dykes. At VI (Fig. 27) a felsite dyke has incorporated a huge inclusion of the breccia, at least 6 metres across (Pl. XIc).

A series of shallowly-dipping ash-flow units, which most likely originated from this vent, lie nonconformably over the granitic terrain adjacent to the south side of the vent.

Lithology

The large body is a pale grey moderately welded ignimbrite. At the northern contact with granitic breccias (and at 26 m and 90 m south of this contact), the rock is a pale grey felsite bearing granitic fragments, with very indistinct foliation shown by crude preferred orientation of dark grey elongate lenticles, less than 2 mm long. Lenticles having round or tapering terminations, axiolitic rims and micropoikilitic centres, are surrounded by a microfelsitic matrix. The matrix is disjointed by a reticulate pattern of fine fractures, healed by medium granular crystallization. Lenticular areas grade into areas without recognizable lenticles. Within 1.5 metres of the contact,

PLATE XI

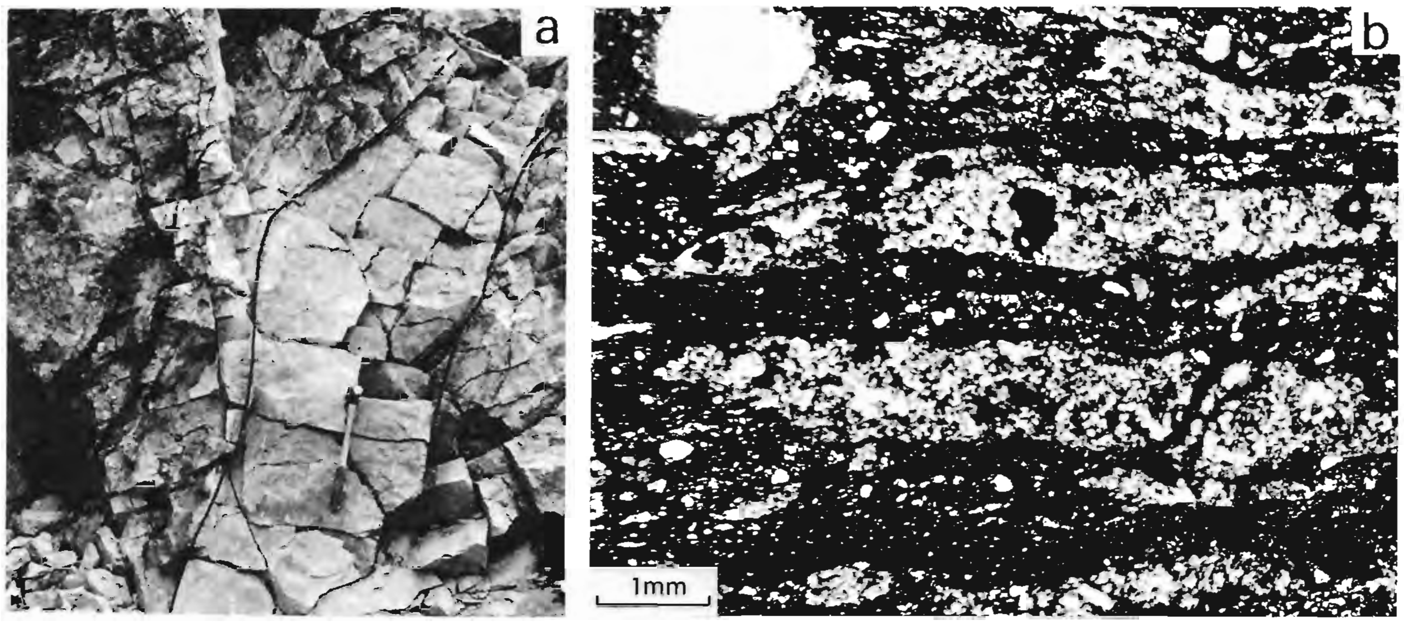


Plate XI. Ignimbrite and felsite dykes and diatreme breccia.

(a) Ignimbrite dyke cutting granitic breccia at reference locality V1 (Fig. 27). Note the eutaxitic structure.
(b) Photomicrograph of ignimbrite dyke in Plate XIa showing lenticles with rounded and tapering terminations. Cross-polarized light.

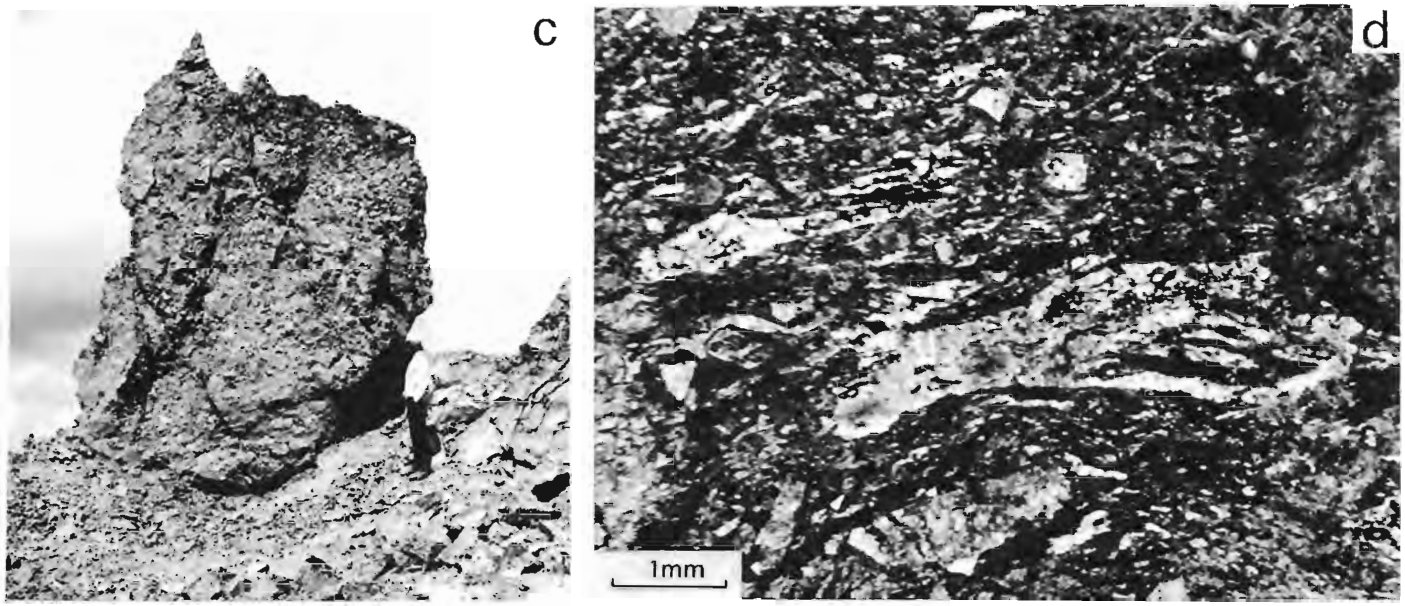
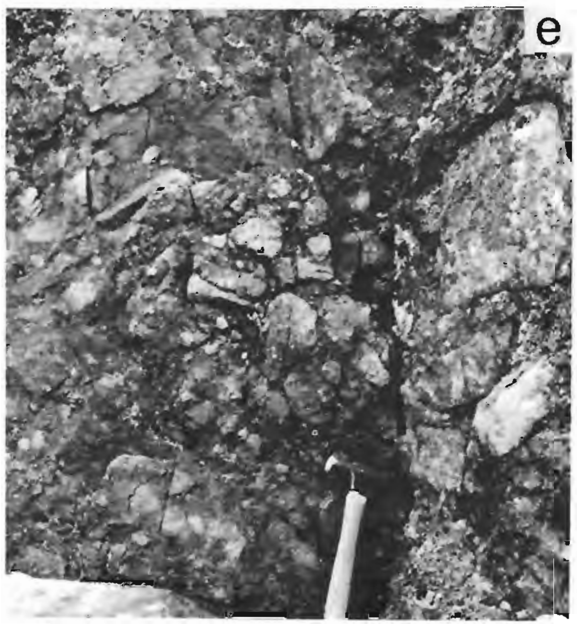


Plate XI continued

(c) Large inclusion of granitic breccia in felsite dyke at reference locality V2 (Fig. 27).
(d) Photomicrograph of ignimbrite from near the top of the dyke at eruptive centre IX (Fig. 33). Note the distinct pumice lenticles. Cross-polarized light.

PLATE XI



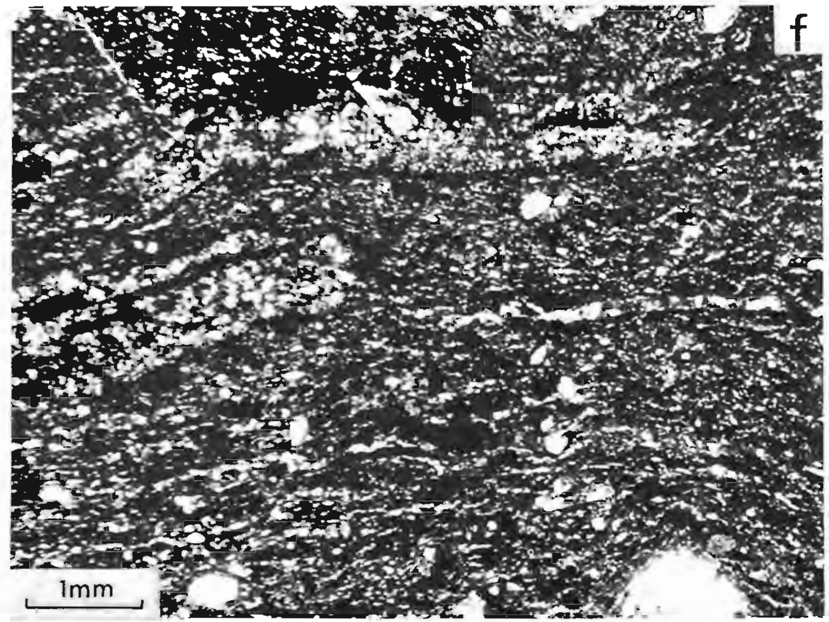


Plate XI continued

(e) Diatreme breccia from eruptive centre III.

(f) Photomicrograph of ignimbrite from near the base of the ignimbrite dyke at eruptive centre IX (Fig. 33). Foliation is imparted by thin tapering lenticles and fine streaks slightly coarser than the groundmass.

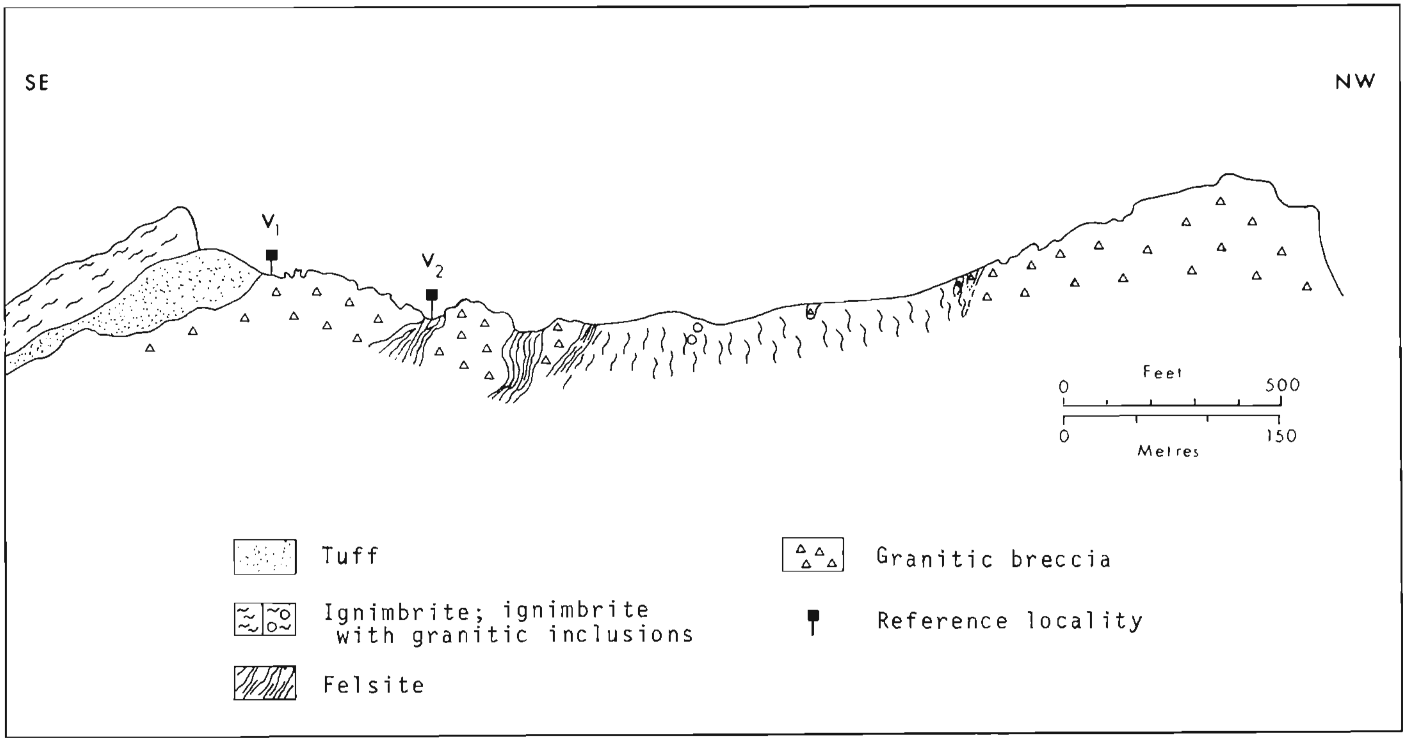


Figure 27. Generalized northwest-southeast cross-section through eruptive centre II (sketch from photograph).

the rock has a well developed eutaxitic foliation in which dark green flattened pumice lenticles are up to 2 by 30 mm (but generally less than 5 mm). Pumice, with axiolitic rims and spherulitic centres, has both rounded and fiamme terminations. Some areas of fine-granular crystallization resemble devitrified glassy blobs that have tended to elongate parallel to the foliation.

Toward the southern contact of the large body the eutaxitic-textured ignimbrite grades into pale buff-grey rhyolite. These gradational zones in the ignimbrite, adjacent to contacts with granitic rocks, resemble chilled margins.

At V2 (Fig. 27) a dyke about 15 metres wide grades from massive porphyritic rhyolite in the north part to a lenticular felsite in the south part. The long, undulatory lenses have rounded to pointed ends without fiamme structures, and axiolitic crystallization. The microfelsitic matrix shows sporadic spherulitic crystallization. In the same general area, an ignimbrite dyke, 60 to 100 cm wide, intrudes the granitic breccia (Pl. XIa). This rock is essentially the same as a densely welded ash flow except that the flattened and stretched pumice mostly has rounded terminations (although some delicate fiamme are also present). Some pumice bears relict perlitic cracks, and many are partly or completely replaced by radiating clusters of pistacite. Pumice has medium- to coarse-grained crystallization; fine wavy streaks of medium-granular crystallization between pumice are interpreted as stretched devitrified shards. Intershard material is cryptocrystalline.

Interpretation

That this is an intrusive ignimbrite complex is indicated by the following features: (1) steeply dipping contacts with granitic rocks, (2) inclusion of huge blocks of granite breccia at contact zones, (3) constant vertical foliation that conforms to the contact, (4) gradation of ignimbrite into fine lenticular felsite at the contact, and (5) a small ignimbrite dyke and tuff dykes intruding the granitic rocks. The presence of ash-flow tuffs and ignimbrites, landslide breccias and dacite lavas at the same or lower elevations as the main ignimbrite body suggest that the present level of exposure may be near the surface that existed at the time of eruption.

The pyroclastic material of the vent exploded through granitic rocks, probably along a fracture zone formed during early stages of cauldron collapse, and flowed out on the irregular granitic terrain as ash flows. Some ash flows of the MacAuley Creek Formation, in the Lemieux subarea, erupted from this vent.

ERUPTIVE CENTRE III

This is a subcircular centre about 900 metres in diameter that is well exposed for a vertical distance of about 450 metres at the peak of Tom Thumb Mountain. It comprises three parts: a central subcircular volcanic breccia pipe 600 metres in diameter; an andesite body which collars the southeast side of the pipe; and an elliptical zone of granitic breccia on the north side of the pipe (Fig. 2). The centre, which is completely surrounded by granitic rocks, lies near the junction of three different granitic bodies: biotite granodiorite, biotite quartz monzonite, and fine-grained quartz monzonite.

The volcanic breccia is completely unsorted, made up of a variety of randomly oriented, subangular to rounded, fragments up to 50 cm across (generally less than 15 cm), in a dark greenish grey, mauve to maroon weathering, grit matrix (Pl. XIe). Lapilli and blocks include granodiorite, pink micrographic leucogranite, quartzite, porphyritic rhyolite, dacite, andesite, and tuff-breccia bearing essentially the same constituents as this breccia. Crystal fragments include euhedral to resorbed quartz and euhedral oligoclase (An_{28}) phenocrysts and quartz, feldspars and chloritized biotite derived from granitic rocks. The matrix grit is composed of ash-size lithic and crystal fragments of the same compositional varieties as the lapilli, surrounded by a groundmass of shards, pumice and dust. Pumice and shards have very fine granular devitrification, and are almost indistinguishable except for relict axiolitic structure in some shards. The matrix has abundant fine chlorite throughout, and some fragments are completely replaced by epidote and chlorite. A typical composition of the matrix is: 40% accessory and accidental fragments, 10% phenocrysts, and 45% matrix (pumice, shards and dust).

The dark grey andesite collar consists of normal oscillatory-zoned plagioclase (An_{20-45}), low sanidine, and (?) quartz phenocrysts, as well as fragments of granitic rocks (and crystal fragments derived from them) and tuff, in a dark grey aphanitic matrix. The matrix is largely a cryptofelsitic mass with a small amount of very fine plagioclase laths. This rock-unit forms gigantic, nearly vertical columns on the northwest face of the mountain.

Granitic breccia, which outcrops over an elliptical area about 900 metres long and 400 metres wide, is very similar to other brecciated granite in the basement rocks. It consists of angular to well-rounded pebble- to boulder-size fragments in a pale green grit composed of sand-size crystal fragments derived from the granitic material. At the margins of this mass the breccias grade into shattered then into massive quartz monzonite. The brecciated area is intruded by many dacitic to andesitic dykes ranging from 3 to 15 metres thick. Over a vertical distance of 200 metres, the breccia mass appears to be a steeply dipping pipe-like body.

Interpretation

This complex is interpreted as a diatreme breccia pipe that drilled its way upward through granitic rocks. That there was more than one stage of diatreme intrusion is suggested by the presence of breccia fragments within breccias – both having the same general composition. The eruptive sequence probably began with subterranean explosions in the sharp cupola of a near surface magma chamber, which shattered and brecciated some of the granitic terrain. A turbulent fluidized mixture of rock fragments, phenocrysts, and gas-charged salic magma intruded upward along the south side of the disrupted granite. Some of the brecciation in the granitic rocks may have resulted from collapse or chimneying following partial evacuation of the cupola by explosive eruptions. Similarly some of the volcanic breccia may represent material that fell back into the vent during the later stages or after the eruption. After explosive eruption (or intrusion only) of the breccias, andesite magma, charged with fine particles of granitic material, intruded along the south contact of the breccia pipe. It is not known if any of this material actually reached the surface, but because of the relatively high altitude of the present vent, with respect to the other volcanic rocks in the cauldron complex, this diatreme was probably a near-surface feature. It may have built a pyroclastic cone which has since been destroyed by erosion.

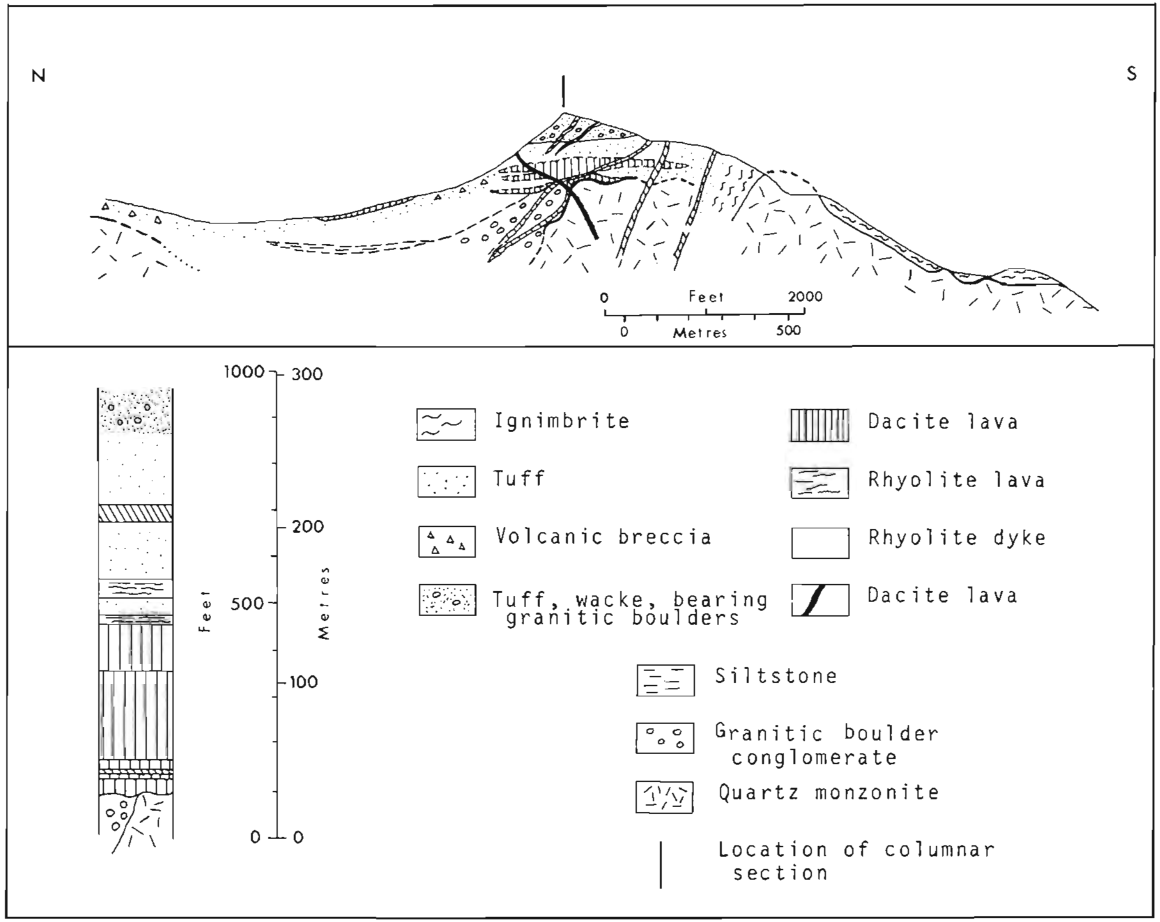


Figure 28. North-south cross-section and columnar section through eruptive centre IV.

ERUPTIVE CENTRE IV

A pile of dacite and rhyolite lavas, tuffs, ignimbrites and breccias outcrops intermittently over a subelliptical area about 1,400 by 2,100 metres. Only about 250 metres of the pile are exposed: the upper part has been removed by erosion. The vent complex is intruded by the ring dyke as well as by a maze of small rhyolite, dacite and andesite dykes. Figure 28 shows the generalized stratigraphic and structural relations of this vent.

The main pile of lavas and pyroclastic rocks lies nonconformably on a highly irregular granitic topography which has been partly filled by wedges of granitic boulder conglomerate and lenses of siltstone. The pile dips approximately 20 to 30 degrees toward the east. These dips, however, may represent the attitudes that have been steepened by post-depositional faulting.

On the south side of the main pile an ignimbrite body widens from a neck about 180 metres wide to a sheet that lies directly on shattered and brecciated granodiorite and quartz monzonite. The lower contact undulates over the granitic topography in steps of greater than 150 metres. The ignimbrite has well developed foliation in vicinity of the neck with dips varying from 50 degrees north to 70 degrees east at the western contact. The eastern side of the neck is in contact with partly welded tuff; the west contacts shattered granodiorite. The outer contacts trend obliquely across the ridge and appears to be steeply dipping with the same trend as the foliation.

Lithology

The main pile consists of basal dacite lavas, a middle sequence of rhyolite lavas and tuffs, and overlying tuffs. The five dark grey to dark green dacite lavas range from 3 to 60 metres thick. They are sparsely porphyritic, amygdaloidal rocks containing 5 to 10 per cent euhedral plagioclase (An_{6-15}) and relict hornblende (replaced by chlorite) phenocrysts in a felty textured matrix of fine plagioclase microlites and crystallites, and irregular patches and clusters of subprismatic quartz crystals. Amygdales are filled with chlorite and carbonate. The matrix bears intense chlorite alteration, and in maroon basal autobrecciated zones of the lavas it has abundant hematite alteration.

Pale greenish grey rhyolite lavas consist of less than 10 per cent euhedral to resorbed quartz, albite (An_{5-10}) and low sanidine phenocrysts in a microfelsitic matrix. Microscopic foliation is defined by alternate layers of slightly different grain size in the matrix.

Tuffs are mainly pale green unsorted, nonwelded, ash-flow deposits composed of pumice, quartz monzonite, rhyolite, dacite, and devitrified vitrophyre lapilli in an ash matrix composed of the same constituents plus quartz and feldspars derived from granitic fragments, quartz and plagioclase phenocrysts, and undeformed pumice, shards and devitrified (?) dust. Shards and pumice have medium- to coarse-granular devitrification. Some are partly or completely replaced by chlorite and carbonate. Very fine chlorite pervades the matrix. Near the top of the succession, tuff contains granitic boulders up to 30 cm and many lenses and laminae of pumiceous siltstone.

On the south side of the main pile the ignimbrite mass is dark grey, moderately densely welded, and contains about 15 per cent lithic and crystal fragments and phenocrysts. Eutaxitic structure is not obvious in hand specimen. Rounded and angular accidental and accessory constituents include granitic material, porphyritic hornblende andesite and pilotaxitic to felty-textured volcanic rocks. Essential constituents include plagioclase and sanidine phenocrysts, devitrified pumice, shards and dust. Near the eastern contact of the "neck" the ignimbrite is greenish grey, and so packed with granitic and crystal inclusions that it resembles a conglomerate.

Interpretation

This pile is interpreted as the east side of a volcanic cone which built up above the southeast extent of the ring-fracture system. Steeply dipping foliation and contacts, and abundance of inclusions at the contacts, suggest that the ignimbrite neck is a feeder to the main ignimbrite body. Although several small rhyolite dykes are present to the east along the ridge, no large rhyolite bodies are present and none is in direct contact with the ignimbrite. This relation would place doubt on the possibility of the ignimbrite "neck" being a fused part of the tuff unit with which it makes contact on the east side. As the precise details of the contacts were not recorded in the field, the possibility must still be entertained (although not considered likely) that the apparent "neck" of the ignimbrite may be a portion of the main ignimbrite mass that has been rotated during post-depositional faulting so that its foliation is steeply dipping.

This vent probably evolved as follows: dacite lavas, issuing from fractures in the faulted, shattered and brecciated granitic basement rocks, effused over the highly irregular fault block terrain; rhyolite lavas followed by ash flows built up the main part of the cone (as far as it is exposed; explosive eruption of ash flows on the south side of the main pile may have been the culminating event of the ash-flow cycle). Rhyolite magma intruded along the ring-fracture system, roughly bisecting the cone, and splayed out into a maze of smaller dykes. The intrusive events, plus the movement along the ring-fracture system may have partly destroyed the main feeders to the eruptions which formed the cone.

The isolation of this volcanic pile from the rest of the map-area makes correlation with the other formations difficult. The underlying thick conglomerate wedge, which is continuous with a thicker conglomerate unit on the west side, is probably correlative with conglomerate of the Lemieux Formation. The sequence dacite lavas overlain by acidic tuffs suggests that this cone evolved contemporaneously with the Jones Creek Formation.

ERUPTIVE CENTRE V

This is an oval centre 2,500 by 900 metres, completely surrounded by granitic rocks. It comprises a cluster of eight andesite bodies on the western side and a large rhyolite body on the eastern side, partly or completely surrounded by tuff.

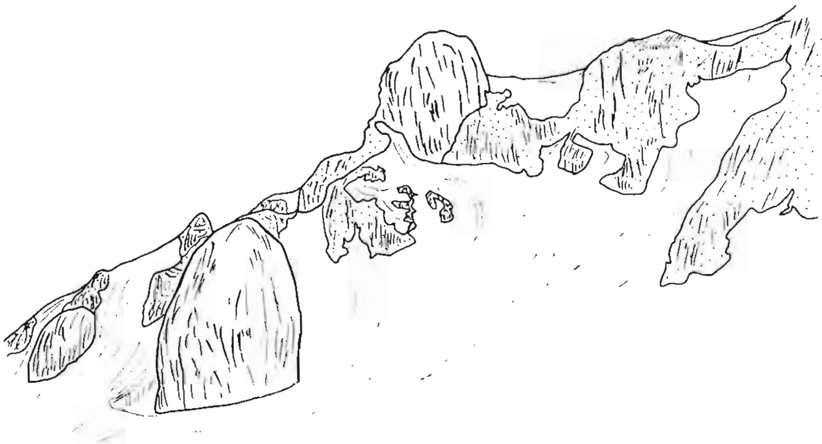


Figure 29. Andesite necks (A) surrounded by tuff (stippled area) and glacier on the western side of eruptive centre V. Vertical exposure about 150 metres. Sketch from photograph.

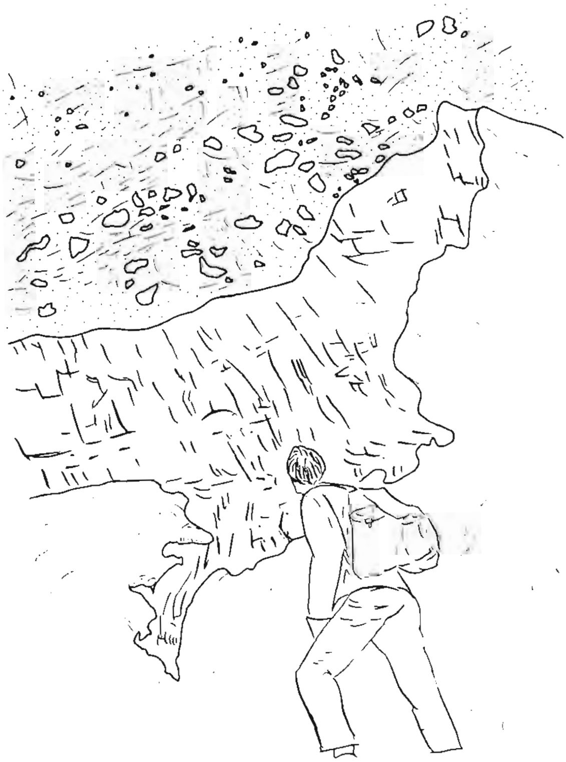


Figure 30. Contact of tuff (stippled area) intrusive into shattered granitic rocks (G, glacier). Sketch from photograph.

Structural Relations

The andesite bodies are nearly vertical necks with circular to oval cross-sections where they outcrop on the northern escarpment of the centre (Fig. 29). Their outer margins have steeply dipping (50 - 70 degrees) layering and are locally autobrecciated. The structural relations of the bodies on top of the ridge were not determined.

The rhyolite body on the east side of the eruptive centre may be part of a dome: it has a nearly vertical western contact; dips of fine laminations vary gradually from vertical near this contact to 45 degrees eastward near the centre; and the eastern contact dips toward the centre.

The green tuff between the andesite bodies is generally massive. At V3 (Fig. 26) the tuff is intrusive into shattered granitic rocks. The contact is very sharp but irregular with dips varying from 50 to 80 degrees. Granitic inclusions make up about 40 per cent of the tuff within a zone extending about 6 metres from the contact. Farther inward from the contact the size and abundance of inclusions decreases (Fig. 30). Granitic inclusions are aligned subparallel to the contact. About 230 metres east of this locality the inclusion-rich tuff is partly welded near the contact with shattered granite. It was not established that the welded tuff is intrusive at this locality or whether it is of ash-flow origin. At least some of the tuff has intruded the andesite bodies, for tuff dykes contain andesite fragments.

The tuff between the rhyolite dome and the cluster of andesite necks is shot through with dark grey finely laminated rhyolite (or dacite) dykes, most of which have gradational contacts. One 75-metre-wide-dyke, for example, grades from finely laminated, dark grey rhyolite to indistinct banded rhyolite with blotchy appearance to greenish grey tuff. The indistinctly banded zone is probably a fused margin adjacent to the rhyolite.

Outward from the western side of this vent area are brecciated granite for the first 150 metres, mixed shattered and brecciated granite for the next 250 metres; and massive granite with some zones of shattering farther away. Shattered and brecciated granite are intruded by many rhyolite, dacite, andesite, and dark grey tuff dykes, generally ranging from 4 to 6 metres thick and rarely up to 60 metres thick.

Lithology

The andesite bodies weather out in relief as dark grey to dark purplish grey bosses, 30 to 300 metres across, above the surrounding recessive tuff. The smaller bodies and margins of larger bodies are dark grey sparsely porphyritic andesite composed of 1 to 3 per cent andesine (An_{35-46}) phenocrysts in a cryptofelsitic to pilotaxitic matrix. Layering is defined by alternating laminae of very fine grained intensely altered microlites and unaltered microlites respectively. The centres of these bodies are purplish grey-weathering porphyritic augite andesite. Phenocrysts (about 30 per cent of the rock) ranging from 0.05 to 2.5 mm give the rock a seriate porphyritic texture. The largest plagioclase crystals have broad unzoned cores and intricately oscillatory-zoned margins. Composition ranges from An_{68} in cores to An_{58-68} in margins. Smaller phenocrysts and microlites range from An_{53-64}. The larger phenocrysts have embayed margins. Euhedral to subhedral augite phenocrysts ($2V_z$: 48°; $Z \wedge C$: 48°) typically have two- or three-unit twinning. The matrix contains stubby plagioclase microlites and intense iron oxide alteration.

The large rhyolite body outcrops over an oval area 900 by 500 metres. Outcrops weather deeply to rusty grey. This is a dark grey rock composed of 1 to 2 per cent oligoclase (An_{29}) and low sanidine phenocrysts in a finely laminated (1 to 4 mm) matrix. Phenocrysts form glomeroporphyritic clusters. Layering is defined by alternating spherulitic and pilotaxitic crystallization.

The green lithic tuff is unsorted and contains angular fragments of granitic rocks and plagioclase, perthitic orthoclase and quartz derived from them, spherulitic rhyolite, pilotaxitic dacite, and pumice. Pumice is partly or completely replaced by chlorite. In one place the rocks are green grit (or lithic tuff) containing only very few pumice fragments. In one locality where the tuff is in contact with shattered granitic rocks it contains not only a high proportion of granitic blocks, but also abundant blocks of banded andesite identical to margins of the andesite bodies. On the western side of the rhyolite body is unsorted pale green or buff-grey massive tuff and tuff-breccia. Lithic fragments in the tuff-breccias locally have very crude preferred orientation. No attitudes were obtained from these rocks because of their generally massive character and frost heaving of the outcrops.

Interpretation

Eruptive centre V is a composite vent in which magmas of different compositions erupted at different times. The mass of green tuff and tuff breccia appears to have formed early; it may be a pyroclastic cone built largely during explosive eruption. Some ash-flow eruptions may also have taken place at this time, followed by intrusion of rhyolitic magma on the east side of the vent to build an (?) endogenous dome. It is not known whether rhyolite lavas effused at the surface. In the west and central parts of the vent area, andesite and dacite magma intruded the tuff to form a cluster of domes, or possibly volcanic necks which were the feeders of lava flows at the surface. That periodic explosive activity continued throughout the history of the vent is suggested by tuff dykes containing fragments of almost all rocks present in the vent area.

ERUPTIVE CENTRE VI

This centre is exposed along the crest of a ridge over an area 750 by 500 metres and through a vertical distance of 300 metres (Fig. 31). It comprises a steeply dipping core of ignimbrite 90 metres wide enclosed by an envelope of tuff ranging from 15 to 90 metres thick. The volcanic rocks are completely surrounded by shattered and brecciated quartz monzonite.

The envelope is a pale green massive devitrified vitric lithic tuff composed of quartz monzonite and crystal fragments derived from it, white rhyolite, and light to dark green chloritized pumice lapilli, in a pale green ash matrix comprising quartz monzonite and crystal fragments, pumice, shards and dust. Near contacts with the quartz monzonite the tuff is choked with angular, lapilli to block-size granitic fragments.

The core is dark greyish green, moderately welded ignimbrite. Pumice is strongly deformed and has long sinuous fiamme ends that have stretched and moulded around lithic and crystal fragments. Plagioclase

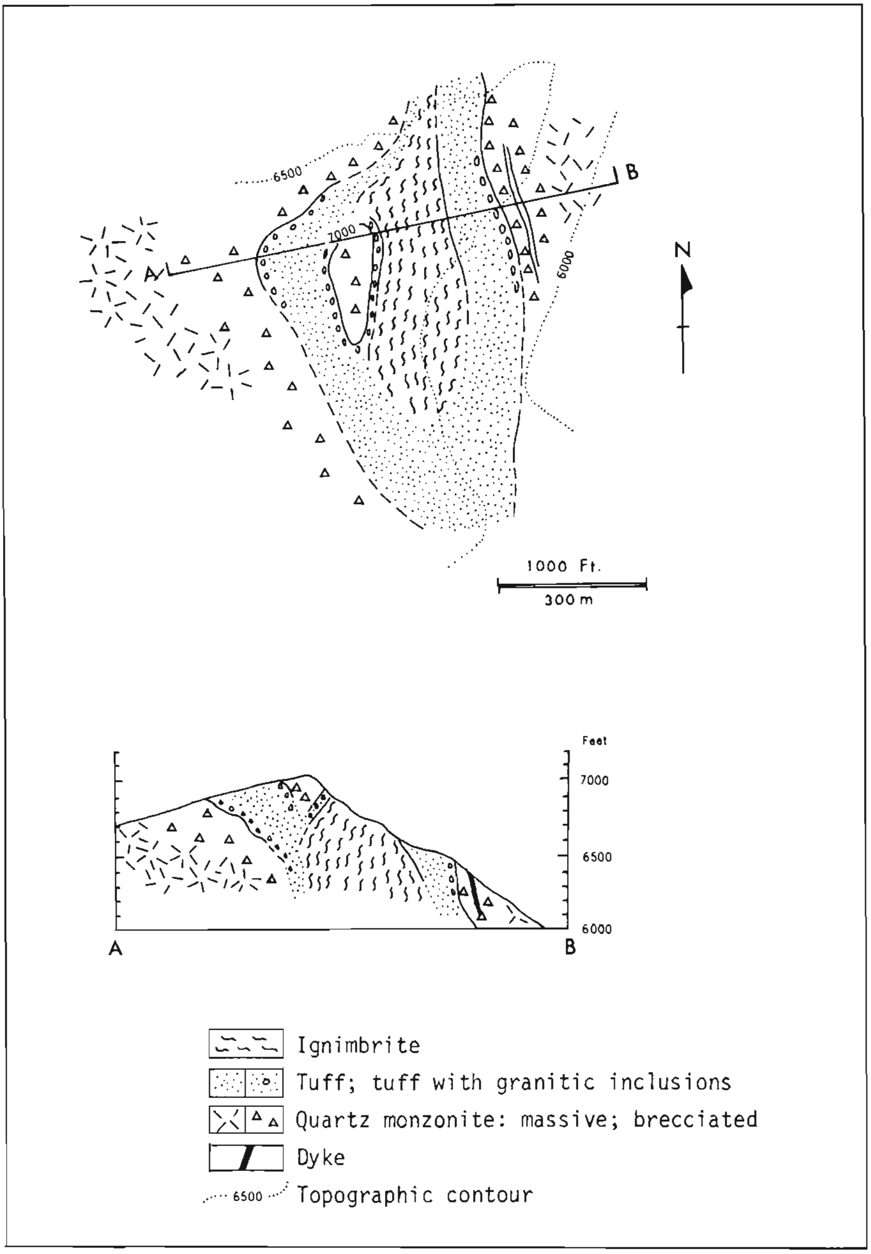


Figure 31. Detailed map and cross-section through eruptive centre VI.

phenocrysts are rare. Accidental constituents include angular to subangular granitic fragments and crystals derived from them.

Dip of eutaxitic foliation within the ignimbrite body varies from 70 degrees eastward on the east side of the body to 58 degrees westward along the western side, thus the body narrows upwards.

Granitic rocks are brecciated for 150 metres on both east and west sides of the eruptive centre, where they grade into shattered then into massive quartz monzonite. Several small faults in the breccia on the east side contain rhyolite and dacite dykes 6 to 10 metres wide. The breccia has up to 50 per cent fine granitic grit matrix for 15 to 30 metres adjacent the east side.

Interpretation

This is a composite tuff-ignimbrite neck that has intruded along a shattered zone in hornblende-biotite quartz monzonite. Shattering and brecciation of granitic rocks may have been caused by a combination of pre-intrusion faulting and subterranean explosions which preceded and accompanied the eruption of gas-charged, particulated magma along a channel in the fault zone to produce the large tuff neck. Lapilli and blocks were plucked from the wall-rocks and incorporated into the turbulent fluidized column.

A high temperature, gas-charged vesiculating froth (probably of lower viscosity than the magma from which the tuff evolved) intruded into the centre of the tuff column. This froth particulated and cooled as it ascended in a conduit narrowing progressively upward. The still plastic pumice and shards in the froth stretched and moulded themselves around rigid lithic and crystal fragments as they entered the constriction.

ERUPTIVE CENTRE VII

This centre consists of an ignimbrite body, which both intrudes and lies upon the surrounding granitic rocks.

Near the north end of the body, where the ignimbrite tapers out, granitic rocks are shattered and brecciated in the immediate vicinity of the contact, but are massive away from the contact. That the ignimbrite has intruded the granitic breccia is suggested by: (1) large slivers and screens (up to 450 by 60 metres) of granitic rocks and breccia within the ignimbrite; (2) ignimbrite between these screens containing abundant granitic inclusions; (3) granitic breccias with irregular dykes and fine seams of ignimbrite between the blocks, where most of the outcrop is crushed granitic matrix; and (4) near the outer contact at one place, gradational sequence of ignimbrite with few small inclusions, to inclusion-rich ignimbrite, to ignimbrite packed with granitic blocks and inclusions, to granitic breccia with ignimbrite dykes and seams, to granitic breccia with no ignimbrite to shattered granite. Foliation in the ignimbrite is variable but generally dips steeply between 45 and 65 degrees. The eastern contact of the ignimbrite is nearly vertical where it cuts through the top of Mount MacAuley. Along the southern sides of the body, tuff and ignimbrite, locally with crude shallow dipping layering and basal tuffaceous grits, overlie the granitic breccia.

Along its west side the ignimbrite body makes a nearly vertical fault contact with the leucocratic granite. Profuse slickensides on the dacite and tuff in vicinity of the contact suggest the fault occurred after emplacement of the body.

Lithology

The partly to densely welded devitrified ignimbrite contains plagioclase phenocrysts, inclusions of granitic material and derived quartz, and feldspars and chloritized mafic minerals, and felty to trachytic-textured volcanic rock.

At the north end of the ignimbrite body where it tapers out, it is a dark green, partly welded tuff, containing up to 45 per cent granitic inclusions near the contact with granitic rocks. About 300 metres from the north end of the body, it is a medium green ignimbrite with prominent eutaxitic foliation and pumice fiamme up to 5 by 20 cm. Here the ignimbrite contains subangular and subrounded blocks of granodiorite up to 4 metres across; generally they are less than 0.5 metre. Near the northeast side of the body the ignimbrite is dark grey and moderately welded. Pistacite fills vesicles in partly collapsed pumice and forms radiating aggregates within the matrix. Pumice has intense hematite and chlorite alteration which gives the rock a black subvitreous lustre. The northwest corner of the body is a very dark grey partly welded lithic tuff composed of 65 per cent angular inclusions less than 5 mm in an intensely altered matrix of spherulitic pumice and devitrified (?) dust. About 300 metres south of the northwest corner, the body at the granitic contact is a black laminated inclusion-rich dacite. Laminations (less than 0.5 mm thick) are layers of microspherulitic crystallization.

Interpretation

Structural relations clearly indicate that this body is both intrusive and extrusive. The intrusive tuff-ignimbrite at the north end marks the vent from which the main part of the body was derived, and probably extruded as ash flows. The ignimbrite was later faulted and intruded by porphyritic rhyolite.

ERUPTIVE CENTRE VIII

This centre comprises andesite and dacite necks, tuff and tuff-breccia that are intrusive into granitic and metamorphic rocks on the east side of a succession of densely welded ignimbrites (Fig. 32).

The dacite and andesite bodies also intrude the pale green tuffs. The bodies are narrow at the base of the exposure and widen upward toward the crest of the ridge. Some of the tuff dykes, particularly near the base of the exposure, contain dacite fragments, whereas others are clearly intruded by the dacite body. The andesite body is brecciated in contact with the unbrecciated dacite body, and the whole intrusive complex is enveloped by a zone of brecciated metamorphic rocks.

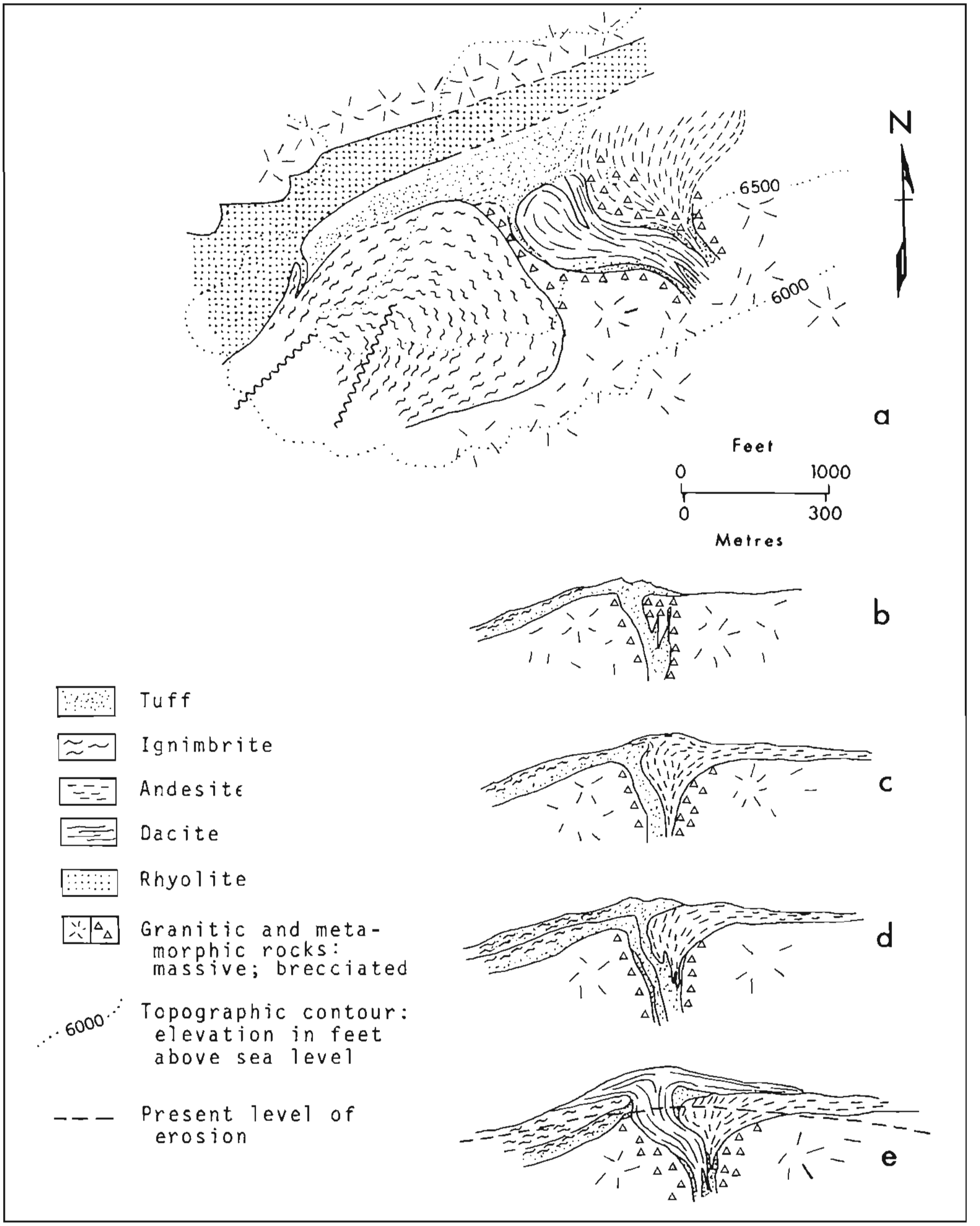


Figure 32. a - Detailed map of eruptive centre VIII.
b, c, d, e - Schematic northeast-southwest cross-sections showing stages of development of the vent area.

Lithology

There are two types of tuff in this vent complex: (1) pale green tuff and tuff-breccia which is along the lower sides and within a dacite body; and (2) dark grey lithic tuff that outcrops on the top of the ridge only. The pale green tuff and tuff-breccia contain lithic fragments of quartz, biotite-quartz schist, dark maroon-grey (?) dacite, pale green, partly welded, rounded pumice, and angular, elongate and partly deformed pumice, set in a pale green lithic-pumice ash matrix. The dark grey tuff is composed predominantly of angular to subrounded lapilli and ash-size material of quartzite, granitic rocks, dacite and moderately welded tuff (almost completely replaced by hematite); and subordinately of moderately deformed pumiceous material. Rare plagioclase phenocrysts are partly resorbed. This rock is poorly sorted but is somewhat better sorted than the pale green tuff.

Dark greyish green, sparsely porphyritic andesite, which forms the east side of the complex, contains euhedral labradorite (An_{64}) phenocrysts in a matrix of trachytic andesine (An_{50}) microlites. The rock is intensely altered (carbonate, chlorite, and hematite) and brecciated along the western margin. Except for slight rotation, the fragments in the brecciated rock have not moved from the parent rock.

A maroon weathering, dark grey dacite body, which forms the central part of this complex, is sparsely porphyritic and spherulitic. About 5 per cent andesine (An_{45}) phenocrysts, with crude preferred orientation, and brown biotite phenocrysts (almost completely altered to chlorite and hematite) are set in a completely spherulitic matrix.

The ignimbrite mass on the west side of the centre consists of pale green to dark grey partly to densely welded ash flows.

Interpretation

Relative brecciation, cross-cutting relations, and types of inclusions within the different bodies indicate that the sequence of intrusion is tuff, andesite, tuff and dacite. Evolution of this centre began with an explosive eruption during which a small pyroclastic cone was probably built and ash flows poured out on the west side (Fig. 32). Wall-rocks were brecciated during this explosive eruption. Andesite magma possibly built a dome or flowed out on the surface along the east side of the vent (Fig. 32). During a second episode of explosive eruption a pyroclastic cone, composed mainly of lithic fragments plucked from the walls of the vent, was built (Fig. 32). High temperature ash flows poured out on the west side of the cone. This explosive activity was followed by intrusion of dacite magma along the west side of the vent (Fig. 32) and possibly effusion of lava at the surface. The dacite may have formed an endogenous dome which closed the neck of the vent during the final stages of activity.

The rhyolite ring dyke is a younger intrusion that is not part of the history of this vent.

ERUPTIVE CENTRE IX

At this locality an ignimbritic dyke and a rhyolite plug intrude quartz monzonite and conglomerates, tuff, ignimbrite and breccias of the Crozier Breccias and the Boudette Creek Formation (Fig. 33). Several small pyroclastic dykes intrude massive and brecciated granitic and metamorphic rocks along the ridge tops west of this centre.

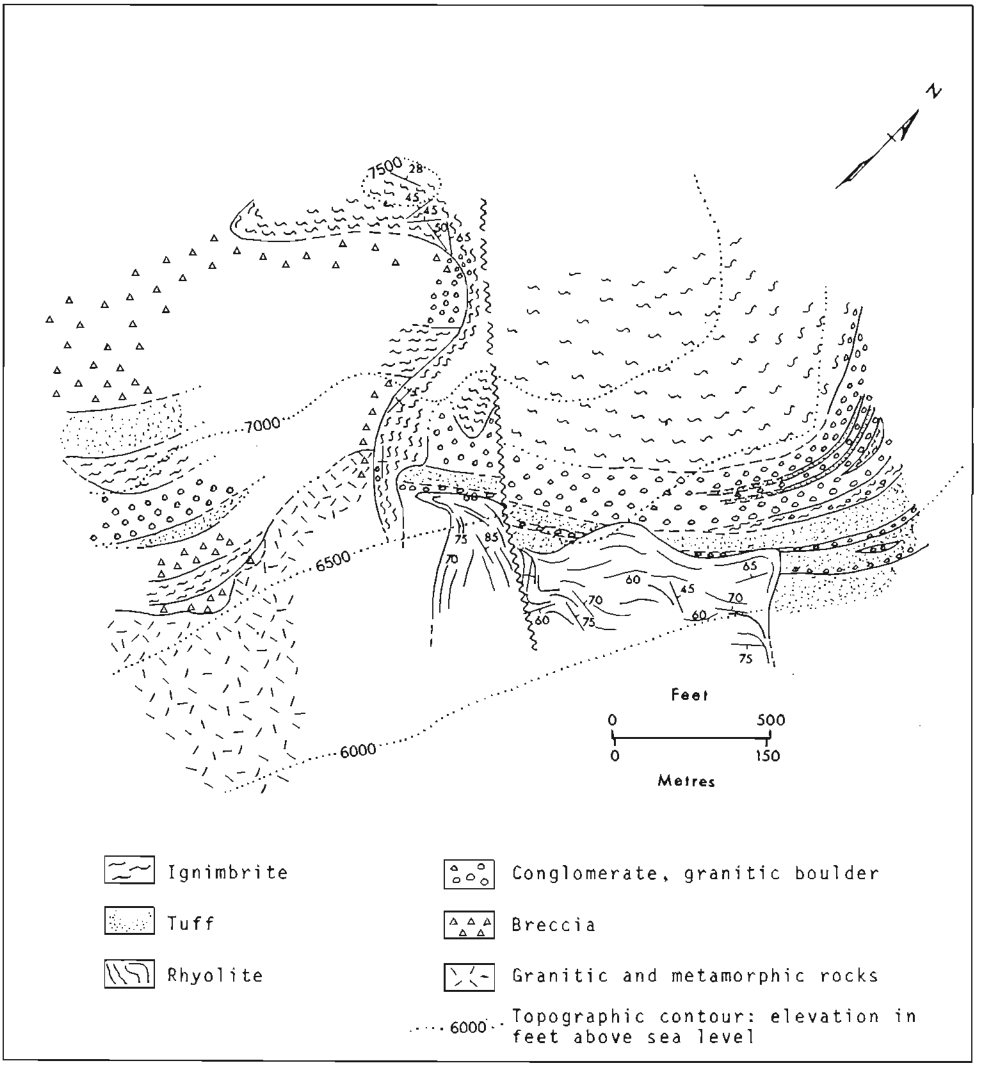


Figure 33. Detailed map showing the ignimbrite dyke and rhyolite intrusion at eruptive centre IX.

Ignimbrite Dyke

The ignimbrite dyke is exposed over a vertical distance of about 180 metrés. It is 23 metres wide and may be as wide as 60 metres near the base of the exposure.

Except for the lowest exposures, only the western contact of the dyke is well exposed; most of the eastern contact is obscured by faulting and talus. The western contact cuts across shattered and brecciated granite and a layered sequence of interbedded granitic boulder conglomerate, breccia, tuff and ignimbrite. Near the top of the dyke, where it cuts granitic breccia and conglomerate, the dyke has included such a large amount of granitic boulders that the contact appears gradational. The overall form of the body, as indicated by the western contact, is a nearly vertical northwest-trending dyke, that curves gently upward toward the top of the ridge, where it passes into a shallow dipping ignimbrite body having aspects of an ash flow.

Foliation, defined by long sinuous streaks and lenticles in the lower exposures of the dyke and by well developed eutaxitic structure in the middle and upper exposures, is vertical and parallel to the outer contact in the lower half of the dyke, and flattens progressively upward in the upper 60 metres of the dyke.

In the lowest exposures the ignimbrite is a light to dark grey rock with well developed eutaxitic structure. Dark green weathering lenticles up to 5 cm long have length to thickness ratios that range from 20:1 to 60:1. They are long, sinuous, undulatory streaks that mold around or pinch and swell between the lithic fragments. Although some larger lenticles have digitated terminations, most smaller ones have slightly rounded ends or taper out to thin points (Pl. XId, f). The rock is completely crystallized. Large lenticles have fine spherulites and locally granular crystallization, surrounded by thin rims of fine prismatic crystals that are perpendicular to the boundary of the lenticles. Smaller lenticles and fine streaks are generally medium-granular aggregates of quartz and feldspars. Material between lenticles is cryptofelsitic. In the middle and upper exposures of the dyke, the ignimbrite contains well developed digitated pumice fiamme and shard structures that are moderately to densely welded; thin sinuous streaks of stretched pumice, like those in the lower exposures, are not present. Where the dyke passes into a shallow-dipping body at the top of the section, the ignimbrite is a normal dark brown densely welded tuff.

Rhyolite Intrusion

The rhyolite is exposed over a vertical distance of 150 metres and a width of 400 metres. It is a pale grey sparsely porphyritic rock with fine laminae (0.25 to 1 mm) of alternating layers of very fine and fine crystallization. The rhyolite has a brecciated margin 1 to 2 metres thick along some contacts, whereas along others it has a very dark grey, finely laminated devitrified margin about 0.5 metre thick. Layering is parallel to the outer contacts but forms complex contorted flow fold structures in the centre of the body.

The irregular outer contact winds its way through the layered rocks of the Crozier Breccias; it is parallel to bedding where in contact with resistant ignimbrite units but cuts across less resistant tuffs and conglomerates.

On the upper west side of the intrusion, tuff is partly welded for about 0.5 metre from the rhyolite, with eutaxitic foliation parallel to the rhyolite contact. Farther away from the rhyolite the tuff is not welded.

Other Pyroclastic Dykes

Along the ridge west of this centre, several ignimbrite dykes (0.3 to 1 m wide) cut granitic breccia. One of the larger, steeply dipping dykes changes to a gently dipping body at the crest of the ridge in the same way as the large ignimbrite dyke previously described.

Along the spur southwest of this centre, several pale green to pale grey tuff dykes cut massive and brecciated granitic and gneissic rocks. Wall-rocks adjacent to these dykes are brecciated and grade laterally into massive rocks. The pale green nonwelded tuff typically consists of angular fragments of medium grey, dark green and dark grey felsite, white finely laminated and spherulitic rhyolite, and granitic and quartz-biotite gneisses that range from 1 to 50 mm, all set in a matrix of dark green to light green altered pumice and pale green shards and dust. In one locality, pale green tuff dykes have intruded along the centre and side of an older porphyritic andesite dyke.

Interpretation

The cross-cutting nature of the lower and western contacts through granitic as well as bedded rocks clearly indicate that this is an intrusive ignimbrite body. The upper part of the dyke where it has incorporated abundant inclusions of volcanic and granitic boulder conglomerate, is the site where the ignimbrite dyke has reached the surface and spilled out on the granitic terrain, carrying with it abundant debris from the wall-rocks and lip of the vent. The dyke reached the surface and flowed out as a pyroclastic flow to form some of the ignimbrite of the Boudette Creek Formation. The smaller scale tuff and ignimbrite dykes to the west of this dyke were probably emplaced during the same series of explosive eruptions.

The rhyolite body, which was probably emplaced after the tuff and ignimbrite dykes, did not reach the surface.

ERUPTIVE CENTRE X

This is a complex eruptive centre 3 kilometres in diameter, consisting of an array of tuff, ignimbrite, rhyolite and dacite dykes, sills and necks that have intruded the basement rocks and volcanic rocks of the Skukum Group. The centre is described with reference to two sections (A and B in Fig. 26).

Section A

This section of the centre consists of several steeply dipping tuff dykes and a large rhyolite dyke (Fig. 34). At the north end of the section tuff dykes, ranging from 5 to 15 metres wide, intrude the base of the section.

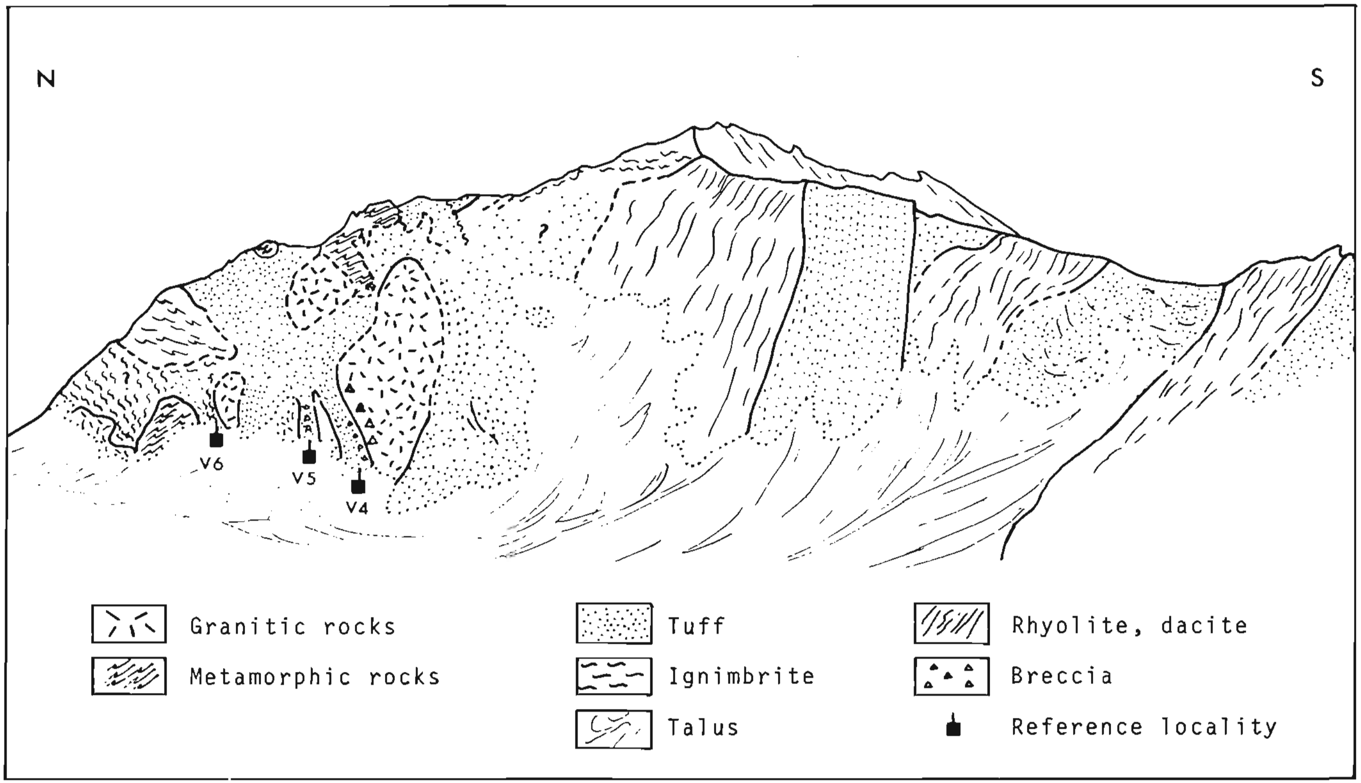


Figure 34. Section A of eruptive centre X. Relief about 300 metres.

They widen upwards and coalesce to form a larger tuff mass that completely surrounds huge masses of granitic, metamorphic and ignimbritic rocks. The dykes display a variety of textures in different parts of the mass. At V4, for example, the contact of the dyke is a mixed zone of granitic breccia and granitic fragment-charged tuff. Fragments in the tuff are aligned parallel to the contact. Inward from this zone the tuff is very coarse, containing fragments of tuff, rhyolite, schist, quartzite, and granitic rocks in a dark green tuff matrix. Layers of fine tuff (about 5 cm wide) within the coarse tuff are parallel to the dyke contact. The main body of the dyke is fine- to medium-grained, pale green tuff containing well-rounded and angular fragments (mainly granitic) up to 20 cm across. The tuff dyke at V5 is lithologically similar to the dyke at V4 except that the margins are medium to coarse tuff and the centre is very coarse tuff-breccia.

At V6 a tuff dyke has a eutaxitic-textured eastern margin which contains stretched pumice lenticles, ranging from minute sizes to 3 by 40 mm, that mold around lithic and crystal fragments. This dyke runs into a partly welded ignimbrite mass that apparently intruded granitic and metamorphic rocks. The eutaxitic foliation along the base of this mass contours around abrupt undulations of the shattered and brecciated quartzite and gneiss. In general, these intrusive tuff bodies are nonwelded in the centre of large masses, but locally have eutaxitic foliation at contacts and in narrow dykes.

Near the centre of this section a nearly vertical tuff dyke, 150 metres thick, has intruded a large rhyolite dyke to the north and bouldery tuff to the south. The tuff consists of fine to coarse ash, containing granitic fragments and quartz and feldspars derived from them, rhyolite, and trachytic felsite fragments in a matrix of undeformed devitrified pumice, shards and dust. The rhyolite dyke is large, dark grey, and finely laminated with an apparent thickness of 180 metres. Laminae dip 60 to 70 degrees northward. On the north side of the dyke it appears to grade into mauve-grey ignimbrite then into partly welded tuff. The precise nature of the contact is obscured by the very closely shattered and frost heaved outcrop.

Section B

This section consists mainly of rhyolite dykes and sills, and dykes and necks of dacite (Fig. 35). The dykes intrude tuff, tuff-breccia, ignimbrite and granitic boulder breccia at the north end of the section and green tuff, tuff-breccia, and interbedded tuff and black shales, siltstone, and volcanic grit at the south end.

At the head of a cirque in the south end of the section, a maze of white rhyolite dykes slash through the enclosing rocks and follow tortuous, pinching and swelling routes upward, following bedding in some place and offshooting across it in others. Dykes range up to 60 metres across near the centre of the cirque and a few centimetres below V 10 (Fig. 35) where they feather out. Near V8 a white rhyolite sill is 360 metres thick. Similar thick bodies form most of the north end of this section. These bodies typically comprise 2 to 5 per cent euhedral sanidine phenocrysts in a microfelsitic matrix. Alternating spherulitic and cryptocrystalline layers (locally accentuated by fine hematite disseminations) form fine laminations in most rocks.

A large rhyolite body at the north end of this section, which contains abundant finely disseminated pyrite, weathers in brilliant shades of yellow,

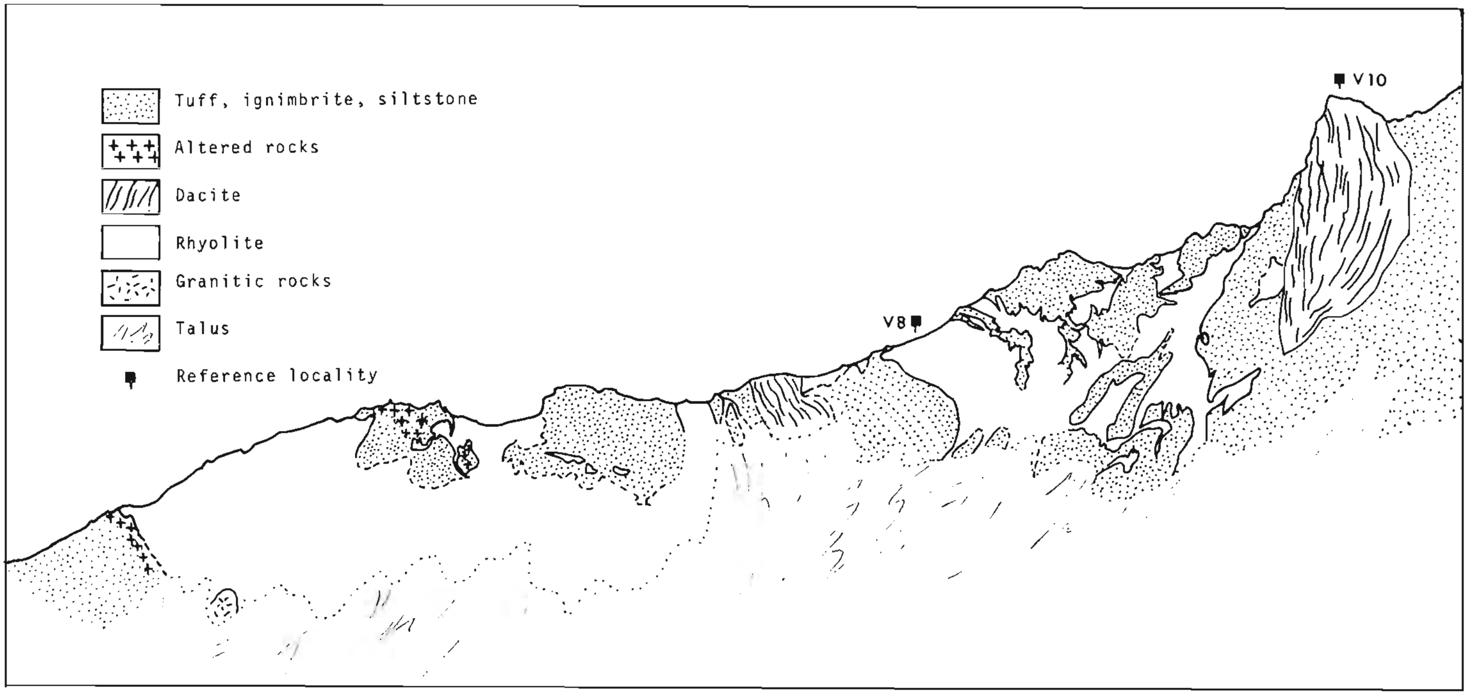


Figure 35. Section B of eruptive centre X (sketch from photograph). Relief is about 200 metres.

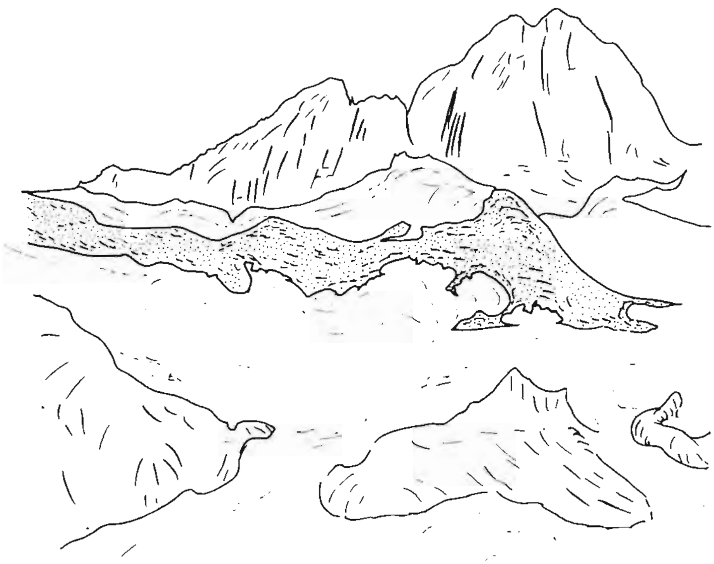


Figure 36. Rhyolite (R) sill that has incorporated and contorted siltstone (stippled area) and tuff (T) near reference locality V8 of eruptive centre X. Total relief is 250 metres.

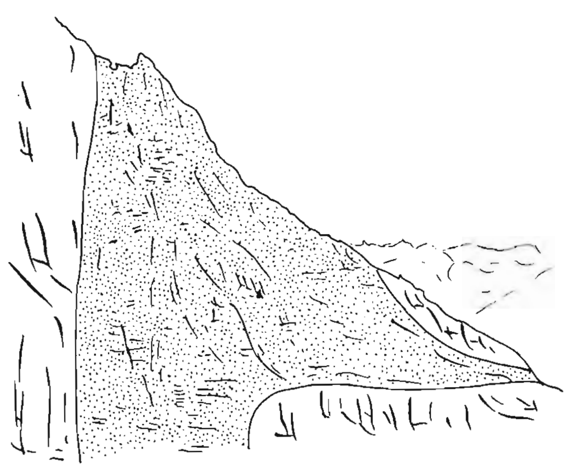


Figure 37. Ring dyke (stippled area) with vertical north (left) contact and horizontal south contact with granodiorite at reference locality V14. Height of cliff is 50 metres.

orange and scarlet. Layering, ranging from a few millimetres to tens of centimetres, commonly accounts for a flaggy cleavage which is generally steeply dipping near V 7 (Fig. 26) but changes drastically in complicated contortions from one place to the next. This variation in attitude is partly the result of rotation along the many small faults which slash through the body. At the southern contact between the rhyolite and the adjacent tuff, both rock types have coarse spherulites and prominent cleavage (5 cm to 3 m apart) subparallel to the contact. Although the fresh rocks appear identical on both sides of the contact, it is marked by a sharp change from rusty-cream weathering rhyolite to rusty grey or grey tuff.

The large sill at V8 (Fig. 35) has some autobrecciation near its margins. The upper contact with a finely laminated siltstone unit is very sharp. At some parts of the contact the rhyolite has partly incorporated and contorted the siltstone into tortuous cusps and hook-shaped protrusions (Fig. 36). The fine laminations in the siltstone are subparallel to the contacts of these small protrusions. This rhyolite sill dips steeply downward and splays into smaller, steeply dipping dykes near the bottom of the cirque. This locality appears to be the source of the huge sill and of the dyke swarm along the cirque walls above.

Grey-green tuffs adjacent to the rhyolite intrusions have been bleached to cream or white rocks. The hydrothermal alteration that pervades the tuff above many of the rhyolite bodies near the north end of the section probably is a result of fumarolic activity.

At V9 (Fig. 26) is exposed the fused contact of a rhyolite dyke which intrudes a nonwelded tuff. This dyke is finely layered, pale mauve grey and ranges from 30 to 60 metres in thickness. The contact between the two rock types is completely gradational. Lithology changes from finely layered rhyolite to dark grey moderately welded tuff (bearing fiamme up to 15 cm long) to nonwelded pale green tuff. Eutaxitic foliation in the contact zone is parallel to the steeply dipping layering in the rhyolite in contrast to the shallow dipping bedding in the tuff farther away from the contact. The contact zone bears very closely spaced cleavage parallel to the foliation in both rocks.

At V10 (Fig. 35) a dark grey layered (?) dacite column has intruded the tuff-breccia sequence and crops out on the ridge as a tall black spine. A similar dark grey finely layered (?) dacite neck, about 300 metres in diameter has intruded the Crozier Tuffs and Lavas at V11 (Fig. 26).

Interpretation

The sequence of events in this eruptive centre, deduced from cross-cutting relations, is similar to that which must have prevailed during emplacement of the Crozier Tuffs and Lavas which lie on the immediate east side of the vent area and form part of the intruded tuff units in the vent area.

Major eruptions from this vent began with intrusion of rhyolite magma into previously deposited tuffs mainly at the northeast end of the vent area. This magma emerged as a series of thick lava flows (the basal lavas of the Crozier Tuffs and Lavas). This event was followed by violent explosive eruptions along the northwest side of the vent area. During these eruptions turbulent fluidized streams of gas and pyroclastic debris drilled their way along fractures in the partly shattered and brecciated basement rocks. Where streams squeezed through constrictions in the irregular (and probably ever-changing) conduits, some of the primary pyroclastic material was fluid enough to stretch and flatten against lithic fragments and the wall of the conduit. This material later cooled to form a eutaxitic ignimbrite. The fluidized medium along fractures separated huge masses of granitic and metamorphic rocks from the conduit walls and these sank into the vent. The weight of some of these subsiding masses may have compacted the underlying tuff mass so that parts of it became welded. At the surface these eruptions deposited a thick sequence of ash-flow tuffs and breccias which formed most of the middle and upper parts of the Crozier Tuffs and Lavas. During brief periods of erosion between eruptions, lakes formed in which silt and sand accumulated.

This activity was followed by intrusion of rhyolite magma along the south side of the vent area to form a maze of huge dykes and sills. It is not known whether this magma effused or whether it solidified in the conduits and essentially sealed them off. Probably the dying stages of eruption from this vent area are represented by intrusion of dacite magma, now represented by three necks and dykes, which may have formed domes at the surface.

Fumarolic activity probably persisted from the time of intrusion of the early rhyolite sills to the close of the volcanic activity.

CONCLUSIONS

The eruptive centres lie along the ring-fracture systems related to both the inner and outer cauldrons. The eruptions have taken place both along fissures and pipe-shaped conduits. Some diatreme pipes apparently drilled their way through granitic rocks (centre III) whereas others intruded along fissures and widened them to create pipe-shaped conduits. Virtually every vent contains evidence of explosive volcanic activity. In vents where both explosive eruption and relatively quiet intrusion or effusion of magma took place, the explosive activity is generally the earlier event (centres IV and X are exceptions). The composition of magma erupted from many vents changed from rhyolite to dacite to andesite with time.

Eruptions from the various centres contributed material to the formations of the Skukum Group as follows: Partridge Lake Formation – centre I; Cleft Mountain Formation – centre I; MacAuley Creek Formation – centre II; Jones Creek Formation and Crozier Tuffs and Lavas – centres X and (?) III, (?) IV, (?) V; Boudette Creek Formation – centres VIII, IX, X. It is not known to which formations centres VI and VII are related, but their lithology and location suggest possibly the Boudette Creek Formation. Apparently many more vents have contributed to the younger formations than to the older ones. Possibly several more centres related to the older formations existed, but have been destroyed by faulting and subsidence along the ring-fracture system, or by subsequent explosive eruptions, or have been covered by the products of younger eruptions. The earliest eruptions apparently originated in the northeastern parts of the complex whereas later eruptions vented along the western and southern parts of the ring-fracture system.

Most of the centres erupted before emplacement of the ring dyke, as indicated by direct cross-cutting relations, or by intrusion of the ring dyke into formations which are obviously related to particular vents. Eruptions from some of the younger centres (for example X) however, may have continued after emplacement of the ring dyke.

THE RING DYKE AND RELATED INTRUSIONS

The ring-dyke complex comprises a series of arcuate rhyolite dykes that together form about 230 degrees of a subelliptical arc (Fig. 26), 30 kilometres long by 19 kilometres wide, around the periphery of the cauldron subsidence complex. The dykes are nearly vertical, pinch and swell, and generally ranging from 150 to 300 metres wide. At the west and southeast ends of the arc the dykes splay out into a maze of smaller dykes and sills.

Many other leucocratic granite, rhyolite and dacite dykes are closely related spatially to the ring dyke by virtue of having intruded along the ring-fracture system.

LITHOLOGY

The ring dyke forms buff to rusty cream-weathering outcrops, in marked contrast to the grey weathering granitic and metamorphic rocks that it intrudes. The lithology is similar in all localities except for variations in the size and abundance of phenocrysts and slight variation in the type of mafic constituents. Centres of the thick portions of the dyke have up to 65 per cent coarse phenocrysts whereas margins have as little as 3 per cent medium-grained phenocrysts.

Central parts of the thick portions of the dyke are massive rhyolite comprising up to 65 per cent (averaging 40 per cent) quartz, sanidine, plagioclase, hornblende and biotite phenocrysts 3 to 10 mm across, in a buff to salmon, aphanitic matrix. A typical sample from V12 (Fig. 26) contains 19% sanidine, 14% plagioclase, 8% quartz, and 5% hornblende and biotite. Smoky quartz forms euhedral to rounded and deeply embayed hexagonal bipyramids. Euhedral, stubby tablets of sanidine have colourless, vitreous cores and salmon, altered margins. Single oscillatory zoned crystals have optic angles ranging mainly, from 40 to 48 degrees, down to 22 degrees (Fig. 39). Both high and low structural modifications are suggested by the position of the optic axial plane, oriented both parallel and perpendicular to the crystallographic (010) plane. X-ray determination by methods of Wright (1968) indicate slightly anomalous low sanidine, with an orthoclase content of between 65 and 70 per cent (using $\bar{2}01$ spacing of heated material). Crystals are most commonly twinned by the Manebach or combined Manebach and Baveno laws: Carlsbad twinning is rare.

White plagioclase in euhedral, elongate tablets with both rectangular and square outlines, forms glomeroporphyritic clusters. One cluster of quartz and plagioclase phenocrysts has graphic interstices. Composition of the complex normal and oscillatory zoned crystals ranges from An_{13-40} within a single phenocryst (Fig. 38). Some rocks bear high albite phenocrysts ($2V_x$: 70°-75°; An_{0-2}). Crystals are twinned according to albite and Carlsbad laws.

Hornblende and biotite phenocrysts make up less than 5 per cent of some specimens and are completely absent in others.

The matrix consists of a very fine grained mass of quartz and feldspars. Intense turbid alteration of feldspars accounts for the salmon colour. Unaltered rocks have a grey matrix.

At chilled margins in the thin dykes, the rhyolite becomes sparsely porphyritic (3 to 20 per cent phenocrysts less than 1 to 5 mm across) and has

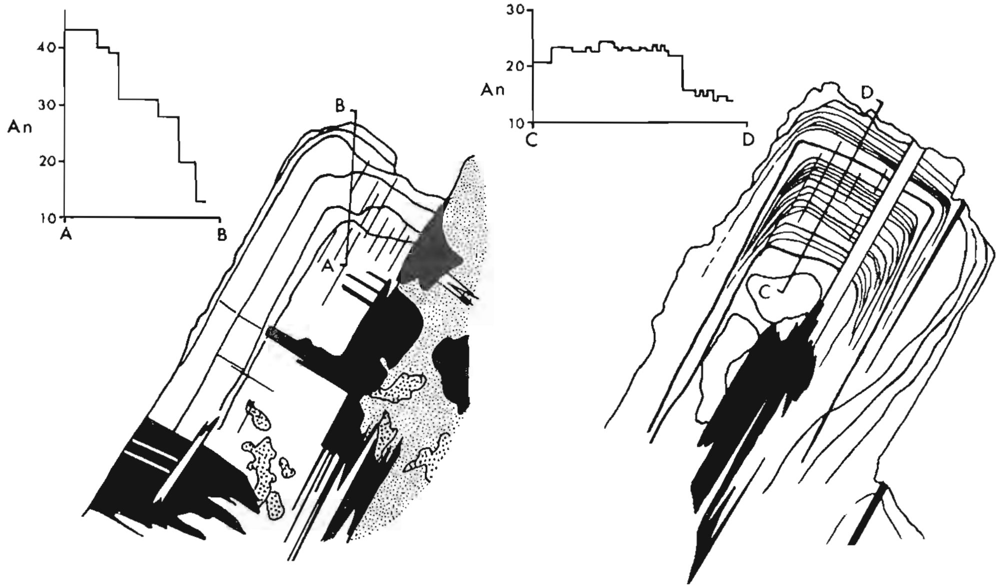


Figure 38. Camera lucida drawings of normal and oscillatory zoned plagioclase from rhyolite of the ring dyke at reference locality V12. Both crystals are about 3 mm across.

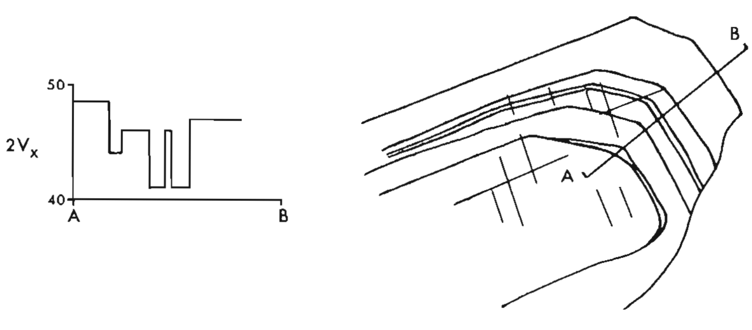


Figure 39. Camera lucida drawing of a zoned sanidine phenocrysts from rhyolite of the ring dyke at reference locality V12. Crystal is about 3 mm across.

a buff to dark grey matrix. Phenocrysts include both high and low sanidine, high albite, and quartz. Mafic minerals, and in some places plagioclase, are absent as phenocrysts. In sparsely porphyritic rocks the relative abundance of phenocrysts is quartz < sanidine < plagioclase. Locally the very fine microcrystalline matrix has a porcellaneous aspect in hand specimen. The matrix contains alternating buff and dark grey layers, 2 to 30 mm thick.

The size and abundance of phenocrysts not only increases toward the centre of the thick parts of the dyke, but also at deeper levels within the dyke. Chilled contacts are most common at higher levels: at lower levels contact zones have 25 to 30 per cent coarse phenocrysts.

STRUCTURAL RELATIONS

The ring dyke is essentially structureless internally except for fine layering at chilled margins. Some thick parts of the dyke have a characteristic coarse blocky jointing.

Contacts of the ring dyke are generally vertical to steeply dipping inward and outward along the northern and eastern parts; inward dips become shallower near the ends of the dyke (Fig. 26). Near V15 the sharp vertical outer contact is exposed for a vertical distance of 330 metres. At V14 the north contact is vertical to steeply dipping but the south contact turns abruptly from nearly vertical to a nearly horizontal (Fig. 37) position, and in one place overturns to dip 50 degrees southward. In this vicinity the ring dyke surrounds blocks of granodiorite up to 150 metres across. The dyke is 30 metres thick at the lower vertical part and at least 600 metres thick where the south contact flares out.

Near the southeast end the ring dyke splays out into a maze of smaller dykes. One dyke intruded the Lemieux conglomerate and spread out as a sill near the top of the exposure. The dyke fingers out along irregular fractures in the granodiorite near V13. Along the west end the main dyke passes into a series of thin inward-dipping dykes that are subparallel to the trend of the main dyke.

The contact of the ring dyke with granitic rocks is generally very sharp. Granitic rocks are shattered and brecciated near the contact and fractures have slickensided surfaces. Near V13 the intruded ignimbrite and volcanic breccias bear closely spaced faults profusely slickensided, grooved, and hematite-stained, whereas the ring dyke bears no evidence of faulting. The faults have thus cut the volcanic sequence before intrusion of the ring dyke. At V14 the ring dyke has intruded along a fault between shattered granodiorite to the north and block faulted, brecciated and shattered siltstones and conglomerate on the south side.

On the north side of Crozier Creek and the east side of Lemieux Creek the ring dyke includes blocks of granitic rocks. Near reference locality V13 a block of ignimbrite has been included and rotated within the ring dyke.

Porphyritic rhyolite of the ring dyke and related small dykes cuts almost every formation of the Skukum Group. It thus appears to be the last major intrusive event. Possibly some of the dykes and intrusions near eruptive centre X and along the south side of Jones Creek may be younger than the ring dyke.

OTHER RING-FRACTURE INTRUSIONS

An arcuate body of leucocratic granite at the head of West Arm has the same trend as the ring dyke. No link with the ring dyke, however, has been found. This is a coarse-grained leucocratic granite, the only similarity with the ring dyke is the granitic composition and the presence of bipyramidal smoky quartz. The body does not have a chilled margin at its contact with granitic rocks to the north. Also, it is intensely sheared where it makes a fault contact with the Partridge Lake Formation east of the head of West Arm (the ring dyke is virtually unaffected by any faulting). A swarm of leucocratic granite dykes on the north side of Crozier Creek and west of Boudette Creek, which trend subparallel to the ring dyke, may also be related to this intrusion.

A variety of other dykes intruded along the ring-fracture system, probably throughout the volcanic history of the complex. In many localities tuff and ignimbrite dykes have intruded the granitic breccias and are sheared, brecciated and in turn intruded by the ring dyke. Adjacent to these areas, the tuff dykes, with trends subparallel to the ring dyke, cut the granitic rocks.

A swarm of steeply dipping linear to slightly arcuate dykes along the south side of Jones Creek are of mauve rhyolite and dark grey silicic rocks. The mauve dykes are sparsely porphyritic with 3 to 5 per cent quartz, sanidine, and plagioclase phenocrysts in microfelsitic, spherulitic matrix. These finely laminated dykes commonly have autobrecciated margins and zones of autobrecciation within them. Laminations are formed by microscopic layers of slightly different coarseness of crystallization and by fine layers of very fine spherulites. Dark grey dykes are very finely laminated (0.25 to 3 mm) to massive rocks composed of 3 to 5 per cent sanidine, plagioclase and quartz phenocrysts in very fine microfelsitic (locally spherulitic) matrix. Some rocks have subvitreous lustre in hand specimen and subconchoidal fracture.

One thick (75 to 120 m), cream to pale green dyke at V16 has a finely laminated contact and massive centre. This dyke is different from any other dykes seen and could be unrelated to the Skukum eruptions.

The rhyolite and dacite intrusions (V17, V18) are enclosed by broad zones of granitic breccias. Locally both granites and dykes are brecciated.

At V19 a large porphyritic (?) dacite intrusion is composed of 10 to 15 per cent glomeroporphyritic clusters of euhedral andesine (An_{45-47}) phenocrysts in an aphanitic matrix of subhedral stubby feldspar microlites and irregular patches of quartz. This body was intruded parallel to bedding in tuff, breccia and grit on the east side but apparently cut across the structure and intruded metamorphic rocks near its western extent. The ring dyke cuts off this body to the north. This intrusion is younger than the Partridge Lake Formation but older than the ring dyke.

Dark grey, fresh basalt dykes have intruded along the contact of the ring dyke and cut volcanic rocks of several eruptive centres. These dykes are younger than any rocks of the Skukum Group and probably are neither related genetically nor in time to the cauldron complex.

PLATE XII

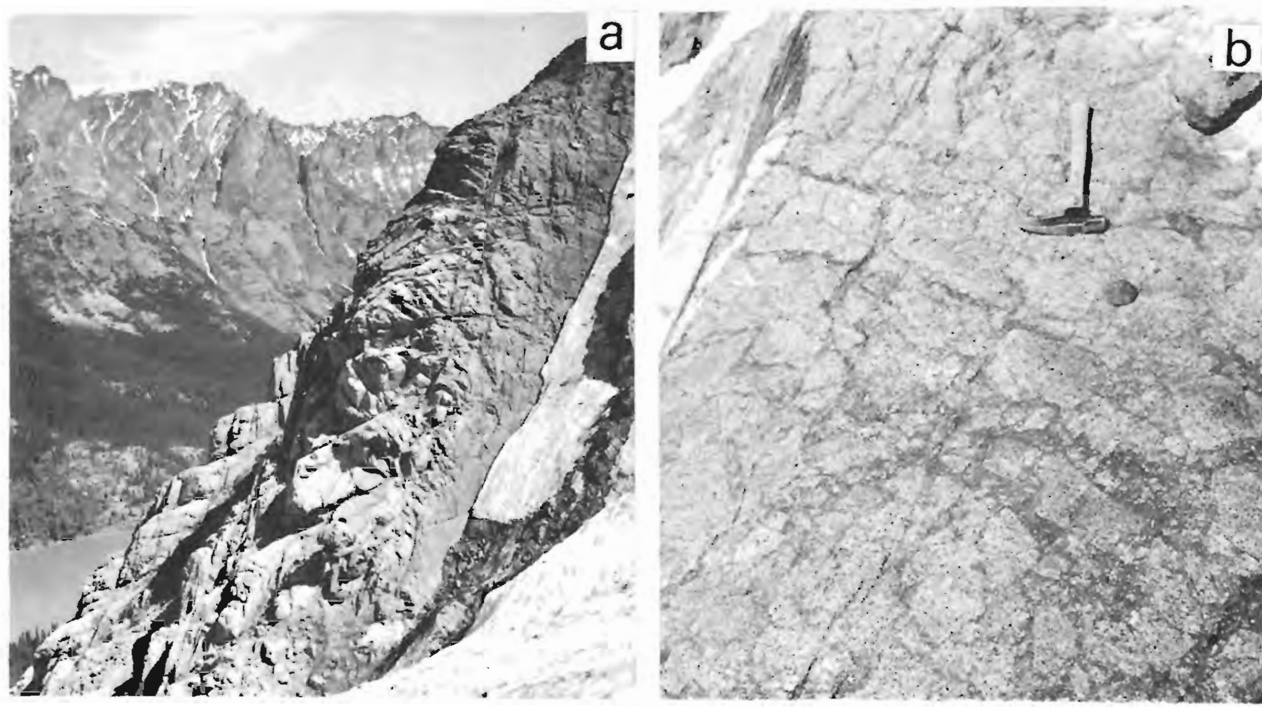


Plate XII. Massive shattered and brecciated granite.

(a) Massive granite above reference locality G8 (Fig. 40). Several sets of joints cut the outcrop.
(b) Granitic breccia grading into shattered granite (towards top of photo) below reference locality G13.

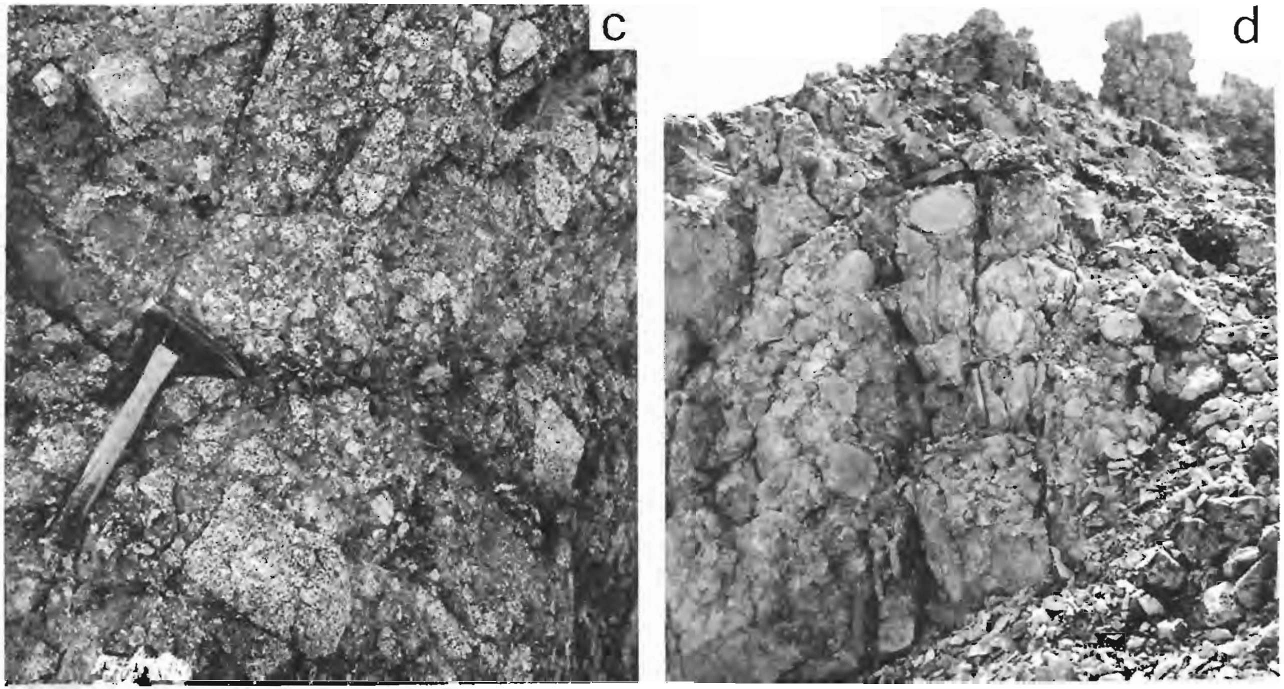


Plate XII continued

(c) Granitic breccia southeast about one kilometre north of reference locality G5.
(d) Roundstone breccia near reference locality G5.

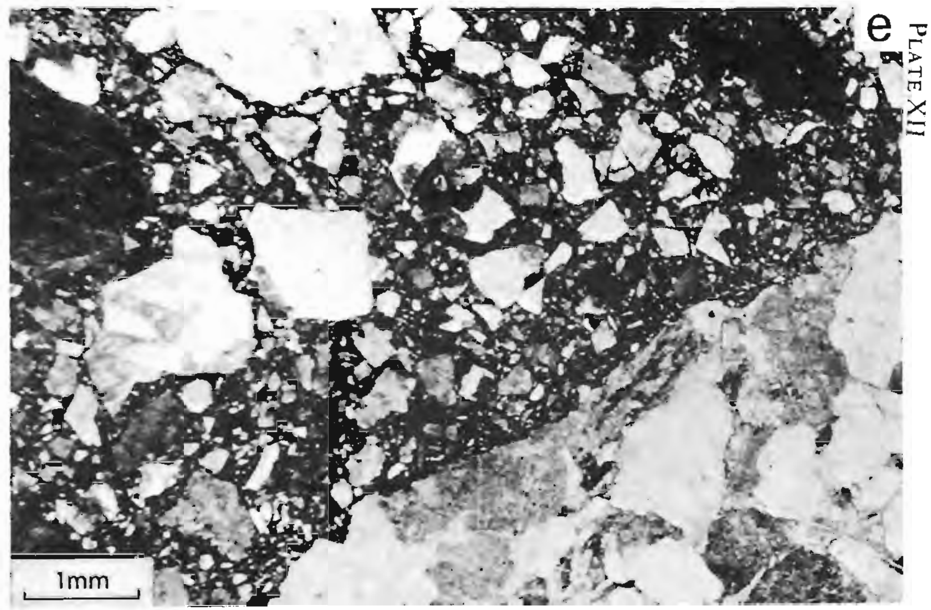


Plate XII continued

(e) Photomicrograph of matrix of granitic breccia at reference locality G5. Plane-polarized light.

DISCUSSION

The leucocratic granite, the porphyritic rhyolite ring dyke, and the swarm of rhyolite to dacite dykes represent several stages of emplacement of dykes along the ring fracture system. The leucocratic granite dykes are interpreted to have been emplaced either during the earliest stage of doming and formation of ring fractures or following the first episode of cauldron subsidence (Chapter V).

Dacite dykes are compositionally similar to the late lava eruptions of the Cleft Mountain, MacAuley Creek and Jones Creek Formations. Emplacement of the first two of these formations was followed by an episode of cauldron subsidence (see Chapter V). These dykes, therefore, may be feeders to parts of these formations or they may have filled fractures following subsidence of the cauldrons. Lavas of the Jones Creek Formation were produced where the dykes reached the surface. These dykes, therefore, probably represent several ages of fracture fillings.

The porphyritic rhyolite ring dyke represents the major episode of ring-fracture intrusion. Lack of evidence of faults in the dyke (whereas the wall-rocks bear ubiquitous evidence of faulting), its crosscutting relation to almost all formations in the complex, and its attitude, indicate that the ring dyke was emplaced along nearly vertical to inward dipping, arcuate fractures and faults during the latest stages of evolution of the complex. No direct evidence for surface volcanism related to the emplacement of the ring dyke has been found. The turning over of the inner contact north of Crozier Creek however, could be in an area where the dyke widened into a dome near the surface or intruded along subhorizontal fractures in the granite. The pinching and swelling ring dyke, therefore, may be the subsurface expression of a series of domes or even lavas, which formed at the surface, but subsequently have been destroyed by erosion.

Emplacement of the ring dyke coincided roughly with late stage doming, which was the last major tectonic event in the history of this complex (see Chapter V). This relation is compatible with dyke emplacement during tensional reopening of the ring fractures by doming (Smith et al., 1961). That some magmatic stoping took place within the ring fracture is evidenced by the huge granitic and ignimbrite blocks within the dyke at several localities.

SHATTERED AND BRECCIATED GRANITIC ROCKS

Rocks of the basement complex have locally undergone considerable disruption and mobilization during the various episodes of explosive eruption and cauldron subsidence that accompanied emplacement of volcanic rocks of the Skukum Group.

In the following discussion, the term 'granite' refers to any rocks with a granitic texture. 'Massive granite' refers to granitic rocks which may possess one or more regular sets of fractures, but are not shattered or brecciated (Pl. XIIa). 'Shattered granite' refers to intensely fractured, coherent granitic rocks characterized by a random network of short, irregular fractures. Locally the resulting angular blocks have parted slightly along fractures but they have not rotated (Pl. XIIb). 'Granite breccia' refers to a mass of granitic blocks separated by fine- to coarse-grained gritty clastic matrix (Pl. XIIc). Blocks have been jostled and rotated. 'Roundstone breccia' refers to granite breccia characterized by abundant subrounded to well-rounded blocks (Pl. XIId).

Shattered and brecciated granites are mainly within the area circumscribed by the ring dyke (Figs. 2 and 40). Broad areas of intense shattering and brecciation are apparently restricted to the eastern and southeastern parts of the map-area; linear and arcuate belts of brecciation occur along faults and along margins of dykes.

Isolated areas of brecciation are found around the peripheries of some eruptive centres south of Jones Creek and in the vicinity of a breccia pipe on Tom Thumb Mountain. Also, breccia forms clastic dykes and isolated masses lying on granitic terrain or within layered successions of the Skukum Group.

In the following sections, the characteristic features of shattered and brecciated granite are generally described, followed by a description and interpretation of specific modes of occurrence.

LITHOLOGY

Shattered granite is characterized by a multitude of hairline fractures of random orientation. The blocks, however, may be separated as much as 7 cm without rotation. Seams of chlorite and epidote, and of very fine granite breccia "heal" the partings between blocks. Locally thin dykes of granite breccia cut the shattered granite.

Granite breccias are typically composed of angular (and locally rounded) granite blocks, ranging from 5 to 9 cm across, surrounded by a matrix of light- to dark-green, coarse- to fine-grained grit. The proportion of matrix to blocks is extremely variable, and locally the rock is essentially all matrix with fragments averaging 3 to 7 mm across. The breccias are completely unsorted and generally show no evidence of layering.

In thin section, the matrix consists of a tightly packed, seriate-textured microbreccia (Pl. XIIe). Fragments are typically of granite (locally metamorphic where metamorphic rocks are associated with the granitic rocks) and quartz, plagioclase, potassic feldspar, and chloritized mafic minerals derived from the granitic (or metamorphic) rocks. The angular to subangular clasts range from 0.02 to 4 mm across. Some of the larger clasts are subrounded. Plagioclase fragments in some specimens contain microfaults and micro kink bands. Minute areas between grains are occupied by chlorite and epidote. Epidote is the main alteration mineral (minute grains and clusters) in breccias that have a pale green typically fine-grained matrix; chlorite is the main alteration mineral, with minor epidote, in breccias that have a dark green typically coarse-grained matrix.

There is a complete gradation from granite breccia with abundant matrix, to granite breccia with sparse matrix, to shattered granite, to massive granite. This gradation is clearly exposed at reference localities G2, G3 and G10 (Fig. 40). Near G10 the gradation from massive to granite to granite breccia may take place within a few metres up to 50 metres.

FAULT BRECCIAS

Granitic breccias and shattered granites that are clearly related to faults are exposed in many localities along the south side of Jones Creek, at reference locality G3, and on the east side of Partridge Lake. Faults in granitic rocks are generally marked by linear or arcuate zones of shattering and brecciation. Individual faults weather out to form prominent topographic lineaments. The ridge southeast of Jones Creek, however, is almost entirely of shattered and brecciated granite which is slashed by a series of closely spaced, subparallel, locally intersecting, faults. Granite breccia grades laterally into shattered granite then into massive granite away from a fault. Narrow single fault zones bear abundant slickensided and grooved walls, both in granite breccia and in shattered granite; abundant slickensided blocks; and little matrix. In broad multiple fault zones, slickensided blocks are not as common and the abundance of rounded blocks is greater than in narrow single fault zones; there are wide variations in the amount of matrix material (locally the breccia is almost entirely matrix) and iron oxide is very sparse.

The following sequence of events is suggested to explain the origin of shattering and brecciation along faults. Shattering of the granite along fractures is thought to have resulted from a sudden release of pressure during opening of the fractures. Open crevices may have become partly filled with rock debris by rock bursting from the walls of the opening. The initial shattering and brecciation could also have resulted from caving or chimneying along fractures and faults that extend down to subsurface openings, such as would be present at the top of a magma chamber after expulsion of magma by pyroclastic eruptions. Chimneying and caving is known to take place very rapidly along faults, fractures and dykes, once it has been initiated (Obert et al., 1967, p. 578).

Movement along shattered and partly brecciated fracture zones resulted in the breaking-up and rotation of blocks in the shattered granite walls, differential grinding and comminution of some granite fragments to a densely packed mass of dust sized crystal fragments. The grooved walls of fractures in breccia, which itself contains slickensided blocks, indicates that there was more than one, and possibly several periods of movement along some faults.

In broad multiple fault zones, movement and brecciation probably took place simultaneously along a multitude of fractures that progressively widened and merged until movement took place throughout a large mass of rock over a broad area. In such a mass, huge blocks would become greatly reduced in size by progressive fragmentation resulting from jostling of blocks and differential grinding. Some blocks would become rounded by abrasion as they jostled against one another and possibly rolled in a pulverized mash of broken crystals.

BRECCIAS ADJACENT TO LARGE DYKES

Shattered and brecciated granite is common along large dykes that have intruded the granitic rocks. The large rhyolite dyke at G14, and the ring dyke provide two examples of this brecciation.

At the Jones Creek locality, a large rhyolite dyke lies along the east side of a broad area of brecciation that is slashed by many small faults and is intruded by several small dykes. The large dyke is displaced several times by small faults along which similar rhyolite dykes have intruded. These small faults bear granitic breccia similar to single faults described previously, and locally both the dyke and the adjacent granite is brecciated. Generally the rhyolite dyke is surrounded by granitic breccia, but in some localities the granitic rocks are shattered or massive.

PLATE XIII

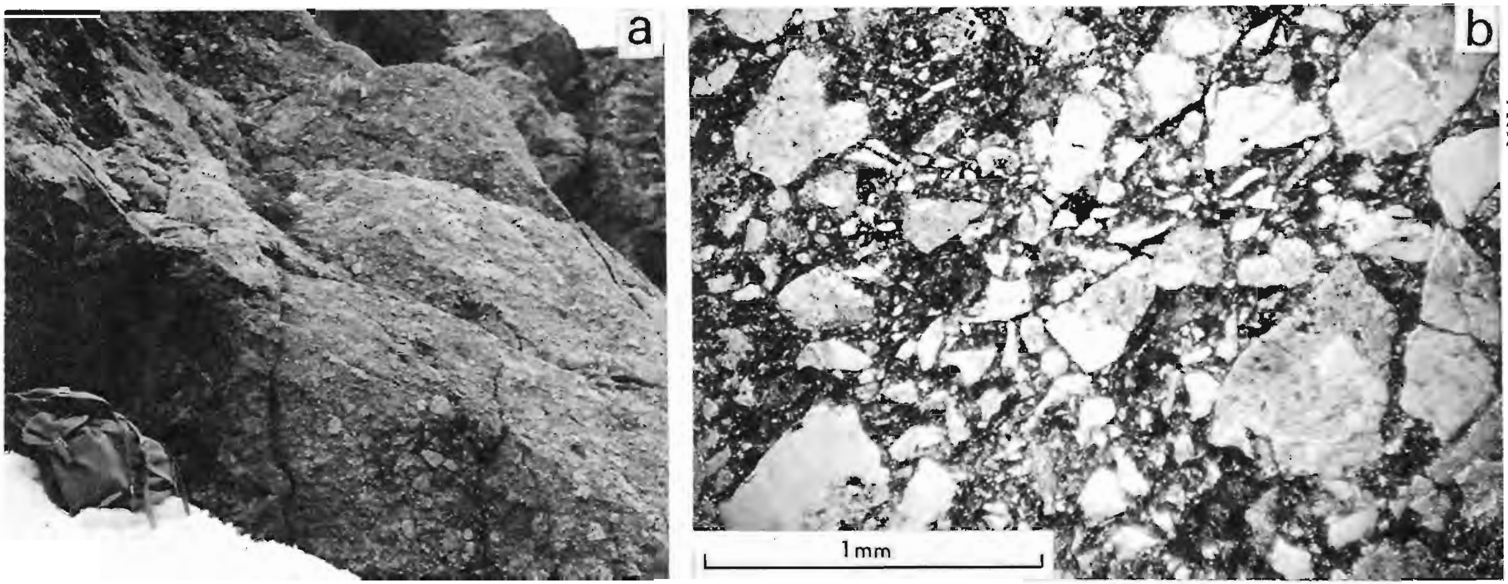


Plate XIII. Clastic Dykes.

(a) Granitic breccia dyke at reference locality G4 (Fig. 40) cutting shattered granite.
(b) Photomicrograph of matrix of breccia dyke in Plate XIIIa. Note dominance of angular fragments.

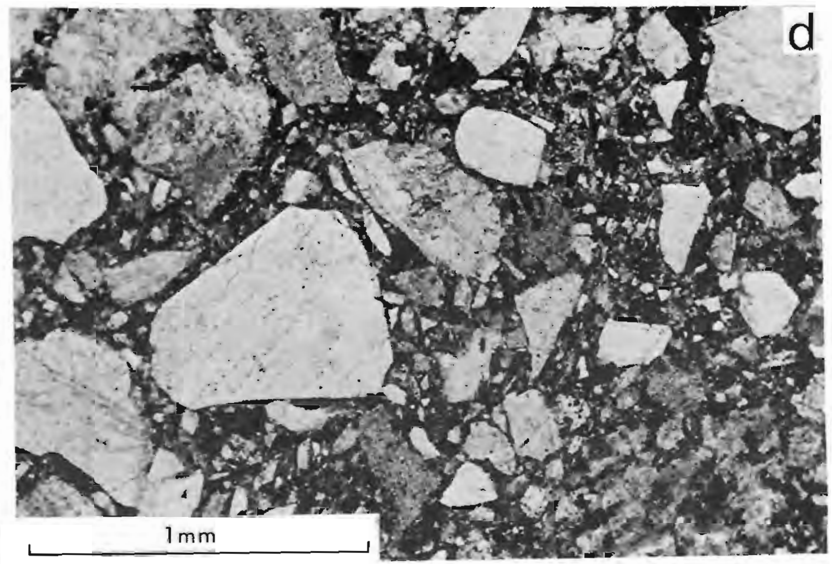


Plate XIII continued

(c) Sharp contact of granitic breccia dyke in Plate XIIIa. Note fine-grained margin.
(d) Photomicrograph of matrix of granitic breccia dyke at reference locality G5. Note rounding of some fragments.

Granite is shattered and brecciated within 150 metres of the outer side of the ring dyke southeast of the head of West Arm. In most other areas, however, the granitic rocks are shattered only over a few metres from the outer contact of the dyke.

Dykes of porphyritic andesite have intruded granodiorite breccia and incorporated abundant granitic clasts up to 0.5 metre across. In one place granite breccia inclusions are strung out in pinching and swelling, discontinuous trains up to 5 cm wide.

Both of these dykes have intruded along proven fault zones. Displacement and brecciation of the dyke south of Jones Creek indicates that faulting continued after emplacement of the dyke. It is concluded, therefore, that brecciation of the enclosing granites was caused mainly during pre-intrusion and post-intrusion fault movement. Some of the brecciation, however, presumably took place as the intruding magma forced its way upward along the fault zones.

BRECCIA DYKES

Granite breccia dykes occur in several localities on the southeast side of Partridge Lake, southeast of Cleft Mountain (reference locality G5) and at G4. Dykes at G4 and G5 are described because they have subtle differences that are interpreted to represent slightly different modes of origin.

At G4 the dyke (Pl. XIIIa, c) intrudes shattered and brecciated granite in an area that is cut by many faults, along the periphery of the inner cauldron (Chapter V). It is about 3 metres wide at the lowest part of the exposure and thins upward. About 90 per cent of the fragments are granitic, 8 per cent are biotite-quartz schist and quartzite, and 2 per cent are dark green-grey volcanic rocks. Angular to subrounded, rarely well rounded, equant granitic fragments range up to 50 cm across (averaging 2 - 8 cm). The dark green matrix (Pl. XIIIb) is composed of tightly packed, seriate-textured, angular to subangular, equant to elongate fragments of the same compositional types as the larger fragments as well as quartz, feldspars, and chloritized biotite derived from the granitic and metamorphic rocks. There is a complete gradation in size of clasts from 0.02 mm to pebble size. The space between fragments contains abundant fine chlorite and minor amounts of epidote.

The only hint of internal structure is the crude alignment of the very few elongated metamorphic fragments; trains of fragments oriented parallel to the contact of the dyke; and a marginal zone 3 to 8 cm wide that contains no coarse fragments. Contacts of the dyke in most places are very sharp, but in some places the dyke grades into granite breccias of the intruded rocks.

At G5 a clastic dyke within quartz monzonite breccia is closely associated with several large and small felsite dykes and at least one ignimbrite dyke. Fragments in the dyke are unsorted, and angular to well rounded. Fragments as small as 2 cm across are smooth, well rounded and have an abraded appearance. No slickensided fragments were observed. Fragments include leucocratic granite, quartz monzonite, hornblende granodiorite, quartzite, and dark green microporphyritic trachyandesite. Virtually all of the larger fragments are the same lithology as the wall-rocks: other types of granitic, metamorphic and volcanic rocks are represented only among the smaller fragments and in the matrix. The pale green matrix is a seriate-textured microbreccia (Pl. XIIId), with grain size ranging from 0.05 to 0.4 mm, comprising angular rock fragments of the same composition as the larger clasts as well as quartz, feldspar, and chloritized mafic minerals. Abundant epidote, as minute grains and irregular clusters of grains that are interstitial to clasts, and as equant and oval clusters of grains, some of which bear radiating structure with chlorite, appears to fill cavities in the fine matrix and partly replace rock fragments and plagioclase. Minor amounts of chlorite are present in minute areas between clasts and as replacement of biotite.

That both of these bodies were emplaced as fluidized mixture of solid particles and gas is suggested by the many features that are consistent with turbulent expanded bed phenomena (Reynolds, 1954, p. 579). These include the lack of sorting; dominance of granitic fragments of the same lithology as the wall-rocks, particularly among the larger fragments (suggesting that they have not been transported far from their source rock); presence of abraded and well-rounded rock fragments mixed with angular fragments; lack of evidence of pyroclastic material or fluid magma in the matrix; presence of cavity fillings in the body at Cleft Mountain; and the abundance of fine matrix of similar composition to the fragments.

Although both bodies were emplaced as fluidized systems, several differences between them suggest slightly different modes of origin: these include size, and uniformity of size, of matrix clasts; degree of roundness of clasts; type of alteration; and association with other pyroclastic and magmatic dykes.

The degree of roundness of fine particles and larger fragments depends upon the length of time that they are violently agitating in the turbulent fluidized state. Small particles take longer to become rounded and smooth than large particles, and with increasing time the particles become progressively smaller and more uniform in size.

From differences in size distribution and roundness of particles in the two dykes, it is suggested that perhaps the G5 dyke was emplaced over a shorter time interval than the G4 dyke. The cause of the different time intervals is probably related to different sources of the fluidizing gas. Although neither dyke contains any pyroclastic particles, close association of the G5 body with pyroclastic and magmatic dykes, and the presence of epidote cavity fillings and epidotization of plagioclase strongly suggests that the fluidizing gas may be of volcanic origin. No such evidence suggesting presence of a volcanic gas was found in the dyke at G4.

The following origin is suggested to account for the lithic and apparent genetic differences between the two dykes. The G5 dyke was emplaced as a mass of particles fluidized by volcanic gas that preceded or accompanied emplacement of pyroclastic dykes and eruption of ash flows. The dyke at G4 is not closely associated with such features as pyroclastic dykes, but it is intimately associated with a zone of faults that lies along the periphery of a large cauldron (Chapter V). An alternative origin for the gas necessary for fluidization can be found in phenomena related primarily to subsidence. Sudden lowering of huge blocks of terrain into subterranean openings would produce violent blasts of compressed gas and air which would fluidize and rapidly sweep masses of brecciated and pulverized rock along fractures and faults. The blasts would be released in short-lived bursts which would not sustain the fluidized state long enough for any except the largest particles to become rounded, nor allow appreciable reduction to uniform size of the finer particles.

EPICLASTIC BRECCIAS

Epiclastic granite breccias are very similar lithologically to breccias formed by the fault and fluidization mechanisms previously discussed. They are typically in intimate association with granitic breccia related to faulting and subsidence phenomena. Genetic types of epiclastic breccia in this area include rock-fall deposits and fluidized avalanche deposits.

Localized deposits made up almost entirely of large angular granitic blocks, with very little fine grained matrix, are interpreted as heaps of rubble and scree resulting from accumulation by rock falls. Sporadic small undulatory lenses of hematitic grit within the breccias locally give them a crudely layered aspect. These bodies lie unconformably on massive, shattered or brecciated granitic terrain. Lack of rounding, dominance of coarse blocks and occurrence as localized pods within granitic terrain suggest that these bodies have not been transported en masse from their initial place of deposition. At G6, for example, where breccia overlies a downfaulted block of a regolith of the granitic terrain, the upper surface is gently undulatory and the lower surface conforms to a series of small fault displacements (in the order of 7 metres) of the underlying faulted regolith. The small faults in the regolith do not persist through the overlying mass of rubble.

Similarly at reference locality G7 roundstone granitic breccia overlies a rhyolite flow and nearby dacite unit which are downfaulted blocks within the shattered and brecciated granitic terrain. Only the largest blocks within the breccia are well rounded. Rounding of the blocks suggests some transport, probably as a landslide. This breccia is almost identical with recent landslide rubble present at the base of cliffs on the east side of Partridge Lake.

Epiclastic breccias at G9 and G10 form narrow elongate bodies or remnant pods that disconformably overlie shattered or brecciated granites and locally lavas. They are unsorted, coarse, blocky breccias comprising angular to rounded granitic blocks in a coarse-grained green grit composed of granitic fragments and crystals derived from granitic rock. The matrix bears abundant chlorite alteration. The deposits typically have a basal zone of unsorted grit, similar to the breccia matrix, which grades upward into the breccia. At G10 two tongue-like units lie one upon the other separated by basal grit which tends to weather out forming a recessive unit. The upper surface, where seen, is generally nearly planar whereas the lower surface conforms to the underlying topography. At a locality just north of G9 the granitic breccia overlies tuffaceous conglomerate which grades downward into pale green gritty tuff and upward into fine basal grit of the avalanche deposit. This transition has closely spaced cleavage, 1 to 3 cm apart, that is subparallel to the base of the avalanche deposit.

Complete lack of sorting and internal structure; presence of both rounded and angular fragments; abundance of matrix; basal zone of fine grit; and planar upper surface are compatible with emplacement as dry rock-fall avalanches. According to Mudge (1965), Kent (1966) and Crandell et al. (1965), during initial rock falls, a sheet of debris quickly entraps and compresses air as it settles. This air passes upward through the debris and tends to fluidize the mass. Compressed air which is trapped beneath the debris forms a cushion which buoys up the mass and reduces friction, hence the mass moves as a turbulent density current until the entrapped air escapes, and the debris settles on the valley bottom. In the Bennett Lake area, the basal fine-grained microbreccia zone probably represents material that was within a compressed, dust-charged, air cushion upon which the blocky avalanche was transported. At G9 the turbulent base of the avalanche partly mixed with the top of a tuff unit, accounting for the gradational contact. During the last stages of emplacement of an avalanche, the flow might be confined to shears in the fine-grained transition zone. This mechanism is suggested to account for the closely spaced cleavage in this zone.

Some of these localized breccia masses could possibly be extrusive breccias that are the surface expression of fluidized, granitic breccia dykes. It would be impossible to distinguish these two modes of origin, unless definite evidence for pyroclastic origin could be found in the matrix, or a definite link between intrusive and extrusive breccias could be found.

More extensive avalanche deposits of this type are discussed with the Lemieux Creek Formation.

At reference locality G11, a unique relation exists where shattered granodiorite is overlain by rhyolite which grades upward into brecciated rhyolite then into granodiorite breccia. The lower contact undulates over a vertical distance of about 15 metres. There are complete gradations between the various layers. The granitic breccia is completely unsorted, with no internal structure. Laterally the granitic breccia layer thins and the rhyolite thickens. The gradational nature of all contacts indicates that all of the succession must have been emplaced at approximately the same time. The gradation from igneous textured rhyolite to clastic textured breccia can be explained if it is assumed that, as a rhyolite lava flowed over the granitic terrain, a mass of granitic breccia avalanched down upon its surface. Blocks of granite sank into, and became intimately mixed with the upper part of the autobrecciated, viscous rhyolite lava. Block faulting, eruption of magma along a fault zone, and avalanching from unstable shattered granite fault scarps is not a remote coincidence in an environment where cauldron subsidence and explosive volcanic activity are known to be intimately associated.

LARGE AREAS OF BRECCIATION

Large areas of brecciation are exposed from the ridge southeast of Cleft Mountain to the Lemieux Creek valley (approximately 5 km across) and along a steep-walled hanging valley east of "Gault" (Fig. 40).

Lithology

The dominant type of granitic breccia consists mainly of angular, with some rounded, granitic blocks in matrix grit that lacks of rounded clasts and pyroclastic material (such as shards, pumice or devitrified glass). Volcanic or accidental clasts are virtually absent except in some clastic dykes.

In the vicinity of the Cleft Mountain mass, there are sharp changes in the colour of the breccia where lithology of the granitic rocks changes. Generally light coloured breccias are in quartz monzonite terrain whereas darker coloured breccias are in granodiorite.

Roundstone breccia forms local pods or elongate sheets overlying volcanic and granitic rocks (G9, G10; see epiclastic breccias) and blocks within intrusive tuffs and dykes. Roundstone breccias, very common at the northwest side of the Gault mass, have ubiquitous slickensides on both well rounded and angular blocks. Some of the blocks are themselves granitic breccia.

At one locality in the Gault mass the breccia is very similar to the clastic dyke at G5.

Structural Relations

Both of these areas lie between major fault zones that are related to two cauldrons which have subsided several hundred metres (see Chapter V). As well, many relationships between the various types of granite breccias and associated massive granite, ignimbrite and tuff provide abundant independent evidence for faulting. The western extent of the Gault mass grades into shattered or massive granite which contains many local linear zones of shattering and brecciation along faults. Several large bodies of ignimbrite and tuff clearly have fault relationships with the enclosing granite breccia as indicated by: (1) fault-bounded slivers of ignimbrite within granite breccia; (2) slickensided and sheared contacts on ignimbrite bodies; (3) position of these bodies at various elevations within the granitic breccia, but at lower elevations than the main mass of ignimbrite (which lies unconformably above the granitic breccia and from which the ignimbrite bodies were probably derived); (4) slickensided blocks in the roundstone breccia. In both masses, huge blocks of massive granite are isolated within (and commonly grade into) the granite breccia.

In the Cleft Mountain mass, many closely spaced faults cut across the ridge.

Near the northeast end of the Gault breccia mass (G12), granitic breccia dykes have intruded the base of the overlying ignimbrite and some of the large ignimbrite blocks are isolated within the granite breccia (near G13). These dykes make up a relatively insignificant proportion of the breccia.

Interpretation

The local tectonic setting of the breccias between major fault zones which correspond to the margins of cauldrons, and the many faults of relatively small displacement within the masses, suggest that faulting and caldera collapse played a major role in their production. The occurrence of roundstone breccias in the Gault mass, in an area of abundant faults, and the ubiquitous slickensides on both rounded and angular blocks, strongly suggests that rounding resulted from 'reworking' of previously formed breccias by later faulting. It is possible, however, that some of the breccias that lack volcanic clasts may represent avalanche deposits that were emplaced during early faulting of the granitic terrain but before deposition of the overlying ignimbrites.

Roundstone breccias at G7, G9 and G10, have been already interpreted as avalanche deposits.

Breccia dykes that intrude ignimbrite in the Gault mass are interpreted as fluidized injections of granitic breccia that were mobilized and emplaced by compressed air blasts generated during collapse of blocks of terrain, in a similar manner to the emplacement of the dyke at G4.

That at least some of the breccias were associated with explosive volcanism and intrusion of volcanic-clastic dykes is indicated by the clastic dyke at G5 (described and interpreted in the section on clastic dykes), which has many lithologic similarities to diatreme breccias. Bodies of similar lithology are also present in the Gault mass. Explosive volcanism has not played a major role in the formation and mobilization of the majority of the breccias however, because: pyroclastic material is lacking in fragments and matrix of the breccias; there is no evidence for hot volcanic gases (such as metamorphism of fragments of vapour phase crystallization in the matrix); and exotic fragments are lacking within the breccia. It is possible that some of the initial shattering and brecciation of the granitic terrain was caused by violent subterranean explosions which resulted from the sudden release and expansion of volcanic gases. Some brecciation, such as observed at eruptive centre VI (see Eruptive Centres) is inevitable during the several episodes of explosive volcanism necessary for eruption of the huge volume of tephra present in this area. If, however, huge areas were brecciated and mobilized by explosive volcanism surely there would be abundant evidence of volcanic activity in the breccias themselves. On the contrary, however, distinct evidence of volcanism within the breccias is of only local significance, whereas there is ubiquitous evidence of faulting.

Faulting and brecciation continued after deposition of the major ash flows, tilting the flows that conformably overlie the breccias; huge blocks of ignimbrite were faulted into the granitic breccia in the Gault mass. More than one period of movement has taken place, as indicated by slickensided, rounded blocks and by granitic breccia blocks within the breccia.

It is concluded that subterranean explosions may have caused initial shattering, brecciation and possibly mobilization of the breccias. Two or more episodes of faulting, collapse and subsidence of huge blocks of granitic terrain produced most of the brecciation over the large areas. These tectonic events may have obliterated evidence of earlier-formed explosion breccias. The disruption was accompanied on the surface by avalanching from fault scarps or from steep cauldron walls and possibly by eruption of granitic breccia flows where fluidized granitic breccia dykes reached the surface.

MINERAL OCCURRENCES

FLUORITE

Small showings of fluorite were found west of Mount MacAuley and east of the head of MacAuley Creek (Fig. 2). In the locality west of Mount MacAuley, violet fluorite in cubes and octahedra up to 3 cm across occurs with pale yellow to grey, dipyramidal quartz and dark brown botryoidal goethite. These minerals line vugs and form encrustations along fractures within the fine- to medium-grained margin of the leucogranite pluton. According to Wheeler (1961, p. 143), most showings are within "a few hundred feet" of the contact of the leucogranite.

Near the head of MacAuley Creek, green fluorite occurs as massive patches in a quartz vein, 1 to 4 metres wide, in ignimbrite of the MacAuley Creek Formation. The vein has layered chalcedonic margins with locally a boxwork structure and vugs encrusted with fine (less than 2 mm) euhedral quartz crystals. On the ridge and in the cirque immediately north of this locality, quartz veins less than 0.5 metre wide contain 1 to 2 cm veins and patches of massive purple fluorite.

COPPER, LEAD AND ZINC SULPHIDES

Scattered sulphide mineralization was found in aplite dykes and associated quartz veins that cut ignimbrite of the Partridge Lake and MacAuley Creek Formations in a cirque east of the head of MacAuley Creek (Fig. 2). These rusty-orange weathering dykes contain finely disseminated pyrite and traces of galena, chalcopyrite and sphalerite along fracture surfaces stained by iron, manganese and locally malachite. Mineralization is generally confined to the dykes but locally occurs along fractures in the enclosing ignimbrite. It is not considered of economic interest.

MOLYBDENITE

Coarse rosettes of molybdenite were found in quartz veins in a single boulder of quartz monzonite from conglomerate of the Lemieux Creek Formation (near the top of reference locality LCX, Fig. 24).

CHAPTER V

STRUCTURAL GEOLOGY

MAJOR STRUCTURAL FEATURES

The main structural features of the Bennett Lake complex include concentric and radial fracture systems, two nested cauldrons and a central dome.

An outer ring-fracture system forms a broad zone around the north and east sides of the complex that is marked by the ring dyke on the outer side and the deep arcuate valleys of Lemieux and Crozier Creeks on the inner side (Fig. 40). A swarm of dykes and possibly the arcuate valley south of Jones Creek delineate this fracture system around the southwest side of the complex. Most of the dykes and faults are vertical to steeply dipping.

An inner ring-fracture system is suggested by two arcuate east-southeast- and northwest-trending faults east and north of "Gault", the deep valley of Jones Creek and the northwest-trending faults and dykes near the headwaters of Jones and MacAuley Creeks.

The ring-fracture systems mark the approximate rims of two nested cauldrons (Fig. 42). A structural contour map (Fig. 41) of the contact between granitic rocks and the Skukum Group clarifies the geometry of the cauldrons. The elliptical outer cauldron is 25 by 15 kilometres across and deepest (at least 900 m) in the northeast side. There is a broad "hill" in the floor of the cauldron south of MacAuley Creek. The altitude of the floor increases steadily westward from this hill. West of MacAuley Creek the relatively high granitic topography is irregular with several steep peaks. The floor rises southward along the east side of the cauldron. West of Lemieux Creek a prominent ridge protrudes above the floor of the cauldron. In general, the depth of the outer cauldron decreases toward the south and southwest.

A subcircular inner cauldron is 11 kilometres across and its floor is about 1,800 metres below the floor of the outer cauldron.

Fault relations in the Skukum rocks suggest further details of these cauldrons where the contact between granitic rocks and the Skukum Group is not exposed. An arcuate graben interrupted the outer caldera floor on the northeast side (Fig. 53c). The north side of the inner cauldron progresses downward in a series of arcuate steps with displacements ranging from 200 to 600 metres. Between Partridge Lake and MacAuley Creek valleys, parts of the faults bounding these steps are arcuate, steeply dipping and concave towards the south. These fault blocks are interpreted to taper out laterally. The southeast side of the inner cauldron is essentially a single wall east of "Gault". No evidence has been found for a step-like arrangement of faults along the southern side.

A structural dome with relief of about 1,500 metres is centred over Partridge Lake. A subradial pattern of major faults and a swarm of northeast-trending minor faults divide the dome into a mosaic of radially dipping blocks (Fig. 40). The southern blocks have dips as great as 55 degrees whereas the northern blocks dip 20 to 30 degrees. The dome is bisected by a major fault along Partridge Lake valley. A series of subparallel normal faults that dip toward the valley bottom on both sides, suggest that this valley lies along a longitudinal graben. The abrupt flattening or reversal of dips of units about hinge zones east of Boudette Creek and southeast of Partridge Lake (Fig. 40)

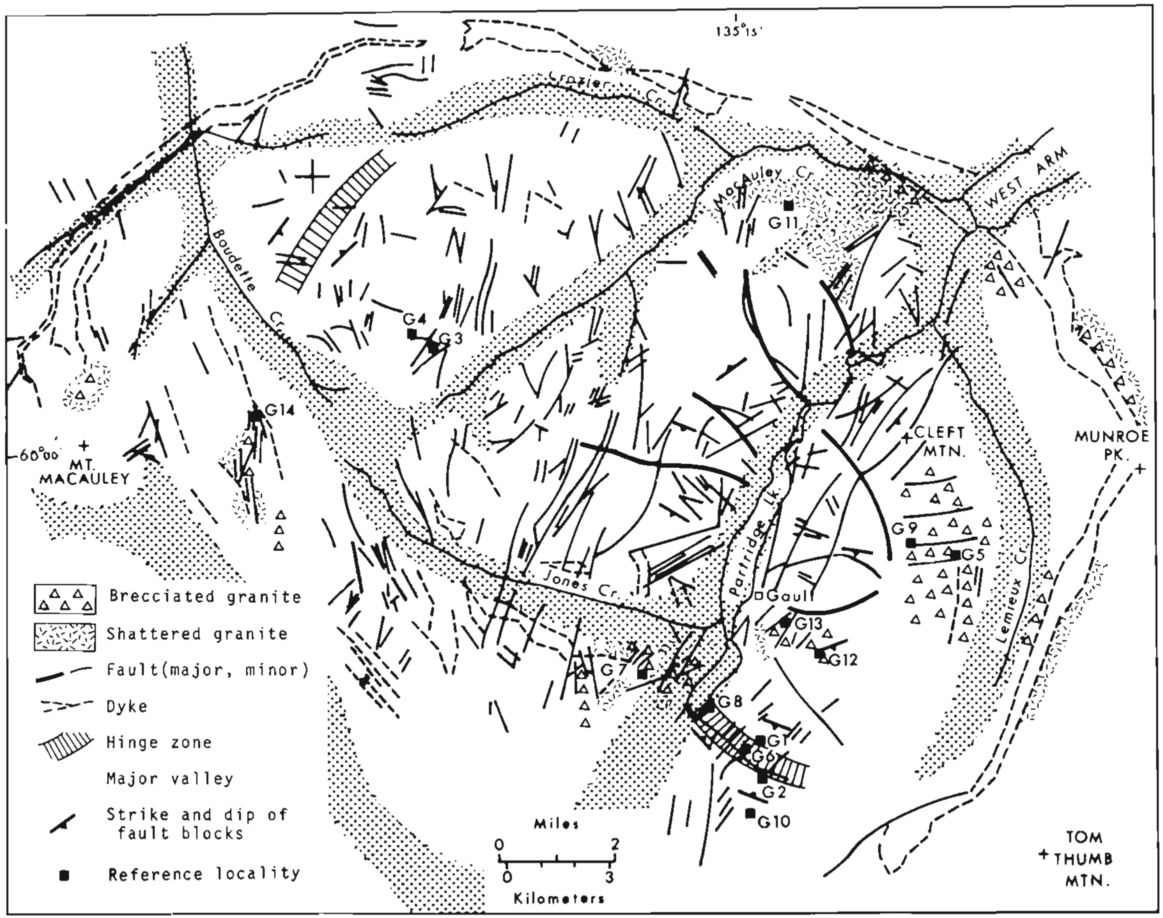


Figure 40. Faults, dykes, areas of shattered and brecciated granitic rocks and major valleys of the Bennett Lake complex (reference localities reproduced from Fig. 7).

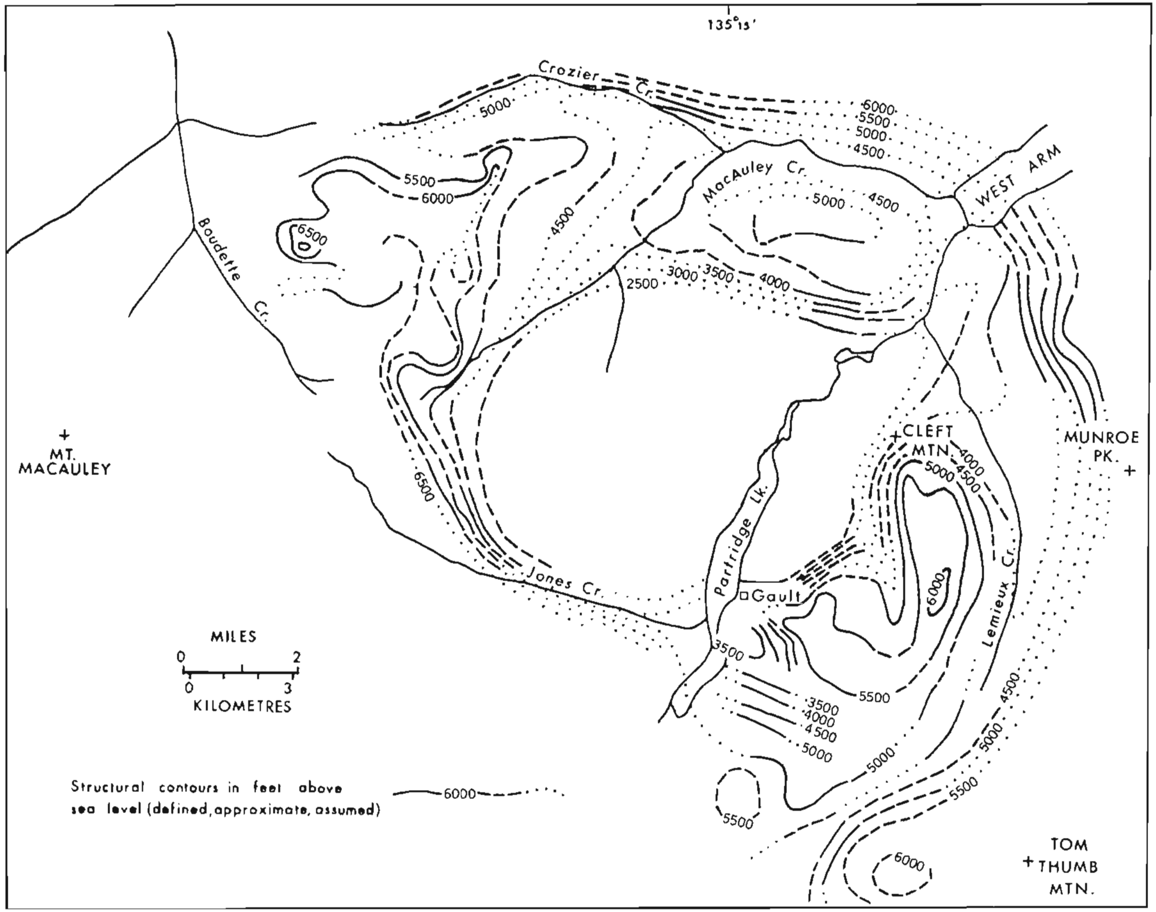


Figure 41. Generalized structural contour map of the contact between the Skukum Group and granitic rocks in the Bennett Lake complex.

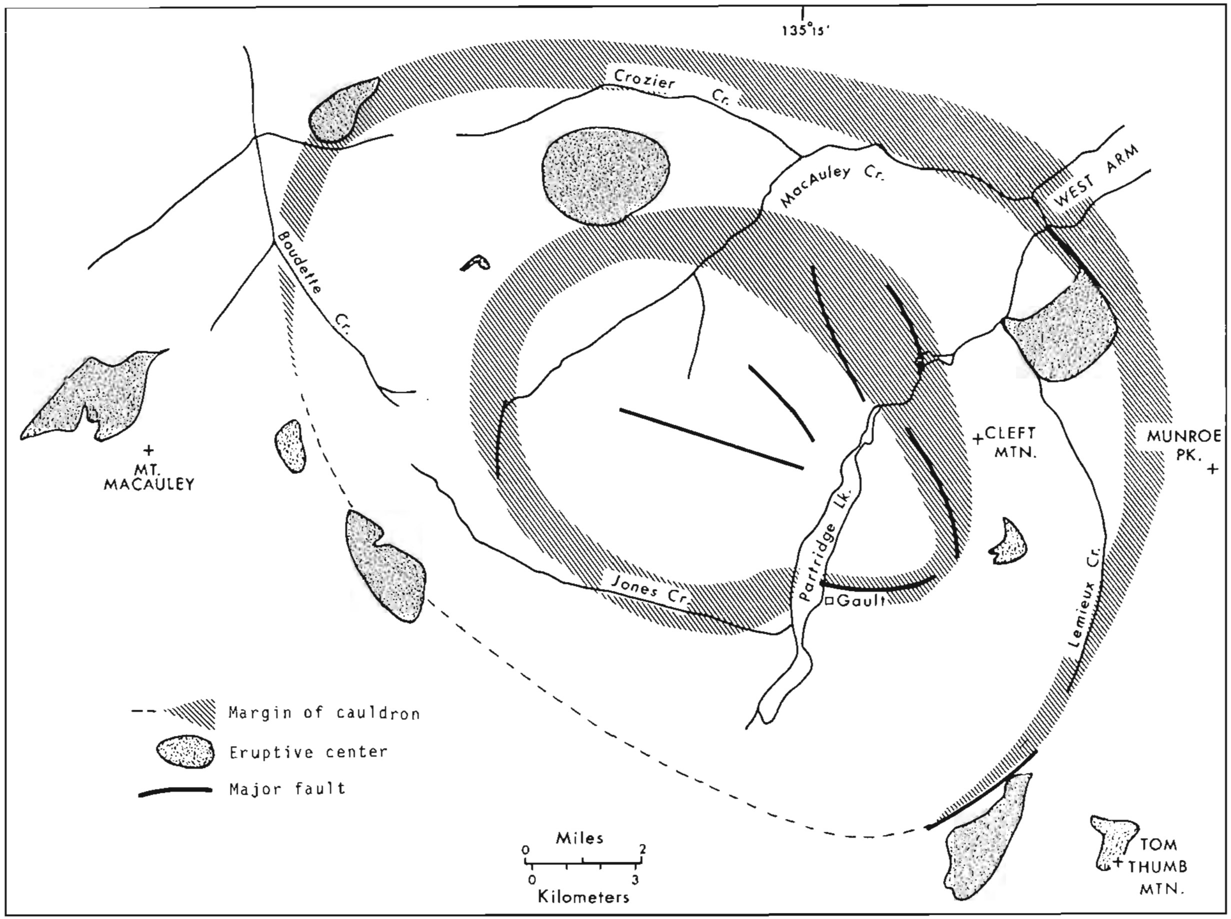


Figure 42. Margins of cauldrons, eruptive centres and major faults in the Bennett Lake complex.

suggest the approximate limit of this dome. The hinge zone southeast of Partridge Lake is marked by intense fracturing but not by major fault displacement.

INTERPRETATION

CONCENTRIC AND RADIAL FRACTURE SYSTEMS

Since Anderson's first theories to explain the formation of cone and ring fractures (Anderson, 1936, 1937) several authors through experiments (Cloos, 1939; Tolansky and Howes, 1954; Field, 1964) or through re-examination of the theoretical stress fields produced in the vicinity of a magma chamber (Baker, 1969; Robson and Barr, 1964; Sigurdsson, 1966; Durrance, 1967; Roberts, 1970) have investigated the processes of formation of arcuate fractures in solids. These workers generally agree that conical fractures (outward or inward dipping), nested cones or sets of spiral cracks, are produced as a result of an upward push due to increased magma pressure.

In the Bennett Lake complex, there were at least three successive stages of arching of the roof of the magma chamber and formation of concentric and radial fractures produced by rising magma. The first stage was a gentle arching over a broad area that generated the outer concentric fractures. These fractures were in existence before the first major ash-flow eruptions, because tuff of the Partridge Lake Formation nonconformably overlies shattered and brecciated granite along the ring-fracture zone, and eruptive centres for the Partridge Lake Formation lie along the outer ring-fracture system. Truncation of pyroclastic cones built at these eruptive centres suggests that the cauldron block subsided along early-formed ring fractures.

The inner ring-fracture system indicates a second stage of arching over a smaller area than the first. Distribution of eruptive centres for the ash flows of the MacAuley Creek Formation along this fracture system suggests that the fractures were the channels along which venting took place and were thus present before these eruptions. Displacements of the MacAuley Creek Formation across faults related to the inner cauldron indicate that major movement took place along these fractures after deposition of this formation. This relationship further indicates that the ash flows of the MacAuley Creek Formation could represent the magma that was removed from the top of the magma chamber to form the subterranean cauldron.

The third and most obvious stage of arching is evidenced by formation of a dome which tilted pyroclastic and epiclastic deposits of the inner caldera, and formed prominent radial fractures.

The various stages of arching and cauldron subsidence indicate periodic upward pulses of magma followed by deflation of part of the magma chamber.

SUBSIDENCE OF THE CAULDRONS

The differential subsidence of the outer cauldron block may be related to the intensity of fracturing along the ring-fracture zone, the shape of the magma chamber, and the shape of the cauldron formed at the top of the magma chamber after rapid escape of some of the magma. Shattered and brecciated granitic rocks form a wide zone along the northeastern and eastern parts of the outer ring-fracture system whereas along the western and southern parts they are restricted to the immediate vicinity of large dykes, narrow zones adjacent to faults and around some eruptive centres. During collapse the cauldron block may have subsided more readily along the less coherent, intensely brecciated northeastern side of the ring-fracture zone than along the relatively "tight" fractures along the southwestern side.

The wide brecciated zone and the mechanism of caldera collapse may be related to the shape of the magma chamber. Possibly a generally dome-shaped magma chamber developed a cupola along the northeastern side. The following features might be expected near such a cupola: intense fracturing of the granitic rocks where the upward-pushing magma was nearest the surface; greater concentration of gases and hence higher gas pressure than in other parts of the magma chamber; subterranean explosions when the gas-charged magma moves into zones of fractured rock (Wright and Bowes, 1968, p. 24); and an area where the roof of the magma chamber would be breached first and thus would be the locus of the first explosive volcanic eruptions. During these eruptions the roof and sides of the cupola would be widened by the erosive action of the explosions, and the broken material thus removed from the walls would be carried upward. Once started, the explosive eruptions and the accompanying brecciation may have migrated along the ring-fracture zone. The net result after evacuation of the upper part of the magma would be a larger cavity and a thinner crustal block above the cupola than above other parts of the magma chamber (Fig. 43A). During subsidence the roof of the cauldron would begin to sag most easily along the relatively incoherent, brecciated northeastern side and it would tend to flap downwards like a giant hinge (Fig. 43B). Subsidence would also take place along the southwestern and southern sides but it would not be as great because the cauldron is shallower in this part of the magma chamber.

Stratigraphic evidence indicates that the arcuate graben formed either during or shortly after collapse of the outer cauldron. It may have resulted from differential displacements along intersecting arcuate fractures.

Subsidence of the inner cauldron probably took place by simultaneous differential movements along the family of fractures that compose the inner ring-fracture system, resulting in the arcuate step-like arrangement of blocks along the north side. Erosion of an area characterized by fault-block topography formed a series of rugged granitic peaks and ridges along the west side of the caldera. Structural-stratigraphic relations of the avalanche deposits of the Lemieux Formation suggest that the caldera walls were caving periodically during the successive movements along the faults bounding the caldera blocks. The main floor of the inner caldera subsided essentially intact.

DOMING

Radial tilting of formations representing almost the entire stratigraphic sequence, and the lack of recognizable disturbance of the dome by later structural features suggest that doming was virtually the last major tectonic event in the history of the complex. Uplift and doming of a central

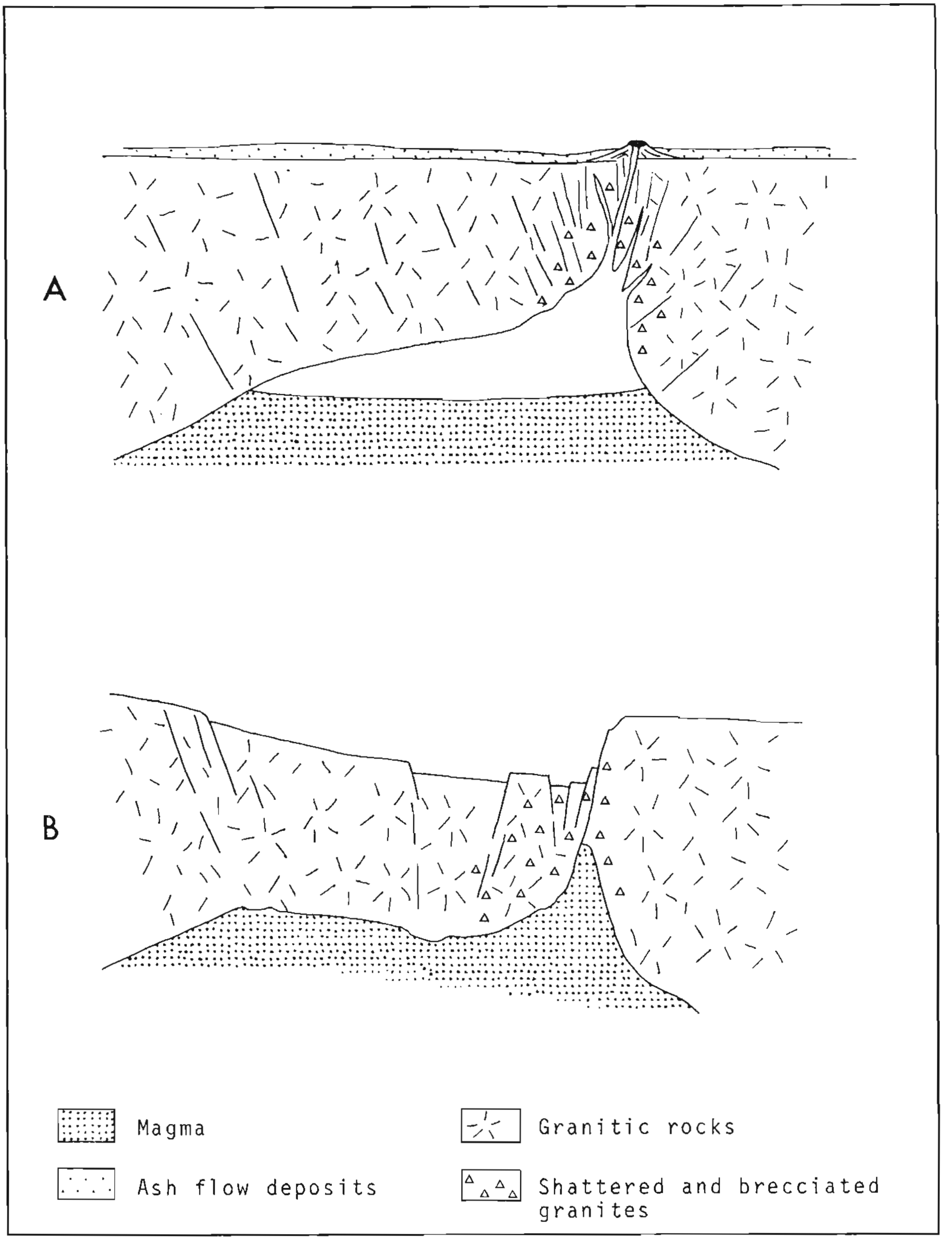


Figure 43. Mechanism of cauldron subsidence along the outer ring fractures of the Bennett Lake complex. A, Evacuation of magma from the cupola leaving an asymmetrical cauldron. B, Subsidence of the cauldron roof.

cauldron block has been called "resurgent doming" by Smith (1968). The following lines of evidence indicate that the dome was produced by an upward force rather than by differential collapse: (1) radial faults that bound radially-dipping blocks (Cloos, 1939; Wisser, 1960); (2) the longitudinal graben now occupied by Partridge Lake valley; (3) a small northwest-trending keystone graben west of Partridge Lake; (4) hinge zones southeast of Partridge Lake and west of MacAuley Creek. The longitudinal graben inferred along Partridge Lake valley is interpreted as a keystone graben formed at the apex of the dome as the roof distended. Why the dome should be bisected along this northeast trend is conjectural. The almost linear trend of Partridge Lake valley, which is in line with the West Arm of Lake Bennett and a linear stream valley to the south of this complex, implies that the longitudinal graben may have formed along a regional fracture trend that was reactivated during the doming.

The asymmetry of the dome in northeast-southwest section, as shown by the steeper dips of major blocks on the south side, may be related to the greater thickness of the Skukum Group in the inner caldera than in the outer caldera. The thin roof above the magma chamber would be easier to lift and would arch gently to form the crest of the dome whereas the adjacent thick roof would tend to tilt upwards to form the flank.

EMPLACEMENT OF MAJOR RING-FRACTURE INTRUSIONS

The location and arcuate shape of the leucocratic granite body at the head of West Arm suggests that it was emplaced along the outer ring-fracture system. This body is not merely an extension of the porphyritic rhyolite ring dyke to the east, for it lacks chilled margins such as are seen on the ring-dyke rhyolite at the same elevation. Also, it is locally intensely sheared whereas the ring dyke is virtually unaffected by any faulting. This body was emplaced either during the early stages of regional tumescence and generation of ring fractures, or following the first episode of cauldron subsidence. In the latter case it may represent magma that moved into the space between the chamber wall and the subsided cauldron block (Fig. 43B).

The porphyritic rhyolite ring dyke cuts virtually all formations of the Skukum Group. The lack of faulting, shattering and brecciation of the dyke indicates that it has not been affected by tectonic or explosive activity since its emplacement. These features suggest that the ring dyke was emplaced either during or after the last major tectonic event, which was resurgent doming. The variable width and tapering out of the ring dyke along the south and southwest sides of the complex are probably related, as is the subsidence of the outer caldera, to the difference in coherence of the granites along the ring-fracture system. Wide brecciated zones along the northern and eastern sides of the complex would be the easiest path for the intruding magma to take in preference to the tighter fractures along the southern side.

The possible coincidence of ring-dyke emplacement with resurgent doming suggests that space could have been provided for the dyke by tensional reopening of the outer ring fractures in response to central doming (as suggested by Smith *et al.*, 1961). Rotated ignimbrite and granite blocks within parts of the ring dyke indicate that some stoping has taken place along the ring fractures during emplacement of the dyke.

FAULT MOVEMENTS AFTER DOMING

Extrapolation of contacts across Partridge Lake valley (notably the southern wall of the inner caldera, as marked by the fault northeast of "Gault" and the valley of Jones Creek; the southern extent of the Cleft Mountain Formation; and the southern contact of the leucocratic granite body at the head of West Arm) indicates that a sinistral displacement in the order of 600 metres has taken place parallel to the valley. The equal displacement of several structural features that developed throughout the entire history of cauldron subsidence and resurgent doming suggests that the movement represents regional faulting postdating this complex. Furthermore, it is possible that some of the north- and north-northeast-trending smaller faults, that are neither concentric nor radial, may be related to post-complex movements.

SUMMARY OF STRUCTURAL EVENTS

The following points summarize the major stages in the structural evolution of this complex.

1. Regional tumescence above a high-level magma chamber generated concentric and (?) radial fractures.
2. Shattering and brecciation of granitic rocks along the northern and eastern parts of the ring-fracture system by subterranean explosions and explosive volcanic eruptions.
3. Emplacement of the first cycle of voluminous ash flows (Partridge Lake Formation).
4. Caldera collapse with subsidence of a large, intact oval block along the ring-fracture system. Concomitant with the major subsidence an arcuate graben with a horst at its eastern end formed along the northeastern part of the caldera floor. An arcuate granite body may have been emplaced along the northeastern side of the complex at this time.
5. Post-collapse effusion of ash flows and lavas (Cleft Mountain Formation).
6. Period of erosion with caving and avalanching from unstable caldera walls; formation of lakes.
7. Arching of the subsided caldera block and formation of the inner ring-fracture system.
8. Emplacement of the second cycle of voluminous ash flows (MacAuley Creek Formation).
9. Caldera collapse with progressive subsidence to form a series of arcuate steps along the northern side, while the south-central block subsided intact.
10. Period of erosion with caving and avalanching from caldera walls; formation of lakes.
11. Post-collapse effusion of ash flows and lavas (Crozier Tuffs and Lavas and Boudette Creek Formation).
12. Resurgent doming with formation of prominent radial faults, a longitudinal graben and segmentation of the caldera block into radially dipping blocks.
13. Emplacement of ring dyke.
14. Fumarolic activity (structural and volcanic quiescence).

Two resurgent cauldron cycles (Smith, 1968) are clearly defined: first cycle by events 1 to 6 (above) and the second cycle by events 7 to 14. It will be shown in Chapter VI that each structural cycle is accompanied by a distinct volcanic cycle which reflects distinct trends of chemical evolution in the magma chamber. The sequence of events in each cycle of the Bennett Lake complex coincides almost exactly with the sequence proposed by Smith in his synthesis of well-known resurgent calderas of the world.

Classification of caldera structures has been discussed by Smith (1968, p. 652) and by Williams (1941, p. 246). The resurgent calderas differ from the classical cauldron subsidences not only with respect to resurgent doming, but also in that late stage major ring-fracture intrusions are thought to be emplaced during tensional reopening of ring fractures (generally of inward dip) rather than during subsidence and major stopping of the cauldron block along outward dipping fractures. The resurgent caldera also differ from the Krakatau type (Williams, 1941, p. 253) in which caldera collapse is piecemeal or chaotic, in that a crustal block subsides essentially intact along ring fractures.

CHAPTER VI

PETROCHEMISTRY

Volcanic rocks of the Skukum Group are of the calc-alkaline suite and range in composition from rhyolite through dacite and andesite to basalt* (Fig. 44). Two cycles of volcanism, each defined by a trend from early salic to late intermediate or mafic compositions, are recognized. The first cycle of volcanism, represented by the Partridge Lake and Cleft Mountain Formations, erupted before and immediately after the first episode of cauldron subsidence. Most of the second cycle is represented by the MacAuley Creek Formation which erupted after the first episode of cauldron subsidence and before the second. Rocks of the Jones Creek and Boudette Creek Formations are regarded as a continuation of the second cycle that erupted after subsidence, rather than as a distinct third cycle.

SAMPLING AND ANALYSIS

Eight samples of granitic rocks, representative of map-units 2 to 4, were chemically analyzed (Appendix II).

Samples of volcanic rocks (Appendix II) were chosen with the aim of determining chemical variation through thick successions of lithologically uniform ignimbrites and lavas (which make up a major proportion of some formations), because very little compositional data can be determined for these rocks by petrographic means. Of the first cycle only one sample was analvzed from the Partridge Lake Formation; of the Cleft Mountain Formation, six samples came from Unit A ignimbrites; nine from dacite lavas (Unit B); and three from andesite lavas (Unit C). No samples came from Unit D ignimbrites or Unit E arenites and tuffs. Of the second cycle, most samples are from Unit B of the MacAuley Creek Formation; none are from Unit A. Only one sample came from the Jones Creek Formation, and two from the Boudette Creek Formation. Two samples were chosen from the ring dyke and eight from other dykes and sills (map-unit 15). As a result of the incomplete sampling, the full extent of compositional variation within each cycle is probably not represented in the chemical plots.

Hand specimens of volcanic rocks selected for chemical analyses were crushed in a jaw crusher then ground to -100 mesh. After coarse crushing, granitic, metamorphic and large volcanic clasts were picked out under a binocular microscope, so that the analyses represent as closely as possible, the source material only.

Most chemical analyses were performed in the laboratories of the Geological Survey of Canada. Major elements in samples were analyzed by X-ray fluorescence spectroscopy for Si, Al, Mg, Fe (total), Mn, Ca, and K, and by wet chemical methods for Na, Fe, P, CO_2 and H_2O. All trace elements were analyzed by quantitative spectrographic methods. The accuracy of major elements values (expected by the laboratory, and as determined by Baragar and Goodwin, 1969, p. 123) are as follows: $SiO_2 \pm 1.2$, $Al_2O_3 \pm 0.7$, $Fe_2O_3 \pm 0.5$, $FeO \pm 0.3$, $MgO + 1.3$, $CaO + 0.4$, $Na_2O \pm 0.2$, $K_2O \pm 0.1$, $TiO_2 \pm 0.05$, $P_2O_5 \pm 0.04$. Analyses for FeO, Fe_2O_3 and Na_2O were performed at Carleton University as a supplement to partial analyses of some samples performed at the Geological Survey. FeO and Fe_2O_3 were in good agreement

*Chemical data are not available for the more mafic lavas, but petrographic study indicates that their compositions range from andesite to basalt.

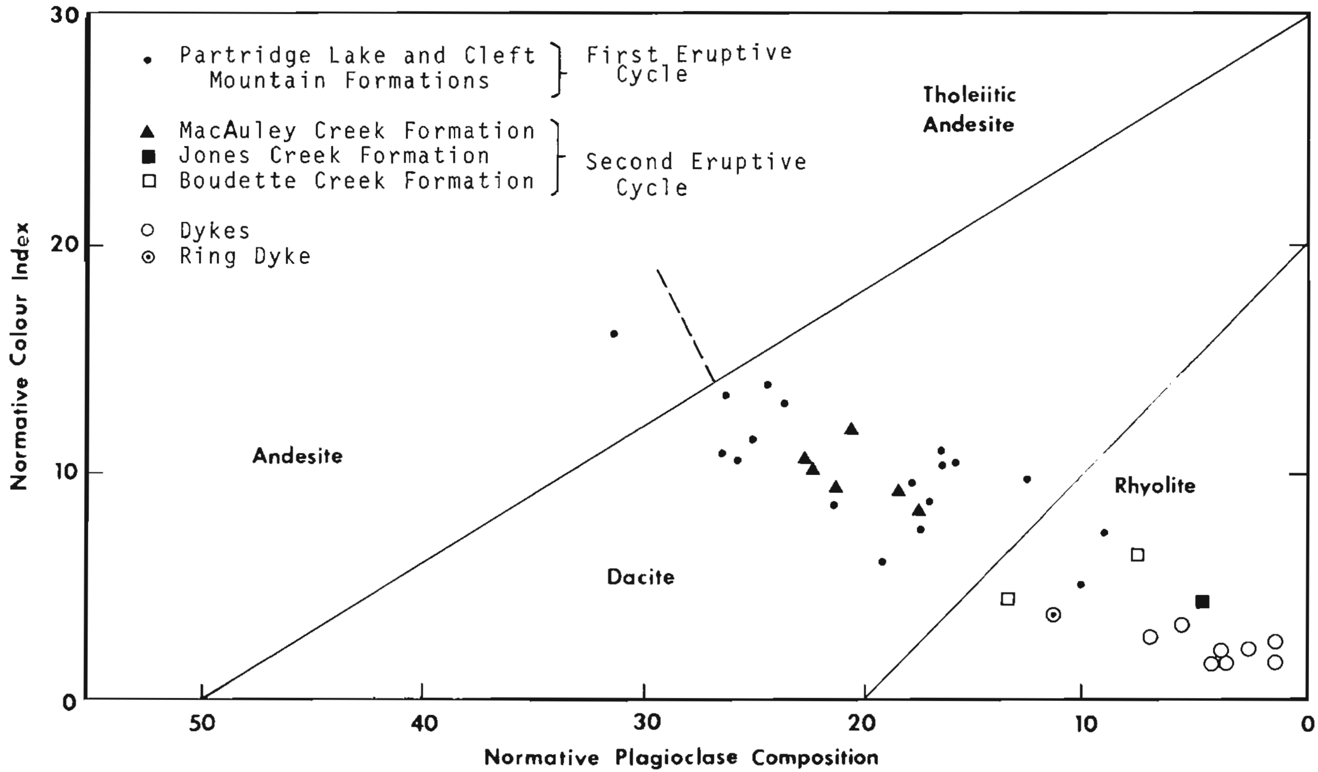


Figure 44. Composition of volcanic rocks of the Bennett Lake complex (Classification after Irvine and Baragar, 1971). Normative colour index = 01 + Opx + Cpx + Mt + Il + Ht. Normative Plagioclase content = 100 An/(Ab + An + 5/3 Ne).

between the two laboratories but values of Na_2O are consistently about 0.8 weight per cent lower for Carleton analyses than for Geological Survey analyses. The Carleton values are adjusted for use in all chemical plots and norm calculations (see Appendix II).

Spectrographic analyses are expected by the laboratory to be accurate within 15 per cent of the values reported for Sr, Ba, Cr, Zr, V, Ni, Cu, Co and Sc; and 30 per cent for Pb and Ga.

Norm calculations were performed by computer at the Geological Survey of Canada using program System Number C60901. Nomenclature of volcanic rocks follows the classification of Irvine and Baragar (1971).

MAJOR OXIDES

Variations of major oxides with height in stratigraphic sections through the first and second cycle rocks are shown in Figures 45 and 46. Although the general trends of oxides are considered to represent primary variations, some of the minor fluctuations in SiO_2, Al_2O_3, Na_2O and K_2O trends may be related to the effects of secondary hydration and groundwater leaching of glassy tuffs and lavas (Lipman, 1965). In the first cycle (Fig. 45), SiO_2 decreases whereas CaO increases upward. MgO, TiO_2 and MnO show a general slight increase upwards whereas K_2O shows slight general decrease. Al_2O_3, FeO, Fe_2O_3 and Na_2O do not show consistent over-all variation. In the second cycle (Fig. 46), variations are very subtle where they can be distinguished. The apparent upward decrease of SiO_2, and Al_2O_3 of 0.5 to 1.5% is within the limits of analytical error and may not be real. An apparent upward increase of Fe_2O_3, MgO, and CaO is very subtle whereas TiO_2 and P_2O_5 show distinct although slight increase. No consistent trend is shown for FeO, Na_2O, K_2O and MnO.

SiO_2-variation diagrams (Figs. 48 and 49) show linear trends with scatter for most oxides. SiO_2 ranges from 57 to 72 per cent in the extrusive volcanic rocks analyzed. Lava flows are almost invariably less silicic than pyroclastic rocks in the first cycle. The ring dyke ranges from 70 to 73 per cent SiO_2 whereas other rhyolite dykes fall between 74 and 78 per cent SiO_2. Most granitic rocks fall between 55 to 72 per cent SiO_2. No analysis is available for the leucocratic granite but petrographic evidence indicates that it is more silicic than the other granitic rocks, probably within the same range as the ring dyke. All other oxides, except the alkalis, decrease as SiO_2 increases. K_2O increases with increasing SiO_2 whereas Na_2O does not show any distinct trend.

Second cycle volcanic rocks show considerable scatter with respect to the first cycle trend for Al_2O_3 and MgO. MgO in the second cycle volcanics lies closer to the trend of granitic rocks than of volcanic rocks.

Trends for the granites generally do not coincide with those for volcanic rocks except at the most silicic ends. Trends of Al_2O_3, CaO and MgO are distinctly higher in granitic rocks than in volcanic rocks; K_2O, Fe_2O_3 and MnO tend to be slightly lower; and those for Na_2O, FeO and TiO_2 overlap. Granitic and volcanic trends intersect generally between 70 and 75 per cent SiO_2. The sequence of granite emplacement as determined from structural evidence and radiometric dating corresponds to increasing SiO_2 content (depicted only with CaO in Fig. 48).

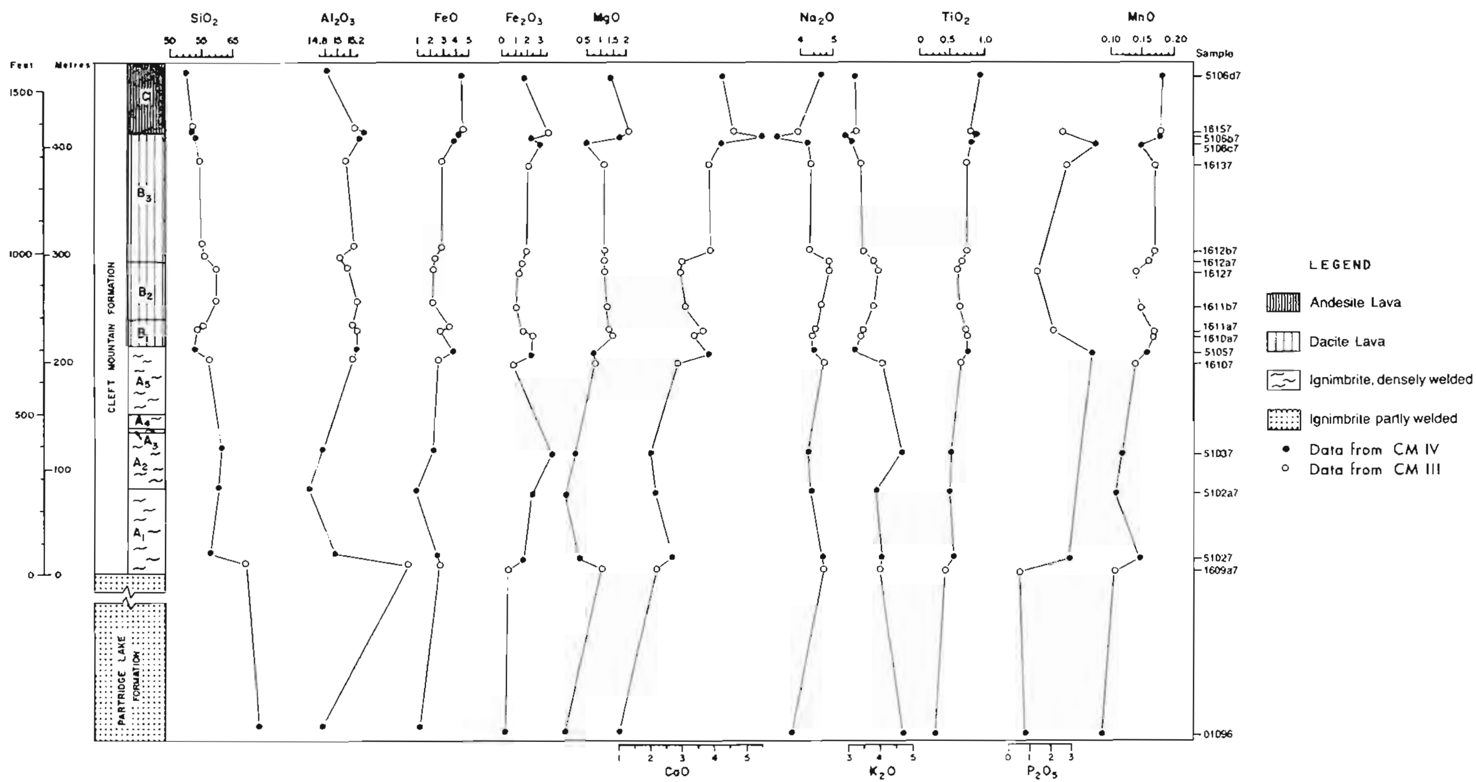


Figure 45. Reference section CMIV of the Cleft Mountain Formation and part of the Partridge Lake Formation showing lithologic features and major-oxide variations in weight per cent, in first volcanic cycle. Open circles are data from reference section CMIII plotted at equivalent stratigraphic positions in CMIV.

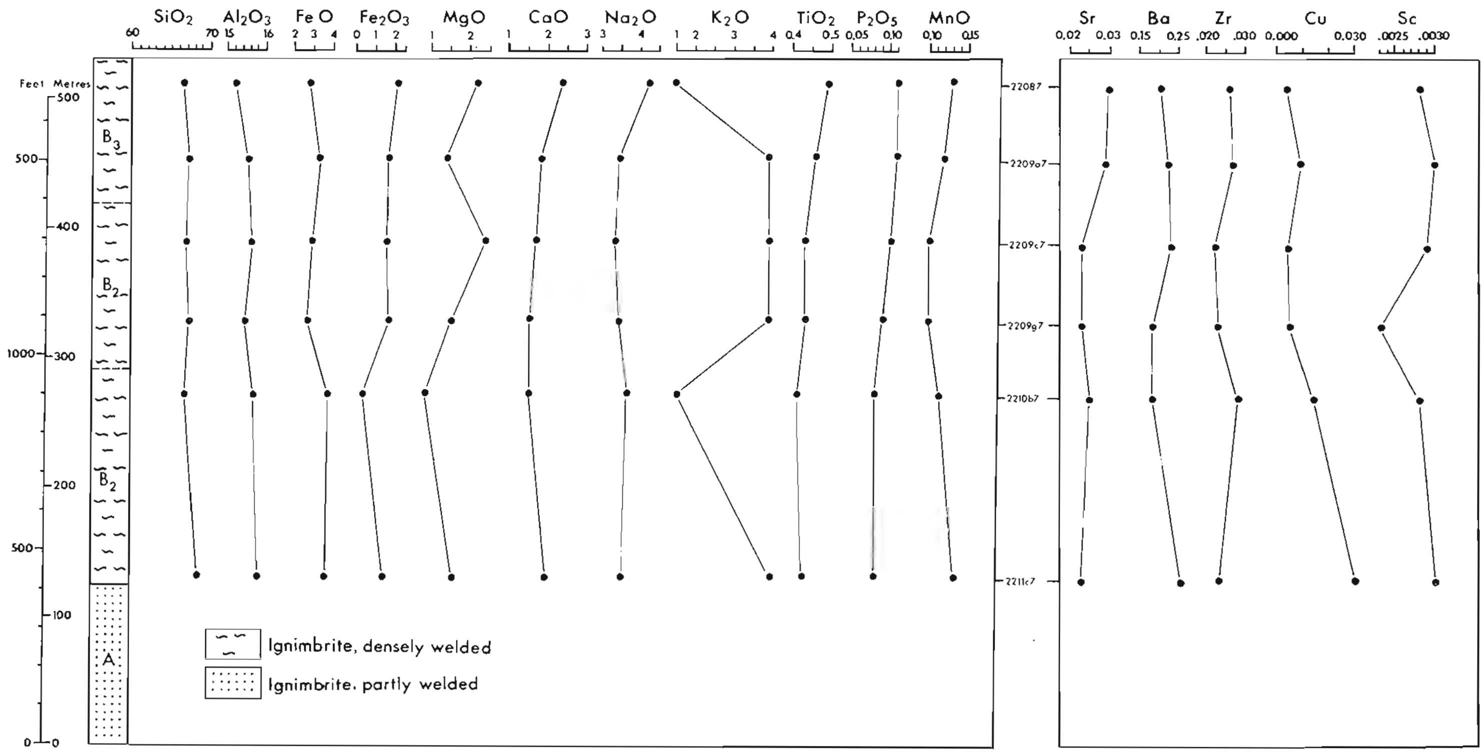


Figure 46. Reference section MCI of the MacAuley Creek Formation showing lithologic units and major-oxide and minor-element variations in weight per cent, of second volcanic cycle.

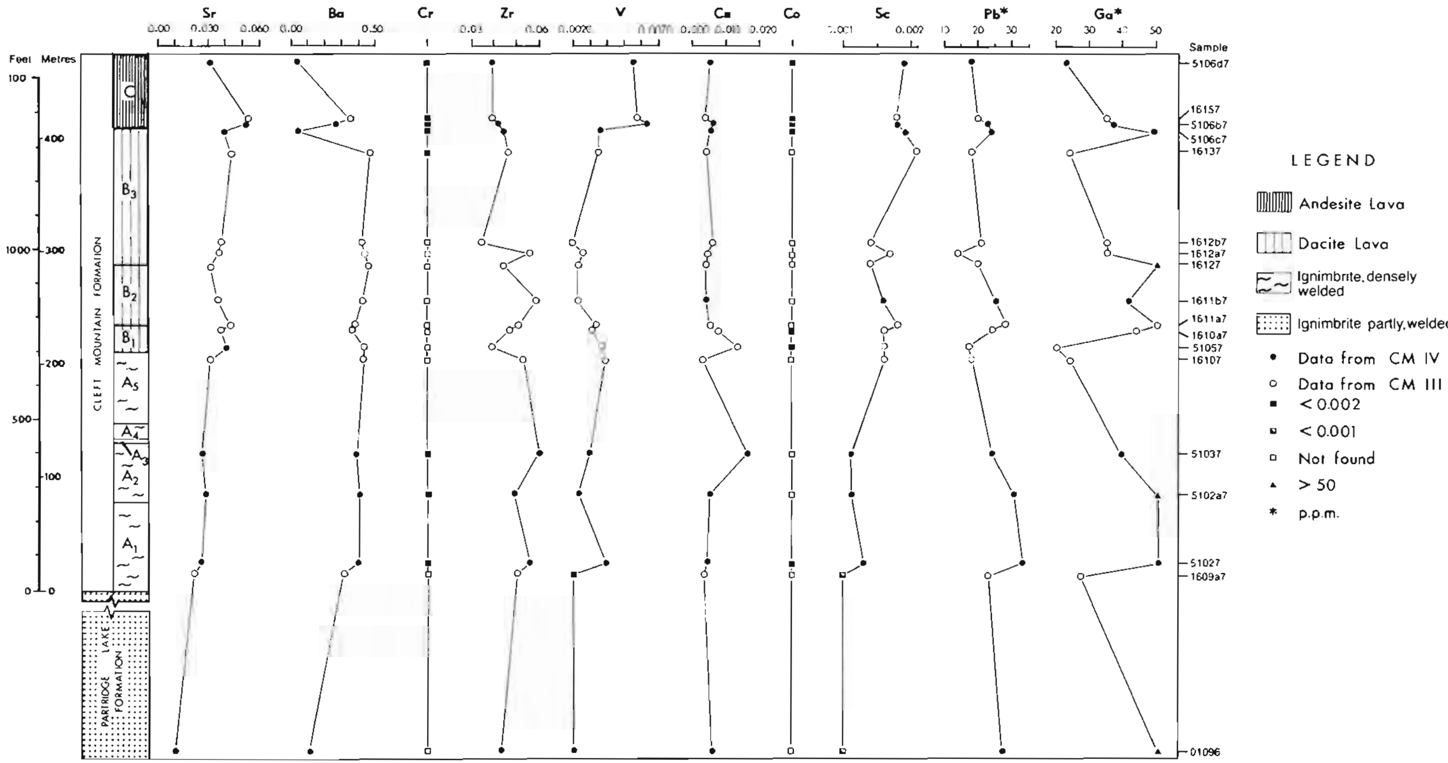


Figure 47. Reference section CMIV of the Cleft Mountain Formation and part of the Partridge Lake Formation showing lithologic features and minor-element variations in weight per cent (except as designated). Open circles are data from reference section CMIII plotted at equivalent stratigraphic positions in CMIV.

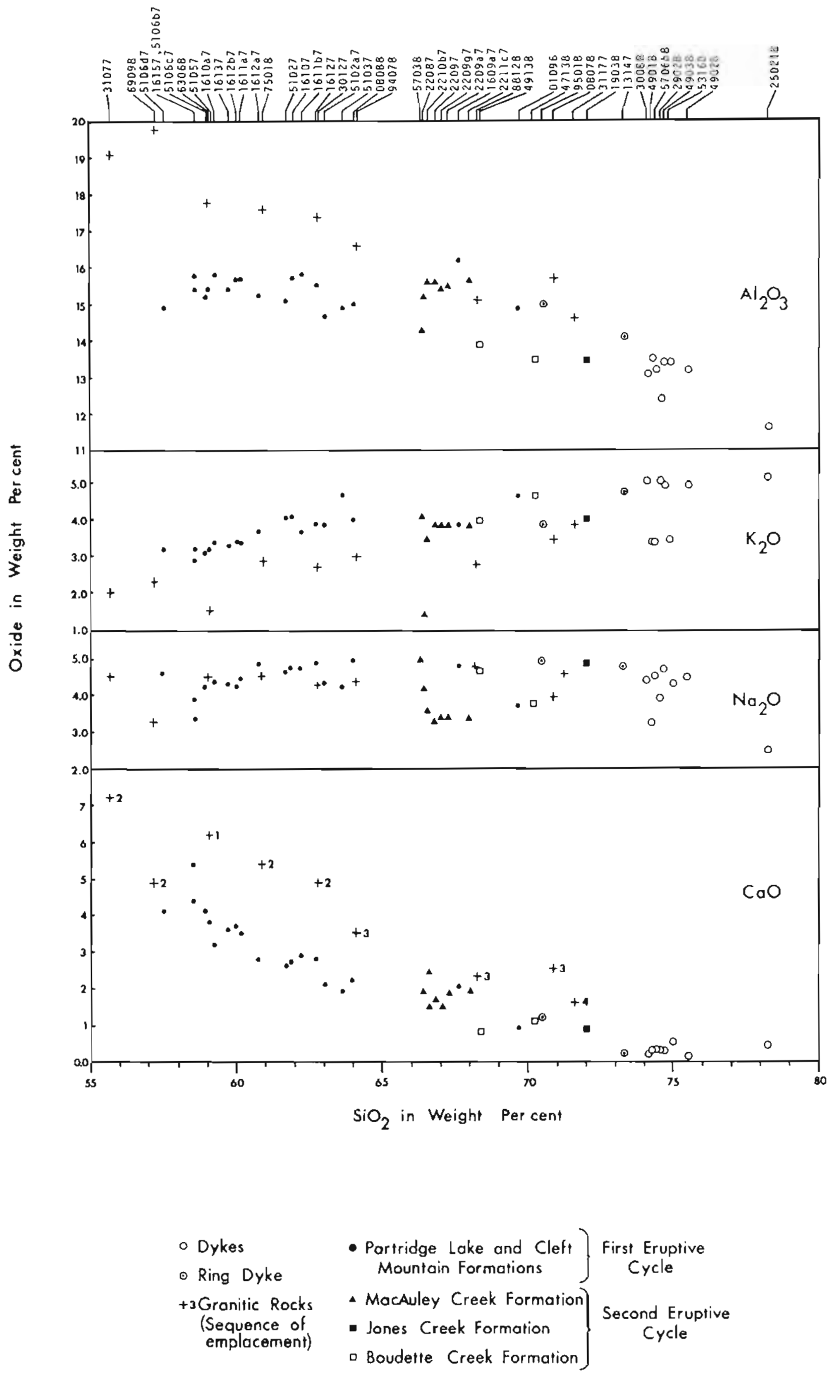


Figure 48. SiO_2-variation diagram for major oxides of volcanic and plutonic rocks of the Bennett Lake complex.

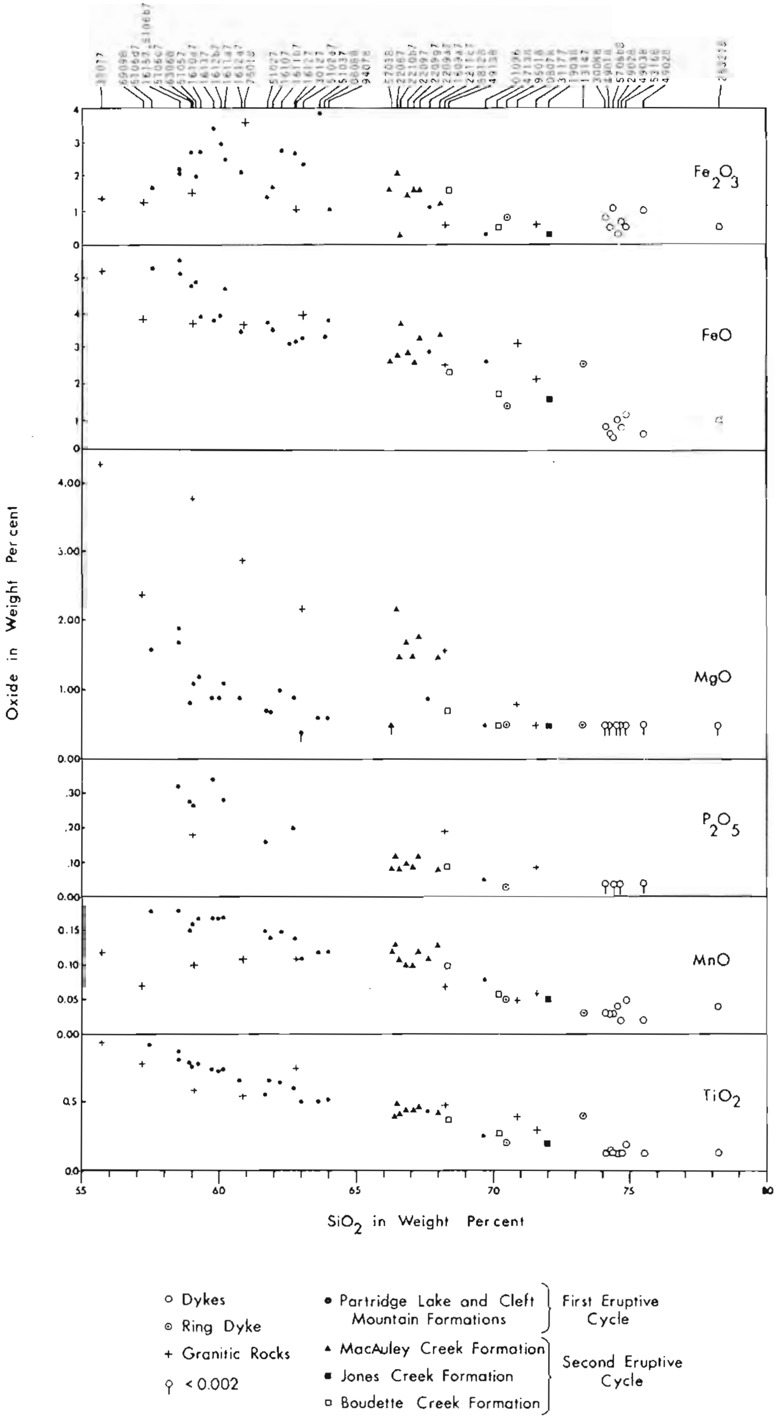


Figure 49. SiO_2-variation diagrams for major oxides of volcanic and plutonic rocks of the Bennett Lake complex.

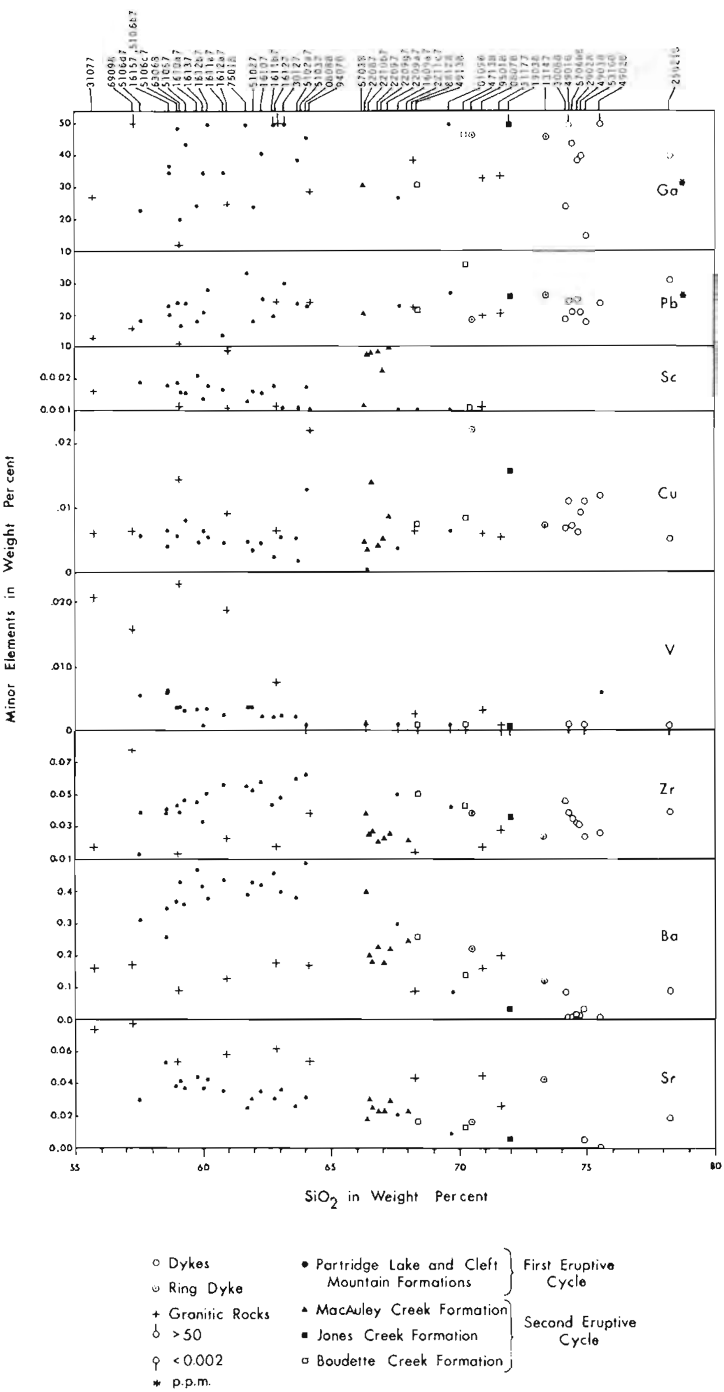


Figure 50. SiO_2-variation diagram of minor elements in volcanic and plutonic rocks of the Bennett Lake complex.

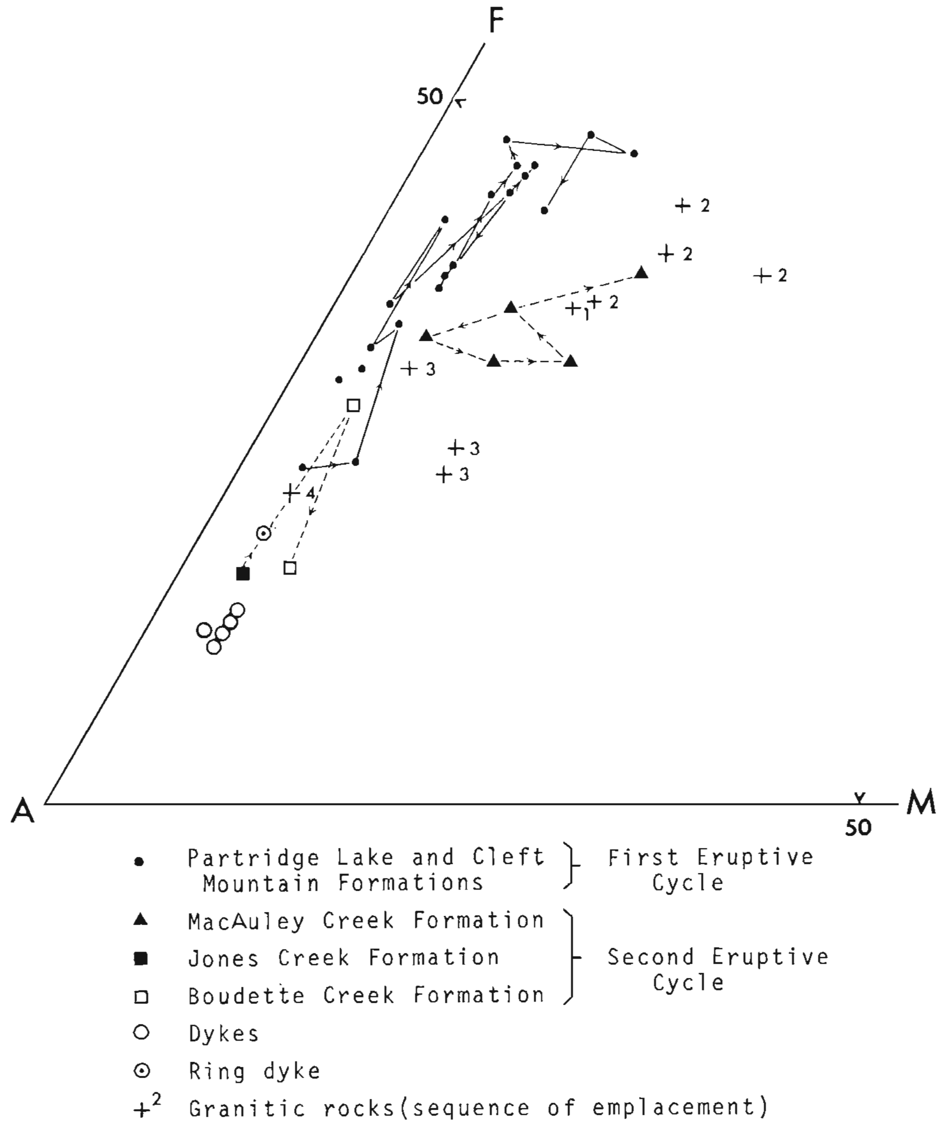


Figure 51. AFM plot of variation of volcanic and plutonic rocks of the Bennett Lake complex. A = $Na_2O + K_2O$; F = $FeO + 0.8998\ Fe_2O_3$; M = MgO, all in weight per cent. Arrows indicate the direction of compositional change of the rocks with time.

MINOR ELEMENTS

Variation of minor elements with height in stratigraphic sections through the first and second cycle extrusive rocks is shown in Figures 46 and 47. In the first cycle there is an upward increase in Sr and Sc. Pb generally decreases upward through the section whereas other elements do not show consistent trends.

In ignimbrites of the second cycle Cu is the only element that shows a systematic upward decrease. Sr is higher in upper than in lower units. Trends are not distinct for Ba, Zr and Sc.

In SiO_2-variation diagrams (Fig. 50) volcanic rocks show distinct linear trends, with relatively little scatter for Sr and V. Sc (with the exception of the MacAuley Creek Formation) Sr and V decrease with increasing silica.

The second cycle volcanic rocks plot well below the first cycle trend for Ba and Zr and well above the trend for Sc.

Vague linear trends for granitic rocks show considerable scatter for most elements. Trends for granitic rocks plot above those of volcanic rocks for Sr and V, and generally below for Ba, Zr and Sc.

The AFM plot (Fig. 51) confirms the trends with time from mafic to salic for the granitic rocks. In contrast, tuffs and lavas of the first cycle demonstrate an irregular trend from salic to mafic. Of the second cycle, only the ignimbrites are represented on the plot, and these show no consistent trend with time. Petrographic study, however, indicates that the tuffs which begin the second cycle are more salic than the ignimbrites and the succeeding lavas are more mafic. Some post-subsidence ignimbrites of the second cycle are more salic than those of the MacAuley Creek Formation, but not enough data are available to establish trends.

INTERPRETATION

Each of the two major volcanic cycles shows a general compositional zonation from salic at the beginning to mafic at the end with many fluctuations in composition near the end of each cycle. The chemical gradation within pyroclastic rocks and single cooling units that have effused very rapidly, requires eruption by progressive emptying of a vertically zoned magma chamber. The compositional variation within stratigraphic sections of each cycle represents in inverted order the compositional zonation that existed in the magma chamber just before and during eruption. Similar interpretations have previously been proposed for compositionally zoned ash-flow sheets (Williams, 1942, p. 156; Katsui, 1963, p. 641-642; Ratté and Steven, 1964, p. D52-D53; Smith, 1960b, p. 833; Lipman, 1966, p. F41; Fisher, 1966).

MAGMATIC DIFFERENTIATION

Figure 52 summarizes the distribution of crystals and chemical constituents in the differentiated magma chamber. Any or all of crystal accumulation, anatectic melting of the salic crust at depth and upward diffusion of volatiles and alkalis could produce a vertically zoned magma chamber. It will be shown that most of the major chemical and mineralogical features can be explained adequately by volatile and alkali transfer in the framework of the structural and tectonic history described in Chapter V.

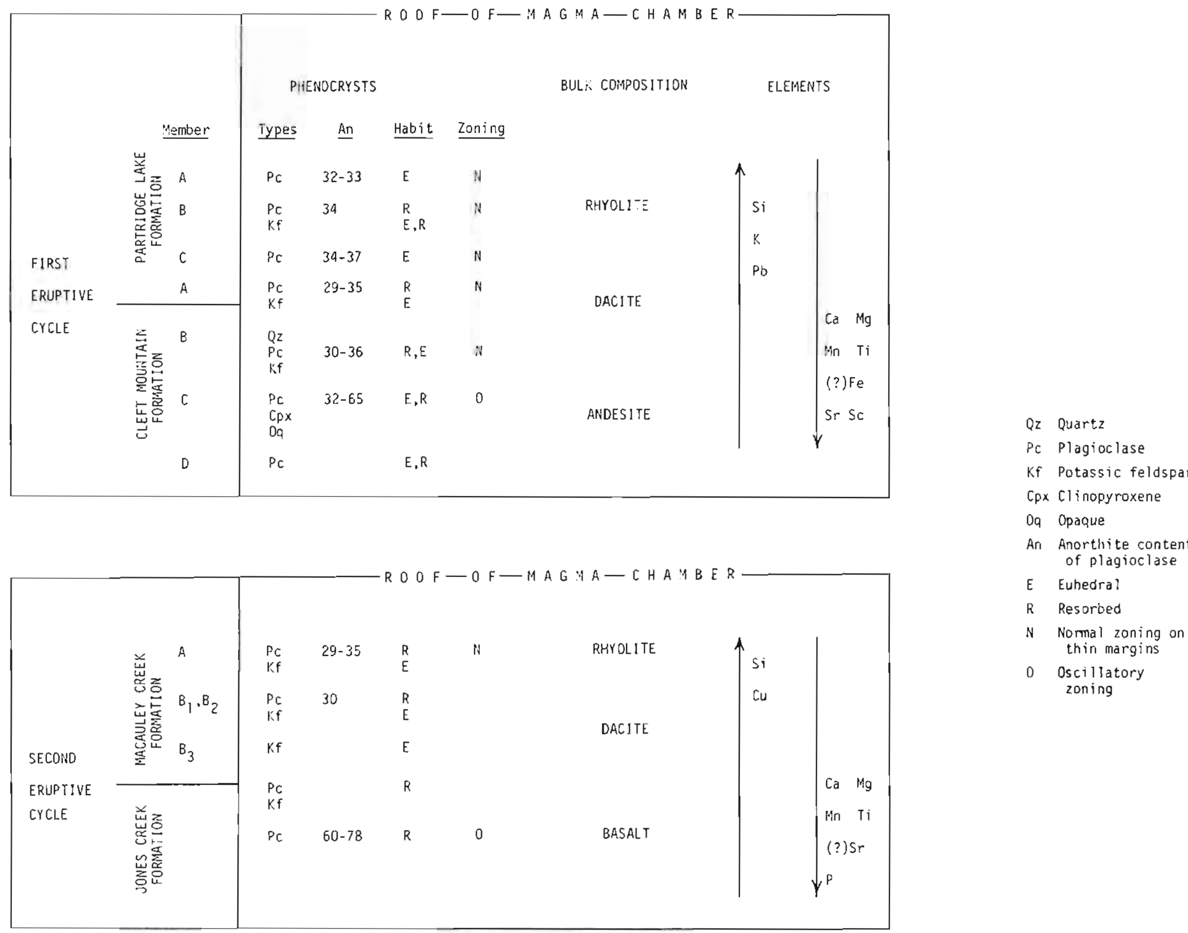


Figure 52. Schematic diagram showing compositional gradations in the magma chamber from which the first and second eruptive cycles were derived.

Crystal Accumulation

Lipman (1966, p. F44) suggested that the early formed feldspars could settle sufficiently rapidly in a rhyolitic magma to prevent effective reaction with the magmatic liquid in place, resulting in a compositional gradation toward the top of the magma chamber. Crystal settling should produce a downward increase in the ratio of plagioclase to potassic feldspar because of the high specific gravity of the plagioclase. In the Bennett Lake complex, a subtle downward trend in the magma chamber (that corresponds to the first cycle) of increasing amounts of phenocrysts and of increasing ratios of plagioclase to potassic feldspars (indicated by upward trends in the stratigraphic succession in Figs. 14, 16 and 17) suggest that crystal accumulation may have some role in magmatic differentiation. In some andesites resorption of larger, more calcic plagioclase phenocrysts, whereas small less calcic phenocrysts are euhedral, suggests that crystal accumulation has taken place and at least partly contributed to differentiation. Pyroxene in these rocks generally forms intergranular crystals rather than phenocrysts suggesting growth in place not accumulation. Variations in phenocryst content throughout the differentiated magma, however, could not possibly account for the range of bulk-rock compositional zonation unless there has been increasingly extensive resorption of plagioclase downward. Although many units exhibit deeply embayed phenocrysts, indicative of resorption, there is no general correlation of phenocryst content, resorption, and composition within the differentiated column. The amount of phenocrysts, for example, is essentially constant throughout the ignimbrites which represent the bulk of the first cycle in spite of the systematically changing chemistry of the rocks. Furthermore, the paucity of phenocrysts at all levels in the magma chamber suggests that crystallization was not sufficiently advanced to produce enough crystals which could settle and account for the variations in bulk-rock compositions.

The proportions and compositions of phenocrysts can reasonably be explained by crystallization in place at different levels in a liquid where composition varied from bottom to top. Increasing anorthite content of plagioclase and decreasing potassic feldspars downward is the expected trend with crystallization from an increasingly more calcic magma of higher temperature downward.

In summary, crystal accumulation may have accounted for some changes in composition, but the effect would not be great enough to account for the over-all variations in bulk composition of the magma.

Fractional Anatectic Melting

A column of fractionated magma with silicic liquid at the top and grading downward to more mafic magma below can be produced by successive anatectic melting of the sialic crust. The first liquid would have a composition at the thermal minimum and successive melting of progressively more mafic and refractory rock would produce successive batches of liquid that would follow a fractionation curve (Lipman, 1966, p. F45).

The theory of fractional anatectic melting implies that the magma chamber was vertically zoned before eruption, and successive eruptions tapped successively more mafic magma with time. In the Bennett Lake complex, however, both the first and second cycles show compositional changes from salic to mafic with time, suggesting that the differentiation processes repeated themselves during the history of this complex. Furthermore, several oscillations from salic to intermediate compositions are recorded near the end of the second cycle between the time of cauldron subsidence and ring-dyke emplacement. Although anatectic melting of a salic crust may have been the ultimate origin of the magma body, the intimate relationship of changing magma composition with near-surface tectonic events suggests that differentiation took place after the emplacement of the magma into a near-surface chamber.

Diffusion of Alkalis and Volatiles

Volatile species, such as water, tend to distribute themselves by diffusion such that they concentrate in regions of lowest temperature and pressure (Kennedy, 1955). Certain metals, such as alkalis and silica tend to coordinate with volatiles and thus concentrate at the upper and outer margins of a magma chamber. By this mechanism the zonation of the magma chamber would be produced before the volcanic eruptions, and the products of volcanism would be successively more mafic with time. In the Bennett Lake complex, each eruptive cycle began with early salic effusions and progressed toward mafic effusion with time, indicating that differentiation took place in the time interval between eruptive cycles. Furthermore, compositional cycles can be directly correlated with episodes of cauldron subsidence. These events suggest that differentiation took place after near-surface emplacement of the magma and that fractional anatectic melting probably was not the main differentiation mechanism.

According to Marinelli and Mittempergher (1966, p. 122) trace elements such as U, Th, F, Zr, B, and Be tend to concentrate in extreme differentiates and can be correlated with the evolution of the potassium content. There is thus a tendency for enrichment of these elements where the differentiation process involves gas concentration. Green (1970, p. 233) suggested that water and CO_2 may be important in allowing selective migration of some minor elements without significant changes in major element abundances.

The important role of gases (probably mainly water) in the evolution of the Bennett Lake complex is suggested by the dominance of pyroclastic rocks and the presence of explosion breccias and shattered granite along ring-fracture zones and near volcanic conduits. Gases must have accumulated at least in the upper parts of the magma chamber as a prelude to the cataclysmic explosive eruption that followed. Chemical compositions of the rocks in the volcanic pile suggest that the top of the magma chamber was also enriched upward in Si, K, Pb, and (?) Cu, and downward in Ca, Ti, Mn, Sr, and Sc (Fig. 52). Elements that have apparently moved upward with the volatiles such as K are present in much higher amounts in volcanic rocks than in granites of corresponding SiO_2 content: conversely, elements such as Ca, Mg, Al and Sr, that have concentrated in the lower parts of the magma chamber are present in much lower amounts than in the granites of the same SiO_2 content (Figs. 48, 49 and 50). The lack of abundant hydroxyl-bearing minerals in the tuffs and ignimbrites is not necessarily in contradiction to a high concentration of water before and during eruption, for the temperature of the magma may have been too high for hydrous minerals to form. During eruption most of the volatiles probably separated very rapidly from the particulated magma and were lost. Fresh volcanic glasses have been shown to contain only a few tenths of one per cent magmatic water upon cooling (Ross and Smith, 1955, p. 1086-1088; Boyd, 1961, p. 415). The remaining water is within the ubiquitous very fine chloritic alteration in most tuffs.

Phenocrysts

The distribution of phenocrysts in the stratigraphic succession indicates that the upper part of the magma was in a less advanced stage of crystallization than the lower part. A higher concentration of volatiles and alkalis near the upper and outer parts of the magma chamber would have lowered the crystallization temperature and thus inhibited crystallization.

Conversely, the paucity of water and alkalis in the lower regions of the magma chamber would have raised the temperature of crystallization of the more mafic magma. Crystallization therefore, would be more extensive in the lower levels than in the higher levels of the magma chamber. This distribution of crystals accounts for the general paucity of phenocrysts amongst the pyroclastic rocks (which were derived from the upper parts of the magma chamber) and the larger amount of phenocrysts in the lavas (which were derived from deeper levels). Fluctuations of pressure resulting from explosive eruptions from the top of the magma chamber would cause periodic fluctuations in the feldspar liquidus that are recorded in phenocrysts with oscillatory zoning.

Near the top of the magma chamber plagioclase phenocrysts alternate from euhedral to resorbed in vertical zones, whereas at intermediate and deeper levels phenocrysts are mainly resorbed or both resorbed and euhedral. In general, euhedral (very rarely embayed) potassic feldspar is present in zones where the plagioclase is deeply embayed. Phenocryst resorption is probably another result of variation in lithostatic pressure following eruption of the first cycle ash flows. During the precipitation of two feldspars, sudden shifting of the feldspar phase boundary could result in potassic feldspar remaining stable while plagioclase began to melt. Rocks containing both euhedral and embayed feldspars record fluctuations of the phase boundary. Shifting of the plagioclase liquidus, in response to pressure fluctuations, may have contributed to melting of plagioclase.

Early rapid eruption and quenching of magma from the uppermost parts of the chamber would preserve the upward trend of increasingly sparse phenocrysts, allowing for only minimal zoning and inhibiting resorption.

Modes of Eruption

The voluminous succession of pyroclastic rocks overlain by dacite to andesite flows indicates that each eruptive cycle began with cataclysmic explosive eruptions followed by quiet effusion of lavas. The first magma to erupt was heavily charged with volatiles and rich in alkalis and silica. Silica and alkalis have the effect of greatly increasing viscosity whereas volatiles tend to reduce it. However, during explosive eruption water would tend to diffuse out rapidly leaving a very viscous alkali-rich fluid which ruptures as the gas expands producing pyroclastic particles (Boyd, 1961, p. 415, indicated that most of the water in fine particles diffuses out within only a few minutes after vesiculation).

Variable viscosity and temperature of the magma are also suggested by the different degrees of welding of the pyroclastic units. The sequence of non- to partly-welded early ash flows to densely welded later ash flows suggests a downward increase in temperature and decrease in viscosity of the magma. This variation is a natural consequence of the zonation in the magma with respect to volatiles and alkalis, with the increase of temperature downward. The degree of welding of the erupted ash flows, however, is also probably influenced by the rate of cooling during eruption. Smith (1966, p. 20) has suggested that emplacement temperature of ash flows is best explained by the cooling effect of admixed air in a vertical eruption column before the ash flow formed; the height of the column, and hence the amount of mixing may be related to vapour pressure in the magma. The violence of eruption increases with the vapour pressure. Violent early eruptions would probably have a greater vertical component and therefore the particulated magma would be greatly cooled by mixing with air and loss of volatiles before forming ash flows. Conversely, the less violent later eruptions (characterized by lower vapour pressure) may have little or no vertical component and form ash flows immediately on reaching the surface. There would thus be a greater conservation of heat and volatiles in these ash flows resulting in higher emplacement temperatures, lower viscosity and denser welding.

In contrast to the viscous, gas-charged magma that produced explosive eruptions, the succeeding magma was poor in volatiles and relatively fluid. This condition is suggested by the massive lavas of dacite composition with a general paucity of vesicles. A condition of superheat (suggested in Chapter IV) in the magma may have been responsible for its initial fluidity. Upon effusion, however, loss of volatiles and superheat, together with the siliceous composition, would render the magma very viscous, tending to inhibit crystallization. Rapid cooling of the liquid produced vitrophyric flows which later devitrified to the felsophyric dacites of the Cleft Mountain Formation.

The next batch of magma to be erupted was the less viscous, partly crystallized andesitic magma which by virtue of its high temperature of crystallization and low viscosity flowed out as lavas which continued to crystallize after effusion.

The lack of a third cycle of explosive volcanism and caldera collapse, may be explained in terms of the volatile content of the magma during the waning stages of the volcano. Most of the volatiles in the magma chamber were depleted during the first and second eruptive cycles. The last vapour-driven explosive eruptions (the Boudette Creek Formation) postdate second-cycle ring-fracture volcanism. The remaining magma at this late stage contained a high proportion of crystals as evidenced by the abundant phenocrysts in the ring dyke. This volatile poor, crystal mush rose to produce the prominent resurgent dome. Ring fractures that reopened during the doming were filled with the partly crystalline magma to form the ring dyke.

COMPOSITION OF THE PARENT MAGMA

It was shown in Chapter III that the granitic rocks underlying the complex follow a distinct trend toward more salic compositions with time. One of the last of these high level intrusions probably was the source of the extrusions. If it can be assumed that the original magma had a roughly uniform composition and then differentiated after emplacement, its composition must have been somewhere between the compositional extremes represented by the volcanic rocks. It is reasonable then, that the parent magma should have a composition that is common to both the granitic and volcanic trends. In many of the silica variation diagrams (Figs. 48 to 50) the granitic and volcanic rocks follow separate trends which generally intersect at compositions near the rhyolite-dacite boundary of Figure 44. It is suggested that this intersection is more than fortuitous and that it represents the composition of the parent magma from which the first-cycle volcanic rocks were derived. It is further suggested that the cluster of second-cycle volcanic rocks, which plot well off the volcanic trend but exactly on the granitic trend, represents the composition of the magma from which the second cycle differentiates were derived.

CHAPTER VII

AGE AND REGIONAL CORRELATION

AGE OF THE BENNETT LAKE COMPLEX

K-Ar ages for four samples of the Bennett Lake complex were determined by M. Shafiqullah at Carleton University. Argon was extracted by the flux-fusion method and determined on an A.E.I. MS-10 mass spectrometer operated statically using argon-38 as a spike. Potassium was determined by flame photometry. The data are presented in Table IV.

Table IV

K/Ar ages of rocks from the Bennett Lake cauldron subsidence complex

Sample No.	Sample	Per cent K_2O	Per cent ^{40}Ar	Age (m.y.)
12017	Matrix of porphyritic rhyolite of ring dyke	4.583	49	50.3 ± 3
03028	Tuff from Partridge Lake Formation	3.149	56	50.6 ± 3
08088	Ignimbrite from Jones Creek Formation	4.657	49	49.9 ± 3
94028	Biotite, from quartz monzonite	7.941	60	57.3 ± 3

^{40}Ar = percentage radiogenic argon in an analysis

λ total = 5.30 10^{-10} yr^{-1}

λe = 0.0585 10^{-10} yr^{-1}

K^{40}/K = 0.0119 atom per cent

Sample 94028 is a medium-grained hornblende-biotite quartz monzonite with only slight alteration, from reference locality G14 (Fig. 7). Fresh hexagonal plates and books of biotite are up to 5 mm across.

Sample 03028 is a partly welded pale green tuff typical of the Partridge Lake Formation. Accidental and accessory constituents were eliminated from the sample by hand picking so that the sample represents essential material only.

Sample 08088 is a dark grey (almost black) subvitreous, densely welded ignimbrite from the Jones Creek Formation. Glassy feldspar phenocrysts, less than 1 mm across, make up less than 2 per cent of the rock. Inclusions are rare. Again only essential material was used for the whole rock analysis. Chemical data for this sample is given in Appendix II and in Figures 48, 49 and 50.

Sample 12017 is a fresh specimen from a sparsely porphyritic chilled border zone of the ring dyke at reference locality V12 (Fig. 26). The rock consists of 10 per cent euhedral quartz, sanidine and high albite in a pale grey to flesh-coloured, aphanitic matrix of quartz and feldspar. Only fresh grey matrix material was used for the analysis.

The significance of the quartz monzonite age is discussed in Chapter III.

Ages of volcanic rocks span the time interval from the early first cycle pyroclastic eruptions to the late stage emplacement of the ring dyke. The dates, which range from 50 to 51 ± 3 m.y., suggest that the two complete cauldron-subsidence cycles could have taken place within a time span of less than one m.y., in middle Eocene time.

Until this study no radiometric dates had been obtained from rocks of the Sloko volcanic province. Other workers (Aitken, 1959, p. 68; Wheeler, 1961, p. 85; Douglas et al., 1970, p. 478, 504) on the basis of stratigraphic and structural evidence, considered the rocks to be Cretaceous or early Tertiary in age. According to Souther (1970, p. 559) the acidic volcanism of the Sloko volcanic province began in early Tertiary time, reached a climax in the Eocene Epoch, declined and ceased before the beginning of the Oligocene Epoch. The radiometric dates presented in this study support Souther's conclusions and indicate the Bennett Lake complex is an example of one of the short lived violently explosive eruptive centres that spewed out large volumes of pyroclastic debris, then ceased eruption abruptly. The complex is an erosion remnant of one of several centres in the Sloko volcanic province that erupted vast sheets of ignimbrite in north-central British Columbia during early Tertiary time.

REGIONAL TECTONIC HISTORY

Souther (1970, p. 566) offered the following explanation for the ultimate origin of early Tertiary volcanism (i.e., the Sloko volcanic province) in the western Canadian Cordillera in terms of Pacific crust spreading eastward relative to North America and sinking beneath the continental margin. In early Mesozoic time a highly mobile eugeosyncline, associated with andesitic island arcs and a deep root-zone of sialic crust was undergoing regional metamorphism. This environment was formed and maintained by the underflow of oceanic crust beneath the edge of the continent along an inclined Benioff zone. Intermediate calc-alkaline magma of the type that dominated Mesozoic volcanism and plutonism in western Canada (Green and Ringwood, 1966; McBirney, 1969; Hamilton, 1969) was generated within or directly above such Benioff zones. "Rapid uplift accompanied by east-west regional extension and block faulting in early Tertiary time may reflect a decrease in the rate of underflow, allowing rebound of the gravitationally unstable root-zone". The base of the root-zone underwent partial if not complete melting during the initial stages of uplift and relaxation. Vast quantities of salic magma were produced and rose passively to the surface to form the high-level early Tertiary intrusions and related explosive volcanism in the Sloko province. The termination of salic, calc-alkaline effusion in the Eocene Epoch presumably resulted from cessation of underflow of the oceanic crust.

CHAPTER VIII

SUMMARY AND CONCLUSIONS

The Bennett Lake cauldron subsidence complex is part of the Sloko volcanic province, which in the study area consists mainly of rhyolite to dacite ash-flow tuffs and breccias with subordinate rhyolite, dacite and andesite lavas. The volcanic and sedimentary rocks constitute seven formations (Partridge Lake, Cleft Mountain, Gault, MacAuley Creek, Lemieux Creek, Jones Creek and Boudette Creek Formations) and two informal units (Crozier Breccias and Crozier Tuffs and Lavas), six varieties of the surrounding granitic rocks have been distinguished.

The following account summarizes the interpretation of the complex and Figure 53 depicts the main stages of the volcanic and structural evolution.

The early Tertiary was a time of passive, high-level intrusion of salic, calc-alkalic magma along the eastern margin of the Coast Mountains. Regional tumescence above a high-level magma chamber distended the overlying granitic rocks and generated concentric and radial fractures. The magma chamber developed a cupola along one side of the concentric fracture system (Fig. 53A). With the initial emplacement of the magma, temperature and pressure gradients were established in the magma chamber. Water and alkalis diffused in the magma and they gradually collected and became concentrated in the upper and outer parts of the cupola, the regions of lowest pressure and temperature. The top of the magma chamber thus became enriched in Si, K, and water and other volatiles and a host of minor elements including Pb and (?) Cu, whereas the lower parts of the magma became increasingly richer in Ca, Mg, Al and Sr. This transfer of constituents (probably aided by crystal accumulation in deeper levels) produced a vertically zoned magma chamber with rhyolitic liquid at the top and andesitic liquid in lower parts.

When gas-charged magma moved into the ring-fracture zones, mainly along the northern and eastern margins of the present complex, the sudden release of gases shattered and brecciated the surrounding granitic rocks. With breaching of the overlying rocks, the gases escaped and carried the brecciated rock upward to form intrusive breccias, some of which reached the surface to form breccia flows. The explosions which followed skimmed the gas-charged magma from the top of the chamber and erupted it at the surface to form a rapid succession of voluminous pyroclastic flows (Fig. 53B). There were three episodes of eruption (represented by the three members of the Partridge Lake Formation) each consisting of several ash flows, many of which were directed south- and southwestward. Quiet effusion of lavas interrupted the last two eruptive episodes.

Evacuation of the upper part of the magma chamber by the previous eruptions was followed by caldera collapse (Fig. 53C). A large, intact, oval block subsided along the ring-fracture system. Concomitant with the major subsidence an arcuate graben with a horst at its eastern end formed along the northeastern part of the caldera floor. Subsidence began before the previous volcanic activity ceased; fluidized rock-falls avalanched down from the growing caldera walls and locally mixed with erupting ash flows. The over-all collapse probably took place as a series of subsidences, following each of the three eruptive episodes. Pyroclastic cones, built above the ring-fracture system were partly destroyed during caldera collapse.

Eruptions from vents along the northeast caldera wall deposited ash flows and lavas which almost filled the arcuate graben to form the Cleft

Mountain Formation (Fig. 53C). Further sinking of the cauldron blocks probably followed these graben-filling eruptions, and magma varying from dacite to andesite rose along the bounding fractures, locally escaping to the surface as lava flows.

During a subsequent period of general volcanic and structural quiescence, avalanches from the unstable caldera walls deposited piles and sheets (up to 200 m thick) of granitic rubble on the caldera floor (Fig. 53D), and silt and sand accumulated in the lake which occupied the partly filled arcuate graben (Gault Formation). Towards the end of this period of erosion streams issuing from southern highlands deposited alluvial fans above the landslide rubble.

Diffusion of volatiles and alkalis in the magma chamber again produced vertical compositional zonation and build-up of vapour pressure in the upper regions. Restoration of pressure in the magma chamber may have caused arching of the roof rocks and generation of the inner ring-fracture system. Minor disturbances related to this arching possibly caused the slumping of soft sediments in the lake.

A series of explosive eruptions from vents along the inner ring-fracture system deposited a pile of voluminous ash flows with total thicknesses up to 700 metres (MacAuley Creek Formation, Fig. 53E). Southeast of Partridge Lake the ash flows first filled in troughs of the very irregular, block-faulted granitic terrain then formed flat-lying sheets. Shocks related to these eruptions set off landslides which avalanched down from the southeast caldera walls.

A second episode of caldera collapse took place along the inner ring-fracture system (Fig. 53F). A subcircular block settled progressively downwards (probably following successive voluminous ash-flow eruptions) to form a series of arcuate steps along the northern side. Avalanches from the gradually rising, unstable, inner caldera walls began intermittently during the early stages of caldera collapse, which overlapped the last events of ash-flow eruption. The bulk of epiclastic caldera fill (the Lemieux Formation) was deposited after cauldron subsidence. It consisted of thick sheets of granitic avalanche rubble on the caldera floor, and thick wedges of volcanic-granitic fragment rubble, scree and talus in local depressions along the western caldera rim. Silt and sand accumulated in a long narrow lake along the western margin of the inner caldera, and streams issuing from southern highlands deposited alluvial fans between stages of avalanching.

Gradual build-up of magma pressure in the underlying chamber possibly reopened some of the previous fractures along which magma escaped to produce a variety of eruptive products (Jones Creek Formation and Crozier Tuffs and Lavas, Fig. 53G). The eruptive series began with the effusion of lavas (andesite to dacite in the southern and eastern parts of the area, but rhyolite in the northern parts) followed by alternating eruption of rhyolite lavas and ash flows. In effect, these effusions degassed and released the pressure in the magma chamber. Rhyolite and dacite dykes sealed fissures along the inner ring-fracture zone. Ash and dust settled in several small lakes which formed in depressions in the irregular topography dominated by landslide, lava and ash-flow deposits.

A final upsurge of the magma (which by this time was probably a crystal-liquid mush) beneath the inner cauldron block arched the roof of the magma chamber into a broad dome (Fig. 53H). The accompanying radial faults and a major northeast-trending graben disjointed the dome into a mosaic

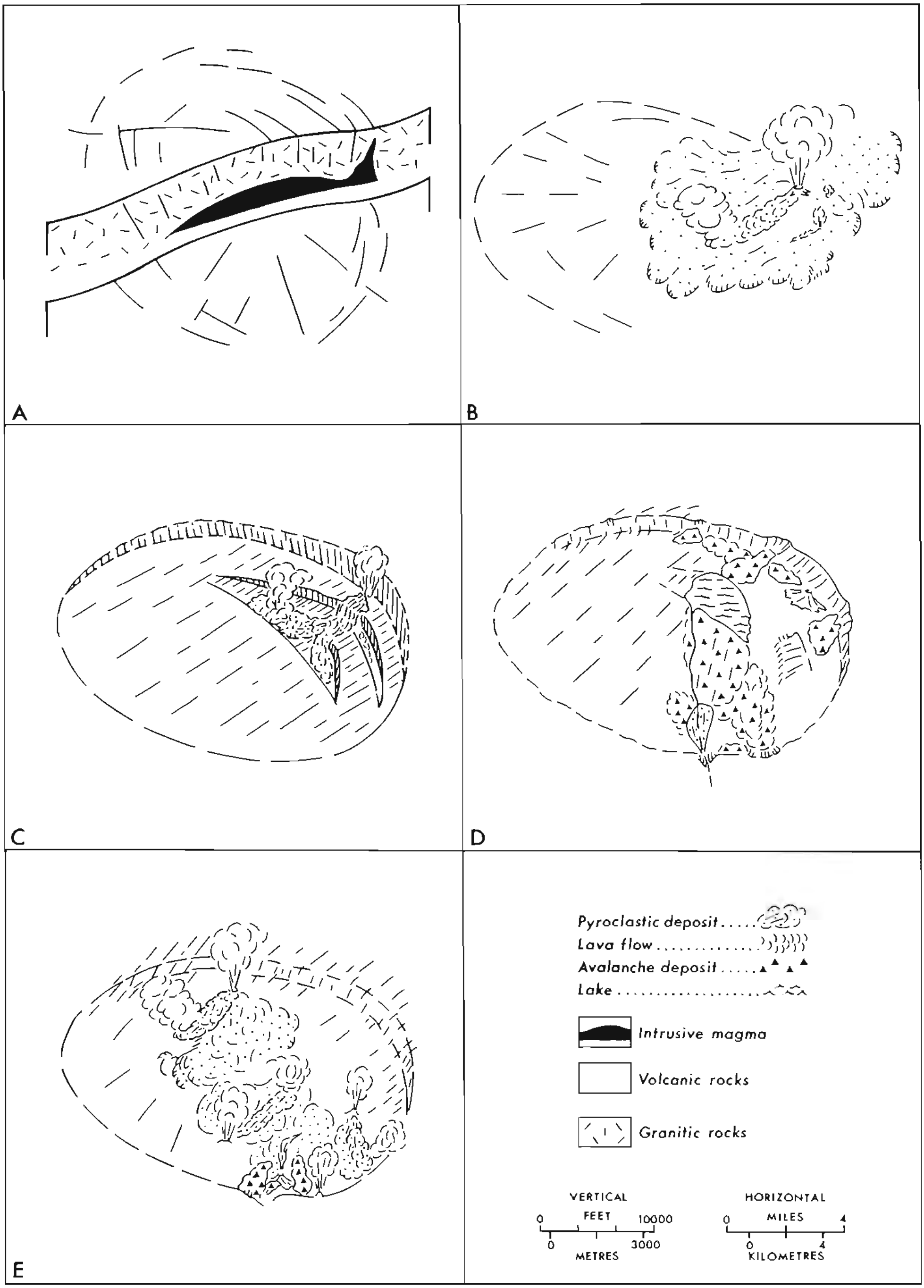


Figure 53. Sketches showing the main stages in the evolution of the Bennett Lake cauldron subsidence complex. A, Regional tumescence. B, First cycle major ash-flow eruptions. C, Caldera collapse and post-subsidence volcanism. D, Epiclastic caldera fill. E, Second cycle major ash-flow eruptions. North is toward the top of each sketch.

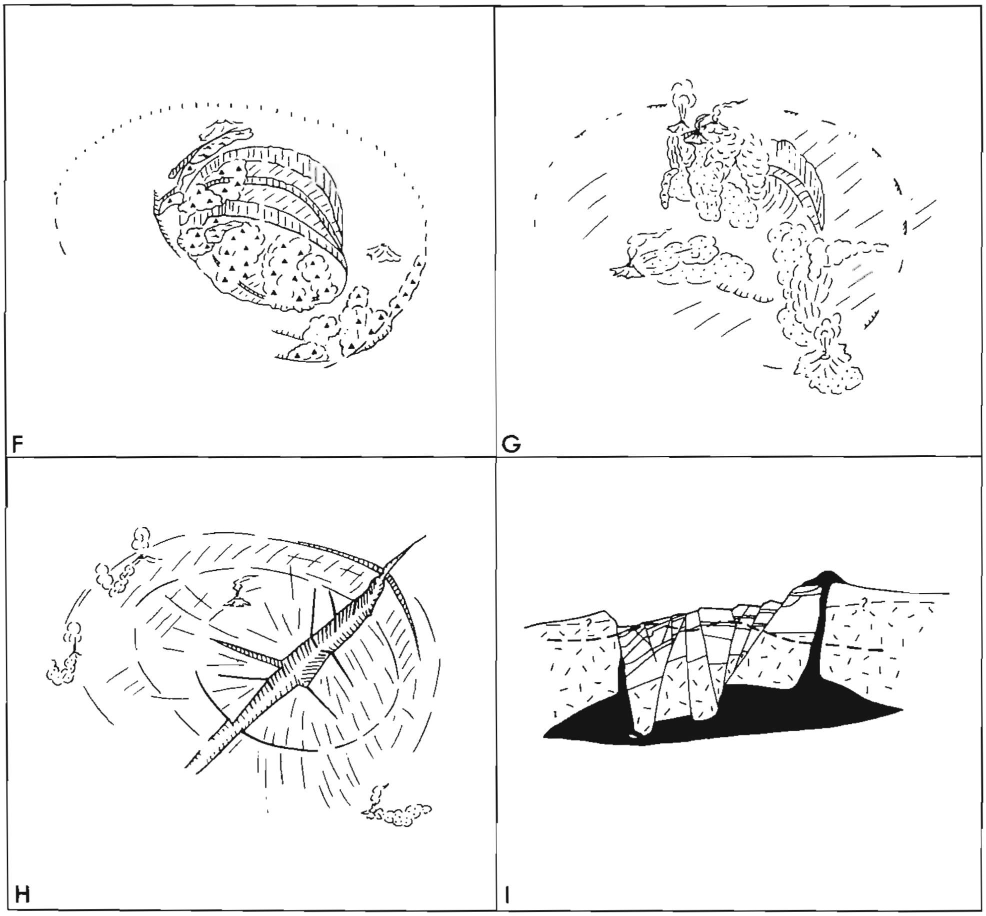


Figure 53 (cont.) F, Caldera collapse and sedimentary fill. G, Post-subsidence volcanism. H, Resurgent doming. I, Resorted northeast-southwest (right to left) cross-section showing emplacement of the ring dyke and present level of erosion (dashed line).

of radially dipping segments. Magma leaking along concentric and radial fractures erupted as ash- and lava-flows from several vents along the western and southern parts of the complex (Boudette Creek Formation). Domes formed at the surface in some of these centres.

The partly crystalline rhyolite magma intruded along peripheral ring fractures, which opened up during the resurgent doming, to form a large ring dyke. Some of the magma reached the surface and formed domes along the northern part of the complex. Hydrothermal alteration of volcanic units near the most recent eruptive centres suggests that fumarolic activity prevailed during the dying stages of the volcano.

In summary, this complex underwent two resurgent-cauldron cycles. During both a central block subsided essentially intact whereas the margins settled in a series of arcuate steps with progressively lower elevations towards the centre. Ash flows and avalanches accompanied the early stages of subsidence of the inner caldera block. Probably only slight arching of the cauldron block took place at the end of the first cycle in contrast to the pronounced resurgent doming of the second cycle.

Within each cycle the volume of erupted pyroclastic material decreased sharply following the early cataclysmic eruptions. The total volume of volcanic and sedimentary material preserved within the cauldron-subsidence complex is estimated to be about 420 cubic kilometres (100 cubic miles). It is not known how much material was deposited outside of the complex.

The gradual compositional change of eruptive products from salic to mafic with time is interpreted as successive tapping of a vertically zoned magma chamber during each eruptive cycle.

Potassium-argon dates of volcanic rocks indicate that the complex is of mid-Eocene age and that the two resurgent cauldron cycles may have taken place within a time span of less than one million years.

The petrochemical discussion (Chapter VI) is limited by the incomplete nature of the chemical data. Further chemical and petrologic studies therefore, are required to permit detailed analysis of the magmatic evolution.

Investigations of cauldron subsidence phenomena in this part of the Cordillera, however, should not be limited to this complex. Detailed study, for example, of outcrops of the Skukum Group in the vicinity of Mount Skukum (about 15 km north of this complex) may reveal another cauldron subsidence complex closely related in time to the Bennett Lake complex. Furthermore, if the Sloko volcanic province, with its tremendous volumes of salic pyroclastic material, can be likened to other dominantly salic volcanic fields in south-central United States and Mexico, there may be a multitude of calderas yet to be discovered which were the eruptive centres of the Sloko volcanic rocks.

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APPENDIX I

Mode and texture of granitic rocks from
the Bennett Lake cauldron subsidence complex

APPENDIX II

Chemical composition of volcanic and plutonic
rocks of the Bennett Lake complex

APPENDIX I

Mode and texture of granitic rocks from Bennett Lake Cauldron Subsidence Complex

Name and Specimen No.		Texture	Quartz	Plagioclase	Potassic Feldspar
Code number in Figure 11 in parenthesis		f fine grained m medium grained c coarse grained ph porphyritic hy hypidiomorphic granular al allotriomorphic granular	py pyramidal crystals	n normal zoning z oscillatory zoning bz broad cores with oscillatory margins my myrmekite at margins s strongly altered sa saussauritized	pt perthitic px phenocryst g graphic intergrowth tb turbid alteration mi microcline twinning B Baveno twins cb Carlsbad twins
Leucocratic granite					
06097	(1)	m-c, hy	43.7	0.3	55.1pt
01147	(2)	m-c, hy	48.8py	1.0	48.8mi, pt
8702b7	(3)	m, al	41.5	2.7	54.1g
01119	(4)	c, al	37.7	8.2	53.2B, cb, pt
Hornblende biotite quartz monzonite					
1509b8	(5)	f, hy	38.6	26.9my	29.4mi, pt
2703a7	(6)	m, hy	31.3	33.8	32.9mi, pt
88138	(7)	m-c	31.1		
28107	(8)	m-c	26.3	38.3	31.3
31058	(9)	m, hy	28.3	40.6n	26.9pt
8814a8	(10)	m-c, ph	28.5	37.9	23.0
16048	(11)	m, hy	30.1	39.4z	24.4pt
88128	(12)*	m-c	31.9	42.0	24.4
08078	(13)*	m, hy	29.9	38.2z	24.0mi, pt
94078	(14)*	m, hy	28.0	42.1my	19.5mi
87128	(15)	m, hy	26.9	49.2n	19.3mi
312048	(16)	m-c, hy	30.9py	47.7	15.9mi, pt
Fine-grained biotite quartz monzonite					
34337	(17)	f, hy	27.3	40.6z	22.4pt
31177	(18)*	f, hy	25.3	39.8n, z	27.8tb, pt
Pink quartz monzonite					
08087	(19)	m	24	17.7	55.1pt, g
1507a7	(20)	m	21.1	33.0n	40.3pt
02047	(21)	m	17.8	51.2	15.0
04027	(22)	m, hy	16.5	38.2sa	37.3pt
Biotite granodiorite					
01129	(23)	m	28.3	44.6z	15.7mi, pt
8710a8	(24)	m, hy, ph	28.2	49.4my	14.7
24138	(25)	m, hy	28.4	55.0	7.7
30127	(26)*	m, hy	18.1	50.7z	8.2mi, pt
59188	(27)	m, hy	13.0	59.9	20.6mi, pt
Hornblende granodiorite					
1210a7	(28)	m, hy	10.3	49.2	25.6
27077	(29)	m, hy	13	52.4	16.7
72048	(30)	m, hy	18.8	50.4	16.8
01019	(31)	m,	23.0	48.0z	22.0mi
27067	(32)	m, ph	23.4	44.6	11.9px
81048	(33)	m, hy	16.6	55.7my, bx	6.3
75018	(34)*	m, hy	15.6	58.9	8.1
63068	(35)*	f-m, hy	15.2	57.1	4.0
7305b8	(36)	f-m, hy	7.8	62.0bz	--

Location of specimens in Figure 7.

Pyroxene in trace amounts occurs in specimens 13 and 32.

Appendix I (cont'd)

Name and Specimen No.	Biotite	Hornblende	Chlorite	Opaque	Accessory	Anorthite content of Plagioclase
Code number in Figure 11 in parenthesis			b replacing biotite h replacing hornblende	mg magnetite hm hematite	a allanite p apatite e epidote c calcite s sphene z zircon	
Leucocratic granite						
06097 (1)	--	--	0.5b	0.4hm,mg	--	?-20
01147 (2)	0.3	--	tr.	hm,mg	--	?-30
8702b7 (3)			0.4	tr.	1.2z,c	
01119 (4)	0.6	--	0.7(b)	0.2	--	6
Hornblende biotite quartz monzonite						
1509b8 (5)	4.9	--	--	tr.mg	0.2p,z,s	20-31
2703a7 (6)	2	--	tr.	tr.mg, hm	tr.	27-31
88138 (7)	1	--	5	.2mg	.2p,z	32
28107 (8)						
31058 (9)	--	--	4.2b	tr.mg, hm	tr.z,p,e	0-20
8814a8 (10)	4.6	3	3.6	tr.mg	0.6p,c	32
16048 (11)	4.9	1.2	--	tr.mg, hm	tr.p,z	21-36
88128 (12)*	--	--	1.2	tr.mg	0.5s	24-31
08078 (13)*	7.2	0.3	0.4	tr.	tr.p,z	24-33
94078 (14)*	6.0	4.6	0.8b	tr.	tr.p,z,s	24-34
87128 (15)	--	--	2.9	tr.	1.7e,s	22-31
312048 (16)	4.7	0.8	tr.b	tr.	tr.p,e,s	22-38
Fine-grained biotite quartz monzonite						
34337 (17)	9.1	--	0.3	0.1mg	0.2z,p	23-41
31177 (18)*	6.9	tr.	0.1	0.1mg	tr.z,p	21-40
Pink quartz monzonite						
08087 (19)	--	--	7.9b	2.9	4.2e	2-35
1507a7 (20)	--	--	4.8b	0.8	0.2	32
02047 (21)	2.4	5.6	4.6b	2.6	3.7e	20-32
04027 (22)	0.1	--	6.3b	1.0mg	0.6p,z	26-30
Biotite granodiorite						
01129 (23)	7.0	--	3.0	0.5	0.9e,p,z,s,a	25-28
8710a8 (24)	5.3	1.8	--	tr.mg	0.6s,c,p,z	25-40
24138 (25)	4.9	2.2	tr.	0.6mg, hm	1.2s	25-40
30127 (26)*	13.7	6.7	0.8b	0.2mg	1.6p,e,z	24-60
59188 (27)	tr.	--	2.8	0.7mg	0.2p,z,s	20-47
Hornblende granodiorite						
1210a7 (28)	tr.	tr.	8.5	1.2mg	5.2e,a,s	24-38
27077 (29)	2.7	9.5	3.4b	0.5mg	1.4z,s	24-46
72048 (30)	--	7.2	4.9h	0.9	1.0z,s,c	26-47
01019 (31)	3	--	2.0	1.0	1.0p,z,e	20-33
27067 (32)	11.1	7.1	--	0.2mg	1.6z,s	19-37
81048 (33)	--	9.1	8.4	0.7mg	2.7s	27-41
75018 (34)*	--	10.2	5.4	0.1mg	1.7s,p,e	
63068 (35)*	6.6	11.7	5.0	0.3mg	0.1p,z,s	25-46
7305b8 (36)	6.1	16.0	5.1h	2.6mg	0.4p,s	24-50

APPENDIX II

CHEMICAL COMPOSITION OF VOLCANIC AND PLUTONIC ROCKS OF THE BENNETT LAKE COMPLEX

Formation	Partridge Lake	Cleft Mountain					
Member		A					
Specimen No.	01096	1609a7	16107	51027	5102a7	51037	51057
MAJOR OXIDES (weight per cent)							
SiO_2	69.7	67.6	61.8	61.7	63.0	63.6	59.0
Al_2O_3	14.9	16.2	15.7	15.1	14.7	14.9	15.4
Fe_2O_3	.3	1.1	1.66*	1.4	2.33*	3.85*	2.0
FeO	2.6	2.9	3.53*	3.7	2.07*	3.34	4.9
MgO	.5	.9	.7	.7	.5	.6	1.1
CaO	.9	2.0	2.7	2.6	2.1	1.9	3.8
Na_2O	3.7	4.8	4.76	4.7	4.32**	4.23**	4.4
K_2O	4.7	3.9	4.1	4.1	3.9	4.7	3.2
TiO_2	.26	.43	.66	.56	.50	.50	.76
P_2O_5	.05	.12	.15*	.16	.15*	.15*	.27
MnO	.08	.11	.14	.15	.11	.12	.16
CO_2	.6	.8		1.5			1.3
H_2O	1.1	.9		1.2			1.4
TOTAL	99.2	101.8		97.6			97.7
MINOR ELEMENTS (weight per cent except for Pb and Ga in ppm)							
Ba	.092	.30	.43	.39	.40	.38	.43
Co	NF	NF	NF	.002	NF	NF	.002
Cr	NF	NF	NF	.002	.002	.002	NF
Cu	.0064	.0039	.0035	.0048	.0054	.017	.014
Ga	50	27	24	50	50	39	20
Ni	NF	NF	NF	NF	NF	NF	NF
Pb	27	23	18	33	30	24	17
Sc	.001	.001	.0016	.0013	.0011	.0011	.0016
Sr	.009	.021	.031	.026	.028	.026	.041
V	.002	.002	.0039	.0039	.0023	.0025	.0037
Zr	.043	.05	.053	.046	.049	.060	.039
Normative composition (molecular per cent)[1]							
Quartz	24.96	16.326	10.335	10.783	17.459	14.841	9.942
Corundum	2.263	.73	.00	.00	.00	.00	.00
Orthoclase	28.726	23.009	25.260	25.541	24.707	28.696	20.030
Albite	34.328	42.988	44.516	44.445	41.560	39.204	41.807
Anorthite	4.277	9.116	9.747	8.414	9.852	8.030	13.763
Diopside	.00	.00	.888	1.024	.118	.251	1.304
Hedenbergite	.00	.00	1.660	2.232	.091	.300	2.314
Enstatite	.713	2.478	1.569	1.523	1.420	1.584	2.562
Ferrosilite	3.702	3.291	2.932	3.320	1.089	1.897	4.547
Forsterite	.00	.00	.00	.00	.00	.00	.00
Magnetite	.324	1.147	1.808	1.542	2.610	4.155	2.213
Ilmenite	.374	.598	.958	.822	.746	.719	1.121
Hematite	.00	.00	.00	.00	.00	.00	.00
Apatite	.108	.251	.327	.353	.337	.324	.598
Normative colour index	5.113	7.515	9.815	10.463	6.075	8.906	14.06
Normative plagioclase	11.1	17.5	17.97	15.90	19.12	17.00	24.5

[1]Norms calculated by the computer at the Geological Survey of Canada using program no. C60901.

Appendix II (cont.)

Cleft Mountain								Cleft Mountain
B								C
5106c7	1610a7	1611c7	1611b7	16127	1612a7	1612b7	16137	16157
58.9	59.2	60.1	62.2	62.7	60.7	60.0	59.7	58.5
15.2	15.8	15.7	15.8	15.5	15.2	15.7	15.4	15.8
2.7	2.7*	2.5	2.75*	2.7	2.13*	2.94*	3.4	2.2
4.8	3.91*	4.7	3.16*	3.2	3.47*	3.88*	3.8	5.6
.8	1.2	1.1	1.0	.9	.9	.9	.9	1.7
4.1	3.2	3.5	2.9	2.8	2.8	3.7	3.6	4.4
4.2	4.35**	4.5	4.64**	4.9	4.91**	4.25**	4.3	3.9
3.1	3.4	3.4	3.7	3.9	3.7	3.4	3.3	3.2
.79	.78	.74	.65	.60	.66	.73	.74	.81
.28	.2*	.28	.15*	.20	.20*	.25*	.34	.32
.15	.17	.17	.15	.14	.16	.17	.17	.18
1.1		.9		1.2			.8	.1
1.4		1.3		1.3			.9	2.3
97.5		98.8		100.0			97.4	98.9
.37	.36	.38	.42	.46	.44	.42	.47	.35
.002	.002	NF	NF	NF	NF	NF	NF	.002
.002	NF	NF	NF	NF	NF	NF	.002	.002
.0057	.008	.0054	.0045	.0041	.0048	.0062	.0046	.0040
49	44	50	41	50	35	35	24	35
NF	NF	NF	NF	NF	NF	NF	NF	NF
24	24	28	25	20	14	21	18	20
.0019	.0016	.0018	.0016	.0014	.0017	.0014	.0021	.0018
.039	.037	.043	.035	.031	.036	.037	.044	.054
.0036	.0031	.0034	.0023	.0023	.0026	.0020	.0035	.0058
.044	.047	.051	.059	.044	.056	.034	.046	.039
11.789	10.982	10.22	12.384	11.381	10.079	12.141	12.746	9.550
.00	.00	.00	.00	.00	.00	.00	.00	.00
19.502	21.282	20.914	22.589	23.665	23.049	21.147	20.594	19.764
40.108	41.333	42.019	43.001	45.134	46.430	40.126	40.734	36.565
14.320	14.330	13.098	11.717	9.002	8.955	14.424	13.684	16.867
1.375	.433	.951	.925	1.572	1.498	1.344	1.069	1.279
2.920	.438	1.495	.773	1.556	1.942	1.737	1.184	1.716
1.661	3.290	2.683	2.387	1.763	1.868	1.941	2.087	4.261
3.528	3.332	4.218	1.996	1.745	2.423	2.509	2.313	5.717
.00	.00	.00	.00	.00	.00	.00	.00	.00
3.002	2.987	2.718	2.968	2.896	2.346	3.232	3.751	2.402
1.171	1.150	1.072	.935	.858	.968	1.069	1.088	1.178
.00			.00	.00	.00	.00	.00	.00
.624	.443	.610	.324	.430	.441	.330	.751	.700
13.66	11.630	13.138	9.984	10.389	11.045	11.832	11.491	16.554
26.4	25.8	23.8	21.45	16.65	16.15	26.5	25.12	31.58

Analyses by the Geological Survey of Canada except as noted:

* Analyzed by C. Murray, Carleton University.

** Values stated multiplied by 1.2 to accord with those of G.S.C.

Appendix II (cont.)

Formation	Cleft Mountain			MacAuley Creek			
Member	C		D	B			
Specimen No.	5106b7	5106d7	08088	22087	2209a7	2209c7	2209g7
MAJOR OXIDES (weight per cent)							
SiO_2	58.5	57.5	64.0	66.5	67.3	66.8	67.1
Al_2O_3	15.4	14.9	15.0	15.2	15.5	15.6	15.4
Fe_2O_3	2.12*	1.66*	1.0*	2.1	1.6	1.5	1.6
FeO	5.17*	5.33	3.80*	2.8	3.3	2.9	2.6
MgO	1.9	1.6	.6	2.2	1.4	2.4	1.5
CaO	5.4	4.1	2.2	2.4	1.8	1.7	1.5
Na_2O	3.37**	4.62**	5.03**	4.2	3.4	3.3	3.4
K_2O	2.9	3.2	4.0	1.4	3.9	3.9	3.9
TiO_2	.87	.92	.51	.49	.46	.43	.43
P_2O_5	.25*	.30*	.1*	.11	.11	.10	.09
MnO	.18	.18	.12	.13	.12	.10	.10
CO_2				1.2	.8	.7	.6
H_2O				1.5	1.0	.6	.9
TOTAL				100.2	100.7	100.0	99.1
MINOR ELEMENTS (weight per cent except for Pb and Ga in ppm)							
Ba	.26	.31	.49	.20	.22	.23	.18
Co	.002	.002	NF				
Cr	.002	.002	.002	.026	.027	.022	.023
Cu	.0064	.0058	.013				
Ga	37	23	46				
Ni	NF	NF	NF				
Pb	23	18	23				
Sc	.0018	.0019	.0014				
Sr	.047	.031	.032	.030	.029	.023	.023
V	.0064	.0055	.002	.0028	.0030	.0029	.0023
Zr	.042	.039	.063	.0034	.0088	.0041	.0051
Normative composition (molecular per cent)[1]							
Quartz	12.243	6.355	11.870	26.081	23.695	22.738	24.733
Corundum	.00	.00	.00	3.012	2.982	3.442	3.463
Orthoclase	18.077	20.095	24.492	8.539	23.570	23.492	23.825
Albite	31.888	44.040	46.751	38.888	31.192	30.175	31.530
Anorthite	19.315	11.110	6.760	11.539	8.391	7.924	7.079
Diopside	2.785	2.824	.809	.00	.00	.00	.00
Hedenbergite . . .	2.975	3.901	2.281	.00	.00	.00	.00
Enstatite	4.135	3.278	1.310	6.264	3.949	6.748	4.277
Ferrosilite . . .	4.417	4.527	3.692	2.470	3.622	3.061	2.552
Forsterite	.00	.00	.00	.00	.00	.00	.00
Magnetite	2.336	1.843	1.082	2.264	1.709	1.597	1.728
Ilmenite	1.277	1.361	.736	.704	.655	.610	.619
Hematite	.00	.00	.00	.00	.00	.00	.00
Apatite	.552	.667	.217	.238	.235	.213	.195
Normative colour index . .	17.926	17.733	9.910	11.702	9.935	12.016	9.176
Normative plagioclase . .	37.70	20.15	12.61	22.9	21.2	20.8	18.32

[1] Norms calculated by the computer at the Geological Survey of Canada using program no. C60901.

Appendix II (cont.)

MacAuley Creek			Jones Creek	Boudette Creek		Ring Dyke		Dykes
B								
2210b7	2211c7	57038	19038	47138	49138	13147	95017	250218
66.6	68.0	66.4	72.0	70.2	68.4	73.3	70.5	78.2
15.6	15.7	14.3	13.5	13.5	13.9	14.1	15.0	11.8
.3	1.2	1.6	.32*	.53*	1.6		.8	.52*
3.7	3.4	2.6	1.52*	1.67*	2.3	2.54*	1.3	.88*
.8	1.5	.5	.5	.5	.7	.5	.5	.5
1.5	1.9	1.9	.9	1.1	.8	.2	1.2	.4
3.6	3.4	5.0	4.94**	3.80**	4.7	4.59**	5.0	2.52**
3.5	3.9	4.1	4.1	4.7	4.0	4.8	3.9	5.2
.41	.42	.40	.20	.27	.37	.14	.20	.13
.08	.08	.08	.1*	.05*	.09		.03	.05*
.11	.13	.12	.05	.06	.10	.03	.05	.04
.5	.7	1.1			.1		.1	
1.4	.9	.6			.9		.4	
98.1	101.2	98.2			98.0		99.0	
.18	.25	.40	.039	.14	.26	.12	.22	.088
		NF	NF	NF	NF	NF	NF	NF
.028	.023	NF	.002	.002	NF	NF	NF	NF
		.0048	.016	.0085	.0076	.0074	.022	.0051
		31	50	47	31	46	47	40
		NF	NF	NF	NF	NF	NF	NF
		21	26	36	22	26	19	31
		.0012	NF	.001	.001	NF	NF	NF
.025	.023	.018	.006	.013	.016	.043	.016	.019
.0028	.003	.002	.002	.002	.002	NF	NF	.002
.014	.003	.039	.037	.044	.051	.025	.039	.040
24.562	23.469	16.257	22.969	25.203	21.161		21.131	39.282
3.834	2.897	.00	.00	.316	.673		.486	1.750
21.694	23.365	25.068	24.467	28.999	24.450		23.320	31.294
33.872	30.920	46.406	45.080	35.590	43.609		45.384	23.021
7.251	9.019	4.609	2.586	5.353	3.494		5.821	1.686
.00	.00	.785	.429	.00	.00		.00	.00
.00	.00	2.892	.601	.00	.00		.00	.00
2.314	4.195	.321	1.188	1.440	1.997		1.396	1.405
5.370	4.102	1.184	1.663	2.019	2.159		1.270	.898
.00	.00	.00	.00	.00	.00		.00	.00
.329	1.271	1.729	.340	.578	1.729		.846	.553
.599	.593	.576	.283	.392	.533		.282	.184
.00	.00	.00	.00	.00	.00		.00	.00
.176	.170	.173	.213	.109	.195		.064	.107
8.612	10.160	7.487	4.504	4.430	6.418		3.793	3.040
17.62	22.6	9.03	4.497	13.10	7.42		11.37	6.83

Analyses by the Geological Survey of Canada except as noted:
*Analyzed by C. Murray, Carleton University.
**Values stated multiplied by 1.2 to accord with those of G.S.C.

Appendix II (cont.)

Formation	Dykes						
Member							
Specimen No.	29028	30088	49018	49028	49038	53168	5706b8

MAJOR OXIDES (weight per cent)

SiO_2	74.6	74.1	74.3	75.5	74.7	74.9	74.4
Al_2O_3	12.4	13.1	13.5	13.2	13.4	13.4	13.4
Fe_2O_3	.32*	.8	.33*	1.0	.7	.57*	1.1
FeO	.88	.7	.47	.5	.7	1.03*	.4
MgO	.5	.5	.5	.5	.5	.5	.5
CaO	.3	.2	.3	.1	.3	.5	.3
Na_2O	3.9**	4.4	3.25**	4.5	4.7	4.33**	4.5
K_2O	5.1	5.1	3.4	5.0	5.0	3.5	3.4
TiO_2	.12	.13	.15	.13	.13	.19	.13
P_2O_5	.05*	.02	.05*	.02	.02	.05*	.02
MnO	.04	.03	.03	.02	.02	.05	.03
CO_2		.1		.1	.1		.2
H_2O		.4		.5	.4		.4
TOTAL		99.1		100.5	100.5		98.1

MINOR ELEMENTS (weight per cent except for Pb and Ga in ppm)

Ba	.012	.0088	.0062	.008	.0081	.034	.0079
Co	NF	NF	NF	NF	NF	NF	NF
Cr	NF	NF	NF	NF	NF	NF	NF
Cu	.0062	.0069	.011	.012	.0093	.011	.0071
Ga	39	24	50	50	40	15	44
Ni	NF	NF	NF	NF	NF	NF	NF
Pb	25	19	25	24	21	18	21
Sc	NF	NF	NF	NF	NF	NF	NF
Sr	NF	NF	NF	.002	NF	.0052	NF
V	NF	NF	.002	NF	NF	.002	NF
Zr	.033	.047	.039	.027	.031	.025	.036

Normative composition (molecular per cent)[1]

Quartz	28.977	26.280	39.864	27.435	25.155	32.047	32.580
Corundum	.038	.00	4.634	.244	.00	1.88	1.788
Orthoclase	30.870	30.582	21.101	29.582	29.587	21.014	20.675
Albite	35.834	40.052	30.618	40.414	42.219	39.464	41.538
Anorthite	1.188	.932	1.219	.431	.688	2.186	1.463
Diopside	.00	.004	.00	.00	.362	.00	.00
Hedenbergite . . .	.00	.002	.00	.00	.226	.00	.00
Enstatite	1.413	.698	1.448	.690	.509	1.401	.710
Ferrosilite . . .	1.060	.397	.207	.00	.318	1.027	.00
Forsterite	.00	.00	.00	.00	.00	.00	.00
Magnetite	.342	.848	.581	.194	.732	.605	.749
Ilmenite	.171	.184	.219	.181	.181	.269	.186
Hematite	.00	.00	.00	.088	.00	.00	.289
Apatite	.107	.021	.110	.021	.021	.106	.022

Normative colour index . .	2.986	2.13	2.456	1.87	2.33	3.302	1.93
Normative plagioclase . .	3.21	2.275	3.822	1.05	1.602	5.26	3.41

[1]Norms calculated by the computer at the Geological Survey of Canada using program no. C60901.

Appendix II (cont.)

Granodiorite					Quartz Monzonite			Leucocratic Granite
30127	3107a7	69097	75017	63068	08078	88128	94078	31178
62.8	55.7	57.2	60.9	59.1	70.9	68.3	64.1	71.6
17.4	19.1	19.8	17.6	17.8	15.7	15.1	16.6	14.6
1.03*	1.35*	1.25*	3.6*	1.5	1.0 *	1.0	.6	.6
3.97*	5.24*	3.86*	3.68*	3.7	3.16*	1.8	2.5	2.1
2.2	4.3	2.4	2.9	3.8	.8	1.6	1.5	.5
4.9	7.2	4.9	5.4	6.2	2.5	2.3	3.5	1.6
4.24**	4.57**	3.24**	4.57**	4.5	2.98**	4.8	4.4	4.6
2.7	2.0	2.3	2.9	1.5	3.5	2.8	3.0	3.9
.76	.94	.78	.54	.59	.39	.41	.47	.30
.15*	.25*	.2*	.2*	.18	.15*	.13	.19	.09
.11	.13	.07	.11	.10	.05	.12	.07	.06
				.1		.1	.1	.1
				.8		1.1	.7	.3
				99.8		99.6	97.6	100.4
.18	.16	.17	.13	.092	.16	.095	.17	.20
.002	.002	.002	.002	.002	NF	NF	NF	NF
.002	.002	NF	.002	.002	.002	.002	.002	.002
.0066	.0063	.0062	.0092	.014	.006	.0064	.007	.0053
50	27	50	25	12	33	41	29	34
NF	.002	.002	NF	.002	NF	NF	NF	NF
24	13	16	10	11	20	23	24	21
.001	.0016	NF	.0011	.001	.001	NF	.001	NF
.062	.074	.078	.059	.054	.045	.044	.055	.026
.0077	.021	.016	.018	.023	.034	.0029	.0058	.002
.019	.018	.078	.023	.014	.018	.015	.029	.029
11.627	.00	13.325	9.289	7.215	23.967	20.436	15.452	22.861
.00	.00	4.04	.00	.00	1.628	.333	.330	.126
15.906	11.592	14.181	11.046	8.875	20.445	16.772	18.220	23.118
37.918	40.207	30.325	41.918	40.415	35.291	43.645	40.570	41.391
20.391	25.184	23.982	20.733	23.953	11.282	10.697	16.559	7.367
1.304	4.352	.00	2.604	3.264	.00	.00	.00	.00
.976	2.226	.00	.850	1.251	.00	.00	.00	.00
5.398	6.720	6.907	6.567	8.862	2.181	4.473	4 .253	1.383
4.040	3.437	4.307	2.143	3.397	3.687	1.731	2.988	2.517
.00		.00	.00	.00	.00	.00	.00	.00
1.073	1.383	1.362	3.7	1.569	1.033	1.059	.644	.629
1.055	1.283	1.133	.739	.822	.537	.578	.672	.419
.00	.00	.00	.00	.00	.00	.00	.00	.00
.313	.513	.437	.412	.377	.310	.276	.409	.189
13.845	22.504	13.710	16.603	19.166	7.438	7.841	8.558	4.948
34.95	38.55	44.1	33.1	37.25	24.22	19.7	29.9	15.1

Analyses by the Geological Survey of Canada except as noted:

*Analyzed by C. Murray, Carleton University.

**Values stated multiplied by 1.2 to accord with those of G.S.C.

APPENDIX III

Measured Sections

A. Gault Formation
B. Lemieux Creek Formation
C. Jones Creek Formation
D. Crozier Subarea

APPENDIX IIIA - GAULT FORMATION

(Location of sections shown in Fig. 18)

SECTION GI

Unit	Lithology	Thickness in feet (metres)* Unit	Height from base
4	Conglomerate, granitic, sharpstone, massive; boulders, biotite quartz monzonite, angular to rounded, smaller boulders and cobbles angular; matrix pale green medium- to coarse-grained grit.	40 (12.4)	530 (161.5)
3	Covered with talus and vegetation. Probably granitic boulder conglomerate.	230 (70)	490 (149.1)
2	Conglomerate, sharpstone, granitic, greyish green; massive. Fragments, biotite quartz monzonite, range from 0.6 to 60 cm, almost all angular to subangular, rare well rounded large boulders; unsorted. Matrix grit fine- to medium-grained, pale green; composed mainly of quartz, feldspar and chloritized mafic minerals derived from granitic rocks; massive. Lower 6 m of the unit contains very few large blocks (most fragments less than 5 cm) in grit matrix.	230 (70)	260 (79.1)
1	Tuffaceous sandstone, green. Top of unit, green gritty sandstone with pebble- to cobble-size angular granitic fragments; massive. Base of unit, sandstone, tuffaceous (?), greyish green, finely bedded. Top of this unit gradational with base of unit.	30 (9.1)	30 (9.1)

*Metric conversions approximate to one decimal place.

SECTION GIV

Unit	Lithology	Thickness in feet (metres) Unit	Height from base
9	Conglomerate, granitic boulder, greyish green; massive completely gradational with cobble-rich sandstone at top of Unit 8. Sharp upper contact, overlain conformably by pale green tuff of the MacAuley Creek Formation.	22 (6.7)	735 (224.0)
8	Sandstone, greyish green, pebbly, medium- to coarse-grained; with increasing amount of granitic pebbles and cobbles upward.	42 (12.8)	713 (217.3)
7	Sandstone, greyish green, medium-grained. Lenses of pale green tuff at top of unit.	130 (39.6)	671 (204.5)
6	Shale, dark grey, fissile.	5 (1.5)	541 (164.9)
5	Sandstone and conglomerate interbedded with discontinuous shale lenses. Sandstone, arkosic, pale greenish grey, fine- to medium-grained; poorly sorted; massive; shale, dark greenish grey, fissile; beds 15-45 cm thick, commonly finger out within the enclosing sandstone.	40 (12.2)	536 (163.4)
4	Shale, dark grey, fissile.	1 (.3)	496 (151.2)
3	Sandstone, green, medium-grained, poorly sorted, massive, same as matrix of underlying conglomerate.	45 (13.7)	495 (150.9)
2	Conglomerate, granite boulder, pale- to medium-grey boulders in medium-green matrix; boulders, cobbles and coarse pebbles (35-45% of the rock) granitic (coarse-grained hornblende-biotite quartz monzonite, fine-grained biotite quartz monzonite, aplite), subrounded to subangular, range from 15-100 cm (average 25 cm). Matrix grit, green, medium- to coarse-grained, composed of angular to subangular quartz, feldspars, chloritized biotite with abundant interstitial chlorite, very fine carbonate. Massive, unsorted.	310 (94.5)	450 (137.2)
1	Covered interval approximately 82 m. Thickness estimated to projected contact on the map.	140 (42.7)	140 (42.7)

SECTION GVII

Unit	Lithology	Thickness in feet (metres) Unit	Height from base
6	Siltstone, dark greenish grey, concretionary; greyish green weathering. Precise thickness not measured.	20 (6.1)	320 (97.6)
5	Breccia with interbedded siltstone. Breccia in most of the unit, dark grey, volcanic fragments composed of light green tuff, chloritized pumice and pale grey felsite, in tuffaceous matrix. Breccia near the base of the unit, same as unit 9 of section GVIII, volcanic fragments composed of trachytic and felty textured volcanic rocks, pumice, quartz, feldspar, in a tuffaceous wacke matrix. Siltstone, dark greyish green, thin beds, finely laminated, slightly undulatory; soft sediment deformation.	135 (41.2)	300 (91.5)
4	Sandstone, pale greenish grey, medium-grained, grain size increases downward into coarse sandstone with granitic fragments. Precise thickness not measured.	30 (9.1)	165 (50.3)
3	Conglomerate and interbedded sandstones. Conglomerate, granitic boulder, massive, coarse gritty sandstone matrix. Base of the unit is coarse sandstone that conformably overlies unit 2. Upper contact of this unit grades into sandstone of unit 4. Thickness of units 3 and 4 combined is 45.7 m; but precise thickness of each unit was not determined.	120 (36.6)	135 (41.2)
2	Shale, dark greyish green, fissile. This unit thins to 0.5 m about 150 m south of this section.	15 (4.6)	15 (4.6)
1	Sandstone-conglomerate sequence below unit 2, not measured.	?	?

SECTION GVIII

Unit	Lithology	Thickness in feet (metres) Unit	Height from base
10	Covered	30 (9.1)	480 (146.4)
9	Sandstone and shale interbedded in lower half of unit; sandstone greyish green, fine- to medium-grained, laminae of dark grey shale; graded bedding, both normal and reverse, scour and fill structures on small scale, microfolds (1 to 2 mm displacement); slightly recessive, fissile. Upper part of unit interbedded tuffaceous wacke and tuff. Shards in the tuff highly altered by chlorite; wacke largely quartz and feldspar fragments with some shard material between. Upper 4.6 m of exposed outcrop tuffaceous sandstone and shale, coarse-grained volcanic breccia, interbedded; sandstone and shale similar to that in lower part of the unit; abundant evidence of soft sediment deformation, small faults to 3 mm displacement, complicated small scale folds, folds within laminae less than 2 mm. These structures are most common where interbedded with coarse volcanic breccia. Volcanic breccia, spotted greenish grey, grain size ranges from dust to 5 cm; bedding indicated by variation in size of fragments; fragments subrounded to angular, of porphyritic dacite, felty textured volcanic rocks, chloritized pumice, feldspathic wacke, granite, quartzite, quartz and feldspar; matrix tuffaceous wacke -- mainly quartz, feldspar with abundant shards and pumice.	58 (17.7)	450 (137.3)
8	Siltstone, calcareous, sandy, greenish grey, fissile, with interbedded shale. Sandstone bed 10 to 15 mm with interbedded shale laminae 1 to 3 mm; graded bedding. Thin section: siltstone composed dominately of angular quartz, feldspar, chloritized mica; subordinately of volcanic fragments, dacite, spherulitic, devitrified tuff; and small amount of shards, mainly replaced by chlorite. Clay-size material between grains has abundant fine micas (mainly chlorite), carbonate, dusted with fine-grained pyrite cubes and some kaolinite.	22 (6.7)	392 (119.6)

Unit	Lithology	Thickness in feet (metres) Unit	Height from base
7	Sandstone and conglomerate interbedded; sandstone, between zero and 15.2 m from the base, medium greyish green, grey to pink granules 3 to 5 mm of granite, quartz, feldspars in green medium- to coarse-grained matrix; faint bedding suggested by rare medium-grained laminae, outcrop has blocky fracture; massive light grey-green weathering, less strongly cliff forming than unit 6; lower contact gradational with breccia below. Rock is very similar to unit 4. At 4.6 m, 1.5 m band of well-rounded, biotite quartz monzonite boulders, 0.3-0.6 m across, light grey weathering. Between 16.8 m and 33.6 m, sandstone, green, fine- to medium-grained, grain size decreases upward; poorly sorted; massive. Thin section: arkose, very poorly sorted with rare trachytic and felty textured volcanic fragments; grains equant, angular to subangular; matrix silty with abundant very fine chlorite, micaceous shreds, irregular patches of carbonate. Bedding suggested by rude preferred orientation of biotite shreds and of rare elongate fragments. Between 33.6 m and 50.3 m, conglomerate, granitic boulder, to bouldery sandstone, green, boulders in coarse-grained grit matrix (coarser than the underlying sandstone); massive, complete gradation with sandstone below, gradual increase in grain size of matrix upwards with increasing amount of cobbles and boulders. Between 50.3 m and top of unit, grit, with interbedded fine-grained sandstone; green, medium- to coarse-grained, grain size decreasing upward; bedding defined by fine-grained sandstone layers; prominent cleavage parallel to bedding.	198 (60.4)	370 (112.9)
6	Breccia, volcanic fragment, medium greenish grey, fragments from 6-50 mm in coarse sandstone matrix; massive. Fragments (35%) 85% of which are angular to subangular, of pale grey tuff and blocks up to 30 cm, partly welded, porphyritic, vapour phase crystallization, foliated and preferred orientation of elongate pumice,	81 (24.7)	172 (52.5)

Unit	Lithology	Thickness in feet (metres) Unit	Height from base
6 cont.	shards, biotite, lithic fragments; biotite gneiss (3%) less than 25 mm, subangular to subrounded, more abundant at the base of the unit than at the top; granitic fragments (7%), less than 12 mm, subrounded to subangular; quartz, feldspar, crystal fragments, less than 3 mm; variety of volcanic fragments (5%) including finely banded, spherulitic rhyolite (?) dacite, and plumose textured fragments with coarse spherulites. Matrix composed of unsorted, fine- to coarse-grained, angular to subangular fragments of same composition as larger clasts; with interstitial very fine chlorite and irregular patches of calcite; disseminated pyrite. Grey-green weathering cliff-forming unit.		
5	Sandstone and shale interbedded; sandstone, calcareous, medium greenish grey, fine- to medium-grained, poorly sorted. Thin section: arkosic wacke, very poorly sorted, bedding indicated by preferred orientation of elongate fragments and by rare discontinuous silty layers. Clasts mainly of quartz, plagioclase, potassic feldspar, brown biotite with cleavage bent around quartz and feldspars; minor granitic fragments, quartzite, felty and microporphyritic volcanic rock; all angular to subangular. Matrix, calcareous with abundant very fine chlorite, disseminated pyrite. Shale, silty, dark grey, recessive beds.	3 (.9)	91 (27.8)
4	Sandstone, green, coarse grained; very poorly sorted; bedding locally suggested by rare medium-grained sandy layers that lack abundant fragments; otherwise massive; blocky fracture with one set of joints parallel to bedding: 20-30% quartz monzonite and rare quartzite fragments, 3-35 mm (averaging 6 mm), angular to subangular, random orientation; quartz and feldspar crystal fragments less than 3 mm. Matrix fine- to medium-grained, grey-green, consists of quartz, feldspar, chloritized biotite fragments, subangular to angular; very poorly sorted, abundant interstitial chlorite, some calcite.	33 (10.1)	88 (26.9)

Unit	Lithology	Thickness in feet (metres) Unit	Height from base
3	Sandstone, medium grey-green, fine- to medium-grained, angular to subangular, very poorly sorted, thin bedded; prominent cleavage parallel to bedding; recessive; gradational contact with underlying shale; fine disseminated pyrite; abundant interstial chlorite. Thin section: composed of quartz, plagioclase, potassic feldspar, minor chloritized biotite; very poorly sorted, angular to subangular, bedding indicated by preferred orientation of elongate fragments, abundant interstitial chlorite.	2.5-3 (.7 to .9)	55 (16.8)
2	Shale, calcareous, dark greenish grey finely laminated 1-3 mm, fissile; weathers dark brownish grey; recessive. Thin section: angular to subangular quartz, feldspar; intensely altered microporphyritic volcanic rock. Wispy lenses rich in carbonate (?), otherwise calcareous material sparse.	22 (6.7)	52 (15.9)
1	Covered.	(?) 30 (9.2)	30 (9.2)
	Top and base of the formation is not exposed, but assumed positions of contacts extrapolated from map boundaries suggest total thickness of formation is about 145 m.		

APPENDIX IIIB - LEMIEUX CREEK FORMATION

(Location of sections shown in Fig. 24)

SECTION LCII

Unit	Lithology	Thickness in feet (metres) Unit	Height from base
3	Conglomerate, granitic boulder; biotite quartz monzonite boulders in green arkosic grit matrix; massive.	150 (45.8)	570 (173.8)

Unit	Lithology	Thickness in feet (metres) Unit	Height from base
2	Sandstone, cobbly to pebbly, green; some thin sandy layers; clasts generally less than 8 cm; matrix, green, coarse-grained arkose grit essentially same as in matrix of the conglomerate. This unit grades upward from pebbly sandstone at the base to cobbly sandstone at the top and into granitic boulder conglomerate of unit 3.	37 (11.3)	420 (128.0)
1	Conglomerate, granitic boulder, massive. Boulders, almost all biotite quartz monzonite, rare pale grey aplite, pale green porphyritic rhyolite, subangular to well rounded, ranging up to 50 cm across, cobbles and boulders make up to 45% of the rock. Matrix, green, arkosic grit, unsorted; massive.	383 (116.7)	383 (116.7)

SECTION LCVI

Unit	Lithology	Thickness in feet (metres) Unit	Height from base
12	Conglomerate, granitic boulder, medium greyish green; boulders range up to 1 m across and make up to 69% of the outcrops; massive. This unit is overlain conformably by tuff of the Jones Creek Formation.	99 (30.2)	585 (178.4)
11	Sandstone, pale greenish grey, medium grained massive, but local faint suggestion of bedding by preferred orientation of elongated fragments. Thin section: arkose, very poorly sorted; contains rare volcanic fragments, felty textured, micro-porphyritic, chloritized tuff and (?) pumice. Weak fabric defined by preferred orientation of slightly elongate fragments.	25 (7.6)	486 (148.2)
10	Conglomerate, granitic boulder, massive.	7 (2.2)	461 (140.6)

Unit	Lithology	Thickness in feet (metres) Unit	Height from base
9	Ignimbrite, greyish green; moderately welded, well-developed eutaxitic foliation; pumice, dark green, replaced by chlorite; matrix pale green aphanitic. Thin section: abundant pumice with very fine granular devitrification; shards almost completely replaced by chlorite; crystal fragments, angular, silt to fine sand size; few phenocrysts of plagioclase and (?) potassic feldspar.	4 (1.2)	454 (138.4)
8	Tuff, medium greyish green, fine-grained, to aphanitic. Thin section: nonwelded tuff composed of crystal fragments of quartz, plagioclase and potassic feldspar, mainly from granitic material, rare felty textured volcanic rocks, pumice, moderately altered matrix of fine shards and (?) dust. Strong preferred orientation of all elongate material including fine platy shards.	25 (7.6)	450 (137.2)
7	Conglomerate, granitic boulder.	135 (41.2)	425 (129.6)
6	Tuff, lithic, devitrified, nonwelded, well bedded. Thin section: slight to moderate alteration of fine material; made up of angular crystal fragments, mainly of quartz, potassic feldspar, plagioclase derived from granitic rocks, granitic rock fragments, and few volcanic rock fragments, surrounded by a cryptocrystalline matrix, probably devitrified dust. Air fall or (?) waterlain tuff.	2 (0.6)	290 (88.4)
5	Conglomerate, granitic boulder, massive.	38 (11.6)	288 (87.8)
4	Tuff, crystal lithic, medium brownish green, medium- to coarse-grained; poorly sorted; massive, but bedding suggested by preferred orientation of some elongate fragments. Thin section: shards with axiolitic crystallization, moderate alteration; all shards and pumice are devitrified, abundant lithic fragments (volcanic and granitic) and plagioclase crystals, and crystal fragments derived from granitic rocks.	7 (2.1)	250 (76.2)

Unit	Lithology	Thickness in feet (metres) Unit	Height from base
3	Conglomerate, granitic boulder, greyish green massive.	19 (5.8)	243 (74.1)
2	Tuff, greyish green, medium- to coarse-grained; bedding indicated by preferred orientation of elongate pumice and lithic fragments, and by alternating diffuse layers of different grain size.	12 (3.7)	224 (68.3)
1	Conglomerate, hornblende-biotite quartz monzonite boulder; boulders, angular to subrounded (few of largest boulders are well rounded) up to 50 cm in diameter, in very coarse-grained grit matrix; massive, slightly recessive compared with the overlying ignimbrites. Sandstone at base of conglomerate grades into the overlying conglomerate within 0.3 to 3 m from the base. Basal sandstone, greyish green, coarse-grained, poorly sorted; massive. Thin section: pumiceous arkose with clasts of granite, coarsely perthitic potassic feldspar, plagioclase, and quartz, 2-5% pumice and microporphyritic trachyte; angular to subangular; matrix silt to clay size particles with abundant fine micaceous (mainly chlorite) alteration. Sandstone at base conformably overlies tuff of the MacAuley Creek Formation.	212 (64.6)	212 (64.6)

SECTION LCVII

Unit	Lithology	Thickness in feet (metres) Unit	Height from base
4	Conglomerate, granitic boulder, massive.	207 (63.1)	860 (262.8)
3	Conglomerate and sandstone interbedded; conglomerate, granitic-volcanic boulder generally higher proportion of volcanic than granitic boulders, and locally about the same amount of each type.	81 (24.7)	653 (199.7)

Unit	Lithology	Thickness in feet (metres) Unit	Height from base
2	Tuff, crystal-lithic, green; plane of bedding suggested by preferred orientation of elongate pumice and some lithic fragments. Lower contact conformably overlies unit 1.	177 (54)	572 (175)
1	Conglomerate, granitic boulder; boulders all granitic for most of unit, but some volcanic boulders near top of unit.	395 (121)	395 (121)

SECTION LCIX

Unit	Lithology	Thickness in feet (metres) Unit	Height from base
6	Sandstone, granitic pebble; coarse grained, poorly sorted; pebbles and cobbles (to 7 cm) of pink to green alternating hornblende biotite quartz monzonite, subrounded to subangular, less than 5% of the rock; matrix dark green grit composed dominately of angular quartz monzonite particles, quartz, and feldspars derived from quartz monzonite, and subordinately of porphyritic dacite and pale green to pale grey felsite. Thin section: arkose, unsorted, area between grains intense green chlorite alteration and abundant carbonate as irregular veinlets and patches. Top of this unit is eroded - unit exposed for 4.9 m.	16 (4.9)	150 (45.8)
5	Conglomerate, granitic boulder, poorly consolidated; cobbles and boulders (40%) of biotite quartz monzonite, angular to well rounded, range from 3 cm to 45 cm; massive except for thin sandy layers at base of unit. Angular pink granitic breccia boulders, of unit 4, occur within basal part of this unit. Matrix, buff-weathering coarse grit.	18 (5.5)	134 (40.9)
4	Breccia, granitic, pink; massive, unsorted; granitic fragments, both angular and subrounded, less than 5 cm, in pinkish to greenish grey matrix composed of angular crystals and granitic fragments that are identical to fragments.	60 (18.3)	116 (35.4)

Unit	Lithology	Thickness in feet (metres) Unit	Height from base
3	Tuffaceous conglomerate (similar to unit 1) with abundant granitic boulders.	13 (4.0)	56 (17.1)
2	Breccia, granitic, dark green, massive; has the appearance of shattered granite rather than epiclastic breccia; no boulders present; matrix and fragments are almost indistinguishable. Exact thickness of exposure not determined but units 2 and 3 combined are 8.5 metres.	(?)15 (4.6)	43 (13.1)
1	Tuff, boulder, dark grey, fine- to coarse-grained; granitic boulders, well rounded, are abundant in the lower 1 to 3 m. Matrix is dark grey (?) tuff composed mainly of pale grey, pale green, to dark green, tuff fragments (1 to 3 mm). Poorly sorted, massive, greyish green weathering.	28 (8.5)	28 (8.5)
	Top of the formation is removed by erosion. Thickness of the exposed section is about 46 m.		

SECTION LCX

Unit	Lithology	Thickness in feet (metres) Unit	Height from base
9	Conglomerate, granitic boulder, greenish grey; thick bedded, crude layers less than 0.5 m that erode to form small benches in the cliff face. Boulders, hornblende biotite quartz monzonite, less than 0.3 m and average 15-20 cm, make up 20-30% of the outcrop; subangular to well rounded; fractured slickensided and coated with chlorite and hematite along many fractures within boulders. Fractures do not penetrate into the matrix. These boulders are derived from a shattered granitic terrain. One large boulder contains quartz veins 1 cm wide containing rosettes of molybdenite up to 2 cm across.	180 (54.8)	680 (207.1)

Unit	Lithology	Thickness in feet (metres)	
		Unit	Height from base
8	Conglomerate, granitic boulder, massive; boulders, biotite quartz monzonite, subrounded to subangular, range up to 0.5 m across, make up 30-40% of the rock; minor pale green ignimbrite blocks; unsorted. Matrix, green grit, massive, no evidence of bedding.	130 (39.6)	500 (152.3)
7	Sandstone, green to grey, medium- to coarse-grained, thinly bedded. Upper bed is arkosic wacke, poorly sorted.	3 (0.9)	370 (112.7)
6	Conglomerate, granitic boulder, massive; subangular to subrounded pebbles, cobbles and boulders of hornblende-biotite quartz monzonite in a green grit matrix. Matrix is arkose with abundant chlorite alteration between fragments.	7 (2.1)	367 (111.8)
5	Sandstone, pebbly, green, amount of pebbles greater than in bottom half than in rest of the unit; bedding indicated by zone of abundant pebbles at the bottom; preferred orientation of elongate pebbles. This unit lies conformably on granitic breccia of unit 4.	10 (3.0)	360 (109.7)
4	Breccia, granitic, massive; angular granitic blocks, making up from 60-80% of the mass, range from cobble size to 1 m across. Area between blocks contains angular granitic debris with finest fraction being angular crystal fragments which gives the appearance of fine crushed crystals. Colour of matrix and of fragment is the same on fresh surface tending to mask the clastic texture. Clastic texture is obvious on the pinkish grey weathered surface.	227 (69.2)	350 (106.7)
3	Conglomerate, granitic boulder, massive; pebbles, cobbles and boulders almost all granitic; range from one to 60 cm, average size range is 7 to 20 cm; make up from 25 to 40% of the rock. Matrix is green arkosic grit, massive, composed of angular fragments all derived from granitic material	18 (5.5)	123 (37.5)

Unit	Lithology	Thickness in feet (metres) Unit	Height from base
3 cont.	with some porphyritic trachytic dacite and tuff. Matrix is silt to clay size material with intense chlorite alteration. Top of this unit is marked by an undulatory conglomerate bed with both pink and grey weathering granitic boulders.		
2	Tuff, greyish green, medium- to coarse-grained; thin bedded (beds distinguished by difference in grain size); strong fabric within beds is defined by preferred orientation of elongate pumice, shards and lithic fragments. Fragments mainly pumice, shards, some pale green tuff and rare granitic and crystal fragments. Coarse beds contain abundant tuff fragments, whereas fine-grained beds are mainly pumice (altered dark green) and shards. All beds are poorly sorted.	43 (13.1)	105 (32.0)
1	Tuff, lithic, greyish green, poorly sorted, massive; angular lithic fragments almost entirely pale grey to pale green tuff, minor porphyritic felsite and granitic fragments. Between 3.5 m and 11 m from the base of the formation abundant angular granitic cobbles and blocks up to 1.5 m across and of granitic fragment breccia occur as lenses and pods within the tuff.	62 (18.9)	62

SECTION LCXII

Unit	Lithology	Thickness in feet (metres) Unit	Height from base
8	Conglomerate, granitic boulder, similar to unit 7, except boulders tend to be smaller, greater proportion of matrix, and outcrop weathers dark grey. Contact between units 7 and 8 is completely gradational but marked by abundant iron oxide alteration. Massive cliff forming unit.	100 (30.5)	1,870 (570.0)

Unit	Lithology	Thickness in feet (metres) Unit	Height from base
7	Conglomerate, granitic boulder. Boulders range up to 3 m across, average 0.5 m, sub-angular to well-rounded pebbles and cobbles (5-15 cm) angular. Pebbles, cobbles and boulders make up 50-65% of the outcrop; essentially all hornblende-biotite quartz monzonite, few rare green porphyritic andesite and one boulder of granitic boulder conglomerate. Matrix, coarse grit, grey-green, of angular granitic fragments, broken crystals of quartz and feldspars derived from granitic rocks, spaces between fragments intensely chloritized. Massive, grey-weathering unit, recessive at base and cliff forming near the top.	780 (237.8)	1,770 (539.5)
6	Ignimbrite, dark greyish brown; well developed eutaxitic structure through the unit, blocky jointing, rectangular columns 1 to 2 m apart, platy cleavage parallel to the foliation and perpendicular to columns; lower contact undulatory, granitic cobbles and some boulders are incorporated in the base of the unit. Thickness ranges from 11 to 15 m.	65 (19.8)	990 (301.7)
5	Conglomerate, granitic boulder.	75 (22.8)	925 (281.9)
4	Ignimbrite, dark greyish brown, massive.	15 (4.6)	850 (259.1)
3	Conglomerate, granitic boulder (similar to unit 1).	535 (163.0)	835 (254.5)
2	Ignimbrite, dark grey-brown, massive.	40 (12.2)	300 (91.5)
1	Conglomerate, granitic boulder, contains up to 30% granitic pebbles, cobbles and boulders with green chloritic matrix; massive, cliff forming unit that weathers pale greenish grey. In some places this unit contains almost entirely angular fragments (breccia).	260 (79.3)	260 (79.3)

APPENDIX IIIC - JONES CREEK FORMATION

(Section measured along the north side of the outcrop 1.5 miles (2.5 km) southeast of "Gault")

Unit	Lithology	Thickness in feet (metres) Unit	Height from base
6	Tuff, light grey, fine to medium grained; thin to thick bedded and laminae 1 to 10 mm thick. Laminae are poorly defined and grade into one another. Bedding is made prominent by preferred orientation of dark green chloritized pumice (?). Thin section: mainly shards; some pumice; crystal poor. Crystals include plagioclase phenocrysts and plagioclase, quartz and potassic feldspar derived from granitic material. Coarse granular devitrification of shards and pumice. Bedding well defined by preferred orientation of shards and pumice.	100	261
5	Siltstone, dark grey, finely laminated (0.2 - 2 mm). Laminae alternating light and dark grey and some pale green (coarser grained): dark grey contain abundant fine biotite; graded bedding. Thin section: poorly sorted, very angular grains, 0.05-0.2 mm. Fragments of quartz, plagioclase, biotite and zircon derived from granitic material. Siltstone and fine sandstone south of this section and probably related to this unit, contains woody plant remains that are not identifiable.	15 (4.7)	161 (49.2)
4	Tuff and siltstone, pale green; medium to finely laminated (1-3 mm) and thin bedded (10 mm thick). Graded bedding, small scale scour and fill structures in tuff laminae. Thin section: tuff; fine shards, dust, some pumice, all devitrified and little crystal material. Plagioclase phenocrysts and crystal fragments with fine chlorite alteration. Tuffaceous siltstone contains abundant crystal fragments and shards.	20 (6.1)	146 (44.5)

Unit	Lithology	Thickness in feet (metres) Unit	Height from base
3	Basalt, lava flow, dark grey, porphyritic; deeply weathered, forms rubbly outcrop; sills and dykes of porphyritic rhyolite transect this sequence.	6 (1.8)	126 (38.4)
2	Tuff, partly welded, pale green, fine- to medium-grained; foliation shown by preferred orientation of elongate pumice fragments. Thin section: plagioclase phenocrysts and fragments of phenocrysts are resorbed and subhedral. Other accessory and crystal fragments include plagioclase, potassic feldspar and quartz, granitic material, pilotaxitic and spherulitic felsite. Pumice is devitrified and partly deformed. Matrix between fragments and pumice is devitrified dust and shards that show 'streaming' around lithic and crystal fragments.	100 (30.5)	120 (36.6)
1	Sandstone, pale greenish grey; massive beds, bedding indicated by preferred orientation of biotite and of slightly elongate grains; coarse grained (0.2-2 mm). Thin section: very poorly sorted, arkose, with abundant biotite, grains equant, angular to subrounded.	10-20 (3 to 6.1)	20 (6.1)

APPENDIX IIID - CROZIER SUBAREA

(Location of sections shown in Fig. 25)

SECTION CRI

Unit	Lithology	Thickness in feet (metres) Unit	Height from base
5	Siltstone and tuff interbedded. The upper half of the sequence is dark greyish green to bluish grey, finely laminated and graded bedded siltstone. The lower half of the sequence is interbedded dark grey siltstone and medium green tuff; beds range from 5 to 20 cm.	225 (68.6)	635 (193.6)

Unit	Lithology	Thickness in feet (metres) Unit	Height from base
5 cont.	Laterally there are local pods of granitic-volcanic pumiceous grit near the base of the sequence, and one 15 m tuff bed near the centre of the sequence.		
4	Tuff-breccia, dark-grey weathering, massive; cliff forming. Base of unit is thin-bedded granitic-volcanic fragment grit with few large blocks of volcanic material; composition of clasts is essentially the same as in unit 3.	86 (26.2)	410 (125.0)
3	Breccia, volcanic-granitic; clasts from sand size to 45 cm across; thick, massive beds, crude bedding indicated by preferred orientation of elongate fragments. Clasts make up to 50% of the rock and the proportion of volcanic to granitic fragments ranges from 3:1 to 6:1. Volcanic clasts include dark green, microporphyritic tuff; cream spherulitic, finely banded rhyolite; maroon rhyolite; mauve-grey, sparsely porphyritic (?) dacite; dark green to medium green intensely altered, devitrified pumice. Crystal fragments include potassic feldspar, plagioclase, and quartz are derived from granitic material. Matrix, grit, dark green weathers rusty buff; in thin section, the matrix is intensely altered with chlorite, epidote and consists of very fine silt size material to 5 mm across of composition the same as in the large clasts, except that there is more crystal fragments: no shards were identified. The rock is very colourful on wet, weathered surface because of the variety of shades of green, grey, maroon, purple and pink fragments. It is unsorted and all fragments are angular to subangular except for a few of the largest blocks that are well rounded. This unit forms massive dark grey weathering cliffs in this section; farther south, however, it becomes a recessive, rubbly zone.	245 (74.7)	324 (98.8)

Unit	Lithology	Thickness in feet (metres) Unit	Height from base
2	Conglomerate, volcanic-granitic, massive; composition and size of fragments is the same as in unit 1 except that the large clasts are well rounded; matrix is pebbly grit, recessive unit.	33 (10.1)	79 (24.1)
1	Breccia, granitic-volcanic, fragments from sand size to blocks 60 cm across; massive. Ratio of volcanic to granitic fragments is about 10:1. Fragments include dark green porphyritic (?) andesite, medium grey to pale green felsites and grey granitic fragments. Matrix is dark green grit composed of clasts of the same composition as the large fragments. This is a cliff forming unit that conformably overlies ignimbrite of the MacAuley Creek Formation.	46 (14)	46 (14)

SECTION CRII

11	Breccia, granitic fragment, brown weathering, massive but slight hint of bedding by fine (2 cm apart) irregular fractures that are parallel to the bottom of the bed. Fragments are almost all granitic except for rare biotite-quartz-feldspar gneiss. Matrix is a medium greenish grey, volcanic grit composed of pale green tuff, pale grey to white rhyolite, and small fragments of granitic material and crystal fragments derived from it.	59 (18)	1,173 (357.8)
10	Conglomerate, volcanic-granitic boulder, brown weathering, massive. Boulders, well-rounded biotite quartz monzonite, biotite-quartz-feldspar gneiss, banded dark grey rhyolite or dacite.	73 (22.2)	1,114 (339.8)
9	Grit, tuffaceous, pumiceous, medium greenish grey, coarse grained; bedding shown by well-developed preferred orientation of elongate fragments. Fragments are mainly light to dark green tuff that range from 1 to 5 mm and rarely larger than 10 mm, and rare crystals and fragments of granitic material, and some pumice; angular to subrounded; poorly sorted.	14 (4.3)	1,041 (317.6)

Unit	Lithology	Thickness in feet (metres) Unit	Height from base
8	Conglomerate, granitic-volcanic boulder; massive.	15 (4.6)	1,027 (313.3)
7	Tuff, devitrified, altered, pumiceous, pale greyish green, massive but locally bedding is suggested by vague tendency for preferred orientation of some elongate fragments. Clasts almost entirely chloritized unwelded pumice, mainly equant shapes, range from less than one to 7 mm (most less than 3 mm); good sorting. Few accessory clasts of cream tuff up to 3 cm. That this is an air-fall tuff is suggested by the good sorting and lack of welding.	136 (41.5)	1,012 (308.7)
6	Tuff, porphyritic (feldspars), altered, medium grey-green. Pumice, altered, not welded; bedding suggested by vague preferred orientation of some elongate pumice and crystal fragments.	43 (13.1)	876 (267.2)
5	Tuff, ash-flow; partly welded, pale greyish green; eutaxitic foliation; accessory clasts are almost entirely pale green tuff.	130 (39.6)	833 (254.1)
4	Tuff, devitrified, medium green; massive ash-flow tuff.	30 (9.2)	703 (214.5)
3	Conglomerate, granitic boulder; massive. Basal 3 to 6 m of the unit has approximately 30% boulders of dark green aphanitic volcanic rocks and dark grey tuff. Sharp contact with the underlying conglomerate.	117 (35.7)	673 (205.3)
2	Conglomerate, granitic boulder, massive; boulders all granitic, subrounded to well rounded.	336 (102.5)	556 (169.6)
1	Conglomerate, volcanic-granitic; massive; large boulders are granitic rocks; small boulders are mauve, dark grey and green volcanic fragments; matrix is darker grey grit.	220 (67.1)	220 (67.1)

Unit	Lithology	Thickness in feet (metres)	
		Unit	Height from base
1 cont.	Volcanic fragments mainly at the top of the unit, lower about two-thirds of unit contain mainly granitic clasts. At 15 m from the base, thin grit parting within the conglomerate.		

SECTION CRIV

Unit	Lithology	Thickness in feet (metres)	
		Unit	Height from base
18	Tuff, pale mauve-grey to pale grey; partly welded pumice fiamme average 1 to 3 cm; clasts of grey to pink rhyolite in devitrified ash matrix.	215 (65.6)	4,428 (1,349.4)
17	Tuff, fine grained, pale grey, massive, unsorted, non-welded; sanidine phenocrysts, quartzite accidental fragments and crypto-crystalline felsite accessories in fine ash matrix of shards and dust. Tuff-breccia parting between this unit and unit 16.	220 (67.2)	4,213 (1,283.8)
16	Tuff, grey-green, partly welded.	60 (18.3)	3,993 (1,216.6)
15	Rhyolite dyke, cream weathering; centre white with very subtle flow layers; margins spherulitic, brecciated, finely banded.	300 (91.5)	3,993 (1,198.3)
14	Tuff, grey-green.	295 (90)	3,633 (1,106.8)
13	Grit, dark grey, schist and granitic fragments.	20 (6.1)	3,338 (1,016.8)
12	Tuff-breccia; fragments (15-40%) of granite, spherulitic, banded rhyolite, green tuff, quartz and feldspar in greenish grey coarse lapilli tuff matrix - pumice and ash between the lapilli.	40 (12.2)	3,318 (1,010.7)

Unit	Lithology	Thickness in feet (metres) Unit	Height from base
11	Rhyolite, lava flow, white, laminated; auto-brecciated at base.	130 (39.6)	3,278 (998.5)
10	Siltstone, dark grey to dark green, graded bedding; laminae 0.5 to 5 mm; with thin interbeds of green pumiceous volcanic sand-stone, poorly sorted wacke or (?) tuff. Abundant soft sediment deformation features such as microfaulting, tuff bed that warps rather than faults. Large scale deformation at rhyolite contact in other areas.	115 (35.1)	3,148 (958.9)
9	Rhyolite sill, white.	1,130 (344.2)	3,033 (923.8)
8	Siltstone, dark grey (almost black), thin bed-ded.	50 (15.2)	1,903 (579.6)
7	Grit, granitic fragment, maroon, dark reddish brown weathering; angular to subangular gra-nitic fragments in matrix of feldspars and quartz cemented by hematite.	55 (16.8)	1,853 (564.4)
6	Siltstone, laminated, dark green to dark brown.	78 (23.8)	1,798 (547.6)
5	Tuff, dark green, fine to coarse grained; thick bedded to massive; locally tuff breccia. At 125 m from the base of the unit the rock is lithic lapilli tuff-breccia containing angu-lar clasts of green tuff, peach feldspar frag-ments, dark green andesite, and mica schist up to 20 cm across; matrix is dark green tuff of similar constituents but with dark green altered, undeformed pumice. Lithology of the middle portion of this unit is not known because of a neck of rhyolite that has intruded it.	570 (173.5)	1,720 (523.8)
4	Breccia, volcanic; massive; blocks and boul-ders mainly rhyolite, some granitic and schist; matrix volcanic grit.	30 (9.1)	1,150 (350.3)
3	Rhyolite, white to buff, very pale greenish weathering; finely layered; top 10 to 15 m is tuffaceous rhyolite, middle upper part is	240 (73.2)	1,120 (341.2)

Unit	Lithology	Thickness in feet (metres) Unit	Height from base
3 cont.	white essentially massive rhyolite, lower two-thirds is autobrecciated finely banded rhyolite, basal zone with abundant fine rhyolite and crystal clasts; foliation defined by trains of chloritic alteration. In thin section: plagioclase, potassic feldspar phenocrysts, rhyolite, granitic fragments, are in microfelsitic matrix of quartz and feldspars; amygdales filled with quartz, feldspar, and hematite. Elongate fragments have preferred orientation. Base of the flow is locally marked by a granitic, tuff, rhyolite fragment breccia.		
2	Rhyolite lava flow, pale greenish grey, brecciated, massive, banding if present is very subtle.	550 (167.5)	880 (268.0)
1	Rhyolite, pale greenish grey, irregular discontinuous fine bands, weathers medium greenish grey. In thin section: phenocrysts of plagioclase, potassic feldspar (some potassic feldspar mantles plagioclase; potassic feldspar has embayed outer margins) in matrix of microfelsitic aggregate of quartz and feldspar. Fine chlorite alteration throughout and large irregular patches of carbonate. Microcrystalline clasts that appear the same as the matrix except slightly coarser grained, have foliation imparted by preferred orientation of chloritic stringers -- these clasts resemble pumice but may also be fluidal banding in rhyolite. This texture occurs at the top of the unit is interpreted as pumiceous frothy top of the rhyolite lava flow.	330 (100.5)	330 (100.5)

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