THE GEOLOGY AND MINERAL
DEPOSITS IN THE VICINITY OF
THE MITCHELL AND SULPHURETS GLACIERS
NORTHWEST BRITISH COLUMBIA

Rodney Victor Kirkham
M.Sc., 1963
THE UNIVERSITY OF
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Frontispiece: Aerial View of the Mitchell-Sulphurets District

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THE GEOLOGY AND MINERAL DEPOSITS IN THE VICINITY OF THE MITCHELL AND SULPHURETS GLACIERS, NORTHWEST BRITISH COLUMBIA

by

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B.Sc., The University of British Columbia, 1960

A THESIS SUBMITTED IN PARTIAL FULFILMENT OF

THE REQUIREMENTS FOR THE DEGREE OF

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of

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We accept this thesis as conforming to the required standard

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Abstract

The Mitchell-Sulphurets region is in the heart of the Coast Mountains of northwest British Columbia. Geologically it is situated on the western edge of the Bowser basin approximately 12 miles east of the main Coast Mountains plutonic complex. The map-area is underlain by partly or wholly metasomatized sedimentary, volcanic, and intrusive rocks. The volcanic and sedimentary rocks are tentatively dated as Lower Jurassic. They probably belong to Lower Hazelton and/or possibly Upper Takla group. The sediments are typical of a greywacke, turbidite suite. The volcanics belong to a marine sequence chiefly comprising pyroclastic members.

Possibly in Jurassic time, the sedimentary and volcanic rocks of the area were invaded by the Mitchell Intrusions. The earlier members of the Mitchell Intrusions were injected as sills and dykes predominantly into the well-bedded sediments. The later members formed larger, more irregular bodies. There are marked mineralogical changes within the intrusions. Differentiation by fractional crystallization and composite intrusion account for original variations in mineral composition, but post-crystallization changes are the cause of unusual rock types. Spilitized diabase, syenodiorite, albite syenite, syenite, quartz syenite, and some granite have resulted from the "deliming" or albitization of the original plagioclases.

Immense quantities of trapped volatiles, which were concentrated by differentiation processes, resulted in phenomenal amounts of rock alteration during the dying stages of the magmatic period. They have had a profound effect on an area of rock about three times that of the intrusions. During the period of rock alteration the area approached an equilibrium environment probably somewhere below 400° C. and probably at moderate pressures. Throughout the area altering fluids probably contained moderate concentrations of Na, K, SiO_2, and H_2S, high concentrations of CO_2 and H_2O, and in the Mitchell Valley trace amounts of HF. The end of the alteration period was sharp, possibly being terminated by the development of major faults which could have permitted the release of the fluids. The chief types of alteration - albitization, carbonatization, sericitization, silicification, chloritization, and pyritization - have affected the rocks in a similar manner throughout most of the area. In most areas secondary minerals in highly altered rocks are the same as those in the slightly altered rocks.

The mineral deposits, which are of the "Porphyry Copper" type, were formed during the alteration period. The presence of large volumes of volatiles at an elevated temperature allowed extensive migration of the metal-bearing solutions from their magmatic source. Disseminated copper and molybdenum mineralization is found in porphyritic, granitic intrusions and in altered volcanic, sedimentary, and intrusive rocks. The large quantities of fluids have also resulted in the separation of the copper and molybdenum sulphides into distinct deposits. The formation of distinct deposits was probably dependent upon the physical-chemical properties of the environment at the time of alteration.

Major faulting occurred late in the alteration period. This marked the end of the Mitchell epoch of magmatic activity. Somewhat later in the history of the area, possibly in Tertiary time, a few keratophyre (basaltic (?)) dykes were emplaced. Extensive erosion by glaciers in Pleistocene and Recent times has sculptured the landforms into their present shapes.

Acknowledgements

The writer would like to thank the persons and institutions that have aided in the completion of this thesis. During the summer of 1961 the writer was assisted in the field by Messrs. Gordon Gutrath, Jacque Brache, and Victor Preto. Special thanks are due to Dr. G.W.H. Norman and Newmont Mining Ltd. for allowing the use, by the author, of information belonging to the company. Dr. Norman also outlined the field study and has suggested many productive ideas during the course of study.

Particular thanks are also due to several employees of the British Columbia Department of Mines and Petroleum Resources for courtesies extended to the writer during the course of preparing the material for presentation. Mrs. T. Regan typed the manuscript; Mr. W. Player made several polished and thin sections; Mr. N. Colvin assayed an electrum specimen and prepared many samples for X-ray powder photographs; and Mr. K. S. Crabtree draughted the legend for the enclosed map. The writer is also indebted to the Department for the unrestricted use of its laboratory facilities.

Finally, the writer would like to thank the members of the Department of Geology at the University of British Columbia who have aided the writer in many ways. Special thanks are due to Mr. N. Church and Dr. K. C. McTaggart. Mr. Church took time from his own work to show the writer standard techniques used in X-ray diffractometer studies. Dr. McTaggart offered much constructive criticism and read the final draft of the thesis.

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CHAPTER I - INTRODUCTION

Nature and Scope of the Study

During the summer of 1960, Newmont Mining Corporation carried out an extensive programme of exploration for mineral deposits in the Unuk River area of northwestern British Columbia . The programme combined an airborne magnetometer survey with a study of regional geology. A series of small magnetic anomalies were discovered in the vicinity of the Mitchell and Sulphurets Glaciers. Later geological work by Joseph Montgomery indicated the existence of several low grade copper deposits. Since much of the copper mineralization occurs in granitic rocks, Montgomery suggested that the deposits may be of the "Porphyry Copper" type.

Encouraged by the discovery of several deposits and by the type of mineralization, Dr. G.W.H. Norman of Newmont Mining Ltd. outlined a detailed geological study of the area. The writer of this paper took the opportunity to combine this detailed geological study of a relatively large area with a laboratory study, and to present the work as a thesis. He has attempted to unravel the geological history of the area and to shed some light on the origin of the mineral deposits.

Much emphasis has been placed on petrology. Since most of the rocks of the area have been more or less metasomatized, a petrological study is of basic importance in reconstructing the geological history. The study of igneous petrology, including a detailed study of fifteen feldspars, and a study of rock alteration have been most heavily stressed.

Methods

To study an area of about 20 square miles two main methods of field mapping were employed: tape and compass traversing, and photogeology. A total of eleven east-west tape and compass traverses were made, and points on the traverse lines were surveyed using triangulation. From the traverses the geology was mapped at a scale of 200 feet to 1 inch. The gaps between the lines and to the borders of the area were completed by mapping on aerial photographs, which had been enlarged to a scale of about 800 feet to 1 inch.

The laboratory research included a study of about three hundred hand specimens, seventy-five thin sections, and about thirty polished sections. Several minerals were identified by X-ray powder photographs. In addition to these normal methods of investigation, a detailed study of fifteen feldspars was made using X-ray diffractometer and universal stage techniques.

The composition of the alkali feldspars was determined on a Norelco Phillips X-ray goniometer by measuring the difference in 2θ between the ($\bar{2}01$) feldspar peak (equals ($20\bar{1}$) peak for triclinic feldspar) and the (101) peak of $KBrO_3$ (Figure 1 after Orville, 1958).

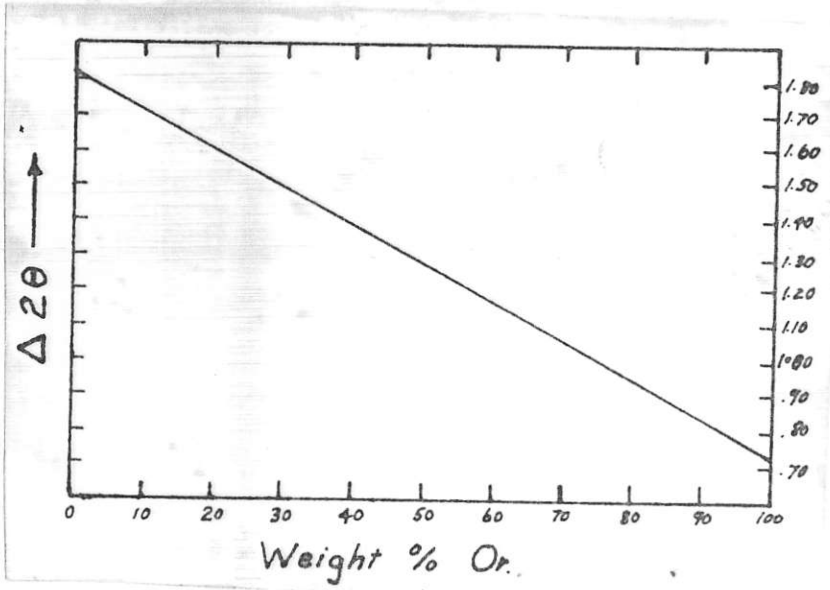


Figure 1: Difference in 2θ between ($\bar{2}01$) peak of synthetic alkali feldspar and (101) peak of $KBrO_3$ for CuK_α radiation plotted against composition. (after Orville, 1958)

Since the degree of accuracy that could be expected in determining the composition of feldspars that had not been heat treated was unclear in the short article by Orville (1958), a series of three standards was run. The composition of these feldspars was taken from reports in the literature. From the results it was concluded that the composition of untreated alkali feldspar could be determined within 3 to 4 per cent of the correct value. It should be noted that Crook (1962) employed exactly the same methods for determining the compositions of alkali feldspars as the writer.

In an attempt to shed some light on the composition, structural state, and thermal history of the plagioclase, the difference in 2θ between the ($1\bar{3}1$) and (131) peaks was measured. The determinations of compositions for the plagioclase feldspars are based on the assumption that they belong to the low-temperature series. This assumption is reasonable since all the associated potash feldspar is approaching low-temperature microcline.

For the X-ray diffraction analyses of both the alkali and plagioclase feldspars, three complete oscillations were run at a $1/4^{\circ}$ per minute over the critical values of 2θ. The average of the six readings was used in determining the composition. Figures 2A and 2B are typical runs at 1° per minute and $1/4^{\circ}$ per minute respectively.

To complement the X-ray diffraction investigation a universal stage study was performed on the same feldspars. A total of about 70 to 80 $2V_x$ determinations were made on a five-axis stage using the procedure outlined by Emmons (1943).

Problems in Mapping

Rock alteration which is ubiquitous in the area has added many problems to the geological mapping. In several places rock types are indistinguishable. At some localities highly altered intrusive plagioclase-hornblende porphyry is a dense, green rock. In the field it is impossible to distinguish this green rock from some altered volcanic or altered sedimentary rock. The style of alteration has considerable variation from one place to another. An effort was made to record these changes but suitable map units that are completely satisfactory could not be assigned.

Throughout much of the area major structures such as faults and contacts, are obscured or completely obliterated. And finally, where slightly altered rocks grade into more highly altered varieties the contact is commonly a zone of considerable width, though on the map it is marked as a line.

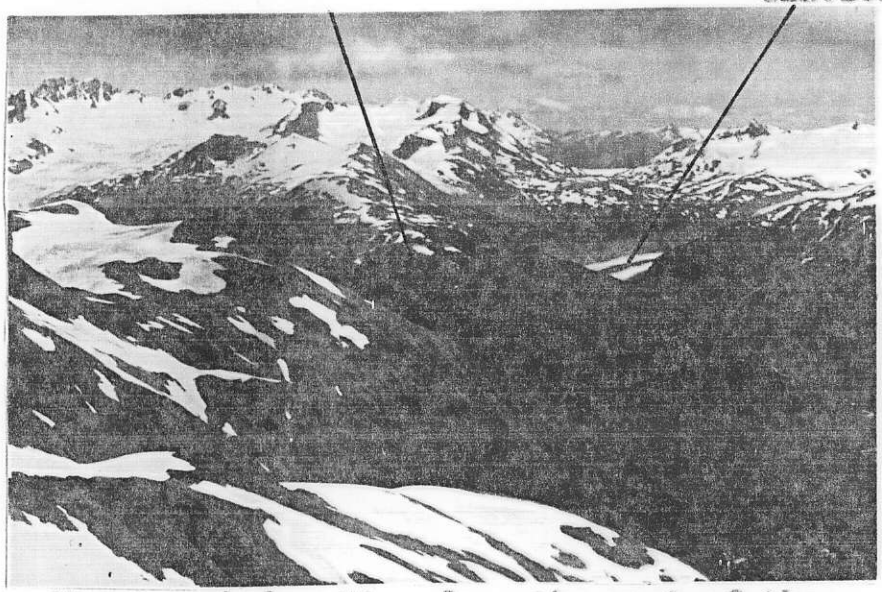
CHAPTER II - HISTORY AND GENERAL CHARACTER OF THE AREA

History

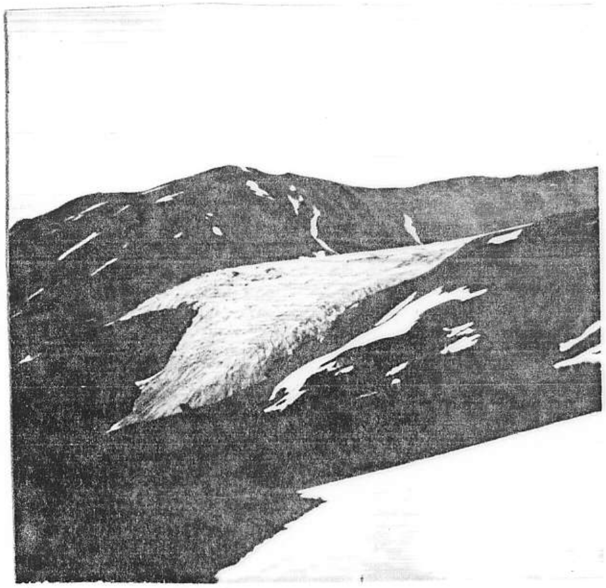
The area has received limited attention even from prospectors and geologists and has not yet been completely mapped by the Geological Survey of Canada largely because it is in a very remote district of British Columbia. The extensive iron staining has undoubtedly attracted some travellers (Photographs 2 and 3). However, examination of most of the stained areas would have revealed only small amounts of disseminated pyrite. Although most prospectors turned away, Bruce and Jack Johnson staked some claims in 1935, and their cairns are still preserved on the divide between the Mitchell and Sulphurets Valleys. Many years ago placer miners obtained a little gold from the lower reaches of Mitchell and Sulphurets Creeks.

Location and Accessibility

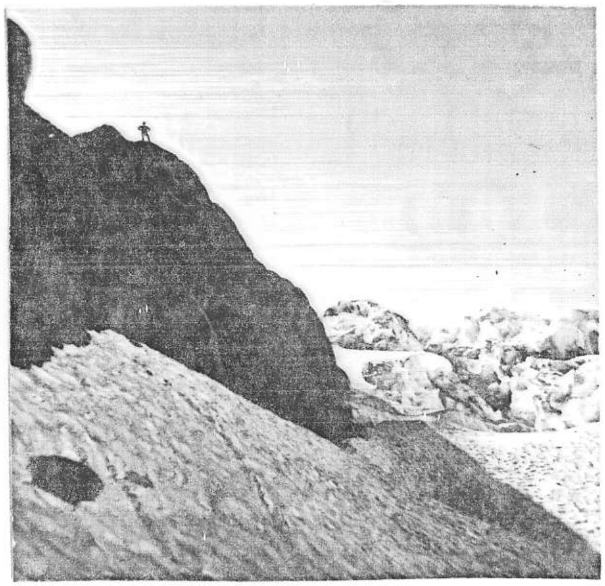
The Mitchell and Sulphurets Glaciers are located in the heart of the Coast Mountains approximately 600 miles north of the city of Vancouver (Figure 3). These glaciers occupy the heads of the valleys of Mitchell and Sulphurets Creeks, which are eastern tributaries of the Unuk River. Down the Unuk River drainage system, the Alaska border and tidewater at Burroughs Bay are 12 and 25 miles to the southwest, respectively. Granduc mine, the closest settlement, is 20 miles by air to the south. The nearest town is Stewart at the head of the Port-



Photograph 1: View from the west of the Mitchell-Sulphurets Region (The Ridge in the foreground obscures the view of the Mitchell Valley).



Photograph 2: View of the hanging glacier in Sulphurets Valley (the prominent iron staining can be seen in the background).



Photograph 3: Typical iron-stained bluff - at the side of the Sulphurets Glacier.

land Canal. It is about 45 miles by air in a southerly direction.

As mentioned above, the area is one of the most inaccessible parts of British Columbia. It is almost completely surrounded by steep mountains and icefields. The river valleys which are the natural access routes support dense foliage and lack good trails. The main valley of the Sulphurets Creek is blocked by a gorge near the river's mouth. The proposed Stewart-Cassiar Highway at its closest point will be 25 miles to the north-east. However, if the iron deposit on McQuillan Ridge is developed by Granduc Mines Ltd., there should be either a road or railway or both within 12 miles of the area.

Topography

The area is characterized by steep-walled, glacier-filled valleys and rounded, snow-capped ridges (Frontispiece). The valley slopes, where not precipitous, are covered by trees and shrubs to an elevation of about 4,000 feet. Above this elevation the valley walls give way to alpine meadows and snow - covered slopes of the rounded ridges. To the east and south of the area, where there are nunatak ridges that exceed 7,000 feet in elevation, the slopes become again very precipitous culminating in horns and arêtes.

Within the map-area the maximum relief is 5,000 feet

Figure 3: Map of British Columbia showing the location of the Mitchell-Sulphurets Region.

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The lowest point is at the southwest border where Sulphuret Creek drains to the west. The highest point is at the northern border where a 6,900-foot ridge projects above an icefield.

In general the land slopes and drains to the west. Main glaciers are fed from the south and east by icefields along the eastern divide of the Unuk River drainage system. The pattern of drainage has separated the district into three east-west-trending topographical divisions. The most northern of these is Mitchell Valley, the middle, Mitchell-Sulphurets Ridge, and the most southern, Sulphurets Valley.

Climate

The district is at the border between the West Coast Marine and Northern Interior climatic regions of British Columbia. Most of the weather systems, which predominantly come from the west, are confronted by several peaks and ridges before they reach the area. This zone in the mountain belt receives from 60 to 100 inches of precipitation per year. The amount of precipitation generally increases to the west.

The winters are long and severe and the summers tend to be cool and relatively short. The summers in the Mitchell-Sulphurets area are characterized by mist and drizzle with sporadic clear, hot days. August is the best month for doing field work because there is less snow on the ground and usually there are more clear days.

The mean temperature for January is from 0° to 10° F., and the mean temperature for July is from 40° to 50° F. The area has less than 50 frost-free days per year, and it has less than 150 days a year over 43° F.

Flora and Fauna

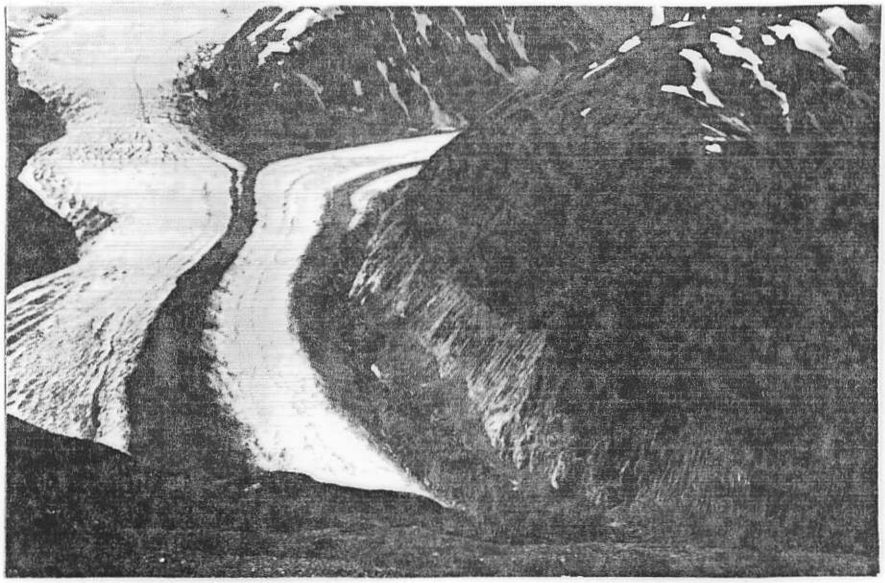
Below 4,500 feet elevation the area is in the Subalpine Forest biotic region; above, it is in the Alpine-Arctic biotic region. Spruce, balsam fir, hemlock, lodgepole pine, aspen, ground alder, and devil's-club, as well as many other shrubs and bushes are common in the Subalpine Forest region. The flora of the Alpine-Arctic region varies from stunted conifers at its base to short grasses on the rocky slopes in its upper regions. Luxuriant alpine meadows abound throughout the area. Many varieties of shrubs, mosses, grasses, and flowers are to be found. By the end of the summer the depth of foliage in these meadows usually ranges from one to five feet. Since many of the mountain slopes are very steep, there are several areas that have a typical snowslide assemblage of broken, twisted, intergrown conifers and ground alder, with undergrowth of devil's-club, stinging nettles, and other objectionable shrubs.

In this area, compared to other regions of British Columbia, birds and other animals are not very abundant. Ptarmigans, Franklin grouse, Hoary marmots, common field and jumping mice, Parry groundsquirrels,martens, porcupines, toads, and less commonly, mountain goats and grizzly bears are seen in the region. Since these animals are not very abundant and there are no fish in the streams and lakes, it would probably be very difficult for a human to sustain life on the local game.

Glaciation

Glaciers have been the most important sculpturing agents in the formation of the present landforms. The steep-walled valleys owe their origin to the glaciers that presently occupy their bottoms (Photograph 4). The rounded ridges that are at present at about 5,000 and 6,000 feet were probably smoothed off during the earlier period of glaciation when the continental ice sheet covered most of the area. Horns and arêtes that occur above 7,000 feet probably projected above the continental ice sheet.

The present existence of glaciers can be attributed to three main factors: the low annual mean temperature, the high precipitation, and the high elevation. Judged from the aerial photographs that were taken in 1956, the Sulphurets Glacier is in a stage of stagnation and the Mitchell Glacier is in a stage of recession. Since 1956 the Mitchell Glacier



Photograph 4: View looking south from Mitchell-Sulphurets Ridge up the Sulphurets Glacier (note the steep valley walls and rounded ridges).

has receded 500 to 600 feet. The prominent trim lines (Frontispiece and Photograph 4) that are present high above both glaciers indicate that they have suffered extensive ablation in recent years. From a study of a hanging glacier in Sulphurets Valley (Frontispiece and Photograph 2), it is apparent that where the frontal lobe of a glacier is very thin, ablation can result in a marked retreat of the glacier.

Glacial and glaciofluvial deposits are common throughout the area. Glacial erratics are found at many localities, including on some ridges above 5,000 feet. Terminal moraines occur to the west of the Mitchell Glacier and in front of some of the smaller glaciers. Prominent lateral moraines are associated with most glaciers, and outwash gravels are very plentiful.

A glacial feature of special note is the Forbes bands that occur on the upper southwest arm of the Sulphurets Glacier (these are beyond the southern limit of the area shown in the Frontispiece). These bands have formed below an icefall. They are convex downstream and diminish in size away from the fall. Near the ice-fall they have a typical asymmetrical wave form. These waves at a maximum, have an amplitude of 30 to 40 feet and a wavelength of a few hundred feet. The waves are composed of brecciated ice. Their shape is clearly due to seasonal variations in flow over the fall, or seasonal variations in the amount of ablation of the material passing over the fall.

CHAPTER III - GENERAL GEOLOGY

Introduction

The map-area (area shown in Figure 4) is near the western edge of the Bowser basin (Gabrielse and Wheeler, 1961) and is approximately twelve miles east of the main Coast Mountains plutonic complex. It contains partly or completely metasomatized, sedimentary, volcanic, and intrusive rocks. The volcanic and sedimentary rocks are probably Lower Jurassic, and the intrusive rocks are only slightly younger.

The volcanic and sedimentary rocks form part of the Lower Hazelton Group and/or possibly part of the Upper Takla Group (?). The intrusions are most likely related to the Coast Mountain period of igneous activity.

Lower Hazelton and/or possibly Upper Takla(?) Group

Sedimentary Members

Sedimentary rocks are predominant in the west half of the map-area. Highly deformed, dark argillites, siltstones, and greywackes make up the greater part of a belt of sedimentary rocks along the western side of the map-area, but at the extreme west end of Mitchell-Sulphurets Ridge pebble and boulder conglomerates are the main rock types. In general conglomerate and argillite are less abundant than siltstone and greywacke. Dark silty limestone occurs at a few localities.

TABLE I

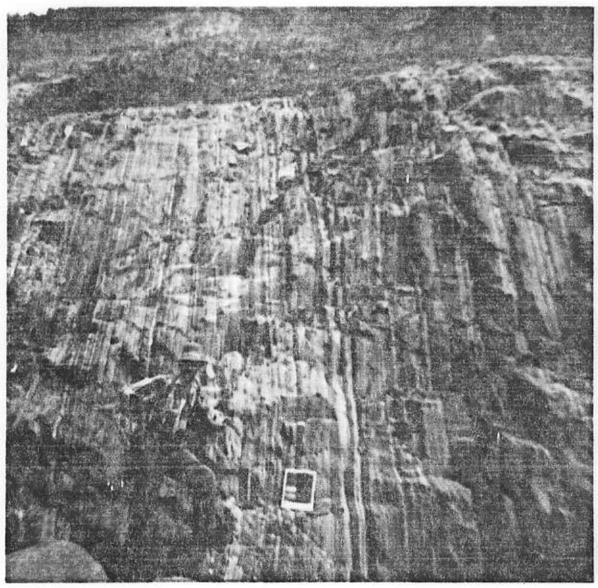
Table of Formations for the Mitchell-Sulphurets Region

Period	Group	Lithology
Recent		Unconsolidated glacio-fluvial and glacial deposits
	Unconformable Contact	
Tertiary (?)	Late Dykes	Keratophyre (basalt (?))
	Intrusive Contact	
Jurassic (?)	Mitchell Intrusions	Granite Syenite and Quartz-Syenite Porphyry Plagioclase-Hornblende Porphyry (Albite Syenite; minor Syenodiorite) - and altered equivalents
	Intrusive Contact	
Lower Jurassic (?)	Lower Hazelton and/or possibly Upper Takla (?)	*Spilitized Diabase
		Intrusive Contact
		Volcanic Members - green and purple lapilli tuff, volcanic breccia, feldspar porphyry - and altered equivalents
		Unconformable or Conformable Contacts (?)
		**Sedimentary Members - carbonaceous argillite, siltstone, greywacke, conglomerate, and minor impure limestone - and altered equivalents

* May be part of the Mitchell Intrusions

** There is some doubt whether the main sedimentary unit in the map-area is stratigraphically above or below the main volcanic unit

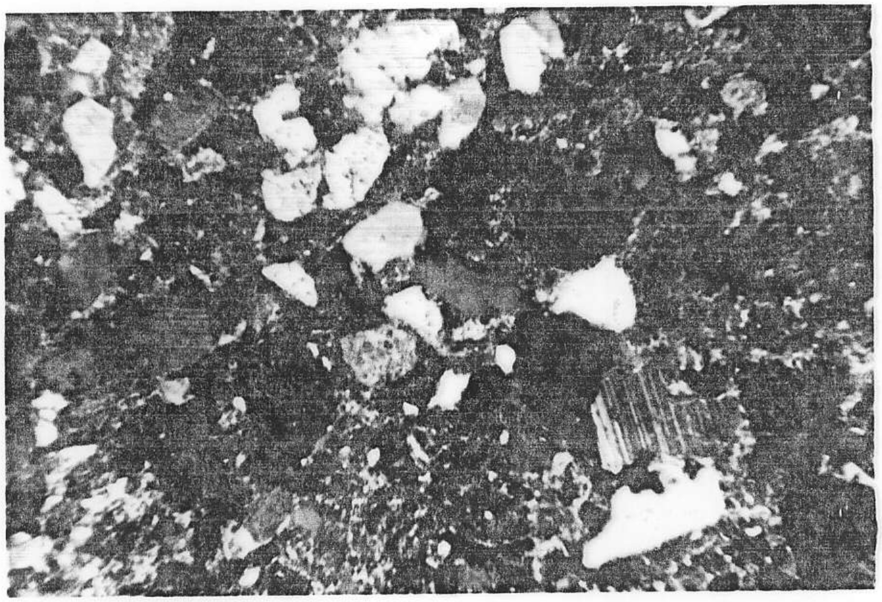
Some of the greywacke sections are typically rhythmically bedded. In one section several miles to the northwest of the map-area, where the rocks are little disturbed, an uninterrupted rhythmic series of interbedded argillite, siltstone, greywacke, and minor fine pebble conglomerate is more than 1,000 feet thick (Photograph 5). In the map-area these rhythmic sections are usually small and disconnected.



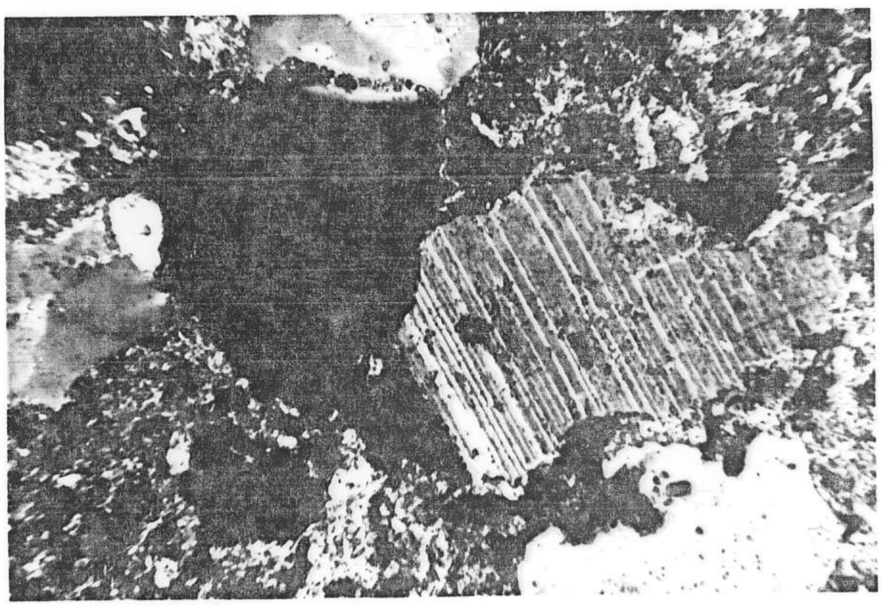
Photograph 5: Rhythmically bedded argillite, siltstone and greywacke (photograph was taken about 6 miles northwest of the map-area).

Sedimentary rocks of the map-area are in all stages of alteration and deformation. Many of these rocks in the western belt are not appreciably altered and are only moderately deformed. Some of the less competent fine-grained sediments contain well developed slaty cleavage. Nearer the intrusions most of the sediments are highly altered. The only exceptions are some black, pyritic argillites and siltstones on the north and south sides of the Sulphurets Glacier that occur as relatively unaltered inclusions in highly altered plagioclase-hornblende porphyry, and some of the sediments in contact with intrusions in the upper Sulphurets Glacier region. Invariably highly altered sediments have lost their dark colour and are usually a pale shade of grey or green. In the most highly altered rocks, locally, well-developed bedding stands out as a last remaining structure while major structures, such as contacts and faults, have been obliterated.

From thin section studies it was noted that a very characteristic feature of both coarse and fine sediments is their extreme immaturity. Always they are poorly sorted and the grains have a low degree of roundness. Most greywackes contain less than 25 per cent quartz and are very high in plagioclase. The conglomerates are comprised chiefly of cobbles and boulders of volcanic rocks, and contain abundant clinopyroxene in both the matrix and fragments. All argillites that were examined in thin section contained sub-angular and sub-rounded quartz and/or feldspar set in a clay



Photograph 6: (K-250) Photomicrograph of altered feldspathic greywacke (X25; polarized light)



Photograph 7: (K-250) Photomicrograph of altered feldspathic greywacke (X80; polarized light)

matrix. Table II gives typical mineral compositions of the sedimentary rocks.

Volcanic Members

Volcanic rocks predominate in the eastern half of the map-area. They comprise pyroclastics intercalated with feldspar porphyry flows. Invariably there are minor amounts of sediments interlayered with the pyroclastics.

In the field these rocks are seen to be in all stages of alteration from fresh-appearing purple and green fragmental rocks and light green and white feldspar porphyry flows to pale, metasomatic equivalents. In the least altered areas it is seen that lapilli tuff and volcanic breccias are the most common rock types. Where the volcanic rocks are partly altered they are usually a pale shade of green. Some are massive greenstones while others are schistose greenstones. In the schistose types the fragments have been elongated. In very highly altered varieties outlines of fragments have been obliterated - the resultant rock in most places is some shade of pale grey or buff.

In thin section it is seen that even the freshest appearing varieties have suffered extensive alteration. This alteration has destroyed many of the original features, although in most sections a clastic texture is still preserved. Any shards originally present in the matrix have been destroyed. All volcanic rocks that were studied in thin section contain

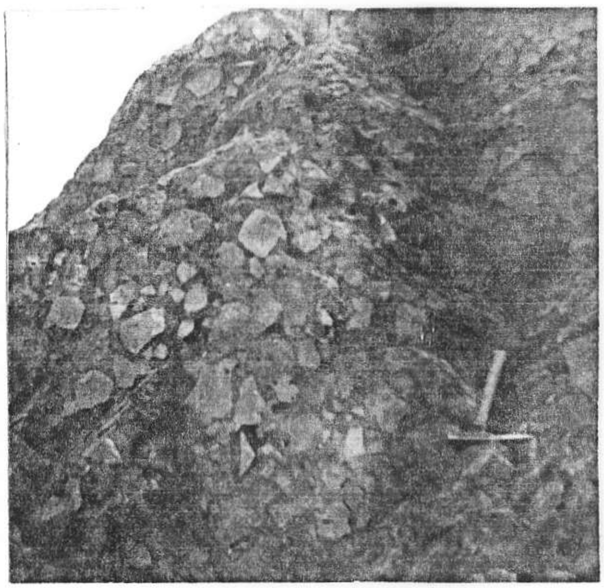
TABLE II - Typical Mineral Compositions of Sedimentary Rocks in the Mitchell-Sulphurets Region

Specimen No.	K-208	K-263	K-65	K-250	K-183	K-28	K-113
Rock Name	Altered Pebble Conglomerate	Altered Pebble Conglomerate	Altered Feldspathic Greywacke	Altered Feldspathic Greywacke	Recrystallized (Granitized) Feldspathic Greywacke	Altered Feldspathic Greywacke	Altered Argillite
Plagioclase	20%	15%	50-60%	30-35% (An_{0-5})	15-20% (An_{0-5})	55-60% (An_{0-5})	15%
Quartz	2% (?)	7%	2-5%	25%	55-60%	10%	-
Clay Minerals	-	-	-	-	-	-	25-35%
Calcite (Sec.(?))	20%	1-2%	15-17%	5%	-	trace	10%
"Sericite" (Sec.)	3%	-	10-12%	10-12%	5-7%	-	5-10%
Biotite (Sec.)	-	-	-	-	4-5%	-	-
Chlorite (±serpentine) (Sec.)	10%	5%	1/2-1%	5%	-	-	-
Epidote (pistacite) (Sec.)	-	5-8% (?)	-	5%	-	25-27%	-
Clinopyroxene	25-35%	20-25%	-	-	-	-	-
Apatite	-	-	-	trace	-	trace	-
Unresolvable Matrix	10%	40-45%	10%	15-20%	15%	-	35% Albite (?)
Opaque Minerals	5%	1-2%	3%	4%	4-5%	5-7%	1%

An% was determined by optical means.
(Sec.) - Secondary Minerals.
Percentages are visual estimations.

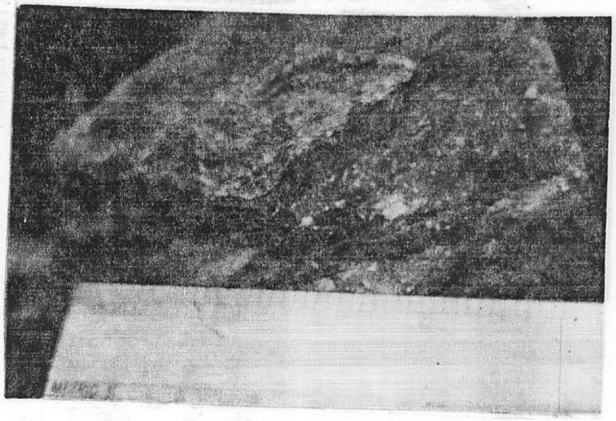
some plagioclase. In every section, except an oligoclase-bearing flow, it was noted that the plagioclase is albite. In most of these specimens the plagioclase is partly replaced by calcite and "sericite" but in a few specimens it is very fresh in appearance.

From the studies that were made, it seems that the volcanic rocks have to reach a relatively intense stage of alteration before they change colour to the paler green and grey varieties. This colour change may be very sharp, and is very similar to the "marble line" in metamorphosed limestones. On one side of the line these rocks may not be recognizable while on the other side they appear unaltered.

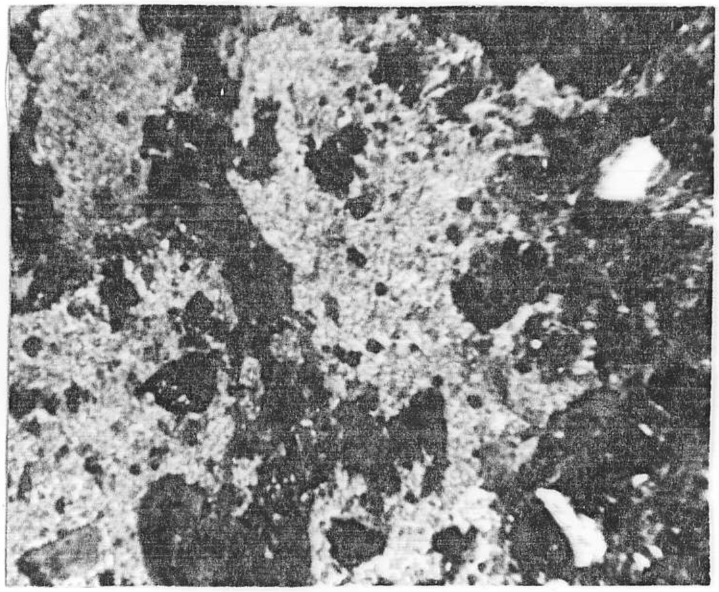


Photograph 8: Typical unaltered flow breccia

Photograph 9: Typical, unaltered pyroclastic breccia (Upper Sulphurets Glacier beyond map-area)



Photograph 10: (K-85) Typical lapilli tuff (appears unaltered in hand specimen)



Photograph 11: (K-85) Photomicrograph illustrating extensive sericitization (X[illegible]0; polarized light)

Age and Correlation of the Sedimentary and Volcanic Strata

Because of structural complexities and pervasive alteration, stratigraphic relationships and age of volcanic and sedimentary units could only be established in less disturbed regions outside the map-area. About six miles north of the Mitchell Glacier at the head of Treaty Creek (p. 27), a volcanic and sedimentary sequence is exposed that is probably the same as the succession in the map-area. The sequence at Treaty Creek comprises well-bedded, green and purple tuffs and volcanic breccias, minor flow rocks, dark argillites, siltstones, and greywackes (Photographs 12 and 13). Conformable formations of sedimentary rocks occur above and below a main volcanic unit. Poorly preserved fossils collected at the top of this volcanic formation, which is shown in Photograph 12, were dated as Early Jurassic by Dr. Hans Frebold of the Geological Survey of Canada. Ammonites including Arieticeras (?) and pelecypods including Weyla sp. were identified. From a locality about 2 miles west of the Treaty Creek Glacier the following fossils were identified:

Psiloceras candense Frebold
Weyla sp.
Pleuromya (?) sp.
gastropods

Age: Hettangian (Lowermost Lower Jurassic)

Rocks at the second locality are probably slightly lower stratigraphically than those at the first.

Exact relationships of fossiliferous rocks at Treaty Creek with rocks of the map-area have not been established, but since strata in the Treaty Creek area trend toward the map-area, it is probably safe to assume that if rocks in the map-area are not exactly the same stratigraphically as those in the Treaty Creek area, then they are at least near the same stratigraphic horizon.

Rocks of similar age and lithology in the Portland Canal district have been called Hazelton group (Hanson, 1935). Some of these units were traced by Hanson to 10 miles of the map-area. But since Hanson mapped these rocks the Hazelton

TABLE III

Typical Mineral Compositions of Volcanic Rocks in the Mitchell-Sulphurets Region

Specimen No.	K-85	K-246	K-291	K-247	K-84
Rock Name	altered volcanic breccia	altered lapilli tuff	altered lapilli tuff	altered tuff	altered feldspar porphyry flow
Plagioclase	15% An_{0-5}	35% An_{0-5}	25% An0	25-30% An_{0-5}	35-40% An_{22-25}
Apatite	-	trace	trace	trace	3% (+sphene)
Epidote (pistacite)	-	4-5%	45%	-	5-7%
"Sericite" (±clay minerals)	60%	12-15%	1-2%	12-15%	10-12%
Calcite	-	8-10%	7-10%	17-20%	3%
Chlorite	-	5-7%	5-7%	7%	15%
Biotite	trace	-	-	-	-
Quartz	-	3%	-	5%	-
Unresolvable mesostasis (plagio-clase ?)	15-17%	25%	10-12%	20%	10-15%
Opaque Minerals	7-10%	2-3%	1/2-1%	6-8%	6%

An% was determined by optical means.
Most of the minerals are probably secondary.
Percentages are visual estimations.

group (also the Takla group) has been revised and redefined (Tipper, 1959).

Tipper, in revising the Hazelton and Takla groups, has assigned tentative ages of mainly Upper Triassic and Lower Jurassic to Takla group and Middle Jurassic, Upper Jurassic, and Lower Cretaceous to Hazelton group. He states that Takla group rocks occur west of the Rocky Mountain Trench and mainly east of the belt of *Cache Creek strata (p. 40). The northern and southern limits have not been defined. Tipper (p. 40) states that it is probably best to consider all Upper Triassic and most of Lower Jurassic strata as part of the Takla group wherever they occur in central British Columbia. On the other hand he states (pp. 38 and 39):

> It seems probable that in time the Takla group will be restricted to Upper Triassic strata, like the Nicola group (Duffell and McTaggart, 1952, pp. 29-31) of southern British Columbia, and the Lower Jurassic strata will be mapped as a new group where possible, as in Nechako River area, but as Hazelton group where they are lithologically inseparable from Middle Jurassic strata, as may be the case in McConnell Creek area.

It would seem, therefore, from Tipper's paper, that it would be best to call Lower Jurassic rocks in central British

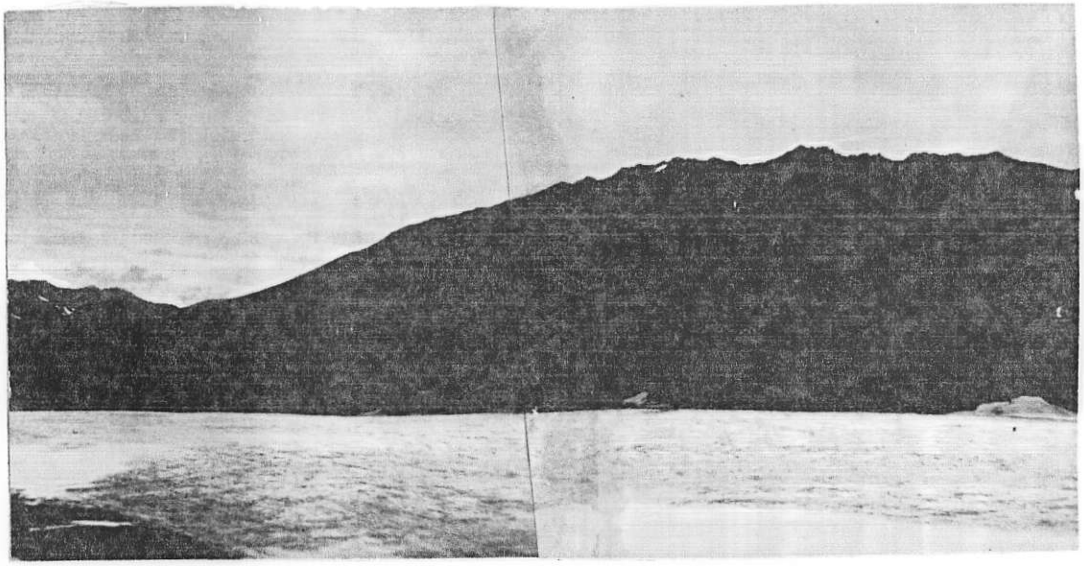
* This belt occurs in the vicinity of Babine and Takla Lakes; therefore it is about 150 miles east of Mitchell-Sulphurets region. This means that most of the rocks that have been called Takla are over 150 miles from the map-area although some that are less than 100 miles distant have also been called Takla.

Columbia Takla group where they can be easily separated from Middle Jurassic rocks and to include them in the Hazelton group where they are not easily separated from Middle Jurassic rocks. Since information is not available on Middle Jurassic rocks of the eastern Unuk region, it is not possible to follow Tipper's suggestions. Since it has not been demonstrated that Takla group rocks extend as far west as the Mitchell-Sulphurets region, it is best to retain Hanson's nomenclature and call these rocks Hazelton group. However, it should also be kept in mind that with further work it could be shown that these rocks more suitably fit into the Takla group as defined by Tipper.

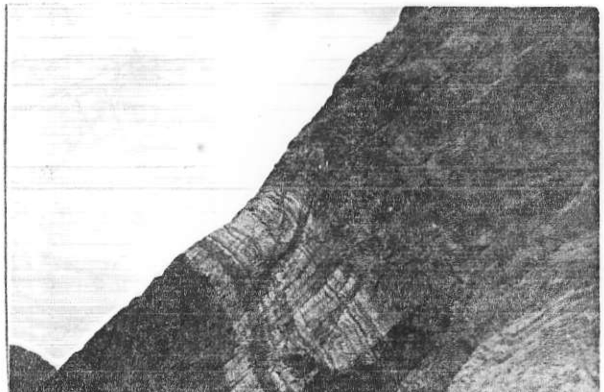
Mode of Deposition of the Lower Hazelton and/or Upper Takla (?) Sediments

Several features of the sedimentary rocks indicate that they were rapidly deposited in a marine environment by turbidity currents. The most significant feature supporting rapid deposition is the extremely low maturity index (Pettijohn, p. 509). Other features are the poor sorting and low degree of roundness of the grains. An open water marine environment of deposition for most of the sediments is indicated by the fact that the majority of the rocks are fossil poor, and that fossils found in these rocks are chiefly pelagic genera, such as belemnites and ammonites.

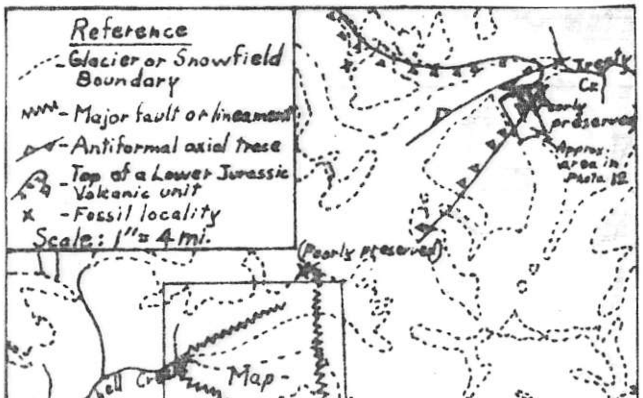
There are several features that are typical of



Photograph 12: Lower Jurassic purple and green tuffs and volcanic breccia overlain by dark argillite, siltstone, and greywacke (axial trace of a major fold lies to the west on the Treaty Creek Glacier).

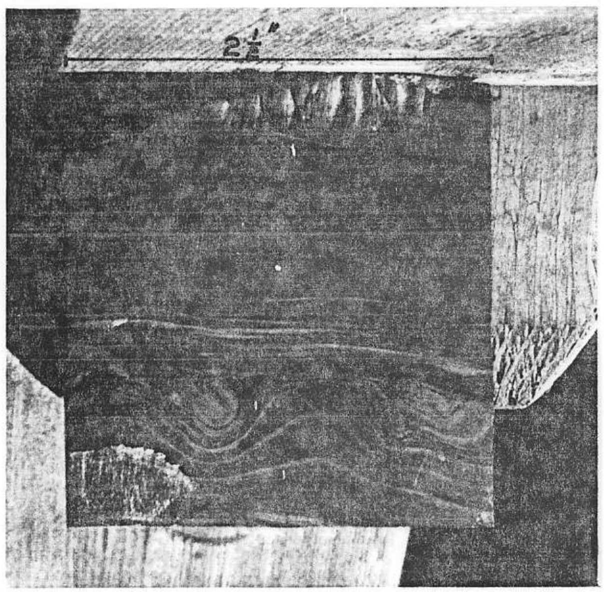


Photograph 13: Close-up of well-bedded purple and green tuffs - (Treaty Glacier).



Sketch map showing location of Treaty Creek Glacier.

turbidity current sedimentation. Rhythmic layering, as described above, is very typical of turbidity current deposition (Pettijohn, p. 617). In some specimens there is distinct evidence of soft sediment deformation that could have been a result of turbidity current action. Argillite fragments are very common in some beds. They probably represent sediments that have been disrupted by turbidity currents. The structure displayed in Photograph 14 could also have been formed by a turbidity current. A current could have eroded and deformed the lower beds, then deposited the upper beds on the former. There is a distinct erosional unconformity between the two units.



Photograph 14: Soft sediment deformation in a siltstone (southwest arm of Sulphurets Glacier - beyond map-area).

The writer thinks that not only most of the finer sedimentary material but also the coarser conglomeratic matter could have been deposited by turbidity currents. These sediments are also very immature. They contain minerals that are very susceptible to weathering, such as plagioclase and clinopyroxene. Sorting in these rocks is poor and the finer material has a low degree of roundness. In thin sections of conglomerates studied, it was noted that there are many crystal fragments of clinopyroxene in the matrix which have been crushed. One can imagine that finer material between the larger cobbles and boulders in the turbidity current would be like ore passing through a ball mill. The observed textures leave the impression that this is a feasible mechanism of deposition.

Even though it is possible that many of the sediments were deposited in deep water by turbidity currents, some at least were laid down in relatively shallow water where there were stable bottom conditions. At three localities in the eastern Unuk area where fossils were collected, the assemblages are typical of a neritic environment. Bottom dwelling pelecypods and gastropods are most abundant, but pecten-type pelecypods, ammonites, and belemnites were also found. All these localities are near the same stratigraphic horizon. They occur in or near the volcanic unit shown in Photograph 12.

Spilitized Diabase

Diabase sills and dykes are common in the western belt of sedimentary rocks. To date none have been found in the eastern half of the map-area.

Megascopically the diabase is fine grained to aphanitic, has a "salt and pepper" texture, and is usually some medium to dark shade of grey or green. In the field it is locally impossible to distinguish some fine-grained diabasic sills from greywacke beds.

In thin section the diabase characteristically has an ophitic texture; corroded, albitic plagioclase; clinopyroxene, and interstitial quartz. Typical mineral compositions of these rocks are shown in the first two columns of Table IV. These rocks tend to be relatively equigranular with grains averaging from 1/10 to 1/2 mm. in size. The plagioclase occurs as irregular subhedral laths and the clinopyroxene as more equant, anhedral, poikilitic crystals. In a few specimens there are coarse, circular clots of epidote (pistacite) and quartz. Where the quartz is in contact with albite, which encloses the clots, a well-developed myrmekitic intergrowth has formed.

The alteration varies widely. Plagioclase (albite) is partly altered to "sericite", epidote, calcite, and clay minerals; clinopyroxene is partly or completely altered to uralite, biotite, chlorite, calcite, and serpentine.

Structural relations of the spilitized diabase are simple. Invariably it is massive and never displays any directional features. In many areas it displays intrusive relationships with the enclosing rock. Most frequently the spilitized diabase was intruded as thin sills into the well-bedded sediments. Less frequently it formed dykes that cut both sedimentary and volcanic rocks. In many areas the sills are highly folded. They have been subjected to similar amounts of deformation as the sediments.

Approximately six miles northwest of the map-area there is evidence that these sills may be the same age as the main volcanic unit described above. The sills occur in great abundance below a similar volcanic unit and feeder dykes extend into it, but no sills occur above the volcanic rocks.

Mitchell Intrusions

Introduction

The name "Mitchell Intrusions" will be used in this thesis to designate all the intrusive rocks occurring in the vicinity of the Mitchell and Sulphurets Glaciers except the late dykes and possibly the spilitized diabase. These intrusions are thought to be related to one another and to the mineralization. It is possible that the spilitized diabase may be part of the Mitchell Intrusions. Some sulphide mineralization is associated with one diabasic dyke and on the western end of the Mitchell-Sulphurets Ridge diabase and plagioclase-hornblende porphyry (part of the Mitchell Intrusion) have been identified in what could be the same dyke body. Unfortunately, however, at the time of mapping the writer was not aware of the distinction between those rock types and thus did not map the critical area where they should be in contact. He, therefore, has no proof that the diabasic bodies are related to the other intrusions.

The Mitchell Intrusions can be subdivided into three distinct lithologic groups: *plagioclase-hornblende porphyry (albite syenite and minor syenodiorite porphyry), syenite and quartz syenite, and granite. These rock types are found in many relatively small intrusive bodies (shown in Figures 4 and 5).

Tuttle and Bowen (1958, p. 127) state that unless rocks containing greater than 80 per cent normative Ab+Or+Q fall into the abc triangle (Figure 16, Appendix), they should not, for genetic reasons, be called granite. This would mean that in order for a rock to be named a granite it should contain over 15 or possibly even 20 per cent quartz. Following this line of reasoning, the writer of this thesis uses the term quartz syenite for rocks of the appropriate composition

*This name is used rather than albite syenite porphyry (etc.) because it is a better field name; it allows for a much greater range in composition; and the writer doubts very much that these rocks crystallized as albite syenite or syenodiorite.

containing from about 3 to 15 per cent quartz. Rocks of the appropriate composition with less than about 3 per cent quartz are termed syenites, and rocks with greater than about 15 per cent quartz are termed granite. It should be noted that some syenites on the north side of the Mitchell Glacier, which are near the contact of a granite, may be abnormal since they are very low in soda feldspar.

Plagioclase-Hornblende Porphyry

In the map-area plagioclase-hornblende porphyry is restricted to the Sulphurets Valley and Mitchell-Sulphurets Ridge. Although none was found in the Mitchell Valley, it is possible that some of the highly altered rocks were this porphyry. Small areas of cross-cutting chlorite-sericite schist which occur to the west of Mitchell Glacier could have been this rock (Photographs 33 and 33A show a relic plagioclase crystal in a clot of sericite). Most of the altered rocks in the lower Sulphurets Valley have been identified as plagioclase-hornblende porphyry.

Because of alteration, these rocks, megascopically, have many variations in appearance. Completely unaltered varieties, of which there are few, have medium grained, dark green hornblende and white plagioclase phenocrysts set in a dense, light-grey matrix(Photograph 15). Usually both types of phenocrysts are present but either one may be more conspicuous than the other. With increasing alteration the colour gradually changes and the phenocrysts become less distinct. Completely altered hornblende-plagioclase porphyry is a massive, pyritic, dense, green-grey rock that is very similar to some of the altered volcanics. Pseudomorphs after the hornblende and plagioclase phenocrysts generally enable one to distinguish the two in thin section (Photograph 32).

In thin section it is apparent that the alteration has resulted in the plagioclase-hornblende porphyry having a variety of textures and mineral assemblages. Typical mineral compositions are listed in columns 3 to 6 inclusive of Table IV. The degree of alteration generally increases from left to right. Despite the variations due to alteration, there are properties that are diagnostic for all the plagioclase-hornblende porphyries. As mentioned above if euhedral or subhedral hornblende and plagioclase phenocrysts are not present, then pseudomorphs, usually of chlorite, calcite, and "sericite", are present after them. In all specimens there is a microcrystalline matrix with an average grain size ranging from 1/2 to 1/50 mm. In many specimens grains of the matrix grade into phenocrysts which have an average size varying from 1 to 3 mm. The matrix and phenocrysts vary in abundance but usually they are in subequal amounts. Some scattered apatite crystals up to 1 mm. in length and scattered microcline crystals, which can be over 10 mm. in diameter, are present in minor amounts.

These two constituents generally survive most of the alteration. Photograph 29 illustrates a relatively unaltered microcline crystal in a highly altered albite syenite porphyry. Syenodiorite has been included in this group since a few specimens taken on the east side of Sulphurets Glacier contained oligoclase rather than albite.

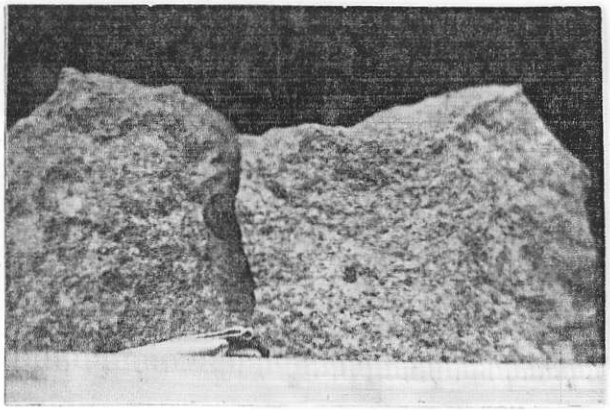
The plagioclase-hornblende porphyry usually forms relatively small- to medium-sized sills and dykes. These bodies have been emplaced along pre-existing weaknesses in the rock. Where well-developed bedding planes were present the magma forced its way between the beds. In some places this process was quite passive, the intrusion having little effect on the sediments, but in other places the intrusions have highly deformed the confining rocks. In many areas in the Sulphurets Valley contorted bedding is to be found immediately adjacent to the intrusions. On the north side of Sulphurets Glacier just above its toe, large, contorted inclusions of carbonaceous argillite and siltstone, some over 100 feet long, are found in the altered albite syenite porphyry (Figure 4).

Most of the plagioclase-hornblende porphyry is massive without any directional features, but in some areas the hornblende and plagioclase phenocrysts are conspicuously aligned. Rusty outcrops and alteration make it difficult to measure these foliations and lineations.

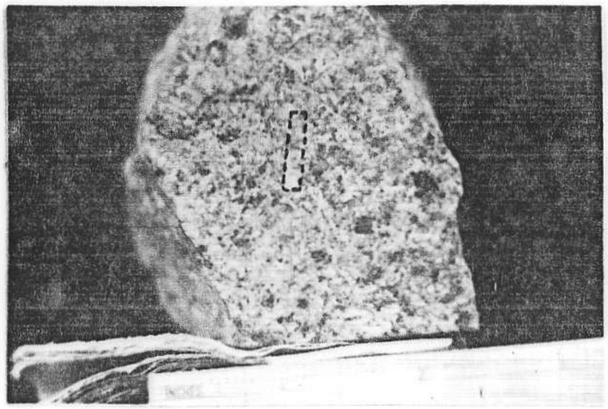
Syenite and Quartz Syenite Porphyry

A major part of the largest intrusion on Mitchell-Sulphurets Ridge and of a main intrusion in the Mitchell Valley is comprised of syenite and quartz syenite porphyry (shown in Figure 4). The only place that syenite porphyry and quartz syenite porphyry occur in small bodies is as satellitic dykes and sills near the contacts of the main intrusions.

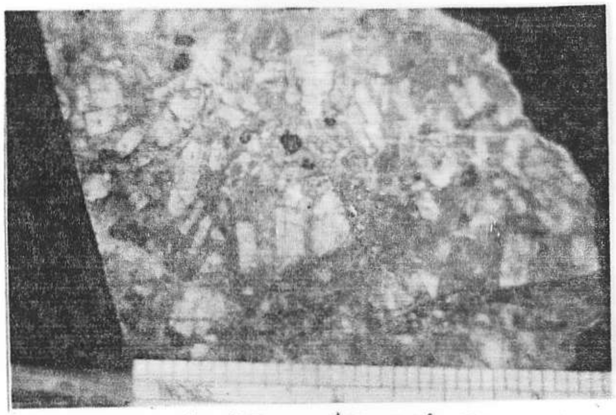
Megascopically, the syenite and quartz syenite porphyry are characterised by porphyritic, granitic textures; many coloured feldspars; lack of visible quartz, and low percentages of mafic constituents. Invariably, these rocks have a porphyritic, granitic texture. The phenocrysts are mainly from 2 to 5 mm. long, but a few specimens contain very coarse phenocrysts, some being over 20 mm. In most specimens potash feldspar forms the largest, most conspicuous phenocrysts but in some, plagioclase is also present as phenocrysts. Although they may have pink or red borders the coarsest phenocrysts are chiefly white. A few specimens of quartz syenite contain pale pink potash phenocrysts. The matrix, which is dominantly fine grained, in most cases amounts to less than 25 per cent of the rock. The feldspars of the matrix may be white, pink, red or light green. The pink and red feldspars are microperthite, the light green is plagioclase (green colour is due to sericitic alteration), and the white may be plagioclase or potash feldspar. The specimens with green plagio-



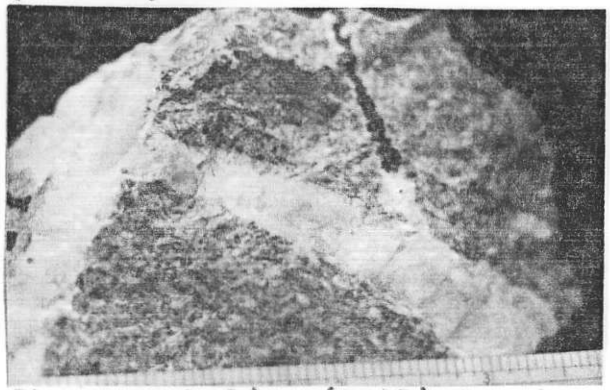
Photograph 15: (K-210 and 211) Albite Syenite (plagioclase-hornblende) porphyry.



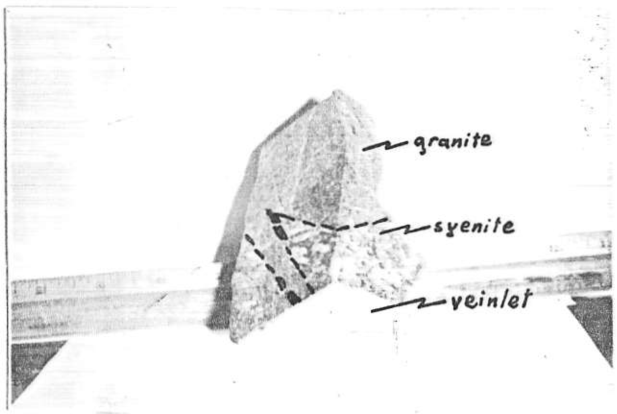
Photograph 16: (K-187) Quartz syenite porphyry (dotted line is the boundary of a feldspar phenocryst).



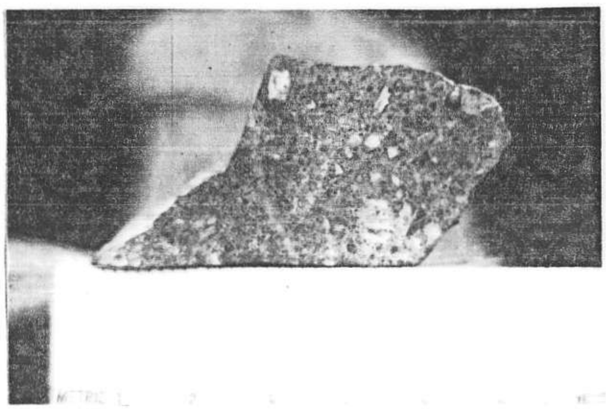
Photograph 17: (K-22) "Crackled" metasomatized syenite porphyry near granite (minute dark lines are mylonite zones).



Photograph 18: (K-11) Syenite porphyry veined by quartz, calcite, and chlorite.



Photograph 19: (K-23) Red granite cutting old white syenite (at the base is a quartz-calcite veinlet containing pyrite and chalcopyrite).



Photograph 20: (K-93) Red granite containing white phenocrysts or xenocrysts that could be relics from the older syenite.

clase and pink or red microperthite have a "Christmasy" appearance. Even though some of the rocks of this group contain considerable quartz, it is never coarse enough to be visible to the unaided eye (except as veinlets). Ferromagnesian minerals at most places amount to less than 10 per cent of the total rock. Most of the primary mafic constituents have been altered to chlorite and other secondary minerals. Unusually large, amber-brown sphene crystals are found scattered throughout some of the syenitic rocks.

The megascopic features of the syenite and quartz syenite porphyry permit an easy field separation from the plagioclase-hornblende porphyry and granites of the district. The plagioclase-hornblende porphyry is readily distinguished by its high percentage of dense matrix, its dark hornblende phenocrysts, and by the overall green colour of the altered varieties. Granites of the map-area, in all places, contain visible quartz. A granite on the north side of the Mitchell Glacier is easily distinguished because it is more equigranular and has a very diagnostic purplish red colour (Photographs 19, 20, and 26).

In thin section the * syenite and quartz syenite porphyry are seen to have a prominent porphyritic texture, subequal amounts of potash and plagioclase feldspar, zoned feld-

* Typical mineral compositions of these rocks are given in columns 7, 8, and 9 of Table IV.

spars, small amounts of interstitial quartz, a low ferromagnesian mineral content, small percentages of alteration minerals, and ubiquitously corroded plagioclase. In the specimens studied feldspar phenocrysts comprise from 50 to 85 per cent of the rock. Most of them are subhedral (irregular in detail) and they average from 1 1/2 to 5 mm. in length. A microcrystalline matrix of irregular, anhedral, low birefringent (feldspar and quartz) (?) grains makes up the remainder of the rock. The average grain size of the matrix is highly variable, ranging from 1/30 to 3/4 mm. in diameter. In most specimens grains of the matrix are gradational to the phenocrysts. Many plagioclase and microcline (untwinned) crystals are zoned. The zoning in the plagioclase is outlined mostly by varying amounts of alteration minerals, and in the microcline it is outlined by differences in extinction and varying amounts of exsolved albite (Photograph 22). The quartz that is commonly present in minor amounts is interstitial to the coarser feldspars. As seen in hand specimen the ferromagnesium content of these rocks is low. Relics of hornblende indicate that it was the main primary mafic mineral. Most of the hornblende exhibits resorption textures (Photographs 23,24, and 24A). An original euhedral outline of the phenocryst illustrated in Photograph 23 is still preserved.

Alteration, although only in minor amounts, is

TABLE IV - Typical Mineral Compositions of the Mitchell Intrusions

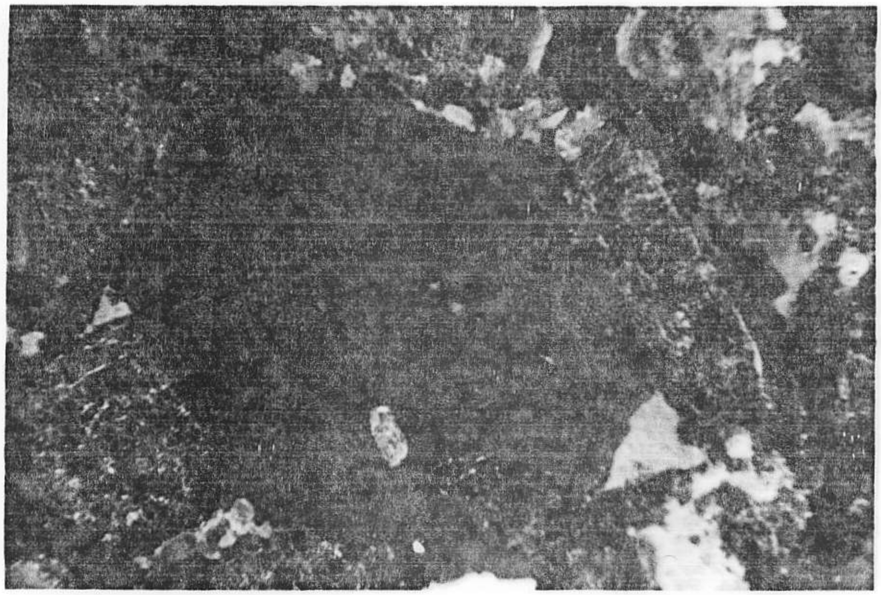
	1	2	3	4	5	6	7	8	9	10	11
Specimen No.	*K-132	*K-209	K-210	K-211	K-112	K-126	K-22	K-187	K-153	K-93	K-23
Rock Name	Spilitized Diabase	Spilitized Diabase	Albite Syenite Porphyry	Altered Albite Syenite Porphyry	Altered Albite Syenite Porphyry	Highly Altered Albite Syenite Porphyry	Syenite Porphyry	Quartz Syenite Porphyry	Quartz Syenite Porphyry	Red Granite Porphyry	Red Granite
Plagioclase	40-50% An_0	55% An_0	25% An_5	30% An_6	40%	10%	17% An_0**	35% An_8	45% An_2	2-5%	2-7% An_0**
Microperthite	-	-	-	-	-	-	75%	44%	30%	73%	70%
Quartz	10%	10-15%	-	1-2% (Sec.)	3-5%	4% (Sec.)	-	3-5%	7-10%	15%	20%
Hornblende	15-20% (Sec.)	trace	23%	15-20%	3-5%	-	-	7%	-	-	-
Clinopyroxene	-	12-14%	-	-	-	-	-	-	-	-	-
Apatite	trace	1%	2-4%	1%	1-2%	trace	trace	1/4-1/2%	1%	1/4%	1/4-1/2%
Sphene	-	-	-	-	1-2%	-	-	1+%	2-4%	-	-
Opaque Minerals	4%	3-4%	1/8%	1-2%	1-2%	2%	1/2-1%	2%	2-3%	2%	1-2%
Unresolvable low bir. matrix	-	-	40%	30%	25%	10%	-	3-5%	-	-	-
Sericite (Sec.)	-	2-3%	-	3-4%	-	50-60%	2%	1%	5%	2%	1/4%
Biotite (Sec.)	-	3-5%	-	-	-	-	-	-	-	-	-
Chlorite (Sec.)	5%	7%	7%	2-3%	10%	10%	1/4%	trace	3-5%	4%	trace
Clay Minerals (Sec.)	10-15%	+2%	-	-	-	-	-	-	2%	-	-
Calcite (Sec.)	-	-	-	1/4-1/2%	10-15%	20%	5%	1/4-1/2%	trace	-	2-3%
Epidote (Sec.)	10%	-	2%	10%	-	-	-	1/2-1%	-	-	-

* May not be part of the Mitchell Intrusions.

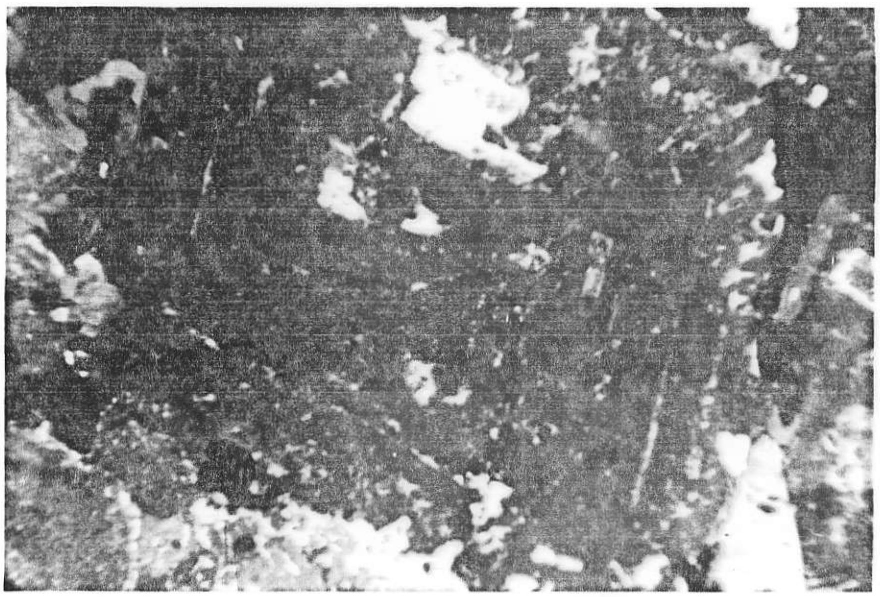
** Plagioclase is in the matrix or associated with microperthite.

(Sec.) - Secondary Minerals

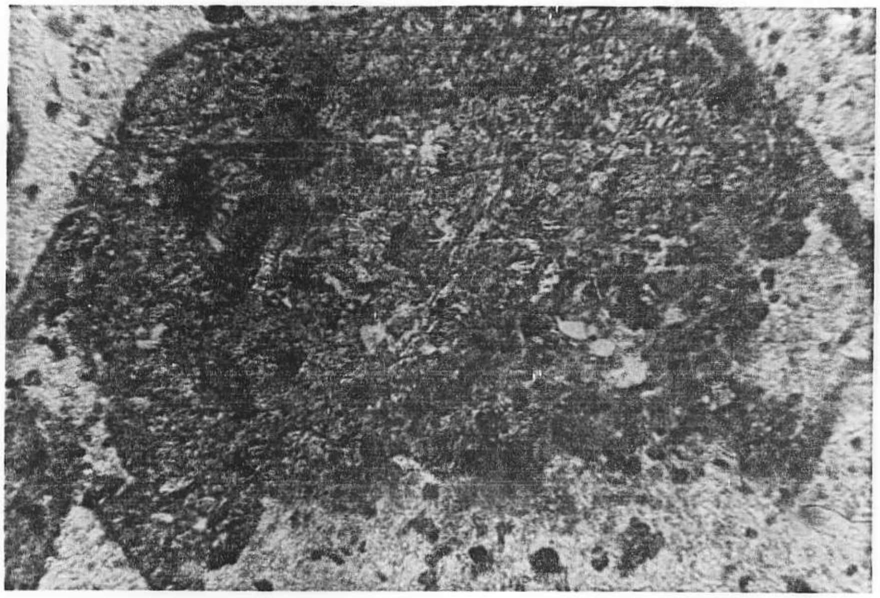
- Microperthite generally contains less than $1/4 = \frac{\text{Plagioclase}}{\text{Microcline}}$ but contains up to $\frac{1}{1} = \frac{\text{Plagioclase}}{\text{Microcline}}$ in the granite.
- Anorthite percentages were determined by optical means.
- Percentages are visual estimations



Photograph 21: (K-288) Photomicrograph of a large microcline crystal surrounded by altered plagioclase crystals in quartz syenite porphyry (X25; polarized light).



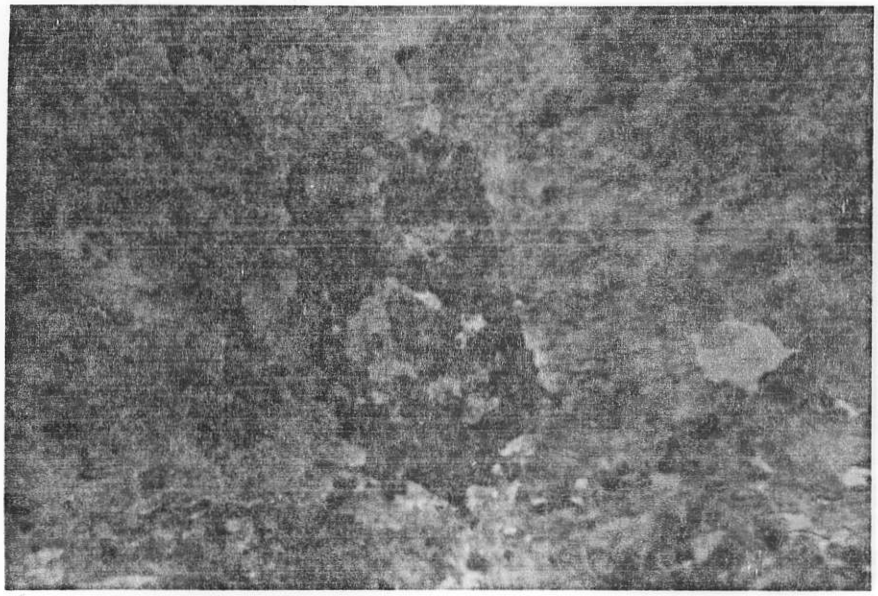
Photograph 22: (K-153) Photomicrograph of a microcline phenocryst with included plagioclase in quartz syenite porphyry; zoning is marked by exsolved albite (X25; polarized light).



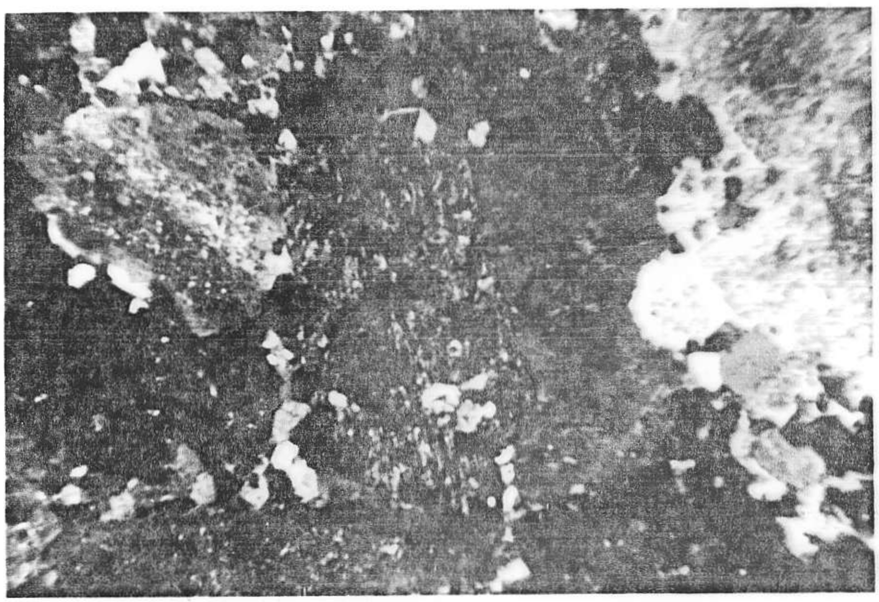
Photograph 23: Photomicrograph of a euhedral hornblende phenocryst partly replaced by grains in matrix (X80; plain light).

present at all places. The plagioclase is invariably partly altered to sericite, calcite, and in a few places to clay minerals. In most thin sections, however, the plagioclase is still recognizable. The primary ferromagnesium minerals in most localities are completely or partly altered to chlorite and in a few localities also to calcite and epidote. The alteration has had little or no effect on potassic feldspar and quartz.

The structural relations of the syenite and quartz syenite porphyry are very complex. Most of the contact areas are complicated by alteration or faulting. The contacts of



Photograph 24: (K-187) Photomicrograph of a typical quartz syenite (resorbed hornblende and a "fused" appearance of grains can be noted - X25; plain light).



Photograph 24A: Photograph 24 with polarized light.

these porphyries with the rocks that they have intruded are gradational. A typical contact of this type is the western boundary of the main intrusion on Mitchell-Sulphurets Ridge. There is a zone of highly chloritized rocks which contains many small, irregular intrusive bodies immediately adjacent to the main porphyry mass. The alteration has obscured the original nature of this zone. Other contacts of the syenite and quartz syenite porphyry are major faults (Figures 4 and 5).

The syenite and quartz syenite are also in contact with granites. On the north side of the Mitchell Glacier the syenitic porphyries, at least in part, are cut by a younger granite. Minor amounts of granite are also associated with the syenite and quartz syenite on Mitchell-Sulphurets Ridge but this granite is distinctly different from the one on the north side of the Mitchell Glacier. Genetically, it is more closely associated with the quartz syenite and syenite porphyry. This granite grades into the quartz syenite which in turn grades into the syenite.

The syenite and quartz syenite porphyry at most localities are massive without any directional features; however, in the immediate vicinity of the younger granite on the north side of the Mitchell Glacier, they show a prominent alignment of the large microcline phenocrysts (Photograph 26). Specimens of these rocks that were examined in thin section are all abnormally low in plagioclase. The writer believes that this alignment is a contact feature and is possibly related to the removal of plagioclase. Another noteworthy internal feature of the syenitic rocks near the granite is the fact that many of them have been shattered. Crystals have been offset along minute fractures and small mylonite zones have developed throughout the rock (Photograph 17).

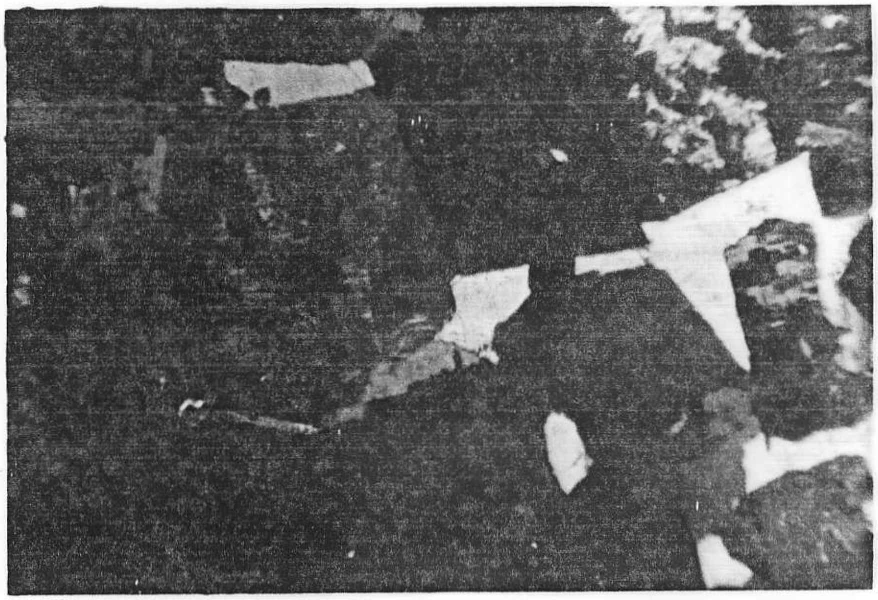
Granite

The distribution of granite was discussed with that of the syenite and quartz syenite porphyry. The type locality for the granite, which cuts the syenitic rocks, is on the north side of the Mitchell Glacier (Figure 4). Only a relatively small area of this granite has been recognized. The granite that grades into the quartz syenite is found in minor amounts scattered throughout the syenite and quartz syenite masses. It may be thought of as a rock essentially the same as the quartz syenite only with a greater amount of free silica. In a very general fashion the quartz content of the Mitchell Intrusions increases to the north and east and is, therefore, seen at a maximum on the north side of the Mitchell Glacier where the cross-cutting granite occurs.

The granite that merges with the quartz syenite is in all aspects the same as the quartz syenite, except it contains more quartz (which is visible in hand specimen). Because of its similarity to the quartz syenite this granite will not be further considered in this section.

In hand specimen the cross-cutting granite (one on the north side of Mitchell Glacier) is a medium-grained, relatively equigranular, dark red rock containing visible quartz and few or no ferromagnesian minerals. It is thus readily distinguished from the syenite and quartz syenite porphyry. Occasionally, the two rock types occur in the same specimen (Photographs 19 and 26), and where alteration minerals coat the fracture surfaces, the true nature of the specimen is obscured. These features result in unavoidable mapping problems. Some of the granite contains large white feldspar phenocrysts (Photograph 20). Quartz, calcite, and less commonly, chlorite veinlets cut the granite. Disseminated chalcopyrite, pyrite, hematite, magnetite, and less commonly molybdenite occur in trace amounts.

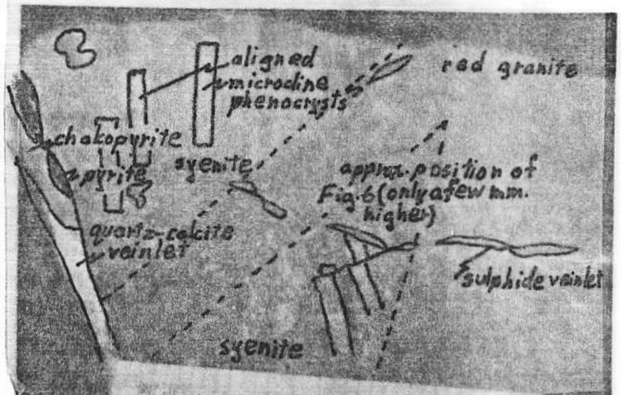
In thin section it is seen that the cross-cutting granite characteristically contains medium-grained, anhedral and subhedral microperthite with interstitial, fine-grained quartz (Photograph 25). A very basic distintion between this granite and the syenitic rocks (including the granite related to the syenitic members) is the fact that it is a one feldspar rock whereas they are two feldspar rocks (Tuttle and Bowen, 1958, p. 130). It contains a single alkali feldspar, micro-



Photograph 25: (K-23) Photomicrograph of the cross-cutting granite (subhedral microperthite with interstitial quartz can be noted - X25, polarized light).

perthite, whereas they contain alkali feldspar and plagioclase. All the plagioclase (albite) in the cross-cutting granite occurs as coarse perthitic intergrowths, is very fine grained interstitial, or in a few places is thought to be a relic product of the older syenitic rocks. The ratio of exsolved albite to microcline in this rock is much greater than in the syenitic rocks. In the late granite it is approximately 1/2 = albite/ microcline and in the syenitic rocks it is approximately 1/10 = albite microcline. In the granite ferromagnesian minerals are scarce or absent. Typical mineral compositions of this rock are shown in columns 10 and 11 of Table IV.

The structural relations of the granite are very complex and many of them are obscured by alteration. In areas that were studied on the north side of the Mitchell Glacier, it was noted that the granite and the syenitic rocks are intimately associated with one another. The exact natures of the contact zones are obscured by alteration. From detailed studies of the hand specimens that were collected, it is thought that the contact is probably gradational. The gradational nature of the contact is attributed to varying amounts of included syenitic material in the intrusive granite. Inclusions in the granite illustrate various stages of disruption and replacement of the syenite. Photograph 17 illustrates a syenitic rock near the contact that had been shattered or "crackled" probably by intrusive processes related to the emplacement of the granite. Photographs 19 and 26 illustrate the granite cutting the syenite (the offset along minute fractures of some of the crystals in the syenite can also be observed). These areas of syenitic material are inclusions in the granite. In thin section it was noted that the large phenocrysts of the syenite are partly transformed to dark purplish red microcline typical of the granite (Figure 6 and Photograph 27). Single crystals of microcline traverse the contact. On the syenite



Photograph 26: (K-23) Red granite cutting syenite porphyry (chalcopyrite and pyrite in quartz-calcite veinlet on left, disseminated chalcopyrite and pyrite throughout, plane surfaces of granite-syenite contact, and aligned microcline phenocrysts in syenite can be noted.

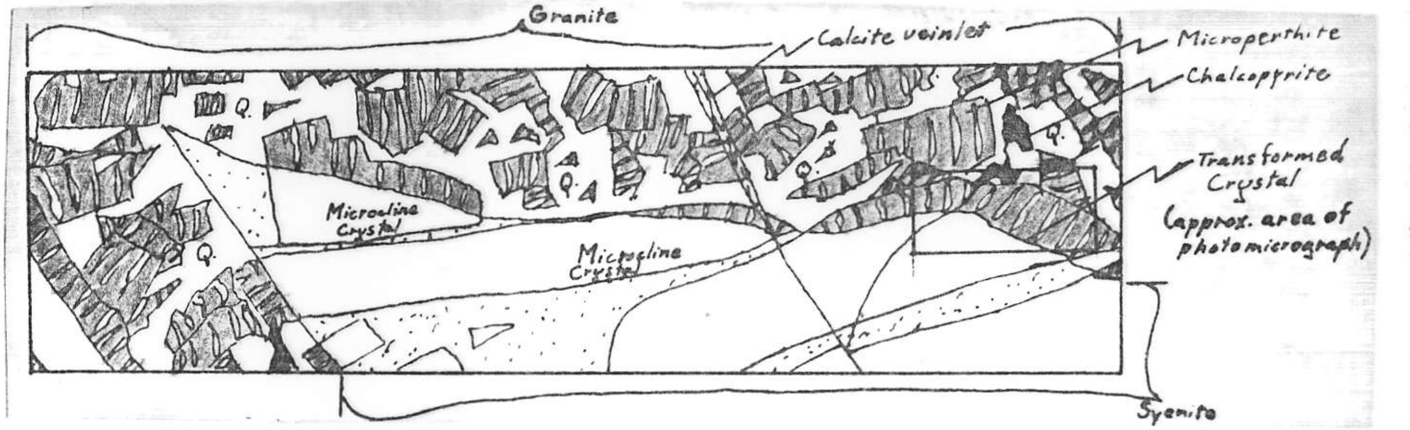
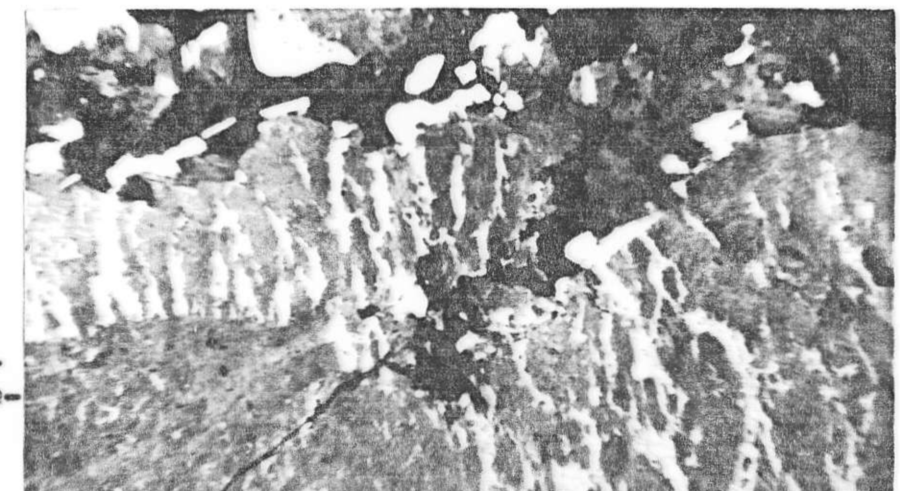


Figure 6: (K-23) Diagram showing the contact relations (as observed in thin section) of the younger granite and the older syenite (the areas containing the red microperthite are granite and the uncoloured areas are syenite; the original plagioclase of the syenite has been destroyed).



Photograph 27: (K-23) Photomicrograph of transformed crystal at syenite-granite contact (X25; polarized light).

side they are white and contain little or no exsolved albite; on the granite side they are dark purplish red and contain abundant exsolved albite. In other specimens large white feldspar crystals typical of the syenitic rocks are found scattered throughout the granite (Photograph 20). These crystals may be plagioclase or microcline. Invariably they are rimmed, veined, and in all stages of replacement by the dark red microperthite. In some specimens euhedral or subhedral forms of what once were obviously single feldspar phenocrysts are now occupied by a mosaic aggregate of crystals with variable optic orientations. The writer believes that these highly corroded white phenocrysts (xenocrysts) represent the last vestiges of syenitic material engulfed by the granite.

Feldspars of the Mitchell Intrusions

A detailed study was carried out on fifteen feldspars from various parts of the Mitchell Intrusions. The locations of specimens used are shown in Figure 15. The results of the X-ray diffraction and universal stage studies are shown in Table V and Figures 7 and 8.

In Table V it can be noted that most of the alkali feldspar consists of two phases. Usually the albite or soda phase is much less abundant than the microcline or potash phase. These features are consistent with those observed in thin section. Antiperthite is absent and in the perthitic intergrowths the exsolved albite is usually less than one

TABLE V- RESULTS OF FELDSPAR STUDY

Specimen No.	Description	av 2θ $(1\bar{3}1)-(131)$ plag.	av 2θ $(\bar{1}01)KBrO_3$ $-(\bar{2}01)$ feld.	Or%- Ab+An%	Ab% - An% *	$2V_x$ K-feld.	$2V_x$ plag. An% by Ritt.Z.
1	Pike's Peak Microcline - reported comp. 95.6% Or, 3.4%, 1.0% An		0.82°	Or_{92}			
2	Amelia Albite - rep. comp. 1.8% Or, 98.2% Ab, 0.4% An	1.06°	1.80°	$Ab+An_{99}$	Ano Ab_{100}		
3	St. Gothard Adularia - rep. Comp. 89.74% or, 9.18%Ab,.10%Ca, .71% Ba -very poor peak for determination.		0.77°	Or_{95}			
K-22	Dark red microperthitic borders - 2 feld. phases K-feld.> Na feld.		1.83° 0.78°	$Ab+An_{100}$ Or_{95}		large xtls. are agg. of small xtls.	
K-22	Large, greyish white phen. -2 feld. phases - only minor exsolved albite		1.86° 0.77°	$Ab+An_{100}$ Or_{95}		71°, 86°, 76° 71°, 80°	
K-23	Large, greyish white phenocrysts (relics from syenite) - only tr. exsolved Ab.		0.76°	Or_{96}			
K-23	Dark, purplish red microperthite - 2 feld. phases $\frac{2}{I} = \frac{Or}{Ab}$		1.85° 0.745°	$Ab+An_{100}$ Or_{98}		72°, 62°, 73°, 70°, 76°, 80° 61°, 78°	112° An_0
K-93	White phenocrysts (syenite relics) -2 feld. phases - Na feld.> K-feld.	1.1°	1.82° 0.75°	$Ab+An_{100}$ Or_{97}	An_0 Ab_{100}	92°	
K-93	Dark, purplish red microperthite -2 feld. phases $\frac{1}{I} = \frac{Or}{Ab}$		1.84° 0.75°	$Ab+An_{100}$ Or_{97}		84°, 82°, 70°, 61°, 80°, 79°	
K-112	White crystals - altered	1.58° 1.59° 1.63°	1.785°	$Ab+An_{97}$	An_{24} An_{24} An_{27}		93°, 98°, 79°, 80° An_0
K-114	Relic, relatively unaltered, large, white K-feld. pheno. scattered throughout alt. rock - neg. Ab.		1.84° 0.785°	$Ab+An_{100}$ Or_{94}			plag. in t.s. 97°, 98°, 98° An_{10-12}
K-153	Inner zone of unaltered plag. crystal	1.355°			$An_{13\frac{1}{2}}$ - $Ab_{86\frac{1}{2}}$		95° An_{13}
K-153	All plagioclase - altered	1.24°			An_8 - Ab_{92}		102° An_4 $91\frac{1}{2}$° An_{12} $89\frac{1}{2}$° An_{10}
K-153	Large, white K-feld. pheno. - scattered throughout - pink borders - 2 feld. phases		1.82° 0.865°	$Ab+An_{100}$ $Or_{87\frac{1}{2}}$		75°, 75°, 71°	
K-153	Small, pink K-feld. crystals - 2 feld. phases		1.87° 0.78°	$Ab+An_{100}$ Or_{95}		79°, 62°, 73°, 69°, 60°, 65°, 62°, 64°, 64°	
K-187	All plagioclase- alt. zoning range	av. 1.22° 1.1°-1.31°			An_7Ab_{93} An_1-An_{11}		96°, 88°, 91°, 94° An_0, An_7, An_0
K-187	Small, pink K-feld. crystals -2 feld. phases		1.825° 0.745°	$Ab+An_{100}$ $Or_{97\frac{1}{2}}$		80°, 71°, 80°, 82°, 83°, 70°	
K-211	All plagioclase-white phenocrysts.	1.37°			An_{15}		96°, 96°, 98° An_9, An_{12}, An_1

* Assuming low temperature

** Location of Specimens is shown in Figure 15

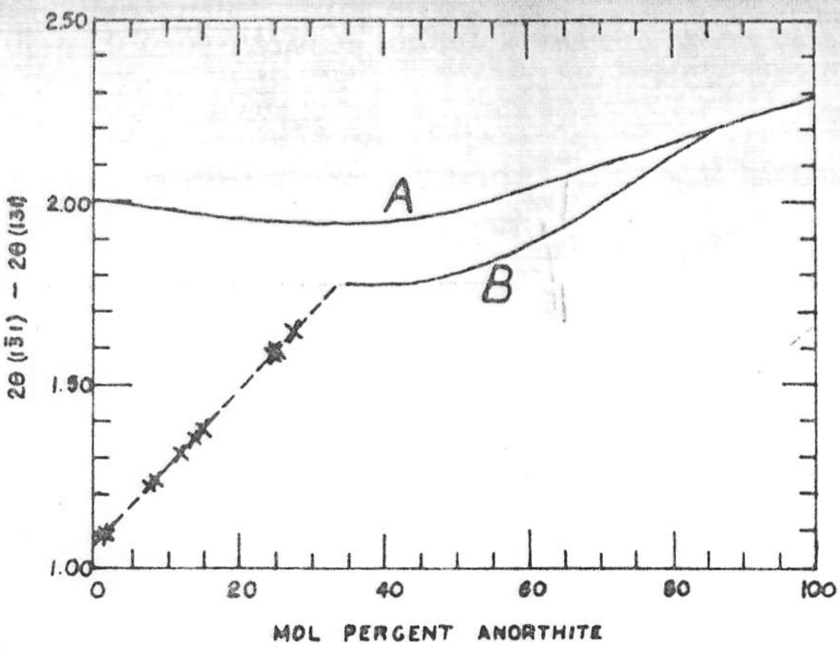


FIGURE 7: Relationship of 2θ(1̄31) - 2θ(131) to Composition for Plagioclase. Curve "A" is for High-Temperature Plagioclase. Curve "B" is for Low-Temperature Plagioclase. (after Smith and Yoder, 1956) "x"'s Denote Composition of Plagioclase of the Mitchell Intrusions Assuming Low-Temperature.

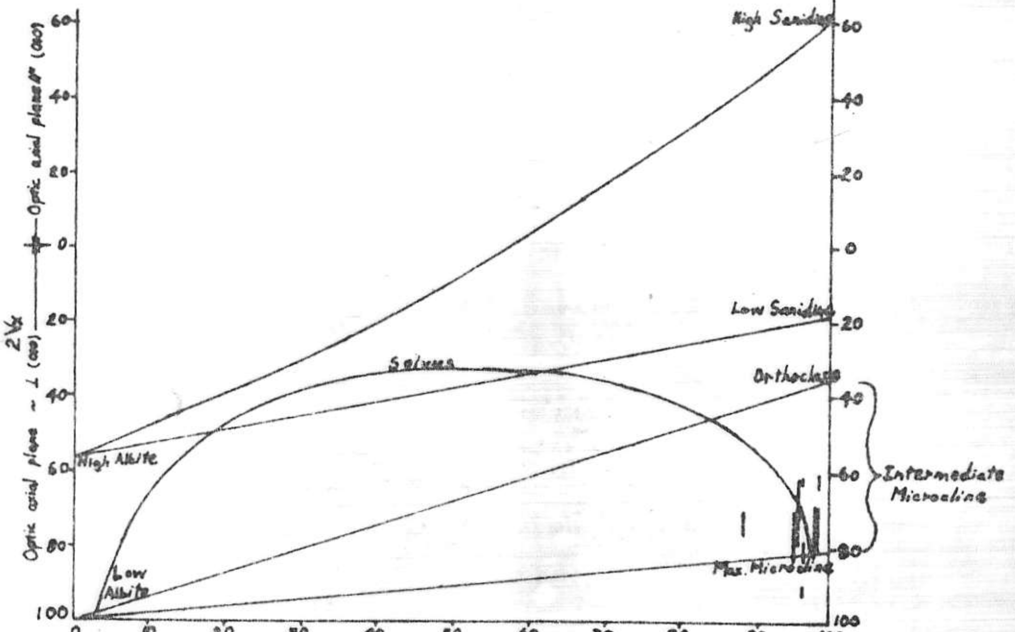


FIGURE 8: Correlation of Optical and Composition Properties of Alkali Feldspar. Lines Parallel to the Abscissa Represent Variation of 2V in Zoned Feldspars Showing a Single Potassic Phase on X-ray Examination. (after Smith and Mackenzie, 1959)

quarter the amount of microcline.

Another feature that should be enlarged upon is the zoning that has been observed in the larger microcline crystals. The X-ray results indicate that the maximum composition range of the potash feldspar in one specimen is probably from $Or_{87\frac{1}{2}}$ Ab+$An_{12\frac{1}{2}}$ to Or_{95} Ab+An_5 (specimen K-153). The former is the composition of a very large white phenocryst and the latter is the composition of very small pink crystals. These feldspars are probably a close approximation of the maximum composition change for the whole area. The composition variation of the zoned crystals of which the $2V_x$ was measured is much less than this maximum variation. For this reason the variations in $2V_x$ probably reflect variations in the degree of ordering of the crystal lattice and not variations in composition.

In using Figure 7 to determine the composition of plagioclase the writer has made the assumption that the plagioclase belongs to the low temperature series. The basis for this assumption is the association of plagioclase with low temperature potassic feldspar. Although this assumption is reasonable, the writer believes that there is probably some departure of the plagioclase from this curve. The X-ray, universal stage, and standard thin section determinations of the anorthite content give similar results but they vary over

10 per cent An. When the anorthite percentage of the plagioclase, as determined by X-ray methods, is plotted against the $2V_x$ (Tuttle and Bowen, 1958, p. 108) it can be noted that the feldspars fall both above and below the curve for the low temperature series. The variations are great enough to suggest that there is a considerable error in the determination of anorthite percentage by the 2θ $(1\bar{3}1) - (131)$ method. Until more is known about this subject these anorthite determinations should only be used qualitatively.

From X-ray diffraction, universal stage, and thin section studies several conclusions can be drawn concerning the methods of investigation and concerning the feldspars from the intrusions:

1. The composition of the plagioclase as determined by X-ray diffraction methods alone should only be used qualitatively.
2. The composition of the alkali feldspar, on the other hand, can probably be determined within 4 per cent accuracy without homogenization by heating.
3. Most of the potassic feldspar of the Mitchell Intrusions is similar in nature. It is intermediate and maximum microcline (Smith and MacKenzie, p. 1181) of the average composition $Or_{95}Ab{+}An_5$.

4. The variations in $2V_x$ of the potash feldspar may be up to 24 degrees in a single specimen. This change in optic angle reflects a variation in the degree of ordering of the crystal lattice, and not a variation in composition.
5. In Figure 8 it is shown that the two crystal phases of the perthite are compatible with and, moreover, support an origin of the perthite by exsolution and not replacement.
6. Most of the exsolution has gone to completion, and yet perthitic intergrowths still persist. This appears contrary to Tuttle and Bowen's conclusion that totally unmixed potassium and sodium feldspar will separate completely in a volatile rich environment (p. 139).
7. It appears, from using Tuttle and Bowen's classification of salic rocks (p. 115, Appendix) that the Mitchell syenite and quartz syenite are group II c subsolvus rocks and that the granite is a hypersolvus granite (Appendix). The facts that the syenite and quartz syenite contain discrete crystals of both plagioclase and microperthite and that the granite contains only discrete crystals of microperthite as their feldspar phases are bases for this distinction.

The writer attributes the apparent inconsistency to post-crystallization changes in the syenite and quartz syenite. The mechanisms involved are explained in the next section.

Genesis of the Mitchell Intrusions

The Mitchell Intrusions are an assortment of injected bodies (Daly, 1933, p. 74) that were emplaced in a hypabyssal environment. Sills, dykes, and irregular stock type masses have been recognized. Earlier plagioclase-hornblende porphyry tended to form the sills and dykes and later syenitic rocks tended to form larger more irregular bodies. Most of these bodies are simple intrusions but a stock-like mass on the north side of the Mitchell Glacier shows evidence of minor composite intrusion. Outside the map-area in the unaltered rocks of the Hazelton and/or Takla (?) group no evidence of regional metamorphism or deep burial can be found. The only high grade metamorphic rocks, suggestive of a plutonic environment are found several miles to the west between batholithic masses of the Coast Mountain complex. These features indicate that the intrusions were emplaced in a hypabyssal environment. The fact that the cross-cutting granite is of the hypersolvus type also supports a hypabyssal environment. Since the rocks of the district show no megascopic signs of regional metamorphism it is safe to assume that the depth of cover at the time of emplacement was probably somewhat less than 30,000 feet, this being the lower limit of the greenschist facies suggested by Turner and Verhoogen (p. 534).

A compositional gradation seems to exist from syeno-diorite and albite syenite (plagioclase-hornblende porphyry) in the Sulphurets Valley Region to the syenite, quartz syenite, and granite on the Mitchell-Sulphurets Ridge and in the Mitchell Valley. Many of the more detailed relationships are still in doubt but a general gradation between these rock types can be established. The mineral paragenesis of the intrusions is shown in Figure 9. The albite syenite and syenitic rocks were not observed in contact but there definitely seems to be a compositional gradation between the two. The main masses of these rock types are separated by major faults and by a very large alteration zone paralleling the faults (Figures 4 and 5). There is one feature, however, that supports compositional gradation. In the zone between the faults, large, white potash feldspar phenocrysts have been found that constitute up to 10 per cent of a highly altered albite syenite porphyry. Similar potash feldspar phenocrysts were one of the first minerals to crystallize in the syenitic rocks above the faults. The close relationship between the syenitic rocks and the granites has already been mentioned. The fact that one granite cuts the syenite clearly indicates that the former must be somewhat later in time. The intimate association of the

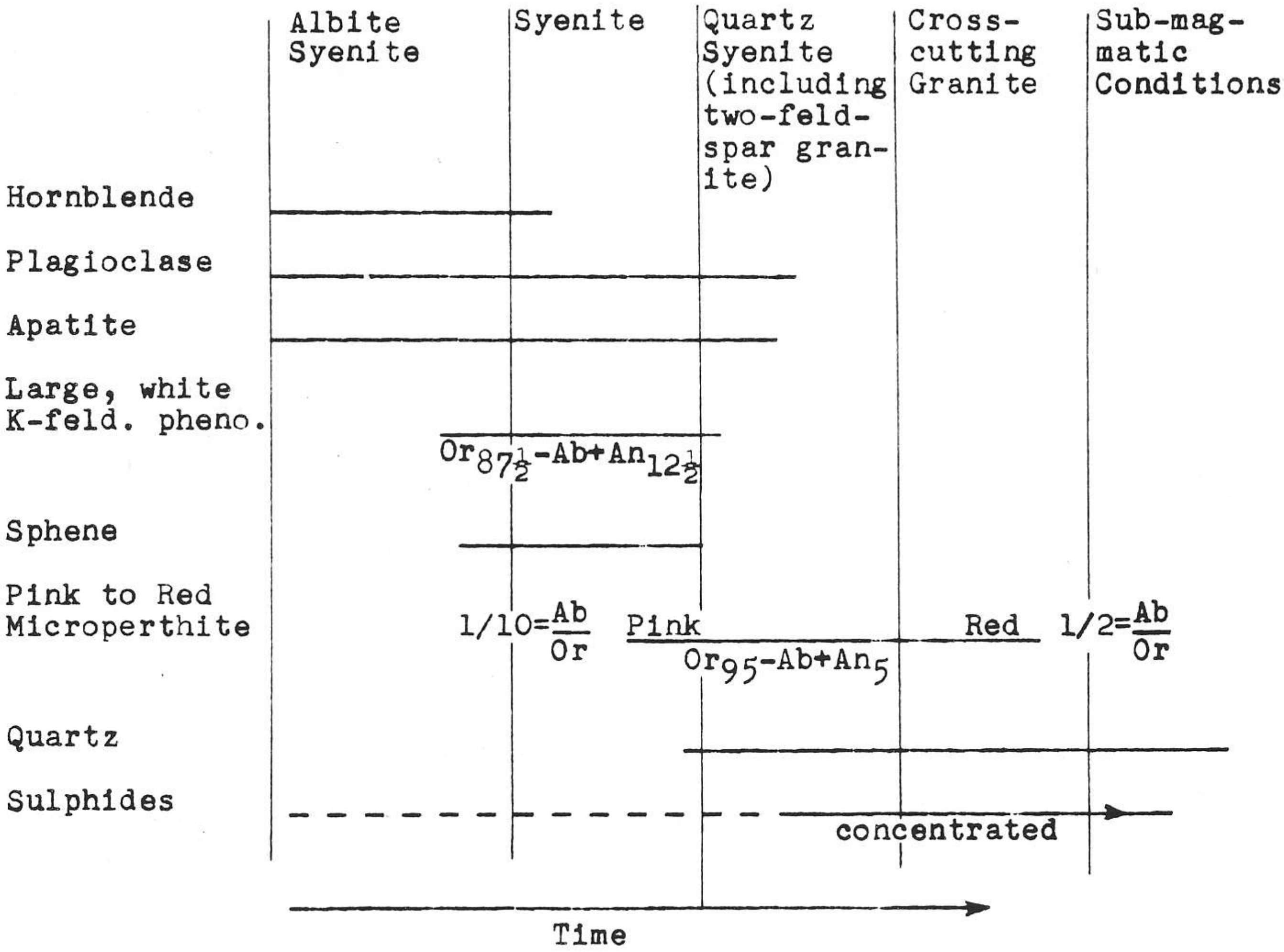


Figure 9: Paragenesis of the minerals in the Mitchell Intrusions.

two, on the other hand, strongly suggests a common origin. The very position of all the intrusions makes it difficult to suppose anything but a close relationship between all the members of the Mitchell Intrusions. Although rather secondary evidence, the fact that disseminated copper, molybdenum, and iron minerals are found associated with all members supports a common origin.

If we first consider the origin of the syenite, quartz syenite, and granites, we will then have better understanding of the problems involved. The writer believes that the syenite, quartz syenite, and granites were derived from a common magma by fractionation followed by albitization of the syenite, quartz syenite and of the two-feldspar granite. The syenitic, two-feldspar rocks crystallized before the one-feldspar granite. If the typical mineral compositions of these rocks are examined (Table IV), it can be seen that the rocks have normal compositions for granites and syenites (Figure 10). This would mean that they have a very low anorthite content. But Tuttle and Bowen (p. 136) state:

> The appearance of plagioclase early in the crystallization of granites, syenites, and nepheline syenites is strongly dependent upon the amount of lime present in the magma. If there is little lime the possibility of plagioclase appearing during crystallization is highly improbable, whereas if the lime content is high plagioclase will certainly be one of the earliest phases to begin crystallizing.

They go on to note that more than 40 per cent of all rocks containing over 80 per cent normative Ab+Or+Q will finish crystallization with a single alkali feldspar, with or without a core of plagioclase. They state, "If fractionation takes place during crystallization, the possibility of completing crystallization with only a single feldspar is greatly enhanced." (p. 137). These facts are directly applicable to the evolution of the Mitchell syenites, quartz syenites, and granites. Using Figure 11, it is easy to see that unless the syenite, quartz syenite, and two-feldspar granite originally contained considerable lime, the plagioclase, which typically comprises about 35 to 45 per cent of the total rock, could not have crystallized as a separate feldspar phase unless the PH_2O was greater than 4,000 kg/cm^2. Such a pressure is unreasonable since it could only be attained below a depth of 8 miles, that is, in a plutonic environment. Therefore, a lime-poor magma would never have been in the two-feldspar field. It is also easy to see how the cross-cutting granite was formed by fractionation of the magma. As the magma differentiated by fractional crystallization it would pass from the two-feldspar field into the one-feldspar field. The soda content of the single feldspar would be increased as fractionation continued. This would explain the higher albite to microcline ratio of the perthites in the one-feldspar granite. To complete the history of these rocks the lime content of the plagioclase must have been lowered after crystallization. The fact that the plagioclases of the syenite, quartz syenite, and two-feldspar granite are invariably altered and in some cases completely missing, although the potash feldspar resists alteration (Photograph 21), indicates that during the alteration period the plagioclase was not in equilibrium with its environment while the microcline was (possibly metastably).

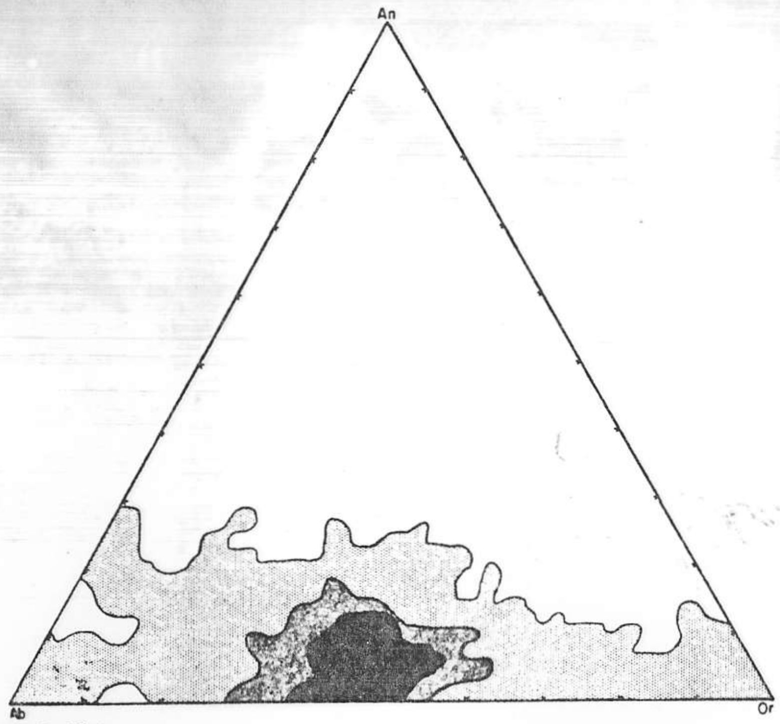


FIGURE 10: *Contour diagram illustrating the distribution of normative Ab, Or, An in all the analyzed rocks in Washington's Tables* (1269) *that carry* 80 *per cent or more normative* $Ab + Or + Q$

Contours more than 1, 2, 3, 4, 5, and 6 per cent. 0.25 per cent counter

(after Tuttle and Bowen, 1958, p. 136)

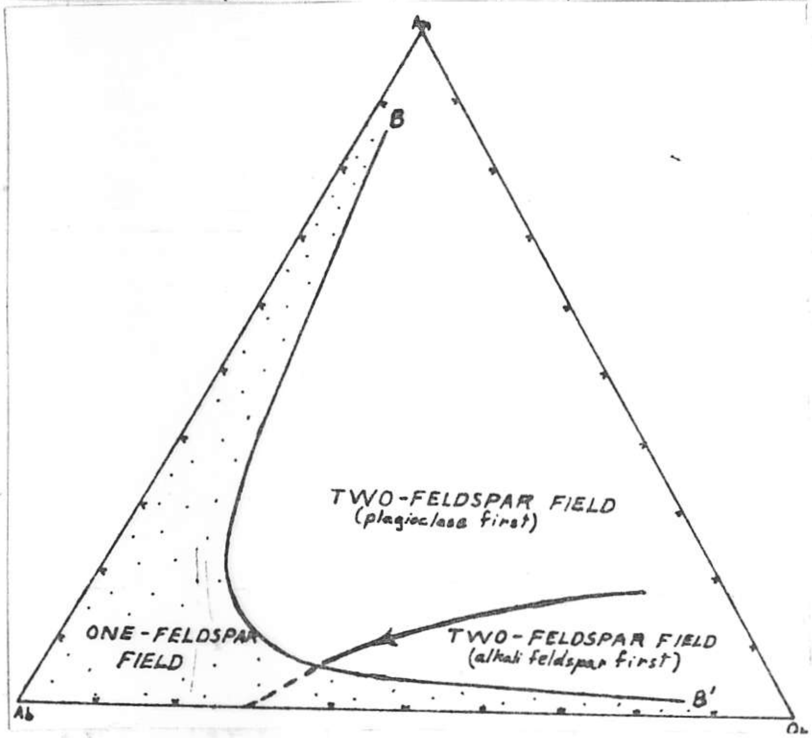


Figure 11: Ternary diagram of the system $NaAlSi_3O_8$-$KAlSi_3O_8$-$CaAl_2Si_2O_8$ (after Tuttle and Bowen, 1958, pp. 132-135). The diagram shows the approximate conditions that might be expected for the crystallization of the Mitchell Intrusions. BB' represents the limit of solid solution.

Besides the "deliming" of the plagioclase described in the preceding paragraph, there are other features that indicate the area has undergone regional albitization, which, at least in part, must have followed the crystallization of intrusions. The spilitized diabases strongly support albitization. The relic clinopyroxene and a well-developed ophitic texture indicate that the rock crystallized as a basalt, but now all the plagioclase is either albite or sodic oligoclase. All the Hazelton volcanic and sedimentary rocks of the area contain mostly albite and less frequently oligoclase. Considering that these are normal eugeosynclinal rocks it is very unlikely that originally the plagioclase did not, at least in some cases, have a higher anorthite content. Regional albitization over an area of at least 20 square miles has surely taken place. Until more is known about the regional distribution of the albitization, the writer hesitates to suggest whether the albitization is related to metasomatism immediately following the emplacement of the Mitchell Intrusions or whether it is related to a more widespread spilitic province.

Since it is probable that all the surrounding rocks have been albitized, it is difficult to see why the syenodiorite and albite syenite porphyry should not also have been affected. The presence of hornblende and plagioclase phenocrysts in rocks is normal and very common, but the presence of albite and hornblende phenocrysts in rocks is far less common. Therefore, taking the simplest explanation, the plagioclase had a much higher anorthite content at the time of crystallization than at present. It can be expected that the plagioclase and hornblende were the first crystals to separate from a dioritic or comparable magma.

Even though extensive metasomatism has obscured many of the original features of the intrusions, guesses can still be made on the nature of the original rock types and on the conditions at the time of emplacement. If, as it appears, all the plagioclase has been albitized, then it is safe to assume that the original rocks probably belonged to a normal calc-alkaline series. Diorites, monzonites, quartz monzonites, syenites, and granites were probably present. The plagioclase-hornblende porphyry (albite syenite and syenodiorite) would have been the more basic types, the syenite, quartz syenite, and two-feldspar granite would have been the intermediate rock types, and the one-feldspar or cross-cutting granite would have been the most acidic member. Compared to the other rock types the one-feldspar granite has remained relatively unchanged.

A general gradation in mineralogical composition between the various members of the Mitchell Intrusions can be accounted for by differentiation by fractional crystallization. There are two distinct possibilities: differentiation in place and differentiation at depth. The writer favours the hypothesis that differentiation took place at depth but only slightly below the observed level. The distribution of the intrusive rock types would permit differentiation in place but there are objections to such a hypothesis. The one-feldspar granite shows cross-cutting relationships; therefore, it has been mobilized to some extent. Secondly, if differentiation was in place there should be considerably more "dioritic" rocks to account for the amount of derived rocks. Although such a large body or bodies of " dioritic" rocks have not been recognized, it is possible that a large portion of the highly altered areas could have been "dioritic" rocks. The writer does not favour differentiation at a great depth because of the distribution of the intrusive rock types. If the magma was at a great depth, the distribution of the rock types should be more irregular.

Late Dykes

Scattered dykes cutting earlier rocks and structures have been mapped in Sulphurets Valley and on Mitchell-Sulphurets Ridge. These dykes, although very narrow, are in some places continuous for great distances. The best example is a low-dipping one that outcrops on the northern slopes of Sulphurets Valley (Figure 4). In hand specimens these dykes are usually dark green and resemble fresh basalt, but in thin section it is seen that they are keratophyres. Typically they contain 25 to 30 per cent albite, 35 to 40 per cent hornblende, a trace of corroded clinopyroxene, and many secondary minerals.

The specimens that were sectioned were taken in areas where the dykes traverse alteration zones. Possibly the albitization is a result of contamination since the dykes were in contact with many readily accessible, reactive, low-temperature minerals.

Structural Geology

Stratigraphic Sequence

The stratigraphic sequence in the Mitchell-Sulphurets Region has not been determined because alteration and intrusions have obscured the relationships. In general there is a large volcanic unit in the eastern half of the area and a large sedimentary unit in the western half, but stratigraphic positioning of these units must await studies in districts that are not as complex as the map-area.

Folds

In the map-area the type of folding could not be ascertained, since sedimentary lamination has been disrupted by widespread intrusion and faulting and in some places has been obliterated by metasomatism. From Figure 12, a stereogram of poles to bedding, it can be seen that the area is characterized by relatively haphazard, moderately to steeply dipping beds most of which strike approximately north-south.

Some features concerning the nature of the regional folding were noted while doing reconnaissance mapping about 5 miles north of the map-area in the vicinity of Treaty Creek Glacier. Near the toe of this glacier and along an eastern tributary glacier part of the crestal region of a major fold is exposed (sketch map, p. 28). The axial trace of this antiform approximately bisects the Treaty Creek Glacier; the plunge is probably low to the north. The main fold is a concentric type with a smooth, round hinge zone and limbs that have steep but opposing dips. There is no significant thickening in the crestal region.

A thick unit of sedimentary rocks occuring above the main volcanic unit which is shown in Photograph 12 contains many closely spaced accordion-type folds (wavelength about 100 feet). These minor folds extend north to the hinge area of the main structure and south to a main icefield (about a total of 4 miles). They are not present along the western limb of the main antiform. Unfortunately where they merge with conformable beds, outcrop is poor. In this area a few outcrops of massive, dark, argillaceous sediments are exposed. Along the eastern limb of the main antiform the accordion-type folds continue for several miles but their total extent is not known. In the most southern exposures that were examined the accordion-type folds were nearly recumbent. If the main antiform has a northerly plunge then this would be the farthest point exposed down the limbs of the main structure.

There are several mechanisms that possibly could be responsible for the formation of these unusual accordion-type folds. Some are less feasible than others. It is not very probable that they were formed at the same time as the main structure. Their geometry differs greatly from that of the main antiform and it is questionable if the thick sedimentary unit could undergo the much greater degree of crustal shortening necessary to form these tight accordion folds over the broader warps. The possibility of two periods of orogenic deformation in these rocks is also very small. The rocks show no evidence of extensive deformation, regional metamorphism, or any other phenomena that might be expected in such areas. There are two other possibilities that seem more feasible. The first is that these accordion folds may be related to a major fault. A more complete knowledge of the regional geology would be necessary to substantiate the existence of such a fault. The second possibility, the one that the writer favors, would be the development of the accordion folds by soft-sediment deformation possibly by gravity sliding. Such structures might be expected in areas where there are unstable bottom conditions and turbidity current deposition. The presences of the nearly recumbent minor folds on the eastern limb of the main antiform supports the latter hypothesis. A change in their attitude would be expected if they have been folded.

The reconnaissance work indicates that regional folds are reasonably simple, relatively open structures which in some areas may be complicated by the presence of minor folds, faults, intrusions, and metasomatized zones.

Schistosity and Cleavage

Schistosity and cleavage are the only other minor structures in the map-area of major importance besides bedding. These structures are found at many places throughout the area. The distinction between cleavage and schistosity in the field has been somewhat arbitrary especially where it has been difficult to distinguish between cleavage and poorly developed schistosity. In general where there is a prominent alignment of micaceous minerals (mainly sericite and chlorite) the structure has been called schistosity, and where there is no prominent development of micaceous minerals it has been called cleavage.

Figure 13 is a contoured stereogram of poles to schistosity and cleavage. Figures 13a and 13b are uncontoured stereograms of poles to cleavage and schistosity respectively. It can be noted that the poles form a broad, irregular girdle along a great circle. This feature shows that the cleavage and schistosity have both been warped. The marked concentration near the south edge of the stereogram is related to the area of best developed schistosity which occurs in highly altered rocks on the south side of Mitchell Glacier. This concentration is not a result of the warping.

In the past empirical observation in the field has shown that in many localities cleavage and schistosity bear a consistent relationship to major structures. This, however, does not seem to be the case in the Mitchell-Sulphurets district. There are some areas that contain well-developed quartz-sericite schists where the schistosity is about 90 degrees to the main faults or lineaments. These areas are nearly as wide as they are long. No folds or shear zones can be found that are responsible for these large areas of well-developed schistosity or cleavage. If this is the case then there should be some other mechanism responsible for the production of these structures. A very significant feature is the direct correlation between the degree of alteration and the development of schistosity. Typically the most highly altered rocks, provided micaceous minerals are present, have the best developed schistosity. The only slightly altered rocks that have good cleavage or any schistosity in them are some of the incompetent sediments. The development of schistosity and cleavage in the Mitchell-Sulphurets region may have been dependent on two factors: The degree of alteration and the amount of stress in the rock at the time of alteration. As alteration proceeded micaceous minerals crystallized and simultaneously the strength of the rock was decreased. If there was sufficient stress in the rock

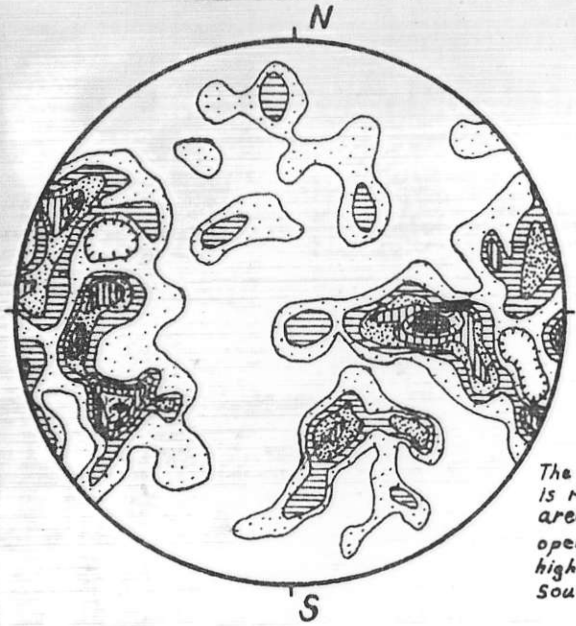


FIGURE 12 : Stereogram of Poles to Bedding Contoured for 1% of Total (100 pts.)

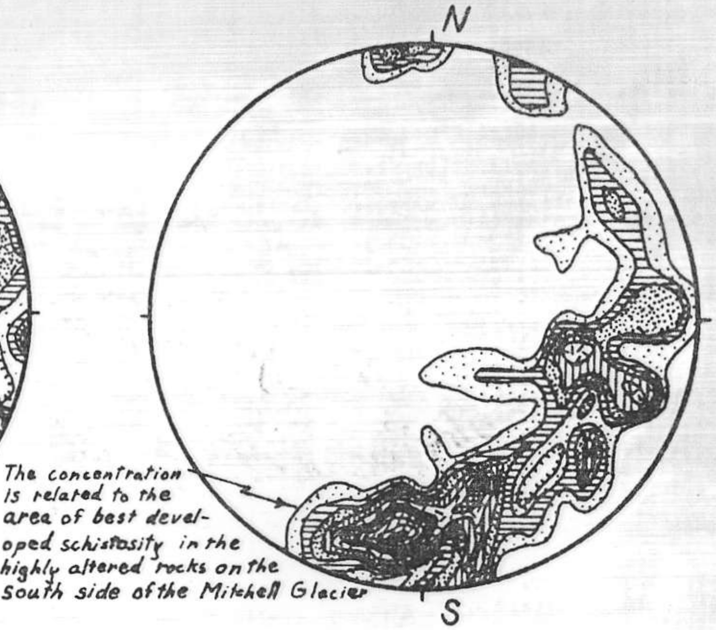
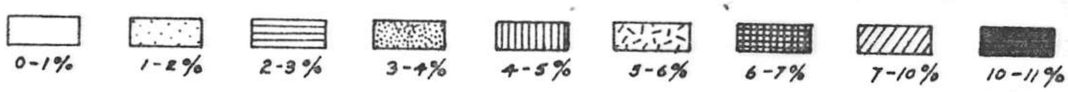


FIGURE 13 : Stereogram of Poles to Schistosity and Cleavage Contoured for 1% of Total (100 pts.)



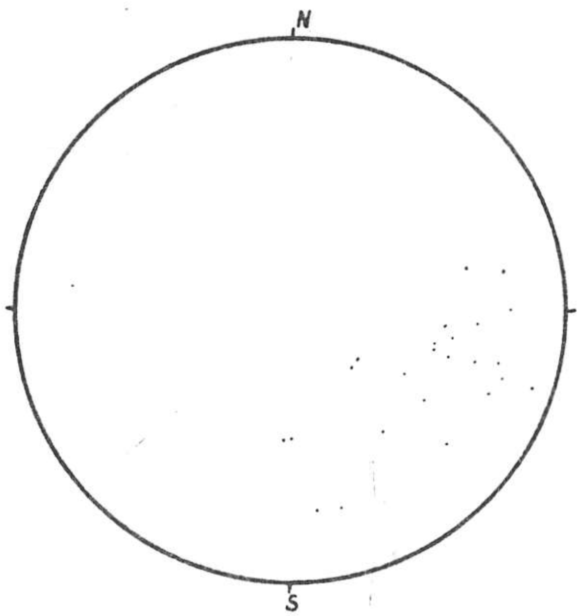


FIGURE 14A : Stereogram of Poles to Cleavage

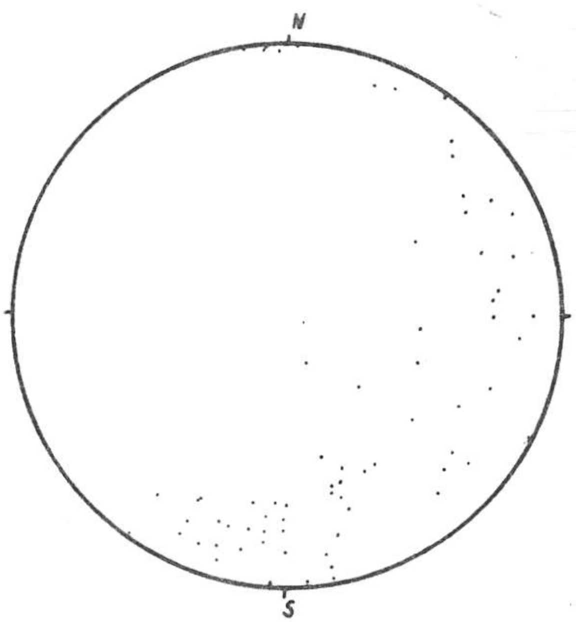


FIGURE 14B : Stereogram of Poles to Schistosity at the time of alteration the micaceous minerals would tend to be aligned perpendicular to this stress. Development of schistosity in this manner would be somewhat similar to the development of axial plane or AB cleavage of folds, but it would be directly related to alteration and not to regional deformation of the rock.

Faults

Faulting is of major structural importance in the area. Main faults that were recognized are close in time to the period of rock alteration and probably were active at the close of the Mitchell magmatic cycle. The faults that are shown in Figure 4 are marked by offsets in lithologies. Many of the faults have only tentative positions (indicated in Figure 4 by question marks), because the metasomatism has affected most faults and has made their recognition difficult. Undoubtedly, there are many minor faults that have not been recognized.

The most important faults are a group that cut the main bodies of the Mitchell Intrusions (the western and central parts of Figure 4). These faults strike approximately north-south and dip about 40 degrees to the west. The upper or most westerly of these faults is the best documented of the group, probably because it is the youngest and has not been as strongly affected by the alteration. At least some movement along this fault is post alteration since it offsets major alteration zones. Movement along this group of faults was probably very complex.

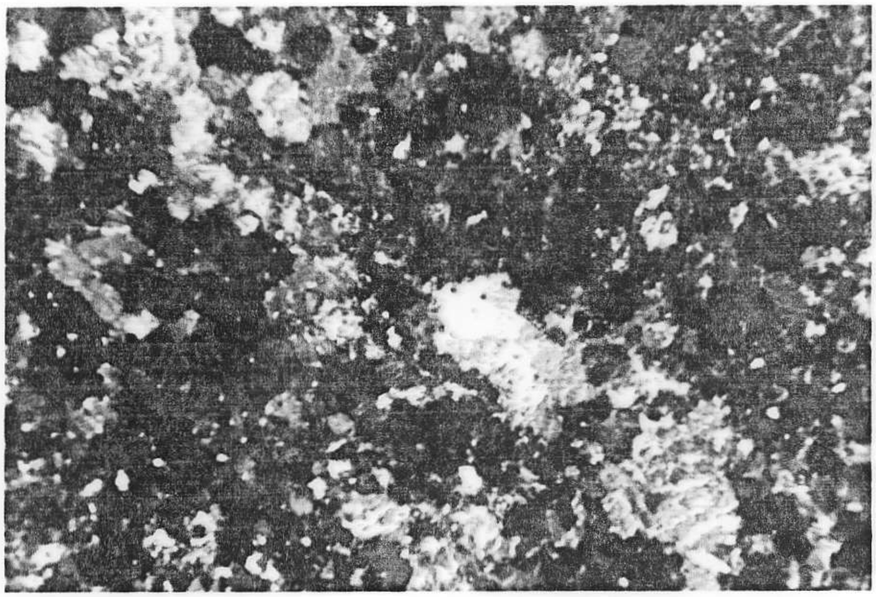
Drag features in the Mitchell Valley (west side down relative to east) are opposite to those observed in places on Mitchell-Sulphurets Ridge. Even though the drag features are of little value in determining the movement, the movement can be estimated from the general position of the intrusions and from the positioning of various intrusive rock types. The rock types on Mitchell-Sulphurets Ridge are very similar to those in the Mitchell Valley but they are distinctly different from those in the Sulphurets Valley. From these features it can be seen that the resultant movement along the faults has shifted the west block to the south and slightly to the east relative to the east block. This movement is of a very unusual type for moderately dipping faults, that is, strike-slip movement with minor thrusting. A general rotational movement on these faults is suggested by the fact that the regional strike is different in the west and east blocks. In the west block units strike slightly to the east of north and in the east block units strike generally to the northwest. The total amount of movement along the faults is unknown. The west block has moved possibly a few thousand feet to the south relative to the east block or it could have moved over a mile.

Besides the faults described above the only other possible major fault that has been recognized is the marked lineament trending north south along the eastern border of the map-area (Frontispiece). Until further information is gathered the writer is reluctant to call this structure a fault for no major offset of lithologies has been demonstrated, and beyond the northern border of the map sedimentary and volcanic units cross the lineament (section AB Figure 5). Certainly at the southeast corner of the map-area this structure is some type of fracture or fault system. There are small but steep-walled gullies along the lineament. If this structure is a fault it is definitely pre-alteration for it has controlled the development of alteration zones.

Mylonite Zones

Mylonite zones have been found associated with major faults, and on a small scale as minute zones in the "crackled" members of the Mitchell Intrusions. The mylonite zones associated with major faults are chiefly in altered rocks. Megascopically, the mylonitized rocks are mostly buff to grey, some have a very distinctive blotchy appearance, and most of them have a "cherty" texture. In thin section these rocks are seen to be characterized by a very fine-grained, microcrystalline, mosaic of feldspar. Most of the mylonites are rich in albite, low in quartz, contain considerable potash feldspar and sericite, and minor amounts of many other minerals.

Minute mylonite zones, which are chiefly in the "crackled" syenitic rocks adjacent to the cross-cutting granite



Photograph 28: (K-76) Photomicrograph of mylonitized granite or quartz syenite (some of lighter grains are microperthitic - X80, polarized light).

on the north side of the Mitchell Glacier, probably formed from stresses developed by magmatic activity. They seem to be closely related to the intrusion of the granite. Some of these zones are present in specimen K-22, shown in Photograph 17.

Tectonic Breccia and Boudinage

There are many breccias in the Mitchell-Sulphurets region of which the origin is unknown, but there is evidence to indicate that a large shear or breccia zone, which is shown in Figure 4 on the north side of the Mitchell Valley, was formed by tectonic activity that is probably related to faulting. The central and eastern parts of this zone are a jumbled complex of brecciated, relatively unaltered sedimentary, volcanic, and some intrusive rocks. On the western border of the area there are features that indicate the zone has suffered extensive shearing. Sedimentary beds are in all stages of disruption. First boudinage structures developed; then as deformation continued the boudins were brecciated and the fragments were jumbled together in a large movement zone. There is no obvious explanation for such a large movement zone, but since the faulting is probably very close in time to the main period of alteration, there is a possibility that this movement zone is a result of a rapid release of volatile materials.

CHAPTER IV - ROCK ALTERATION

Introduction

Alteration is widespread in the rocks of the Mitchell-Sulphurets Region. If the Mitchell Intrusions are considered to be the source of the altering fluids, it is interesting to note that the visible portion of the alteration halo is greater than three times the area of the intrusive bodies. All rocks of the area, even the ones that megascopically appear to be fresh, have been affected to some extent (Photographs 9 and 10). Weak propylitization is the most common type of alteration throughout the area. Regional albitization of the plagioclase feldspar has also taken place but it is questionable if this phenomenon is directly related to the main period of alteration or whether it is related to a more widespread spilitic province. Albite, calcite, sericite, quartz, chlorite, and pyrite are the most common secondary minerals. The distribution of these and other secondary minerals, determined from thin-section analyses, is shown in Figure 15. The preservation of pseudomorphs with increasing alteration indicates that a major portion if not all of the alteration has taken place at constant volume.

Time of Alteration

The major period of rock alteration must have followed the consolidation of most of the Mitchell Intrusions. Possibly it was synchronous with or closely followed the crystallization of the cross-cutting granite. Large portions of the plagioclase-hornblende porphyry and moderately large portions of the syenite and quartz syenite have been altered. In contrast, the areas of cross-cutting granite that have been examined, although they show much evidence of veining by quartz and calcite, do not contain much rock alteration. The inference follows, that since the cross-cutting granite is the youngest of the Mitchell Intrusions, alteration may have been continuous with crystallization. Although this might well have been true, it should be noted that the minerals in the cross-cutting granite are not as susceptible to alteration as those in other rocks. This leads to another inference that the minerals in the granite were closer to being in equilibrium in the alteration environment than those in the other members of the Mitchell Intrusions.

The field relations make it difficult to fix the relative time of the periods of faulting and alteration. Large alteration zones have been offset by major faults. The sharp upper limit of alteration on the north slopes of the Mitchell Valley is a result of its being mainly a fault contact. On the other hand, many major faults have been rehealed and obliterated by alteration and have also controlled the development of some alteration zones. Moreover, the mylonite zones that were examined have been affected by alteration. These faults with their associated mylonite zones zre definitely post intrusion.

The only simple explanation would be that the major periods of faulting and rock alteration were very close in time.

Nature and Temperature of the Altering Fluids

A study of the products of alteration gives some indication as to the nature and temperature of the altering fluids. As stated before, the main alteration minerals in the Mitchell-Sulphurets region are albite, calcite, sericite, quartz, chlorite, and pyrite (?). Chlorite and pyrite are less abundant than the others. It is known that the alkali content governs the formation of zeolites, sericite, and kaolin in alteration zones at temperatures below 400° C. Turner and Verhoogen in discussing experimental work done by Noll (p. 577) state:

> At lower temperatures (below 400° C.) it depends upon the alkali concentration of the active solutions whether zeolites, sericite, or kaolin are formed..........
>
> Kaolin originates from SiO_2- or Al_2O_3-gels in neutral solutions free of alkali metals or in acid solutions containing alkali metals, at temperatures below 400° C.; on the other hand, montmorillonite forms in alkaline solutions of the alkali metals, and at higher concentrations of potash, sericite appears. At very high concentrations of alkali, zeolites, especially analcite appear.

If, as the writer believes, alteration in the Mitchell-Sulphurets region is predominantly a low-temperature phenomenon (below 400° C.), then from Noll's experimental work it would seem that the altering fluids contained moderate concentrations of the alkali metals. These conditions could possibly account for the extensive albitization as well as for the sericitization. These concentrations were probably relatively uniform over large areas since there is no evidence of strong zonation.

Besides the alkali metal content, the solutions must also have carried considerable carbon dioxide or soluble carbonate to facilitate the extensive formation of calcite. In the case of the map-area silica would have been displaced from lime silicates and calcite would have formed. Turner and Verhoogen (p. 578) state:

> Whereas silica readily displaces carbon dioxide from carbonates at moderate and high temperatures, many silicates are converted with equal ease to carbonates by hydrothermal reaction with solutions containing carbon dioxide or soluble carbonates, at low temperatures. Autometasomatic replacement of such minerals as feldspars, augite, and olivine by carbonates is a common deuteric process illustrated by igneous rocks of widely different composition.

This feature also explains why no skarn zones are found near the intrusions even though there are many limy rocks in the vicinity. Besides the liberating of the silica from the silicates by the carbon dioxide or soluble carbonate, quartz was probably added to the solutions at their source. Many quartz veinlets are found in the granites and syenitic rocks, some of which are relatively unaltered.

The presence of hydrogen sulphide or some such sulphur-bearing compound in the altering fluids would be the easiest way to account for the formation of pyrite in the altered rocks. The ferromagnesian minerals such as hornblende, pyroxene, and biotite would be replaced by a magnesium-rich chlorite and by iron sulphide. The reason for believing that this type of chlorite may be relatively rich in magnesia is discussed later.

Many of the hand specimens, examined in this study, contain inconspicuous quartz, calcite, chlorite, and in a few from Mitchell Valley, fluorite veinlets. These minerals at many places form a network of criss-crossing veinlets, which average from 1/32- to 1/4 of an inch in width. In some areas fractures containing these veinlets may have been the only channel-ways for the altering fluids.

There are several reasons for believing that alteration throughout the area is uniformly a low-temperature variety. First, there is no evidence of steep thermal gradients. Alteration varies in intensity but there is no significant change in the types of secondary minerals from place to place (Figure 15). Secondly, high-temperature alteration minerals, such as calc-silicates, potash feldspar (except metastably), pyrophyllite, tourmaline, etc., have not been found. Thirdly, all secondary minerals that have been identified, except the potash feldspar, are compatible with and support a low-temperature origin. The potash feldspar, which is thought to be secondary, is found only adjacent to some intrusive contacts in high-temperature zones where low-temperature metasomatism has been superimposed. The potash feldspar is possibly a metastable relic of the earlier high-temperature metasomatism. The ubiquitous nature of secondary calcite probably signifies a widespread, relatively uniform low-temperature environment of alteration. Turner and Verhoogen (p. 578) state that secondary hydrothermal calcite is a product of low-temperature metasomatism rather than moderate or high temperature.

In summation the active fluids at the time of metasomatism probably contained moderate concentrations of Na, K, SiO_2, and H_2S, high concentrations of CO_2 and H_2O, in the Mitchell Valley trace amounts of HF, and were at some elevated temperature probably below 400° C. for a considerable period of time.

Degree of Alteration

The altered rocks can be subdivided into two groups depending on the degree of alteration. The first group includes those rocks in which relics of original high-temperature constituents are in all stages of replacement by low-temperature minerals. With continuing alteration the primary minerals that were susceptible to replacement became more and more altered until a point was reached that all the minerals susceptible to alteration had been completely destroyed. This point marks the start of the second group of altered rocks. Now with continuing alteration the secondary minerals increased in size and developed better or what might be described as "fresher" crystals (Photograph 34). Photographs 29 to 33 illustrate the first group and Photographs 34 and 35 illustrate the second group. Such a subdivision may be of primary importance in distinguishing the alteration zones that make the best host rocks for the ore minerals. From this preliminary study of the Mitchell-Sulphurets region it seems that the deposits that have the best chance of being ore grade are in the second group and that the less promising deposits may occur in either group.

Judging from the varying degrees of alteration of rocks over large areas, the writer believes that there were probably many "centers" of alteration. Unless such minerals as sericite and calcite can form over an extremely wide range of temperatures, there was probably not significant temperature variations from the highly altered rocks to the outlying areas. Also, as shown by results of Noll's experiments in the previous section, the concentrations are important for governing the formation of alteration minerals in an environment of low temperature. That sericite is widespread, and kaolin, other clay minerals, and zeolites are negligible, mean that the concentrations in the altering fluids probably did not vary greatly from the highly altered rocks to the less altered rocks. This leaves one critical variable; that is, the degree of soaking or the amount of altering solutions to which the rock was exposed.

The quartz-sericite schist probably represents the highest grade of alteration. Bateman (p. 104) states:

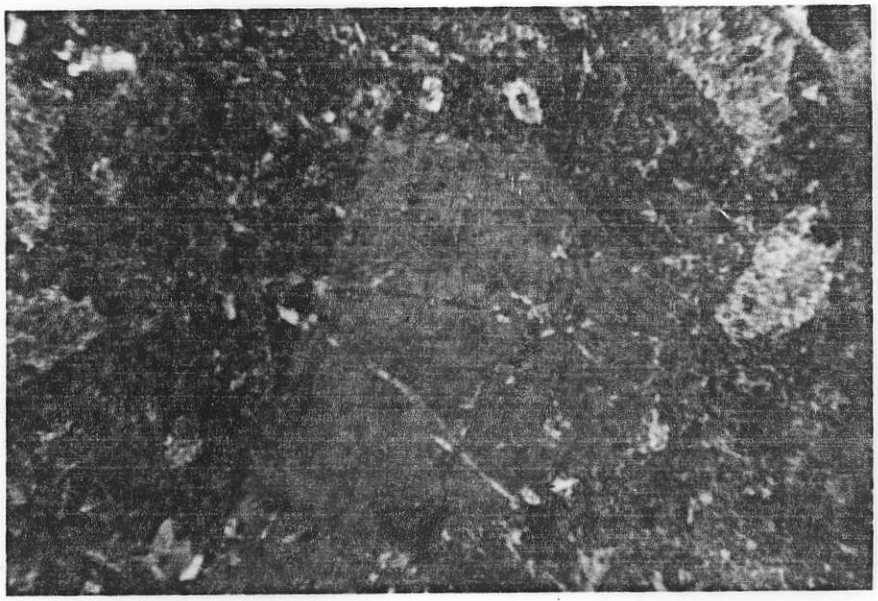
> With most rocks, except limestone and quartzite, the end product of alteration is a rock composed mostly of sericite and quartz. The original feldspars, ferromagnesian minerals, and micas are all changed to sericite, and silica is generally added.

Since the greatest development of quartz-sericite rocks is in the Mitchell Valley (there are also considerable quantities of quartz-sericite schist about where the legend is in Figure 4) the main center of alteration was probably near the cross-cutting granite.

Susceptibility of Minerals to Alteration

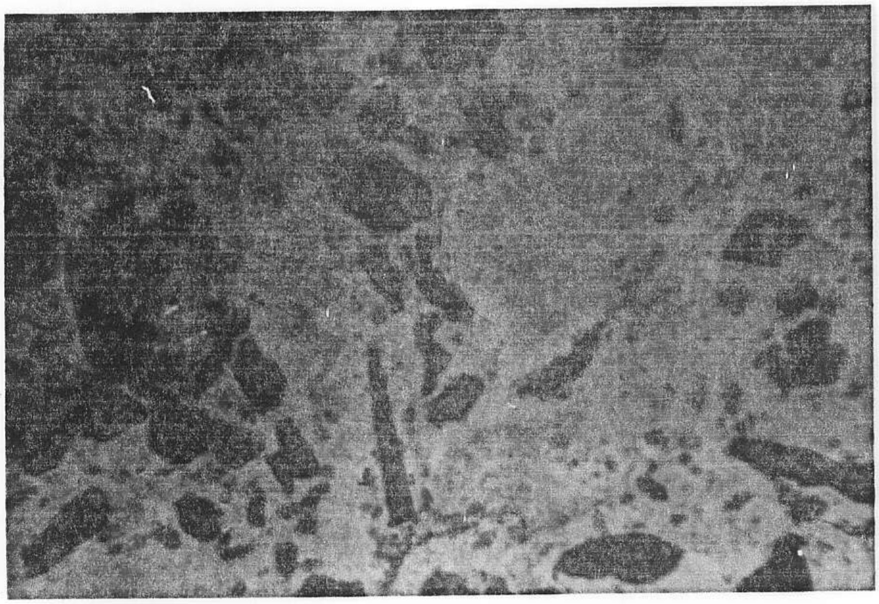
In general ferromagnesian minerals and plagioclase feldspar were by far the most susceptible to alteration, and apatite, potash feldspar, and quartz resisted alteration.

A general alteration series can be established by using the pseudomorphs in the altered plagioclase-hornblende porphyry. Photographs 30 to 33A illustrate increasing alteration in these rocks. Photograph 29 shows a relatively unaltered microcline phenocryst in an otherwise highly altered porphyry. In these rocks the hornblende is most commonly replaced by chlorite, calcite, pyrite, and trace amounts of silica. In some of the least altered rocks it is replaced

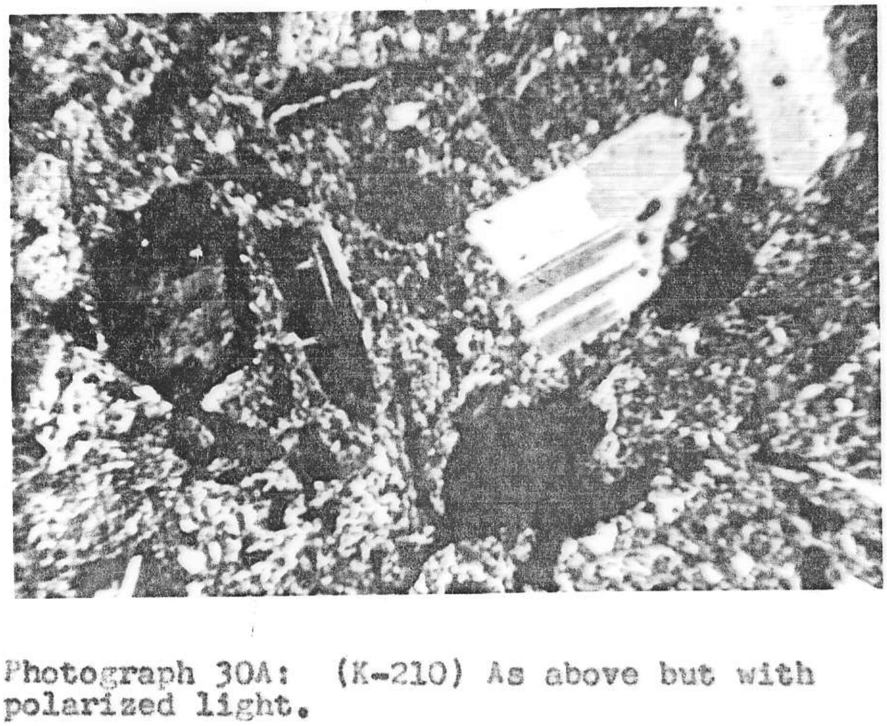


Photograph 29: (K-167) Photomicrograph illustrating a relatively unaffected microcline phenocryst in an otherwise highly altered albite syenite porphyry (X25; polarized light).

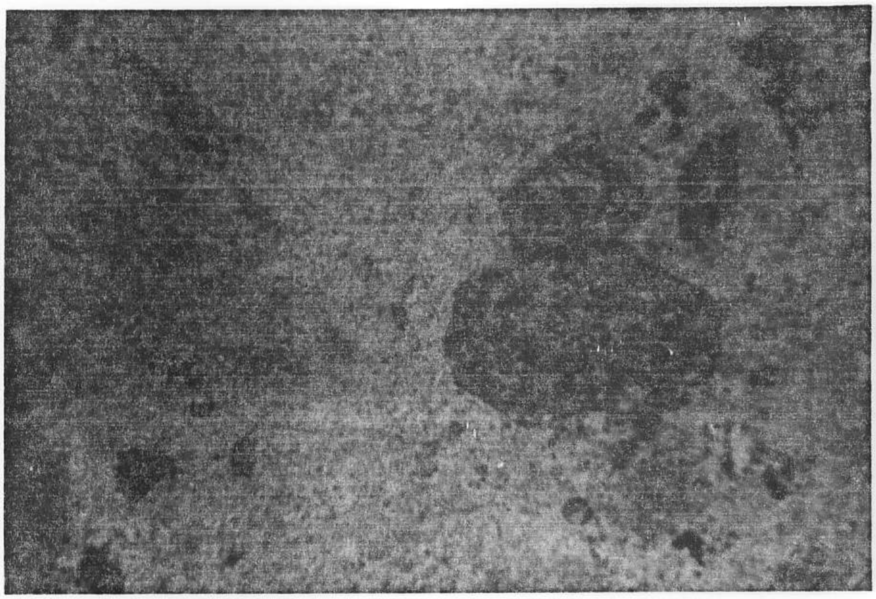
by epidote and perhaps actinolite (?). In the more highly altered rocks sericite has accompanied the chlorite, calcite, and pyrite in replacing hornblende. The plagioclase in all these rocks, whether the hornblende is altered or not, is albitized (some oligoclase). This feature leads one to believe that the albitization could be independent of the rest of the alteration. Calcite and sericite are the main secondary minerals that replace plagioclase. Occasionally minor clinozoisite is present. Even though the plagioclase and hornblende are equally altered in the lowest zones, relics of plagioclase are present in rocks where nearly all vestiges of



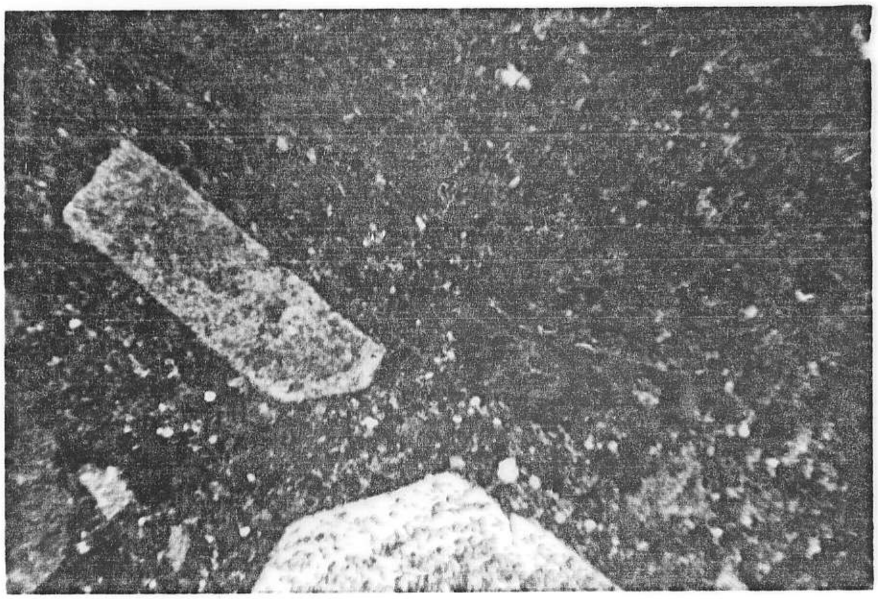
Photograph 30: (K-210) Photomicrograph of a relatively unaltered plagioclase-horhblende (albite syenite) porphyry (X25; plain light).



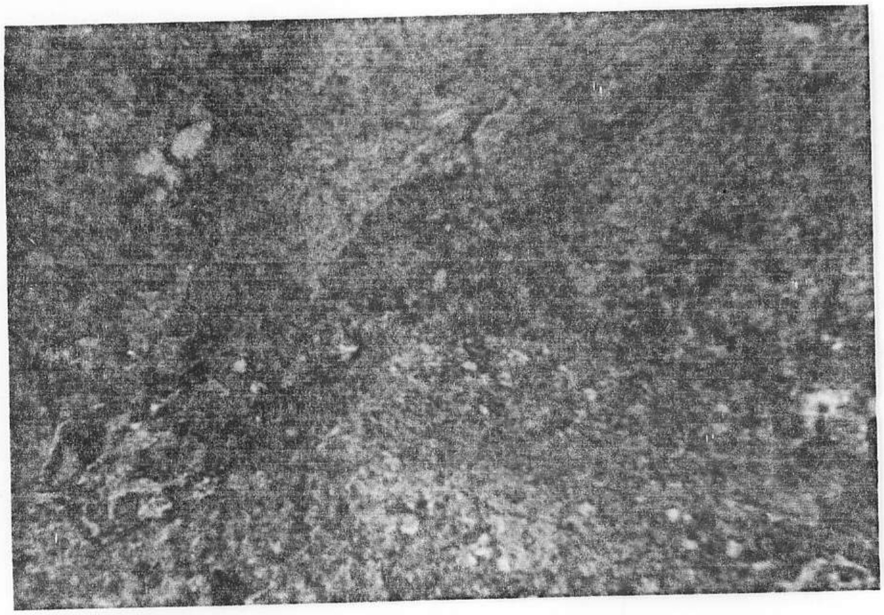
Photograph 30A: (K-210) As above but with polarized light.



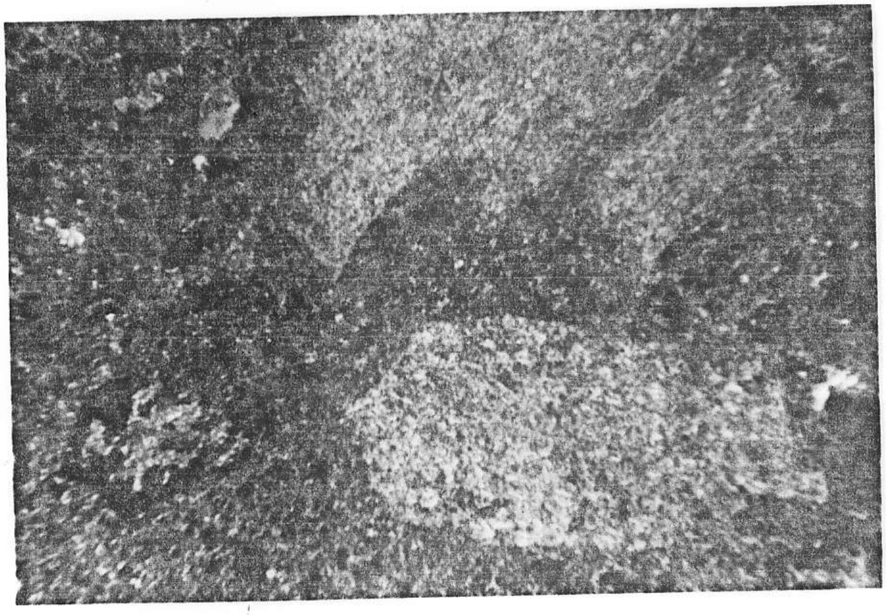
Photograph 31: (K-112) Photomicrograph illustrating partly altered plagioclase-hornblende porphyry (X25; plain light).



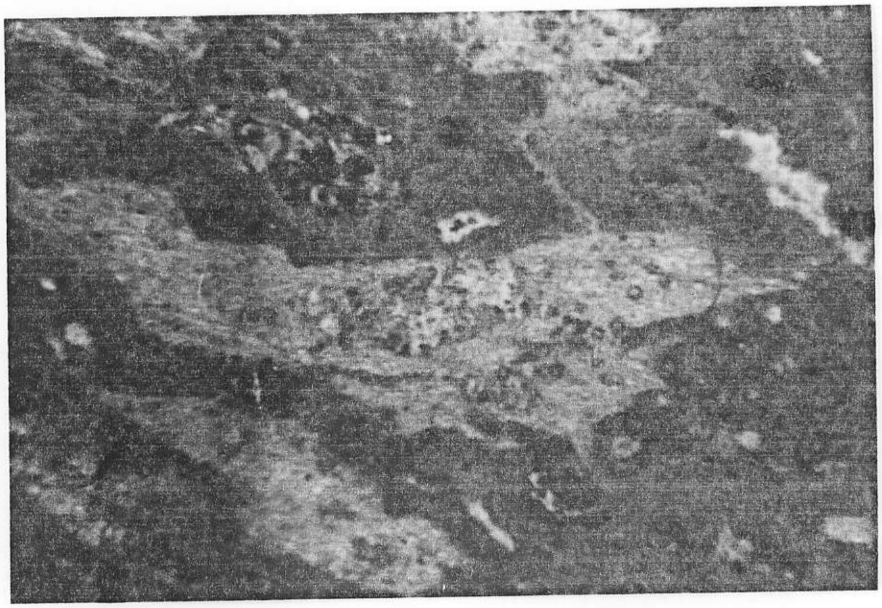
Photograph 31A: (K-112) As above but with polarized light.



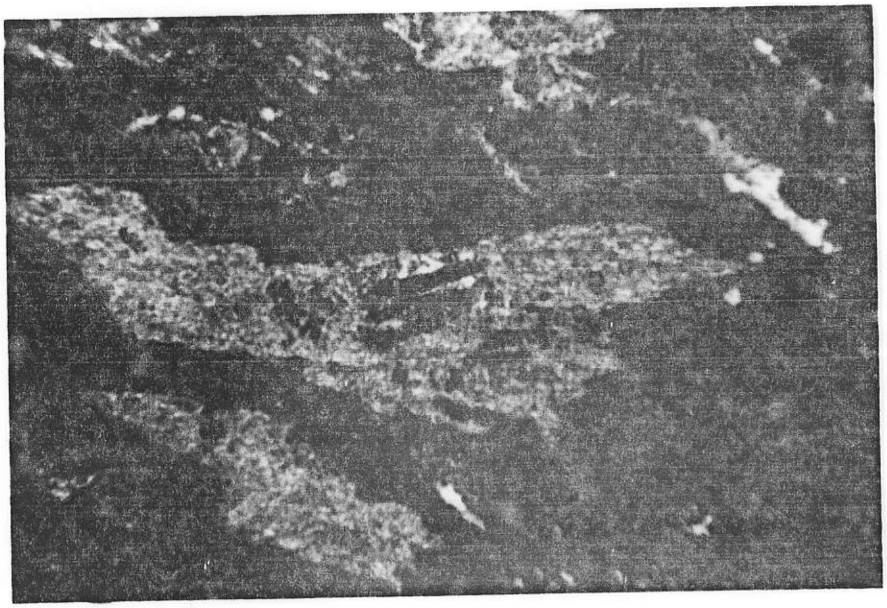
Photograph 32: (K-126) Photomicrograph illustrating a highly altered plagioclase-hornblende porphyry (sericite-calcite-chlorite pseudomorphs after plagioclase and hornblende can be seen - X25; plain light).



Photograph 32A: (K-126) As above but with polarized light.



Photograph 33: (K-25) Photomicrograph illustrating almost completely replaced plagioclase-hornblende porphyry (?). (In the center of the largest sericite clot is a relic of plagioclase - X25; plain light).



Photograph 33A: (K-25) As above but with polarized light.

hornblende have been destroyed. The potash feldspar resisted alteration until most of the plagioclase had been destroyed.

Alteration Minerals

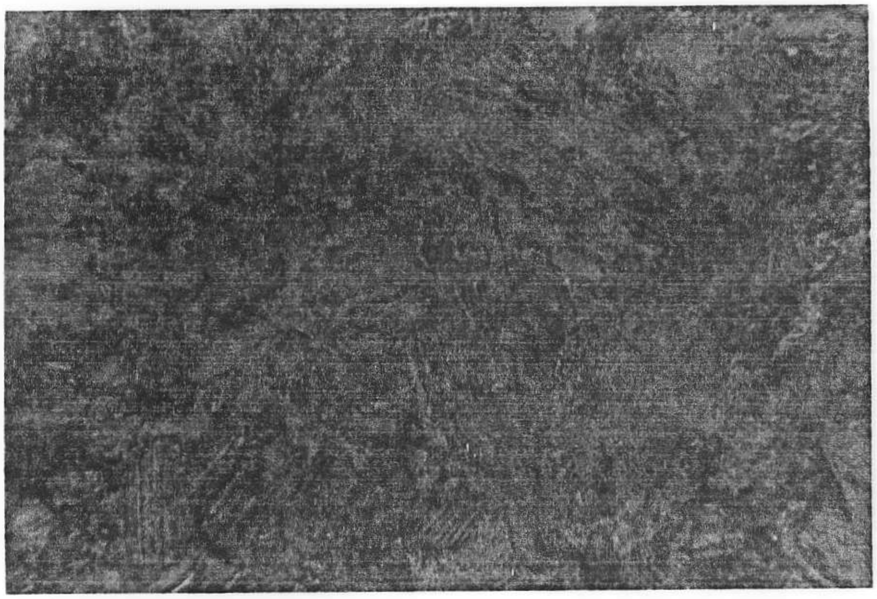
Alteration minerals will be discussed in an approximate order of decreasing abundance. The distribution of alteration minerals is shown in Figure 15.

Albite - Albitization is ubiquitous in the area. Plagioclase, a common mineral in the region, everywhere is either albite or oligoclase. Besides the main occurrences described throughout the thesis, minor amounts of albite are also found lining veinlets, both in mylonites and in some syenitic rocks. This type of albite appears to have grown in place of other minerals, whereas most of the secondary albite is replacement of pre-existing plagioclases.

Some of the sedimentary rocks and mylonites, which are rich in albite, have developed a silicified appearance. This appearance results from the rock breaking through grains instead of around them. This type of fracture results from the interlocking nature of grains in these microcrystalline rocks.

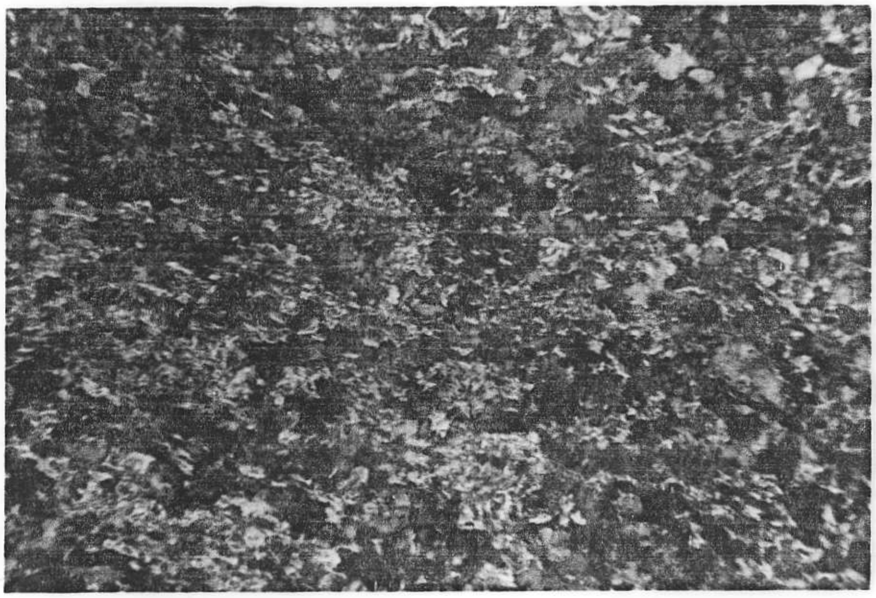
The evidence for albitization has been discussed in the section on the genesis of the Mitchell Intrusions.

Calcite - Secondary calcite, usually in minor amounts, is found in most rocks of the area. It typically replaces lime-bearing silicates. With or without quartz it is also common as small veinlets. Calcite and chlorite are associated with chalcopyrite and pyrite in a main mineralized zone on Mitchell-Sulphurets Ridge (Photograph 34). Some sedimentary rocks contain large percentages of calcite, but it is not known whether this calcite is primary or introduced.



Photograph 34: (K-285) Photomicrograph illustrating calcite-chlorite host rock of a mineral deposit on Mitchell-Sulphurets Ridge (X80; plain light).

<u>Sericite</u> - Sericitic alteration is one of the most widespread types developed in the area. Most commonly sericite is found as an alteration product of plagioclase, but in more highly metasomatized zones it has also replaced other silicate minerals. Well-developed quartz-sericite schists are found in the Mitchell Valley and in some



Photograph 35: (K-86) Photomicrograph of quartz-sericite schist (no relic minerals remain - X80; polarized light).

places in the Sulphurets Valley. At a few localities these schists contain chlorite, minor apatite, rare relics of plagioclase (Photograph 33), and at one locality - to the west of Mitchell Glacier they contain minor biotite. The presence of sericite in these schists from six widely separated localities in the Mitchell Valley has been confirmed by X-ray powder photographs (the localities are shown in Figure 15). In a mineralized mylonite zone on the upper northern slopes of Sulphurets Valley sericite occurs with relatively abundant fine-grained hydrothermal biotite.

The styles of replacement by sericite are many. In some specimens minute flakes of sericite have formed uniform grids throughout host minerals. In some, the flakes are randomly scattered throughout the host; while in others, they have formed alteration zones in the host. In a few specimens the sericite flakes have formed single train-like veinlets. A few of the highly altered rocks contain pseudomorphic clots of sericite after plagioclase.

Quartz - Secondary quartz is abundant in the quartz-sericite schists, massive silicified rocks, and in veinlets which mainly occur in the schists, syenitic rocks, and granites but also in other rocks throughout the area. In the low grade altered rocks it is difficult to separate the primary quartz from the secondary quartz.

Two distinct generations of quartz veinlets have been found in the quartz-sericite schist. The first generation is by far the most abundant and is closely connected to the formation of the schist itself. These veinlets usually average about 1 inch in width and may comprise over 50 per cent of the rock. In all places they parallel the schistosity and are usually separated by areas of granular quartz, sericite, chlorite, and pyrite. They may have been formed by metamorphic differentiation. These veins are invariably barren. The second system of veins usually cuts the first at high angles. These generally do not comprise more than 2 per cent of the rock. At many localities they contain coarse chalcopyrite and, in a few rare cases, galena, sphalerite, and tetrahedrite. In one area small amounts of chalcopyrite had migrated considerable distances from these veins into the country rock.

Chlorite - Chlorite is common as a minor constituent throughout the region, but in a few places it occurs in abundance. Where it is subordinate to quartz, sericite, and calcite, the altered rocks in most places are pale buff or some shade of grey, but where it is abundant the rocks are some shade of green. Only the rocks that contain greater than 5 per cent finely disseminated chlorite have a greenish tint. In a few specimens the sericite as well as the chlorite is green.

Variations in the types of chlorite have been noted in thin section. Chlorite found as a widespread alteration product is pale green approaching colourless, is weakly pleochroic, and has anomalous blue or brown birefringence. Chlorite found locally in some mineralized areas is a much darker green, is strongly pleochroic, and commonly displays anomalous royal purple birefringence.

W. G. Jeffery, in his work on the Campbell Chibougamau Mine in Quebec, has described a similar phenomenon (unpublished thesis, 1959, pp. 149 and 158). He was able to divide the chlorites in that area into two groups: Chlorite I and chlorite II. Chlorite I has a high magnesium content and chlorite II is rich in iron. These two groups were distinguished by their optical properties. The main diagnostic properties are as follows (after Jeffery, p. 149):

Type I	Type II
Usually colourless or pale green	Green
Pleochroism - nil to faint	Pleochroism - strong
Length fast - negative elongation	Length slow - positive elongation

He states:

> Between the two variations the optic angle passes through zero, the chlorite is isotropic, and the birefringence is nil. As the birefringence decreases from that of types I and II they can be termed respectively low chlorite I and low chlorite II.

At the Campbell Chibougamau Mine chlorite II is found chiefly as wall rock alteration associated with sulphide mineralization, whereas, type I is not associated with mineralization. He cautions against using the chlorites as a guide to ore since chlorite II is also found in shear zones that are not mineralised.

Following Jeffery's distinction of the two varieties, the writer believes that the dark green, more strongly pleochroic chlorite which is found in some of the copper mineralized areas, could be richer in iron than the chlorite found as a widespread alteration product. The elongation of most of the chlorites in the map-area is negative (length fast) and only a few have positive elongation even in the ore zones. Possibly this means that all the chlorites of the area contain considerable magnesia. Hey (1954) in his review on chlorites has noted that the optical properties do not vary proportionally to changes in the Fe total/ Fe+Mg ratio. From his charts it can be seen that variations in the optical properties are also dependent upon the amount of silicon present, but still optical variation reflect a general variation in iron and magnesium content. In the "ore" zones it is quite possible that the copper, upon entering the rock, replaced the iron of the pyrite which then entered the chlorite. The writer has no proof for this hypothesis but offers it as feasible explanation for the observed phenomena.

<u>Pyrite</u> - Small amounts of disseminated pyrite are widespread throughout the area. Pyrite is included with the alteration minerals because the formation of the bulk of it was probably more closely connected with the alteration processes than with other sulphide deposition. Wherever observed, it is older than the other sulphides. Pyrite associated with magnesian (?) chlorite and calcite in most areas has formed as a replacement product of pri-

mary ferromagnesian minerals. The pyrite in the regionally altered rocks constitutes typically less than 5 per cent of the total rock. Amounts greater than this are rare and have undoubtedly resulted from the addition of iron to the rock.

Clay Minerals - Clay minerals have been noted in a few specimens, especially from rocks of low grade alteration. A clay mineral (or minerals) has been recognized selectively replacing certain zones of plagioclase crystals in the syenitic rocks. This mineral (or minerals) could not be resolved in X-ray powder photographs. Although the possibility that they may have been overlooked or mistaken for sericite is still considered, clay minerals do not appear in great abundance in the map-area. Large kaolinized zones or any "chalky" type altered rocks have not been observed.

Epidote - (Usually pistacite, minor clinozoisite). Epidote occasionally occurs in abundance but it is not one of the major alteration minerals of the area. Ferromagnesian minerals in some of the least altered rocks are replaced by pistacite. Clinozoisite was identified in a few thin sections as an alteration product of plagioclase.

Biotite - Minute flakes of hydrothermal biotite exist in a few areas in similar types of occurrences as sericite. The highest concentration of secondary biotite was noted in a porcelaneous mylonitized rock which occurs on the upper northern slope of Sulphurets Valley. This rock contains minor disseminated chalcopyrite and molybdenite.

Potash Feldspar - Potash feldspar is not a common alteration product in the area but it has been included in this section since it is found intimately associated with chlorite adjacent to some of the intrusive contacts. Moreover it does not seem to be in dyke-like bodies. In these contact areas it is difficult to distinguish between dykes and metasomatized country rock. Potash feldspar has also been found as a constituent of microcrystalline, mosaic aggregates in mylonitized rocks. Here the potash feldspar was probably an original product of the rock that recrystallised upon mylonitization. Photograph 28 illustrates such a mylonite.

CHAPTER V - MINERAL DEPOSITS

Introduction

The Mitchell Intrusions appear to have been the focus for the development of several mineral deposits. These deposits occur both in the intrusive rocks and in the surrounding altered rocks. Excluding the gold-silver deposits, about which little is known, the most promising deposits, economically, are of a disseminated nature and are of very low grade but possibly contain very large tonnages.

Types of Deposits

1. Disseminated Copper in or Very Closely Associated with Members of the Mitchell Intrusions.

Hematite, magnetite, pyrite, chalcopyrite, and to a lesser extent molybdenite have been found very sporadically disseminated throughout or immediately adjacent to the syenite, quartz syenite, and granites. Similar mineralization has been found associated with the plagioclase-hornblende porphyry but in most places it is in smaller quantities. Even in the syenitic and granitic members over any significant area, the copper and molybdenum would only amount to traces. Noticeable concentrations have been recognized in some areas. To date, the most promising of these areas is an alteration zone in the central part of the main intrusion on Mitchell-Sulphurets Ridge. In places this deposit has been tested by diamond drilling, which indicates that average grade would probably be in the order of

.3 to 1 per cent copper. Pyrite and chalcopyrite are the only metallic minerals found in abundance in this zone, but specks of molybdenite have been recognized in a few places. Magnetite and hematite have been found in concentrations in or adjacent to this zone. Chalcopyrite is the only primary copper mineral that has been identified. It occurs in subequal amounts with the pyrite.

Three possible origins for the existence of this altered zone have been considered by the writer. They are faulting, explosive brecciation, and the alteration of a sheet of sedimentary rocks included in the intrusion. The writer favors the last hypothesis. The gangue material consists of altered rock comprising calcite with lesser amounts of chlorite and quartz (Photograph 34). Although some of the chloritic areas have developed small shear surfaces, no significant faults can be demonstrated in this zone. In one area near the top of the ridge, a small zone of breccia was noted as having rectangular blocks of altered porphyry set in what appears to be a granulated porphyry matrix. This breccia could well have been formed by a volcanic type explosion (Carr, 1960 and White et al, 1957) but the area is off to one side of the main zone and is insignificant in size. For three reasons the writer believes that the zone merely represents a sedimentary sheet caught up in the process of intrusion. The first reason is that where sediments have been observed in contact with similar types of intrusive rocks, they have been altered in a comparable manner. The second reason is that as this zone extends to the south it spreads out into a much larger area of altered rocks in which relic bedding still persists. The third reason is that blocks of limestone and one block of dragfolded, well-bedded sediments have been found in the center of this zone at the top of the ridge.

Another area in the Mitchell Intrusions that has significant concentrations of copper and minor amounts of molybdenum is the main body of cross-cutting granite on the north side of the Mitchell Glacier. Typical mineralization of this type is shown in Photograph 26. At this locality pyrite, chalcopyrite, and occasionally molybdenite occur as sulphide veinlets, sulphide-bearing quartz, calcite, and rarely chlorite veinlets, and as disseminations throughout the rock. In this area the granite and syenite have been "crackled". Mineral-bearing solutions have permeated the resultant closely spaced fractures and have invaded the rock between the fractures. There are areas up to 50 feet in diameter that contain a stockwork of these veinlets. These areas have a considerable concentration of sulphides but the mineralized zones tend to be sporadic and widely separated by large areas of barren rock. There is no extensive alteration associated with these "ore" zones. As yet, no continuity of these deposits has been demonstrated and the bulk of the rock is far too low grade to be mined at a profit.

2. Disseminated Copper in Massive Pyritic Replacement Bodies in Sedimentary Rocks

To date only one such body has been found in the area. It is shown in Figure 4 to the west of the Mitchell Glacier. At this locality sedimentary rocks have been highly replaced by pyrite. The pyritic replacement was selective, being controlled by the composition of the sedimentary layers. This differential replacement has preserved the sedimentary lamination in otherwise very highly altered rocks. These rocks have the silicified appearance that was described in the section on alteration minerals where albite is discussed. In thin section it is seen that these rocks are high in albite, contain considerable epidote, and have minor amounts of quartz. The pyrite content varies from about 1 to over 75 per cent. Most of the pyritic rocks are barren but local areas contain concentrations of chalcopyrite disseminated throughout or in minute quartz veins. In this same area concentrations of chalcopyrite and trace amounts of galena have been noted at the "noses" of what appear to be completely replaced and possibly boudinaged plagioclase-hornblende porphyry dykes. Sparse small veinlets of purple fluorite are found in these zones.

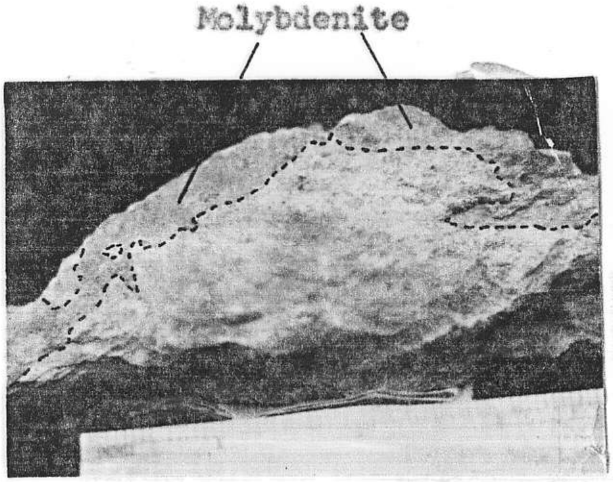
3. Disseminated Copper and Molybdenum in Mylonite Zones

The only noteworthy example of this type of deposit is on the upper northern slope of Sulphurets Valley. The iron staining over the deposit is a much darker brown than over the surrounding rocks. The attitude of this zone is similar to that of the major faults of the vicinity. The strike is approximately north-south and the dip is about 45 degrees to the west.

Pyrite, chalcopyrite, and molybdenum are very finely disseminated throughout an extremely fine-grained, porcelaneous, light grey and green rock. In thin section it is seen that this rock comprises mainly microcrystalline feldspar (albite and potash feldspar (?)), sericite, and fine-grained, hydrothermal biotite. Minor to trace amounts of chlorite, calcite, and apatite are also present. In hand specimen this rock appears silicified but no quartz was identified in thin section. The sulphides tend to be relatively evenly distributed throughout the rock. They are only visible as minute specks to the unaided eye. The grade of this deposit is probably somewhat less than 1/2 per cent copper and .02 per cent molybdenum.

4. Disseminated Molybdenum in Quartz-Sericite Schist

Disseminated molybdenite has been noted in a few localities in quartz-sericite schist but the only significant concentration found to date is on the south side of the Mitchell Glacier at an elevation of about 4,000 feet and at a distance of about 4,000 feet to the east of the main porphyry intrusions. The only chalcopyrite found in this area is in rare scattered quartz veinlets. The molybdenite appears to have been concentrated in quartz-sericite schist near the contact of a massive zone. The massive zone generally is a few hundred feet to the south. In the areas that the writer examined the molybdenite occurs as coatings on the cleavage surfaces, coarse flakes (some rosettes) in cross-cutting quartz veins, and as minute, cross-cutting veinlets of pure molybdenite. The molybdenite coating the cleavage surfaces is poorly illustrated in Photograph 36. Pyrite is the only other metallic mineral that occurs in abundance in these deposits. The overall grade of this deposit is probably very low.



Photograph 36: (K-81) Molybdenite coating cleavage surfaces in quartz-sericite schist.

5. Vein Deposits

Several types of veins are found throughout the region especially in the central and eastern parts of the map-area. Quartz, calcite, barite, quartz-calcite, and quartz-calcite-barite veins have been observed. The quartz veins are by far the most common and the largest. Barren quartz veins up to ten feet wide have been found. Quartz veins containing chalcopyrite, pyrite, galena, and sphalerite have been found that range up to 5 feet in width, but in most places they are small and tend to be irregular. Quartz veins containing only chalcopyrite are more common than the ones with galena and sphalerite. In the outlying areas beyond the map borders a few complex sulphide veins have been found that contain argentiferous tetrahedrite. To date these have proved to be of little importance. However, some quartz-calcite-barite stringers were noted that contain pyrite, galena, sphalerite, tetrahedrite (?), and electrum. One sample that was assayed has indicated that these veinlets may contain considerable gold and silver. The economic importance of these stringers has not yet been ascertained. Barren calcite and barren barite veins up to two feet wide have also been encountered but no ore minerals were associated with them.

Primary Metallic Minerals

Little information was gathered from a mineralographic study. Most of the ore minerals tend to be finely disseminated and in discrete grains. Only rarely are they found in contact with one another and even then the relations are not clear. The main feature that came out of the study was the fact that pyrite is invariably older than the other sulphides. It was observed veined and replaced by chalcopyrite in many sections and in one section it was replaced by galena.

<u>Pyrite</u> - Pyrite was considered in the section on rock alteration. There is no clear distinction between pyrite in the mineral deposits and pyrite disseminated throughout the altered rocks. Perhaps where pyrite is finely disseminated with indications that little if any iron was added to the rock, it may be considered as a product of alteration. Whether more closely connected to the alteration or to other sulphide mineralization, pyrite is by far the most abundant and the earliest sulphide mineral of the area.

<u>Pyrrhotite</u> - It is far less abundant than pyrite but is found in similar types of occurrence either by itself or with pyrite. The largest area containing disseminated pyrrhotite is on the upper southwest arm of the Sulphurets Glacier beyond the southern border of the map. Pyrrhotite and chalcopyrite veins varying from 1/2 inch to 2 feet in width have been found associated with a dia-

base dyke along the west side of the Sulphurets Glacier.

Hematite - Specular hematite has frequently been found in the syenite, quartz-syenite and granites. It occurs as small specularite or quartz-specularite veinlets and as disseminations throughout the rock. On Mitchell-Sulphurets Ridge large concentrations of disseminated hematite and hematite-bearing quartz veinlets occur in the quartz syenite adjacent to an altered zone. Numerous specularite-bearing quartz veinlets have also been found on the north side of the Mitchell Glacier above a large altered zone in syenitic rocks. In some of these veinlets the hematite is associated with a green sphalerite.

Magnetite - As are pyrite and hematite, magnetite is found in trace amounts disseminated throughout or near the Mitchell Intrusions. The only place that it was observed in abundance was on Mitchell-Sulphurets Ridge where it forms the matrix of a small area of breccia. It has also been found in veinlets up to 3 inches wide in both the Mitchell and Sulphurets Valleys. There is no close relationship between the magnetite and economic sulphide minerals.

Chalcopyrite - Disseminated chalcopyrite in trace to minor amounts is widespread in or near the Mitchell Intrusions. It is randomly scattered throughout rock or is concentrated in minute veinlets. Invariably the chalcopyrite is associated with pyrite and as described above, it is sometimes associated with molybdenite. The pyrite-chalcopyrite and the chalcopyrite-molybdenite ratios are variable. Typically the pyrite is in greater amounts than the chalcopyrite and the molybdenite is in lesser amounts.

Molybdenite - In most areas that molybdenite is found, it is only in trace amounts. Besides the main occurrences that were described above, molybdenite occurs also as films on bedding planes in some of the highly altered sediments.

Sphalerite, Galena, and Tetrahedrite - These minerals are not abundant, but they have been found in various types of veins throughout the area. The veins are usually in the outer regions of alteration.

Electrum - Electrum as scaly aggregates has been found at one locality. Here it is associated with sphalerite, galena, and probably tetrahedrite (?). These minerals occur in quartz-calcite-barite stringers that are scattered throughout the altered rock. The electrum is visible to the unaided eye and is a silver white colour. The gold and silver of some electrum was separated from the other constituents. The ratio of gold to silver was determined to be 46.2/43.8 (assayed by N. Colvin).

Secondary Minerals

Limonite, malachite, and to a lesser extent azurite and ferrimolybdite exist in the map-area. As shown in Photographs 2 and 3 iron staining is common throughout the whole area. In most areas these stains are only very thin coatings. The only exception is in the cirque basin to the south of the toe of the Sulphurets Glacier. Here solutions, running over a pyritic quartz-sericite schist higher on the hill, have deposited in the basin a spongy iron gossan, which in places is probably greater than 20 feet thick. At other localities malachite has been found locally in abundance but usually it is a residual weathering product and the weathering has not continued to any great depth. The possibility of any supergene enriched zones is small, for glaciation has stripped the area of any but the most recent weathering products.

Genesis of the Altered Rocks and Mineral Deposits

In the Mitchell-Sulphurets region the altered rocks and mineral deposits were formed in waning stages of magmatic activity. Their formation was facilitated by the presence of large quantities of volatile materials that had been trapped in the vicinity of the Mitchell Intrusions. These fluids were possibly concentrated during the differentiation processes. The early differentiates suffered extensive auto-metamorphism by these residual volatiles. There was possibly a complete gradation between the residual granitic magma and the hydrothermal solutions. As the parent magma was fractionating with crystallization, the volatile components would have been concentrated in the residual silicate melt. The altered rocks indicate that active fluids probably carried considerable alkali material with them, indicating a possible gradation from the magma to the hydrothermal conditions.

The major period of alteration and subsequently developed mineral deposits mainly followed the complete crystallization of the silicate magmas. This is indicated by the fact that essentially all of the altered rocks were formed at a sub-magmatic, elevated temperature probably somewhere below 400° C. Although to begin with, the alteration was probably a higher temperature variety near the intrusions.

A comparison with the Highland Valley area brings out important differences in the environments of ore deposition in what might have otherwise been similar "Porphyry Copper" type deposits. Whereas in the Highland Valley area the volatiles may have escaped through volcanic vents, in the Mitchell-Sulphurets region they lingered for some time after the crystallization had ended. The presences of vast amounts of volatiles in the rocks not only facilitated the extensive rock alteration but also allowed considerable migration of the metal-bearing solutions. In the Highland

Valley region the contrast in environments is marked by steep thermal gradients, lack of extensive rock alteration, and the localization of the mineral deposits in sub-volcanic structures (White et al, 1957, p. 503).

The mineralizing fluids in the Mitchell-Sulphurets district probably travelled through ~~the~~ main structural conduits of the area to the points of deposition. The nature of ~~the~~ conduits was probably quite variable. In some places they may have been faults; in others, permeable schistose zones; in others, brecciated zones; while still in others, they may have been "crackled" areas. The factors governing the sulphide deposition would be the physical-chemical properties of the rocks and the environment.

For some unknown reason, possibly the development of major faults, the temperature following alteration was probably lowered very rapidly. As has been shown in previous sections, some main faults were probably active during the main period of rock alteration. Possibly the formation of those faults permitted the escape of the volatile materials. If the temperature fell gradually it would be expected that argillic or similar types of alteration, on a large scale, would have been superimposed on the higher grades of alteration.

In order to give a complete explanation of the genesis of the altered rock and mineral deposits of the district the importance of a structural trap should be considered. As it has been shown, some apparent differences in the "Porphyry Copper" type deposits can be explained by the history of the volatile phases. The most important feature is whether the fluids are trapped in the vicinity of the intrusions or whether they are rapidly released to the surface. If the volatiles are not rapidly released to the surface, the nature of the confining rocks becomes very important. If the confining rocks are permeable or have permeable structures within them, the gases or supercritical fluids will continually travel away from their magmatic source. These conditions will be marked by compositional and thermal gradients. There would be a center of alteration with successively lower grades of alteration away from this center. The second case is that of the Mitchell-Sulphurets district. The writer believes that an impermeable "trap" rock must have been present for the area to obtain a relatively uniform environment of alteration. A suitable "trap" rock in the map-area is the volcanic horizon along the eastern border. From reconnaissance mapping it is considered feasible that the major anticline, which outcrops in the Treaty Creek area, was the trapping structure. Following the end of crystallization the volatiles would be travelling and diffusing away from their magmatic source. As they entered the cooler surrounding rocks, their temperature would be lowered and the temperature of the rocks would be increased. Finally they would reach the limit of their migration when they could not permeate the massive volcanic rocks. Temperature and diffusion gradients would be set up within this confined system. The evidence indicates that some sort of equilibrium was probably reached below 400° C. In this environment of relative equilibrium it appears that the soaking of the rocks continued for some time. Such a theory could account for most of the observed phenomena of the area.

Classification of the Mineral Deposits

The deposits of the Mitchell-Sulphurets region are similar to the "Porphyry Coppers" of the southwestern United States and western South America. The Mitchell-Sulphurets deposits have all the main characteristic features: very large tonnage, low grade copper and minor molybdenum mineralization associated with porphyritic granitic rocks. As with most of the "Porphyry Coppers" chalcopyrite is the main primary ore mineral. Pyrite is probably more abundant in the Mitchell-Sulphurets deposits than in most "Porphyry Coppers". Many of the orebodies in the "Porphyry Copper" deposits have large horizontal dimensions. This is not true of all the Mitchell-Sulphurets deposits; however, there are other "Porphyry Coppers", such as, Bethlehem and San Manuel that have large vertical extents. Pervasive albitization is not a common type of alteration in the "Porphyry Coppers", but in the Mitchell-Sulphurets district it could be related to a spilitic province and not to the intrusions.

The deposits in the Mitchell-Sulphurets region are possibly of the mesothermal type, but since the temperatures and pressures at the time of their formation have only been estimated, this conclusion is speculative. All features of the alteration indicate that it is mainly a low-termperature variety, probably having developed at some elevated temperature below 400° C. The pressures were probably moderate, but conditions can only be assumed. Since the intrusions were emplaced in a hypabyssal environment, and there is no evidence that the hydrostatic pressure exceeded the confining pressure, it is probable that moderate pressures existed.

CHAPTER VI - SUMMARY AND CONCLUSIONS

Summary

The sequence of geological events in the Mitchell-Sulphurets region may be briefly summarized as follows:

1. Deposition of the Upper Takla (?) and/or Lower Hazelton rocks in a typical eugeosynclinal environment

   The sedimentary rocks of the area were deposited in an open-water marine environment probably by turbidity currents. The volcanic rocks are chiefly water-lain pyroclastics.

2. Intrusion of diabasic sills and dykes particularly into the well-bedded sediments

3. Emplacement of the plagioclase-hornblende porphyry, syenite, quartz syenite, two-feldspar granite, and one-feldspar granite in that order (combined differentiation with minor composite intrusion followed by post-crystallization changes have resulted in the present intrusive rock types)

4. Regional albitization

   This alteration may have taken place over a long period of time but at least in part it has followed the consolidation of the Mitchell Intrusions.

5. Extensive rock alteration and mineral deposition took place in the waning stages of the Mitchell magmatic period

6. Major faulting during the late stages of rock alteration and mineral deposition
7. Intrusion by scattered, thin keratophyre (basaltic (?)) dykes

   Possibly the albitization of these rocks was caused by contamination.
8. Extensive erosion by glaciers in Pleistocene and Recent time.

Conclusions

The mineral deposits in the vicinity of the Mitchell and Sulphurets Glaciers are of the "Porphyry Copper" type. To date no orebodies have been outlined but exploration is continuing. It is possible that these deposits will be of major importance in the future.

The mineral deposits were formed in the latter stages of magmatic activity associated with the Mitchell Intrusions. Important differences between these and other "Porphyry Copper"-type deposits can be explained by variations in the history of the volatile phases. In the Mitchell-Sulphurets region the volatiles, which were concentrated during differentiation, probably lingered or were trapped for a long period after crystallization had ended. These lingering fluids caused the tremendous amount of rock alteration and possibly could have been responsible for the albitization of the plagioclases in the earlier members of the

Mitchell Intrusions. The presence of these volatiles also allowed extensive migration of the metal-bearing fluids from their original magmatic source. This could be an objectionable feature governing the economic accumulations of copper, and molybdenum. It could permit greater dispersion of these metals.

The structural states of the feldspars are compatible with the thermal history of the area. The extensive ordering of the feldspars, in these hypersolvus rocks of hypabyssal intrusions, was promoted by the trapped volatiles.

Future studies in the district could add information on the stratigraphy of the Lower Jurassic of northwestern British Columbia, on the formation and stratigraphic relationships of turbidity current sediments, on the spilite problem, on the formation of unusual igneous rock types, on the development of rock alteration, on the migration of metals from a magmatic source, and on many other related subjects.

APPENDIX

Classification of Salic Rocks
(after Tuttle and Bowen, 1958, pp. 129 and 130)

"Turning now to the classification of the rocks whose compositions place them in or near "petrogeny's residua system", we can first divide these rocks into two broad groups:

(I) Hypersolvus granites, syenites, and nepheline syenites, characterized by the absence of plagioclase except as a component of perthite.

(II) Subsolvus granites, syenites, and nepheline syenites, characterized by both potassium feldspar and plagioclase feldspar.

Group (II) can be further divided into three subgroups on the basis of the albite content of the alkali feldspar:

(A) Ab of potassium feldspar > 30 per cent by weight.

(B) Ab of potassium feldspar < 30 and > 15 per cent by weight.

(C) Ab of potassium feldspar < 15 per cent by weight.

This is a genetic classification in the sense that Groups I and IIA can be considered high-temperature rocks (and therefore undoubtedly owe their origin to magmatic processes), whereas rocks in Group IIC completed crystallization or recrystallization at low temperatures. Group IIB occupies an intermediate position between IIA and IIC. Replacement or metasomatic rocks will undoubtedly fall in IIC, but, as has been pointed out elsewhere (Tuttle, 1952), the fact that a rock falls in this group is not evidence that it has not had a magmatic history because unmixing of plagioclase from potassium feldspar can and must go on if cooling has taken place in the presence of volatile materials which flux such a reaction....

"The above classes of salic rocks can be further subdivided on the basis of the alkali-feldspar modification. Only three subdivisions are considered here although many other combinations are known. For example, the following phases may be found in a single alkali feldspar crystal from the Beinn an Dubhaich granite: (1) high albite, (2) low albite, (3) monoclinic potassium feldspar, and (4) triclinic potassium feldspar. Feldspars can be placed in or between the groups by measuring 2V and using the graph proposed by Tuttle (1952, p. 557).

(I) Hypersolvus Granites, Syenites, and Nepheline Syenites

(1) sanidine-high-albite perthite

(2) orthoclase-high-albite perthite

(3) microcline-low-albite perthite

(II) Subsolvus Granites, Syenites, and Nepheline Syenites

(A) potassium feldspar composition Ab $>$ 30 per cent

(1) sanidine-high-albite perthite

(2) orthoclase-low-albite perthite

(3) microcline-low-albite perthite

(B) potassium feldspar composition Ab < 30 and > 15 per cent

(1) sanidine-high-albite perthite

(2) orthoclase-low-albite perthite

(3) microcline-low-albite perthite

(C) potassium feldspar composition Ab < 15 per cent

(1) orthoclase-low-albite perthite

(2) microcline-low-albite perthite

(3) microcline "

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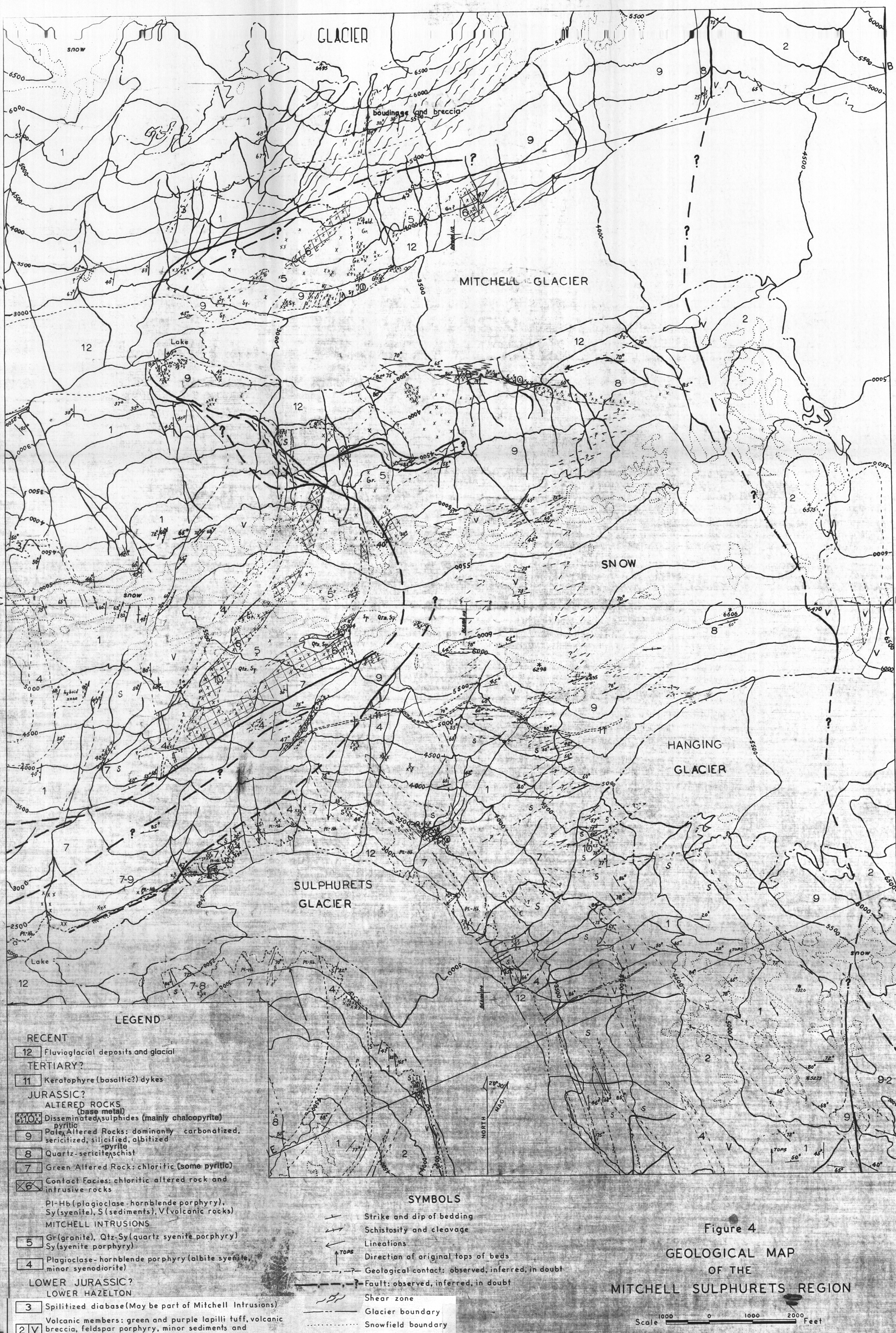
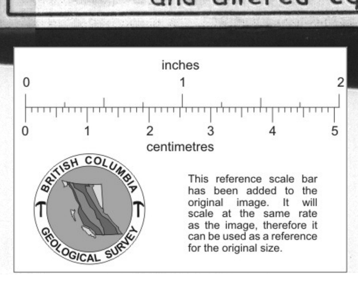


Figure 4

GEOLOGICAL MAP OF THE MITCHELL SULPHURETS REGION



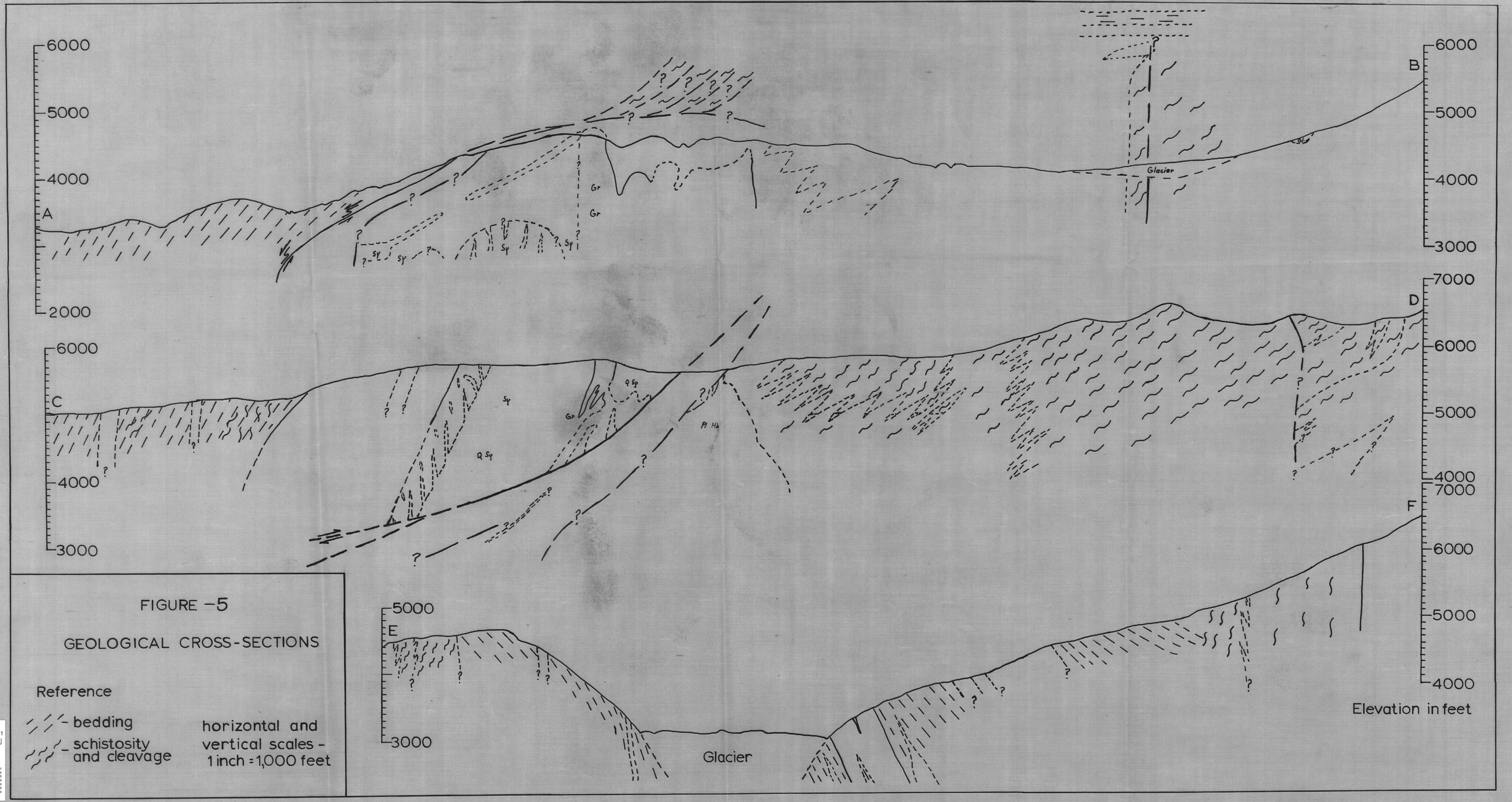


FIGURE -5

GEOLOGICAL CROSS-SECTIONS