The Origin and Emplacement of the Rock Units in Mule Creek, Northwestern British Columbia

by

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Submitted as the
equivalent of the Honours Qualifying Examination
for the degree of
Bachelor of Science
with Honours in Geology and Physics
Dalhousie University
1983

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B.Sc. HONOURS THESIS

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Title: THE ORIGIN AND EMPLACEMENT OF THE ROCK UNITS IN MULE CREEK, NORTHWESTERN BRITISH COLUMBIA

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Date: May 4 1983

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Abstract

In 1982 field work was carried out in northwestern British Columbia for Noranda Exploration Company, Ltd. Here a sequence of porphyritic and vesicular volcanic flows containing interbedded gypsum was discovered. Finely disseminated sulphide was found within this gypsum. Whether economically important quantities of copper-bearing sulphides exist here is unknown at this time.

Microscopic study of thin sections, and X-Ray diffraction spectra, show the mineralogy to be representative of greenschist facies metamorphism. Sulphur isotope data: δS^{34}= +11.7 for gypsum and +11.3 for barite are interpreted as indicating a middle to late Permian age for these sulphates.

The Denali fault system is a dynamic fault zone active since Cretaceous-Jurassic time and presumed still active. This system is responsible for assembling the series of originally temporally and spatially separated units observed today in Mule Creek. The pulsing of this system through time has produced extensive brecciation and shearing over the whole study area.

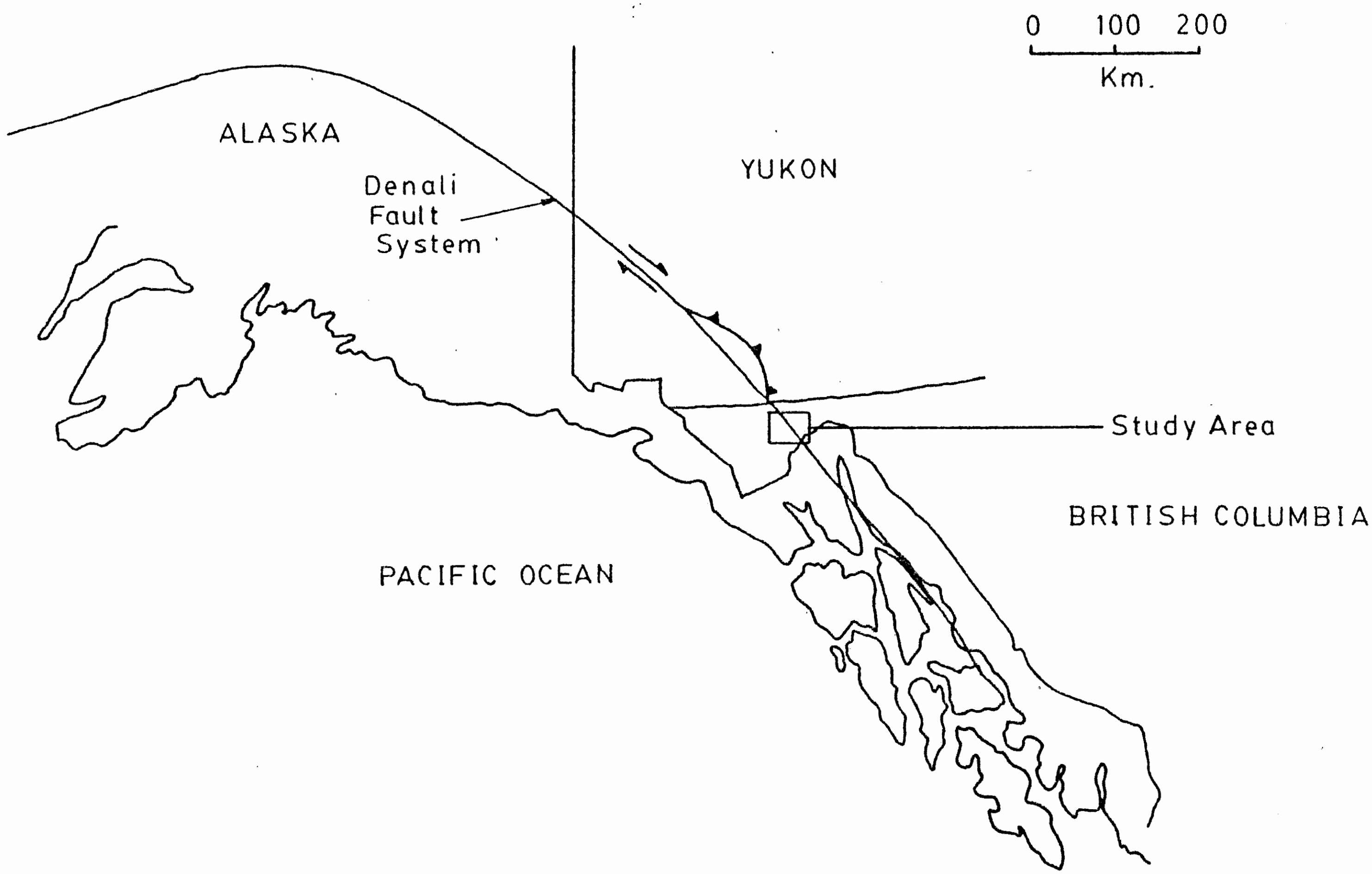


Fig. 1. Map showing location of study area and of the Denali Fault System

Chapter 1

Introduction

A sequence of altered volcanic rocks containing a unit of gypsum was discovered by geologists of Noranda Exploration Company, Limited, during the summer field season of 1982. This gypsum unit contains finely-banded sulphides. In this volcanic sequence, in the vicinity of the gypsum, is a zone containing veined and nodular barite and disseminated sulphides.

The study area is in northern British Columbia at 59°47'N and 136°34'W. It is situated just to the east of the Haines Road in a northwesterly-trending valley. The valley has a flat floor and is bounded by the Datlasaka Range of the St. Elias Mountains to the southwest, by the Kusawak Mountains to the southeast and by the Coast Mountains to the east and northeast. The elevation of the valley floor is fairly constant at about 900 m above mean sea level. The mountains bounding the valley rise abruptly to an elevation of about 1800 m, producing a marked local relief of about 900 m.

Glacial alluvium carpets the valley. The vegetation of the area consists of local grasses, moss, sparse stunted trees and large patches of thick brush, 1 to 2m tall, locally called buck brush. The valley divides two watershed areas, these being the Tatshenshini River to the north and the Kelsall

River to the south. Drainage of this area is effected via several creeks joining in the southwest corner of the valley and flowing easterly in Mule Creek until the southeasterly-flowing Kelsall River is encountered.

The only exposure of bedrock occurs in the gorge cut by Mule Creek in an easterly direction across the southern end of the valley. This gorge begins where the Haines Road crosses the creek and quickly deepens to about 20m. From this point to the Kelsall River - about 1000m - the gorge gradually deepens to a depth of about 50m. The walls of this gorge are very steep and can be climbed in a few places only. Therefore, detailed sampling of the gorge is impossible.

All previous geological work has been mapped at small scale. In the late eighteen hundreds and the early part of this century, various members of the Geological Survey of Canada and of the United States Geological Survey conducted preliminary reconnaissance of the area and its mineral deposits. In 1948, K. DeP. Watson, of the British Columbia Department of Mines, conducted the first detailed study in this region. The Squaw Creek - Rainy Hollow area was covered, an area about 2000km^2. The Geological Survey of Canada began "Operation St. Elias" in 1974 as a regional study of the

St. Elias Mountains in Yukon and northern British Columbia. The results are the work of G.H. Eisbacher and others.

Field work for this thesis consisted of three days of mapping and sample collecting. Several photographs of the area were taken from the ground and from a helicopter, by the author. The length of section studied is about 1100m along the Mule Creek gorge. As well, outcrops exposed approximately one kilometre to the south were investigated. In all, twenty-two outcrop locations were sampled and several representative samples of the gypsum and barite were collected. Mapping of the area was conducted at a 1:10 000 scale.

The aim of this thesis is to describe the rock units of the Mule Creek area. Emphasis will be on the gypsum and barite units and the possibility of related sulphides in economic amounts. The metamorphic and deformational history will be discussed and related to the present situation.

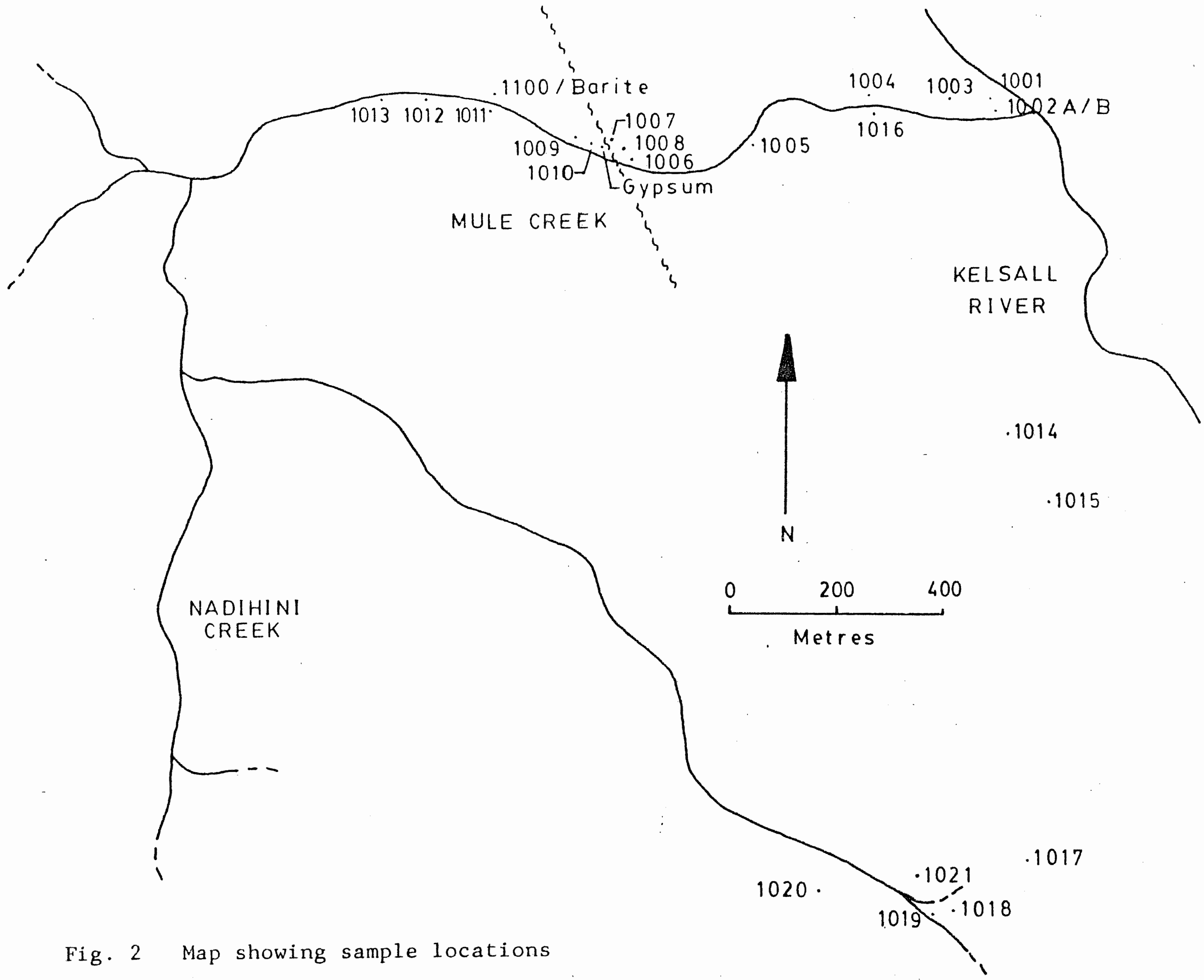


Fig. 2 Map showing sample locations

Acknowledgements

I wish to thank Mr. Ron MacArthur of Noranda Exploration Co., Ltd. for affording me the time during a busy exploration season to conduct field work for this thesis and for shipment of samples from the field to Dalhousie.

Dr. G.C. Milligan is thanked for a much needed very critical review of this manuscript and helpful hints and suggestions during the preparation of this work.

I wish to thank my mother, Mrs. Josephine M. Rogers, for having the patience to type all this.

Appreciation is extended to Dr. R.A. Jamieson for greatly illuminating some very murky thin sections.

Chapter 2

Analysis Techniques

Analysis of samples collected in the field has taken several routes. Thin sections for transmitted light were made of each specimen. Three samples - two from the barite-rich veins and one of the gypsum - were submitted for polished thin sections to be studied under reflected light. During the lapidary process, however, the gypsum sample was destroyed.

All the volcanic and intrusive rock samples are too altered to allow absolute age determinations.

Gypsum, barite and sulphides were separated for analysis of sulphur isotopes. The gypsum and sulphides were separated in tetrabromoethane in the usual way. Barite and sulphides were separated by froth flotation. The method is as follows: Fill a 150ml test tube half full of potassium amyl xanthate solution and add 200 to 300mg of sample. Concentration of the xanthate is purely arbitrary. The author dissolved 2 or 3 pellets of xanthate in about 100ml of water. No acid or alkali was added. Sufficient air bubbles are produced by the vigorous shaking of the stoppered test tube. At intervals, the froth collected at the top of the solution, and the attached sulphide grains, are poured off.

Estimates of mineral percentages were made from thin sections and compared with estimates made from X-ray diffraction spectra. Some rocks are too fine-grained or altered and deformed to allow accurate visual estimates of mineral percentages, so X-ray spectra were made to back up visual estimates and to provide information where the thin sections could not.

Cleavage development in the sedimentary rocks, and shearing and brecciation in the volcanic and intrusive rocks, were studied in thin section to determine the tectonic history of these rocks.

Aerial photographs at a scale of about 1:70 000 reveal some large scale features of the area. Topographic contrasts and the location of major rifts of the Denali System are highlighted. Photographs that I took enhance definition of the splay fault cutting Mule Creek.

These analyses and the study of the existing reports of the region form the basis of this thesis.

Chapter 3

Rock Units

Field mapping and study of hand specimens and thin sections have identified several lithologic units. These units include:

1. Argillite and limestone 2. Brecciated Conglomerate
3. Intermediate to felsic volcanics 4. Brecciated shale
5. Dyke 6. Silicic extrusive rock 7. Greenstone
8. Gypsum 9. Barite-quartz veins 10. Diorite

A description of these rock units follows.

1. Argillite and Limestone

Unconformably underlying grey to cream-coloured limestone in Mule Creek is a light to dark grey argillite (samples 1002A and 1002B). The outcrop occurs at the bottom of the gorge where Mule Creek enters the Kelsall River. To the south, about one kilometre, is an outcrop of similar material (sample 1017), which is interbedded with a tan to brown limestone. This brown limestone is not related to the limestone that outcrops above the argillite in Mule Creek. Several cleavages are developed in the argillite and in the tan to brown limestone, and quartz-filled fractures are present in the argillite.

The argillites are very fine-grained and thin sections show the grains to be elongated from stress. (See Fig.4 p.21) X-ray spectra show the predominant mineral to be quartz, with about twenty per cent albite and ten to fifteen per cent chlorite.

The grey to cream limestone outcropping in Mule Creek above the argillite strikes northwest with a vertical dip. From thin section study this is determined to be fine-grained calcite with minor detrital, granular quartz. Some zones of the carbonate have recrystallized to coarse-grained aggregates. Brecciation is evident in this rock.

2. Brecciated-Conglomerate

Immediately upstream of the limestone in Mule Creek is an outcrop of massive rusty-brown rock. This rock is composed of small elongate clasts, ranging in size from 1 to 10mm. The predominant mineral is quartz together with about 15 per cent albite. Chlorite forms the interstitial material. Iron staining is pervasive between clasts and in fractures in the clasts. The clasts are multi-crystalline fragments resulting from extensive brecciation of an earlier crystalline rock. Pressure solution is evident between grains.

3. Intermediate to Felsic Volcanics

Adjacent to the brecciated conglomerate is a sequence of massive and pillowed volcanic rocks represented by samples 1005, 1014 and 1015. With this sequence are some fine-grained brown to grey-black rocks. Samples 1004 and 1016 represent these rocks. No definite orientation of these rocks could be determined in the field due to inaccessibility in the Mule Creek gorge.

The volcanic rocks display extensive quench textures and large vesicles, up to 1cm, filled with coarse secondary calcite. (See Fig.5 p.21.) These rocks are composed of about 55% albite, 10% chlorite and 35% calcite of which about 25% is contained in vesicles. The chlorite is interstitial to the fine albite laths and may well be replacing glass.

Sample 1004 is a very fine-grained, grey-black rock, with many veins. These veins are vertical, parallel and composed of calcite. The mineral grains are elongated and strained as are the sparse opaque blebs. Fracturing pervades the rock and coarse-grained calcite fills these fractures. The mineralogy of this rock is 40% calcite, 25% albite, 20% quartz and 15% chlorite. Sample 1004 has a texture indicative of a fine-grained sedimentary rock. Pressure solution cleavage is well developed in this rock.

Sample 1016 is a brown-grey rock containing 30% calcite, 45% albite, 15% quartz and 10% chlorite with a significant amount of finely disseminated pyrite. Extensive fracturing similar to that in sample 1004 is present. Sample 1016 has a fine-grained crystalline texture with finely disseminated pyrite throughout. Brecciation is evident in both samples.

4. Brecciated shale

To the west of the massive and pillowed volcanic rocks is a very soft brown to black carbonaceous shale. In general, the outcrop is crumbling fragments of rock and dust - the dust being sooty and black. Sample 1006 is from a more competent bed within this unit.

Sample 1006 is a finely laminated rock with a pronounced "crinkling" of these laminations. It is composed almost entirely of fine-grained quartz displaying a wavy extinction. Chlorite forms about 10% of the rock. Two cleavages are well developed. One is a pressure solution cleavage which is then cross-cut by a brittle fracture cleavage. The quartz grains are elongated in the direction of the pressure solution cleavage and the surfaces of this cleavage are coated with brown and black iron oxides. The fracture cleavage cross cuts all fabrics in the rock, in places developing small zones of brecciation (see Fig.3).

5. Dyke Rock

Cross cutting these shales is a dyke of unknown origin. Its mineralogy is 70% albite, 20% quartz and 10% chlorite.

Iron oxide staining is pervasive. Small apatite crystals are found inside the albite. The dyke is 2 to 3 metres thick and extends about 50m across the outcrop.

6. Silicic volcanic rock.

Outcropping above the black shales where the dyke has cut to the surface is a rock represented by sample 1007. This rock is fine-grained and massive in hand specimen. Iron oxide staining is pervasive giving it a rusty-tan colour. The rock is composed of 70% albite, 10% quartz, 15% chlorite and minor calcite. Occurring sparsely throughout the rock are small, irregular black specks. The rock is porphyritic, with albite now forming the phenocrysts, and has been brecciated extensively.

7. "Greenstone"

To the west of the black shales and the silicic extrusive is an outcrop, about 400m in length, of dark green rock. This rock is represented by samples 1009, 1010, 1012 and 1100. The most easterly sample is 1010 with 1009 and following samples being progressively more westerly. Sample 1020 is of a similar rock type outcropping about one kilometre to the south. These rocks are composed of: chlorite, albite, tremolite, epidote and opaque minerals. Many shear surfaces have developed in these rocks. Slickensides occur on many of these surfaces. Considerable brecciation is evident in all samples with 1012 and 1100 displaying the most. Sample 1010 displays relatively little brecciation but has been the most severely sheared. Lenticles of epidote appear stretched and flattened; these may be remnants of epidote-filled vesicles. Small zones of quench textures are still preserved in this rock.

Samples 1009 and 1020 appear almost identical in thin section - sample 1020 being slightly coarser grained. These two rocks are porphyritic in texture. The phenocrysts are recrystallized aggregates of albite. The groundmass is composed of chlorite, tremolite and minor epidote. Opaque grains are distributed throughout the rock. Brecciation has fragmented much of the albite, epidote and opaques. The masses of chlorite and tremolite are twisted and bent. Minor calcite occurs in small fractures.

Sample 1011 is a vesicular volcanic rock. The groundmass is composed of felted masses of the fibrous minerals and albite. The vesicles are lined with coarse-grained epidote and filled with chlorite. Quench textures are preserved in the groundmass. This is the least brecciated of all the samples. Shearing has stretched some of the vesicles, producing small stringers of fine-grained epidote (See Fig. 6, p.22)

Samples 1100 and 1012 are extremely brecciated rocks. The albite and opaques are completely fragmented with each fragment being suspended in a fibrous, felted matrix of chlorite and tremolite. Of the two, sample 1012 is much finer grained and contains less albite. A greater degree of brecciation is most probably responsible for this.

At the outcrop scale all these rocks appear similar, although closer study reveals several differences. These rocks represent a series of interbedded vesicular and porphyritic volcanic flows.

8. Gypsum

The gypsum is interbedded in the greenstone flows between sample location 1010 and the black shales. The single outcrop is a slumped exposure of bedded gypsum about 9m thick. Several sinkholes, up to 15m deep and 30 to 40m across, are found on the valley floor behind the slump exposed in the gorge of Mule Creek. These sinkholes are fault bounded in a straight line against the black shale contact. Late in the exploration season, after I had returned to University, a Noranda Exploration geologist discovered another outcrop of gypsum and two locations of sinkholes approximately two kilometres to the southeast.

Several zones can be distinguished within the exposure. From bottom to top as the outcrop is oriented they are:

Zone 1. A zone of finely-laminated impure gypsum consisting of four subzones. A layer of laminated gypsum, rich in epidote and chlorite, is sandwiched between two layers of limonite-stained, fine-grained gypsum. The limonite staining is surficial and is most probably a weathering product. The first layer is about 15cm thick while the limonite-stained layers above and below it are about one metre each in thickness. The laminations are less than one millimetre thick in all these layers. The fourth subzone is much purer than the layers below it, but it still contains faint lamellae of impurities, giving a banded appearance. The laminations are of the order of millimetres. This fourth layer is about 20cm in thickness and the gypsum has a faint pinkish colour.

Zone 2. This is a chaotic zone composed of chlorite, epidote, gypsum, calcite and quartz. Several small specks of malachite staining are evident on this sample. Some laminations, where present, are very fine - less than one millimetre. Other areas of this zone are folded and distorted to the point of appearing as a marble cake with no definite order to the mineral pattern. The thickness of this layer is about 2m.

Zone 3. A genuinely massive layer of white gypsum containing faint lamellae of chlorite and epidote lies above the chaotic zone. Bands of fine-grained pyrite and chalcopyrite (accompanied by malachite-staining) can be found in this zone. The pyrite is in the form of cubes randomly oriented in a gypsum matrix. The crystals occur singly and range in size from about 50 to 500μ. This zone is also about 2m thick.

Zone 4. Above this is a finely laminated layer of white gypsum that grades upward into another layer rich in chlorite and epidote. A final thick laminated layer of fine-grained white gypsum caps off the outcrop. The total thickness of this zone is about 2.5m.

The entire outcrop is cut by several openings produced by dissolution of gypsum along fracture surfaces. Precipitation of minor amounts of calcite has occurred on the outcrop surface and in these openings. Massive areas of the outcrop are less deeply weathered than areas of laminated minerals.

9. Barite-quartz veins

Nodular pods and thin veins of barite and quartz outcrop to the west of the gypsum in the greenstone volcanic rocks. The nodules range in size from 10 to 30 cm in length. The veins are up to 10cm wide and several metres in length. The walls of the veins are not sharp contacts but grade from greenstone through a narrow zone of wall rock fragments in vein material and then into the vein material. Small, sparse blebs of pyrite and chalcopyrite (as well as malachite staining) occur in the vein material and on wall rock fragments. Within the nodules small, irregular blebs of pyrite and chalcopyrite (malachite staining) are immediately evident. Reflected light microscopy shows the blebs to have very irregular, serrated boundaries. Small rounded to sub-rounded grains of pyrite are contained within the chalcopyrite. These blebs are up to about two millimetres across.

10. Diorite

Outcropping in the upper part of Mule Creek, and to the south, is an equigranular intrusive rock represented by samples 1013, 1019 and 1021. Sample 1013 is composed almost entirely of albite and tremolite with some chlorite and quartz. Samples 1019 and 1021 contain primary clinopyroxene with no tremolite. In 1019 albite, quartz, chlorite and clinopyroxene are about equally abundant, along with 10% calcite. Sample 1021 has about 30% each of albite and clinopyroxene with 20% chlorite, 10% quartz and minor calcite. Most probably this was originally a diorite intrusive. These rocks have been brecciated and fractured.

Sample 1018 is a coarse-grained rock, darker than the above. The mineralogy is 80% albite, 10% clinopyroxene (titaniferous augite) and some chlorite with minor amounts of sericite, quartz and iron oxide staining. Brecciation is evident in the albite. This rock is an alkaline basalt but its relationship to the surrounding rocks is not clear.

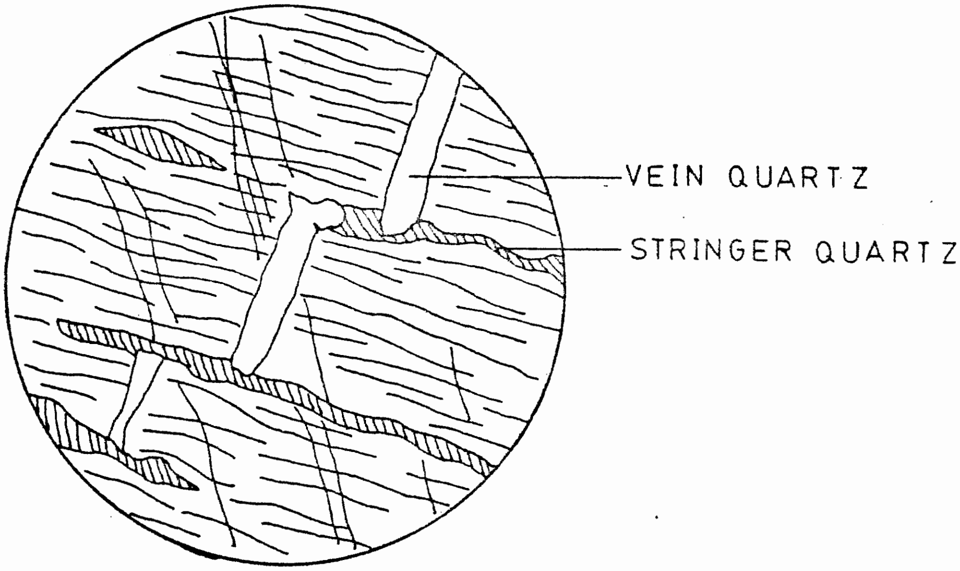


Fig. 3 80x
SAMPLE 1006

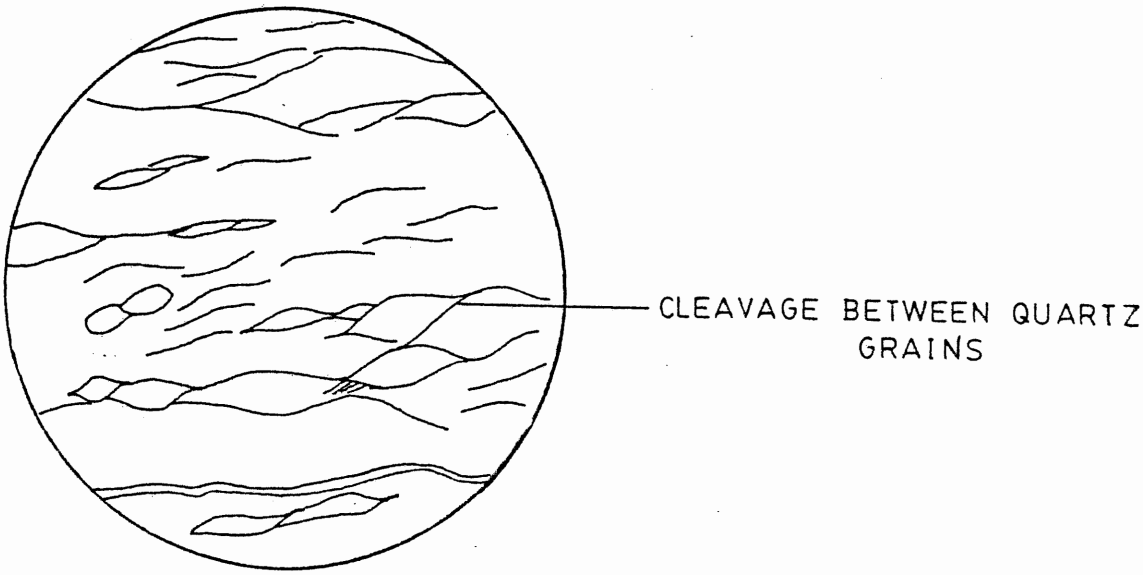


Fig. 4 80x
SAMPLE 1002 B

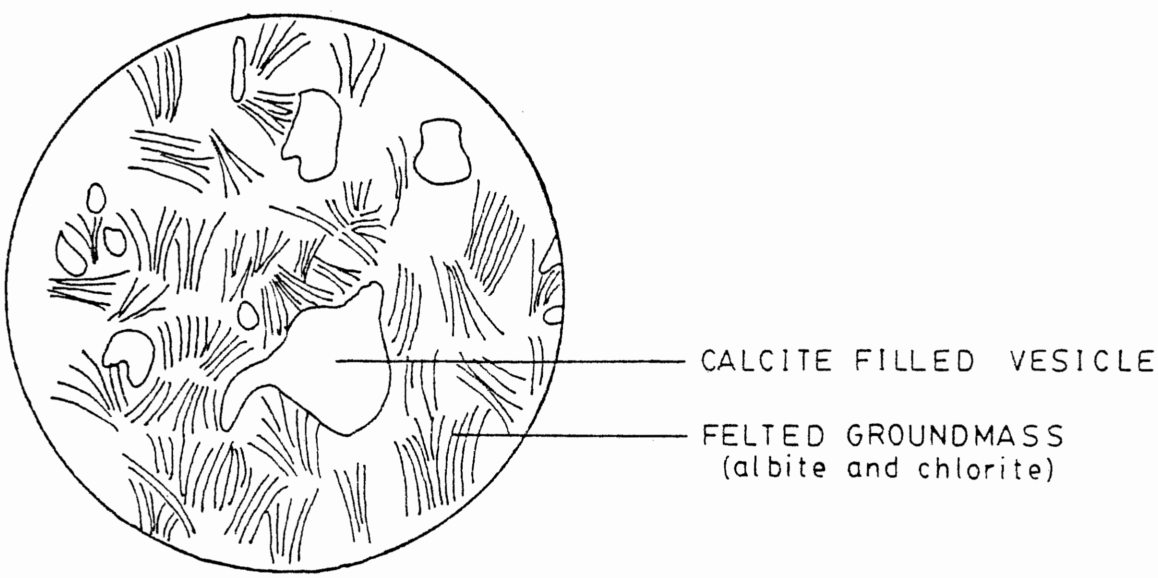


Fig. 5 80x
SAMPLE 1005

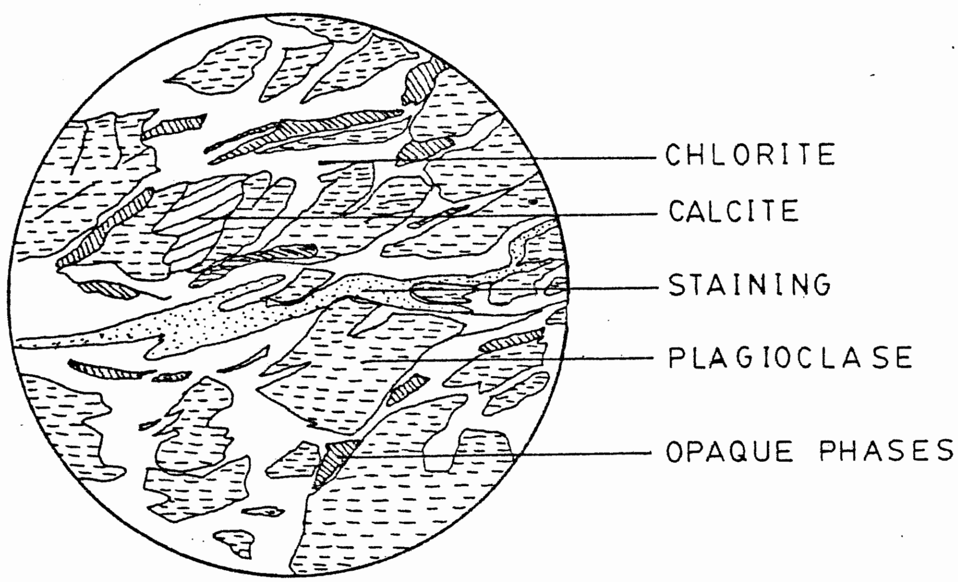


Fig.7 80x
SAMPLE 1100

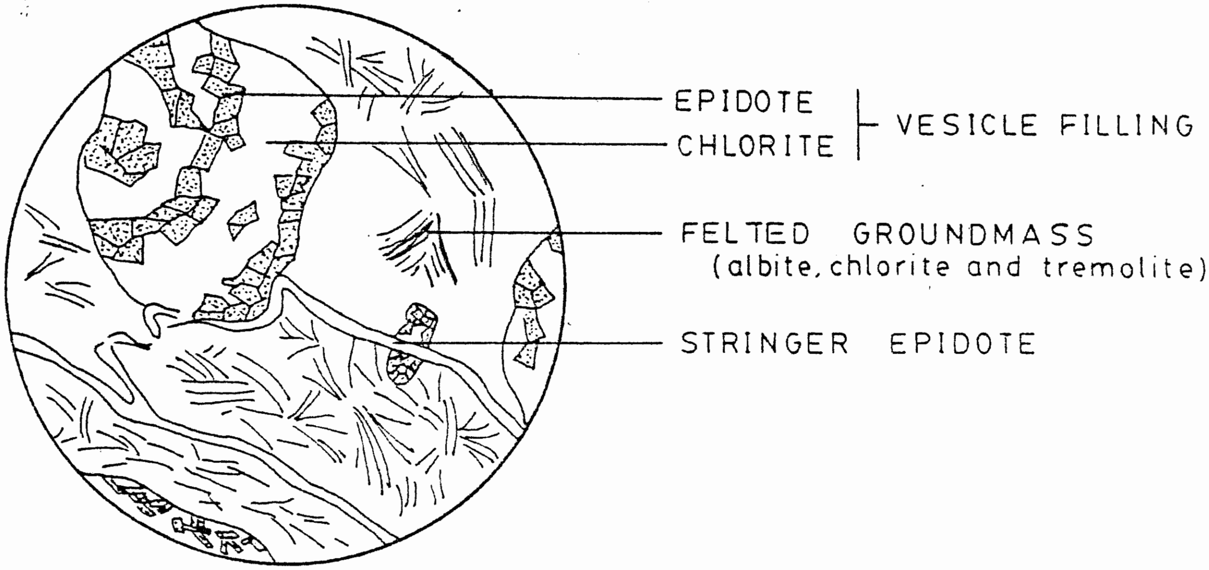


Fig.6 20x
SAMPLE 1011

Chapter 4

Deformation

The Denali fault system is a well-defined fault zone dividing the St. Elias Mountains to the west from the Coast Plutonic Complex to the east. This system is a right lateral strike-slip fault at least 1000km in length with an offset of about 300km (see Fig.1). According to Eisbacher (1976), the Denali system was active as early as latest Mesozoic and early Tertiary time. The system is presumed to be still active although no direct evidence for motion after Miocene and possibly Pliocene has been found.

A major branch of this system cuts across Mule Creek between the black shales and the greenstone and is shown by the truncation of the gypsum sinkholes (see Fig.8). A slight topographic contrast of about one metre is seen when crossing this fault, the greenstone being slightly lower. This is most probably due to a difference in erosional resistance between the rocks on either side of the fault. The vegetation becomes more sparse over the shales. In the gorge one small drag fold was observed in the shales. Samples 1010, 1009 and 1011 are located progressively more westerly from the fault and respectively show a decrease in

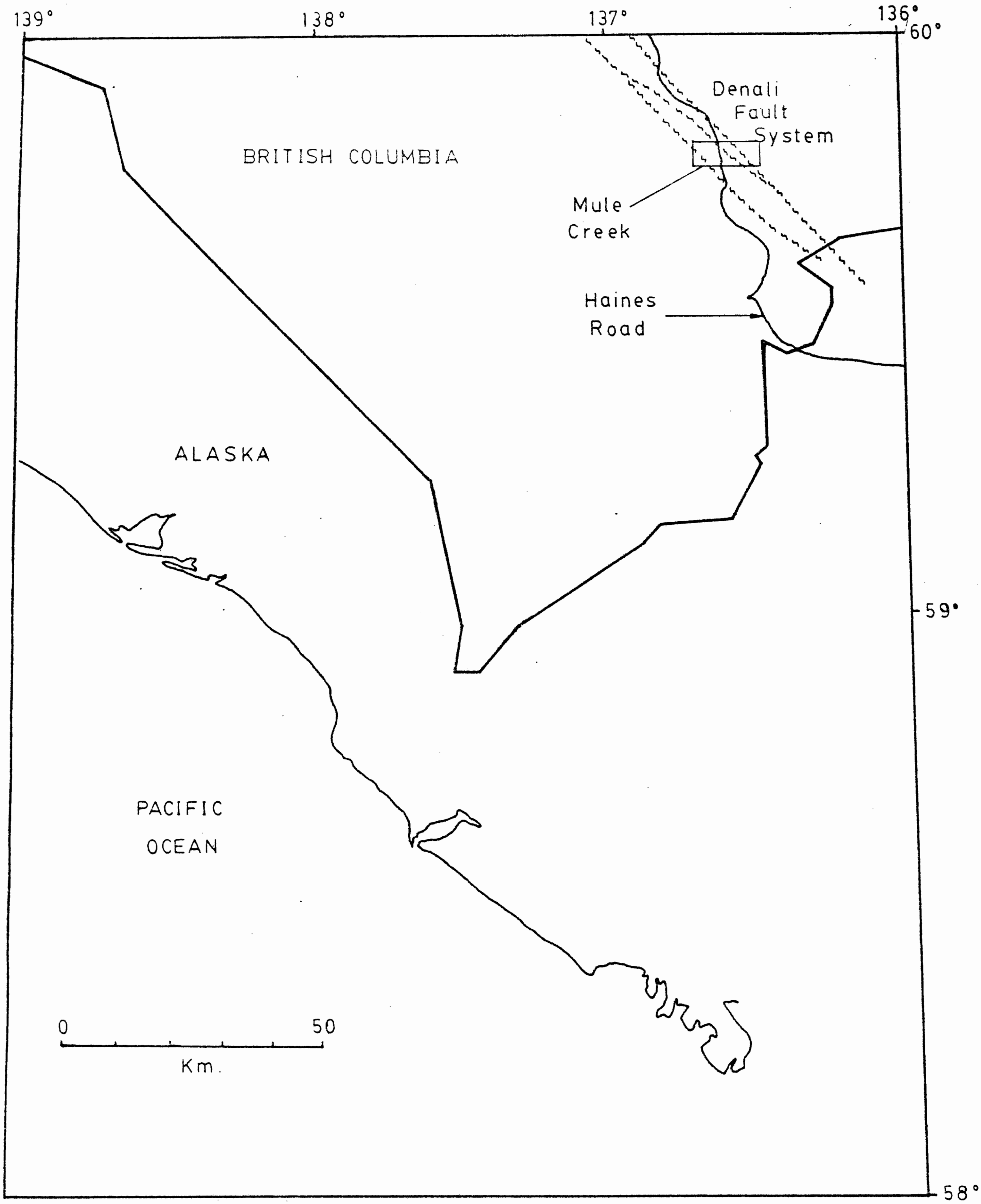


Fig.8 Showing Mule Creek in Denali Fault System.
After Campbell and Dodds (1979.)

brecciation and shearing. The degree of metamorphism appears to be greater in the greenstone than in the shales and the intermediate to felsic volcanic rocks.

The Denali system is a series of faults that form a zone of fault activity. 300km of lateral offset has been achieved with a series of pulses of this system, through time. With each pulse, additional shearing and brecciation resulted in the rocks. The most brecciated samples are 1012 and 1100 (greenstone) which are near the diorite intrusive. In a rock already sheared by fault motion, brecciation to the degree seen in these samples could be produced by the additional stresses attending intrusion of a body such as the diorite.

The sedimentary rocks have developed several cleavages, best seen in the argillite outcrop in Mule Creek. Some brecciation is evident along these cleavages. Each quartz grain shows strain through an elongation parallel to the cleavage and a wavy extinction. This is also seen in the black shale adjacent to the fault cutting Mule Creek.

These rocks are all allochthonous, being transported by orogenic processes from their place of deposition to their present location. Such transport, principally by thrusting, may also explain the extensive shearing and brecciation visible in this area.

Metamorphism

The metamorphism of the rocks in the Mule Creek gorge has progressed to the greenschist facies. The sedimentary rocks show chlorite has grown, presumably from clay minerals. The quartz is still fine-grained showing no recrystallization although some pressure solution has occurred. The limestone shows some zones of recrystallization.

The dyke rock and silicic volcanic rock have albite as their plagioclase and have developed chlorite. The dyke rock has apatite needles growing in the albite. The felsic volcanic rocks are similarly altered. The groundmass of these rocks shows dark nondescript areas most probably zones of devitrified glass. Textures are essentially unaltered.

The diorite intrusive shows a range of metamorphic grade. In Mule Creek gorge no clinopyroxene remains -- only felted zones of tremolite and chlorite. The samples to the south, however, show alteration to a lesser degree. Sample 1019 displays some tremolite developing from clinopyroxene but the original mineral is still clearly recognizable. Sample 1020 shows only slight alteration of the clinopyroxene. All the diorite samples have albite as their plagioclase reflecting a degree of metamorphism.

The most complete metamorphism is developed in the greenstone volcanic rocks. The mineral assemblage is characteristic of greenschist facies rocks. These include albite, chlorite, epidote, tremolite and calcite. All of these minerals are found in these rocks. Epidote and tremolite are most abundant in the originally vesicular rocks. Chlorite is slightly higher in the porphyritic rocks.

The metamorphic minerals in the greenstone volcanic rocks and the diorite are felted and intergrown. Some of the tremolite and chlorite appears to be overgrowing other growths of these minerals. Some of these mineral growths appear twisted and bent while others are not. This would indicate that the metamorphism occurring in these rocks was a continual process that occurred over some time. In this time, occasional pulses of the fault system have displaced the growing minerals. As metamorphism continued successive pulses stressed the mineral growths more and more, while newer growths reflect less deformation.

The laminations within the gypsum have also been metamorphosed, predominantly to chlorite and epidote and, therefore were probably originally mainly clay impurities in the gypsum. Some zones of the gypsum appear coarse-grained, possibly indicating a recrystallized form.

Structure

An unconformity exists in Mule Creek and the Kelsall River between the underlying argillite and the overlying grey to cream limestone. To the south this unconformity is found between the argillite and the greenstone volcanic rocks.

In Mule Creek the argillite dips gently to the north-northeast while in the southern outcrop the dip is almost vertical. The overlying limestone has a vertical dip and strikes northwest. The brecciated black shale also dips steeply to the northeast.

The gypsum within the greenstone has been displaced downslope by translation and dips to the northeast. No ductile or flowage features were observed in the outcrop.

Therefore, several units of various ages have been similarly deformed. This suggests the same process is responsible for all the deformation. The most likely mechanism capable of this is the motion of the Denali fault system.

Sulphur Isotopes

Four samples: two of sulphate - one from gypsum and one from barite; and two of sulphide - one extracted from gypsum and the other from barite - were submitted to McMaster University for sulphur isotope analysis (see Table 1). No standards were included.

Sulphur occurs in nature in predominantly two isotopes - S^{32} and S^{34}. Sulphur isotope analyses are quoted as the difference between the analysed sample and a standard. The accepted standard is the Cañon Diablo meteorite, with S^{32}/S^{34} equal to 22.22. The standard thus has δS^{34} equal to 0 parts per thousand ($^{o}/oo$). Positive and negative values indicate enrichment and depletion of the heavy isotope respectively compared to the standard. Circulating currents in such a large sulphate reservoir as the ocean serve to provide an isotopic source of essentially constant sulphur ratio, whether precipitation is occurring or not - at least in a somewhat open sedimentary basin. As a result, the precipitated sulphate will approximately reflect the oceanic sulphate isotope ratio.

The bedded nature of the gypsum outcrop indicates precipitation from a reservoir - sea water. Hence the

SAMPLE	δS^{34}
GYPSUM	+11.7
BARITE	+11.3
SULPHIDE from GYPSUM	-29.5
SULPHIDE from BARITE	- 5.0 *

Table 1: SULPHUR ISOTOPE ANALYSES

* Due to difficulty in separating the sulphide from the barite some sulphate impurity inevitably contaminated the sample. Therefore this value should be interpreted as a maximum value and may be somewhat higher than the actual value for this sample.

isotope ratio of the gypsum most probably reflects the ocean water sulphur isotope ratio at the time of deposition. If the basin is restricted, the isotope ratio will become smaller due to bacterial reduction of sulphate to sulphide. This means δS^{34} becomes more positive. Sangster, (1968) (from Thode and Monster (1965)) quotes values of δS^{34} for ancient oceans throughout Phanerozoic times. (See App.3) The only δS^{34} value smaller than those quoted for the gypsum and the barite here occur for middle to upper Permian time. As sulphide fractionation would only increase δS^{34}, it cannot be the reason for such a low δS^{34} value. Therefore, the sea water δS^{34} value must have been low at the time of deposition of the gypsum and barite found in Mule Creek. For this reason I postulate the gypsum, and at least immediately accompanying greenstone volcanic rocks, to be middle to upper Permian in age. These rocks are believed to be Triassic or later (Watson, 1948) on the basis of correlation with fossiliferous sedimentary rocks interbedded with the greenstone at other locations.

The δS^{34} values for the sulphide samples - predominantly pyrite - are very low. With the prevalence of sulphate in the gypsum and barite, it is most likely that sulphate reducing bacteria existed in this environment. The bacteria reduce only the lighter isotope to sulphide leaving the heavier isotope as sulphate. This fractionation leads to a depletion in the δS^{34} value. The amount of depletion is dependent on the rate of biogenic reduction. If biogenic reduction is the reason for such low δS^{34} values, particularly in the case of the sulphide extracted from the gypsum, the rate of reduction must have been very high as the fractionation factor usually ranges from 0-25^{o}/oo with a typical value of about 15^{o}/oo, (Sangster, 1968).

Chapter 5

Interpretation

The oldest rocks (Watson, 1948) in the area are the argillite and limestone of Paleozoic age. The unconformably overlying grey to cream limestone is of unknown age (possibly also Paleozoic).

The greenstone volcanic rocks and the diorite intrusion may be of Mesozoic or late Paleozoic age, (Watson, 1948). Watson deduces this age through similarities of these rocks with rocks of Lower Mesozoic age in southeastern Alaska. Between the greenstone volcanic rocks and the the grey to cream limestone, and separated from them by faults, are the black shales, the intermediate to felsic volcanics and the brecciated arkosic conglomerate. The age of these is unknown.

The argillite and limestone and the grey to cream limestone are waterlain sedimentary rocks. The bedding attitudes observed in the field show extensive tectonic deformation, the result of the Cordilleran orogeny. The presence of bedded gypsum within the greenstone indicates these rocks to be waterlain also. The formational environment may have been a marginal basin, or a more open oceanic one. Which one is unclear at this time, although the presence of gypsum suggests a somewhat restricted environment allowing precipitation of the sulphate mineral. The late Paleozoic or early Mesozoic age of these rocks is contemporaneous with the early formational stages of the Cordilleran orogeny, during which time early basinal structures formed.

The Dezadeash Flysch of Jurassic-Cretaceous age (Eisbacher, 1976) lies to the north of Mule Creek. The Dezadeash formation is a sequence of turbidite deposits composed of sandstone, siltstone and shale. Grain size decreases from east to west in this sequence. In the west, beside the Denali Fault, the sequence is composed of finely parallel-laminated siltstones and shales. The fine laminations, grain size and maturity suggest the black shale in Mule Creek to be a distal facies. Motion of the Denali system rules out the possibility of these rocks being a part of the Dezadeash sequence; however, more than one basin developed during this time. Therefore, these black shales may be an equivalent distal facies formed in another basin to the south of the Dezadeash basin.

The origin and time of emplacement of the crosscutting dyke is unclear as its only exposure is an outcrop within the black shales. This dyke may or may not be the feeder for the extrusive rock exposed in a small irregular outcrop above the black shales. One piece of evidence supporting this possibility is the similar mineralogical compositions of the two rock samples.

The felsic to intermediate volcanic rocks adjacent to the black shales are waterlain volcanic rocks. This is evidenced by their pillowed and massive nature. These volcanic rocks were probably extruded in the same basinal feature where the brecciated black shales were deposited. The two units appear conformable, although the exposure of this contact is limited - being overgrown by grasses and brush. The metamorphism observed in the volcanic rocks may be produced by changes in temperature and pressure conditions in the conventional way, or may be spilite alteration associated with the subaqueous extrusion of these rocks. Without further study, either explanation is a possibility. On the opposite side of the volcanic rocks is a black sedimentary rock - shale. Sample 1016 is a volcanic rock interbedded with these shales. Beside these is a brecciated arkosic rock flanked by deeply eroded and vegetation-covered banks.

Several possibilities exist for the origin of the brecciated arkosic rock: (1) A brecciated arkosic sedimentary rock; (2) A pyroclastic breccia; (3) a combination of (1) and (2). A purely pyroclastic breccia is unlikely as the rock is more than 75 per cent quartz. The most likely source for a pyroclastic rock is the nearby volcanics, but these contain no quartz and no volcanic fragments can be found in this rock. Sedimentary reworking could remove the volcanic fragments through erosion but still no quartz source can be postulated. The erosion of a quartz-rich rock - quartzite - could explain the composition of this rock. The grain size is comparable to a fine conglomerate. Foliation and brecciation present can be explained as associated with the faulting described earlier. For these reasons, I believe this rock to be a sedimentary conglomerate produced by erosion of a fine-grained quartz-rich rock. New evidence may suggest otherwise.

In summary, argillite and limestone were deposited during Paleozoic time. The Cordilleran orogeny began producing somewhat restricted marine areas where the greenstone volcanic rocks, gypsum and barite formed. Continuing orogenic processes produced basins similar to the Dezadeash basin, depositing fine-grained sedimentary rocks and intermediate to felsic submarine flows. Subsequent uplift produced the conglomerate. During this time the Denali system formed and the diorite intrusion occurred as the orogen matured. Pulsations of this fault system produced the extensive brecciation seen in the conglomerate, greenstone and black shales. The time of the dyke rock is unknown. Uplift with erosion and glaciation produced the exposure seen at present.

These various units were separated in both time and space during their formation. The Denali fault system is seen as the primary mechanism responsible for assembling these units in their present configuration. The geologic environments move from marine to terrestrial while the time frame spans from the Paleozoic to at least Paleocene and most probably the present day.

Conclusions

The rocks of Mule Creek can be divided into several subunits. These include the greenstone volcanic rocks and diorite intrusive; the brecciated shale, felsic to intermediate volcanic rocks and the brecciated conglomerate; and the argillite and limestone. All these units have been brecciated and sheared to a greater or lesser extent - the units nearest the fault branches being the most deformed. The metamorphic grade of the region is greenschist facies although individual units reflect slightly different degrees of this metamorphism.

Upon first observation the greenstone would appear to be a nondescript unit. Closer inspection, however, reveals it to be a series of porphyritic and vesicular extrusive rock. Bedded gypsum is interbedded with these flows. Fine-grained iron and copper sulphides occur as laminated bands in the gypsum. Small blebs of chalcopyrite are found disseminated throughout the barite-quartz nodules and veins. These relationships suggest the possible presence of copper-bearing sulphide minerals in economic quantities. To substantiate or disprove this statement further field-work will be necessary.

Previous work by Watson (1948) suggested these rocks to be early Mesozoic or later in age. δS^{34} data here suggest the possibility of a late Paleozoic age for the gypsum, barite and greenstone volcanic rocks. The sulphide may have been produced through migration of biogenically reduced hydrogen sulphide within the veins, until metals were encountered, causing precipitation.

The assembly and varying degrees of deformation of these rock units is the result of continued motion of the Denali fault system. This motion has occurred in a pulsing fashion through time from Jurassic-Cretaceous to present. The brecciated shale, felsic to intermediate volcanic rocks and the brecciated conglomerate are thin slices of these units that have been caught in the fault system and transported to their present locations. Glaciation has then carpeted this region with a layer of till up to a few metres thick.

Appendix 1

MINERAL PERCENTAGES ESTIMATED FROM THIN SECTION

Sample	Mineral	Percentage	Comments
1001	Calcite	99	Quartz in small rounded detrital grains
	Quartz	1	
1002A	Quartz	90	Quartz very fine grained.
	Chlorite-Clays	10	
1002B	Quartz	90	Quartz very fine grained.
	Chlorite-Clays	10	
1003	Quartz	85	Iron staining in interstitial areas.
	Opaques	Minor	
	Chlorite	5	
	Albite	10	
1004	Calcite	25-30	Calcite is secondary Quartz very fine grained.
	Quartz	60	
	Chlorite-Clays	10	
1005	Calcite	15	
	Chlorite	5	
	Felted Groundmass	80	
1006	Quartz	90-95	Interstitial iron staining.
	Chlorite Clays	5-10	
	Opaques	Minor	
1007	Albite	80	
	Chlorite	10	
	Unknown Mass	10	
1008	Albite	70-80	Interstitial iron staining.
	Chlorite	20	
	Calcite	Minor	
	Opaques	Minor	

Sample	Mineral	Percentage	Comment
1009	Albite	50-60	Some albite occurs as recrystallized phenocrysts
	Chlorite	20-25	
	Tremolite	5-10	
	Calcite	Minor	
	Epidote	3-4	
	Opaques	1-2	
1010	Albite	50	
	Tremolite	20	
	Chlorite	10	
	Epidote	20	
1011	Albite	40	
	Tremolite	15	
	Chlorite	25	
	Epidote	20	
1012	Albite	50	
	Chlorite	25	
	Epidote	10	
	Tremolite	5-10	
	Opaques	4-5	
1013	Albite	20-40	Very fine grained dark masses cannot be determined.
	Tremolite	40	
	Chlorite	15	
	Unknown mass	10-15	
	Calcite	Minor	
1014/ 1015	Calcite	40-50	
	Albite	30-35	
	Chlorite	15-20	
1016	Unknown - fine grained mass with 1-2 opaques		

Sample	Mineral	Percentage	Comments
1017	Quartz	90	Quartz is very fine grained detritus.
	Chlorite-Clays	10	
1018	Albite	70	
	Clinopyroxene	20	
	Chlorite	10	
1019	Minerals too dark and altered to identify except clinopyroxene-tremolite masses 35-40.		
1020	Albite	55-65	
	Chlorite	20	
	Tremolite	10	
	Epidote	3-4	
	Opaques	2-3	
1021	Clinopyroxene	40	
	Opaques	Minor	
	Dark unknown mass	60	
1100	Albite	65-70	
	Chlorite	20	
	Calcite	5-10	
	Opaques	2-3	
	Epidote	Minor	

Appendix 2

MINERAL PERCENTAGES ESTIMATED FROM

X RAY DIFFRACTION SPECTRA. (MAJOR MINERALS)

Sample	Mineral	Peak Height	Intensity Factor	Product (P.H.x I.F)	Total	Mineral Percent
1002B	Quartz	60.	1.00	60		66
	Chlorite	2.3	4.95	11.4	91.0	13
	Albite	7.0	2.80	19.6		21
1003	Quartz	66	1.00	66		76
	Chlorite	1.5	4.95	7.4	87.4	8
	Albite	5.0	2.80	14		16
1004	Calcite	13.5	1.65	22.3		42
	Albite	4.25	2.80	11.9	52.6	23
	Quartz	11.0	1.00	11.0		21
	Chlorite	1.5	4.95	7.43		14
1005	Calcite	14	1.65	23.1		34
	Albite	14	2.80	39.2	68.2	57
	Chlorite	1.2	4.95	5.94		9
1006	Quartz	65	1.00	6.50	73.4	89
	Chlorite	1.7	4.95	8.42		11
1007	Quartz	14	1.00	14.0		12
	Albite	30	2.80	84.0	115.3	73
	Chlorite	3.5	4.95	17.3		15
1008	Quartz	16.0	1.00	16.0		21
	Albite	19.8	2.80	55.3	77.3	71
	Chlorite	1.2	4.95	5.94		8
1009	Chlorite	2.3	4.95	11.4		17
	Albite	19	2.80	53.2	69.6	76
	Tremolite	2.0	2.50	5.0		7

Sample	Mineral	Peak Height	Intensity Factor	Product (P.H. x I.F.)	Total	Mineral percent
1010	Albite	13	2.80	36.4		50
	Tremolite	6.0	2.50	15.0		20
	Epidote	4.5	3.25	14.6	73.4	20
	Chlorite	1.5	4.95	7.43		10
1011	Albite	24	2.80	67.2		42
	Tremolite	12	2.50	30.0	161	19
	Chlorite	5	4.95	24.8		15
	Epidote	12	3.25	39.0		24
1012	Tremolite	14	2.50	35.0		20
	Chlorite	10	4.95	49.5	171.7	29
	Albite	23	2.80	64.4		38
	Epidote	7	3.25	22.8		13
1013	Tremolite	18.5	2.50	46.3		40
	Albite	15	2.80	42.0	115.5	36
	Chlorite	4.5	4.95	22.3		19
	Quartz	5.0	1.00	5.0		5
1014	Albite	5.5	2.80	15.4		25
	Calcite	2.5	1.65	41.3	61.6	67
	Chlorite	1.0	4.95	4.95		8
1016	Calcite	31	1.65	51.2		30
	Albite	27	2.80	75.6	168.6	45
	Quartz	27	1.00	27.0		16
	chlorite	3.0	4.95	14.9		9
1017	Quartz	120	1.00	120		66
	Chlorite	5	4.95	24.8	181.2	14
	Albite	13	2.80	36.4		20

Sample	Mineral	Peak Height	Intensity Factor	Product (P.H.x I.F.)	Total	Mineral percent
1018	Albite	90	2.80	252		82
	Chlorite	2.7	4.95	13.4		4
	Quartz	8.5	1.00	8.5	309	3
	Clinopyroxene	7	5.00	35.0		11
1019	Albite	17	2.80	47.6		23
	Quartz	45	1.00	45.0		21
	Chlorite	9	4.95	44.6	210.3	21
	Calcite	11	1.65	18.2		9
	Clinopyroxene	11	5.00	55.0		26
1020	Albite	17	2180	47.6		69
	Tremolite	25	2.50	6.25	68.7	9
	Chlorite	3	4.95	14.9		22
1021	Chlorite	6	4.95	29.7		22
	Quartz	15	1.00	15.0	136.7	11
	Albite	15	2.80	42.0		31
	Clinopyroxene	10	5.00	50.0		36
1100	Chlorite	8	4.95	39.6		12
	Quartz	11	1.00	11.0	332	3
	Albite	88	2.80	246		74
	Calcite	21	1.65	34.7		11

Appendix 3 S^{34} values for ancient oceans from Sangster (1968)[after Thode and Monster (1956) except where noted].

PERIOD	EPOCH	S^{34}o/oo (ocean water sulphate)
Quarternary	(modern ocean)	+ 20.1
Tertiary	Miocene	+ 20.9*
	Eocene	+ 18.4
	Paleocene	+ 19.0
Cretaceous	Lower	+ 15.8
Jurassic		+ 19.3
Triassic	Upper	+ 13.1
	Lower	+ 25.1
Permian	Upper	+ 10.6
	Middle	+ 9.6
Pennsylvanian	Lower	+ 17.6
Mississippian		+ 14.5
Devonian	Upper	+ 22.3
	Middle	+ 22.4
	Lower	+ 16.7
Silurian		+ 24.2
Ordovician		+ 26.9
Cambrian		+ 28.8
Pre-Cambrian	Proterozoic Eon	+ 14.6

* Holster and Kaplan (1966)

Appendix 4

Minerals Actively Sought in Diffraction Data Analysis

Mineral	Window (°2θ. CuKα Radiation)	Range of (D-Spacings) (Å)	Intensity Factor[a]
Amphibole	10.30-10.70	8.59- 8.27	2.50
Analcite	15.60-16.20	5.68- 5.47	1.79
Anatase	25.17-25.47	3.54- 3.50	0.73
Anhydrite	25.30-25.70	3.52- 3.46	0.90
Apatite	31.80-32.15	2.81- 2.78	3.10
Aragonite	45.65-46.00	1.96- 1.97	9.30
Augite	29.70-30.00	3.00- 2.98	5.00
Barite	28.65-29.00	3.11- 3.08	3.10
Calcite	29.25-29.60	3.04- 3.01	1.65
Chlorite	18.50-19.10	4.79- 4.64	4.95
Clinoptilolite	9.70- 9.99	9.11- 8.84	1.56
Cristobalite	21.50-22.05	4.13- 4.05	9.00
Dolomite	30.80-31.15	2.90- 2.87	1.53
Erionite	7.50- 7.90	11.70-11.20	3.10
Goethite	36.45-37.05	2.46- 2.43	7.00
Gypsum	11.30-11.80	7.83- 7.50	0.40
Halite	45.30-45.65	2.00- 1.99	2.00
Hematite	33.00-33.40	2.71- 2.68	3.33
Kaolinite	12.20-12.60	7.25- 7.02	2.25
K-Feldspar	27.35-27.79	3.26- 3.21	4.30
Magnetite	35.30-35.70	2.54- 2.51	2.10
Mica	8.70- 9.10	10.20- 9.72	6.00
Montmorillonite	4.70- 5.20	18.80-17.00	3.00
Palygorskite	8.20- 8.50	10.70-10.40	9.20
Phillipsite	17.50-18.00	5.06- 4.93	17.00
Plagioclase	27.80-28.15	3.21- 3.16	2.80
Pyrite	56.20-56.45	1.63- 1.62	2.30
Rhodochrosite	31.26-31.50	2.86- 2.84	3.45
Quartz	26.45-26.95	3.37- 3.31	1.00
Sepiolite	7.00- 7.40	12.60-11.90	2.00
Siderite	31.90-32.40	2.80- 2.76	1.15
Talc	9.20- 9.55	9.61- 9.25	2.56
Tridymite	20.50-20.75	4.33- 4.28	3.00
Gibbsite	18.00-18.50	4.93- 4.79	0.95

[a]The intensity factors are determined by 1:1 mixtures with quartz by obtaining the ratio of the diagnostic peak intensity of each mineral with the intensity of the diagnostic peak of quartz, which is assigned a value of 1.00. The detection limit in weight percent of the minerals in a siliceous or calcareous matrix can be obtained by multiplying the intensity factor by 0.12.

(after Cook _et al_, 1975)

Appendix 5

Correlation Graphs

These graphs show the correlation of mineral percentages as determined by X-Ray diffraction versus optical determination from thin section.

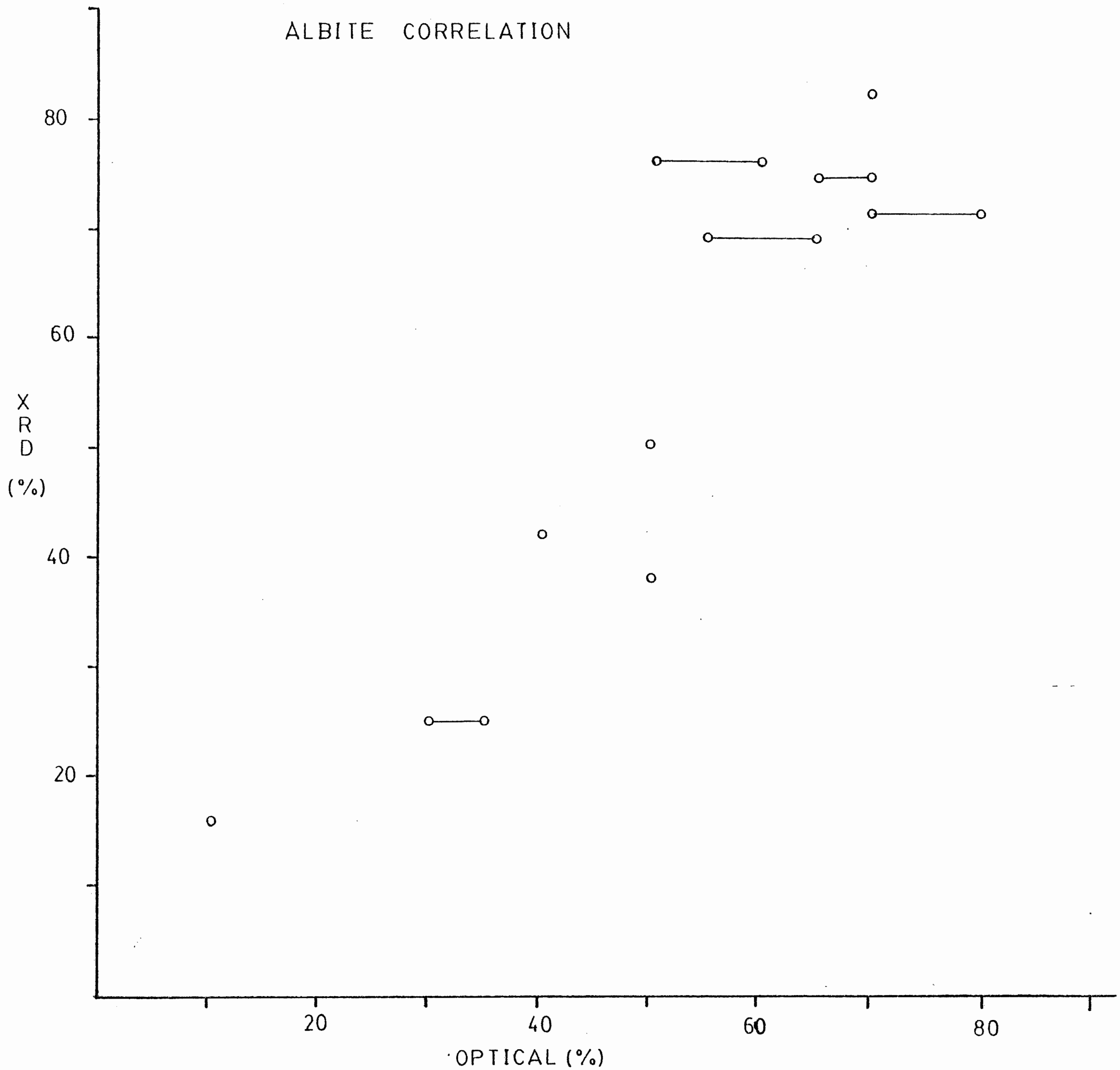
Graph 1: Albite Correlation

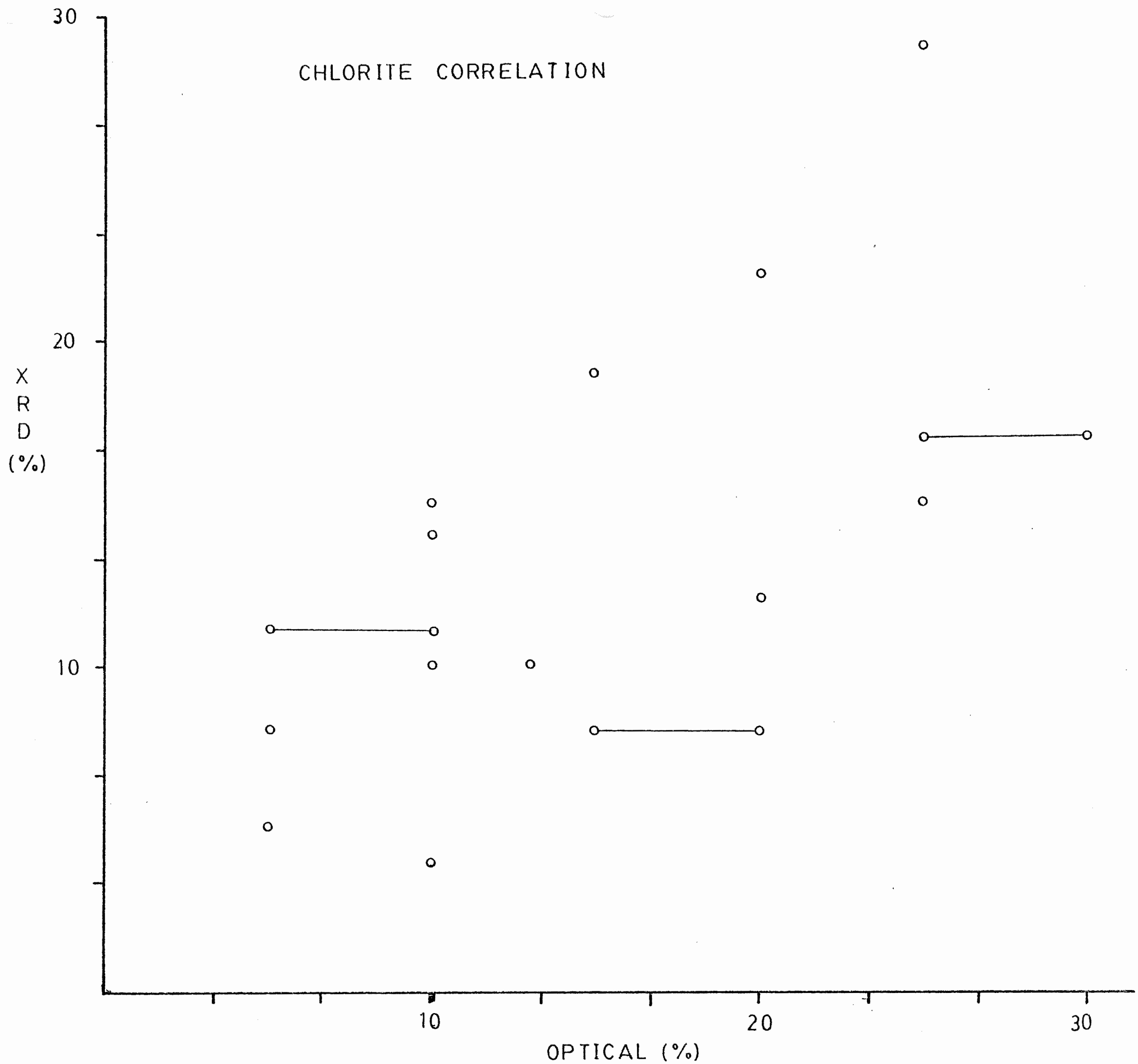
Graph 2: Chlorite Correlation

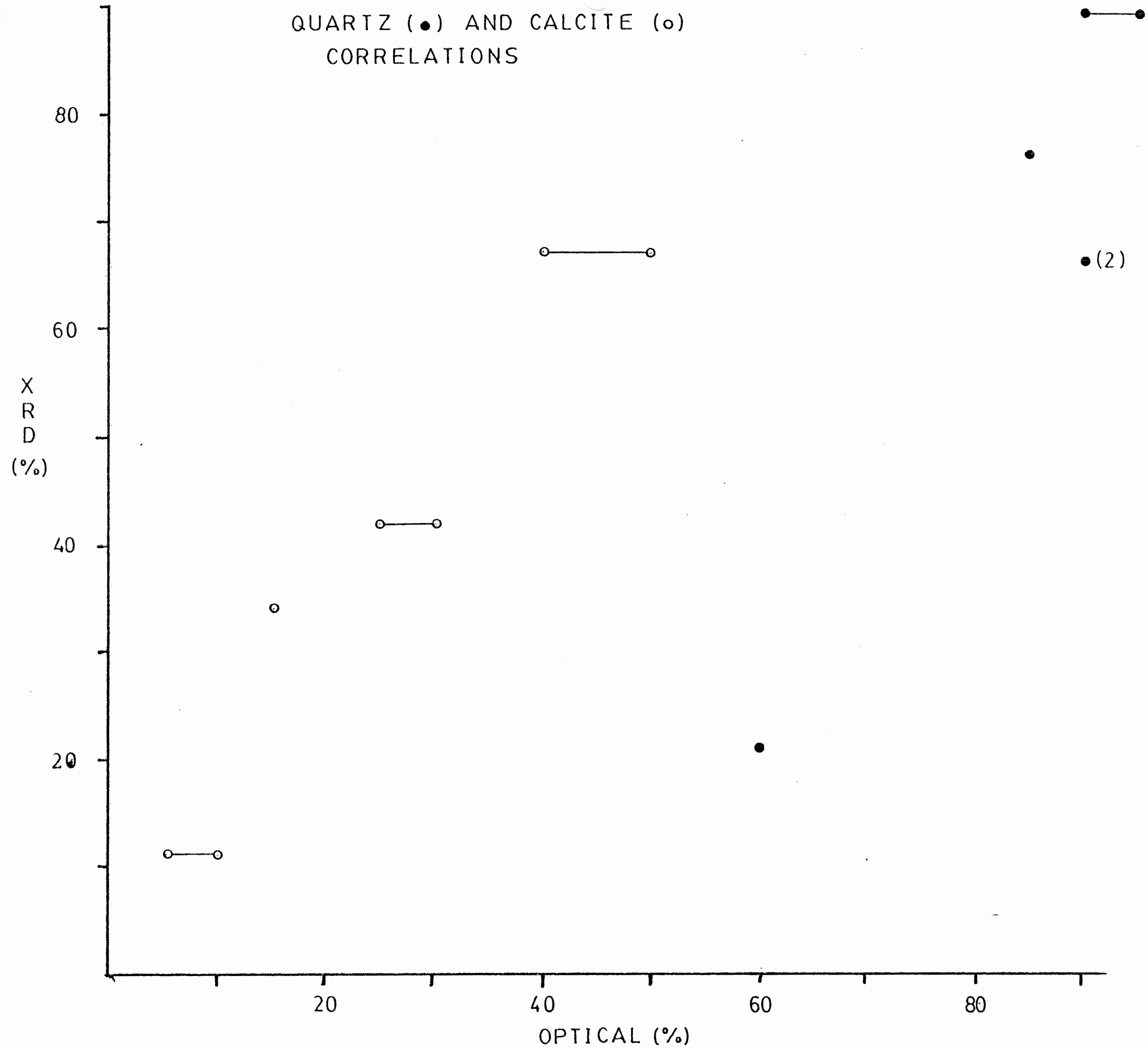
Graph 3: Quartz and Calcite Correlations

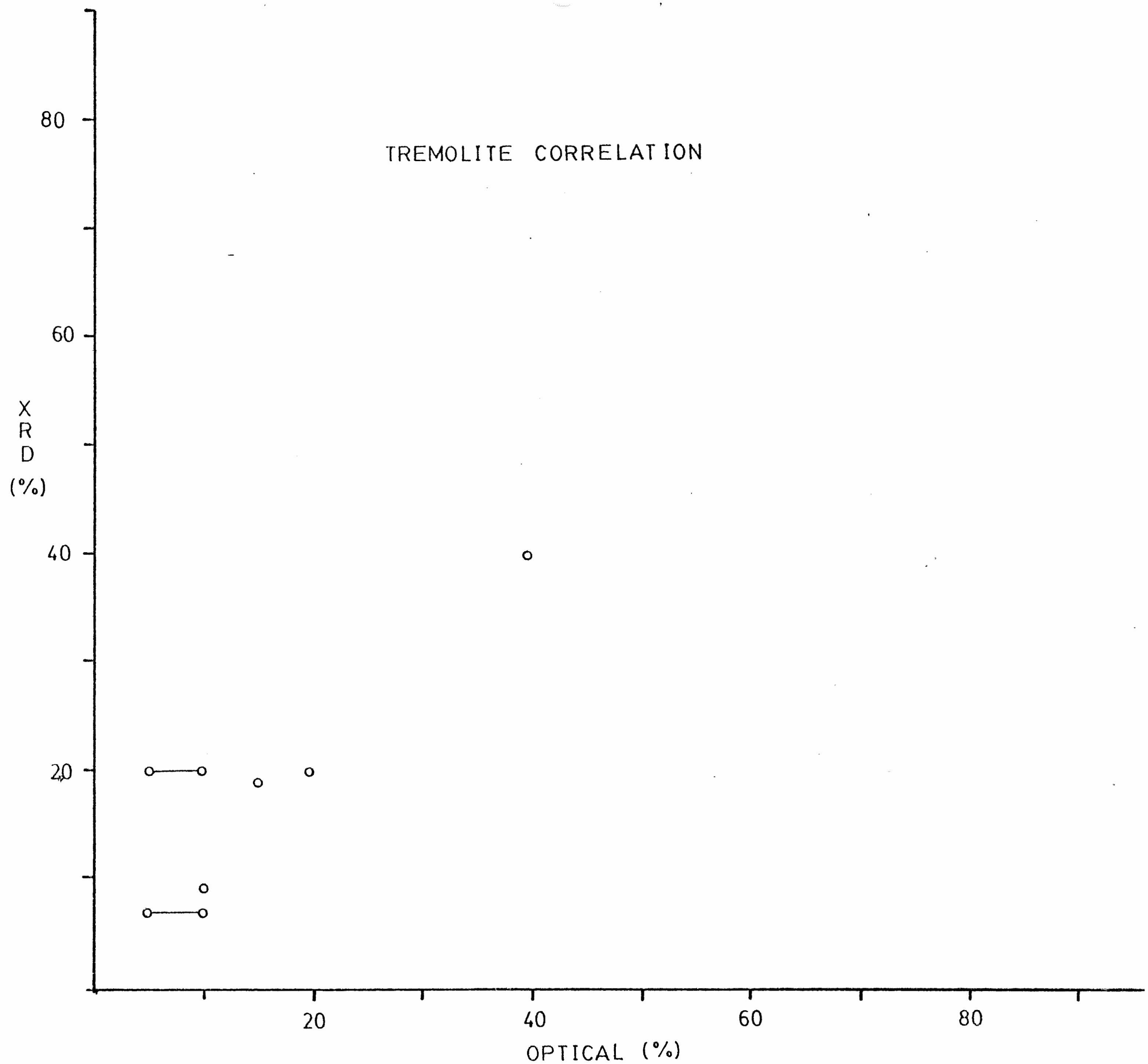
Graph 4: Tremolite Correlation

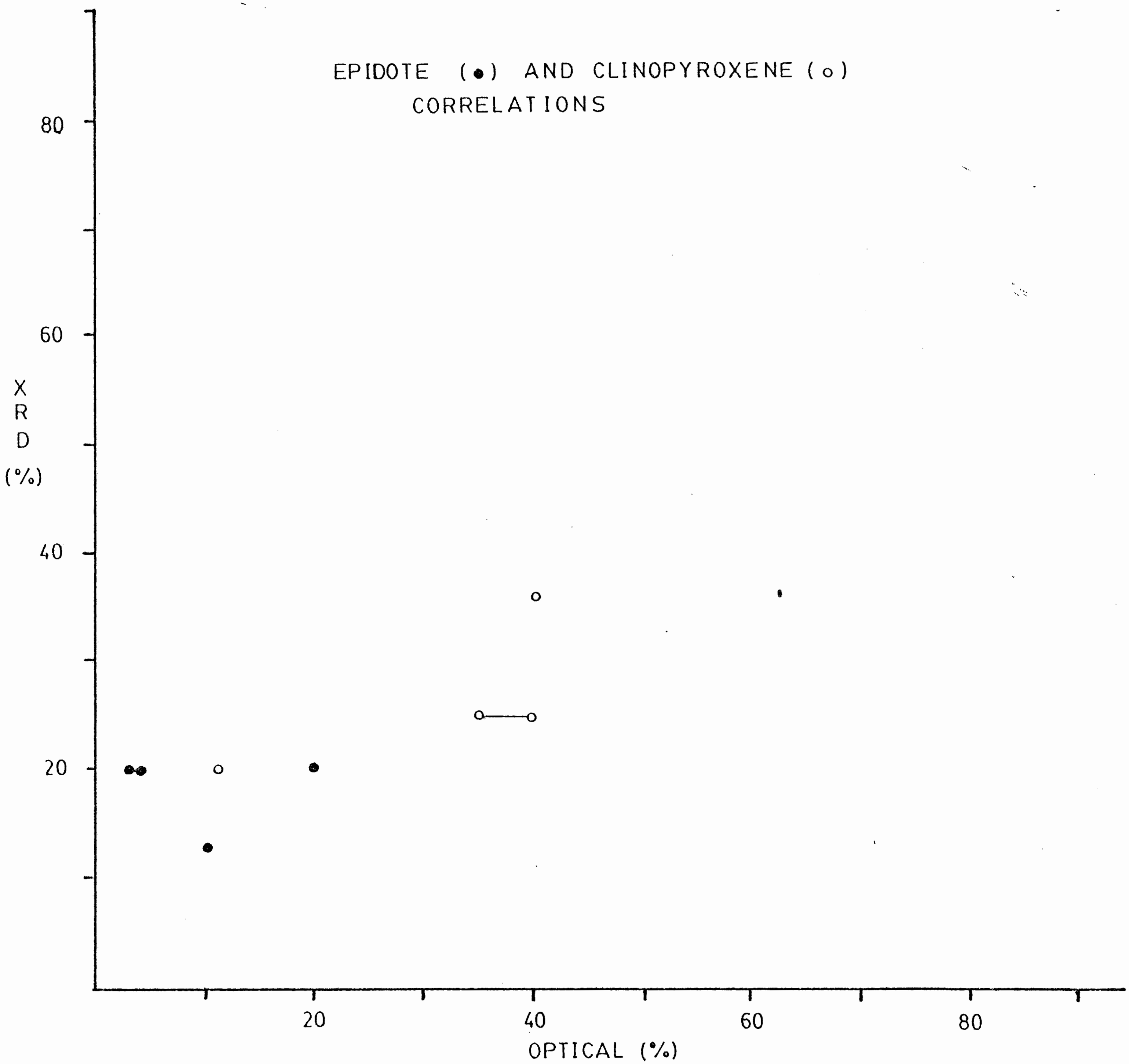
Graph 5: Epidote and Clinopyroxene Correlations


ALBITE CORRELATION
80
60
X
R
D
(%)
40
20
20
40
60
80
OPTICAL (%)


CHLORITE CORRELATION
30
20
10
X
R
D
(%)
10
20
30
OPTICAL (%)


QUARTZ (•) AND CALCITE (o)
CORRELATIONS
80
60
40
20
XRD (%)
(2)
20
40
60
80
OPTICAL (%)


TREMOLITE CORRELATION
80
60
40
20
X
R
D
(%)
20
40
60
80
OPTICAL (%)



EPIDOTE (•) AND CLINOPYROXENE (o)
CORRELATIONS
80
60
X
R
D
(%)
40
20
20
40
60
80
OPTICAL (%)

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SCALE
1:10,000

Metres 200 100 0 200 400 600 800 1000 Metres

REVISED	MULE CREEK	
PROJ. No. 1012	SURVEY BY:	DATE: Nov./82
N.T.S. 114P/15E	DRAWN BY:	SCALE: 1:10,000
DWG. No.	**NORANDA EXPLORATION**	
	OFFICE: Vancouver	