

MINERALOGICAL AND ISOTOPIC RELATIONS IN THE
PORT RADIUM PITCHBLENDÉ DEPOSIT, GREAT BEAR LAKE, CANADA

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ABSTRACT

This thesis integrates the data from field, petrographic, X-ray, and lead and uranium isotopic studies on the Port Radium pitchblende deposit, Great Bear Lake, Canada.

The oldest rocks exposed are andesitic-dacitic bedded tuffs and flows of the Echo Bay group. Overlying detrital rocks of the Cameron Bay group were accumulated before intrusion of hypabyssal, dacitic porphyry bodies and granitic rocks. Sandstones of the Hornby Bay group lie unconformably on the above groups and on denuded granitic rocks. Folds are generally open in the Echo Bay and Cameron Bay groups; the Hornby Bay group is flat-lying. The Echo Bay group was metamorphosed to hornblende hornfels facies rocks, probably during intrusion of granitic rocks.

Fault and fracture zones, most commonly striking northeasterly and dipping steeply north, were in places loci for the successive introduction of "giant quartz veins", diabase dykes, and complex vein mineralizations. In the development of the Port Radium deposit, six stages of metallic and non-metallic vein mineral deposition are recognized. Three periods of wall rock alteration are correlative with episodes of vein mineralization. Tuffs of the Lower Echo Bay sub-group are the predominant host rocks to the ore mineralization. Localization of the pitchblende is attributed to physical factors. Diabase sills, intruded after development of the Port Radium deposit, were fractured during late-stage movements on the veins.

An age of 1820 ± 30 million years is assigned to a granitic rock at Port Radium on the basis of the lead-uranium isotopic analyses of seven zircon fractions. This sets a lower limit on the age of the Echo Bay and Cameron Bay groups and an upper limit on the age of Hornby Bay group and diabase dykes. In the zircon fractions, uranium and radiogenic lead concentrations increase with decreasing average grain size. All fractions show the discordant age pattern $Pb^{206}/U^{238} < Pb^{207}/U^{235} < Pb^{207}/Pb^{206}$. On a "Concordia" diagram, points representing the different zircon fractions define a chord intersecting the Concordia curve at 1815 and 50 million years.

Microscopic and macroscopic samples of three pitchblende specimens from the Port Radium mine were analysed isotopically for lead and uranium. For a specimen of pitchblende in carbonate gangue, concordant lead-uranium ages were obtained on two microscopic samples. The age, 1445 ± 20 million years, is the only concordant age which has been measured for the Port Radium ores. It places a lower limit on the age of the "giant quartz veins", the diabase dykes, and possibly the Hornby Bay group, and an upper limit on the diabase sills. For a specimen of pitchblende in siliceous gangue, two analyses define a chord intersecting the Concordia curve at 1450 and 300 million years. In general, Port Radium pitchblende samples show evidence of past loss of lead; the lead was removed from the vein systems. Comparison of isotopic data on microscopic and macroscopic samples from the same specimen shows that the microscopic samples can be less discordant and

have higher lead-lead ages. Analyses of a number of lead-uranium systems in the same specimen offers a possible means of determining the age of mineralization and the age of an episodic disturbance.

Of eight samples of galena and one of chalcopyrite analysed isotopically for lead, three are ordinary lead, four J-type anomalous lead and two possibly mixtures of ordinary lead and radiogenic uranium lead derived from the pitchblende. The ordinary lead is finely disseminated through the other vein minerals and was probably introduced shortly after the pitchblende. The J-type lead occurs in late, lenticular veinlets and was not formed by mixing with radiogenic lead from the pitchblende ores. Because of the absence of mixing and because of considerations concerning the geochemical character of the source system for the J-type lead, this lead was probably introduced less than 300 million years ago. Disturbances to the lead-uranium systems of the zircon and pitchblende samples provide further isotopic evidence for processes probably active within the last 200-300 million years but not recognized on the basis of geological field data.

Additional isotopic work to confirm and elaborate on these interpretations is suggested.

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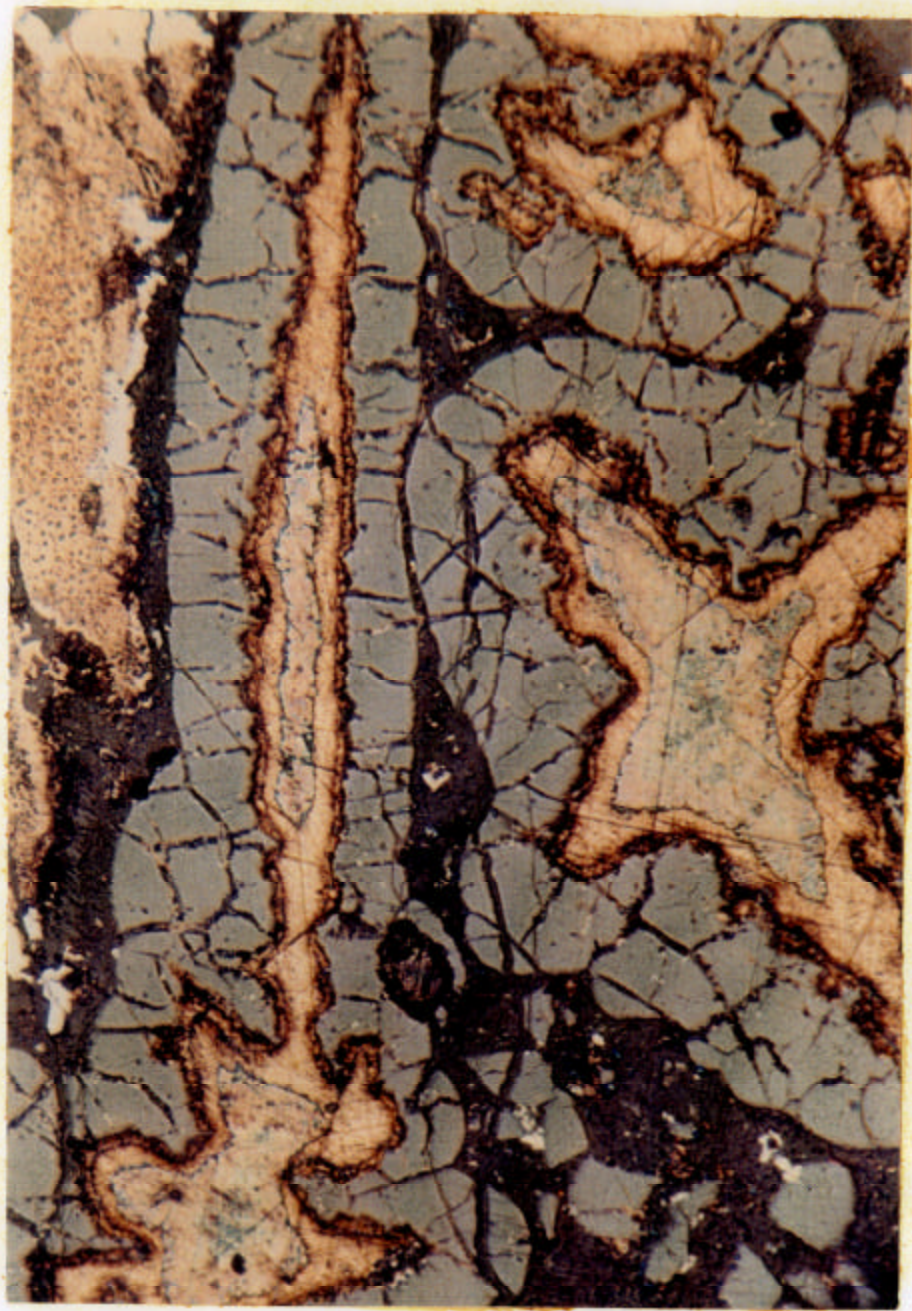
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Frontispiece

Pitchblende dendrites (medium grey) with zoned native silver cores. Exposure to air causes the zones to become visible. Brownish mineral on left side is air-tarnished niccolite. B vein, 1175 level. x130

MINERALOGICAL AND ISOTOPIC RELATIONS IN THE
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INTRODUCTION

During the period 1951 to 1954, the writer was employed as a geologist at Eldorado Mining and Refining Limited's Port Radium mining operation. Duties included underground and surface mapping. The geological study of the Port Radium pitchblende deposit was subsequently continued at the California Institute of Technology. The initial laboratory program undertaken was primarily a study of the vein mineralogy and wall rock alteration. Approximately 450 thin sections and 130 polished sections were examined. Seventy-five samples were X-rayed using either powder photograph or diffractometer techniques.

As the research progressed, it became apparent that a lead-uranium isotopic study might clarify some problems which could not be solved by the classical geologic approach. Accordingly, seven zircon fractions, three pitchblende samples and nine galena samples were analysed isotopically.

The Port Radium deposit was discovered in 1930 by G. A.

LaBine. Milling operations commenced in 1933 and ceased in 1960 upon exhaustion of the ore reserves. An historical summary of the operation is given in Appendix B.

Location and Access

Port Radium, the name of the mine, and of the company-owned town, is situated on LaBine Point about half way up the east side of McTavish Arm, Great Bear Lake in the Canadian NorthWest Territories. It is at longitude $118^{\circ}02'$ W and latitude $66^{\circ}05'$ N and is 30 miles south of the Arctic circle. Figure 1 is a location map.

There are no roads connecting Port Radium with other settled communities. It is accessible by water, through the Mackenzie River system, from railhead at Waterways, Alberta. This route is approximately 1380 miles long and is ice-free from about mid-July until mid-October.

By air, Port Radium is 275 miles northwest of the gold mining community of Yellowknife, N.W.T., on Great Slave Lake and 930 miles north of Edmonton, Alberta. Wheeled aircraft can land on the ice at Port Radium in winter and, in summer, on an unsurfaced landing strip at Sawmill Bay which is 30 miles southwest of the mine. The latter necessitates commuting to the mine by boat or by pontoon-equipped aircraft. Charter aircraft are available in Yellowknife. Current rates are approximately \$0.50 per mile for Cessna 180 aircraft and \$1.05 for Otter aircraft.

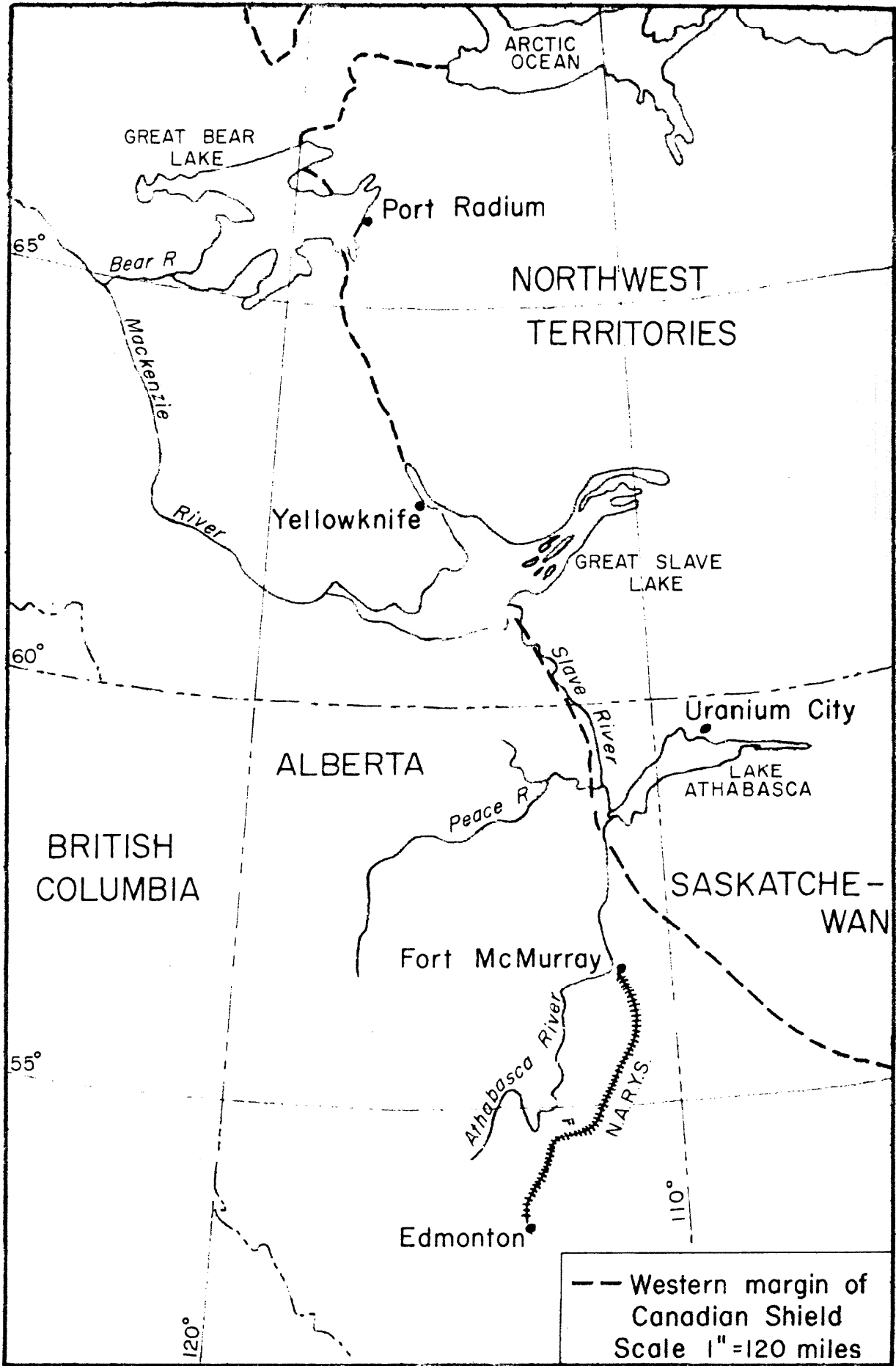


FIGURE 1 - LOCATION MAP

Climate

The climate is sub-Arctic. The mean annual temperature ranges between 17° and 21°F while the maximums and minimums rarely exceed 85° and -45°F respectively. However, winter temperatures only a few miles inland are commonly 10° to 20° lower than at Port Radium.

Small lakes commence freezing over in the latter part of September; the bays of Great Bear Lake in mid-October; and Great Bear Lake itself generally in early November. In the spring, the bays commence to open in late May or early June and the ice leaves Great Bear Lake sometime in July.

The average annual precipitation, which is spread throughout the year, is 10 to 12 inches. The large number of lakes, typical of the Canadian Shield, and the low evaporation rate tend to obscure the sub-arid nature of the climate.

Physiography

The western margin of the Canadian Shield passes in a more or less northerly direction, about 20 miles west of Port Radium, through McTavish Arm of Great Bear Lake. Thus, the major portion of the lake basin is underlain by Paleozoic and Mesozoic strata. Topography on the post-Cambrian strata is relatively rounded and subdued. In contrast, the topography along the eastern shore of Great Bear Lake, where Precambrian rocks crop out, is quite rugged; cliff faces several hundred feet high are common. The present Precambrian surface appears to be a partially-dissected, irregular plateau which slopes gently to the east. Discontinuities in this

surface have been controlled more markedly by fractures of north to east trend than by changes in bedrock lithology.

Great Bear Lake is 511 feet above sea level and the maximum relief in the vicinity of Port Radium is approximately 1000 feet. The depth of the lake is not known. The shore line is very irregular; hidden bays are common.

The area was glaciated by Wisconsin Laurentide ice which moved in a west-northwest direction (Craig, 1960). The most conspicuous features of the glacial action in the vicinity of Port Radium are: disrupted drainage; scoured hill-tops; erratics; and the partial filling of all depressions with glacial drift. Inland, eskers are common. Relict, proglacial-lake shorelines are best exposed 40 miles north of Port Radium at Hornby Bay where Craig found the highest beaches to be 470 feet above the present lake level.

PREVIOUS WORK

A reconnaissance trip by Bell (1902) to Great Bear Lake is of only historic interest since he did no local mapping. Following the discovery of the Port Radium uranium deposit in 1930, Kidd (1933) mapped approximately 3000 square miles east of McTavish Arm of Great Bear Lake for the Geological Survey of Canada. (The locations of geographic features cited are shown in Fig. 2.) A report and an accompanying reconnaissance map, on a scale of 1 inch to 4 miles, were published. During the next three to four years, when prospecting and development activity was at its height, several short technical and semi-technical reports on local features were published but detailed mapping of large areas was not attempted.

From 1944 to 1947, detailed mapping in the vicinity of Port Radium was undertaken by officers of the Geological Survey of Canada in cooperation with the staff of Eldorado Mining and Refining Limited. As a result, a number of classified Special Reports with accompanying maps on a scale of 1 inch to 400 feet were issued. Although the reports were later de-classified, only a few copies of each were originally printed and they have long since been unavailable. They included papers by the following: Jolliffe and Bateman (1944), Thurber (1946), Feniak (1947), and Fortier (1948). The mapping was extended north to the MacAlpine Channel area on a smaller scale by Feniak (1949). Parsons (1948) mapped approximately 4000 square miles southeast of Port Radium on a scale of 1 inch to 4 miles. Campbell (1955, Fig. 2) compiled available geologic data on the McTavish Arm area in the course of an investigation of the geology at Port Radium.

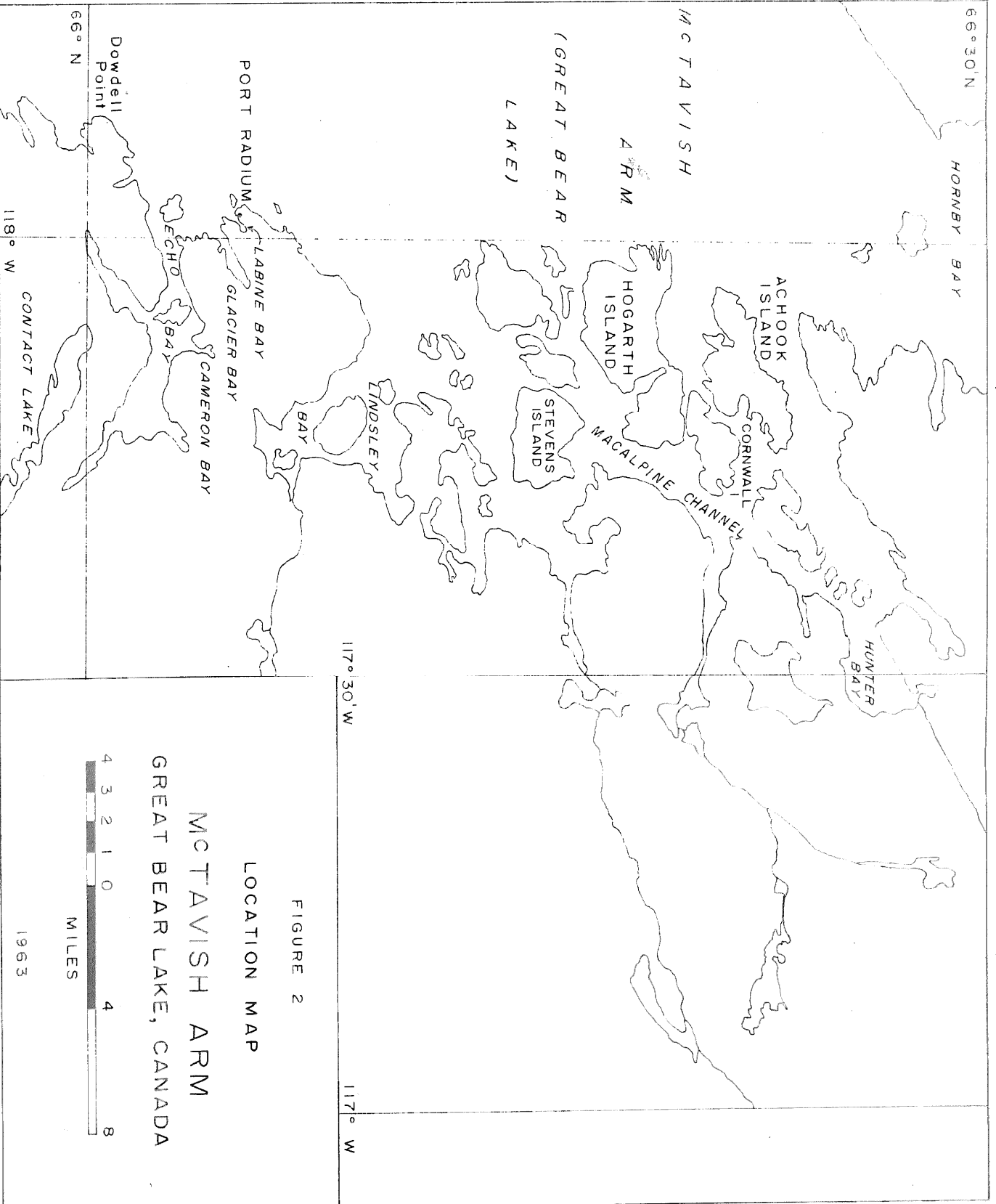
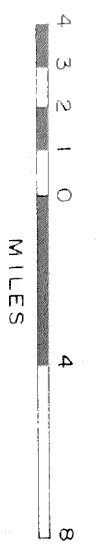


FIGURE 2
 LOCATION MAP
 MCTAVISH ARM
 GREAT BEAR LAKE, CANADA



1963

His work will be discussed under "Local Geology".

During the summers of 1959 and 1960, Eldorado geologists conducted reconnaissance mapping over 12,000 square miles of terrane lying to the east of Port Radium. The mapping was done from helicopters flying parallel flight lines two to four miles apart. A preliminary, unpublished report covering part of this field work was prepared by Mursky (1960).

Also during the summer of 1959, officers of the Geological Survey of Canada used helicopters to map the region lying between Great Bear Lake and the Arctic coast and extending east from Port Radium for 170 miles. Approximately 50,000 square miles were mapped using a helicopter flight-line spacing of six to seven miles. A preliminary map with marginal notes was issued (Fraser, 1960).

Reports dealing primarily with the geology of the mine, are those by Kidd and Haycock (1935), Murphy (1946), Murphy (1948) and Campbell (1957).

REGIONAL GEOLOGICAL SETTING

Paleozoic and younger strata cropping out around the south, west and north sides of Great Bear Lake have not been mapped in detail and will not be considered here. In the following sections, the Precambrian geology in the vicinity of McTavish Arm, Great Bear Lake, is discussed briefly.

Lithology

Table 1 lists the formations cropping out in the McTavish Arm area. Three sedimentary-volcanic stratigraphic groups, called the Echo Bay, Cameron Bay and Hornby Bay groups, have been differentiated in the field. The former two are relatively restricted in distribution cropping out primarily along the east shore of McTavish Arm. The Hornby Bay group crops out in Hornby Bay about 30 miles north of Port Radium and is exposed over an extensive area north and northeast of McTavish Arm. The predominant rock types in the McTavish Arm area are granitic rocks and intrusive and extrusive feldspar porphyries.

Echo Bay Group

The oldest known rocks in the area belong to the Echo Bay group which has been correlated by Parsons (1948), Campbell (1955), and others with the Snare group exposed between Great Bear and Great Slave Lakes. The Echo Bay group has been subdivided into a lower, dominantly sedimentary, sub-group having a known thickness of 4300 feet above an intrusive granite contact, and an upper, dominantly volcanic, sub-group at least 5000 feet thick (Feniak, 1947). The

TABLE 1: Table of formations, East shore of McTavish Arm, Great Bear Lake, Canada.

<u>Formation</u> *	<u>Rock Type</u>	<u>Description</u>
(Youngest)	Minor quartz, hematite, carbonate.	veinlets
	Diabase	sheets, sills
Port Radium deposit	Major mineralization	veins
	FAULTING	
	Diabase	dykes
	Quartz	"giant veins"
	FAULTING	
Hornby Bay group	Sedimentary rocks	sandstone, quartzite, conglomerate.
	UNCONFORMITY	
	Granitic intrusives	stocks and batholiths.
	INTRUSIVE CONTACT	
	Feldspar-hornblende porphyry intrusives	irregular to sill-like.
	INTRUSIVE CONTACT	
Cameron Bay group	Sedimentary rocks (1000+ ft.)	conglomerate; some arkose and flows.
	DISCONFORMITY ?	
Upper Echo Bay sub-group	Andesitic flows (5000+ ft.)	some interbedded pyroclastics and sedimentary rocks
Eldorado Vent deposit	crystal tuff	tuff-filled vents
Lower Echo Bay sub-group	Sedimentary rocks (4300+ ft.)	bedded and massive tuffs; some fragmentals and flows.

* All formations with the possible exception of the younger diabase are probably Proterozoic in age.

Lower sub-group is restricted in distribution, appearing only on LaBine Point, on Dowdell Point six miles to the southwest and possibly as windows in the Hornby Bay sedimentary rocks northeast of Great Bear Lake. It is host to the Port Radium deposits and will be discussed in detail under "Local Geology".

The Upper Echo Bay sub-group, in contrast to the Lower sub-group, is moderately widely distributed in the Echo Bay area. It consists of porphyritic and amygdaloidal andesite flows interbedded with andesitic pyroclastics. Minor sedimentary interbeds, particularly near the center of the section, are reported. The flows are massive and essentially devoid of primary structures except near their tops where flow breccias, oriented phenocrysts and amygdules are common. Phenocrysts of light grey to pink plagioclase, with or without accompanying hornblende phenocrysts, are set in a maroon to dark-grey or greenish-grey, very fine-grained groundmass. The maroon color results from the presence of very finely disseminated hematite. On the weathered surface, the flows are buff to reddish brown with characteristic light spotting imparted by the feldspar phenocrysts.

Cameron Bay Group

The Cameron Bay group, which crops out over large areas between Lindsley and Echo Bays and further north in the Hunter Bay area, more or less conformably overlies the Echo Bay group. Nowhere, however, has a normal contact between the two groups been discovered. Feniak (1947, p. 4) and Thurber (1946, p. 7) believe that the two groups are in fault contact at the only two places where contacts have been observed. The Cameron Bay group has a minimum thickness of

1000 feet. Deposited first was a section of poorly sorted, poorly bedded, ferruginous boulder to pebble conglomerate and ferruginous arkose, with minor intercalations of porphyritic andesite similar to the Upper Echo Bay andesite. This section is overlain by greywackes, grits and some pyroclastics. Essentially all rock types of the Echo Bay group are represented in the angular to moderately well rounded boulders of the Cameron Bay conglomerate. Thus, a significant time interval between the accumulation of each group is suggested despite the general concordance of the bedding.

Hornby Bay Group

The Hornby Bay group crops out at the north end of McTavish Arm where it unconformably overlies the Cameron Bay group and is itself unconformably overlain by Paleozoic and Mesozoic strata. The basal Paleozoic sandstone north of Great Bear Lake contains worm-like burrows and may be Cambrian in age (Fraser, 1960). Fossils of middle Devonian age were found in dolomite more than 500 feet above the Paleozoic base. Feniak (1949) describes the Hornby Bay group as rusty red, fine- to medium-grained quartzitic sandstone grading upward to white, coarse-grained quartzitic sandstone. Interbeds of pebble conglomerate are present. In the area mapped by Feniak, the Hornby Bay strata seldom dip more steeply than 10 degrees.

Intrusives

Hypabyssal porphyritic rocks and plutonic granitic rocks were intruded after deposition of the Cameron Bay group but before deposition of the Hornby Bay group. The hypabyssal rocks are the

oldest intrusives. They occur as irregular sills, stocks and dykes and constitute approximately 25 percent of the rocks exposed in the McTavish Arm area. The hypabyssal rocks vary considerably in composition. Various workers applied names ranging from rhyolite to andesite. Mursky (1960) states that dacite and latite are the most common types. The groundmass is very fine crystalline to microcrystalline thereby hindering attempts to classify the porphyries by use of the microscope. Phenocrysts constitute about 20 percent of the rock. Andesine is the most common phenocrystic mineral and in many exposures the only one. Other phenocrystic minerals are green hornblende, quartz and, in a few instances, potassium feldspar or augite. The most common field designation of the porphyry bodies has been "feldspar porphyry".

Similar bodies of porphyry occur in a 60 mile by 300 mile belt which extends from about 70 miles northwest of Yellowknife to about 80 miles northeast of Port Radium. This belt parallels the western margin of exposure of the Canadian Shield.

Cutting all pre-Hornby Bay group rocks are bodies of granitic rocks reaching batholithic proportions. These generally range in composition from granodiorite to granite but dioritic phases are known to occur locally. More than one age of intrusion is represented. Feniak (1947) separated the major granitic intrusives on Dowdell Peninsula, six miles south of Port Radium, into three groups based on field relations. These are, from oldest to youngest: quartz monzonite-aplite complex; granodiorite-diorite complex; granite.

A number of additional minor granitic intrusives were reported by various workers.

Common in the McTavish Arm area, as elsewhere in the northwest portion of the Canadian Shield, are dykes and sill-like bodies of basic igneous rocks generally called diabase. Their mineralogy will be discussed under "Local Geology". The sill-like bodies are generally conformable but locally are cross-cutting. In massive rocks, such as granites, they appear to be fracture controlled. Thus, they are really sheets or flat-lying dykes. Their surface traces are very irregular. A number of exposures cropping out over a 100 square mile area in the Echo Bay region may belong to a single or to a few closely related intrusions. If so, they could represent part of a broad, dish-shaped sheet which averages about 100 feet in thickness. The diabase dykes occupy, in several places, all of the known major fracture systems. In general, they dip steeply and average less than 100 feet in width. Some dykes are traceable for as much as 50 miles along strike.

"Giant Quartz Veins"

Although pegmatite dykes are virtually unknown, quartz veins in the McTavish Arm area of sufficient size to form mappable units are quite common. They are termed "giant quartz veins" and "quartz stockworks". Some have been traced discontinuously along strike for several tens of miles; widths up to 1000 feet for the zone are known. Most dip steeply and follow northeast-trending fault or fracture zones but a few strike north-south and others, northwest. The different strikes, and even different phases of the same vein, may reflect quite different ages of vein development.

Most of the large quartz veins show evidence of at least two

or more ages of mineralization. The earliest stage quartz, which usually forms the main mass of the vein, is normally massive and white. Cutting and bordering this stage and also forming a stockwork in the host rock is banded, fine- to coarse-crystalline quartz commonly showing comb structure. Later quartz veins cut both of the above, and also cut previously altered wall rock remnants in the stockwork. Hematite or specularite, locally abundant, accompanies the second and some of the later stages of quartz. Copper minerals and, rarely, pitchblende, occur locally and appear to have been deposited late in the sequence of vein development. Wall rock alteration, consisting of silicification, sericitization, chloritization and hematitization, extends outwards from the veins for upwards to 100 feet.

The quartz veins are best developed in a belt which is similar in location to the porphyry belt mentioned above. A genetic relationship between the two is doubtful as the granitic bodies were intruded between the emplacement of the porphyry and the quartz. Also, quartz veins occur in fractures cutting the porphyry and in granite far removed from any known porphyry.

Metamorphism

In the reports cited under "Previous Work", officers of the Geological Survey of Canada commented on the marked contrast between the dominantly hydrothermal alteration in the Great Bear Lake area and the common regional and contact metamorphism in the Great Slave Lake area. Minerals wholly or partly attributed to hydrothermal alteration include chlorite, white mica, quartz, biotite, hornblende, actinolite,

epidote-zoisite, leucoxene, carbonates, orthoclase, magnetite, hematite, and pyrite. The most intense alteration effects appear to be spatially related to the granodiorite-diorite phases of the larger intrusions. These intrusions also recrystallized the intruded rocks within a few feet or a few tens of feet of the contact.

Exposed to the east and south of Port Radium in the Echo Bay area are zones of pyritic gossans up to several tens of feet across. The pyritization is in many places accompanied by silicification. Kidd (1933) thought that the pyritization might be related to the granodiorite while Feniak (1947) suggested that it may be related to the quartz monzonite-aplite complex. Feniak also noted that the pyrite was probably introduced before the formation of the prominent northeast trending fault zones. He observed that some large gossans in the Echo Bay area are separated from similar gossans on the opposite side of the Cameron Bay fault by about the same distance as are faulted segments of intrusive rocks.

Feniak reported that on Dowdell Peninsula there are numerous "impregnations, blebs, and even dykes of magnetite, hematite, apatite and less commonly, actinolite". The largest body is lenticular and measures approximately 250 feet by 30 feet. He was not able to suggest an origin for the bodies. Similar impregnations occur in the Port Radium mine area.

Structure

Structures in the Echo Bay and Cameron Bay groups exposed along the east side of McTavish Arm are imperfectly known. The sedimentary and volcanic rocks of those groups occur as elongate roof

pendants in intrusive feldspar porphyry and granitic rocks.

Direction of elongation is northerly. The strata strike from northwest to northeast and usually dip less steeply than 45° . Folds are open except locally. Forty to fifty miles inland, folds are tighter and, in places, isoclinal.

Ten miles southeast of Port Radium, Cameron Bay strata are folded into a gentle syncline which trends northwest. To the west of the syncline, exposed Echo Bay group rocks are homoclinal and have easterly dips up to 40° . Strikes on Dowdell Peninsula are to the northwest; in the vicinity of Port Radium, they are north and northeast.

The general features of the folding and tilting of the strata are probably related to the granitic intrusions and the subsequent uplift. At least locally, however, the sedimentary rocks were folded during the intrusion of feldspar porphyry bodies. This occurred at Port Radium where lower Echo Bay strata are tightly folded. Similar strata on Dowdell Point are also tightly folded but the cause of the folding there is not known.

At least four fault and fracture systems are recognizable on the east side of McTavish Arm. The better developed systems form prominent topographic lineaments which in some instances can be traced for several miles. Along fault zones, fault breccias are more characteristic than intensely sheared rock. All the systems are steeply dipping. The strikes of the systems are: (1) $N30^{\circ}E$ to $N60^{\circ}E$; (2) east; (3) northwest; (4) north. A possible fifth set is represented by almost flat, unmineralized fractures in some of the Port Radium veins and by the shallow-dipping diabase sheets (sills)

which were intruded at least in part along fractures.

The No. (1) system forms the most prominent topographic lineaments in the district and was probably the first to develop. Major elements belonging to this set are 10 to 15 miles apart. The main members of the system strike $N60^{\circ}E$ but segments and branches diverging to $N30^{\circ}E$ are common. Dips are steep to the north. Apparent displacement on faults in the system is usually right-hand and normal. Feniak (1947) concluded there was an apparent right hand displacement of $\approx 1\frac{1}{2}$ miles on the Cameron Bay fault which is about three miles south of Port Radium. This conclusion was based on the correlation of intrusive rock segments on either side of the fault. Evidence concerning the direction of dip slip was conflicting. The diabase sill crosses the Cameron Bay fault without apparent displacement but is cut by late stage fractures. At least some displacement occurred on north-east striking faults after the deposition of the Hornby Bay group (Kidd, 1933). Members of the northeast system were occupied in turn by "giant quartz veins"; by diabase dykes; and by a succession of vein mineralizations which include the Port Radium pitchblende ores and most of the known metallic vein mineralizations in the district.

Members of the No. (2) fracture system have east strikes and are subsidiary sets to the northeast-trending system. They merge with the latter on each end. Although there was little apparent displacement along them, brecciation of the wall rocks is common. Diabase dykes were locally emplaced along the east-trending system but "giant quartz veins" were not. The absence of "giant quartz vein" mineralization on them suggests that the fractures formed subsequent to that mineralization or were not permeable zones at the time of its

emplacement. In the Port Radium mine, pitchblende was introduced after brecciation of the diabase.

Fractures of the No. (3) system, which have northwest strikes, contain very little mineralization but locally were channelways for diabase dyke intrusion. They may have formed by tensional forces resulting from regional uplift.

Fractures of the No. (4) system trend almost due north. Fault displacements occurred on some members of the system. On Achook and Cornwall islands, in Great Bear Lake 25 miles north of Port Radium, faults possibly belonging to this set show apparent strike-slip displacements of up to 500 feet (Feniak, 1949). Inland from Port Radium, two poorly defined, north-trending topographic lineaments about 20 miles apart can be traced for 50 to 60 miles on aerial photographs. Minor north-trending faults offset the northeast-trending veins in the mine. However, the time of initial development of the north-trending set relative to the other fracture sets is not known.

LOCAL GEOLOGY

The area to be discussed is about three-quarters of a mile square. It centers on the mine at LaBine Point and extends north to Bear Bay. Figure 3 is a geologic map of the LaBine Point area. It is a reproduction of a map by Campbell (1955, Fig. 5) on which the lithology has been revised to conform with new data obtained in this study. The formations are listed in Table 2.

The oldest exposed rocks on LaBine Point are sedimentary rocks of the Lower Echo Bay sub-group. The strata generally strike northerly and dip easterly but there are many local complexities to the structure. Approximately 2800 feet of Lower Echo Bay strata are exposed. A body of massive crystalline tuff, called the Eldorado Vent deposit, crops out on the northern part of the map area. It probably accumulated in Lower Echo Bay time. Sill-like and irregular bodies of intrusive feldspar porphyry occur throughout the map area but are best developed on the eastern portion of the area. Unless specifically stated otherwise, any reference to "feldspar porphyry" in this section concerns bodies thought to be intrusive in origin. A granitic body, younger than the feldspar porphyry, underlies the lake immediately off LaBine Point. The eastern contact of the granite strikes northeast and dips steeply southeast into the underground workings. Diabase dykes cut the above formations. A diabase sill is exposed immediately east of the map area. It strikes northerly and dips easterly.

The Eldorado vein zones trend east and northeast across LaBine Point. Figures 4 and 5 are longitudinal sections of the vein.

TABLE 2: Table of formations*, Eldorado Mine Area, Port Radium, N.W.T.

<u>Formation</u>	<u>Description</u>
Mineralization	Minor late veinlets of quartz, carbonate, hematite, chlorite, and sulphide minerals.
	FRACTURING
Diabase sill	Medium grained, greenish-grey, dark grey weathering.
	FRACTURING
Mineralization	Hematite, pitchblende, arsenides, sulphides, native elements; intervening fracturing and brecciation.
	FRACTURING AND BRECCIATION
Diabase dykes	Fine to medium grained, brownish-grey, rusty weathering.
	FRACTURING
Mineralization	Quartz stockworks and "giant quartz veins!"
	FAULTING AND FRACTURING
Biotite granite	Coarse grained, generally pink, batholithic proportions.
	INTRUSIVE CONTACT
Hypabyssal Intrusives	Tabular bodies and fingers of feldspar-hornblende porphyry.
	INTRUSIVE CONTACT
Eldorado Vent deposit	Remnant caldera of massive crystalline tuff.
	INTRUSIVE CONTACT
Tuff series: Upper Beds (800 ft.)	Brown, fine-crystalline, poorly bedded plagioclase-rich tuffs; one bed pebble conglomerate.
Transition formation (500 ft.)	Tuff breccias; fine-crystalline tuffs; minor dacitic flows.
Mine series: Mine formation (800 ft.)	Pink, thin bedded and massive, micro-crystalline albite tuffs.
Cobalt Island formation (700 ft.)	Pink and grey, moderately thin bedded microcrystalline albite tuffs, in part calcareous; minor quartzite and limestone.

* Modified after Campbell (1955)

The veins are flanked by alteration zones of microcline, hematite, chlorite, white mica, carbonates, and several minor minerals. The major portion of the ore is confined to a zone lying between large feldspar porphyry bodies on the east and granite on the west. Ore shoots occur principally where Echo Bay sedimentary rocks form one or both walls of the veins. The vein mineralization is complex. Several stages of mineralization can be recognized.

Stratigraphic Units

Lower Echo Bay Sub-group

Early workers considered the Lower Echo Bay sub-group to be a sequence composed predominantly of cherty argillites grading up-section into tuffaceous sedimentary rocks. Campbell (1955) concluded that the "cherty argillites" were initially almost pure cherts which attained their characteristic pink and dark-green, thin laminations through metasomatic introduction of ferromagnesian minerals. He subdivided the Lower Echo Bay sub-group at LaBine Point into four somewhat arbitrary units as follows:

Tuff series (youngest)

Upper beds (800 feet thick) - brown, cherty and silty bedded tuffs.

Transition formation (500 feet thick) - buff fragmentals and cherty tuffs. Some cherts and flows.

Mine series (oldest)

Mine formation (800 feet thick) - thin-bedded, ferruginous cherts and massive cherts.

Cobalt Island formation (700 feet thick) - moderately thin-bedded quartzites and cherts, generally calcareous. Thick bedded crypto-crystalline cherts.

The thickness given for each formation is approximate. The

formations are gradational and only gross differentiation is possible in the field. There are no good marker horizons. The sub-division into formations is useful principally for petrographic and structural discussions.

The specimens examined for the present study were predominantly Mine formation rocks. The Mine formation is the principal sedimentary rock exposed in the underground workings and is host to most of the ore shoots. It has been shown in this work to be composed of microcrystalline^{*}, sodium-rich plagioclase tuffs rather than chert. It differs from the overlying tuff beds chiefly in crystal size, uniformity of bedding, and concentration of ferromagnesian minerals. The Mine series is thus more closely related genetically to the overlying Tuff series and to the Eldorado Vent deposit of massive crystalline tuff than was formerly thought.

Mine series.- The Mine series crops out on the central and western portions of LaBine Point (Fig. 3). It is characteristically a sequence of pink and dark-green to black, microcrystalline, thin-bedded tuffs in which there are lenticular beds of massive, pink, microcrystalline, plagioclase tuff. Thin interbeds of fine- to medium-crystalline plagioclase are present. The lowest beds exposed are in intrusive contact with feldspar porphyry on Cobalt Island which lies 400 feet off-shore from LaBine Point. Excluding some of the lowermost beds, about 80 percent of the Mine series is composed of pink

* Grain size designations used for sedimentary textures are:
microcrystalline - <0.1 mm
fine crystalline - 0.1 mm to 0.25 mm
medium crystalline - 0.25 mm to 0.5 mm
coarse crystalline - 0.5 mm to 1 mm

plagioclase. The plagioclase ranges in composition from albite to sodic oligoclase. For simplicity, it will be called "albite". The techniques used for identifying the albite and problems relating to its origin will be given in a discussion at the end of this section on the stratigraphic units.

Excluding some unusual effects near veins, pink coloration in the rocks on LaBine Point is essentially synonymous with "feldspar". The coloration is caused by minute quantities of granularly or intergranularly dispersed hematite. Similar coloration was not observed on quartz. Where quartz is sufficiently abundant in sedimentary rocks to be megascopically visible, it is grey.

The Mine series is thin bedded; units a fraction of an inch thick are common. Neither ripple marks nor cross bedding were observed. Graded bedding is uncommon (Plate 1A). The albite grains are lobate and interlocking (Plate 1B). Microcrystalline quartz interbanded with or intergranular to albite rarely exceeds 10 percent of the specimen (Plate 2). The quartz grains may be slightly more rounded than the albite grains but the data is not conclusive (Plate 2A). Quartz decreases in abundance up-section and is uncommon in the Mine formation. Bedding in the Mine series is accentuated by ferromagnesian minerals, principally hornblende and magnetite. Diopside is less widely distributed. Garnet and scapolite occur locally. Concentrations of apatite, biotite, hornblende and magnetite have almost completely replaced the rock in places, destroying the bedding in the process. These concentrations will be discussed under "Metamorphism". A minor percentage of quartz, more coarsely crystalline than that discussed above, is commonly present with the ferromagnesian minerals. Other

minor minerals are epidote-allanite, pyrite, sphene, potassium feldspar, and zircon.

Lenticular beds of essentially massive, microcrystalline albite occur in both the Cobalt Island formation and the Mine formation. The albite cannot be distinguished from the albite interbedded with ferromagnesian minerals. The lenticular beds reach widths of 40 feet and strike lengths of several hundred feet. They are the best horizon markers in the mine. Campbell (1955) states that their lower contacts are gradational while their upper contacts may be either sharp with intraformation breccia or gradational.

The Cobalt Island formation, which crops out on the western tip of LaBine Point and on Cobalt Island, is different from the overlying Mine formation in three principal aspects. These are: tuffs of the Cobalt Island formation rather commonly contain from 10 to 35 percent carbonate in rhombs and patches; interbeds of grey quartzite are present; two, thin, lenticular limestone beds are present on Cobalt Island near the base of the section. The limestone beds reach a maximum thickness of 20 feet and crop out along a strike length of 200 feet. Feniak (1947) noted that there are two similar limestone beds near the base of a "cherty argillite" sequence of Lower Echo Bay strata on Dowdell Point, six miles southwest of Port Radium. Underlying that sequence on Dowdell Point is an undesignated thickness of maroon and green "argillites". Specimens of the grey quartzite interbeds of the Cobalt Island formation were not available for this study. The lack of pink coloration in those beds is taken as suggestive evidence that they are true quartzites.

The presence of argillites (on Dowdell Point), limestone beds,

calcareous tuffs, probable quartzite beds, and some microcrystalline quartz with albite suggests that the lower beds of the Cobalt Island formation accumulated under conditions of normal marine sedimentation. Tuffaceous plagioclase became an increasingly abundant constituent. When the Mine formation was being accumulated, it was the dominant constituent.

Tuff series. - The lower 500 feet of the Tuff series overlying the Mine series was designated by Campbell as the Transition formation. The Transition formation is gradational below into the Mine formation and above into the rest of the Tuff series. Its distinctive features are the presence of beds of poorly defined fragments and occasional discontinuous dacitic flows. Beds of massive, microcrystalline albite are less common than in the Mine formation but more common than in the overlying tuffs.

The tuffs of the Upper beds of the Tuff series are pink to brown; unevenly thin-bedded; show little evidence of sorting; and are microcrystalline to medium crystalline. The principal mineral is oligoclase but some albite, quartz and orthoclase may be present. In the microcrystalline varieties, sub-angular to sub-rounded grains up to 0.5 mm are set in a matrix of finer grained feldspar. Minor hornblende and magnetite in disseminations and aggregates are present.

The fragmental units, which occur in discontinuous beds up to 40 feet thick, have a tuffaceous matrix similar to the tuffs described above. They contain thinly distributed, angular, pink fragments usually less than one inch in diameter of microcrystalline albite similar to the Mine series albite.

Near the top of the Tuff series is a 100 foot thick bed of

conglomerate. Campbell (1955) noted the cobbles in the conglomerate are "cherts", porphyritic felsites and, less commonly, granitic rocks. The series is overlain by flows of the Upper Echo Bay sub-group.

In the underground workings, the Transition formation is best exposed in the general vicinity of the junction of Nos. 5 and 7 veins. The overlying Tuff series beds are best exposed in the No. 2 shaft area.

Eldorado Vent deposit

Cropping out on the northern part of LaBine Point and extending across Bear Bay is a homogeneous, unstratified body of massive crystalline tuff measuring more than one mile in length (Fig. 3). Campbell was the first to discern that this is probably a remnant of a caldera and named it the Eldorado Vent deposit.

In form, the body flares outwards near the present surface on the southern side where it truncates and lies on top of beds of the Mine series. Its eastern contact is approximately parallel to the Transition formation. However, data from underground diamond drill holes indicates the massive crystalline tuff locally truncates beds of the Transition formation (Campbell, Fig. 12). There is no indication of either an unconformity or of contact metamorphism.

Campbell describes the lithology as being buff to brownish with black peppering, generally monominerallic, the main constituent being oligoclase grains which average about 0.3 mm across (Plate 3A). Up to 10 percent quartz and locally andesine, albite and orthoclase may be present. The black "peppering" results from the presence of hornblende, magnetite and, less commonly, biotite which Campbell

attributed to metasomatic replacement of the oligoclase. Locally, these "metasomatic" minerals reach concentrations of 50 percent of the rock. The oligoclase grains commonly contain white mica and may have rims of unaltered albite (Plate 3B). Some chlorite is usually present.

A similar body of massive crystalline tuff crops out two miles further north near the shore of Great Bear Lake.

Campbell suggested that the Eldorado Vent deposit formed in late Lower Echo Bay time and ushered in the volcanism of the Upper Echo Bay sub-group. It seems probable, however, that initial explosive volcanic activity in what is now the Great Bear Lake area commenced earlier and provided much of the feldspar deposited in the Mine series and in the Tuff series.

Intrusives

Feldspar porphyry. - A body of feldspar porphyry, 500 to 700 feet thick and sill-like in its broader aspects, strikes northerly from LaBine Bay to McDonough Lake and beyond. It dips easterly at 20° to 30° . The Mine series sedimentary rocks lying to the west of it have been intruded by numerous smaller fingers, dykes and irregular bodies of related feldspar porphyry (Figs. 4 and 5). Contacts between porphyry and sedimentary rocks range from very sharp to diffuse over several feet. The diffuse contacts are in the form of lenses, apophyses, fingers and "eyes" of porphyry along the contact zone and resulted from both injection and recrystallization. Massive concentrations of hornblende, magnetite, biotite and apatite are common in the sedimentary rocks near the porphyry contacts. These metamorphic zones are best developed below the footwall of the main porphyry sill.

The porphyry is typically maroon or greyish-green to buff in color, the maroon cast being the result of disseminated hematite dust. Present as phenocrysts, which constitute from 15 to 50 percent of the rock, are light grey to white, subhedral to euhedral, oligoclase-andesine feldspar, dark green hornblende and, very rarely, quartz (Plate 4A). The feldspar phenocrysts average 2 to 3 mm in length and are more abundant than the hornblende phenocrysts which are absent in some places. It is for the latter reason that the rock is commonly referred to as a "feldspar" rather than as a "hornblende-feldspar" porphyry.

The matrix, particularly in the maroon-colored varieties, is microcrystalline and is composed of feldspar laths, hornblende blades, quartz, magnetite, and at least some potassium feldspar. Magnetite also occurs as euhedral inclusions in the phenocrysts and in obvious late veinlets (Plate 4B). Locally, it may constitute more than 5 percent of the rock. The porphyry has not been analysed chemically. It is probably a dacite although it has generally been called an andesite.

The most common alteration of the porphyry is chloritization of the hornblende phenocrysts. In many specimens, these are completely chloritized. Associated alteration minerals are biotite, carbonate and epidote. The feldspar phenocrysts are less altered, commonly exhibiting only incipient white mica. Where alteration of the feldspar is more intense, white mica is the predominant mineral and carbonate and epidote are subordinate minerals. Leucoxene is common in the vicinity of magnetite and hornblende grains. Alteration products in the ground mass, in approximate order of decreasing abundance, are:

chlorite; carbonate; quartz; epidote-allanite; leucoxene; and biotite. Apatite occurs in irregular patches and locally in veins. The major portion of it, as well as some of the magnetite, was probably introduced after the porphyry crystallized.

Granite. - A granitic body lying under Great Bear Lake crops out on Cobalt Island and again to the northeast on LaBine Point (Fig. 3). Its western contact dips steeply to the east into the mine workings. This body has always been called "granite" but the particular specimens examined for this study are quartz monzonite. Sampling is insufficient to give an average composition so it will be referred to here as "granite" with the realization that it may be predominantly quartz monzonite.

The rock is characteristically mottled pink and dark green to black, the pink color being due to hematitic dusting of the plagioclase. Near veins, it is bleached and the plagioclase has a pale greenish cast. It is medium grained and equigranular. The principal minerals and their approximate percentages are: quartz - 25; oligoclase - 35; orthoclase - 25; hornblende - 10-15; and minor biotite. The plagioclase shows little zoning. Accessory minerals are magnetite, pyrite, apatite, sphene and zircon.

Alteration of the granite is generally similar to that of the feldspar porphyry except that in the granite, white mica alteration of the plagioclase and chloritic alteration of the hornblende are about equally well developed. Near the veins, the plagioclase and hornblende are almost completely altered. The degree of alteration decreases outwards from the veins but no specimen examined was completely free of alteration. Leucoxene almost always accompanies chlorite. Biotite

is altered to chlorite and locally to white mica. Carbonatization and epidotization are minor alterations. Orthoclase shows only incipient, unidentified alteration. Quartz is unaltered.

The granite-stratified rock contact is sharp. Metamorphic effects definitely attributable to the granite are negligible. Patches of diopside-garnet skarn in the intruded Cobalt Island formation rocks do not appear to be spatially related to the granite. Even recrystallization of the rocks immediately adjacent to the contact was minor. Lower Echo Bay sub-group rocks on Dowdell Point were only weakly metamorphosed by the granite body which intruded them (Feniak, 1947).

Cutting the edge of the granite and extending for up to 1500 feet into the sedimentary rocks are narrow, steeply-dipping, aplite dykes. They are offset by the veins.

Diabase. - Two diabase dykes and a diabase sill are exposed in the mine. The dykes are 20 to 30 feet wide, dip steeply and strike northwest. The southern one cuts across the center of LaBine Point and is well exposed in the mine workings. Following it from the southeast, it intersects No. 1 vein, is diverted along that vein to the west for several hundred feet, crosses on its regional strike to No. 2 vein where it is diverted to the west only a few feet and then crosses to No. 3 vein. It follows No. 3 vein for 1500 feet on surface, makes a gentle loop to the north and returns to No. 3 vein in the western workings of the mine (Figs. 4 and 5). It has a chilled contact in the vein zones but was brecciated by later movement on the veins and healed by the vein mineralizations. Thus, in age, it appears to be younger than the initial development of the vein structures but older than most of the vein minerals.

Little is known about the northern of the two diabase dykes. It has a northwest strike and dips steeply. On surface, it crops out immediately south of McDonough Lake. Underground, it is exposed in the 250 level and 500 level drifts on No. 5 vein, west of the No. 7 vein junction. It is hematitized in the immediate vicinity of No. 5 vein.

Several fracture-controlled diabase dyklets occur in the mine. They are microcrystalline throughout and usually less than three feet wide. In distribution they are too erratic to form mappable units. They cut the "giant quartz vein" type mineralization but not later types of vein mineralization and were probably emplaced at the same time as the larger diabase dykes.

The diabase sill strikes northerly and dips gently to the east. It crops out in a steep bluff east of the mine. A similar body crops out on Cobalt Island off LaBine Point. The structural relations of the two are such as to suggest that they belong to a single sheet which once curved over the top of the presently exposed rocks on LaBine Point. It is exposed in the mine in the most eastern workings on No. 1 vein (Fig. 4). The sill is not offset by No. 1 vein which, on entering the diabase, pinches to a few discontinuous veinlets of quartz and carbonate. It is, therefore, probably younger than all but the latest stages of vein mineralization.

Although an age difference is indicated for the dykes and the sill, they are quite similar petrographically. Textures in both are intergranular rather than ophitic. Minerals and their approximate percentages are:

<u>Mineral</u>	<u>Dyke</u>	<u>Sill</u>
Augite	40%	45%
Labradorite	50%	45%
Magnetite - Ilmenite	7%	3%
Quartz	Minor	5%
Apatite	Minor	Trace
Sphene	Minor	Minor

Secondary minerals in both are biotite, chlorite, leucoxene, carbonate and white mica, the total of which is less than 5% in the least altered specimens. The sill contains a minor amount of micrographic quartz in orthoclase.

Origin of the Mine series

The microcrystalline plagioclase in the Mine series rocks is very difficult to identify microscopically. Twinning was not observed except on some of the larger grains. Intergranular hematite hinders attempts to determine the refractive indices relative to those of other minerals present. The refractive indices are, however, equal to or less than the index of canada balsam. Except for the latter point, the plagioclase looks deceptively like chert.

To facilitate the determination of the sodium content of the plagioclase, eight specimens were X-rayed with a Norelco diffractometer. Standard grease-smear, powder techniques were tried first but proved unsatisfactory. Excellent data was obtained by uncovering the thin sections and placing the rock slices directly into the X-ray beam. For determination of the sodium content, curves given by Smith and Yoder (1956) for the 2θ separation of the $\bar{1}\bar{3}1$ - 131 peaks were used. Those authors pointed out that the method is not dependable. It appears, however, to give a useful approximation to the chemical composition for

plagioclase which has a very small $\bar{1}31 - 131$ separation. This is the case for the Mine series plagioclase. For the eight specimens, the compositions determined for the plagioclase ranged from An_4 to An_{12} .

Selected chips of pink, microcrystalline plagioclase from two specimens were analysed chemically for sodium and potassium*. The results obtained were as follows:

<u>Specimen</u>	<u>K₂O(%)</u>	<u>Na₂O(%)</u>
S 31 (Mine formation)	0.17	11.66
S 69 (Cobalt Island formation)	0.17	11.25

Since the maximum Na_2O content of albite is 11.8%, the plagioclase samples analysed contain essentially no anorthite molecule or other mineral impurities. The plagioclase composition determined from X-ray data for specimen S 31 was An_4 . This same specimen is illustrated in Plate 1B.

A number of thin sections and rock slices were stained for both potassium feldspar and sodium-rich plagioclase using the procedures described by Bailey and Stevens (1960). This permitted easy recognition of microcrystalline quartz associated with the microcrystalline albite. The presence of quartz was confirmed on the X-ray diffractometer charts. Quartz was absent in many specimens and, by visual estimate, rarely exceeded 10 percent in any specimen.

Thus, although the data is not extensive it is sufficient to demonstrate with reasonable certainty that the principal mineral in the microcrystalline Mine series rocks is sodium-rich plagioclase. It constitutes 70 to 80 percent of the rocks. Campbell (1955), on the basis of the inferred high quartz content and the interlocking nature

* Analyst: A. D. Maynes, California Institute of Technology.

of the grains, concluded the Mine series rocks originated by the colloidal deposition of silica and iron oxide with subsequent metasomatic introduction of ferromagnesian minerals.

It is apparent that the Mine series, the Tuff series, the Eldorado vent deposit, and the feldspar porphyry intrusives are quite similar mineralogically. All are plagioclase-rich, quartz-poor and have hornblende and magnetite as the chief mafic constituents. In the absence of chemical analyses, it is not known whether the formations more closely approach andesite or dacite in bulk composition. Actually, the Mine series, and possibly the other formations to a lesser extent, is much richer in sodium than the average andesite or dacite and is probably equivalent to a keratophyre in bulk composition.

The presence of hematite intergranular to albite probably has no bearing on the origin of the Mine series. Hematitic dusting of feldspar grains is common to all rock types except the diabase sills in the Echo Bay district. The red coloration of the rocks is, however, most pronounced in the immediate vicinity of LaBine Point. Although the largest concentrations of hematite occur immediately adjacent to the veins, an episode of pervasive hematitization is indicated by the fine dusting of hematite through the rocks.

Structures indicative of a volcanic flow origin were not observed in the Mine series rocks. Lithic fragments were not recognized except in the overlying Transition formation. In the Transition formation, the lithic fragments are of microcrystalline albite tuff similar to that in the Mine series. The texture of the Mine series rocks does not appear to have resulted from devitrification.

In the Mine series rocks, the thin, uniform laminations, the

restricted range of very small grain sizes, and the apparent absence of primary sedimentary features except graded bedding, points to deposition in water beyond the limits of wave action. Further, the absence of detrital textures suggests that the sediments may have accumulated from wind borne crystal ash. However, in that case one might expect to see outlines of devitrified glass shards and more variation in grain sizes. It seems probable that the grain sorting was accomplished in water but that transport was not prolonged enough to produce complete rounding of the grains. If so, the presently observed lobate nature of the grains resulted from recrystallization.

There is no basis for deciding whether the plagioclase was initially deposited as albite or was more calcic and was albitized in sea water. The rocks presently contain an average of about 20 percent of ferromagnesian minerals. These minerals in part cross cut bedding indicating some mobilization during metamorphism. This does not necessarily imply, however, that there was a major introduction of elements into the rocks during metamorphism. The plagioclase was presumably derived through the explosive disintegration of andesitic or dacitic rocks. Some ferromagnesian minerals probably accompanied the plagioclase at time of deposition. On the other hand, the paucity of aluminous minerals, except for local concentrations of biotite, suggests that no significant quantities of clay minerals derived from normal rock weathering accompanied the plagioclase to the deposition site.

Overlying the plagioclase-rich tuffaceous rocks of the Lower Echo Bay sub-group are the "andesitic" flows of the Upper Echo Bay sub-group. It is concluded that the area was a hornblende andesite or

dacite province throughout Echo Bay time.

Structure of Stratified Rocks

The lenticular beds of massive crystalline albite tuff are the best horizon markers in the mine. Projections are limited to a few hundred feet at most. In the absence of these marker beds, strata cannot be projected between underground workings on the different veins. Thus, only the gross features of the structure are known. These gross features were described and illustrated by Campbell (1955, Figs. 31, 32). No attempt has been made here to work out the structure in greater detail. The following is a summary of Campbell's descriptions.

The basic structure is a homocline in which the beds strike northerly and dip easterly. This is best illustrated by Cobalt Island formation beds on Cobalt Island and by Tuff series beds on the eastern side of the mine. In between, Mine series beds are complexly folded, particularly in the vicinity of feldspar porphyry intrusives which apparently caused much of the observed folding. Local folding and undoubtedly some tilting and broad warping of the strata are attributable to the granite. The porphyry bodies do not appear to have been folded with the sedimentary rocks.

The major features superimposed on the homocline are two northerly trending anticlines and an intervening syncline. The beds in the anticlines appear to be "draped" over steeply dipping feldspar porphyry intrusive bodies. Near the present surface, the folds are isoclinal and slightly overturned to the east. In general, beds in the western part of the mine strike east or west of north and dip

steeply west. Further east, the beds strike north to northeast and dips are less steep and to the southeast.

Open and isoclinal folds with amplitudes of a few feet occur in sedimentary rocks well removed from intrusives. These smaller folds probably reflect larger, unrecognized structures. Near porphyry intrusives, beds are displaced along parallel fracture sets. Individual displacements seldom exceed ten feet but the aggregate displacement might be substantial.

Metamorphism

Excluding for the present plagioclase and quartz, the principal metamorphic minerals, in approximate order of decreasing abundance, are hornblende, magnetite, diopside, biotite, apatite, garnet, scapolite, potassium feldspar and sphene. The position of potassium feldspar in the sequence is the one most in doubt. The above sequence also corresponds to the frequency of occurrence of the minerals except that apatite should precede biotite in the sequence and potassium feldspar and sphene should precede garnet. Sodium-rich plagioclase is, of course, the most abundant mineral. Plagioclase was recrystallized to some degree. Minor quartz, recrystallized or introduced, is a moderately common associate of the ferromagnesian minerals.

The principal retrogressive metamorphic minerals are carbonate, chlorite, white mica, epidote-allanite, pyrite, and leucoxene. Minor biotite possibly belongs with this group of minerals.

Mineral Distribution

Garnet and scapolite are restricted to the metamorphosed Mine series rocks and in particular to the calcareous tuffs of the Cobalt Island formation. Diopside is also most abundant in the same beds. It constitutes 50 percent or more of some specimens. In addition, 5 to 10 percent of diopside is common in specimens from the upper beds of the Mine series and the lower beds of the Tuff series. Specimens from the upper Tuff series beds were not available for study. Diopside was not observed in specimens of the Eldorado Vent deposit.

The average hornblende content of the Mine series is about 15 percent. In the Tuff series and the vent deposit, the hornblende content is probably slightly lower. In individual specimens, the hornblende concentration varies from nil to about 70 percent. It is the principal ferromagnesian mineral accentuating the laminations in the Mine series rocks. It also occurs in cross fractures and, with biotite and/or magnetite, in massive replacement zones which destroyed the bedding of the sedimentary rocks. The best developed of those zones is a discontinuous one 50 to 100 feet wide underlying the main feldspar porphyry sill in the mine. Campbell (1955) states that similar but smaller zones occur preferentially over the upper terminations of some of the smaller porphyry bodies and appear to grade downwards into "aphanitic porphyry" which will be described in a later paragraph. In the massive concentrations of ferromagnesian minerals, either biotite or magnetite may be more abundant than hornblende. The principal occurrences of biotite are in such massive concentrations and in the "aphanitic porphyry" type rocks. Elsewhere in the Mine

series rocks, biotite is only locally present.

The average magnetite content of the stratified rocks and the vent deposit is estimated to be 3 or 4 percent. It is rarely present in the absence of both hornblende and biotite. In specimens in which those minerals are particularly abundant, the magnetite content of the rock may be 20 or 30 percent. Apatite is less abundant than magnetite but similarly distributed.

Specimens commonly contain a fractional percentage of sphene and the occasional zircon grain. Potassium feldspar, identified only in stained thin-sections, may be a common associate of ferromagnesian minerals in the Mine series rocks. Its average abundance is believed to be less than two percent. Grains of clear quartz are distributed similarly to potassium feldspar but are more abundant. These quartz grains are larger than the quartz grains of apparent sedimentary origin. The latter occur intergranular to albite; the former occur in ferromagnesian mineral zones (Plates 2, 5 and 6). Some original carbonate occurs in the Cobalt Island formation tuffs. Carbonate observed in other rocks is probably hydrothermal in origin.

What was considered to be a minor variety of the porphyry in the field was called "aphanitic porphyry". It is microcrystalline to fine-crystalline and contains some crystal aggregates but no true phenocrysts. Plagioclase is subordinate to hornblende, biotite, and magnetite which in some specimens constitute over 80 percent of the total rock. In specimens in which biotite is the predominant ferromagnesian mineral, the rock is brownish and has a megascopically distinctive appearance. The biotite flakes are usually preferentially oriented. A characteristic feature of the "aphanitic porphyry" is

that the plagioclase grains and ferromagnesian minerals are equigranular. In most metamorphosed Mine series rocks, the ferromagnesian minerals are much more coarsely crystalline than plagioclase and vary considerably in grain size. Although plagioclase in the "aphanitic porphyry" normally occurs intergranular to the ferromagnesian minerals, it also occurs in aggregates or laminations. The texture of the aggregates is very similar to that of the microcrystalline albite in the bedded tuffs.

Bodies mapped as "aphanitic porphyry" are in part conformable and in part cross cutting. The latter are generally located near the flanks or tops of bodies of the normal, intrusive feldspar porphyry. It is doubtful that any of the "aphanitic porphyry" is intrusive. It appears to be hornfels produced by contact metamorphism, possibly in part of beds having an unusual composition initially. It is even possible that some of the conformable zones are thin flows not recognized in the field.

Texture

In texture, the metamorphic rocks tend to be hornfelsic. Laminations can be seen in thin section to be more diffuse than they appear in hand specimen. Biotite grains are commonly preferentially oriented and hornblende grains occasionally. The other minerals normally have no apparent preferred orientation. Sphene, magnetite and, to a lesser extent, diopside are the most idiomorphic of the metamorphic minerals. Garnet, scapolite, apatite and plagioclase occasionally show poikiloblastic texture. In apatite, the enclosed mineral grains are usually hornblende or magnetite. In many places,

however, magnetite fills fractures in apatite. The poikiloblastic texture in plagioclase is rare and resulted from the growth of plagioclase grains up to about one millimeter long around microcrystalline albite. Had the process continued, well-defined plagioclase porphyroblasts would have become common.

The average grain size of all the minerals excluding plagioclase is about 0.2 to 0.3 mm. In general, grains of diopside, magnetite, biotite and sphene are smaller than the overall average and grains of hornblende, scapolite and garnet larger. Albite is a special case. The common, microcrystalline occurrence of albite has been described. The microcrystalline albite contains aggregates and thin laminations in which albite grains up to 0.3 mm are common and up to 1.0 mm rare. This is a primary feature, apparently a type of poorly developed graded bedding. Metamorphic minerals may have developed preferentially along the coarser grained laminations. In the vicinity of metamorphic minerals, it is difficult to distinguish between original large grains of albite and recrystallized albite. Some recrystallization of the albite undoubtedly did occur. The lobate, interlocking nature of the microcrystalline albite grains in the tuffs may be the result of minor recrystallization.

Metamorphic facies

The mineral assemblage hornblende-diopside-plagioclase (quartz-biotite-magnetite) appears to be most closely equivalent to the hornblende hornfels facies as defined by Fyfe et al (1958, p 209) for the metamorphism of an intermediate to basic rock of igneous or tuffaceous origin. The plagioclase in the rocks at Port Radium is

undoubtedly richer in sodium than would be expected in such an assemblage. For the metamorphism of calcareous rocks, the corresponding hornblende hornfels facies mineral assemblages given by Fyfe et al are diopside-grossularite-plagioclase-quartz or diopside-grossularite-calcite-quartz. The latter assemblage presumably corresponds to what would be the equilibrium assemblage for the calcareous tuffs of the Cobalt Island formation. Scapolite also occurs locally in the Cobalt Island formation rocks. Whether it was formed by the attainment of a higher temperature or by higher halogen partial pressures is not known.

Discussion

Campbell (1955) attributed the metamorphism of the rocks at Port Radium to contact metasomatism caused by the feldspar porphyry bodies. He considered the metasomatism to be primarily a "basification"-the introduction of Ca, Fe and Mg. Some of the more important factors which led him to this conclusion were:

- (1) Inferred high quartz content ("chert") of Mine series rocks;
- (2) Commonly observed occurrences of ferromagnesian minerals in cross fractures in the sedimentary rocks;
- (3) Apparent spatial association of garnet and scapolite, grading outwards to hornblende, magnetite and biotite, over the tops of some of the smaller porphyry bodies;
- (4) Apparent spatial associations of some large concentrations of hornblende, magnetite, biotite and apatite near (below) the main porphyry sill in the eastern part of the mine.

Campbell noted that the metamorphic minerals even close to the porphyry bodies do not show signs of strain and concluded that "basification" continued after emplacement of the porphyry. Also, minor veins of magnetite and apatite occur in the porphyry bodies.

Except for the first factor listed above - the inferred high quartz content of the Mine series rocks - these observations are well founded. It seems doubtful, however, that the hypabyssal porphyry bodies could supply sufficient heat and sufficient quantities of Ca, Fe and Mg to produce the observed metamorphic effects. Both hornblende and diopside occur hundreds of feet from any known porphyry body indicating the attainment of moderately high temperatures over a large area. The required addition of elements to the Mine series rocks is alleviated somewhat because the rocks were tuffs, not cherts. Furthermore, although mobilization of elements on at least a small scale is unquestioned (Plate 5A), the rocks probably initially contained some mafic minerals in addition to plagioclase. Even so, local metasomatism apparently occurred in areas now containing large concentrations of hornblende, magnetite, biotite, or apatite.

Alternative explanations for the cause of the metamorphism encounter difficulties. Perhaps the most important of these involve:

(1) The apparent spatial relationship between the metamorphic zones and the feldspar porphyry bodies;

(2) The apparent negligible metamorphic effects produced by the granite;

(3) The apparent limited depth of burial of the Mine series rocks at the time the granitic rocks were intruded. No granitic bodies are known to intrude the Hornby Bay group rocks which overlie the

Cameron Bay group. The indicated depth of burial of the Mine series rocks at the time of granitic intrusion is approximately 10,000 feet plus whatever thickness of Cameron Bay group rocks has since been eroded.

The only alternate explanation which may be compatible with the observations is that the metamorphism of the LaBine Point rocks took place during the intrusion of the granitic bodies (but probably before the intrusion of the granite at LaBine Point). Most of the officers of the Geological Survey of Canada (see Previous Work) who worked in the district attributed the observed metamorphism to intermediate phases of the granitic intrusions. The closest known such body to Port Radium is three miles to the east (Kidd, 1933). A closer body would undoubtedly be required to produce the metamorphism.

If the metamorphism was caused by granitic bodies, then the feldspar porphyry bodies had been intruded before the metamorphism took place. A critical consideration in this regard is that the main concentration of ferromagnesian minerals occurs under the large feldspar porphyry sill. The porphyry bodies may have guided rather than supplied the metasomatic solutions in the LaBine Point area. As stated previously, Feniak (1947) noted on Dowdell Peninsula, concentrations of magnetite and apatite which, apparently, are not related to porphyry intrusions. The Eldorado Vent deposit and the Tuff series would not be expected to and do not show as pronounced metamorphic effects as the Mine series because their mineral assemblages were closer to equilibrium assemblages under the metamorphic conditions. Finally, there is the question of the attainment of a relatively high temperature, under a restricted depth of cover, over a large area during the

crystallization of diopside. Through most of the period when lower and upper Echo Bay group sedimentary and volcanic rocks were accumulating and intermittently during the accumulation of Cameron Bay group rocks, the area was one of volcanic activity. It is possible that an abnormally high temperature gradient developed and continued through the period of intrusion and metamorphism.

Retrogressive Metamorphism

Retrogressive metamorphism affects all rock types in the district. Chalcopyrite and possibly some species of chlorite may be restricted to hydrothermal alteration zones immediately adjacent to veins. Most of the secondary minerals are widely distributed but show a marked increase in concentration near veins. Included with this group of minerals are quartz, carbonate, chlorite, white mica, microcline, hematite, pyrite, and leucoxene. Apatite, in addition to being a mineral formed during progressive metamorphism, is a vein and wall rock alteration mineral. Four minerals, epidote, allanite, biotite, and albite, are more abundant outside the pronounced wall rock alteration zones than they are within the zones. Epidote and allanite are considered to be retrogressive minerals because they occur in veinlets and as intergranular alteration minerals in diopside and hornblende. Brown biotite replaced hornblende but not extensively. Green biotite was seen in occasional specimens within the wall rock alteration zones and may have been a vein-controlled alteration mineral. Rims of clear albite occur in places on plagioclase grains in feldspar porphyry and in massive crystalline tuff. This albitization does not appear to be vein-controlled.

ELDORADO VEIN ZONES

Kidd and Haycock (1935) made a detailed study of the vein mineralogy using specimens collected mainly from surface pits on Nos. 1, 2, and 3 veins. Campbell (1955), whose work has already been referred to, made a more comprehensive study of the entire deposit. Numerous generalized descriptions have been published from time to time but almost all are summaries of the former work. Cathro (1959) studied arsenide minerals in polished section from a single occurrence of these minerals in the lower part of 5 - 10 ore shoot on No. 5 vein.

General Characteristics

The ore bearing structures at Port Radium are an integral part of a regional, northeast-trending fault and fracture system. Traced inland, the Port Radium structures converge with a more southerly and stronger member of the same system, the Cameron Bay fault. An inset in Fig. 5 shows the spatial relationships of the vein structures on LaBine Point. No. 1 vein and Bear Bay Shear, the most southerly and most northerly, respectively, of the main veins are the strongest members in the set. Either the main members of these two or branch members converge to both the northeast and southwest outside the mine area. Thus, they define a lenticular block, measuring approximately 11,000 feet in length and 2600 feet across at the widest point. Almost all mining operations were conducted within the western end of this block. Campbell (1955) postulated that the Eldorado fracture system formed as a result of release of tensional forces attendant upon movement on the Cameron Bay fault, followed by relaxation and gravity

downdropping within the lenticular block.

Apparent movements on individual veins in the mine are generally small and, even on the same vein, commonly conflicting. For No. 1 vein, Murphy (1946) postulated apparent left-hand displacement of 300 feet whereas Campbell (1955) postulated normal movement with a maximum net slip of 200 feet near the widest part of the lenticular block and decreasing net slip towards the ends. Campbell's conclusion was based partly on the fact that near the west end of the block, No. 1 vein cuts a narrow limestone bed without apparently displacing it. Within the mine, the off-setting of porphyry bodies by No. 1 vein can be adequately explained by a rotational movement of about 5 degrees with the hanging-wall moving relatively counter-clock-wise. Little or no separate, translational movement is required. The scissor-point for this movement lies in the vicinity of the extreme, lower east workings of No. 1 vein. Horsetailing of No. 1 vein in this area may be the result of such a movement (Fig. 6). The resultant displacement in the western workings is largely normal and is on the order of 100 feet. Because of the erratic nature of the porphyry contacts, apparent left and right-hand movements result.

Apparent displacement on Bear Bay Shear is 300 feet left-hand. The displacement may be mainly dip slip. On No. 2 vein, apparent left and right-hand movements of up to 20 feet are observable. Total net slip is probably small and is unknown in direction. Known displacement on other veins in the system is negligible.

One cross-cutting fault at the mine can be traced with reasonable certainty from the surface to the deepest level of underground workings. It strikes from slightly west of north to east of

north and dips steeply east. It cuts across No. 2 vein about 2000 feet east of the shaft (Fig. 4). Apparent displacement is approximately ten feet left-hand. The fault zone is up to two feet wide and contains veinlets of quartz and carbonate in a chloritized matrix.

A similar cross-fault offsets Nos. 7 and 8 veins. Other faults belonging to the same set are known locally.

The veins are very diverse in character; they range from single fractures containing an inch or so of vein minerals; to breccia zones healed by mineralization; to 40 foot wide vein zones exhibiting shearing and multiple introduction of vein minerals. Nos. 3, 4 and 7 veins are primarily tension zones of fracturing and/or brecciation which begin and end on other members of the system. Nos. 1, 2, 5 veins and Bear Bay Shear, are stronger, more continuous and exhibit more shearing. This applies in particular to No. 1 vein and Bear Bay Shear which may have up to two feet of gouge along footwall shear planes. No. 8 vein and Silver Island vein are branches of No. 5 vein and No. 1 vein respectively.

The tension members of the system dip from vertically to steeply north or south, and have a more or less east-west strike. The shear members dip somewhat less steeply north and have a general north-east by east strike. All the main veins with the exception of Bear Bay Shear have a shallow, concave-north bend, and most of the veins tend to steepen towards surface. These two factors are considered to have been important in ore localization.

The steepening towards surface may have been the result of approach to the original surface at the time of fault formation or of approach to an overlying more competent body of feldspar porphyry now

eroded away. That deposition took place at relatively shallow depths is evidenced by: predominant open-space deposition of the ore minerals; the type of brecciation; numerous vugs in the veins; branching and horsetailing of the veins; nature and degree of fracturing in the wall rocks.

There are local indications that the veins changed attitude so as to enter more competent bodies at a more nearly normal angle. On a broad scale the concave-north swing of the veins may have been the result of their approach to the large, competent body of granite on the west. This, however, does not explain the apparent southward bend of Bear Bay Shear as it approaches the granite. Actually, information on Bear Bay Shear in the western part of the mine is based on fragmentary data obtained in a few drill holes. The main branch of the vein may continue on its general course into Great Bear Lake.

The veins have different characteristics in different rock types. All appear to be severely restricted in width on entering the granite. Elsewhere, No. 1 vein and Bear Bay Shear tend to have more or less uniform widths through all rock types except in the post-ore diabase sill. In the sill, No. 1 vein is reduced to a few discontinuous fractures containing minor, late, quartz-carbonate mineralization. The other veins are more restricted in the more competent rock bodies such as the porphyries than in the sedimentary rocks (Plate 7).

The predominant non-metallic vein minerals are quartz, chlorite, white mica, and carbonate. Chlorite and white mica were deposited at about the same time and are intimately intermixed in specimens from all the veins. White mica is less abundant than chlorite and was not seen in a specimen in the absence of chlorite. Although the

chlorite has a greener streak, the two minerals cannot be reliably distinguished in hand specimen. In the megascopic descriptions of the veins which follow, the name "chlorite" will be used for mixtures of chlorite and white mica.

The principal metallic vein minerals are hematite, pitchblende, copper sulphides, cobalt-nickel arsenides, and native silver. The general order of deposition, from oldest to youngest, of the vein minerals was: quartz and hematite; pitchblende and quartz; quartz and arsenides of cobalt and nickel; chlorite and white mica; carbonates and sulphides; silver minerals.

The predominant hydrothermal alteration products in the wall rocks are carbonates, chlorite, white mica, hematite, and microcline. The widths of the alteration zones vary from negligible to 60 feet and average less than 10 feet. Alteration is generally more pronounced in the Mine series tuffs than in the other rock types.

The data in the following table gives an indication of the relative economic importance of the individual veins. The data was compiled by Eldorado geologists, in particular R. J. Cathro.

<u>Vein</u>	<u>Tons Ore</u>	<u>% U₃O₈</u>
1	256,000	0.84
2	393,000	0.64
3	314,000	0.64
4	11,000	0.35
5	80,000	0.64
7	18,000	0.90
8	3,000	0.45
Bear Bay Shear	9,000	0.55
Silver Island	nil	

In the following sections, the individual veins will be described in greater detail. Longitudinal sections of the veins are

shown in Figures 4 and 5.

No. 1 Vein

No. 1 vein has been explored along a strike length of 6200 feet and through a vertical distance of 1300 feet. It strikes $N80^{\circ}E$. on the western end and $N60^{\circ}E$ on the eastern end. Near surface it is almost vertical. The dip in the lower west workings is about $58^{\circ}N$ and in the lower east workings about $64^{\circ}N$. The result of these changes in attitude is a gentle concave north warp which moves eastward with depth. Superimposed on this warp are lesser flexures.

The No. 1 vein zone reaches a maximum width of 40 feet and averages about 10 feet. In some places, it is reduced to a narrow zone of chlorite shearing. Vein width is not controlled by the host rock except, as stated, in the diabase sill. The footwall is generally marked by relatively continuous shear planes on which there may be up to two feet thickness of gouge. Common with most other vein zones in the mine, subsidiary shears and fractures, with or without gouge, lace their way back and forth across the zone. This feature is particularly marked on No. 1 vein. In places, the zone splits into two subparallel zones of more or less equal development. Both may be ore bearing but the footwall one is more favorable. In the lower east workings, about 1000 feet east of the shaft, the vein has numerous sharp bends and it branches to such a degree that it is not possible to say which is the main branch. The branching does not appear to have been controlled by the overlying porphyry body. It occurs in the vicinity of the postulated scissor point for rotational movement but cannot be definitely attributed to that.

The predominant vein minerals are quartz, hematite, chlorite, and white mica. The initial stages of mineralization on No. 1 vein parallel the development of the giant quartz veins (See Regional Geological Setting) which No. 1 vein represents on a smaller scale. Veins of quartz and hematite, although not everywhere present, are the most abundant in the zone; at least 50 percent of the total vein material is of this type. It accounts for the unusual width of No. 1 vein. Quartz is predominant but hematite locally constitutes the larger percentage of the assemblage. It seems probable that the early phases of the same mineralization produced the red coloration of the wall rock.

The next most abundant vein types are greenish, crystalline quartz and chlorite. They constitute possibly 30 percent of the total vein material in the upper sections and over 50 percent at depth. Veins of predominantly quartz may grade along strike into veins of predominantly chlorite. The quartz was deposited first and was later sheared and chloritized.

A number of additional types of quartz are present in lesser quantities in the vein zone. Chalcedonic, greenish to white quartz was veined by quartz and hematite of the "giant quartz vein" type. It was observed only on the 650 level. A brownish, vitreous, hematitic quartz is typically associated with pitchblende and is called "ore quartz" at the mine. It is preferentially located along or near the footwall of the zone but does occur anywhere in the zone. Pitchblende is present in it as stringers and lenses, individual lenses rarely exceeding one foot in thickness. Ore shoots averaged 3 to 5 feet in width; one near-surface stope had an ore-width of 25 feet. The wider ore sections are

the result of an increased number of stringers of pitchblende.

Brecciated ore is common.

Cobalt and nickel arsenides and chalcopyrite are more widely distributed than the pitchblende. They were emplaced later than the pitchblende and have their own distinctive gangue mineral associations. Dolomite is locally abundant. Native bismuth occurs locally and native silver rarely. A vein of arsenides and native bismuth, 6 inches wide and 200 feet long, occurred on the hanging wall of the No. 12 ore shoot (No. 1 vein).

No. 2 Vein

No. 2 vein was explored along a strike length of 5000 feet and a vertical interval of about 1750 feet. It is the only vein explored, from the internal winze, below the 1300 level. It is sub-parallel to No. 1 vein and exhibits some of the same gross structural features, namely: a broad concave-north bend in the central part of the mine with the strike changing from $N80^{\circ}E$ on the western end to $N60^{\circ}E$ on the eastern end; the dip steepens near surface; the average dip increases from about $60^{\circ}N$ on the west of the shaft to $67^{\circ}N$ on the east. No. 2 vein exhibits pronounced branching and bending in the lower east workings. The location of this branching is about 500 feet east of the similar situation on No. 1 vein but no correlation is known between the two. On No. 2 vein, some of the branches are ore bearing while essentially no ore is found in the area of extreme branching on No. 1 vein. No. 2 vein is a much weaker structure than No. 1 vein. It averages about 3 feet in width. The footwall slip-plane rarely contains more than one inch of gouge.

Dolomite and rhodochrosite are the predominant vein minerals in parts of the 21, 22 and 23 ore shoot areas (Fig. 4). These same areas contained the only extensive silver ore shoots that have been mined. Elsewhere quartz and /or chlorite are predominant although dolomite in lesser quantities is also widely distributed. Pitchblende and chalcopyrite are the most abundant metallic minerals. Arsenides are widely but rather sparsely distributed.

Ore shoots rarely exceed 5 feet in width and average two to three feet. In many places, they occupy the full width of the vein. Breccia-type ore with "ore quartz" is the most common but in some areas, particularly at depth, the pitchblende occurs in a chloritic matrix with little associated quartz. In the Winze area stopes, the "ore quartz" tends to be more rosy than brown in color. The 2-14 ore shoot contains associated apatite. No specimens from the other Winze ore shoots were examined under the microscope.

No. 3 Vein

No. 3 vein is a tension zone between No. 2 vein on the east and No. 5 vein on the west. Since it dips more steeply than No. 2 vein, their intersection moves westerly with depth. The strike length and vertical extent of No. 3 vein are, respectively, 2000 feet and 1300 feet. It was essentially completely explored with the exception of that portion lying within the granite on the west. A larger percentage of it was ore-bearing than any other vein in the mine. Ore widths ranged from one foot to 20 feet and averaged about four feet.

Although considered as a single vein, it is actually an integral set of fractures having different characteristics and

mineralogy. On a broad basis, it shows the similar concave north bend as Nos. 1 and 2 veins with the strike changing from $S75^{\circ}E$ on the west to $N80^{\circ}E$ on the east. Local changes in strike, accompanying branching, are many and abrupt. The predominant dip is steeply north but vertical and steeply south dips are common. A diabase dyke occupies much of the footwall of the upper, eastern portion and much of the hanging wall of the lower, central portion.

The No. 32 ore shoot (Fig. 5) is up to 20 feet wide at the junction with a branch vein and averages about 6 feet. It is primarily a breccia vein containing numerous wall rock fragments healed with brown quartz which in turn was brecciated, healed and replaced by bornite, chalcopyrite and chlorite. Arsenides and carbonates are sparse.

The No. 33 and 35 ore shoots also exhibit considerable brecciation. Gangue, particularly brecciated red quartz, is more abundant than in the 32 ore shoot section. Chlorite is moderately abundant. Chalcopyrite, arsenides and carbonate occur sparingly. Microclinization and hematitization of the wall rocks is particularly prominent.

The No. 31 ore shoot, lying on the underside of a porphyry tongue, varies from a breccia vein to a series of weak, mineralized fractures cutting the wall rocks. Pitchblende is present primarily as lenticular stringers with little gangue other than chlorite. Massive chalcopyrite occurs abundantly near the 650 level but sparingly elsewhere. Arsenides are present only in minor quantities. Apatite is quite abundant in the central part of the shoot. Additional gangue minerals are brown and white quartz, carbonate and chlorite.

The No. 34 ore shoot is in part on No. 3 vein proper and in part on a branch called No. 3 North vein. On the former it tends to be a true vein in character and on the latter a breccia vein containing numerous wall rock fragments, particularly of diabase which forms the footwall. Chloritic and red to brown quartz are the most abundant vein minerals but carbonate, arsenides, chalcopyrite and tetrahedrite locally constitute important percentages of the vein.

No. 4 Vein

No. 4 vein is a west-diverging, south branch of No. 3 vein. It is on strike with the eastern section of No. 3 vein and branches at a bend in the latter so was probably an extension of No. 3 vein at one stage in the vein system development. Its average dip is 75° N. The junction of Nos. 3 and 4 veins is characterized by extensive hematitization and microclinization of the wall rocks.

No. 4 vein was unimportant economically and was explored over a strike length and vertical extent of only about 600 feet. It is predominantly a two to three foot wide chloritic fracture zone containing minor quartz. Minor pitchblende occurred as fine stringers and disseminations.

No. 5 Vein

No. 5 vein joins Bear Bay Shear on both ends and possibly at depth also. None of the junctions are within the mine area. It was explored over a strike-length of 4000 feet and vertical extent of 1200 feet. The ore was confined to the upper 500 feet.

On the western end it strikes $N60^{\circ}E$ and on the eastern end

N40°E. It has an average dip of 65°N but whereas it steepens towards surface on the western end, it flattens towards surface on the eastern end. The ore shoots average about three feet in width.

No. 5 vein varies from a zone five or more feet wide to a series of narrow fractures containing less than six inches of mineralization. Hematitic to white quartz is the predominant vein mineral. Dolomite is extensively distributed and locally chlorite is the most abundant mineral. Pitchblende is associated with brown "ore quartz" and with chlorite. Arsenides and native bismuth are widely distributed and locally abundant as in portions of the 54 ore shoot. Native silver is also widely distributed but in trace quantities.

The 54 oreshoot occurs on a steep section of the vein where the Eldorado Vent deposit forms the hanging wall. The 5 - 10 ore shoot occurs on an unusually shallow-dipping (55° to 60°) section near the junction with No. 7 vein.

No. 58 ore shoot is on a near-surface, hanging wall branch of No. 5 vein. The branch vein strikes parallel to No. 5 vein and was called No. 6 vein at the time the shoot was mined. However, it is too restricted in extent to be given special consideration. The area is characterized by extensive microclinization of the wall rocks.

No. 7 Vein

No. 7 vein is one of a group of interrelated tension zones extending from Bear Bay Shear on the west to No. 5 vein both on the east and down dip. The veins have a more or less east-west strike and dip vertical to steeply north. Two of the group contained economic concentrations of pitchblende. These were designated No. 7 vein and

No. 7 North vein. Both maximum strike length, which occurs at the present surface, and the dip extent are on the order of 700 feet. Exploration was carried to approximately 600 feet below surface. The zone is characterized by extensive hematitization and microlinization of the wall rocks.

No. 7 vein is a zone of discontinuous fracturing which locally widens to 15 feet. Mineralization is meager except in the wider portions where brown "ore quartz" and dolomite are the predominant gangue minerals. Arsenides, native bismuth and chalcopyrite are locally abundant. Native silver occurs sparingly. Pitchblende heals earlier wall rock breccia and also occurs in stringers and in massive, lenticular veins up to two feet wide.

An unusual feature in the area is an inverted conical or pear-shaped body consisting of apatite, magnetite, pyrite, chalcopyrite, and minor carbonate. The body extends from the 250 level 200 feet up the vein and measures approximately 100 feet by 150 feet horizontally at its area of maximum size. No. 7 vein, where it passes through this more competent body, pinches to a 6-inch-wide vein of carbonate, arsenides and chalcopyrite. The apatite and magnetite formed during metamorphism. The pyrite may have been deposited either before or after the development of the vein structures but probably before. The carbonate and chalcopyrite occur principally in the hanging wall of the vein and are considered to be hydrothermal in origin. Minor marcasite replaces the pyrite and is veined by chalcopyrite.

No. 8 Vein

No. 8 vein is also a member lying between Bear Bay Shear and No. 5 vein. It lies south of No. 7 vein and dips approximately 85° S. Its strike is $N65^{\circ}$ E, parallel to Bear Bay Shear on the north. It does not crop out as it joins Bear Bay Shear about 100 feet below the present surface. On the east, it merges with No. 7 vein and at depth with No. 5 vein.

No. 8 vein was explored along a strike length of 600 feet and a vertical interval of 500 feet. It is characterized by discontinuous slips and meager mineralization. The zone averages less than three feet in width. The chief metallic minerals are pitchblende in lenticular veinlets, chalcopyrite and minor arsenides. Dolomite is the most abundant gangue mineral. Some chlorite and narrow veins of buff to grey quartz are usually present.

Bear Bay Shear

The gross features of this zone have been described in previous sections. In the mine area, it strikes $N65^{\circ}$ E and dips 75° N. Information on it comes from one 300-foot-long drift and a number of diamond drill holes.

Particularly characteristic of the zone is shearing and intense fracturing, hematitization and microclinization of the wall rocks. Considering its prominence the amount of introduced vein material is relatively minor. Narrow veins of hematitic quartz and of carbonate are the most common. The main metallic minerals are pitchblende, arsenides and chalcopyrite.

Silver Island Vein

This vein is a west-diverging, south branch of No. 1 vein. It is not shown in the longitudinal sections. It strikes S60°W and dips vertical. The strike becomes more northerly and the dip flattens as it approaches No. 1 vein. Information on the vein is derived from a 150-foot-long drift on the 650 level and from a number of drill holes. It is a weak, branching structure, averaging two to three feet in width, with discontinuous slip planes. Shearing and brecciation are relatively minor. The main gangue minerals are quartz, chlorite, and carbonate. Hematite is present locally. Late veinlets of calcite and quartz cut the above minerals. Metallic minerals include arsenides, chalcopyrite, sphalerite, and galena. Pitchblende is exceedingly rare. Native silver concentrations up to 800 ounce/ton were obtained in diamond drill holes on the 650 level. However, the values are quite erratic and this, coupled with the fact that the vein crops out under Great Bear Lake to which it has permeable connections, prevented successful exploitation.

B Vein

B vein is a branching fracture zone diverging westerly from No. 1 vein. It is similar in attitude to Silver Island vein and lies between that vein and No. 1 vein. B vein was explored by one 300-foot-long drift on the 1175 level and by a number of diamond drill holes. The zone is composed of erratic veinlets of carbonate and chloritic quartz less than two feet wide. Brown "ore quartz" is present locally and has minor pitchblende associated with it over a 20 foot drift length. Other metallic minerals, also minor in abundance, are chalcopyrite,

arsenides and native silver.

There was no production from the vein.

MICROSCOPIC DESCRIPTIONS OF THE VEIN MINERALS

Mineralization Stages

The vein minerals are subdivided into six episodes of deposition as follows:

Stage 1: Quartz and hematite:

- (a) Minor white, chalcedonic quartz;
- (b) Quartz and hematite of the "giant quartz vein" type; brecciation.

Stage 2: Pitchblende and quartz:

- (a) Cream to grey, medium-crystalline quartz;
- (b) Pitchblende;
- (c) Brownish to red, vitreous, hematitic quartz.

Stage 3: Quartz and cobalt-nickel arsenides:

- (a) White comb quartz; reddish to grey crystalline quartz; brecciation of earlier minerals;
- (b) Arsenide minerals and minor grey quartz;
- (c) Minor grey crystalline quartz and translucent, euhedral quartz.

Stage 4: Chlorite and white mica:

Brecciation and extensive replacement of earlier minerals; initial deposition of sulphides.

Stage 5: Dolomite and sulphides:

- (a) White to buff, medium crystalline dolomite accompanied by minor siderite and barite;
- (b) Continued deposition of dolomite with deposition of zinc, copper and lead sulphides.

Stage 6: Rhodochrosite and silver minerals:

- (a) Pink to red, hematitic, fine-crystalline rhodochrosite;
- (b) Silver sulphides and native silver;
- (c) Native bismuth - possibly deposited before the silver minerals.

Much of the vein material of stages 1, 2, and 3 was deposited in open spaces and brecciation of it during later stages of mineralization was common. Following stage 3, the major portion of the vein minerals formed by the replacement of earlier minerals.

Campbell (1955) subdivided the mineralization into five episodes comparable to the above. He included dolomite with rhodochrosite and most of the sulphide minerals with chlorite, in essence eliminating stage 5 given above. The subdivision into six stages is considered advisable because of conflicting evidence concerning the time of deposition of the sulphide minerals relative to the deposition of the micaceous minerals and dolomite.

Criteria for Sequential Relations of the Minerals

Several criteria are used for establishing the sequential relations of the vein minerals. Contemporaneous deposition of minerals probably occurred but is difficult to prove. As Noble (1950, p 238) points out, the criteria in polished sections usually fix the end but not the beginning of deposition of a mineral. Conflicting evidence on the order of deposition can result from several factors including: more than one generation of a mineral; deposition of a mineral over a long time interval relative to that of associated minerals; only mutual boundary relations exhibited; only minor quantities of a mineral

present providing few relationships for observation. For minerals commonly showing only mutual boundaries, such as the sulphides in the Port Radium ores, it is necessary to rely on the repetition of minor criteria to establish the relative ages.

The criteria found to be most useful for determining the sequential relations in the Port Radium ores can be divided into three groups. These are discussed below.

1. Veining, fracturing and brecciation. Criteria falling in this group are common and generally dependable;

(a) Subsequent veins - veins of one or more minerals indiscriminantly cutting across grains of several minerals;

(b) Healing of breccia fragments by later minerals;

(c) Fracture filling - filling of fractures in one mineral by one or more other minerals; grades into type (b) on the one hand and into replacement textures on the other. A special variant of this in the Port Radium ores is the filling of syneresis cracks in pitchblende with quartz which was later replaced by other minerals;

(d) Irregular, veinlike penetrations of one mineral into another. Criterion not considered too dependable. Examples are chalcopyrite in sphalerite and bornite.

2. Layer and growth structures:

(a) Crustification - the successive deposition on the walls of fissures of a number of minerals. Most commonly observed for pitchblende and for a number of the early episodes of quartz. In specimens in which only part of the fissure filling is available for study, the botryoidal side of a pitchblende layer is presumed to point towards the center of the fissure;

(b) Zonal growth of crystals - very common in the arsenide minerals. The outer layers are considered to be younger. Overgrowths of a different mineral are interpreted in the same way;

(c) Perched grains - a variant of the above and also common in the arsenides. Minute crystals of one arsenide are deposited on larger, usually zoned grains of other arsenides;

(d) Discontinuous rhythmic layering - euhedral grains of one mineral on which were deposited grains of a second followed by re-deposition of the first mineral. Not too common and not considered to be very dependable. Examples are hematite and sphalerite in dolomite. In a restricted sense, this can also be interpreted as essentially contemporaneous deposition.

3. Replacement textures:

(a) Replacement veins - a type of subsequent vein which developed by the replacement of the walls of fractures or of other zones of weakness; most commonly observed for non-metallic minerals replacing other non-metallic minerals and metallic minerals;

(b) Crystallographically controlled replacement. Zonal replacement of arsenide grains by copper and bismuth minerals is common. Other examples are radial replacement of rammelsbergite by native bismuth and cleavage replacement of dolomite also by native bismuth;

(c) Replacement guided by grain boundaries. In the absence of more dependable relationships, a sulphide occurring along the boundary between other sulphide grains and non-metallic mineral grains is considered to be the youngest mineral of the group. Arsenides formed ring structures by replacing quartz along grain boundaries;

(d) Pseudomorphic replacement. Unit pseudomorphs of one mineral after another do not provide a useful criterion in the Port Radium ores. Pseudomorphic replacement of structures, for example, of pitchblende breccia fragments, is common but not an essential criterion for establishing the relative ages. In the wall rocks, microcline pseudomorphically replaced albite grains;

(e) Remnant inclusions of one mineral in another - generally not a dependable relationship. Corroded grains of pyrite in other sulphides are considered to be older than those sulphides.

Vein mineral associations are shown in Plates 8 to 35 inclusive. The order of mineral deposition is summarized in tabular form under, "Summary of Sequential Relations".

Opaque Minerals

Pitchblende

Both Kidd and Haycock (1935) and Campbell (1955) devoted considerable space to describing textures and sequential relations of pitchblende. The former authors described the following forms of pitchblende, all of which show gradations of one to the others:

- (1) Botryoidal;
- (2) Colloform - up to 1 cm or more in diameter;
- (3) Cellular - ring-like, either in unsystematic irregular arrangement or, less commonly, arranged in regular lines; thin walls common;
- (4) Dendritic - some forms showing an apparent cubic pattern and others an irregular pattern;
- (5) Spherulitic - usually less than 50 microns, in quartz

gangue and believed to represent the closing stage of pitchblende deposition;

(6) Brecciated - fragments of all other types;

(7) Vein - narrow, persistent, fissure vein-type but showing botryoidal forms.

A number of these forms are illustrated in Plates 8 to 13. Forms 1, 2 and 5 vary primarily in the size of the individual units and the interrelationships of the units.

Kidd and Haycock described two types of pitchblende: (1) a hard dense form giving a black powder and having a UO_2 to UO_3 ratio of 10 to 2.2; (2) a softer, sooty form giving a greenish-grey powder and having a UO_2 to UO_3 ratio of 10 to 100. They observed the second type only in carbonate gangue on No. 2 vein and considered it to be a hydrothermal alteration product of the first. In the present study, sooty pitchblende was seen in both quartz and carbonate gangue and at depths below surface of up to 800 feet. It appears to be related to fractures open to circulation of ground waters.

Campbell's description of the forms of pitchblende more or less parallels that of Kidd and Haycock. He emphasized that all pitchblende is botryoidal microscopically and that much of the pitchblende was comminuted and mechanically transported at the time of chlorite deposition. Other points of similarity between interpretations of Kidd and Haycock, and Campbell are:

(1) Pitchblende was one of the earliest metallic minerals deposited being older than the arsenides and sulphides (Plates 14 to 20 inclusive);

(2) Deposition took place from siliceous colloidal solutions.

Radial and concentric fractures, called "syneresis cracks", are very common in botryoidal pitchblende and are attributed to post-depositional dehydration and shrinkage of the pitchblende (Plates 14A and 16).

Megascope and microscopic evidence for the early introduction of pitchblende is abundant. In some carbonate sections, however, pitchblende occurs as dendrites and sinuous veins enclosed in dolomite or rhodochrosite. Among the most plausible explanations are:

- (1) The pitchblende structures are antecedent;
- (2) A second introduction of pitchblende occurred during the period of carbonate mineralization;
- (3) An early generation of carbonate was deposited with pitchblende;
- (4) Some of the pitchblende deposited early was dissolved by late carbonates and redeposited.

Based on relationships in individual hand specimens, any one of these alternatives could appear to be the most probable explanation. Nos. 2 and 4, in particular, would be extremely difficult to distinguish. In one specimen, a sinuous veinlet of pitchblende in carbonate has arsenides deposited on its botryoidal side and also in syneresis cracks (Plate 20). The arsenide rim is now discontinuous, apparently having been partially replaced by carbonate. In other specimens, sinuous veins of pitchblende wholly within carbonate can be traced to where one side of the pitchblende vein rests on early quartz. In still another specimen containing dendritic pitchblende and arsenides in carbonate, the pitchblende-arsenide structures form a self supporting network when the carbonate is removed by dissolution with acid (Plate 17A). In Plate 12, the veinlike zone of pitchblende is probably older than the

enclosing carbonate. The carbonate replaced quartz on which the pitchblende is presumed to have rested. In the third dimension, the pitchblende "vein" is disrupted by the carbonate. A similar explanation appears probable for the pitchblende "vein" in Plate 19A but the evidence is less definite.

Although a second generation of pitchblende may have been deposited with carbonates, conclusive proof that it exists has not been found.

Iron Minerals

Hematite (Fe_2O_3). - Hematite is one of the more ubiquitous minerals spatially and possibly also in the temporal sequence although it is only locally abundant.

The major portion of it, occurring in the hematitic quartz of the "giant quartz vein" type and in the red alteration of the wall rocks, is pre-pitchblende in age. It was introduced also with ore quartz during and following the deposition of pitchblende. Minor quantities were introduced with quartz associated with the arsenides. Dolomite and especially rhodochrosite contain hematite in the form of botryoids, rhythmic bands, fracture fillings and disseminations. The evidence suggests that hematite now enclosed in carbonate is in part antecedent, in part contemporaneous, and in part younger than the enclosing carbonate.

Finally, hematite occurs with quartz, carbonate, and chlorite in minor quantities in vugs and very late veinlets.

Specular-hematite is particularly common in veins of hematitic quartz on No. 1 vein. It coats cleavage surfaces of dolomite and lines vugs.

Pyrite (FeS₂). - Although local heavy concentrations of pyrite occur in the wall rocks, it is unusually rare in the veins. It is younger than pitchblende and older than chalcopyrite and the other sulphides (Plate 27A). It was not observed in contact with the arsenides.

Magnetite (Fe₃O₄). - Magnetite is abundant in the wall rocks but it is very rare in the veins. It was positively identified only in specimens from the 1 - 22 ore shoot on No. 1 vein where it occurs in minute veinlets in massive pitchblende. The sample location is immediately above the post-ore diabase sill. The magnetite is replaced by hematite, pyrite, and chalcopyrite.

Goethite (Fe₂O₃·H₂O). - Cathro (1959) identified by X-rays small hairs of goethite in quartz in the No. 5 vein arsenide suite which he studied. It was not observed in the present study.

Marcasite (FeS₂). - Marcasite was observed in a specimen from No. 5 vein near its junction with No. 7 vein. The specimen contained pyrite, sphalerite, dolomite, chalcopyrite and galena in that order of deposition. The marcasite replaced pyrite and was replaced by galena and possibly by chalcopyrite.

Marcasite was observed in three other similar, minor occurrences.

Other Minerals. - Pyrrhotite and minor pentlandite were observed in specimens of sulphidized wall rock which is cut by narrow fractures containing dolomite (No. 5 vein, 500 level). The local suite of minerals, in order of deposition is: magnetite; pyrite; pyrrhotite and pentlandite; pyrite; marcasite; sphalerite; chalcopyrite; and galena. Minor dolomite, possibly contemporaneous with the

marcasite, forms the only gangue. The second generation pyrite is questionable. The first generation pyrite and magnetite appear to be remnants of replaced wall rock. Some near-by veinlets contain fluorite.

Cobalt-Nickel Arsenides

The Port Radium ores contain a number of cobalt, nickel and iron arsenides and sulphides which are microscopically very similar. Forty X-ray powder photographs of arsenide minerals were made using a Norelco X-ray source and a Debye-Scherrer 114.6 mm camera. Samples were drilled from polished sections, pulverized and mounted on glass fibres using glue for cement.

Considerable difficulty was experienced in identifying the X-ray patterns, partly because almost every sample contained two or more minerals and partly because powder diffraction data in the literature is incomplete for many of the arsenide solid solution series. In making identifications, the work of Berry and Thompson (1962) was much more useful than the cards of the American Society for Testing Materials.

Arsenides in the Port Radium deposit are widely distributed and exhibit a multitude of complex interrelationships. The 40 X-ray analyses run for this study represent only a limited sampling. It is probable that unrecognized species are present as a number of films contained lines which could not be identified. The species identified by X-rays are: niccolite; rammelsbergite; skutterudite; safflorite; cobaltite; alloclasite; gersdorffite; ullmanite; glaucodot; and arsenopyrite. The first four account for over 90 percent of the total arsenides in the deposit. Loellingite, surprisingly, was not identified

and apparently is not present. Minerals reported by Kidd and Haycock (1935) or Campbell (1955) but not definitely identified in this study are: smaltite-chloanthite (species now discredited - probably members of the skutterudite series), loellingite, cornyite, and polydynite. A few grains of the latter were tentatively identified with the microscope.

Mutual association of the arsenides is so common that it is rare, except for niccolite and rammelsbergite, to see an area more than a few millimeters square that contains only one arsenide. Rims, usually a fraction of a millimeter wide, of one arsenide on another are so prevalent as to be the rule. Also common are rhythmic bands, veinlets, and irregular replacement patches. Contemporaneous deposition is believed to have produced some of these relations but is difficult to prove.

In the following sections, the individual minerals will be described briefly. Plates 21 to 26 inclusive show textures and associations of arsenide minerals.

Niccolite (NaAs). - Niccolite in many places has only minor quantities of other arsenide minerals associated with it. It forms lenticular veins from a fraction of an inch to several inches wide. Poorly developed botryoidal surfaces on niccolite are common. Niccolite is one of the earliest if not the earliest arsenide deposited. In some specimens, it forms the core for rims or radiating crystals of rammelsbergite but in others the two show mutually regular boundaries suggesting possible contemporaneous deposition.

Rammelsbergite (NiAs₂). - The X-ray patterns for rammelsbergite show small shifts indicating possible varying compositions. Rammelsbergite occurs both as fine grained, equigranular aggregates

and as long, radiating, bladed crystals. Twinning is common. The bladed form was particularly susceptible to replacement by native bismuth parallel to the grains (Plate 25B). Rims of safflorite and veining by gersdorffite are common.

Deposition was probably in part contemporaneous with and in part subsequent to niccolite deposition.

Safflorite $(\text{Co,Fe})\text{As}_2$. - All X-ray patterns for safflorite agreed with that given for safflorite V by Berry and Thompson (1962, p 100).

Safflorite invariably occurs in association with another arsenide. It occurs as narrow rims on rammelsbergite and, less commonly, on niccolite. In some sections, safflorite apparently replaced skutterudite and in others the two are rhythmically banded and may be contemporaneous. Where more massive, safflorite usually has a petal-like aggregate form. In both quartz and carbonate safflorite occurs as dendrites, rings, and clusters of small crystals. A second arsenide is associated with these in the form of rims, in some cases of cobaltite, or of fine intergrowths of unidentified arsenide. In one specimen, safflorite occurred in a submicroscopic intergrowth with alloclasite.

Skutterudite $(\text{Co,Ni,Fe})\text{As}_3$. - Skutterudite occurs in euhedral, but due to mutual and foreign growth interference, incomplete cubes. Some cubes show small octahedral faces in hand specimen. The largest cubes seen measured approximately one centimeter across.

In polished section, discontinuous zoning of quartz and other arsenides is prevalent within the crystals (Plate 21). Etching with FeCl_3 makes the banding more obvious. In some cases, the second

arsenide is anisotropic and appears to be safflorite; in others it may be nickel-rich skutterudite. In one specimen, zoned skutterudite has an overgrowth of clear skutterudite. A sample drilled from the contact and X-rayed yielded a film having two skutterudite patterns mutually displaced (Plate 22A). In the sample illustrated in Plate 23B, rammelsbergite has an overgrowth of safflorite on which was deposited minute rims first of alloclasite and then of cobaltite.

Relative to the other arsenides, skutterudite appears to be younger than niccolite and rammelsbergite and both contemporaneous with and older than safflorite.

Alloclasite (Co,Fe)AsS . - Alloclasite has not been previously reported in the Port Radium ores. Tentative identification of alloclasite is based on an X-ray pattern which showed up strongly in eight films and weakly in some additional ones. The pattern resembles somewhat a shifted rammelsbergite pattern. The range of measured "d" values for the four strongest lines on eight films are compared below with the "d" values for alloclasite and rammelsbergite given by Berry and Thompson (1962, p 101 and 105):

	<u>o</u> <u>d A</u>	<u>o</u> <u>d A</u>	<u>o</u> <u>d A</u>	<u>o</u> <u>d A</u>
Alloclasite (Berry and Thompson)	2.75	2.47	2.39	1.81
Alloclasite (this study) - Range	2.77- 2.78	2.47- 2.50	2.38- 2.40	1.81- 1.82
Rammelsbergite (Berry and Thompson)	2.84	2.56	2.49	1.88

Since not all samples were run with internal standards, the precise range in "d" values for the alloclasite is not known.

In polished section, alloclasite has similar anisotropism to

safflorite and is not quite as white as skutterudite. In etch reactions, it is similar to glaucodot. It is invariably very finely crystalline.

Alloclasite resembles safflorite in its occurrence as rings and aggregates in quartz, and as rims on other arsenides. It replaces skutterudite. It is generally intimately intergrown with a second arsenide, in most cases safflorite. One section contains alloclasite, a second arsenide and streaks of gangue all of extremely fine grain size and giving the general appearance of having been pulverized by fault movement. The whole is permeated by equally fine grained chalcopyrite.

Alloclasite was deposited at about the same time as safflorite.

Cobaltite (CoAsS). - Cobaltite is minor in quantity and is present primarily as narrow rims on safflorite and skutterudite. It also occurs as tiny veinlets cutting these minerals and niccolite and rammelsbergite. In one section, it forms a rim on a carbonate veinlet cutting safflorite and glaucodot, the latter being a rim on the former (Plate 22B).

Glaucodot (Co,Fe)AsS. - Glaucodot was identified in only one X-ray film. As stated above, it forms a rim on safflorite. Some of the extremely narrow rims on safflorite in quartz, too narrow to determine whether the mineral is isotropic or anisotropic, may be glaucodot. Also, small cubes, probably of glaucodot, are present in quartz.

Gersdorffite (Ni,Fe,Co)AsS. - Gersdorffite is widely distributed but not abundant. Because it tarnishes rapidly in air, it can be identified microscopically only in freshly polished sections.

It occupies distinct but irregular veinlets, both fracture filling and replacement, in the arsenides described above. Locally gersdorffite forms rims on the earlier arsenides. It also occurs as small, euhedral crystals in quartz. A second, isotropic arsenide slightly lighter in color but otherwise microscopically identical to gersdorffite may also be present.

The main deposition of gersdorffite followed the introduction of glaucodot. Minor gersdorffite, however, may have been deposited after niccolite and rammelsbergite but before skutterudite. In a single specimen (Plate 24B), euhedral gersdorffite in niccolite appears to have been replaced by the niccolite.

Ullmanite (NiSbS). - Ullmanite was identified only in one X-ray film. It occurred associated with a rim of cobaltite and gersdorffite on niccolite.

Arsenopyrite (FeAsS). - Arsenopyrite is very rare. It was identified only in one X-ray pattern and in one specimen from Silver Island vein. It occurs in characteristic euhedral crystals and is corroded by sphalerite and other sulphides. Kidd and Haycock (1935) recognized it only in a few sections and considered that it might have been a metamorphic mineral inherited from wall rock replacement. No additional light can be thrown on that problem here.

The paucity of arsenopyrite and apparent lack of loellingite suggests that the metal bearing solutions were iron deficient relative to cobalt and nickel. On the other hand, the solutions deposited quartz containing minor hematite contemporaneous with the deposition of some of the arsenides so the Eh of the solutions may also have been a factor.

Summary of Arsenides. - Brecciation of the pitchblende-quartz veins and replacement by arsenides and later quartz is obvious both megascopically and microscopically. However, the major portion of the arsenide minerals were deposited in open spaces. The approximate order of deposition was:

1. Niccolite and rammelsbergite
2. Gersdorffite (?)
3. Skutterudite
4. Safflorite and alloclasite
5. Glaucodot
6. Gersdorffite
7. Cobaltite

This confirms the general progression of deposition from nickel-rich to cobalt-rich arsenides given by both Kidd and Haycock (1935), and Campbell (1955). Campbell considered that there was a distinct break in the arsenide sequence marked by the introduction of quartz. It is more probable that this "break" was simply the recommencement of quartz deposition. Quartz was deposited previous to niccolite and then intermittently during the deposition of skutterudite and later arsenides. It is rhythmically, although discontinuously, interbanded with skutterudite with no evidence for replacement of one by the other. Tiny veinlets of quartz cut early arsenides and are in turn veined by later arsenides. This feature is local rather than deposit-wide.

Some specimens from an arsenide body in the 72 ore shoot on No. 7 vein show what can best be described as "gravity settling" although this cannot be confirmed as the field orientation of the

specimens is not known (Plate 23B). In any event, the phenomenon indicates quiescent, contemporaneous deposition of quartz and arsenides. Skutterudite, safflorite and rammelsbergite were deposited in open spaces. Remaining open spaces were partially filled, all on the same side, with minute grains of arsenides suspended in quartz. Locally, clear, euhedral quartz was deposited next and the remainder of the open space was filled with dolomite containing minor chalcopyrite. Many of the minute arsenide grains are zoned, appearing to have a safflorite core and cobaltite rim.

Most of the ring and dendritic arsenides occur in grey quartz related to the arsenide period of deposition. While the dendritic forms may have grown in open space, the other forms appear to have developed by replacement of quartz along grain boundaries. The origin of the arsenide dendrites will be discussed in a later section.

Molybdenite (MoS₂)

In the 13 ore shoot, No. 1 vein, molybdenite was observed in chloritic shears which also contain slickensided arsenides. The position of molybdenite in the mineral deposition sequence is not known.

Leucoxene

Minute grains of leucoxene are a common inclusion in chlorite. Also occurring in chlorite are aggregates up to about 100 microns across of brownish, highly birefringent grains. Their color, birefringence and high index of refraction suggest that they are epidote or allanite grains but sphene is also a possibility. In reflected light, these mineral grain aggregates commonly have an adamantine luster.

Bismuthinite (Bi_2S_3)^{*}

Bismuthinite was identified by X-rays. It was observed in specimens from the 54 ore shoot on No. 5 vein and the 72 ore shoot on No. 7 vein. Cathro (1959) noted its occurrence in the 5 - 10 ore shoot on No. 5 vein. Present only in minor quantities, it forms small, irregular replacement patches in arsenides. In skutterudite, replacement is crystallographically controlled. Bismuthinite is replaced by chalcopyrite and native bismuth.

One specimen, from an unknown location, contains inch-long blades of bismuthinite replacing coarse crystalline dolomite. The bismuthinite is replaced crystallographically by sphalerite, chalcopyrite, tetrahedrite and native bismuth.

Sphalerite (ZnS)

Sphalerite is widely but sparsely distributed. Megascopic quantities are rarely observed. It replaces quartz associated with late arsenides. In a specimen from Silver Island vein containing isotopically ordinary galena, it is veined by dolomite. In a specimen from No. 5 vein containing isotopically anomalous galena, it is rhythmically interbanded with dolomite. The fact that dolomite was introduced over a relatively long time interval can readily account for these relationships. However, considerations relating to the lead isotopic data to be discussed in later sections, leaves little doubt

* Plates 27 to 32 inclusive illustrate sulphide mineral associations.

that there are two generations of sphalerite.

The first generation sphalerite is younger than the arsenide minerals and older than galena. For the most part, it is also older than the copper minerals but locally sphalerite appears to have been deposited after chalcopyrite (Plate 28B).

Galena (PbS)

Galena is more common than sphalerite but megascopic quantities are relatively rare. Two isotopic types, one ordinary and one anomalous, have been identified mass spectrometrically. The ordinary type is very finely crystalline and is intimately associated with the other sulphides and the silver minerals. The anomalous type occurs in lenticular veins up to one inch in width and several inches in length. It is distinctly coarser crystalline and more massive than the ordinary type. The isotopic ratios of the anomalous galena demonstrate beyond doubt that it did not form by mixing of ordinary galena with radiogenic lead produced by the decay of uranium in the veins.

Considering the age of the deposit, approximately 20 percent of the uranium has disintegrated to lead. If this lead has aggregated and taken up sulphur to form a third isotopic type of galena, it is not obvious microscopically. On polished surfaces of pitchblende, even minute blebs which could be galena are rare. However, galena does occur locally with other metallic and non-metallic minerals in fractures in pitchblende. Quantities are small and the isotopic composition of such galena is not known but it appears to belong to the main period of sulphide mineralization. The aggregate

of relationships indicates that the ordinary galena is younger than sphalerite and the copper minerals and older than the silver minerals.

The anomalous, coarse-crystalline galena is the most abundant type in the veins. It usually occurs in dolomite and is associated with, but younger than, sphalerite and chalcopyrite (Plate 28A). There is nothing distinctive microscopically about the anomalous galena except that silver minerals are not seen in association and the mineralogy is simple. The dolomite gangue cannot be distinguished from other vein dolomite. In short, if this galena was not known to be isotopically anomalous, there would be no obvious reason for giving it special consideration. Problems relating to its genesis will be discussed in later sections on lead and uranium isotopes.

Copper Minerals

Chalcopyrite (CuFeS₂). - Chalcopyrite is the most abundant and widespread metallic mineral in the veins. It was introduced during the main period of sulphide mineralization and again, in very minor quantities, in late, cross-cutting veinlets. These veinlets cut both the main veins and the wall rocks and contain one or more of the following: quartz, chlorite, dolomite, hematite. A possible third, minor generation of chalcopyrite accompanied the anomalous galena within the veins. Local concentrations of chalcopyrite in the wall rocks probably formed at the same time as the main period of chalcopyrite vein mineralization.

In the veins, chalcopyrite is younger than sphalerite and older than galena, chalcocite and covellite and the silver minerals. With bornite and tetrahedrite, it most commonly shows mutual boundaries

which are not interpretable. While overlapping deposition of the three is probable, the aggregate of minor relationships indicates that the order of cessation of deposition was: tetrahedrite, bornite, chalcopyrite. However, in the 34 ore shoot, No. 3 vein, tetrahedrite appears, megascopically, to vein chalcopyrite.

Chalcopyrite occupies fractures in pitchblende and in the arsenides. Its replacement of these minerals while common, was not extensive.

Tetrahedrite. - The name "tetrahedrite" as here used refers to members of the tetrahedrite-tennantite series. A single sample X-rayed yielded a pattern intermediate between the end-member patterns.

Tetrahedrite is a common vein mineral but is less widely distributed than chalcopyrite which it invariably accompanies. It is most abundant on No. 3 vein, particularly in the 34 ore shoot where it veins and extensively replaces arsenides (Plate 24A). It attacked the arsenides much more readily than did chalcopyrite.

Bornite (Cu_5FeS_4). - Bornite is also widely distributed and is most abundant on No. 3 vein. The largest concentrations occur in the 31 and 32 ore shoots.

Its general sequential relations have been discussed under "Chalcopyrite". It vigorously attacked and pseudomorphically replaced pitchblende structures, much more so than did chalcopyrite (Plates 18 and 27B). Exsolution-like blades of chalcopyrite in bornite are common. While some of these are probably due to exsolution, others, generally larger and wedge-shaped, are related to fractures and are more likely the result of replacement (Plate 29A).

White mica either accompanied or closely followed the

deposition of bornite and chalcopyrite. Closely spaced blebs of these minerals in the white mica are common (Plates 31B and 32). Some specimens show the white mica apparently wrapping around the metallic grains while in others this texture is not obvious.

Aikinite ($\text{Cu}_2\text{S} \cdot 2\text{PbS} \cdot \text{Bi}_2\text{S}_3$). - Aikinite was identified in one X-ray film. Additional fainter lines in the pattern agreed reasonably well with those given for pearceite II by Berry and Thompson (1962) but the presence of the latter mineral was not confirmed.

Aikinite is younger than chalcopyrite but otherwise its location in the paragenetic sequence is not known. Occasional minute white grains disseminated in tetrahedrite and too small to yield diagnostic data, may be aikinite.

Bournonite ($\text{Cu}_2\text{S} \cdot 2\text{PbS} \cdot \text{Sb}_2\text{S}_3$). - A mineral not X-rayed but tentatively identified as bournonite on optical and etch test data, was observed in two specimens, one from No. 1 vein and one from No. 8 vein. In polished section, the mineral is slightly lighter grey than tetrahedrite, about as hard as chalcopyrite, moderately strongly anisotropic and etches slowly with 1 : 1 HNO_3 . It is negative to the other standard etch-test reagents (Short, 1940).

In both occurrences, bournonite occurs in tetrahedrite and is the same age or younger.

Chalcocite (Cu_2S) and Covellite (CuS). - Chalcocite and covellite were seen only in exceedingly minute quantities. They usually occur as disseminated grains in chloritic quartz gangue and as border replacements on grains of bornite and chalcopyrite. Covellite replaced chalcocite.

Kidd and Haycock stated that covellite was abundant in

surface specimens. They considered it to be the youngest sulphide deposited and supergene in origin. In this study, it was observed microscopically in specimens at least 900 feet below the surface so both supergene and hypogene covellite may be present.

Silver Minerals

Isolated occurrences of silver minerals are present on all veins, with the possible exceptions of No. 4 vein and Bear Bay Shear, to depths below the present surface of at least 1200 feet. The main concentration, however, occurs above the 375 level on the central portion of No. 2 vein. A lesser silver ore shoot occurs on Silver Island vein. The gangue mineral most intimately associated with the silver minerals on No. 2 vein is pink rhodochrosite which veined and replaced dolomite.

Kidd and Haycock (1935) studied 120 polished sections from the silver bearing section of No. 2 vein. They reported four silver minerals in addition to native silver. Because the variety of relationships seen by them far exceeds those observed in the present suite, in which the silver minerals are a minor constituent, the following sequential relations are summarized from Kidd and Haycock.

Stromeyerite ($\text{Ag}_2\text{S} \cdot \text{Cu}_2\text{S}$). - Stromeyerite occurs usually in minor quantities. It replaces carbonate gangue, chalcopyrite, galena, and tetrahedrite. It is believed to be younger than chalcocite and older than argentite, native silver and covellite.

Jalpaite ($3\text{Ag}_2\text{S} \cdot \text{Cu}_2\text{S}$). - Jalpaite is very rare and its relationships to the other minerals was not definitely established. It is believed to be younger than stromeyerite and probably older than

argentite and native silver.

Argentite (Ag_2S). - Argentite occurs as veinlets and irregular replacement patches in galena, tetrahedrite, and chalcoppyrite. Its most common habit is narrow border and cleavage crack replacement of galena. While it is probably younger than stromeyerite, deposition apparently ceased before the close of native silver deposition.

Hessite (Ag_2Te). - Hessite is distributed similarly to argentite but its exact position in the sequence of silver mineral deposition could not be determined.

Nothing in the above descriptions conflicts with relationships observed in the present study.

Native Silver. - Native silver is much more abundant than all the other silver minerals combined and is more widely distributed. It occurs as leaves and wires in dolomite (Plates 30B and 31A); as veinlets and irregular replacement patches, usually associated with rhodochrosite, in pitchblende, sulphides and the other silver minerals; and as cores in dendrites of pitchblende and arsenide minerals. It was probably the latest metallic vein mineral to be deposited although its age relative to native bismuth was not established.

Native Bismuth

Native bismuth is widely distributed but is most abundant on Nos. 1 and 5 veins. It is spatially associated with the arsenides and is not distributed similarly to native silver. The most common modes of occurrence of native bismuth are: (1) Replacement of arsenides in veins, patches and crystallographically oriented blebs;

(2) Pseudomorphic replacement in thin plates along cleavage planes of coarse crystalline dolomite. Locally, it forms interlacing veins, rarely as much as one inch wide, healing fractures in dolomite. Hexagonal plates of native bismuth up to one-half inch wide are present in these veins.

Native bismuth clearly replaces arsenides, dolomite and chalcopyrite. Where present with other sulphides, which is not common, clear-cut age relations are lacking. It was not seen in contact with the silver minerals. Its position in the paragenetic sequence is somewhat indefinite. It was probably deposited after the sulphides but may have been deposited either before or after the silver minerals.

Non-Opaque Minerals

The principal non-opaque vein minerals are quartz, chlorite, white mica, and carbonates. The order listed is the approximate order of deposition although quartz was introduced in several stages. Quartz accompanied the deposition of pitchblende and the arsenide minerals. Chlorite and white mica apparently overlapped with the deposition of the sulphide minerals. Dolomite accompanied the deposition of the sulphide minerals.

The mineral called "white mica" above, Campbell (1955) considered to be, "montmorillonite and various amounts of sericite and/or iddingsite". No montmorillonite was recognized in this study. If clay minerals, with the possible exception of illite, are present in the veins they are minor in quantity.

Plates 33 to 35 show some of the relationships of non-opaque

minerals.

Feldspar

Red (hematite-dusted) microcline is a common alteration mineral in wall rock fragments within the veins (Plate 33A). As far as is known, the microcline formed only by replacing plagioclase in the wall rock fragments and is not a true vein mineral. Not all wall rock fragments contain microcline. In many fragments microcline, if it was present, has been replaced by later alteration minerals.

Of the red-colored wall rock fragments, about one half are hematitic quartz and the other half hematitic microcline.

Apatite

Anhedral apatite is quite widely distributed in minor quantities. On portions of No. 3 vein, it is relatively abundant and occurs in patches up to an inch across. It is invariably red due to hematite on fractures and for this reason looks superficially like hematitic quartz in hand specimen; it is probably more abundant than has been recognized.

Practically every other vein mineral, including ore quartz, can be observed on fractures in apatite. The most important exception to this is pitchblende which, although seen in the form of partial rims around apatite grains, in no specimen was seen invading apatite. Both the pitchblende rims and the apatite are fractured and replaced by later minerals. Plate 33B shows apatite replaced by chalcopyrite. A fractured grain of apatite partially replaced by quartz of unknown age occurs in a specimen of the earliest known vein quartz. Thus, the

evidence points to apatite being one of the earliest vein minerals.

Quartz

Quartz, as hematite, is spatially and temporally ubiquitous. It is the most abundant of the vein minerals. Several generations can be recognized based on crystallinity, contaminants and intervening fracturing or brecciation. Some of these generations are sharply defined while others are gradational and appear to represent continuing quartz deposition during the introduction of other minerals. The main types, from oldest to youngest, are described below:

(1) The earliest quartz generation is white to greenish in color and chalcedonic. Minor apatite is associated with it. Recognized only on No. 1 vein, it occurs as remnants in the quartz to be described next;

(2) The second quartz type is milky in color, medium crystalline, banded, and contains from nil to predominant hematite in rosettes, bands and patches. It resembles the "giant quartz vein" generation previously described and is the principal quartz of the Stage 1 deposition. It is most abundant on the upper portion of No. 1 vein, on Bear Bay Shear, and on the western portions of Nos. 2 and 5 veins. Vugs containing buff dolomite, euhedral quartz, specularite and chalcopyrite are common. Also common are breccia fragments of red altered wall rock. Individual veins range up to 10 feet in width and several tens of feet in length;

(3) The above types were brecciated previous to the introduction of a reddish to brown, hematitic, vitreous quartz which closely accompanied the deposition of pitchblende (Stage 2). This quartz is

the one which has been referred to previously as "ore quartz" and whose distribution has already been discussed.

It is fine to medium crystalline. The hematite occurs to some extent as a dusting but more commonly as intergranular fillings and rhythmic bands. Some hematite in discontinuous fractures in the quartz is believed to belong to the closing period of this deposition. The earliest stages normally contain little hematite and are cream to grey in color. The later stages not only were deposited on existing quartz-pitchblende veins but also healed breccia fragments of these veins. Phases of the late stage hematitic-quartz mineralization can not always be distinguished microscopically from some of the Stage 1 hematitic quartz;

(4) Quartz accompanying the deposition of arsenides (Stage 3) varied from white through rose or reddish to grey. In places, it was deposited directly on pitchblende-quartz veins in open spaces, but elsewhere formed the matrix for breccia fragments of these veins.

In an undisturbed area, the following open-space sequence may be observed: white comb quartz; reddish to grey crystalline quartz with minor rhythmically interbanded hematite; early arsenides; later arsenides with minor grey crystalline quartz; and, finally, minor translucent euhedral quartz. The complete sequence is rarely visible in one specimen. The early white quartz of this age forms individual veins up to two or three feet wide and accounts for much of the quartz in the veins;

(5) Little if any quartz accompanied the deposition of the sulphide minerals. Minor quartz was, however, deposited in late cross-cutting fractures which transected the veins and extended into the

country rock.

Chlorite and White Mica

Chlorite and white mica are considered together because their distributions are similar and because they formed during the same time interval.

The predominant chlorite is pale to medium green, weakly pleochroic and length slow. The birefringence varies from almost isotropic to greyish white. A bluish cast to the birefringence is common. However, the "Berlin-blue" and purplish to brownish birefringent colors considered to be diagnostic of penninite were not observed. Chlorites having upper first order birefringence are comparatively rare.

The "white micas" may be either "sericite" or illite. A third possibility, nontronite, is considered improbable.

The average length of individual grains of chlorite and white mica is in the range of 25 to 50 microns. Plates 0.25 mm in length are exceptional. The usual habit, particularly in the case of chlorite, is in mats of randomly oriented grains. There is no evidence to suggest a distinct time-break between the introduction of white mica and chlorite exclusive of minor late veinlets of chlorite. The two are intimately intergrown in a manner compatible with overlapping deposition. The limited evidence, however, favors cessation of chlorite deposition before that of white mica. That viewpoint is adopted here. The observed relationships in wall rock specimens are identical to those in the veins.

The general distribution of chlorite and white mica was

discussed in the sections on the individual veins. Both occur on all levels on all veins. They are superceded in total quantity by quartz and, combined, are comparable in total quantity to the carbonates. In many areas, particularly in the eastern part of the mine, they are the most abundant vein minerals. White mica is perhaps 50 percent as abundant as chlorite. Where white mica is present, chlorite is also but the reverse does not hold true. If kaolin group minerals are present in the veins, they are intimately intermixed with chlorite and white mica and could not be distinguished microscopically.

In relation to the other vein minerals, chlorite and white mica were later than quartz, pitchblende and the arsenides, overlapped somewhat with the sulphides and carbonates and were earlier than the silver minerals and most of the carbonate. Veins of carbonate cutting chlorite and white mica are shown in Plate 35A. Pitchblende was particularly susceptible to comminution and replacement by chlorite (Plate 34). Campbell (1955) described this relationship in detail. Autoradiographs show "ghosts" and dispersed fragments of pitchblende of all sizes scattered through chlorite. Campbell considered that transportation of pitchblende fragments up to a few tens of feet may have occurred. Replacement of the arsenide minerals, even where brecciated, was much less vigorous. More commonly, the gangue minerals, chiefly quartz, enclosing the arsenides were replaced.

The copper minerals, chalcopyrite, tetrahedrite, and bornite, probably overlapped chlorite and white mica in time of deposition. A commonly observed feature is chalcopyrite and to a lesser extent bornite inter-leaved with white mica (Plate 31B). The white mica shows a tendency to wrap around the sulphide plates rather than butt against

them suggesting that the white mica is contemporaneous with or younger than the copper sulphides (Plate 32B). Elsewhere, copper sulphides vein the micaceous minerals thus indicating an apparent contradiction in age relations.

Carbonates

Four carbonates - dolomite, calcite, rhodochrosite and siderite - were identified by X-rays. Dolomite and calcite were further distinguished in hand specimen by the use of the alizarine red S stain described by Friedman (1959).

Dolomite constitutes more than 90 percent of the total carbonates. It is the predominant vein mineral on portions of Nos. 2, 3, 5, 7, 8, and Silver Island veins. It is commonly medium-grained but ranges from very fine- to coarse-grained. In color, it is white, cream or buff.

Siderite was identified only in sections from the central and east portions of No. 2 vein but may be more widely distributed. Where observed, it was rhythmically interbanded with dolomite. In one banded specimen, quartz and hematite which were apparently deposited contemporaneously with the carbonates occurred in thin partings between carbonate zones. The siderite is finer grained than the associated dolomite. It is buff in color but becomes tan on exposure to a moist atmosphere.

Rhodochrosite is primarily restricted to the silver bearing section on the upper central portion of No. 2 vein. It does not, however, always accompany silver either on No. 2 vein or on other veins. It is pink to red, the red color being due to tiny patches

and botryoids of hematite. Plate 35B shows botryoids of hematite in dolomite which are better developed than most hematite botryoids in rhodochrosite. Rhodochrosite is younger than dolomite which it veins. It closely accompanied the introduction of the silver minerals.

Calcite is widely but sparsely distributed. It is most easily recognized in late veinlets, with quartz, chlorite, hematite or chalcopyrite, which cut all other vein minerals and also the wall rocks. These veinlets vary from mere coatings on tight fracture surfaces to veins a few inches wide. In addition, most specimens containing other carbonates also contain some calcite. The major portion of this calcite is intergranular or occurs along cleavage planes and is commonly related to fracture fillings of the type described above. Some of it, however, is so intimately dispersed through the other carbonates, particularly dolomite, that it is not possible to say whether the texture is due to contemporaneous deposition or replacement.

Apparent contradictions arise concerning the relative times of deposition of chlorite and white mica, dolomite, and copper sulphides. Dolomite is a common gangue mineral associate of the arsenide minerals and probably utilized similar vein openings. There is ample megascopic and microscopic evidence for the replacement of arsenides by chlorite and white mica and for the replacement of chlorite and white mica by dolomite. Very locally, chlorite and white mica apparently replaced dolomite along cleavage planes. As previously stated, microscopic evidence suggests that the copper sulphides were in part contemporaneous with or older than white mica but the evidence also indicates that the major portion of the dolomite was deposited

before the deposition of copper sulphides directly associated with it.

It is possible that a minor generation of dolomite was deposited at the close of the arsenide stage of deposition and before chlorite and white mica but that does not completely explain the anomalous relationships. In the absence of satisfactory evidence to resolve the relationships, it is concluded that copper sulphides were introduced either during two generations or during an extended period of deposition which overlapped with the deposition of chlorite and white mica, and dolomite.

Barite

Barite occurs sparingly in the carbonate section of upper No. 2 vein and in a specimen from the 1175 level on B vein. It forms two to three mm long, bladed crystals extensively replaced by hematite around the edges and on fractures. Hematite also forms botryoidal structures within the barite crystals.

In age, barite is slightly earlier than or essentially contemporaneous with dolomite.

Other Minerals

Present in minor quantity in numerous sections containing chlorite and white mica is an orangy to brownish, micaceous mineral which has not been identified. It apparently has second order birefringent colors but these are obscured by the natural color of the mineral. It post-dates chlorite and locally rims and replaces dolomite grains.

Fluorite occurs in the occasional veinlet cutting the wall

rocks. It was not observed within the main veins.

Dendritic Vein Structures

Pitchblende and arsenide dendritic structures are widely distributed in the Port Radium ores although they are representative of only a very minor percentage of the total quantities of those minerals. A number of those structures, and some associated ring and cellular forms, are illustrated by photomicrographs (Plates 36 to 42).

In dendrites there are three mineralogical zones to consider - the core, the wall, and the enveloping matrix. Pitchblende and arsenides are the only significant wall minerals. Quartz and dolomite are the principal matrix and core minerals. Chlorite rarely predominates (Plate 40A). In a few specimens with a dolomite matrix, native silver, with or without some argentite, is the main core mineral (Plate 39). However, many dolomite-matrix specimens contain no visible native silver anywhere in the specimen. Sulphides occur both in the matrix and the cores but are unimportant. Chalcopyrite is moderately common as a disseminated replacement of pitchblende walls. Arsenides are minor minerals in the matrix and core of pitchblende dendrites but the reverse relationship was not observed.

All above minerals, in addition to occurring in the matrix and core, also occur in fractures and breaches in the pitchblende and arsenide walls. The walls, however, were rarely extensively replaced. Pseudomorphic replacement, preserving the dendritic structure of the walls, was even rarer. Only two reasonably good examples of pseudomorphic replacement, each about one millimeter in length, were observed. In a portion of the specimen represented by Plate 36A, hematite

replaced pitchblende. In a portion of the one represented by Plate 38B, dolomite replaced the main, central arsenide zone of the dendrite wall. In specimens containing native silver cores, native silver is a rare matrix mineral. It occurs in the occasional fracture in pitchblende walls but was not seen in arsenide walls.

The relationships given above are consistent with the known sequence of deposition of the vein minerals.

Safflorite is the principal arsenide in the arsenide dendrites (Plates 36B, 38, and 42B). Montgomery (1948) described and presented photomicrographs of safflorite dendrites from Gowganda, Ontario. Except that the Gowganda dendrites contained cores of native silver rather than dolomite, his descriptions could apply almost word for word to the specimen represented here by Plate 38B. The safflorite in the dendrites forms small tubes which apparently developed under cubic (or octahedral) control. This is best revealed by dissolving the matrix carbonate with acid. One of the axes dominated during growth and normally four rows of tubes grew out at right angles to the dominant axis. The tubes in any one row (or possibly the tubes in the two rows at 180 degrees to each other) usually grew to comparable lengths but exceptions are numerous. The main axis can be considered to be a first order tube and the ones at right angles, would be second order. On the latter in places grew third and fourth order tubes. The arsenide in the wall forms a tapered closure on the outer end of every tube. It is common for the arsenide walls to be rimmed on both the outside and inside with minute, euhedral crystals of another arsenide.

Montgomery emphasized that the forms and their apparent angular relationships in section are dependent on the position and

orientation of the plane of observation. A typical tube in cross section is roughly circular and has a central, cross-shaped core. The shape of this core may be important when considering the origin of the dendrites. In longitudinal section, the tubes look somewhat like long petals. A section cut at a small angle to the length of the tube can produce what appears to be a tapering septum lying longitudinally in the tube. All these types of forms can be seen in Plate 38B. The end of each arm of the cross-shaped core was a potential point of growth of a subsidiary tube. This readily explains why the arms of the crosses as seen in cross section show unequal development. An excellent example of unequal development can be seen near the lower left corner of Plate 39B.

The pitchblende dendrites show many similarities to the safflorite dendrites. They too apparently developed under cubic crystallographic control. In order to examine them in three dimensions, dendrites represented by Plates 37A and 39A were freed by dissolving the matrix carbonate with acid. Instead of being tube-shaped the individual dendrites are shaped like the tapering ends of broad swords. They are covered with minute, contiguous botryoids of pitchblende. Down what would be the ribs on the flat sides of the sword and down the outer edges, the botryoids are larger. Between these four rows of larger botryoids, and positioned in rows at right angles to the length of the dendrite, are smaller botryoids. In cross section, the core is then still cross-shaped but has two long arms and two short arms at right angles. This is the most typical form.

The pitchblende dendrites may be joined apparently randomly near a common center or may be joined in flat rows with the "sharp

edge of the sword" to the "sharp edge". The edges are joined almost to the tip and the row as a whole then has a serrated appearance like a bread knife.

The descriptions given above have been formulated in terms of the appearance of the pitchblende and safflorite walls whereas it is possibly the original mineral present in the core which was important in determining the shape of the dendritic structures. Montgomery (1948), and Bastin (1950) concluded that dendrites from the Gowganda and Cobalt areas of Ontario formed by the encrustation of silver dendrites with arsenides. The silver was later partially replaced by carbonate and other minerals. This theory was a reversal of the earlier, generally held view point that the arsenides were deposited before the native silver. The main arguments advanced in favor of early silver were:

1. Silver can and does crystallize in dendritic forms;
2. The arsenide minerals in the dendrite walls are commonly orthorhombic and could not exert cubic control on the growth pattern;
3. Silver is the common core mineral in the Gowganda and Cobalt areas;
4. If silver was not deposited first then some trace should be found of the original core mineral;
5. Silver shows both euhedral outline and evidence of having been replaced by the arsenides.

Opposed to the theory of early deposition of silver were the following:

1. Silver cuts the arsenide walls and merges with the silver in the cores. (This argument is circumvented by proposing

two generations of silver);

2. It is geochemically more difficult to explain the deposition of silver as the first metallic mineral;
3. Minerals other than silver occupy the cores;
4. Some of the isometric arsenides can form cubic, lattice-like growths somewhat similar to dendrites.

In considering the origin of the Port Radium dendrites, the following must be taken into account:

1. Dendrites having walls of pitchblende and of arsenides are known; both types appear to have developed under cubic control but the forms are not identical;
2. Minor arsenides occur in the cores and walls of pitchblende dendrites but the reverse was not observed;
3. Arrested, pseudomorphic replacement of pitchblende dendrites by arsenides was not observed; in only one specimen were both arsenide and pitchblende dendrites observed;
4. Arsenide ring-structures (Plate 42B) and arsenide dendrites occur in the same specimens and may be gradational to each other;
5. Pitchblende ring-structures and spherulites (Plates 40B, 41 and 42A) apparently are not gradational with pitchblende dendrites and were not observed in specimens containing dendrites;
6. Dendrites occur in matrices of both quartz and carbonate;
7. Silver is one of the youngest minerals in the paragenetic sequence; an early deposition has not been recognized;
8. Dendrites observed in this study are as common in areas in the mine not known to contain silver as in areas known to contain

silver;

9. Silver was not seen in dendrites in a quartz matrix and was not present in all dendrites in a carbonate matrix;

10. No comparable dendrites consisting of silver without encrustations of arsenides or pitchblende were observed, even in specimens containing abundant silver in carbonate gangue.

A single origin for the dendrites, consistent with the known sequence of deposition of the minerals, is not tenable. This would demand that the dendrites were initially all of pitchblende and formed in a quartz matrix. Arsenide dendrites would then have formed by replacing pitchblende and the carbonate matrix by replacing quartz. Around some dendrites, the original quartz matrix was replaced by carbonate, by chlorite, and by minor quantities of other minerals but other dendrites undoubtedly formed in a carbonate matrix.

A critical question is possibly the identity of the original mineral or minerals which formed the cores of the dendrites. Or are dendrites able to grow in a matrix of quartz or carbonate, uninfluenced by the crystal boundaries of these minerals and controlled by the cubic uraninite structure and the cubic structure of isometric arsenides?

Perhaps the strongest argument in favor of wall encrustation of an original core mineral is that all the dendrites have closed ends. If the core mineral was native silver, than at least one generation earlier than that recognized in the Port Radium veins is required or very late generations of pitchblende and arsenides are required. If the proposition is accepted that there was an early generation of silver, then it must also be accepted that this silver was completely removed from some areas after being coated with pitchblende and

arsenides. More difficult to accept, however, is the corollary that every silver dendrite was sought out and encrusted by arsenides or pitchblende. No good silver dendrites, unencrusted, were seen in this study. Kidd and Haycock (1935) studied polished sections of ores from some of the highest silver shoots in the mine. Although not specifically stated by them, it appears that the only dendrite-like forms of silver they observed which were not associated with pitchblende or arsenides occurred with soft, manganiferous carbonate in dolomite. The form of these they attributed to rhombic control by the dolomite, not to cubic control by silver.

For comparison with the Port Radium dendrites, native silver dendrites in the mineralogical collection of the California Institute of Technology were examined. Some important differences exist between the two. The native silver dendrites in the collection have square, not cross-shaped cross sections. Also, in a single specimen the cross-sectional areas of the dendrites vary greatly; in a general way, the longer a dendrite is, the larger is its diameter. The Port Radium dendrites tend to be more uniform in cross-sectional area.

A rather simple explanation for the origin of the dendrites in the Gowganda and Cobalt ores was possible. Silver was abundant and the only important minerals to be considered were silver, arsenides, and carbonates. At Port Radium, the addition of quartz as a matrix mineral and pitchblende as a dendrite wall mineral complicates the interpretations. It is concluded that chemical or crystallographic factors having a bearing on the growth of dendrites in general, not just on those at Port Radium, have been overlooked. The question concerning the origin of dendrites with cores of native silver and

walls of arsenides or pitchblende should be re-opened.

WALL ROCK ALTERATION

General Characteristics

The wall rock alteration minerals are divided into the three groups listed below. The more important minerals, based on quantity and distribution, are underlined.

(Oldest)

Group (1) Apatite, microcline, hematite, quartz

Group (2) Chlorite, leucoxene, white mica, sulphides

Group (3) Carbonates

(Youngest)

Within the groups, there was probably overlap in time of formation of some of the minerals listed but for other minerals there is no evidence on which to assign relative ages. The period of formation of a mineral in the wall rocks apparently corresponded closely to the period of formation of the same mineral in the veins.

Albite (in the form of rims on plagioclase grains), biotite, epidote and allanite are more abundant outside than inside the wall rock alteration zones and are attributed to retrogressive metamorphism. If any of them formed in significant quantities adjacent to the veins, they were formed early and replaced by later alteration minerals.

The alteration suite given above is different from previously established alteration suites in two principal aspects. The microcline was formerly thought to be jasper and was mapped as such in the field; the white mica was formerly thought to be clay minerals. Minor quantities of kaolin group minerals may be present. This problem will

be discussed under "Group 2 Alteration Minerals".

The alteration minerals have somewhat different distribution patterns but show neither persistent, uniform zoning nor consistent spatial distribution relative to ore shoots. A generalized zoning, outwards from the veins, is: chlorite and white mica; chlorite and carbonates; carbonates. Microcline is erratically distributed. In general, the alteration zone is wider on the hanging wall than on the footwall, in sedimentary rocks than in other rock types, and adjacent to wider vein sections. However, cause and effect cannot be clearly separated. Aside from compositional influences by the host rocks, the hanging wall sedimentary rocks are the most fractured. Fracturing favored not only wide vein development but also penetration of the walls by hydrothermal solutions. It is probable that the degree of fracturing controlled the width of the alteration zone more directly than did other factors. Vein junctions are favorable locations for wider than average alteration zones. Complete alteration of the host rock may extend six inches or locally, as in the case of microclinization, 60 feet from the vein wall. Generally, hanging wall sedimentary rocks are almost completely altered within a foot or two of the veins and more than 50 percent altered within three to five feet of the veins. Beyond five feet, the degree of alteration usually decreases rapidly and the hydrothermal alteration merges with alterations attributed to retrogressive metamorphism. Remnant plagioclase remains in the alteration zones after complete replacement of the mafic minerals.

The alteration zones at Port Radium are too erratic and too "telescoped" to make the facies concept useful. Thus, there is little basis for attempting to correlate the suite with the hydrothermal

alteration facies proposed by Creasy (1959) or Burnham (1962). The assemblage microcline-chlorite-white mica-quartz, which is common, would correspond to the muscovite sub-facies of the phyllic facies as defined by Burnham but the microcline at Port Radium was distinctly early and was replaced by chlorite and white mica.

Plates 43 to 48 are photomicrographs of wall rock alteration specimens.

Group 1 Alteration Minerals

Apatite

Apatite is a metamorphic mineral which occurs in erratic concentrations with magnetite and hornblende. It is also considered to be a vein-controlled, hydrothermal mineral because it occurs in the veins and because its concentration commonly increases in the alteration zones. However, it is not possible to say whether a particular concentration of apatite is hydrothermal or metamorphic. The most important reason for this is that apatite is one of the earliest hydrothermal minerals. Although the time interval between metamorphism and hydrothermal alteration was sufficiently long to permit formation of the vein structures, one followed the other directly in terms of the sequential relations of the minerals.

The average apatite content of the altered rocks is estimated to be less than one percent. A specimen may contain 30 to 40 percent apatite but such concentrations are extremely local. Apatite is anhedral, rarely subhedral. Optically oriented grains several centimeters long have been observed but more commonly apatite concentrations are composed of an aggregate of grains up to a few

millimeters long.

The age of apatite relative to microcline is not known. The nature of their association - anhedral grains of apatite in microcline - does not permit drawing conclusions in this regard. Apatite fractured readily and alterations later than microclinization filled the fractures. It was, however, moderately resistant to chemical attack and except in places of complete or almost complete alteration of the original rock, was not reduced to remnant "islands" in the new minerals.

Microcline

Microcline was identified by inserting uncovered thin sections directly into the beam of an X-ray diffractometer. The typical microclinized specimen is brick-red to maroon, hard, dense and microcrystalline. The original rock fabric is preserved. Where the alteration is complete, the rock resembles jasper. Microscopically, the microcline is untwinned, shows a very marked Becke line effect with the index of refraction below that of canada balsam, and has a birefringence of about 0.006. The texture is pseudomorphic after the plagioclase which the microcline replaced (Plate 43). The red coloration is caused by a dusting of hematite which is more concentrated than in the unaltered plagioclase but still minor in percentage. The hematite dust is usually so uniformly distributed in the microcline as to make the two minerals appear to be co-genetic (Plate 43B).

Microcline replaced only plagioclase. As a more or less complete replacement of the original rock, it locally extends further from the veins than any of the other alteration minerals. However, it

is much more restricted in distribution than chlorite, white mica or carbonate. It is best developed on No. 4 vein, on the western end of Nos. 2 and 3 veins, and on portions of Nos. 5, 7 and 8 veins. The width of the microclinized zone increases upwards. In two areas, microclinized zones extend more than 60 feet from the veins. These areas are the junction of Nos. 3 and 4 veins on the 250 level and the junction of Nos. 5 and 7 veins also on the 250 level. In the former area, the altered rocks are predominantly microcrystalline Mine series bedded tuffs. In the latter, they are fine crystalline tuffs of the Tuff series and feldspar porphyry. Although plagioclase-rich rocks were the most readily microclinized, structural factors - fracturing and tensional openings - were probably very important in localizing microcline.

Pre-pitchblende wall rock fragments in the veins are microclinized and microcline is believed to be earlier than the pitchblende. Microcline was extensively replaced near the veins by chlorite, white mica, and carbonates. As a result, the rocks changed in color from red to grey and green. The color change resulted only from replacement, not from "bleaching". Even minute, remnant "islands" of microcline still retain their red color.

Hematite

The hematite content of the altered rocks rarely exceeds five percent and probably averages less than one percent. Hematite is included with the major alteration minerals because of its wide distribution.

The most characteristic occurrence of hydrothermal hematite

is the dusting in microcline previously discussed. Whether or not the period of hematitization was of longer duration than that of microclinization is not known. Other types of occurrences of hematite are: discreet grains and diffuse patches at the site of earlier grains of iron-bearing minerals; minor disseminations in carbonate, possibly co-genetic with the carbonate; minor in late veinlets.

Evidence in support of the introduction of iron into the wall rocks from the veins to form hematite is limited. Significant introduction of iron probably occurred only adjacent to "giant quartz vein" type mineralization, in particular adjacent to No. 1 vein west on the 650 and 800 levels.

Quartz

Quartz is a common mineral in hydrothermally altered specimens but the major portion of it can be attributed to:

- (1) Microcrystalline quartz of primary, sedimentary origin;
- (2) Fine to medium crystalline quartz of metamorphic origin occurring in the vicinity of altered mafic minerals;
- (3) Late veinlets with carbonate and other minerals.

In addition, sub-microscopic quartz released during the hydrothermal alteration of the rocks is probably present. Quartz reflections for some of the thin sections X-rayed were stronger than expected on the basis of the visible quartz.

It is concluded that silicification, implying transport of silica from the veins into the wall rocks, was a very minor alteration. It may have been essentially restricted to those areas where the veins are occupied by "giant quartz veins".

Group 2 Alteration Minerals

The minerals included in this group are chlorite, white mica, leucoxene, and sulphides.

Seven uncovered thin sections containing microscopically visible layer-silicates were selected for direct X-ray diffractometer analyses. Quartz and chlorite in all of them prevented identification of the white mica present and prevented positive identification of any kaolin group minerals which may have been present. On all diffractometer charts, the strongest reflections excluding quartz peaks were in the $7.15 \overset{\circ}{\text{A}}$ and $3.57 \overset{\circ}{\text{A}}$ positions corresponding to 1st and 2nd order basal reflections for kaolin minerals and 2nd and 4th order basal reflections for chlorite minerals. Reflections in the $10 \overset{\circ}{\text{A}}$ and $14 \overset{\circ}{\text{A}}$ positions were about 20 percent and 30 percent, respectively, as strong as reflections in the $7 \overset{\circ}{\text{A}}$ position. Grim (1953, p 87) states that the $14 \overset{\circ}{\text{A}}$ reflection is usually suppressed in iron-rich chlorites. X-ray identification of the layer-silicates in the Port Radium suite is obviously not practical without first making mineral separates.

In thin section, some of what was identified as neutral to pale green chlorite, with a first order white interference color, may be a kaolin group mineral. If a kaolin group mineral is present, it formed in feldspar grains and is intimately intermixed with chlorite and white mica. The microcrystalline texture and the presence of remnant feldspar grains prevents using the indices of refraction in thin section for positive identification.

Chlorites

In the immediate vicinity of the veins, chlorite is the most abundant alteration product. In total quantity of alteration, it is probably exceeded by the carbonates which penetrated further into the walls, and thereby affected a much larger volume of rock.

Several types of chlorite, showing considerable variation in color, pleochroism and birefringence, are present. The two most abundant varieties are one which is medium green and weakly pleochroic with normal, greyish-white birefringence and one which is neutral to drab green, essentially non-pleochroic and isotropic. Both are length slow. In addition, pale to medium green, weakly to moderately pleochroic penninite is a common alteration mineral. By "penninite" is meant those chlorites having anomalous interference colors. Anomalous blue and anomalous purplish or brownish interference colors are equally common and may be observed in the same thin section and in places even in the same grain. Two uncommon varieties of chlorite are one which is brilliant green, strongly pleochroic to pale yellow and has upper first order or higher birefringence and one which is yellowish-green, weakly pleochroic and also has upper first order birefringence. Occurring locally is a colorless chlorite.

Albee (1962) states that magnesium-rich chlorite is biaxial positive and length fast while iron-rich chlorite is biaxial negative and length slow. The atomic ratio $\text{Mg} : \text{Fe} + \text{Mg}$ at the sign change is approximately 0.52. Immediately on the magnesium-rich side, interference colors are anomalous brown; on the iron-rich side, anomalous blue. With increasing magnesium or iron content, the interference

colors also increase. In the sense of Albee's definition, the Port Radium chlorites, both in the veins and in the wall rocks, are predominantly iron rich. The essentially isotropic chlorite may be a "penninite" whose Fe: Fe + Mg ratio is close to 0.52. However, the interference color of this chlorite appears to pass into greys which are not particularly anomalous.

Penninite is less abundant than the main varieties of chlorite mentioned above and does not form as large replacement patches. Chlorite veinlets are, however, most commonly penninite. Such veinlets cut the groundmass chlorite.

Except where the chlorites have pseudomorphically replaced the mafic minerals on the fringes of the hydrothermal alteration zones, they are characteristically very fine grained, grain sizes on the order of 50 to 100 microns being common (Plate 44A). From mafic mineral centers, chloritization spread out and coalesced to form dense mats studded with leucoxene (Plate 44B). Every specimen within the hydrothermal alteration zones contains at least some chlorite and within two to three feet of the veins a chlorite content of 20 to 30 percent is common. More than 50 percent chlorite in a specimen is unusual. Specimens of tuffaceous rocks which have a high chlorite content usually also contain carbonates (Plate 45A).

Leucoxene

What is called "leucoxene" is opaque in transmitted light and adamantine in reflected light. Under high power magnification it is, however, frequently seen to be aggregates of brownish, elongate, highly birefringent minerals which probably include rutile and sphene.

These minerals are widely distributed, at least minute amounts being present in every alteration specimen examined. Concentrations of two or three percent by visual estimate are common. They are closely associated with chlorite, occurring normally as discreet centers on mafic minerals chloritized in situ. Altered diabases, in particular, show megascopic white spotting, the white spots being at the locations of former opaque grains (Plate 45B).

Leucoxene probably formed at the same time as chlorite from elements already present in the rocks.

White Mica

Grains of white mica average less than 50 microns in length. Grains 500 microns in length are exceptional and appear to be confined to the pseudomorphic replacement of earlier micaceous minerals. More than one white mica may be present although no basis for making a systematic subdivision was found. The mineral is neutral to very pale green, non-pleochroic and has indices of refraction generally less than but overlapping those of the associated chlorite. The larger grains yield biaxial negative figures with a small 2V and upper second order interference colors. Further work is required to determine the mineral species.

White mica occurs adjacent to all veins on all levels but is not as abundant as chlorite or the carbonates. It reaches a maximum concentration of 40 to 50 percent adjacent to the veins although more commonly does not exceed 20 percent. The concentration decreases sharply outwards from the veins except in areas where there is an exceptionally wide zone of chloritization.

In the intrusive rocks, white mica is the characteristic hydrothermal alteration mineral in plagioclase (Plate 46A). It also occurs with chlorite as a coarse crystalline replacement of biotite in the granite (Plate 46B). In the tuffaceous rocks, it replaces plagioclase and earlier formed microcline. The texture of the white mica varies, with increasing intensity of alteration, from isolated blades to boxworks to sinuous laceworks. Veinlets of white mica are uncommon. Some coarser grained laminations in the microcrystalline tuffs were preferentially replaced by white mica (Plate 47A). Elsewhere, pronounced preferential replacement of microscopic, lenticular partings in the tuffs can be attributed only to differences in original composition of the beds.

Accumulated evidence supports an overlapping to younger age for white mica as compared to the abundant, low-birefringent chlorite in the alteration zones. White mica rims aggregates of chlorite grains (Plate 47B) and extends into the chlorite along wedge-shaped fractures. Also, sinuous zones of white mica cut across patches of groundmass chlorite. Both the white mica and the groundmass chlorite are cut by late veinlets of chlorite.

Sulphides

Pyrite and chalcopyrite are the only significant sulphides in the wall rock alteration zones. Except in a few areas of massive sulphidization, chalcopyrite is confined to the immediate vicinity of the veins and is much less widely distributed than pyrite. This is the reverse of their relative abundance in the veins in which chalcopyrite is the dominant sulphide and pyrite relatively rare, and

suggests that the iron for the wall rock pyrite was derived primarily from the rocks with only sulphur being introduced.

The concentration of hydrothermal pyrite exceeds one or two percent only locally. Pyrite occurs in clusters of subhedral grains with white mica along tight fractures and in disseminations. It appears to be more closely related in time of formation to white mica than to any other alteration mineral. This correlates with the observed association of white mica and sulphides in the veins. Pyrite was replaced by the carbonates and locally by chlorite and leucoxene.

In a few areas, particularly in the 34 ore shoot area on No. 3 vein and the 72 ore shoot area on No. 7 vein, chalcopyrite is an important constituent of the wall rock alteration. The sulphidized body in the 72 ore shoot area was described on page 59. It is by far the largest in the mine and contains from 10 to 15 percent disseminated chalcopyrite. In some of the smaller sulphidized bodies, chalcopyrite is more massive.

Chalcopyrite in the wall rocks replaces pyrite and is at least in part younger than the carbonates.

Group 3 Alteration Minerals

Carbonates

Replacement carbonate in the wall rocks exhibits all gradations in concentration from diffuse centers in plagioclase and mafic grains to dense, fine-crystalline mats totalling 70 percent or more of the specimen. The grain size tends to increase with intensity of replacement. Only rarely does the carbonate exhibit euhedral form

(Plate 48A). Two specimens of carbonate X-rayed were dolomite but that cannot be considered to be an adequate survey of the bulk of the carbonate.

In the intrusive rocks carbonates are distinctly subordinate to chlorite and white mica as alteration minerals. In these rocks, quantities of carbonates in excess of a few percent are restricted to the immediate vicinity of the veins. In the massive crystalline tuff and especially in the Mine series rocks, carbonates are in many places the major alteration minerals. They are most concentrated along the carbonate-rich portions of Nos. 2, 3, 4, 5 and 8 veins. The concentration outwards from the vein is erratic probably reflecting both degree of fracturing and favorability of particular beds in the host rock. The carbonate content can drop from over 50 percent adjacent to the vein to 10 percent two feet from the vein and rise again to 20 or 30 percent, say, 20 feet from the vein.

Carbonatization was the last major hydrothermal alteration. It seems probable, however, that some of the carbonate was formed earlier from the appropriate ions released as alteration progressed. In previously unaltered rocks, carbonates replaced both the plagioclase and the mafic minerals, particularly diopside. In previously altered rocks, they replaced substantial quantities of microcline and chlorite (Plate 48B). They replaced apatite and quartz to a moderate degree. There is little evidence for significant replacement of white mica by carbonates.

SUMMARY OF SEQUENTIAL RELATIONS

The order of deposition of the vein minerals and wall rock alteration minerals is summarized in Table 3. The time of deposition of each mineral is represented by a horizontal line, the length of which has little significance. The most significant feature is the position of the right end of a line which represents the presumed time of cessation of deposition of a mineral relative to the other minerals.

Vein mineral deposition was predominantly in open spaces during stages 1, 2 and 3 and predominantly by replacement during stages 4, 5 and 6. Brecciation of previously deposited minerals occurred during or following stages 1, 2 and 3. Renewed fracturing of the wall rocks occurred between the formation of microcline and chlorite and probably correlates with one or more of the periods of vein mineral brecciation. Wall rock alteration minerals were apparently deposited at about the same time as the same minerals in the veins. If this is correct, very little alteration of the wall rocks occurred during vein mineralization stages 2 and 3 - the pitchblende and arsenide episodes of open-space deposition.

Some of the uncertainties concerning the sequential relations of the vein minerals are listed below:

1. Relative order of deposition of some of the arsenide minerals and of some of the sulphide minerals;
2. Time of initial deposition of the sulphide minerals relative to the micaceous minerals and dolomite;
3. Time of deposition of native bismuth relative to the silver minerals.

TABLE 3: Sequential relations of the vein and wall rock alteration minerals.

Vein Minerals	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6
Apatite						
Quartz						
Hematite						
Pitchblende						
Fe-OO Arsenides						
Pyrite						
Chlorite						
White Mica						
Barite						
Siderite						
Dolomite						
Sphalerite						
Tetrahedrite						
Bornite						
Chalcopyrite						
Galena						
Calcite						
Rhodochrosite						
Silver Minerals						
Native blimuth						
<u>Wall Rock Alteration Minerals</u>						
Apatite						
Microcline						
Hematite						
Quartz						
Chlorite						
White Mica						
Pyrite						
Chalcopyrite						
Carbonates						

Note: Stages 1, 2 and 3 - predominantly open space
 Stages 4, 5 and 6 - predominantly replacement

LOCALIZATION OF PITCHBLENDE

The major portion of the ore occurs in Mine formation rocks usually near the contact with one of the other geologic units: feldspar porphyry; massive crystalline tuff; diabase; granite; or massive meta-sedimentary rocks (Figures 4, 5 and 6). Campbell (1955) considered ore localization to have been influenced mainly by physical rather than by chemical factors. A summary of his statements in favor of physical control follows:

(1) The Mine formation lithologic units were relatively less competent than the other rock types. The veins tended to widen and the degree of fracturing to increase on passing from a more competent into a less competent rock (Plate 7);

(2) Major vein junctions were favorable loci for ore deposition. Such areas are also areas of greater fracturing;

(3) More steeply dipping portions of the veins were more favorable than less steeply dipping portions. Dilatancy tended to be greater on the steeper portions.

A summary of Campbell's arguments opposing chemical control of ore localization is:

(1) Pitchblende was one of the earliest vein minerals and its location could not have been influenced by later vein or alteration minerals. Red alteration (hematitization) while related in time to pitchblende deposition is not related in space. It should be attributed to a common effect rather than to a controlling reaction;

(2) Apparently identical Mine formation lithologic units were favorable in one place but not in another;

(3) Deposition was predominantly open-space, suggesting little chemical exchange with the wall rocks.

The writer concurs with this general viewpoint. Further, it is felt that the deposit as a whole was localized by a structural feature larger than those considered by Campbell. This is the broad, concave north bend of the veins to which reference was made on page 49. Figure 7, a composite plan of Nos. 1 and 2 veins, was prepared to illustrate this feature. It is in effect a subsurface contour plan of the veins with the contour interval being equal to the level interval. The projected traces of the principal footwall geologic contacts are shown on the plan to facilitate a comparison of host rock control with structural control. Not only is the deposit confined within the broad, concave north section of the veins but individual ore shoots favor similar, smaller flexures. A good example of this is in the No. 13 ore shoot area, No. 1 vein. With depth, the vein changes from concave north to concave south and the ore shoot bottoms at the level of the change. Such a change in concavity is necessarily accompanied by a decrease in the dip of the vein. Steepness and direction of concavity are, therefore, partially inter-related.

The main, concave north feature in the vicinity of the deposit is the most pronounced one of its type anywhere along the vein structures within a distance of two miles to the northeast. No. 2 Shaft (Figure 4) is near a small, concave north bend in No. 1 vein and is the site of the only known ore shoot on No. 1 vein northeast of those shown on Figure 7. Bear Bay Shear has a predominantly concave south form and contained little ore. It is perhaps not accidental, however, that $1\frac{1}{2}$ miles to the northeast some pitchblende

was deposited near a concave north bend of the eastward continuation of Bear Bay Shear. A shaft was sunk on the showing on the north shore of Cross Fault Lake and a few thousand pounds of pitchblende were mined.

It is concluded that movement on the veins was such that dilatancy tended to be greatest in the areas where the veins were concave north. This, in conjunction with the other physical factors cited, controlled the localization of the individual ore shoots.

If some unidentified vein mineral was chemically directly responsible for the localization of pitchblende by decreasing the solubility of uranium in solution or by reducing it from the U^{6+} to the U^{4+} state, then the localization was still indirectly due to physical causes. The unidentified mineral, for example an early sulphide, must have preceded pitchblende and been localized by the same physical conditions to which the localization of pitchblende is now directly attributed.

OUTLINE OF SOME GEOLOGIC PROBLEMS

The sequence of the principal geologic events in the McTavish Arm area of Great Bear Lake is reasonably well known. The events, from oldest to youngest, are summarized below:

1. Accumulation of Echo Bay group and Cameron Bay group sedimentary and volcanic rocks;
2. Intrusion of hypabyssal feldspar porphyry bodies with accompanying folding and possibly some metamorphism;
3. Intrusion of at least three phases of granitic rocks with accompanying folding, tilting and metamorphism;
4. Accumulation of Hornby Bay group sedimentary rocks above an unconformity;
5. Fracturing, faulting, and introduction of "giant quartz veins"; quartz veins introduced at least in part before deposition of the Hornby Bay group;
6. Renewed fracturing and intrusion of diabase dykes;
7. Fracturing and brecciation; deposition of several stages of metallic mineralization (the Port Radium deposit) with intervening fracturing;
8. Intrusion of diabase sills;
9. Minor fracturing and late stage mineralization - cuts diabase sills;
10. Accumulation of Paleozoic and Mesozoic strata now exposed northwest and southwest of Port Radium.

The Hornby Bay group may be younger than the Port Radium pitchblende deposit. A minimum age for the diabase sills is not known.

Although generally considered to be Precambrian, they conceivably could be much younger.

Events relating to the fracture systems in the McTavish Arm area attest to a complex history of unknown duration. Fractures developed during or before emplacement of the "giant quartz veins" and minor movement occurred on some fractures after intrusion of the diabase sills. The several stages of metal mineralization observable in the Port Radium vein system may have been introduced over a brief span of geologic time or over a period of tens or even hundreds of millions of years. The veins contain possible second generation pitchblende in carbonate gangue and lenticular veinlets of isotopically anomalous galena which is apparently younger than the silver mineralization. An isotopic study of that pitchblende and galena offers a possible means of clarifying geologic events which occurred between deposition of first generation pitchblende and accumulation of Paleozoic strata. For that period, known to be almost one billion years long, the field data provides little information on the geologic history.

In addition, little is known concerning absolute ages of events. Tentative ages for the formations assigned on the basis of the classical field geology have been greatly revised in recent years and are still being revised. Data published by several investigators indicates an apparent age of approximately 1400 million years for unquestioned first generation pitchblende. Recently published potassium-argon ages indicate a minimum age of about 1700 million years for granitic bodies correlative with the granite at Port Radium. No other absolute ages are known.

With the hope of obtaining more information on absolute ages and of gaining insight into geologic processes, a limited lead-uranium isotopic study was undertaken. The isotopic data is presented and discussed in the following sections.

INTRODUCTION TO LEAD-URANIUM ISOTOPIC STUDY

Previous isotopic studies on Port Radium vein minerals will be discussed in detail in later sections. The studies were carried out primarily by Nier (1938, 1939), by the Toronto group (Cumming et al, 1955) and by the Lamont group (reported in Eckelmann and Kulp, 1957). All three groups analysed the same sample of ordinary galena and in addition the Toronto group analysed one sample of anomalous galena. More extensive analyses were made on pitchblende. Nier obtained lead-uranium chemical data and lead isotopic data on one sample, the Toronto group on one sample and the Lamont group on two samples. All samples yielded discordant lead-uranium ages. In addition, the Toronto group obtained lead isotopic data, not accompanied by chemical concentration analyses, on 13 samples of pitchblende.

Still earlier work, consisting primarily of straight chemical analyses and lead atomic weight calculations, is summarized by Cumming et al (1955).

For this study, isotopic analyses were completed on seven zircon fractions from two samples of granite, on three specimens of pitchblende, and on eight specimens of ordinary and anomalous galena. In addition, one specimen of chalcopyrite was analysed isotopically for lead. One of the galena samples was derived from a diabase dyke exposed 1 1/2 miles from Port Radium. The remaining galena samples came from the mine.

Some specific considerations affecting the sample choice and treatment are listed below:

1. To obtain an absolute age for the Port Radium granite

and to examine discordance patterns in zircon concentrates. At the time the study was initiated, no data was available on the age of the granitic bodies intruding the Cameron Bay group;

2. To see if an age could be established for the diabase sill exposed in the Port Radium mine;

3. To investigate possible variations in lead and uranium concentrations with the size of the pitchblende sample analysed;

4. To analyse samples of pitchblende enclosed in carbonate veins. This pitchblende could be second generation and could be significantly younger than the larger concentrations of pitchblende in siliceous gangue;

5. To examine the isotopically ordinary and the isotopically anomalous leads for information on ore forming processes;

6. To see if the nature or time of geological disturbances to lead-uranium systems could be determined.

Experimental

The chemical analytical procedures are given in Appendix A. All work was carried out in California Institute of Technology laboratories used exclusively for similar isotopic studies. Procedures were such as to minimize contamination from all sources during sample treatment.

Isotope dilution techniques were used for determining lead and uranium concentrations in samples. Isotope ratios were measured on a 60 degree sector, 12 inch, single focusing mass spectrometer constructed by C. R. McKinney. A detailed description of standard operating procedures for the spectrometer is given by Chow and

McKinney (1958). For concentration runs, 12 stable sets of isotope ratios were considered sufficient and for composition runs, 15 sets. By a "set" is meant two peaks for each isotope obtained by scanning up and then back down. In so far as possible, peaks were recorded at better than 50 percent of full-scale chart deflection at as high an ion current as was permissible for stability and sample life. The average deflection was obtained graphically on the mass spectrometer chart for the two peaks in each set and these values were then averaged arithmetically. Sets obtained under obviously unstable conditions as indicated by erratic deflections of the collector or grid (total signal) pens were discarded.

To the arithmetic averages, a velocity discrimination correction proportional to the square root of the mass ratio was applied. The factors used are listed below (McKinney, 1961):

U^{238}/U^{235}	-	1.0060
Pb^{206}/Pb^{204}	-	1.0050
Pb^{206}/Pb^{207}	-	0.9975
Pb^{206}/Pb^{208}	-	0.9950

For concentration determinations, the quantity of tracer (spike) used was normally varied so as to give U^{235}/U^{238} and Pb^{206}/Pb^{208} ratios close to unity.

Analytical Errors

Analytical errors affecting the processed mass spectrometric data can arise from many sources. A number of the possible sources are random. Included in this category are contamination from reagents or glassware, errors in spike aliquoting, mass spectrometer "memory",

and variations in mass spectrometer performance. Biased errors can arise also from several sources including particular steps in the analytical procedure, consistent loss of sample to glassware, incorrect choice of common lead, and use of incorrect factors for normalizing the raw mass spectrometric data.

It is possible to evaluate many of these errors by analysing reagent blanks, by altering the analytical procedures and by analysing the same sample several times. Such steps are carried out routinely in the California Institute laboratory by L. T. Silver (personal communication). The results indicate that errors of the type listed above are not significantly greater than precision errors in mass spectrometric measurement. Reagent blanks normally carry less than 0.2 micrograms of lead and negligible uranium.

The reproducibility of data from the mass spectrometer used for this study was reported on by Chow and McKinney (1958) and Chow and Patterson (1959) in connection with analyses of ordinary leads. Silver and Deutsch (in press) discuss the reproducibility of data in connection with the analyses of zircon samples. For the reproducibility they assign the following values: $\pm 0.5 - \pm 1.5\%$ for $\text{Pb}^{206}/\text{Pb}^{204}$; $\pm 0.3\%$ for $\text{Pb}^{206}/\text{Pb}^{207}$; $\pm 0.3\%$ for $\text{Pb}^{206}/\text{Pb}^{208}$; $\pm 0.5\%$ for $\text{U}^{235}/\text{U}^{238}$. For some of the zircon fractions analysed in this study, somewhat larger errors are assigned because of either low ion current intensity or ion current instability during the mass spectrometric measurement. Somewhat larger errors are assigned also to the pitchblende data because of the small abundance of Pb^{204} in the samples and hence the lower measurement precision.

The relative constancy of a number of calculated radiogenic

Pb^{207}/Pb^{206} ratios, disregarding natural variations among the samples, suggests that the error assignments are realistic and that the choice of common lead was not grossly incorrect. Possible errors in the uranium isotope decay constants are not included in the apparent age error assignments.

Constants Used

The following constants were used in calculations and for preparation of graphs:

$$\begin{aligned}\lambda(U^{238}) &= 1.537 \times 10^{-10}/\text{yr.} \\ \lambda(U^{235}) &= 9.72 \times 10^{-10}/\text{yr.} \\ \lambda(\text{Th}^{232}) &= 4.99 \times 10^{-11}/\text{yr.} \\ U^{235}/U^{238} \text{ (today)} &= 1/137.8\end{aligned}$$

For many purposes, however, tables by Stieff et al (1959) were used. In the preparation of those tables, a value of $4.88 \times 10^{-11}/\text{yr.}$ was used for thorium and $1/137.7$ for the uranium ratio.

ISOTOPIIC STUDY OF GRANITE ZIRCONS

Until recently, very little isotopic work has been done on different size fractions of zircon from the same rock. Tilton et al (1957) concluded that there was no correspondence between age discordances and crystal size, amount of radiation damage or optical appearance. They were studying, however, primarily single zircon concentrates from rocks widely scattered geographically and of widely different ages. Niccolaysen et al (1958) studied three fractions from the same rock. The common lead content was so high that Pb^{207}/U^{235} ages could not be calculated and they made little attempt to draw conclusions from the data. The Pb^{207}/Pb^{206} ages were about 1870 million years for each fraction and the Pb^{206}/U^{238} ages ranged from 642 to 816 million years, increasing with increasing average crystal size of the fractions. By far the most detailed study of variations within zircon families from a single rock is a continuing study by Silver and co-workers (Silver, 1963a, 1963b; Silver et al, 1963; Silver and Deutsch, in press). In general they find that radioactivity, parent and daughter concentrations and degree of discordance increase with decreasing average size of zircons from the same rock. Since it is possible for such variations to yield more information on geological history than just the age of the rock in question, the study of Port Radium granitic zircons was undertaken.

Descriptions of Samples

Cropping out on off-shore islands immediately west of the Port Radium mine and again further north on the mainland is a granitic

body. Its eastern contact dips steeply eastward into the western workings of the mine. One and one half miles north of the mine is an island called "Granite Island" which is about three quarters of a mile long and which is composed entirely of a similar granitic rock type. Although there is no continuous exposure, it is most probable that these separate outcrops are part of one and the same body.

Two bulk samples of the granite were collected, one from an underground cross-cut and one from Granite Island. More specifically, the locations from which these samples were taken are:

A. Granite Island (Sample S206) - on the south shore approximately 1200 feet from the east end (Fig. 7). The sample was removed by blasting. The exposure was uniform except for a few thin aplitic veinlets which were eliminated from the sample. Collected - 61 pounds;

B. Mine (Sample U159) - in 1302 X-cut North, approximately 80 feet south of the No. 2 vein - 3 vein junction and 580 feet north of No. 1 vein. (See projected location on No. 2 vein longitudinal section, Fig. 4.) On the 1300 level and approximately that distance below the present surface. The area sampled is the least altered exposure of granite in the mine. It is near the center of a 150 foot wide apophysis which extends eastward 250 feet beyond the sample site on the footwall of No. 2 vein. Collected - 36 pounds.

Microscopically, specimens from the two samples are almost identical except for the degree of alteration. The rocks are medium grained and equigranular. The principal minerals and their approximate percentages are: quartz - 25, oligoclase - 35, orthoclase - 25, hornblende - 10, biotite - 5. The samples analysed are thus quartz

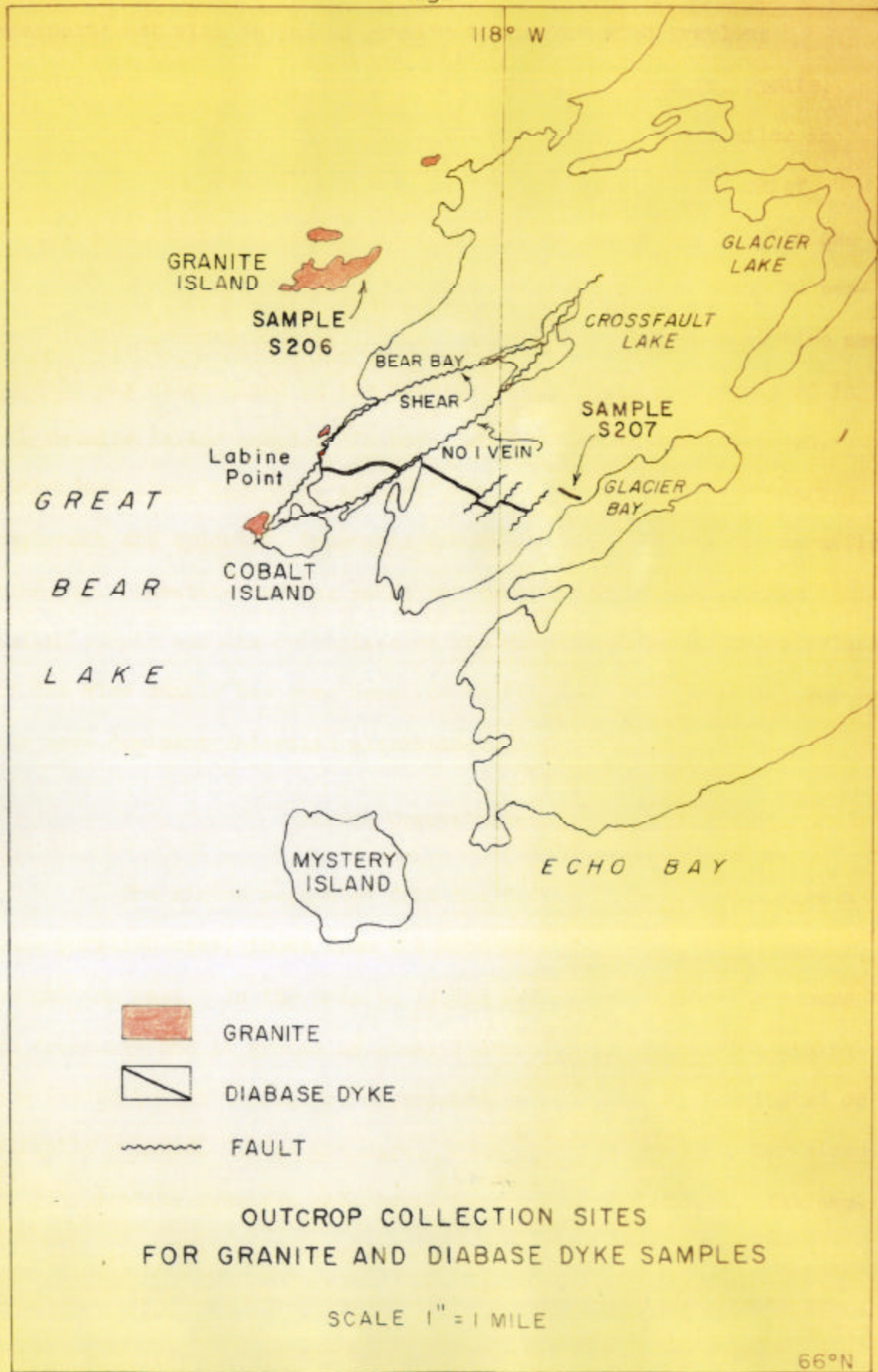


Figure 7

monzonite but will be called granite to conform with previous nomenclature. Accessory minerals are magnetite, ilmenite, pyrite, apatite, sphene and zircon. The secondary minerals are similar in both rocks but are more extensive in the Mine sample. The chief alterations are sericitization and chloritization of the plagioclase which is 80 - 90 percent altered in the Mine sample and about 70 percent altered in the Granite Island sample. Hornblende and biotite are extensively chloritized in the Mine sample but only moderately so in the Granite Island sample. In both samples, quartz is uncorroded, orthoclase shows incipient alteration and there is minor secondary carbonate and epidote. Leucoxene occurs in small patches on the mafic minerals. Hematite dusting makes the plagioclase of the Granite Island sample and the orthoclase of the Mine sample pink. Plagioclase of the Mine sample has some hematite in it but is pale greenish due to the more dominant chloritic alteration.

Zircon Concentrates

The zircon separates from the Granite Island sample have a pale purplish cast; those from the Mine are off-white with a very slight tan cast. In the Granite Island sample, some hematite occurs on fractures and in grains or zonal distribution. The zircon grains are predominantly tetragonal dipyramids, either sharply terminated or slightly rounded. Twins are rare. Common inclusions are other zircon grains, apatite crystals and, less commonly, opaque grains. All show random distribution. Zoning is common but not well developed. Despite the higher hematite content, the Granite Island zircons are somewhat more translucent than those from the Mine. This may be due

in part to fracturing which is more extensive in the latter. It is possible that the fractures in the Mine sample zircons were also once coated with hematite and that the hematite was reduced by hydrothermal solutions. This is difficult to explain, however, in view of the hematite remaining on adjoining feldspar grains. Closer to the vein, the rock is strongly bleached and no hematite remains.

Following the procedure of Silver and Deutsch (in press), the zircon concentrates were given a one hour wash in hot, concentrated HNO_3 . Those authors found acid washing to equal or exceed the efficiency of hand-picking for removal of other radioactive species such as uranothorite and apatite. Sphene, quartz and feldspar grains were removed by hand-picking in so far as possible. The final concentrates were over 99 percent pure.

Results

Lead and uranium isotopic data was obtained on five zircon fractions from the Granite Island sample and on two from the Mine sample. The data and the apparent ages derived from it are presented in Table 4. It is apparent that fractions A-1* and A-5 gave somewhat unusual results. Possible reasons for this will be considered here.

Fraction A-1 gave the most discordant Pb/U ages and the lowest $\text{Pb}^{207}/\text{Pb}^{206}$ age. The latter is within analytical error and may not be significant. The sample was prepared and analysed four years previous to the other fractions from the same rock. It is distinguished from the other samples for the following reasons:

*The designations A-1, A-2, etc. refer to zircon size fractions given in Table 4.

TABLE 4: Isotopic data on granite zircons

Sample	Size	Weight (Grams)	Observed Atom Ratios				Radiogenic Lead		Concentrations (ppm)	
			$\frac{Pb^{206}}{Pb^{204}}$	$\frac{Pb^{206}}{Pb^{207}}$	$\frac{Pb^{206}}{Pb^{208}}$	Atom Percent $Pb^{206r} \frac{1}{Pb^{207r} Pb^{208r}}$	Pb^r	U	$\frac{U^2}{eU}$	
<u>Granite Island</u>										
A1	R200 ³	0.1488	347±3	6.80±.03	3.749±.02	78.45	8.45	13.10	215.1	953.7±10
A2	R200	0.0373	463±4	7.25±.03	4.343±.02	79.16	8.58	12.26	237.9±2	835.3±8
A3	R325	0.0725	739±3	7.88±.04	5.008±.02	79.30	8.61	12.09	249.3±2	892.4±9
A4	P325	0.0844	785±15	7.91±.04	4.940±.05	78.91	8.61	12.48	273.3±3	916.2±9
A5	P400	0.03075	541±7	6.96±.04	3.920±.03	76.29	9.07	14.64	359.4±4	1264.6±13
<u>Port Radium Mine</u>										
B1	R200	0.1160	493±3	7.33±.03	4.546±.02	79.50	8.65	11.85	242.2±2	999.4±10
B2	R325	0.1466	379±6	6.89±.03	3.907±.02	78.52	8.57	12.91	254.7±2	1030.8±10

¹Pb^r = radiogenic lead

²eU = radiometric equivalent uranium plus thorium

³R = retained on mesh size indicated

P = passed mesh size indicated.

Continued

TABLE 4: Isotopic data on granitic zircons (Continued)

Sample Size	Atom Ratios		Apparent Ages* (millions of years)			
	$\frac{Pb^{208r}}{Pb^{206r}}$	$\frac{Pb^{207r}}{U^{235}}$	$\frac{Pb^{207r}}{Pb^{206r}}$	$\frac{Pb^{206}}{U^{238}}$	$\frac{Pb^{207}}{U^{235}}$	$\frac{Pb^{207}}{Pb^{206}}$
<u>Granite Island</u>						
A1 R200						1790 \pm
A2 R200	0.1549	0.2620	0.1084	1515 \pm 30	1640 \pm 40	1800 \pm 25
A3 R325	0.1525	0.2573	0.1085	1490 \pm 30	1625 \pm 40	1805 \pm 20
A4 P325	0.1581	0.2735	0.1092	1575 \pm 35	1680 \pm 45	1815 \pm 25
A5 P400	0.1919	0.2511	0.1189	1460 \pm 50	1680 \pm 80	1970 \pm 200
<u>Port Radium Mine</u>						
B1 R200	0.1491	0.2239	0.1088	1315 \pm 30	1515 \pm 40	1810 \pm 20
B2 R325	0.1643	0.2255	0.1092	1325 \pm 30	1520 \pm 40	1815 \pm 20

* Error assignments are precision errors only.

1. It represents the R200 zircon fraction freed by the initial pulverizing of the Granite Island sample. The A-2 to A-5 zircon fractions were obtained subsequently by combining and re-pulverizing the retained 50 mesh and passed 300 mesh portions. Thus, while not probable it is possible that A-1 represents a different part of the family of zircons than A-2 to A-5;

2. The A-1 fraction represents zircons which were non-magnetic at a Frantz Isodynamic separator setting of 1.2 amperes while the other fractions, with the exception of A-5, were non-magnetic at 1.6 amperes;

3. It is believed that the different conditions for fusion used on A-1 may have introduced some loss of lead by volatilization as PbCl_2 ;

4. The spike used for determining the lead concentration was a common lead as opposed to a Pb^{208} rich spike used for the other fractions.

The A-1 lead composition data and uranium concentration are probably dependable and will be compared with that from the other fractions. The lead concentration data is undoubtedly not dependable and will not be considered further.

Concerning A-5, the pass 400 mesh size fraction, the data is unique for the samples studied. It has the highest $\text{Pb}^{207r}/\text{Pb}^{206r}$ * and $\text{Pb}^{208r}/\text{Pb}^{206r}$ ratios. The concentrations of uranium and radiogenic lead are distinctly higher. Considered individually, the Pb/U apparent ages are not unusual but the $\text{Pb}^{207r}/\text{Pb}^{206r}$ age, at 1970 million years,

* Pb^{206r} , Pb^{207r} and Pb^{208r} refer to radiogenic components of the measured lead.

is much higher than that obtained for any other zircon fraction. The difference, an apparent age increase of some 12 percent, is well outside normal analytical errors. The pertinent question is whether the increased Pb^{207r}/Pb^{206r} ratio is the result of real or accidental causes. Six ways in which this ratio could be increased relative to the others are:

1. Laboratory contamination from Pb^{207} spike or some mixture relatively rich in Pb^{207} and Pb^{208} ;
2. Laboratory contamination from an older radiogenic lead system being analysed at the same time;
3. "Memory" effect in the mass spectrometer from one of the above types of samples;
4. Indigenous older lead-lead systems in the sample resulting from:
 - (a) A separate mineral phase not removed during zircon concentration and acid washing steps;
 - (b) A physically distinct, "older" population of zircons;
 - (c) An older mineral phase, either zircons or other minerals, occurring as inclusions in the zircons;
5. Appropriate loss of lead from the other fractions so as to give them consistent but lower lead-lead ages;
6. Preferential loss of U^{238} intermediate daughter products from fraction A-5.

After careful consideration of these possibilities, it is concluded that the most probable cause of the unusual data obtained for the A-5 fraction is No. 1 above - laboratory contamination.

Because of the small size of the sample, the addition of only 0.06 micrograms of Pb^{207} to the lead composition portion of the extraction would have raised the apparent lead-lead age from 1815 to 1970 million years.

Despite this conclusion, No. 4, indigenous contamination, cannot be entirely ruled out, partly because the A-5 fraction was unusual in being the most magnetic one analysed (non-magnetic at 0.9 amperes) and in having the highest equivalent uranium content. Indigenous contamination would require that the fraction be composed of two uranium-lead systems, one having on the average an apparent lead-lead age on the order of 1815 million years and the other much older giving a composite age of 1970 million years. Silver and Deutsch (in press) have pointed out that less than one percent of a highly radioactive mineral such as uranothorite can contribute as much radioactivity as all the zircons in a concentrate. Thus, if the acid wash procedure was not 100 percent effective in removing all the remaining highly radioactive species, the isotopic data could be anomalous. Any analogy between this work and that of Silver and Deutsch can, however, be carried no further as they found uranothorite to yield very discordant ages with low lead-lead ages. The presumed indigenous contaminant in fraction A-5 would have to be highly radioactive because of its small abundance yet pronounced effect on the zircon data and, at the same time, would have had to preserve a much older lead-uranium system during crystallization or recrystallization of the zircon. Microscopic evidence does not support this view.

Fraction A-5 will not be considered further.

The common lead used for the corrections is "laboratory

lead" - that analysed on reagent blanks on a routine basis by Dr. Silver. The atomic ratios of this lead, relative to $Pb^{204} = 100$ are: $Pb^{206} = 17.83$, $Pb^{207} = 15.55$, $Pb^{208} = 37.62$. The assumption is that the major portion of the common lead in the analysed sample comes from the reagents. While this is not entirely justified, the samples are sufficiently radiogenic to make the apparent ages relatively insensitive to changes in the composition of the common lead used for corrections. Had a 2000 million year old "model" lead ($U: Pb^{204} = 8.5:1$) been used for the common lead correction, the apparent lead-lead ages would have been increased by a maximum of 10 million years. This is less than analytical errors.

Discussion

Considering the data presented in Table 4, uranium and radiogenic lead increase in concentration with decrease in zircon size fraction. The ratio Pb^{206}/Pb^{204} shows a similar but less definite trend. The Pb^{207r}/Pb^{206r} apparent ages increase slightly with decreasing size fraction but are within analytical errors. The Pb^{206r}/U^{238} and Pb^{207r}/U^{235} apparent ages show no consistent trends. All fractions however, show the general apparent age trend: $Pb^{206r}/U^{238} < Pb^{207r}/U^{235} < Pb^{207r}/Pb^{206r}$. Comparing the Granite Island and Mine samples, the most obvious differences are, for the Mine sample: more discordant lead-uranium ages, higher uranium concentrations, higher uranium to equivalent uranium ratios and possibly lower Pb^{206}/Pb^{204} ratios.

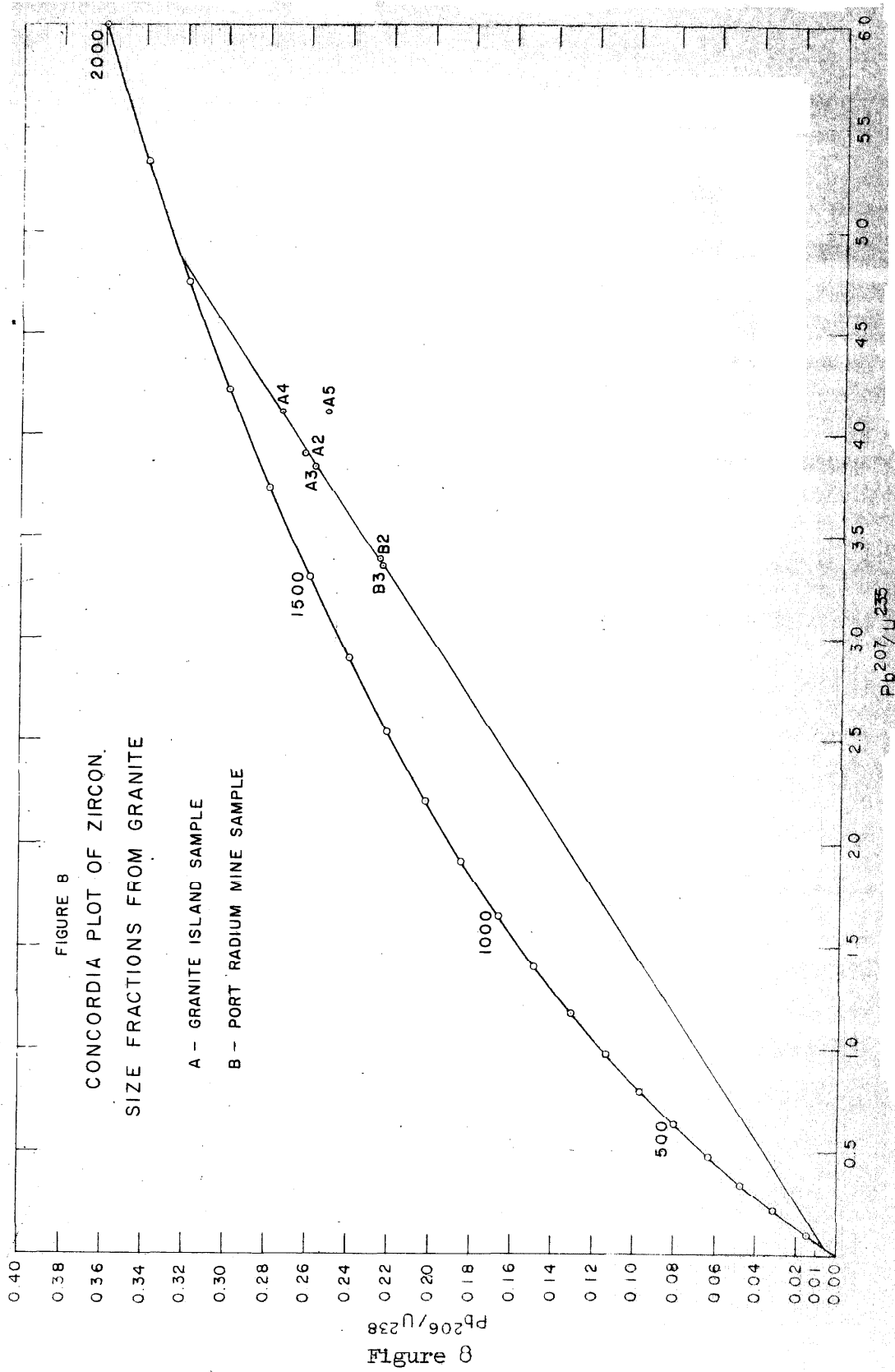
The Pb^{208}/Pb^{206} ratios do not vary systematically with size fraction, nor does the Pb^{208r}/Th^{232} ratio, using for Th^{232} a value

equated to the excess equivalent uranium over the uranium concentration. However, for the A-2, A-3, and A-4 zircon fractions, with increasing age concordance there is an increase in the percent of $\text{Pb}^{208\text{r}}$, the ratio $\text{Pb}^{208\text{r}}/\text{Pb}^{206\text{r}}$, and the ratio U/eU. (The relative $\text{Pb}^{208\text{r}}/\text{eTh}^{232}$ ratio would also increase and hence the apparent lead-thorium age.) As indicated by the U/eU ratio, the eTh shows the opposite trend to the $\text{Pb}^{208\text{r}}$ trend.

For zircon fractions from the Johnny Lyon granodiorite, Arizona, Silver and Deutsch (in press) found similar radiogenic lead and uranium concentration trends, namely increasing concentrations with decreasing average crystal size. These they attributed to systematic concentration variations in the zircon lattice as a function of grain size, the latter presumably related to magmatic history. They also found increasing age discordance with increasing uranium and thorium content, apparently reflecting the greater ease of natural disturbance of more metamict zircon grains found in the finer size fractions. The Port Radium zircons apparently did not respond as uniformly to later disturbances as did the Johnny Lyon zircons.

The atom ratio $\text{Pb}^{206}/\text{U}^{238}$ is plotted against the atom ratio $\text{Pb}^{207}/\text{U}^{235}$ in Figure 8. This is the familiar "Concordia" diagram described by Wetherill (1956). Systems yielding concordant lead-uranium ages plot on the curve. Discordant systems which have lost lead or gained uranium plot below the curve while those which have gained lead or lost uranium plot above. It is only the effect of differential gains or losses, not the changes in the absolute concentration values, which can be recognized.

As Wetherill pointed out, for a single or "episodic"



disturbance a point representing the system on the Concordia diagram plots on a chord joining the true age of the mineral with the age of disturbance. Considering the case for loss of lead, the distance which the point moves along the chord is directly proportional to the percentage of lead lost.

In Figure 8, a chord drawn through the points representing the various zircon fractions intersects the Concordia curve at 1820 million years on the upper end and 50 million years on the lower end. The points (exclusive of A-5) fit to within 0.5 percent of their absolute values which is less than analytical error. On the other hand, analytical error permits the lower Concordia curve intersection to vary between about zero and 100 million years. If all analytical errors were biased, which is improbable, the lower intersection could be as high as 200 million years.

The percent of relative lead loss (or equivalent uranium gain) which would result in the present positioning of the points is: A-4 - 14; A-2 - 18; A-3 - 20; B-2 - 30; B-1 - 30. Thus, there is a 16 percent difference in discordance between A-4 and B-1. Errors in determination of the concentrations of uranium or lead would result in shifting the point along a line passing through the point and the origin. Since the chord as defined passes close to the origin, shifts due to concentration errors would be essentially parallel to the chord and difficult to detect.

The array of points represents related lead-uranium systems, within the zircon families which have undergone varying degrees of disturbance. A variety of phenomena might explain the pattern. These include:

1. Loss of lead in the laboratory;
2. Recent, natural leaching;
3. Continuous diffusion of lead out of the system as suggested by Tilton (1960);
4. Episodic loss of lead (or gain of uranium) as suggested by Wetherill (1956);
5. Intermediate daughter loss.

Accidental lead loss in the laboratory is most likely to occur during two steps in the procedure. These are the acid wash step and the borax fusion step. The strongest argument against loss of lead during fusion (except for sample A-1) is lack of correlation between fusion times, which varied from 50 to 90 minutes, and grain size or degree of discordance. Silver and Deutsch (in press) using identical fusion procedures obtained an array of points fitting a chord which does not pass through the origin.

Washings from the acid wash step were not analysed. The acid wash experiments of Tilton (1956) on ten mineral separates do not clarify the situation. He found an apparent direct correlation between the mobility of uranium, thorium and lead isotopes and the age pattern observed. That is, for samples with discordant lead-uranium ages, relatively more uranium and Pb^{206} than thorium and Pb^{208} entered the washings while the reverse held true for samples having discordant Pb^{208}/Th^{232} ages. The source of the acid soluble phase, whether from within the crystals or from minor impurities, was not established by Tilton. Also, unfortunately, only for one sample (Quartz Creek, Colorado microlite) did the lead-uranium apparent ages follow the more usual discordant pattern of the type observed at Port Radium, namely

$Pb^{206r}/U^{238} < Pb^{207r}/U^{235} < Pb^{207r}/Pb^{206r}$, and in that case, the acid wash data failed to show a significant correlation with the age pattern. If any of Tilton's data has application to the present situation, it would appear to be that concerning the soluble percentage of each element. While his data is not complete in this regard, that given shows the percentage of uranium dissolved to be greater than the percentage of lead and generally greater than the percentage of thorium. If this pattern is applied to the Port Radium zircons, it would result in making the apparent ages less discordant than they actually are. That is, the effects of the acid washing would be to move the points on Figure 8 away from the origin. The considerations here concern only the effect of an acid wash step on a natural discordant pattern, and are not concerned with correspondence between natural and laboratory leach environments.

It is felt that the discordant pattern as observed is the result of natural phenomena. Direct proof is lacking. The fact that the chord passes near the origin makes it an important question.

Recent leaching is considered improbable because the "B" sample, collected 1300 feet below the surface, shows greater discordance than the "A" sample collected at surface.

The chord is much steeper than the continuous diffusion curves published by Tilton (1960). To account for the observed pattern by diffusion would require diffusion rates which changed markedly in the past. Wasserburg (1963) showed that if the diffusion coefficient is made time-dependent, the slope of the diffusion curve is altered. For the special case for which the diffusion coefficient is directly proportional to the integrated radiation damage to the crystal, the

diffusion curve is not as steep as the chord in Figure 8. Nicolaysen (1957) presented a table of figures which can be used to calculate the concordant age of a discordant mineral assuming that its discordance is due solely to continuous solid diffusion of lead during the life of the mineral. Employing his data, the concordant age of the A-2, A-3 and A-4 fractions is in the range of 1860 to 1870 million years and that of the B-1 and B-2 fractions about 1940 million years. If continuous diffusion were the sole answer to the discordance problem, the implication is that the two granitic exposures differ in age by 70 to 80 million years. Although the Granite Island samples are separated from granitic outcrops on the mainland by a 3/4 mile wide water channel, it is very doubtful that they represent separate intrusions. Their similar mineralogy and lead-lead ages are confirming evidence for a single age.

A combination of diffusion and episodic loss would be difficult if not impossible to assess.

Loss of Rn²²² from the U²³⁸ decay chain would make the Pb^{206r}/U²³⁸ age low, the Pb^{207r}/Pb^{206r} age high and the Pb^{207r}/U²³⁵ age fairly close to the true age. In view of the consistency of Pb^{207r}/Pb^{206r} ages and scatter in the Pb^{207r}/U²³⁵ ages, this is ruled out as the major cause of the discordance. Likewise, that the major cause is physical, resulting in Pb²⁰⁷ deficiency due to cumulative recoil effects as suggested by Russell and Ahrens (1957), is considered unlikely. The spread in discordant ages is not uniform enough.

There is no obvious correlation between the degree of discordance and the common lead content as suggested by Tilton et al (1957).

It is concluded that the discordance is caused predominantly by a relatively recent episodic lead loss (or losses) although variable, continuous diffusion may have contributed to the overall discordant pattern. It is felt that the losses are larger than can be reasonably accounted for by analytical errors. On the other hand, there is no geologic event to which the disturbance can be definitely attributed. Possible events are a rise in the geothermal gradient due to burial under Paleozoic and Cretaceous sediments and/or events related to the intrusion of the diabase sheet. The Paleozoic and younger sedimentary rocks are presently exposed on the north and south shores of Great Bear Lake on a line just west of the Fort Radium mine. There is no reason to believe that these sediments did not once cover the mine area but the depth of burial cannot even be conjectured. (If it were possible to definitely prove that the discordance pattern of the zircons is due to recent episodic geologic causes, this might be used as evidence for a substantial depth of cover by post-Cambrian sediments.)

The pitchblende in the Lake Athabasca region, 500 miles southeast of Port Radium, was deposited 1900 million years ago and was probably disturbed 1200 and 100 - 200 million years ago (Eckelmann and Kulp, 1956). There is no evidence for geologic events of those ages in that area. Kuovo (1958) found a linear discordant pattern for some Finnish zircons with the chord intersecting the Concordia curve at 100 and 1700 million years. He attributed this to recent leaching. Tilton (1960, p 2938), however, suggested that it might be due to continuous diffusion although the points do not fit the diffusion-loss curve well. Nicolaysen et al (1958) found a

0 - 2050 million year chord for some South African monazites and attributed the disturbance to recent leaching. In both the Finnish and the South African cases, no known recent geologic event can account for the disturbance of the lead-uranium systems. On the other hand, Silver and Deutsch (in press) are able to point to a geologic event based on field evidence to explain their 90 million year to 1650 million year chord.

It is obvious that a better understanding of discordant patterns in zircons awaits more detailed work on stability of the isotope systems in zircons.

Interpretation of Age of the Granite

From the data presented, the true age of the granite is considered to be 1820 ± 30 million years. This places a minimum age on Echo Bay and Cameron Bay group rocks and on the feldspar porphyry intrusives. It places a maximum age on the Hornby Bay group rocks and on the diabase intrusions.

The age is compatible with potassium-argon ages published by the Geological Survey of Canada (1961, 1962) on granitic rocks and metasedimentary rocks in the same general area of the Canadian Shield (Table 5). Two of the granitic rocks dated lie 80 miles north and 80 miles northeast, respectively, from Port Radium and all the remaining samples came from locations 75 to 150 miles south to southeast of Port Radium. The metamorphic rocks belong to the Snare group which is correlated with the Echo Bay group at Port Radium. The granitic rocks, ranging from granite to quartz monzonite and granodiorite, are correlated with post-Snare group intrusives either on the basis that

TABLE 5: Published potassium-argon ages, Great Bear Lake area*

<u>Location</u>	<u>Sample No.</u>	<u>Rock Sampled</u>	<u>Mineral Sampled</u>	<u>Approx. Age</u>
Intrusive Rocks				
North of Port Radium	60-37	Granite	Biotite	1745 m.y.
Northeast of Port Radium	60-39	Granite	Biotite	1765
Margaret Lake	60-42	Porphyritic granite	Biotite	1725
Maryleer Lake	60-45	Quartz monzonite	Biotite	1850
Camsell River	61-55	Quartz monzonite	Biotite	1785
Little Crapeau Lake	61-58	Intrusive porphyry	Biotite	1765
Metamorphic Rocks				
Grant Lake	60-40	Schist	Biotite	1720
Grant Lake	60-41	Same sample	Altered biotite	1720
Grant Lake	61-56	Same sample	Sericite on feldspar	1855
Emile River	60-43	Schist	Biotite	1710
Saddle Lake	61-57	Schist	Biotite	1810
Basler Lake	61-59	Quartzite	Muscovite	1815

* Data published in Geological Survey of Canada Papers, 61-17 (1961), 62-17 (1962).

they are observed cutting Snare group rocks or are seen to be unconformably overlain by Hornby Bay group rocks.

ISOTOPIC STUDY OF PITCHBLENDE

For lead-uranium isotopic analyses, samples of pitchblende were selected for specific geologic reasons rather than for any attempt to refine published ages or broaden sample coverage. These samples were:

1. Pitchblende in carbonate gangue;
2. Pitchblende adjacent to a post-ore diabase sill;
3. Apparently undisturbed, banded pitchblende in siliceous gangue;
4. Brecciated pitchblende in siliceous gangue.

The first was selected because microscopic data cannot rule out the possibility of there being a second generation of pitchblende, either redistributed or newly introduced, associated with the carbonate-silver mineralization. If this were so, it was hoped that the isotopic data on this pitchblende would show whether the carbonate-silver mineralization followed closely the first generation pitchblende or was separated from it by a substantial time interval.

The second was selected to see if the intrusion of the diabase disturbed the lead-uranium system in the pitchblende. Given ideal circumstances, it might be possible to date approximately the time of diabase intrusion.

The third and fourth samples were selected for intercomparison and for comparison with the carbonate sample. Only "pin-hole" sized samples were treated on the fourth (brecciated pitchblende) sample and, unfortunately, no lead composition data was obtained from it. It will not be discussed further.

Previous Work

Several attempts were made to date the Port Radium pitchblende deposit by chemical means before the first mass spectrometry-derived date was published by Nier (1939). The early work, including that of Nier, is summarized by Cumming et al (1955) in tabular form. Four chemical-lead ages ranged from 1250 to 1450 million years, one was 1700 and another 2000 million years. The former group are close to the true age. This is not surprising if the lead-uranium systems were not severely disturbed since the interfering factors, common lead and thorium, are normally in low abundance in the Port Radium ores.

The combined chemical-isotopic ages derived by Nier (1939), Cumming et al (1955) and Eckelmann and Kulp (1957) will be tabulated in a later section. No other isotopic ages are known to have been published, excepting Pb^{207}/Pb^{206} apparent ages by Cumming et al.

The thorium content of the Port Radium deposit is very low. Eckelmann and Kulp (1957, p 1133) considered thorium to be absent but were probably not justified in stating this as a general conclusion considering the small number of thorium determinations which have been made. The highest percent of thorium reported, an average of four determinations on the same material, is 0.006 (Marble, 1939). The sample analysed by Marble contained 29.39 percent uranium giving a uranium:thorium ratio of 4900:1.

Eckelmann and Kulp (1957) reported laboratory radon leakage of less than one percent on two pitchblende specimens they studied. They also found Pb^{206}/Pb^{210} ages to agree with Pb^{206}/U^{238} ages indicating that the pitchblende is presently in radioactive equilibrium.

This is further substantiated on a larger scale by data in Progress Reports on the mining operation in the 1930's. The radium-uranium ratio given in the reports, presumably based on production data since the uranium half-lives were imperfectly known at that time, calculates to 98.4 percent of equilibrium using the presently accepted half-lives.

On the other hand, Yagoda (1946) identified small, highly radioactive spots in quartz near pitchblende in a Port Radium sample as RaSO_4 . He estimated that these particular spots were deposited a maximum of 20,000 years ago. Thus, some recent leaching of radium is demonstrated but it must be concluded that such leaching was relatively minor.

Kuroda (1955) found the average $\text{Ra}^{223}:\text{Ra}^{226}$ ratio on three specimens of Port Radium pitchblende to be about 0.048 which value is significantly higher than the 0.046 ratio expected for equilibrium conditions and a $\text{U}^{235}:\text{U}^{238}$ ratio of 1:137.8. Kuroda also found Ra^{226} to be in equilibrium with U^{238} and the ratio $\text{ThO}_2:\text{U}_3\text{O}_8$ to be less than 1:1000.

Description of Samples

The sample locations are shown on the longitudinal vein sections (Figs. 4 and 5).

Sample 013 (Spectrometric analyses C1 and C8).

Sample 013 was collected in the 11 ore shoot, No. 1 vein, approximately 500 feet below the present surface. It contains about 40 percent pitchblende and the remainder is predominantly quartz. The quartz and the pitchblende show gross rhythmic banding resulting from open space deposition and are believed to be contemporaneous for

the most part. Plate 49A is an autoradiograph of the hand specimen. The pitchblende is botryoidal although this is more obvious in polished section than in the autoradiograph. The quartz is in part very fine-grained, brownish and hematitic, and in part coarse watery crystals, showing comb structure.

Other minerals, distributed through both the quartz and the pitchblende and younger in age, include very minor hematitic carbonate and one to two percent sulphides. Of the sulphides, bornite and chalcopyrite are the most abundant. They occur associated with the carbonate, intergranular to the quartz, in very thin, discontinuous rims on the pitchblende, and in fractures and syneresis cracks in the pitchblende. A few grains of an arsenide mineral occur near a quartz-pitchblende contact. A minor quantity of a white mineral resembling galena, but distinctly softer, occurs in the quartz. It may be a silver mineral. Occasional grains of other minerals including tetrahedrite are present.

Compared to most Port Radium pitchblende specimens, specimen 013 shows only minor physical disturbance. Brecciation and later replacement of pitchblende is the rule rather than the exception in the ores.

Sample P.R. 33 (Spectrometric analyses C-3 to C-7 inclusive).

Sample P.R. 33 came from the 72 ore shoot, No. 7 vein approximately 150 feet below the present surface. The principal minerals are pitchblende and medium grey, fine crystalline dolomite. Plate 49B is an autoradiograph of the hand specimen. The pitchblende and dolomite are interbanded and lie in a zone between zones of carbonatized, chloritized quartz containing minor arsenide minerals.

Microscopic evidence suggests that the pitchblende was replaced by the dolomite but it is possible that they are contemporaneous. Plate 50A is a photomicrograph of a pitchblende zone showing little evidence of replacement and Plate 50B illustrates a pitchblende zone which was apparently extensively replaced by dolomites. These zones correspond to zones of different density in Plate 49B.

Chalcopyrite, possibly amounting to one percent of the total sample, occurs associated with the carbonate and finely disseminated through the pitchblende.

Sample P.R. 85 (Spectrometric analysis C-2).

Sample P.R. 85 came from l-22 ore shoot, No. 1 vein, near the No. 2 shaft. It was approximately 350 feet below the present surface and 20 feet above a 150 foot thick diabase sill. A two-inch wide pitchblende veinlet is bordered and veined by hematitic, chloritic quartz and minor carbonate. In detail, the pitchblende is criss-crossed by minute, lenticular veinlets of pyrite and chalcopyrite. The chalcopyrite appears to be younger than the pyrite. The sulphides are estimated to be roughly five percent as abundant as the pitchblende. Hematite appears to be of two ages, one associated with early quartz and a second in late veinlets. Small laths of specularite are scattered through the gangue minerals.

In general, there is more pyrite, hematite and specularite associated with the pitchblende in this specimen than in other areas in the mine. In another sample from the same stope, magnetite occurs in fractures in the pitchblende. It is the only specimen from the mine in which such an association was observed.

Sample Size

Two sizes of pitchblende samples were analysed isotopically for lead and uranium. One is referred to as a "pin-hole" sample and was obtained by drilling a hole about 0.5 mm in diameter in the surface of a polished section. The drill used was a manually rotated diamond point mounted on a microscope lense attachment for a Leitz metallographic microscope. The area to be sampled was selected optically, the drill substituted for the lense and the hole drilled by carefully raising the microscope stage while rotating the drill. Two pin-hole samples weighed on a micro balance (only one of which was analysed) had the following weights: 87 ± 4 micrograms, and 91 ± 4 micrograms. Thus, for a rough estimate, the weight of a single pin-hole sample of the size indicated above can be taken to be 100 micrograms or less. This provides sufficient lead and uranium for isotopic analyses of moderately pure Port Radium pitchblendes but is barely adequate for duplicate lead runs if these are desired.

The advantages of using pin-hole samples are that contamination can be kept to a minimum and the nature of contaminants is better known. Also, the data presumably applies to a more homogeneous lead-uranium system. Larger samples may contain several lead-uranium systems zonally, radially or otherwise disturbed. Possibly the chief disadvantage of using pin-hole sized samples is that laboratory contamination is a more serious problem.

Single pin-hole samples were used for three analyses (C-1, C-2, C-3) and two adjacent pin-holes for one analysis (C-7). Plates 51 to 53 inclusive are photomicrographs of polished sections showing

sampled areas. The different shades of pitchblende in these photographs result from the use of different films.

For comparison with the lead-uranium systems in the small pin-hole samples, chip samples from two of the same specimens, P.R. 33 and 013, were analysed. The chips were cut from hand specimens during polished section preparation. One weighed 30.10 grams and measured approximately 1.5" by 0.5" by 0.4". The other weighed 25.25 grams and measured approximately 1.75" by 0.9" by 0.2". No attempt was made to exclude either metallic or non-metallic minerals associated with the pitchblende. It was considered possible that if the pin-holes showed a lead deficiency, this missing lead might be found to have been re-deposited in adjacent minerals.

On the 013 chip sample, lead composition and lead and uranium concentration data were obtained on the combined solution from acid leaching, and from HF digestion of the acid leach residue. For the P.R. 33 chip, similar isotopic data was obtained separately on the acid leach solution and on the HF digested residue. In addition, a crystalline precipitate which settled out of the HF digestion solution was fused with borax and analysed for lead and uranium concentration but not for lead composition. Its lead composition was considered to be identical to that in the HF digestion analysis. Additional details on sample processing are given in Appendix A.

Results

The results of the isotope dilution analyses and the apparent ages of the pitchblende samples are presented in Table 6.

TABLE 6: Isotopic data on pitchblende

Analysis ¹ No.	Weight (Grams) ²	Concentration % ³		Observed Ratios					
		U	Pb ^r	Pb ²⁰⁶ / Pb ²⁰⁴	Pb ²⁰⁶ / Pb ²⁰⁷	Pb ²⁰⁶ / Pb ²⁰⁸	Pb ²⁰⁷ / Pb ²⁰⁴	Pb ²⁰⁷ / Pb ²⁰⁸	Pb ²⁰⁸ / Pb ²⁰⁴
013 - C-1	(100 x 10 ⁻⁶)	(59.66)	(10.61)	5,770	11.20	85.04	515	67.81	
P.R. 85 - C-2	87 x 10 ⁻⁶	66.11±.7	10.69±.11	4,620	10.57	48.74	436	94.89	
P.R. 33 - C-3	(100 x 10 ⁻⁶)	(64.76)	(15.49)	6,090	10.88	127.3	560	47.84	
P.R. 33 - C-4	30.10	46.53±.5	2.87±.03	21,600	11.04	546.6	1953	39.46	
P.R. 33 - C-5	30.10	1.97±.02	0.81±.01	23,200	11.07	653.7	2096	35.49	
P.R. 33 - C-6	30.10	0.0002	5.11±.9	(Uses C-5 composition)					
P.R. 33 - C-4,5,6	30.10	48.50±.5	8.79±.9						
P.R. 33 - C-7	(200 x 10 ⁻⁶)	(68.87)	(15.79)	8,260	10.91	163.9	755	50.19	
013 - C-8	25.25	41.86±.5	4.18±.04	3,120	12.00	72.25	260	43.17	

¹ C-1, C-2, C-3, C-7 are pin-hole samples; C-4 - acid leach; C-5 - HF digestion; C-6 - borax fusion.

² Bracketed figures are probable maximum weights.

³ Bracketed figures apply to weight estimates
Pb^r = radiogenic lead.

Continued

TABLE 6: Isotopic data on pitchblende (Continued)

Analysis No.	Atom Percent			Atom Percent Pb ^r		
	Pb ²⁰⁴	Pb ²⁰⁶	Pb ²⁰⁷	Pb ²⁰⁶	Pb ²⁰⁷	Pb ²⁰⁸
013 - C-1	0.016	90.81	8.10	91.56	7.95	0.48
P.R. 85 - C-2	0.019	89.66	8.48	90.58	8.30	1.13
P.R. 33 - C-3	0.015	90.91	8.36	91.63	8.22	0.15
P.R. 33 - C-4	0.004	91.54	8.29	91.74	8.25	0.01
P.R. 33 - C-5	0.004	91.58	8.28	91.76	8.24	0.00
P.R. 33 - C-6	(Uses C-5 composition)					
P.R. 33 - C4,5,6	0.004	91.57	8.28	91.75	8.24	0.005
P.R. 33 - C-7	0.011	91.11	8.32	91.64	8.22	0.14
013 - C-8	0.029	91.12	7.60	92.54	7.29	0.16

Continued

TABLE 6: Isotopic data on pitchblende (Continued)

Analysis No.	Atom Ratios		Apparent Ages* (millions of years)			
	$\frac{^{206}\text{Pb}}{^{238}\text{U}}$	$\frac{^{207}\text{Pb}}{^{235}\text{U}}$	$\frac{^{207}\text{Pb}}{^{206}\text{Pb}}$	$\frac{^{207}\text{Pb}}{^{238}\text{U}}$	$\frac{^{207}\text{Pb}}{^{235}\text{U}}$	$\frac{^{207}\text{Pb}}{^{206}\text{Pb}}$
013 - C-1	0.1894	2.2680	0.0868	1130 \pm 20	1220 \pm 20	1380 \pm 15
P.R. 85 - C-2	0.1703	2.1516	0.0916	1025 \pm 20	1180 \pm 20	1485 \pm 15
P.R. 33 - C-3	0.2551	3.1531	0.0897	1475 \pm 20	1465 \pm 20	1442 \pm 15
P.R. 33 - C-4			0.0899			1448 \pm 15
P.R. 33 - C-5			0.0898			1444 \pm 15
P.R. 33 - C-4,5,6	0.1935	2.3961	0.0898	1150 \pm 150	1260 \pm 150	1446 \pm 10
P.R. 33 - C-7	0.2445	3.0235	0.0897	1425 \pm 25	1435 \pm 25	1442 \pm 20
013 - C-8	0.1075	1.1686	0.0788	665 \pm 20	795 \pm 20	1190 \pm 15

* Error assignments are precision errors only

TABLE 7: Published isotopic data on pitchblende

Sample No. and Location	Concentration %		Atom Percent		Apparent Ages (Millions of Years)				Ref.		
	U	Pb ^r	Pb ²⁰⁴	Pb ²⁰⁶	Pb ²⁰⁷	Pb ²⁰⁸	Pb ²⁰⁶			Pb ²⁰⁷	
							U ²³⁸	Pb ²³⁵		U ²³⁵	Pb ²⁰⁶
K7 - Contact Lake	19.46	0.22	.01	92.3	7.50	0.27	840	960	1220	A	
K16 - No. 5 vein, 54 shoot	6.51	1.40	0.12	86.4	9.27	4.27	1230	1305	1405	A	
K18 - No. 1 vein, 13 shoot	48.85	8.39	0.24	82.6	9.66	7.52	1010	1100	1240	A	
Mer 10 ² - No. 1 vein, surface ¹	52.32	10.51	0.056	89.02	8.69	2.23	1210	1280	1420	B	
T425 ³ - No. 1 vein, surface	52.32	10.51	0.083	88.10	8.95	2.87	1200	1290	1460	B	
Mer 10 - (Recalculation of ages)							1220	1275	1395	A	
Mer 10 ⁴ - (Recalculation of ages)							1220	1245	1330	C	
Mer 9 ⁵ - Beaverlodge Lake, N.W.T.	51.2	2.49	0.051	91.36	5.76	2.82	330	370	420	B	
Mer 9 - (Recalculation of ages)							340	380	680	A	

¹ Pb^r = radiogenic lead component.

² Uses concentration data of Marble (1936); ages recalculated.

³ Uses concentration data by Marble (1936); new Pb isotope determination; same specimen as Mer 10.

⁴ Ages recalculated using $\text{Pa}^{223}/\text{Pa}^{226} = 0.048$.

⁵ Ages recalculated by Cumming et al.

References: A - Eckelmann and Kulp (1957); B - Cumming et al (1955); C - Kuroda (1955).

In Table 7, published lead-uranium isotopic data is given. Not included are isotopic analyses of lead extracted from pitchblende samples for which there is no lead and uranium concentration data. Table 7 does include, however, isotopic data for two other areas of pitchblende mineralization near Port Radium. One, Contact Lake, is 10 miles southeast of Port Radium and the other, Beaverlodge Lake (not to be confused with Beaverlodge, Saskatchewan), is in the Hottah Lake area about 60 miles southwest of Port Radium.

Choice of Common Lead

The choice of the common lead to be used for correcting the measured lead is an important consideration. Three different leads, singly or as mixtures, are immediately obvious as possible choices.

These are:

	<u>204</u>	<u>206</u>	<u>207</u>	<u>208</u>
(1) Typical "laboratory" lead	1.00	17.83	15.55	37.62
(2) Port Radium ordinary galena	1.00	15.87	15.30	35.50
(3) Port Radium anomalous galena	1.00	22.63	16.06	41.86

As discussed in a previous section under zircons, "laboratory" lead is the average composition of lead found in blanks at the present time in this laboratory. The galenas will be discussed in detail in a later section.

It might be argued that "laboratory" lead should be used for correcting the pin-hole samples since they are small and susceptible to contamination. It might also be argued that one of the galenas be

used for correcting the chip samples since they not only contain large quantities of radiogenic lead but include sulphide and gangue minerals. For instance, the lead composition portion of analysis C-2 contained approximately 7 micrograms of radiogenic lead and 0.1 micrograms of common lead from all sources; the P.R. 33 chip contained approximately 2.65 grams of total lead although, of course, the final aliquots analysed contained only fractions of milligrams of lead. As a matter of fact, apparent ages were calculated using "laboratory" lead for pin-hole corrections and the ordinary galena for the chip samples. This refinement in choice of common lead is, however, unnecessary as the age variation produced is less than one million years for the least radiogenic sample, C-8.

The ordinary galena was chosen in preference to the anomalous galena because the latter was probably deposited long after the pitchblende. While this argument may be sound for the small pin-hole samples whose microscopic contamination is better known, it does not necessarily apply to the chip samples. Anomalous galena could have been deposited near the earlier pitchblende and be included in the chip analysed. In any event, choice of the anomalous galena over one of the above leads makes a negligible difference in the calculated ages.

Much more important considerations are whether Pb^{204} or Pb^{208} should be used for the index of common lead and whether the lead in sulphides associated with the pitchblende may not be quite different from that so far observed in galenas. For this work, the ordinary galena with Pb^{204} for the index was used. Eckelmann and Kulp (1957) used the ordinary galena and Pb^{208} for the index. Cumming et al (1955) used the anomalous galena and, apparently, Pb^{204} for the index.

Using Pb^{208} in place of Pb^{204} has a more pronounced effect on the lead-lead ages than on the lead-uranium ages. For analysis C-2, which has the highest percent of Pb^{208} , using Pb^{208} for the index reduces the lead-lead age from 1485 to 1375 million years. For analyses C-4 and C-5, which have negligible Pb^{208} , the ages are unaffected. The other samples fall between these extremes.

The lead ratios were plotted on $\text{Pb}^{206}/\text{Pb}^{208}$ versus $\text{Pb}^{207}/\text{Pb}^{208}$ and $\text{Pb}^{206}/\text{Pb}^{204}$ versus $\text{Pb}^{207}/\text{Pb}^{204}$ graphs. Analyses C-1 and C-8, both from specimen 013, showed no pattern and would not be expected to since their lower radiogenic $\text{Pb}^{207}/\text{Pb}^{206}$ ratios show evidence of significant past losses of lead or intermediate daughters. The remaining points define a straight line, a 1450 million year isochron, on the Pb^{208} plot. On the Pb^{204} plot, these same points with the exception of C-2 plotted within 0.20 percent of their value from a straight line, also a 1450 million year isochron. C-2 plotted approximately 1.5 percent of its value off the line. (It should be noted, of course, that points C-3 to C-7 inclusive are derived from the same sample, P.R. 33.)

The above suggests that at least sample P.R. 33 contains no thorium or a uniform uranium-thorium ratio and that Pb^{208} , having smaller measurement errors, may be the best index. However, it can be shown that the uranium-thorium ratio cannot be uniform and that to use Pb^{208} for the index implies far greater mass-spectrometric measurement errors in Pb^{204} than are reasonable. Also, using Pb^{208} for the index would destroy the consistency of the P.R. 33 lead-lead ages, at 1445 million years, by dropping the pin-hole lead-lead ages

to approximately 1425 million years. Although this age spread could be explained by minor past loss of lead, or addition of uranium, in the vicinity of the pin-holes, the present data suggests that Pb^{204} is the best index for the pitchblendes.

Discussion

The data presented in Table 6 is supplemented with a "Concordia Plot", Figure 9, identical to the one used for the zircon samples. Figure 10 is also a Concordia Plot on which the published pitchblende data is combined with that obtained in this study.

Of particular interest for specimen P.R. 33 are the four independently measured Pb^{207}/Pb^{206} ages which differ by only ± 0.21 percent. Analyses C-3 and C-7 are essentially concordant at 1445 million years. The small discordance exhibited by these two pin-hole samples from the same polished section is in the opposite sense and could be literally interpreted as a small, recent loss of lead for C-7 and loss of uranium for C-3. The degree of discordance is probably an indication of analytical reproducibility including spike reproducibility. On the other hand, the composite of the P.R. 33 Chip sample analyses, C-4, C-5 and C-6, shows a recent loss of lead or gain of uranium which is outside analytical errors. A large error is assigned to this composite primarily because of unfavorable atomic ratios in the spiked aliquot of C-6, the borax fused residue. The residue proved to contain over 50 percent lead and only 0.002 percent uranium. Such extreme concentrations were not allowed for when spiking. However, the discordance is 22 percent, equivalent to a loss of lead of 0.76 grams, and is not accounted for by the analytical errors.

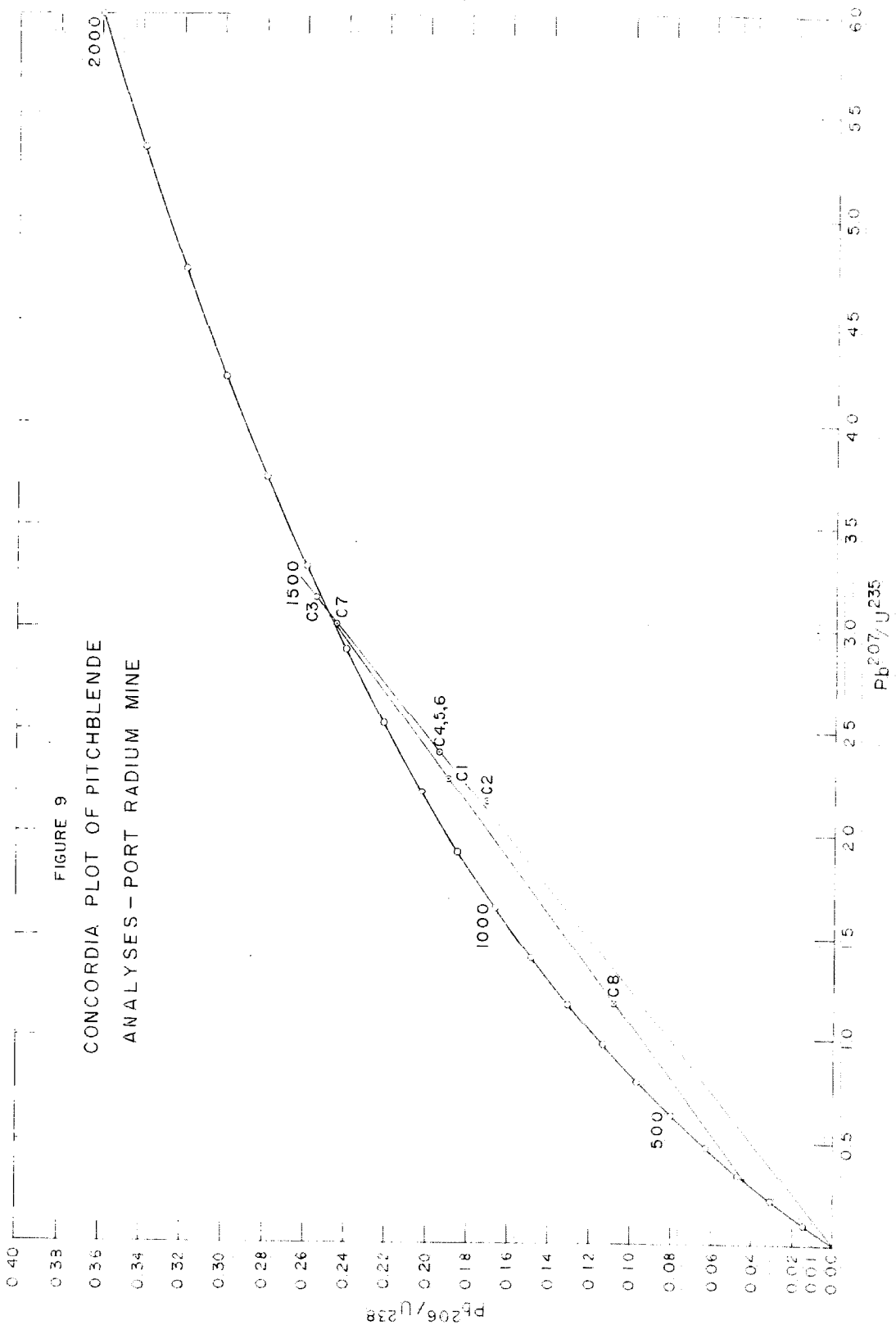


Figure 9

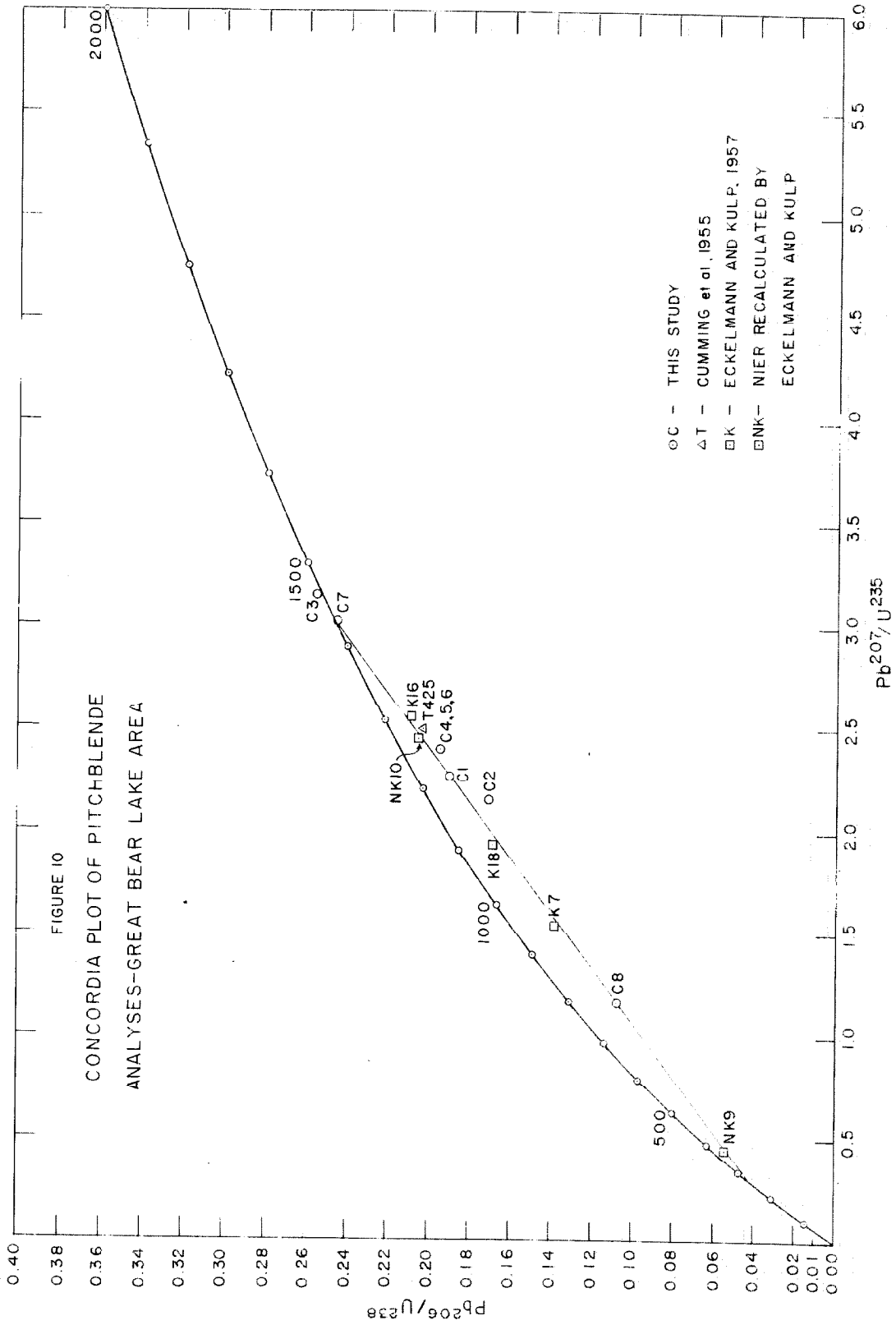


Figure 10

As a matter of interest, the percentages of the total lead and uranium entering the three extractions for sample P.R. 33 were:

	<u>% U</u>	<u>% Pb</u>
Acid leach	95.9	32.7
HF digestion	4.1	9.2
Borax fusion	0.0004	58.1

Sample P.R. 33 contains two types of pitchblende. One, from which pin-holes C-3 and C-7 were derived, is fractured but bright and relatively unaltered. The other appears to be diffuse, ghost-like remnants in dolomite. All gradations between the two exist. It would be of interest to analyse a pin-hole sample from the diffuse mineralization to see if it showed similar discordance to the total sample.

Analyses C-1 and C-8, from sample O13, show not only marked discordance but evidence of past loss of lead as indicated by the Pb^{207}/Pb^{206} ratio ages. In Figure 9, the points representing these samples plot on a chord which intersects the Concordia curve at approximately 1450 and 300 million years. The Chip sample shows greater discordance than the pin-hole, similar to the relation for sample P.R. 33. One mechanism for producing the observed pattern might be deposition of pitchblende 1450 million years ago and episodic loss of lead 300 million years ago, the system remaining closed to transfers of lead and uranium at all other times. No known geologic event, however, other than possible burial by Paleozoic sediments, can be called on to produce the episodic loss. A second possible mechanism for producing the discordance is continuous diffusion of lead (Tilton, 1960). The chord is only slightly less steep than the continuous diffusion curve for a 1450 million year old mineral. The different

degrees of discordance for the pin-hole and chip samples make it obvious, however, that lead loss was not uniform throughout the specimen. Lead loss was probably greater in the vicinity of permeable fractures. Micro lead-uranium systems more discordant than the chip (total) sample must be present. Analyses of these would undoubtedly yield clarifying information.

Several features about analysis C-2 from sample P.R. 85 make the data difficult to interpret. It is the most discordant pin-hole sample and has the highest lead-lead age, Pb^{208} concentration, and sulphide content. The lead-lead age at 1485 million years is above the "concordant" lead-uranium age for P.R. 33. Sample P.R. 85 came from the vicinity of a post-ore diabase sill and it was chosen with the thought that its lead-lead age might be low reflecting the time of intrusion of the diabase. This is not the case. In part because the only isotopic analysis on the specimen was that on a single pin-hole, there can be no unique explanation of the differences between this specimen and the others. Some possible explanations are: (1) the higher lead-lead age is real, relatively unaffected by the diabase and represents an early period of pitchblende mineralization. Cumming et al (1955) reported individual lead-lead ages of 1475 and 1500 million years; (2) the diabase acted in some way to alter the isotopic ratios, by say, introduction of an older radiogenic lead or of a sulphide high in Pb^{208} which isotope should have been used for the common lead index; (3) the analysis, which contained a total of only 0.1 micrograms of common lead, was contaminated in the laboratory with lead relatively rich in Pb^{207} and Pb^{208} .

The radiogenic Pb^{207}/Pb^{206} ratio for an unaltered mineral

1450 million years old is 0.0900. The "older radiogenic lead" alluded to under condition (2) above means any lead having a higher ratio than 0.0900 but in no way implies that the parent mineral must be older than 1450 million years. Lead extracted from 1450 million year old pitchblende at any time in the past, say in excess of 100 million years ago, would have a ratio significantly higher than 0.0900. Redistribution of such lead would make depleted specimens appear younger and enriched specimens appear older as observed today. Net loss of uranium in the past, leaving some unsupported radiogenic lead, would, of course, have a similar effect to gain of lead. If later effects such as recent leaching were superimposed on the above, recognition of the original disturbance would be difficult. That local transfers of lead or uranium could have occurred in a pitchblende deposit the size of the Port Radium one seems entirely probable. It is commonly stated that for pitchblende, the Pb^{207}/Pb^{206} age is minimal (e.g. Eckelmann and Kulp, 1957, p 1138). One important implication of the above discussion is that lead-lead ages older than the true age are possible. Incorporation in the pitchblende at the time of deposition of radiogenic lead from an earlier system is not necessary to produce the older lead-lead age.

For specimen P.R. 85, concentration in sulphides of older radiogenic lead mobilized thermally from nearby pitchblende by the diabase seems possible. The sulphides are too finely and intimately distributed through the pitchblende to permit preparing completely pure concentrates of either for analysis (Plate 53). The pitchblende-sulphide system in specimen P.R. 85 presently shows, however, a net loss of lead (or gain of uranium). To explain the older lead-lead age

in the above manner also requires, therefore, a more recent removal of lead.

The data presented in the tables and in Figure 9 permit making the following general statements concerning the three specimens analysed:

1. Pin-hole samples and chip samples can exhibit different degrees of discordant ages; these differences must reflect in part the sampling method and can move the data points to and from the origin on the Concordia plot;

2. Chip samples can show greater discordance than pin-hole samples from the same specimen;

3. Pin-hole and chip samples from the same specimen can show different Pb^{207}/Pb^{206} ages reflecting geological disturbances;

4. Using a Concordia plot, the above offers a possible means of determining the time at which an episodic disturbance occurred.

The data presented probably reflects both geologic and accidental disturbances. Additional analyses are required to more completely define the significance of the latter. However, it appears possible that pin-hole sampling could become an important new tool in the study of radioactive deposits. Experiments could readily be set up to prove its applicability;

5. An undissolved residue from an acid leach may contain much of the lead and very little of the uranium initially present in a sample. Whether or not the lead isotopes were fractionated would depend on the nature of the sample;

6. The specimens show the effects of both past and recent (geologic and/or laboratory) loss of lead (or addition of uranium).

Age of Pitchblende Mineralization

In addition to the age data presented in this work, Cumming et al (1955) have published lead-lead ages for thirteen samples of pitchblende for which lead and uranium concentration data were not obtained. These ages, in millions of years, are: 1305, 1330, 1385, 1385, 1390, 1400, 1410, 1420, 1440, 1450, 1465, 1475, and 1500. Assigned error ranged from ± 20 to ± 150 million years.

A Pb^{206} spike used at the California Institute of Technology came from Port Radium ores through the University of Chicago (Chow and McKinney, 1958). This is presumably representative of a relatively large sample of pitchblende. The radiogenic $\text{Pb}^{207}/\text{Pb}^{206}$ ratio of the spike gives an age of 1432 million years.

Kuroda (1955) suggested that the $\text{Ra}^{223}/\text{Ra}^{226}$ ratio experimental determined for a relatively unaltered sample be used for age calculations in preference to the value 0.046 which corresponds to a $\text{U}^{238}/\text{U}^{235}$ ratio of 137.8. By implication, if the radium ratio is found to be unusual, the condition existed for radium or its progenitors for an appreciable portion of the life of the mineral. For three Port Radium pitchblendes, Kuroda measured an average $\text{Ra}^{223}/\text{Ra}^{226}$ ratio of 0.048. If this ratio were used for the Port Radium samples, it would lower the calculated ages substantially. However, its use can not be justified. Kuroda and others found Ra^{226} to be in equilibrium with U^{238} . This rules out not only loss of Ra^{226} but loss of U^{234} which Rosholt (1963) found to be the case for a number of Colorado Plateau uranium ores. Further, the natural uranium isotope ratios were measured in specimen P.R. 33 for this study. The $\text{U}^{238}/\text{U}^{235}$ ratio

measured, 137.0 ± 1.5 , was not as accurate as desired because of ion current instability but is higher than the value 132 which would be required to produce an $\text{Ra}^{223}/\text{Ra}^{226}$ ratio of 0.048. Thus, barring the addition of protoactinium to the samples, Kuroda's ratio seems unexplainable and there is no basis for using it for age calculations on Port Radium pitchblendes.

The concordant isotopic ages obtained for pin-holes C-3 and C-7 from specimen P.R. 33 are interpreted as the true age, at 1445 ± 20 million years, of the pitchblende mineralization in the carbonate gangue. These are the only concordant ages which have been measured for Port Radium pitchblendes. Younger lead-lead ages measured on other samples could readily result from loss of lead in the past. Older lead-lead ages, up to 1500 million years, could result from: an earlier age of pitchblende; old radiogenic lead, transported with and deposited with the colloidal pitchblende; redistribution of radiogenic lead at sometime in the past from 1450 million year old pitchblende; incorrect choice of common lead or isotope index.

Favoring a single age for the pitchblende mineralization is the intersection in Figure 9 of the chord for the siliceous sample, 013, with the Concordia curve at approximately 1450 million years.

Sample P.R. 33, coming from a massive pitchblende vein enveloped in carbonate gangue yielded concordant ages but only discordant ages have been found for pitchblende in siliceous gangue. This may be a question of sampling or it may be that the carbonate host has tended to neutralize acids formed in the zone of oxidation before these reached the pitchblende.

The data from the Contact Lake and Beaverlodge Lake areas

are included in Table 7 and shown on Figure 10 for purposes of comparison with the Port Radium samples. The chord shown on Figure 10 is the same chord as is shown in Figure 9 and is controlled by points C-1 and C-8. They do not form a unique or significantly different pattern. It has long been maintained that the Beaverlodge Lake-Hottah Lake area southwest of Port Radium represents a much younger age of pitchblende mineralization because lead-lead ages generally fall in the range of 400 to 600 million years. The oldest lead-lead age published, by Cumming et al (1955), is 680 million years. (However, the same authors say that no possible age can be calculated for another sample, Tor. No. 89, which, using Port Radium common galena for the common lead correction, gives a lead-lead age of 940 million years. A large percentage of common lead does make this figure unreliable.)

Until such time as more detailed isotopic work is carried out on the mineralization at Contact Lake and Beaverlodge Lake, there is no compelling reason for assuming that the mineralization is younger than that at Port Radium. The existing data can be readily explained by loss of lead during the Paleozoic from 1450 million year old pitchblende. Eckelmann and Kulp (1957, p 1136) have reached a similar conclusion.

ISOTOPIC STUDY OF GALENAS

Introduction

Galena is a relatively rare mineral in the Port Radium deposit. Two distinct isotopic types have been recognized. An ordinary galena occurs in very fine disseminations. It apparently was introduced with the main sequence of sulphide minerals, but before the silver minerals, and probably not too long, geologically speaking, after the pitchblende. The other is an anomalous galena of the J-type and appears to be the more abundant of the two. It is more coarsely crystalline and commonly occurs in distinct veinlets or fracture fillings which are usually subparallel to the main veins. The mineralogy of the occurrences is relatively simple. Silver minerals were not seen associated with J-type galena. The J-type galena was apparently introduced later than all the major vein minerals.

Both types of galena are commonly associated with and younger than dolomite, pyrite, chalcopyrite and sphalerite. Although these associated minerals have not been analysed isotopically for lead, it appears that they too were introduced during two periods. If so, the quantities introduced during the second generation were minor.

Radioactive disintegration of the uranium in the pitchblende has produced large quantities of lead-some 3.5×10^6 pounds by the quantity of uranium extracted during mining operations. The discordant pitchblende age patterns indicate that substantial quantities of this radiogenic lead have been moved from the site of formation. Such mobilized lead could simply aggregate along fractures or other

imperfections in the pitchblende, could be transported into immediately adjacent minerals or could be transported long distances, possibly completely out of the deposit. The isotopic composition of this mobilized lead can yield additional information on the geologic history. It is assumed that it would form sulphides by acquiring sulphur either independently or in conjunction with other elements. To date, galena composed entirely of uranium lead has not been recognized.

Three samples of the ordinary galena and four of the anomalous galena were analysed isotopically. Two other samples, one of galena and one of chalcopyrite-tetrahedrite, possibly contain mixtures of ordinary lead and radiogenic lead from the pitchblende in the veins. The general paucity of specimens of galena free from contaminating pitchblende makes analyses of lead in other sulphides a more profitable avenue of approach for future study.

Previous Work

A single sample of ordinary galena, collected from No. 2 vein on surface in the 1930's, was eventually analysed by three different laboratories. One sample of J-type galena was analysed by one of the same laboratories. The isotopic data will be tabulated in a later section.

Descriptions of Samples

Except for two of the samples, P.R. 26 and S207, the galena sample locations are shown on Figures 4 and 5.

Ordinary Leads

Sample P.R. 26 - this is a core sample from 495 feet in depth in diamond drill hole No. 5-230. It is an intersection on Silver Island vein which is a south branch of No. 1 vein. Depth below present surface was approximately 450 feet.

Minor arsenides, sulphides and native silver are present in Silver Island vein but pitchblende occurs only in trace quantities. The predominant gangue minerals are quartz and carbonate. In specimen P.R. 26, the minerals and their paragenetic sequence, from oldest to youngest, are: arsenopyrite, quartz, sphalerite, chalcopyrite, dolomite and galena. There is some overlap in time among the last three. Sphalerite is the predominant sulphide. All are very fine-grained.

Sample P.R. 88 - this is also a core sample and came from 142 feet in depth in diamond drill hole No. 6 - 199 inclined downward from the 650 level. It is from No. 3 North vein, immediately on the hanging wall of a pre-ore diabase dyke. Depth below present surface is 800 feet.

At the location of the diamond drill hole intersection, the vein is only about two feet wide and consists predominantly of quartz stringers in altered Mine series rocks. Minor sulphides are present but no pitchblende. The paragenetic sequence is pyrite, quartz, chalcopyrite, sphalerite and galena. Minor marcasite is younger than the pyrite but older than the galena. The pyrite is probably remnant from wallrock alteration. Carbonate gangue appears to be in part earlier than chalcopyrite and in part later in veinlets associated with sphalerite and galena.

Sample S207 - the galena used for this determination was derived from a diabase dyke in which it was present as minute cubes. The sample location is near the north shore of Glacier Bay, one and one-half miles east of Port Radium (Fig. 7). The dyke is about 50 feet wide and strikes N65⁰W towards Port Radium. It is similar in mineralogy and attitude to the pre-ore diabase dyke in the mine. There are periodic diabase outcroppings in the intervening ground. While the sampled dyke may not be the same one as occurs in the mine, it undoubtedly belongs to the same system and period of intrusion.

The diabase sample was initially selected in the hope that it might contain sufficient apatite or zircon to permit dating. A site well removed from the mine was chosen to avoid possible influence from the uranium mineralization and attendant wall rock alteration. However, the entire eastern shore of Great Bear Lake is cut by northeast-trending fractures and faults of similar origin. The galena in the diabase is interpreted as being cogenetic with the sulphide mineralization in the mine rather than with the diabase itself. The diabase dyke in the mine was brecciated previous to being mineralized with pitchblende and sulphides.

Anomalous Leads

In previous sections, the term "anomalous galena" has been used when referring to J-type (Joplin-type) galenas (Houtermans, 1953). The same terminology will be used in future sections but for convenience leads which are mixtures of ordinary lead and uranium lead derived from the pitchblende in the veins are also described in this section.

The J-type galenas are rich in uranium leads and in thorium leads and give negative ages. Samples P.R. 41, 87, 90, and 91 are J-type. Two samples, P.R. 3 and P.R. 42, are mixtures of uranium lead and ordinary lead.

Sample P.R. 41 - from No. 5 vein, immediately east of No. 7 vein junction, 550 level; approximately 570 feet below present surface.

Deposition was primarily in open space. Chalcopyrite and sphalerite were deposited on grey dolomite. This was followed by pink to cream, rhythmical-banded hematitic dolomite and then galena. Marcasite appears to be in part younger than galena and in part pseudomorphic after pyrite which is older than chalcopyrite.

Sample P.R. 87 - from the 21 ore shoot, No. 2 vein, approximately 360 feet below the present surface.

Chloritized, carbonatized wall rock fragments are suspended in medium grey, medium crystalline dolomite. Both contain replacements of irregular grains and discontinuous veinlets of sulphides. The sulphides, in order of deposition, are: pyrite, chalcopyrite, sphalerite and galena.

Sample P.R. 90 - from the 34 ore shoot, No. 3 vein, approximately 800 feet below the present surface.

The analysis was run on a few grams of coarse crystalline galena supplied by G. Mursky. It is known only that the galena was associated with carbonate in a veinlet.

Sample P.R. 91 - from 202 east drift, No. 1 vein (250 level east); approximately 220 feet below present surface.

The specimen is a one inch wide, coarse crystalline galena vein associated with dolomite. It came from a collection made early

in the life of the mine and the exact location from which it was derived is not known.

Sample P.R. 3 - from the 34 ore shoot, No. 3 vein, approximately 800 feet below present surface.

Pitchblende replaced an early generation of quartz. This was followed by an extensive deposition of arsenides which closed with the deposition of quartz, in part euhedral. Still later chalcopyrite and tetrahedrite extensively replaced all the earlier minerals. The chalcopyrite and tetrahedrite are intimately intermixed but end-stage deposition of the tetrahedrite appears to have post-dated the chalcopyrite.

Analysed for lead was a mixture of chalcopyrite and tetrahedrite which was apparently free from pitchblende as evidenced by an autoradiograph.

Sample P.R. 42 - from the 21 ore shoot, No. 2 vein, approximately 400 feet below the present surface.

The minerals present, in order of deposition are: carbonate, sphalerite, chalcopyrite, galena and hessite or argentite. The sphalerite-chalcopyrite relationships are indefinite. Two small grains of native silver were observed. Pitchblende occurred nearby in the stope but none is present in the specimen.

Results

The isotopic data is presented in Table 8. Published isotopic data on galena samples is given in Table 9.

The three published analyses by three laboratories on ordinary galena were obtained on portions of the same lead salt,

TABLE 8: Isotopic data on Fort Radium galena samples

Sample No. and Location	<u>Atom Percent</u>			<u>Observed Atom Ratios</u>					
	Pb 204	Pb 206	Pb 207	Pb 206	Pb 207	Pb 208			
<u>Ordinary galenas</u>									
P.R. 26 - Silver Island vein	1.482	23.45	22.79	15.92±.03	1.038±.002	0.447±.001	15.25	15.30	35.41
P.R. 88 - No. 3 North vein	1.478	23.48	22.62	15.88±.03	1.038±.001	0.448±.001	15.30	15.34	35.46
S207 - Diabase, Glacier Bay	1.473	23.42	22.60	15.90±.03	1.036±.001	0.446±.001	15.34	15.34	35.63
<u>Anomalous galenas</u>									
P.R. 41 - No. 5 vein	1.222	27.85	19.64	51.29	22.79±.06	1.418±.002	0.543±.001	16.07	41.97
P.R. 87 - No. 2 vein	1.240	27.87	19.85	51.04	22.48±.04	1.404±.002	0.546±.001	16.02	41.17
P.R. 90 - No. 3 vein	1.218	27.81	19.60	51.38	22.83±.04	1.419±.002	0.541±.001	16.09	42.18
P.R. 91 - No. 1 vein	1.225	27.49	19.68	51.61	22.43±.03	1.396±.001	0.533±.001	16.07	42.12
P.R. 3* - No. 3 vein	0.624	62.39	14.70	22.29	99.95±.25	4.245±.007	2.80±.002	23.54	35.70
P.R. 42 - No. 2 vein	1.435	25.22	22.35	50.99	17.58±.04	1.128±.002	0.495±.001	15.58	35.54

* Sample P.R. 3 is an intergrowth of chalcopyrite and tetrahedrite.

TABLE 9: Published isotopic data on Port Radium galenas

Sample No.	Location	Atom Percent			Atom Ratios			Ref.	
		Pb ²⁰⁴	Pb ²⁰⁶	Pb ²⁰⁷	Pb ²⁰⁶ / Pb ²⁰⁴	Pb ²⁰⁷ / Pb ²⁰⁴	Pb ²⁰⁸ / Pb ²⁰⁴		
Nier No. 1	No. 2 vein surface	1.48	23.59	22.66	52.27	15.93	15.30	35.50	1
Tor. No. 411	(Same specimen)	1.444	23.69	22.60	52.35	16.34	15.65	36.25	2
Lamont No. 4	(Same specimen)	1.464	23.61	22.59	52.34	16.13	15.43	35.75	3
Tor. No. 282	Same specimen as P.R. 91	1.189	28.31	19.79	50.64	23.81	16.64	42.59	4

1. Nier, 1938
2. Russell and Farquhar, 1960.
3. Eckelmann and Kulp, 1957.
4. Cumming et al, 1955.

derived from a No. 2 vein outcrop specimen. The ratio variations, up to about five percent, are therefore an indication of interlaboratory differences. The published analyses are of secondary interest only and cannot be combined with the present data obtained on a still different mass spectrometer.

The data for samples Tor. No. 282 and P.R. 91 gives an additional interlaboratory comparison. These analyses were run on material from the same hand specimen although not representative splits. Tor. No. 282 has not had applied to it a standard correction which the Toronto group recently applied to most of their earlier analyses (Russell and Farquhar, 1960).

Discussion

Graphs of Pb^{206} , Pb^{207} and Pb^{208} normalized to Pb^{204} are shown in Figures 11 and 12. Sample P.R. 3 plots off-scale on the projection of a line joining the ordinary galena samples and sample P.R. 42.

The three samples of ordinary galena, P.R. 26, P.R. 88 and S207 are essentially identical within analytical errors. Despite a great deal of effort by numerous investigators, no model has been developed which will permit precise dating of ordinary galenas. In fact, agreement has not been reached on criteria for distinguishing a so-called ordinary galena from a slightly anomalous galena. The distinction depends on the model chosen. Lack of general agreement is understandable since models must be based on assumptions concerning such basic problems as the sources of the lead, continental development, chemical differentiation in the mantle and crust and the nature of the

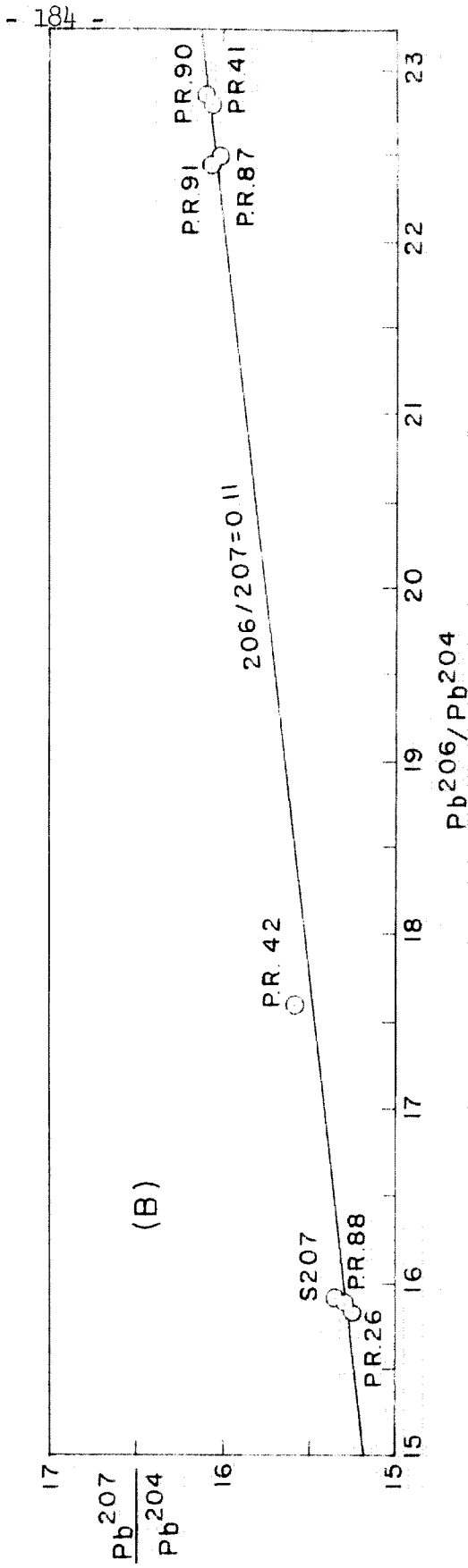
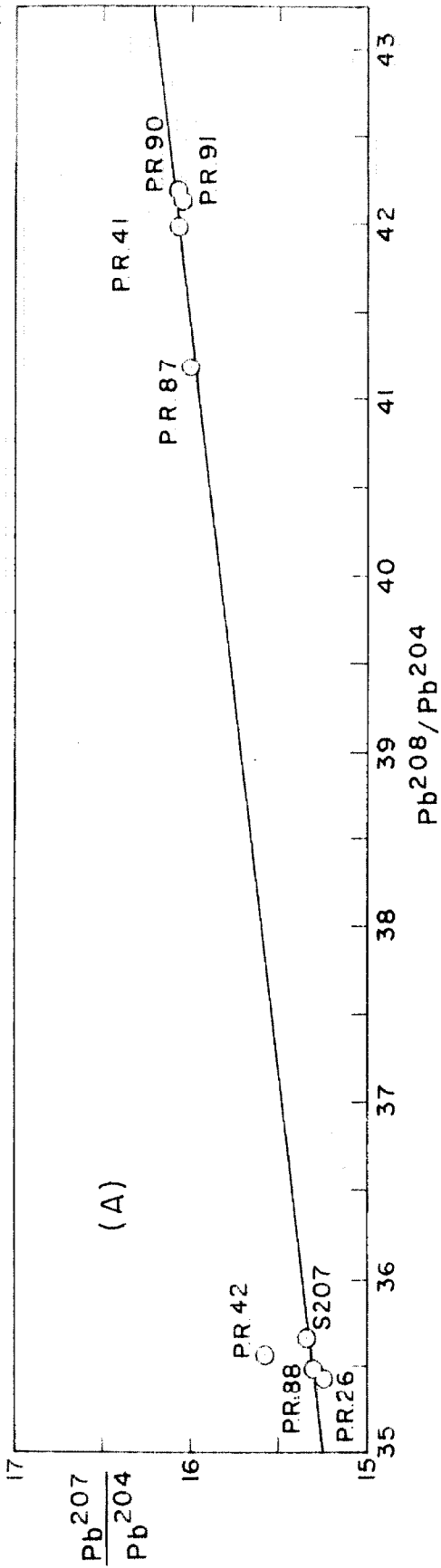


Figure 11: Isotopic composition of Port Radium galenas
 Fig. 11A: Plot of Pb^{207}/Pb^{204} versus Pb^{208}/Pb^{204} . Fig. 11B: Plot of Pb^{207}/Pb^{204} versus Pb^{206}/Pb^{204} .

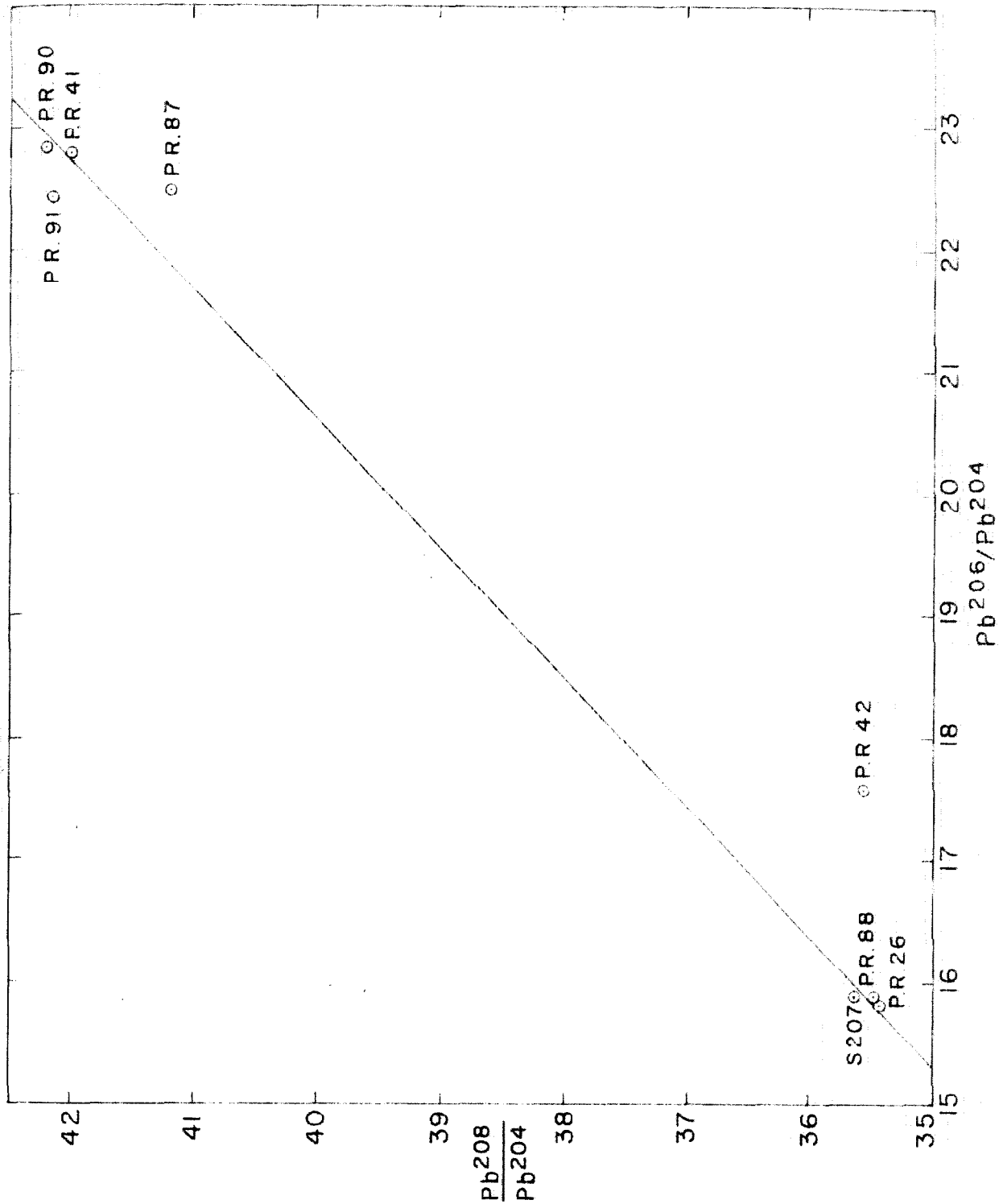


Figure 12: Isotopic composition of Port Radium galenas
Plot of $\frac{Pb^{208}}{Pb^{204}}$ versus $\frac{Pb^{206}}{Pb^{204}}$.

ore-forming process. Investigations of the type reported on and suggested by Patterson and Tatsumoto (In Press), should assist by placing restrictions on model parameters.

Russell and Farquhar (1960) summarized the models developed for dating galenas and presented tables for use in making age calculations. Using these tables, the age of the Port Radium ordinary galena ranges from 1500 to 1700 million years depending on the model chosen. Considering the precision of the method, the age is not grossly incompatible with the known geological history and the other geochronological data. The ordinary galena is younger than the pitchblende and therefore should have a maximum age not in excess of 1450 million years.

For the Holmes-Houtermans model, the present day ratio of U^{238}/Pb^{204} would be approximately 8.6 in the source system.

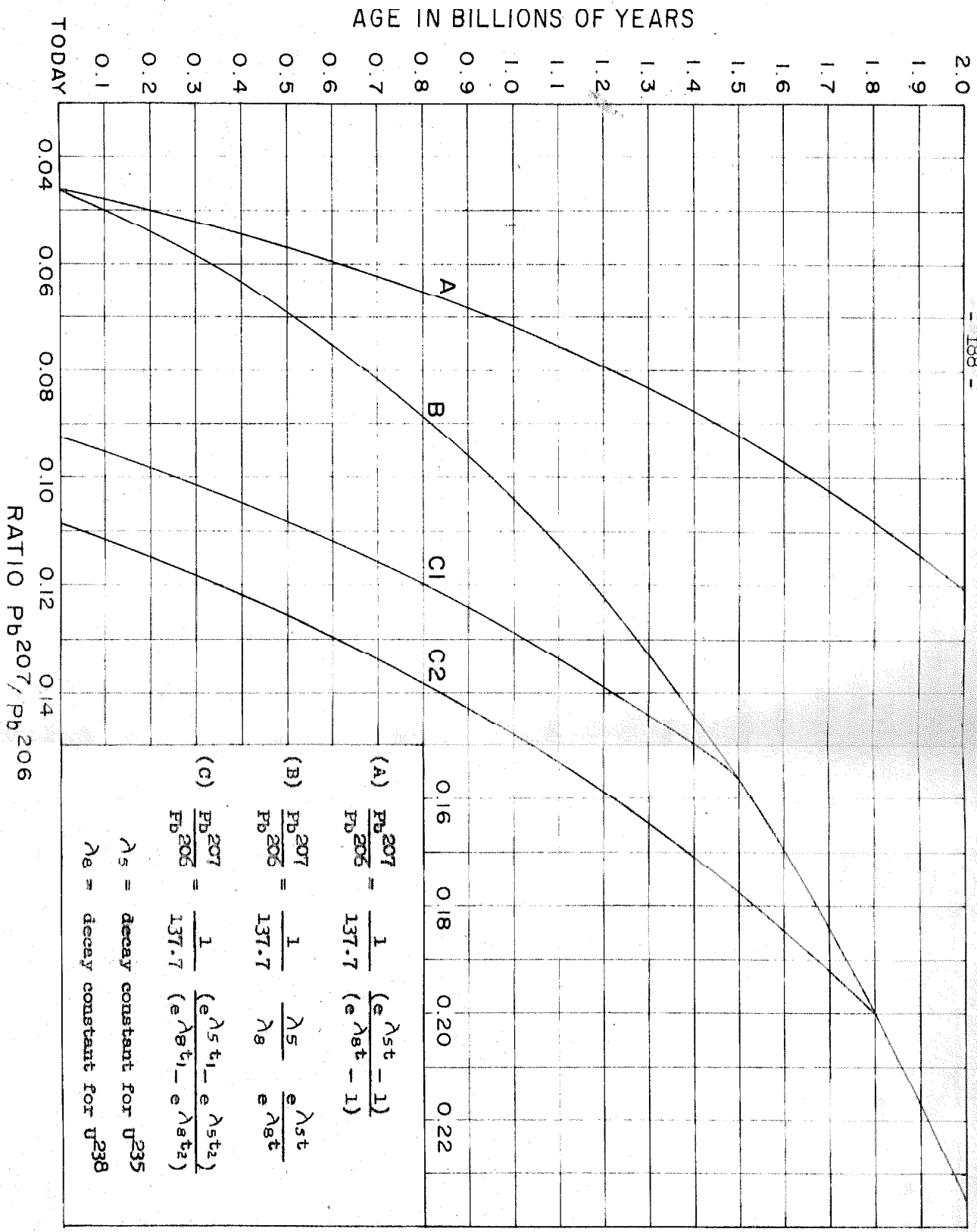
Samples P.R. 3 and P.R. 42 are mixtures of the ordinary lead and radiogenic lead derived from disintegration of pitchblende in the veins. That they are not mixtures of the J-type lead and radiogenic lead is obvious from Table 8. The J-type lead contains an increment of radiogenic Pb^{208} as well as of Pb^{206} and Pb^{207} . Pb^{208} is therefore a valuable index for tracing the J-type anomalous lead in the veins.

For samples P.R. 3 and P.R. 42, the excess Pb^{207}/Pb^{206} ratio are $0.097 \pm .003$ and 0.15 ± 0.04 respectively. In determining these ratios, Pb^{208} was used for the common lead index. The large uncertainty in the P.R. 42 ratio arises from the small absolute value of the increment.

The significance of the increment ratios can be considered either by use of appropriate equations or graphically. The latter

method is chosen here because of the greater ease of visualizing the implications. Aldrich and Wetherill (1958) give examples of this type of graphical treatment using the Concordia diagram. The slope of any line in the Concordia diagram can be given in terms of its Pb^{207}/Pb^{206} ratio. The basic concepts are: (1) The slope of the tangent to the Concordia curve at any time t gives the instantaneous Pb^{207}/Pb^{206} production rate for that time; (2) The slope of a chord between any two times t_1 and t_2 on the Concordia curve gives the cumulative Pb^{207}/Pb^{206} production ratio for the period t_1 to t_2 ; (3) From (2) it follows that the slope of a chord between any time t and the origin gives the integrated Pb^{207}/Pb^{206} production ratio to the present and hence the Pb^{207}/Pb^{206} age for an unaltered mineral t years old. Aldrich and Wetherill pointed out that since different scales are generally used for plotting the abscissa and ordinate, this must be taken into account when determining the Pb^{207}/Pb^{206} slope. They did not, however, point out that when the Concordia curve is plotted convex downward as is usual, the Pb^{207}/Pb^{206} ratio gives the reciprocal to the conventional slope. Thus, lines having lower Pb^{207}/Pb^{206} ratios have higher conventional slopes in the diagram. (In Aldrich and Wetherill's Fig. 13, p. 290, the chords are incorrectly labelled, the steepest line being shown as having the highest ratio.)

Since the slopes of lines in the Concordia diagram cannot be readily determined without using tables, Figure 13 has been prepared. This figure was prepared with the aid of values given by Stieff et al (1959). In it, Pb^{207}/Pb^{206} atom ratios plotted against time show: the integrated ratios to the present; the instantaneous production ratios; and cumulative production ratios originating from two arbitrarily



(A) $\frac{Pb^{207}}{Pb^{206}} = \frac{1}{137.7} \frac{(e^{\lambda_5 t} - 1)}{(e^{\lambda_8 t} - 1)}$

(B) $\frac{Pb^{207}}{Pb^{206}} = \frac{1}{137.7} \frac{\lambda_5}{\lambda_8} \frac{e^{\lambda_5 t}}{e^{\lambda_8 t}}$

(C) $\frac{Pb^{207}}{Pb^{206}} = \frac{1}{137.7} \frac{(e^{\lambda_5 t_1} - e^{\lambda_5 t_2})}{(e^{\lambda_8 t_1} - e^{\lambda_8 t_2})}$

$\lambda_5 =$ decay constant for U^{235}
 $\lambda_8 =$ decay constant for U^{238}

Figure 13: Growth curves for atom ratio Pb^{207}/Pb^{206} . A. Integrated ratio to the present. B. Instantaneous ratio at any time in the past. C. Cumulative ratio between times t_1 and t_2 in the past. For curve C1, t_1 is 1.5 billion years; for curve C2, t_1 is 1.8 billion years. Curves derived from values in tables of Stieff, et al (1959).

selected times. The curves shown for the cumulative production ratios are two of an infinite family of curves.

Sample P.R. 42 has a Pb^{207}/Pb^{206} increment ratio of $0.15 \pm .04$. From Figure 13, 0.15 is the instantaneous production ratio 1450 million years ago. A reasonable interpretation is that the ordinary lead was introduced into the veins within a few tens of millions of years after the pitchblende and became mixed with initially produced radiogenic lead. The imprecision in the value 0.15 would, however, permit mixing of ordinary lead with cumulative radiogenic lead produced from 1450 million years down to a minimum of 750 million years. In the latter case, the time of ordinary lead mineralization and the time of mixing need not be the same. The uranium concentration in P.R. 42 was not measured. It is probably small because the sample was drilled from an area of galena in a field containing no microscopically visible pitchblende. If any were present, it would contribute radiogenic lead having a Pb^{207}/Pb^{206} ratio of 0.09 - the integrated ratio from 1450 million years to the present. The net effect would be to raise the minimum age of 750 million years given above and thus shorten the time interval over which ordinary lead introduction and mixing could take place.

For Sample P.R. 3, the ratio of the Pb^{207}/Pb^{206} increment is 0.097 ± 0.003 . Although the sulphides in the sample were thought to be free of pitchblende based on an autoradiograph, a later alpha-activity count showed some uranium to be present. Thus, the radiogenic lead contains a portion which is directly supported. The measured ratio, 0.097, is so close to the ratio 0.09 for a 1450 million year old mineral that severe restrictions are placed on deductions. If the

difference between the values is real as it apparently is, the lead is a three-component mixture. As an example, it could be composed of 43 percent ordinary lead, 50 percent directly supported radiogenic lead and seven percent radiogenic lead having a Pb^{207}/Pb^{206} ratio of 0.15 - the latter from the 0.15 value for P.R. 42. On the other hand, a mixture of ordinary lead and radiogenic lead produced down to the relatively recent past could produce the observed ratio. There can be no unique interpretation to this data. However, it must be emphasized that samples P.R. 3 and P.R. 42 are not mixtures of J-type lead and another lead as evidenced by the Pb^{208}/Pb^{204} ratios.

Finally to be considered is the anomalous J-type lead which has all three radiogenic isotopes added to common lead. It is improbable that the mixing took place within the Port Radium veins. It occurred more likely in a body of rock relatively near the earth's surface and in which the U^{238}/Pb^{204} and Th^{232}/Pb^{204} ratios were higher than in the original source area for the ordinary lead.

The Pb^{207}/Pb^{206} ratio of the increment for the anomalous lead is 0.11 ± 0.01 . The value 0.11 is the instantaneous production ratio for lead 1050 million years ago (Fig. 13) which age then becomes the maximum for introduction of the anomalous lead into the Port Radium veins. The source from which the lead was derived, however, could have been and undoubtedly was older than 1050 million years. In this case, the time of introduction would have been less than 1050 million years, because the older the source rock, the younger must be the time of mineralization. Any chord having a slope of 0.11 on the Concordia diagram, Figure 9, could approximately define at its upper intersection

the age of the source rock and at its lower the time of mineralization. Since a 0.11 slope chord through the origin intersects the Concordia at 1825 million years, the latter is the approximate maximum age for the source rock. The Echo Bay group strata and/or the granitic rocks are the most probable source rocks unless the lead migrated downwards. It is possible that the J-type galena was introduced at the same time as the diabase sill whose age is known only to be younger than the pitchblende.

For the immediate source area of the J-type galena, a Th/U ratio of approximately 3.2 is indicated by the Pb^{208} to Pb^{206} radiogenic increment. If the age of this source rock was approximately 1800 million years, the U^{238}/Pb^{204} ratio in it would have been about 22 which is not unreasonable for a granitic body. For younger source rocks, the U^{238}/Pb^{204} ratio would increase reaching an extremely high value of about 400 for an 1100 million year old source, assuming that the anomalous lead is representative of the total source-rock lead. This fact tends to favor an older age for the source rock and hence a younger time of introduction of the anomalous lead.

It appears to be quite important that the J-type lead shows a limited range of composition with no evidence of a significant mixing with either the ordinary lead or the substantial amounts of radiogenic lead which must have been present in the ores at the time of its emplacement. Thus it appears that the J-type lead must have been emplaced after those processes which disturbed the uranium-lead systems in the ores, and by a process which did not significantly mingle with the ordinary lead systems distributed through the veins.

CONCLUDING DISCUSSION

The integration of a study of the uranium and lead isotopic relations with the structural and mineralogical studies of the district has provided an unusual basis for discussion of the origin and history of the Port Radium pitchblende deposit and their geological setting. The present work is by no means all-inclusive and it is apparent that there are a number of extensions of this type of investigation which might be valuable. In the following statement, the salient results and some possible directions for additional work are presented.

The 1820 million year age for the granite places a minimum age on the Echo Bay group, including the hypabyssal feldspar porphyry bodies, and on the Cameron Bay group. Since the Snare group has been correlated with the Echo Bay group, it may also place a minimum age on that group. During Echo Bay time, the McTavish Arm area was a hornblende andesite-dacite province, possibly abnormally rich in sodium. Accumulation of dominantly tuffaceous sedimentary rocks was followed by accumulation of volcanic flows. The major metamorphic effects observed in Echo Bay group rocks were probably caused by granitic intrusions following intrusion of the hypabyssal porphyry bodies.

The "giant quartz veins" and some of the diabase dykes of the region are bracketed by the 1820 million year age for the granite and the 1450 million year age for the Port Radium pitchblende. Diabase dykes probably related to those at Port Radium cut the Hornby Bay group which rests unconformably on granite. One such dyke is a feeder to a differentiated ultrabasic intrusive, called the Muskox Complex,

approximately 80 miles northeast of Port Radium. The Geological Survey of Canada (1961) obtained a 1155 million year age on a biotite separate from that Complex and concluded that this was then a minimum age for the Hornby Bay group. If, as suggested here, the feeder diabase is correlative with the dykes at Port Radium, then the Hornby Bay group is at least 1450 million years old. Collaborating evidence for this comes from unpublished data by Dr. L. T. Silver who has kindly given permission for its use here. On an apatite separate from a granophyric differentiate of the Muskox Complex, Dr. Silver obtained a Pb^{207}/Pb^{206} age of 1500 ± 100 million years. The diabase dykes in the mine at Port Radium may not be much older than the pitchblende. The vein structures had already formed at the time of their intrusion.

Six stages of metallic and non-metallic mineral deposition are recognized in the formation of the Port Radium veins. Three periods of wall rock alteration are correlative with episodes of vein mineralization. Localization of pitchblende is attributed to physical rather than chemical causes. Pitchblende, associated with quartz, was one of the earliest minerals deposited. The isotopic data obtained on the only carbonate-gangue specimen analysed does not substantiate or preclude a second generation of pitchblende.

In general, Port Radium pitchblende samples show evidence of substantial past loss of lead. Most of this mobile lead has been removed from the vein systems. If uranium losses have occurred they have always been exceeded proportionally by lead loss. The only concordant ages obtained were for selected microscopic (pin-hole) samples of the pitchblende in carbonate gangue. A comparison of isotopic data for microscopic and macroscopic samples from the same

specimen suggests that selected microscopic samples can be and may be consistently less discordant. Analyses of a number of lead-uranium systems in the same specimen may make possible the determination of the absolute age of mineralization and the time of an episodic disturbance. However, studies of this type must take into consideration the problems of sampling.

Following the deposition of the pitchblende 1450 million years ago, there is a negligible record of geologic activity in the McTavish Arm area for an interval of nearly one billion years. The diabase sill at Port Radium was intruded after the pitchblende and was later fractured and mineralized with minor quantities of quartz, carbonate, chlorite and hematite. Similar veinlets cut the other rock types and the Port Radium veins. A minimum age for the diabase sill cannot be established from the existing isotopic data.

On geologic evidence, the ordinary galena was probably deposited with the majority of the other vein minerals shortly after the pitchblende. It is finely disseminated in pre-existing vein minerals suggesting that the solutions transporting ordinary galena permeated the veins. Locally, it may be mixed with radiogenic lead derived from the pitchblende, but generally it appears free of mixing. The J-type galena occurs associated with simple sulphides in late, lenticular veinlets in the main veins. There is no evidence for significant mixing of the J-type galena with radiogenic lead from the pitchblende even where there is a close spatial association. A reasonable calculation of the maximum age for its emplacement is approximately 1050 million years. A maximum age for its source rock system is calculated to be about 1825 million years, which suggests

the associated granite (and possibly the wall rocks) as a reasonable source. J-type galena was probably introduced at a time of fracturing and at a time when hydrothermal solutions were not sufficiently active to mix completely with lead already present. The cause of the fracturing is conjectural. It could have been attendant with warping accompanying burial or erosion or with intrusion of the diabase sill. In any event, the J-type galena was apparently introduced after loss of significant quantities of radiogenic lead from the pitchblende ores. Otherwise, one would expect to find leads composed of mixtures of radiogenic lead and J-type lead.

A number of independent lines of isotopic evidence suggest late Paleozoic or Mesozoic influence on the Precambrian isotopic systems. The lines of evidence include: disturbance of the lead-uranium systems in the granite zircons; loss of lead possibly 300 million years ago from some of the pitchblende; introduction of J-type lead after loss of lead from the pitchblende; and restrictions placed on the age of the source rock for the J-type lead by the Pb^{207}/Pb^{206} increment and the U^{238}/Pb^{204} ratio. A source rock for the J-type galena approaching the geochemical character of the granite or possibly the tuffaceous rocks is indicated by the U^{238}/Pb^{204} ratio restriction, and for such an old source rock a young age of separation of the lead is required. These data thus provide evidence for activity of a process whose character is otherwise unknown since no independent geological evidence has pointed to its existence. The most reasonable interpretation suggests this activity occurred within the last 200 - 300 million years.

Confirmation and elaboration of these interpretations might

be sought by additional isotopic investigations in the ores and wall rocks of the district. Sulphides other than galena probably contain most of the ordinary lead in the veins. Further lead isotopic study of these sulphides might yield clarifying information on times of mineralization and on times of pitchblende disturbance. Samples of sulphidized wall rocks should be included for analyses. Additional work on microscopic samples of pitchblende from the same specimen is definitely warranted. Attention should be paid in particular to obtaining microscopic samples differing markedly in degree of discordance. An isotopic study of zircon, biotite and common lead in the tuffaceous rocks and hypabyssal porphyry bodies might give information on the times of sedimentation and metamorphism. If possible, an attempt should be made to date the diabase sill directly.

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APPENDIX A

Laboratory Procedures

A. Zircons

The procedure for preparation of zircon concentrates are essentially those reported by Silver and Deutsch (in press). The main steps are:

- (1) Reduction of rock to passed 50-mesh size by crushing and pulverizing;
- (2) Preliminary concentration on Wilfley table;
- (3) Treatment in heavy liquids, first in s-Tetrabromoethane (density 2.96) and then in Diiodomethane (density 3.33);
- (4) Sizing on 100, 200, 325 and 400-mesh screens after first removing magnetics with a hand magnet;
- (5) Concentration of zircons in each size fraction with a Frantz electromagnetic separator;
- (6) Removal of pyrite either by roasting over a Bunsen burner and re-processing on the Frantz separator or by acid washing as below;
- (7) Acid washing of all concentrates for one hour in concentrated HNO_3 maintained just below the boiling point;
- (8) Hand-picking of remaining impurities normally totalling less than 1% at this stage;
- (9) Alpha-particle counting of a pulverized, representative reaction;
- (10) Chemistry for extraction of lead and uranium either on the total zircon concentrate or on a representative fraction.

The standard chemical procedure employed was that of Tilton et al (1955) as modified by Silver et al (1963). Steps in the chemical procedure are:

(1) Fusion of zircon in J.L. Smith platinum crucible using approximately ten times the weight of sodium tetraborate flux as the weight of the sample;

(2) Solution of fused sample in steps in warmed evaporation tank with a total of about 100 ml. of 2N HCl;

(3) Centrifugation of solution and digestion of silica residue in a platinum crucible with HF and HClO₄. Dissolution of new residue in 15 ml. of 6.5N HCl and addition of this to original supernate;

(4) Dilution to 250 ml., extraction of lead for composition determination on 70% fraction and spiking of remaining 30% with U²³⁵ and Pb²⁰⁸ rich tracers for concentration determinations. Smaller fraction again split for separate extraction of lead and uranium;

(5) Extraction of lead from the solutions in separatory funnels is as follows (reagent quantities are approximate and are for the larger, composition aliquot, somewhat smaller quantities being used for the spiked aliquot):

(a) Addition of 20 ml. 25% ammonium citrate and 2 ml. 2% KCN; pH adjusted to 9 with NH₄OH; lead extracted with a 20 ml. solution of dithizone in chloroform;

(b) Lead stripped from dithizone layer with 35 ml. dilute HCl;

(c) Repeat of step (a) in clean separatory funnel using

about one half the reagent quantities;

(d) Evaporation to dryness of dithizone layer and digestion of lead dithizonate residue with 15 - 20 drops each of concentrated HNO_3 and HClO_4 ;

(e) Final residue dissolved in 1/2 ml. of 1/2% NH_4NO_3 solution, transferred to one ml. centrifuge cone; lead sulphide precipitated with H_2S , collected by centrifuging and loaded on a tantalum filament for the mass spectrometric determination;

(6) Uranium extraction procedure is as follows:

(a) Addition to aliquot of one ml. $\text{Al}(\text{NO}_3)_3$ and sufficient 20% NH_4OH to neutralize; centrifuge; discard supernate;

(b) Solution of precipitate in 10 ml. concentrated HNO_3 and transferring to a separatory funnel;

(c) Addition of 30 ml. $\text{Al}(\text{NO}_3)_3$, stripping of aqueous phase with 45 ml. hexone and back-stripping of hexone phase with 45 ml. of quadruple-distilled water;

(d) Evaporation of this aqueous phase to 10 ml., addition of 20 ml. saturated NH_4NO_3 and second stripping in a separatory funnel with 20 ml. of hexone;

(e) Second back-stripping of hexone layer with 30 ml. of 2N HCl; evaporation to dryness of aqueous layer;

(f) If residue dark brown rather than light brown or yellowish, addition of few drops concentrated HNO_3 and re-evaporation to dryness before proceeding with (g);

(g) Solution of residue in a drop of concentrated HNO_3 and pipetting onto a tantalum filament.

B. Pitchblende

The pin-hole pitchblende samples were dissolved in approximately 10 ml. of concentrated HNO_3 , allowed to stand for about one hour in a heated evaporation tank, transferred to a 250 ml. volumetric flask and diluted to volume. Spiking and the extraction of lead and uranium followed the same procedures as for the zircons. Lead composition and lead and uranium concentration data was obtained on all pin-holes.

Treatment of pitchblende chip-samples was:

Sample P.R. 33 (Carbonate sample): - The chip was placed in a teflon beaker, concentrated HNO_3 was added and the beaker was placed in a warmed evaporation tank. After 24 hours, the solution was centrifuged and a lead-uranium analysis (C4) run on an aliquot of the supernate. The residue was treated with HF and HClO_4 and eventually evaporated to dryness. A portion of this new residue failed to stay in solution in either HNO_3 or HCl. The solution was centrifuged and an aliquot of the new supernate analysed isotopically (C5). An aliquot of the remaining precipitate, which was highly radioactive due to concentration of uranium daughter products, was fused with borax spiked with U^{235} and Pb^{208} and analysed isotopically (C6).

The treatment of each aliquot was the same as for the zircons and pin-hole samples. For analysis C6, the lead composition data from analysis C5 was used. All reagents used were purified. The total quantities used were approximately: concentrated HNO_3 - 200 grams; 10N HCl - 200 grams; 52% HF - 65 grams; HClO_4 - 20 grams;

Sample 013 (Siliceous sample): - The chip was broken into pea-sized fragments and treated with concentrated HNO_3 . The residue

from this was treated with HF and HClO_4 and evaporated to dryness. This new residue was dissolved in HCl and the solution added to the HNO_3 solution. A single aliquot of this composite solution was analysed isotopically (C8).

Total reagents used were approximately: concentrated HNO_3 - 220 grams; 10N HCl - 120 grams; 52% HF - 120 grams; HClO_4 - 40 grams.

Despite the large quantities of reagents used for the chip samples, the lead proved to be very radiogenic. Chemical treatment of the chip samples, up to the point of extraction of lead and uranium from final small aliquots, was carried out in an area separate from the contamination control laboratory.

C. Galenas

For each isotopic analysis, a single grain of galena was selected from a powdered sample using a binocular microscope. The grain contained on the order of 50 micrograms of lead. Chemical treatment followed a procedure formerly in use by Dr. C. C. Patterson, of the California Institute of Technology:

- (1) Dissolution of galena in 10 ml. 6.5N HCl, evaporation to dryness and solution of residue in 10 ml. 1% HNO_3 ;
- (2) Addition of 2 ml. of KCN solution (1 gm. KCN in 100 ml. 10% NH_4OH) and adjustment of pH to 8 with NH_4OH ;
- (3) Extraction of lead with 10 ml. of a dithizone in chloroform solution and back-stripping with 10 ml. of 1% HNO_3 ;
- (4) Repeat of steps (2) and (3), evaporation to dryness and preparation of lead sulphide as for the zircon samples.

For sample P.R. 3, the only non-galena sample treated, the

lead was extracted from 0.62 grams of intergrown chalcopyrite and tetrahedrite. The sample was crushed to a maximum particle size of two mm. and given a mild, 10 minute wash with dilute HNO_3 to remove tarnish from original fracture surfaces. It was then dissolved in HNO_3 and lead extracted as for the zircon samples.

APPENDIX B

Historical Summary of the Port Radium Mining Operation

The closure of the Port Radium mine in September of 1960, due to depletion of ore reserves, brought to an end an important chapter in the exploitation of radioactive deposits. Discovered in 1930 by G. A. LaBine and E. C. St. Paul, the deposit provided sufficient radium to break Belgium's world-wide monopoly on new stocks of that element. During and after the Second World War, it provided important quantities of the suddenly strategic element, uranium.

The mine operated continuously from 1932 until 1960 except for the period 1940 to 1942. Disruption of radium markets caused by the Second World War resulted in the mine being closed in the spring of 1940. In 1942, it was quietly re-opened at the request of the United States Government which was by then engaged in the Manhattan Project. Two years later, the shares of the company were purchased by the Canadian Government as a security measure and the name of the company was changed from Eldorado Gold Mines Limited to Eldorado Mining and Refining Limited. Now that the mine is closed, the time is opportune to set down some of the highlights of its 30 year history.

Transportation

In 1930, it was by no means obvious that so isolated a deposit could be successfully exploited. Previous to that time, very few aircraft had ever penetrated the Great Bear Lake region, and, although there were limited facilities for transporting materials on the Mackenzie River, no attempt had been made to extend the route up

the fast-flowing Bear River and across Great Bear Lake. To complicate matters, the water routes were ice-bound for nine months of the year.

Water transportation graduated from 10 ton capacity scows to 400 ton capacity barges and air transport from single engine bush planes to multi-engine cargo planes capable of carrying 10 ton payloads. The use of better equipment and the application of modern freight-handling techniques resulted in reduction of water rates from 20 cents to 3 3/4 cents per pound and of air rates from 85 cents to 8 or 9 cents per pound. The latter rate is equivalent to approximately 20 cents per ton-mile for the 930 mile distance from Edmonton to Port Radium.

Mining

The veins were developed from a three-compartment vertical shaft, called the No. 1 shaft, collared in the hanging wall of No. 2 vein and eventually deepened to 1300 feet. Levels were established at intervals of 125 feet except for two intervals which were 150 feet. The depth under development was increased in 1952 when a vertical winze, collared on the 1175 level* 2400 feet northeast of No. 1 shaft, was sunk adjacent to No. 2 vein. This permitted exploitation of the deposit down to the 1675 level which is approximately 1750 feet below the surface.

During the life of the mine, two additional shallow surface shafts were sunk northeast of No. 1 shaft but these did not contribute significantly to the total production.

* The name given to each level corresponds to its approximate distance in feet below the adit level. The levels are: adit, 125, 250, 375, 500, 650, 800, 925, 1050, 1175, 1300, 1425, 1550, and 1675.

Total development figures for the mine are:

Shaft sinking	2,437 feet
Lateral	135,664 feet
Raising	44,755 feet
Diamond drilling	500,000 feet (minimal estimate)

Permafrost in the mine extended to depths up to 350 feet.

Below the permafrost zone, the veins were generally saturated with water. Flows once opened, were difficult to control and endangered the existence of the mine. As a result, the lower levels were developed by line-driving parallel to and 30 to 40 feet from the veins. Ore sections outlined by diamond drilling were further drilled and then sealed by grouting with cement before stoping commenced.

The major portion of the ore was mined by standard cut-and-fill methods using development waste for back-fill. This system best suited the general conditions of unstable vein walls and erratic ore shoot boundaries.

Ore Treatment

Late in 1933, a gravity concentration plant with a capacity of 50 tons per day was put into operation. By 1940, the capacity had been increased to 125 tons per day and by 1950 to its ultimate capacity of 170 tons per day.

Pitchblende was concentrated primarily with jigs and tables. In the 1930's, copper-silver flotation concentrates were produced in addition to pitchblende and pitchblende-silver gravity concentrates.

It was not possible to increase U_3O_8 recovery in the gravity plant much beyond 75 percent and still maintain an acceptable concentration ratio. This led to research on leaching of the ores

and culminated in the construction at Port Radium in 1952 of a 300 ton per day acid leach plant which used sulphuric acid produced locally from elemental sulphur. This plant treated both current gravity plant tailings and reclaimed tailings from earlier operations. The earlier tailings although dumped into Great Bear Lake had fortuitously settled in a 90 foot deep depression along the trace of No. 1 vein where it crosses from the mainland to Cobalt Island. Almost 100 percent of the tailings were recovered with a dredge which operated continuously from 1952 until 1960. In all, the dredge recovered 340,000 tons averaging 0.28% U_3O_8 .

Basically, the leaching process involved oxidation by sodium chlorate, leaching with sulphuric acid and, following reduction with powdered aluminum, precipitation of uranous arsenates and/or phosphates. It was not necessary to add arsenic or phosphorous-bearing compounds to the process as these elements are indigenous to the ores. In 1958, the precipitation portion of this process was superseded with a solvent extraction process using amine and diesel oil. The net result was an increase in uranium recovery from 98 percent to 99.8 percent and an increase in the grade of precipitate from approximately 45 percent to 81 percent.

Because up to 7 tons of chemicals were required for each ton of concentrate refined, the refining plant was built near industrial centers, at Port Hope on Lake Ontario. The process was perfected by the Mines Branch in Ottawa. The refinery went into operation in January of 1933 treating, initially, ore hand-cobbed in the summers of 1931 and 1932 from surface pits at Port Radium. Capacity, at first only a few hundred pounds per day, was gradually

increased to process: (1) increased production from Port Radium; (2) part of the production from the Shinkolobwe deposit during the Second World War and; (3) part of the production from new Canadian uranium mines which commenced operations in the 1950's. It is still the only uranium refinery in Canada and turns out numerous products including uranium metal.

Production

Primarily because of pre-World War II suppression of radium production data and Government-imposed wartime and post-war secrecy on uranium production, complete production data for Port Radium is not available. The data presented here, is believed, however, to be reasonably accurate. It has been pieced together from available company files, from published reports and from data published in trade journals. In addition Messrs. H.E. Lake, R.C. Powell, and R.M. Berry, all Eldorado officers, provided valuable information.

High transportation costs precluded active exploitation of the deposit for elements other than uranium, radium and silver. Uranium and radium occurred in the mineral pitchblende. Up until 1942, radium was the chief product and uranium the by-product. Thereafter, their roles were reversed. Radium was not recovered after about 1950 because of economic competition from artificial radioactive isotopes. Silver occurred primarily as the native element, associated with pitchblende, in near-surface ore shoots on No. 2 vein. These were largely exhausted by 1939 and, thereafter, silver was of little importance.

The estimated uranium production is given below:

Gravity Plant

Ore treated (mined)	1,100,000 tons
Average grade	0.68% U_3O_8
Content	14,920,000 lbs. U_3O_8
Production	9,590,000 lbs. U_3O_8
Average Recovery	64.3%

Leach Plant

Tailings treated	800,000 tons
Production	4,040,000 lbs. U_3O_8

Total (Concentration Plants)

Production	13,630,000 lbs. U_3O_8
Overall recovery	91.4%

Refinery

Production	12,825,000 lbs. U_3O_8
Average recovery	94.1%
Average recovery based on lbs. U_3O_8 mined	86.0%

The figures do not include approximately 90,000 lbs. of U_3O_8 concentrated by hand-cobbing in surface pits. For the later years, recoveries exceeded 99 percent in both the leach plant and refinery.

The 15,010,000 pounds of U_3O_8 (including the hand-cobbed production) present in the ore extracted from the deposit contained approximately 1920 grams of radium*. As a result of process losses and of the change in emphasis from radium to uranium extraction, only about 450 grams of this were recovered. Total free-world production up to 1950 was possibly 2000 grams and to 1960, 3000 grams.

* Based on 0.128 mg of radium per pound of U_3O_8 - the ratio which was established for the deposit in the 1930's. This is approximately 98% of the theoretical radium content under equilibrium conditions.

An estimated 1,500,000 ounces of silver were recovered. The deposit probably contained in excess of 3,500,000 ounces; some remains unmined. Gravity plant losses of silver were high in as much as optimum conditions for recovering pitchblende were not optimum for recovering silver.

Some copper in the form of copper-silver flotation concentrates and very minor cobalt were recovered in the late 1930's. However, the most important source of production of miscellaneous elements was the pitchblende gravity concentrates in which other heavy minerals were unavoidably concentrated. Total production of miscellaneous elements is estimated as follows:

Cu	-	250 tons metal
Co	-	250 tons metal
Ni	-	140 tons metal
Pb	-	110 tons metal
Po	-	1000 microcuries
RaD(Pb ²¹⁰)		1500 microcuries (by extraction from old radium sources.)

The copper occurs primarily as chalcopyrite, the cobalt and nickel as arsenides and the lead as the disintegration product of uranium. Native bismuth also occurs in the ores but there is no record of any having been marketed.

An estimated breakdown of the total revenue is:
uranium - 91% plus; radium - 7%; others - less than 1.5%.

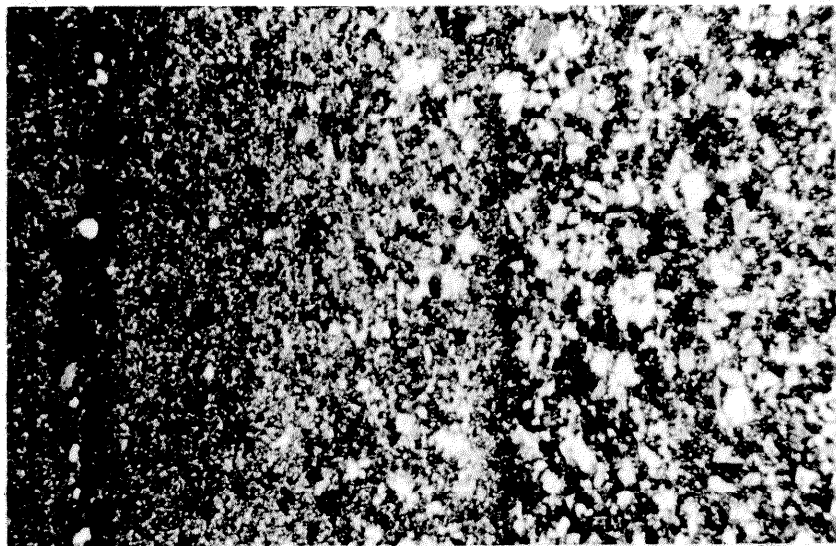
APPENDIX C

Explanation of Plates

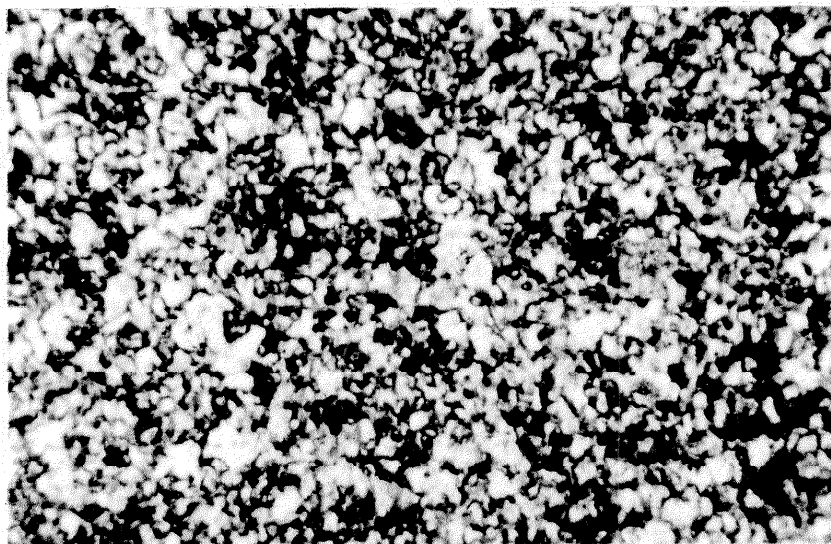
All plates are photomicrographs unless indicated otherwise.

The plates are grouped as follows:

	<u>Plates</u>	<u>Pages</u>
1. Host rock textures and structures	1 - 7	216-222
2. Pitchblende and associates	8 -20	224-236
3. Arsenide minerals and associates	21-26	238-243
4. Sulphide minerals and associates	27-32	245-250
5. Non-opaque vein minerals	33-35	252-254
6. Dendritic structures in the veins	36-42	256-262
7. Wall rock alteration minerals	43-48	264-269
8. Specimens analysed isotopically	49-53	271-275

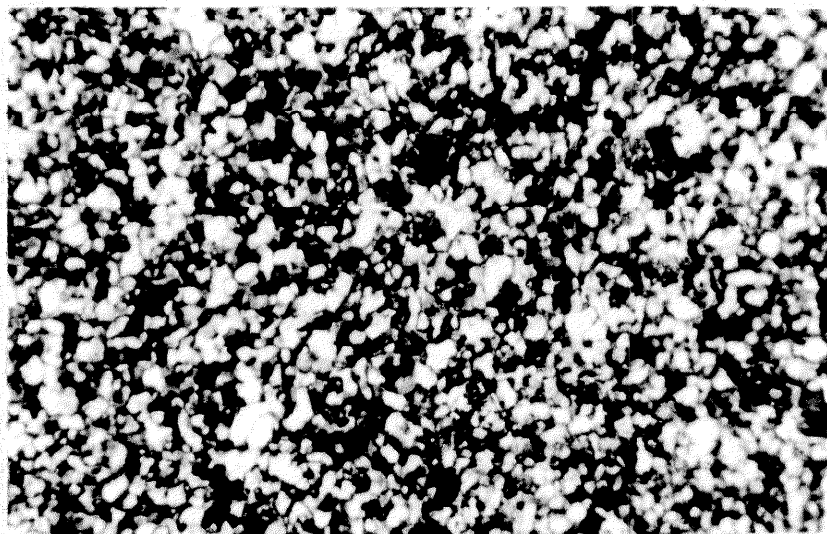


1A

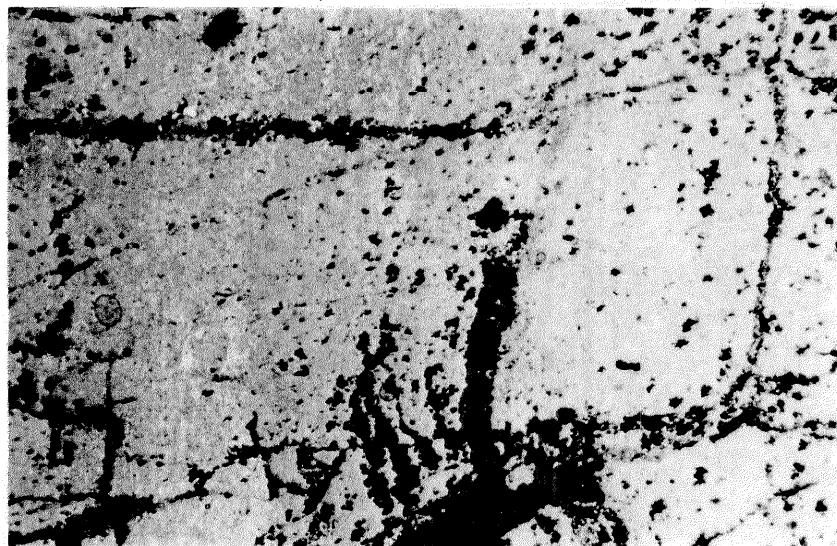


1B

- 1A. Excellent but unusual example of graded bedding in Mine series tuffs. Composed of albite and finely disseminated magnetite, carbonate and chlorite. Crossed nicols. Outcrop specimen, north of No. 3 vein. x10.
- 1B. Typical texture of Mine series bedded tuff. Albite is the only mineral present. Crossed nicols. Outcrop specimen, north of No. 1 vein. x135.

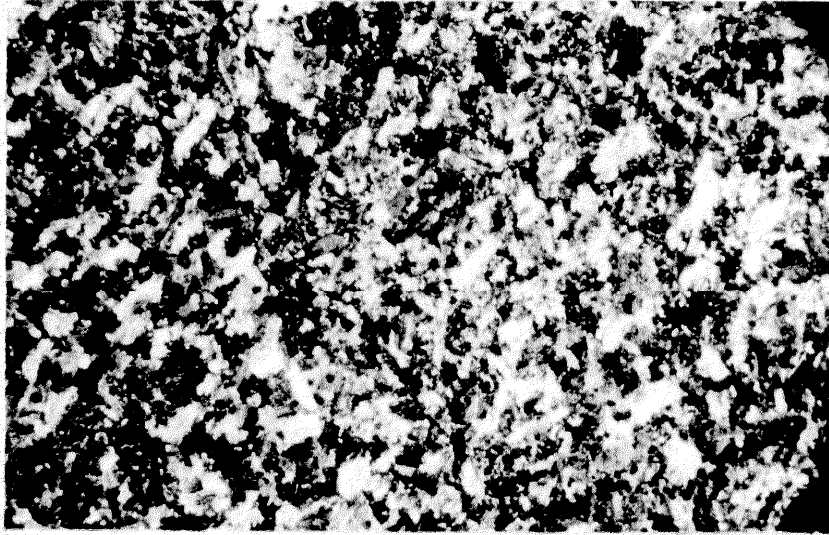


2A

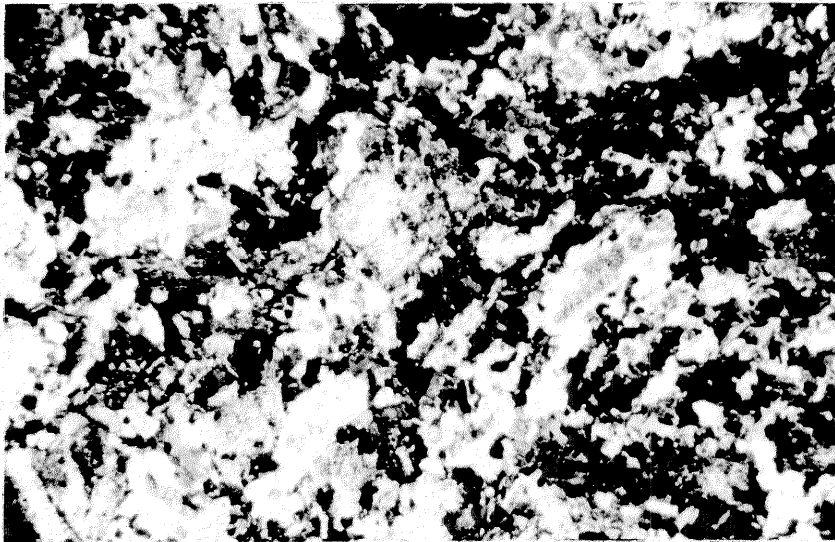


2B

- 2A. Example of intermixed quartz (most of white grains) and albite in Mine series tuffs. Grains possibly slightly more rounded than those in Plate 1B. Albite stained using method of Bailey and Stevens (1960). Crossed nicols. Outcrop specimen, north of No. 2 vein. x135
- 2B. Best observed example of interlaminated quartz (light grey) and albite (medium grey) in Mine series tuff. Albite stained. Dark mineral is predominantly diopside. Outcrop specimen, south of No. 2 vein. x10

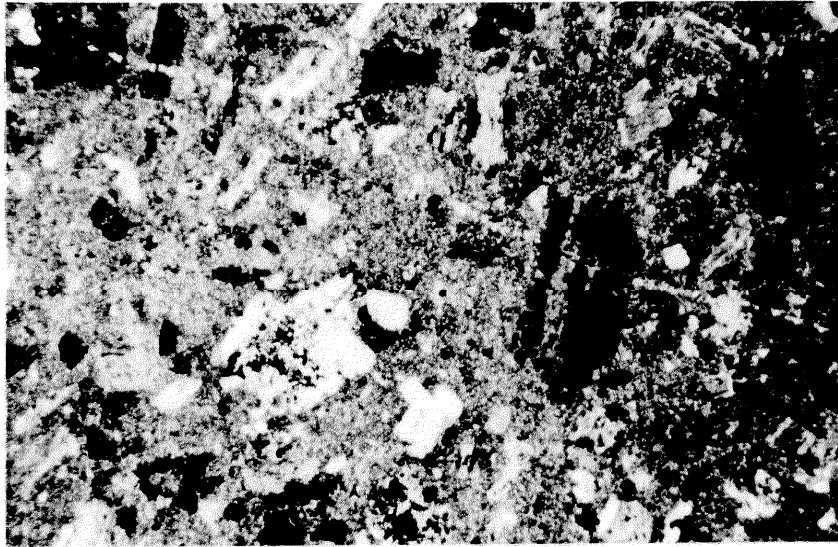


3A

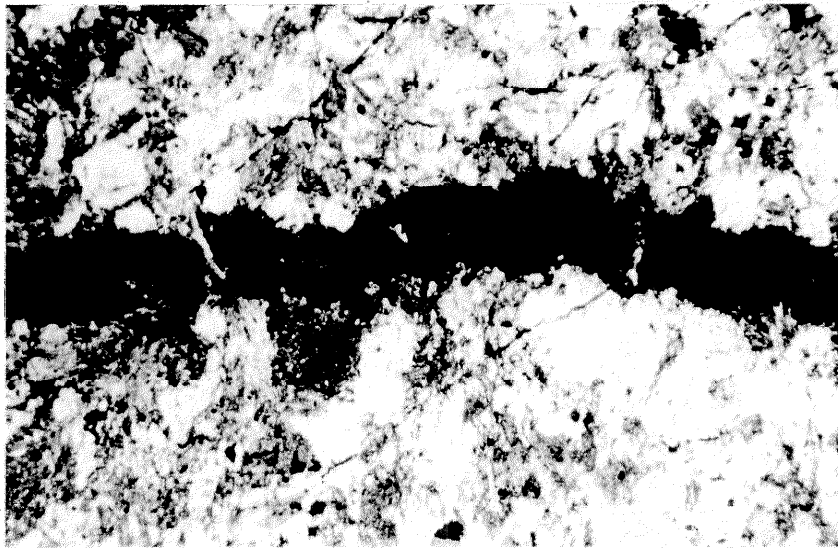


3B

- 3A. Typical texture of massive crystalline tuff. Contains plagioclase, and finely disseminated hornblende and magnetite. Outcrop specimen, near Dumpy Lake. x10
- 3B. Unusual development of albitic rims on sericitized plagioclase in massive crystalline tuff. Dark patches are predominantly fine-grained brown biotite. Crossed nicols. Outcrop specimen. x33

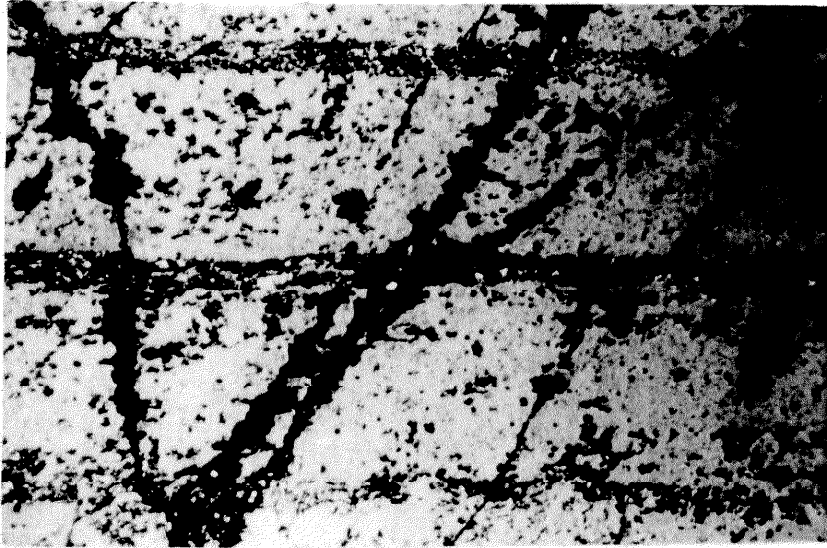


4A

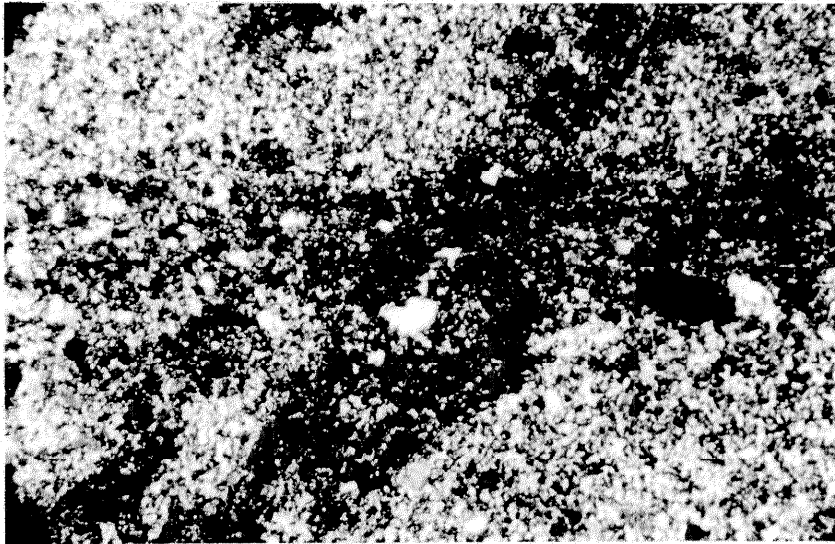


4B

- 4A. Typical texture of hornblende-feldspar porphyry. Larger and darker phenocrysts are mainly plagioclase; remainder are hornblende. Crossed nicols. Outcrop specimen, southwest of McDonough Lake. x10
- 4B. Example of late magnetite vein (black) cutting feldspar porphyry. Outcrop specimen, near junction of Nos. 2 and 3 veins. x10

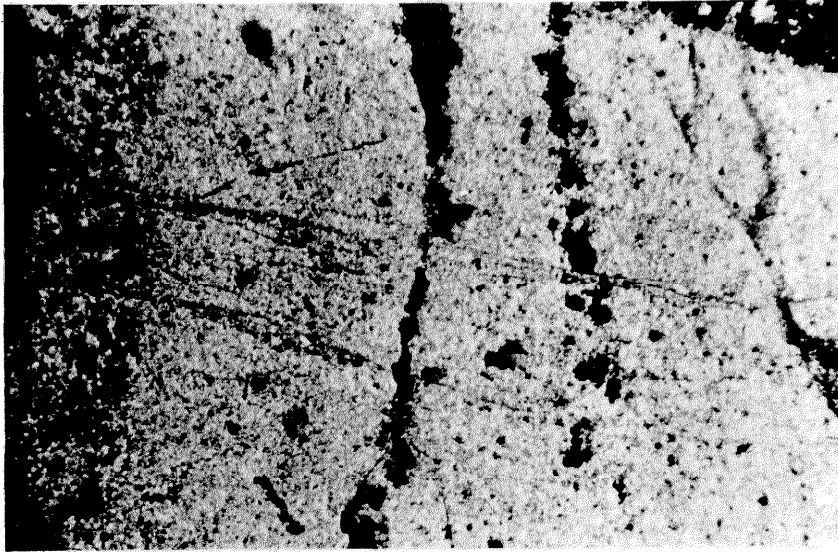


5A

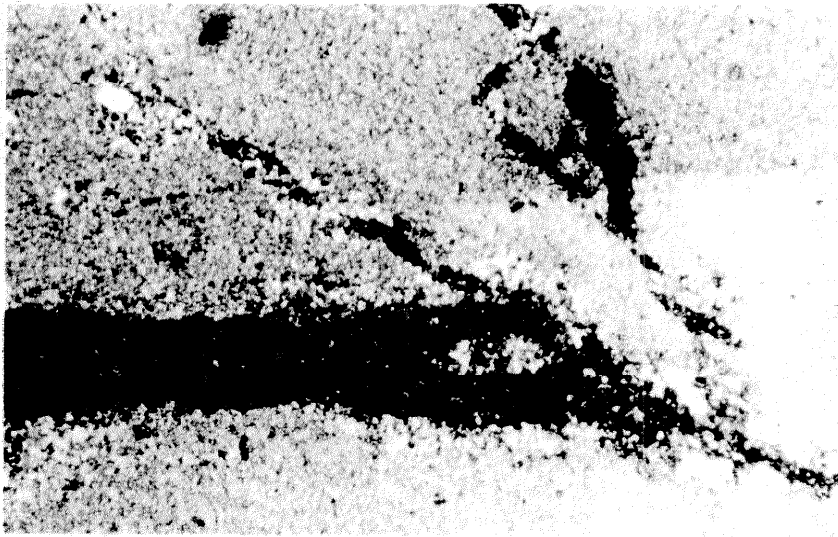


5B

- 5A. Bedded Mine series tuff stained for albite (medium to light grey, most of section). Note that diopside (black) occurs parallel to original laminations and in cross-fractures. Note also that quartz (white) is essentially restricted to the diopside zones which are parallel to original laminations. Outcrop specimen. x10
- 5B. Enlargement of central portion of Plate 5A. Large white grains are quartz. Crossed nicols. x33



6A



6B

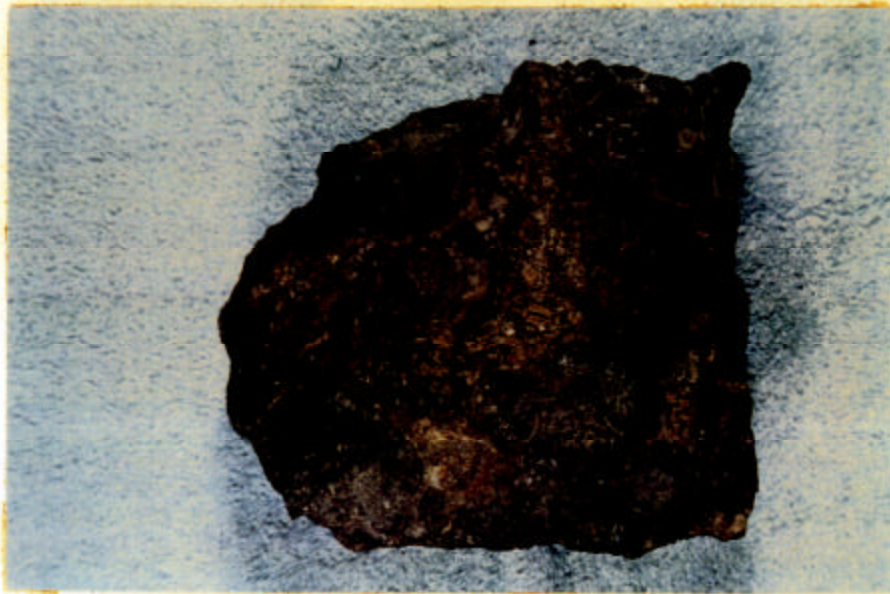
- 6A. Mine series tuff, stained for albite (grey). Note tendency of diopside (black) to follow coarser grained bands which contain some quartz (white grains). Minor carbonate with diopside and in cross-fractures. Crossed nicols. Outcrop specimen, north of No. 1 vein. x10
- 6B. Mine series tuff stained for albite (grey) except for lower right-hand corner. Quartz (white) appears to be concentrated on margins of diopside-carbonate bands (black). Crossed nicols. Outcrop specimen, north of No. 2 vein. x10



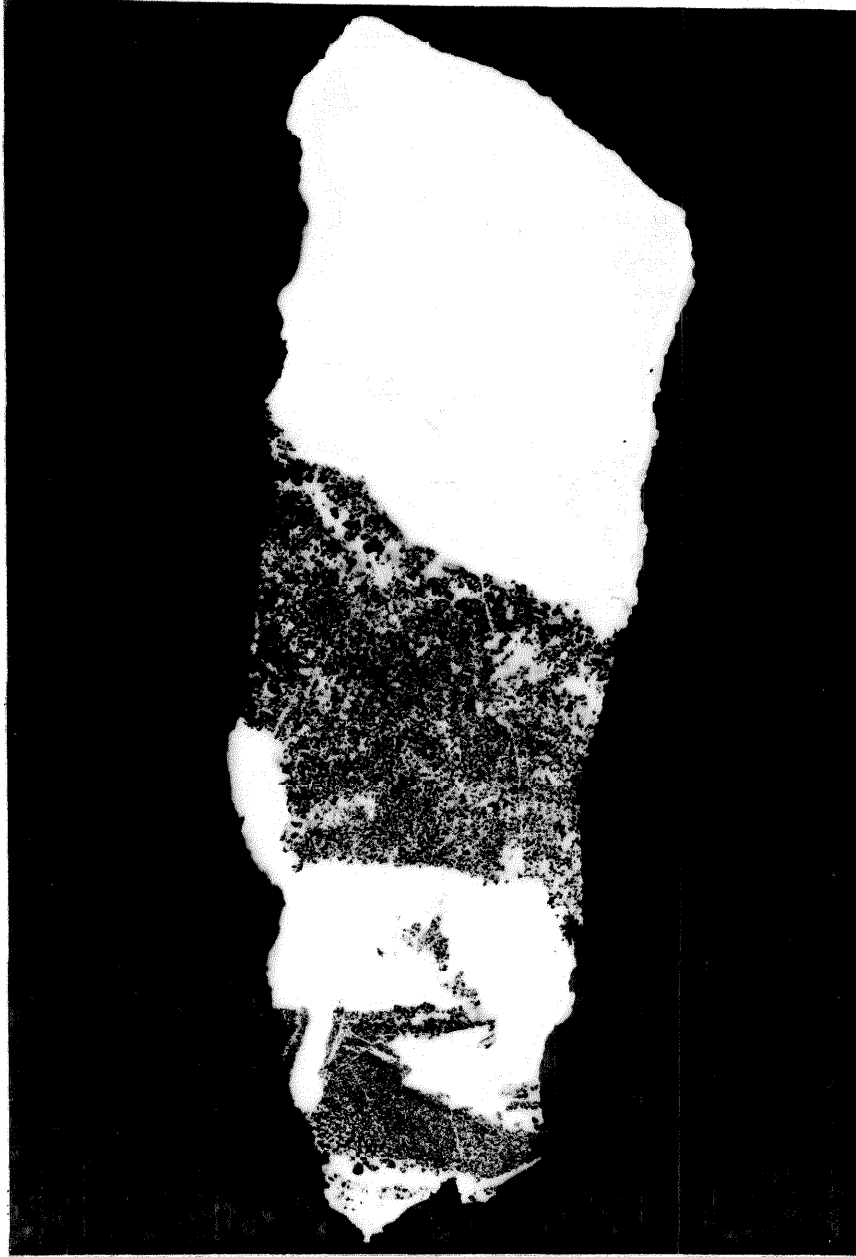
No. 2 vein, 250 level east, drift back. Note narrowing of vein to left within more competent body of feldspar porphyry. The vein widens to three feet, 20 feet to the right of the location photographed, where it enters Mine series tuffs. The scale shown is six inches long.

PLATES 8 TO 20

PITCHBLEND AND ASSOCIATES



Hand specimen of botryoidal pitchblende. Photograph courtesy of C. M. Trigg. xl/2



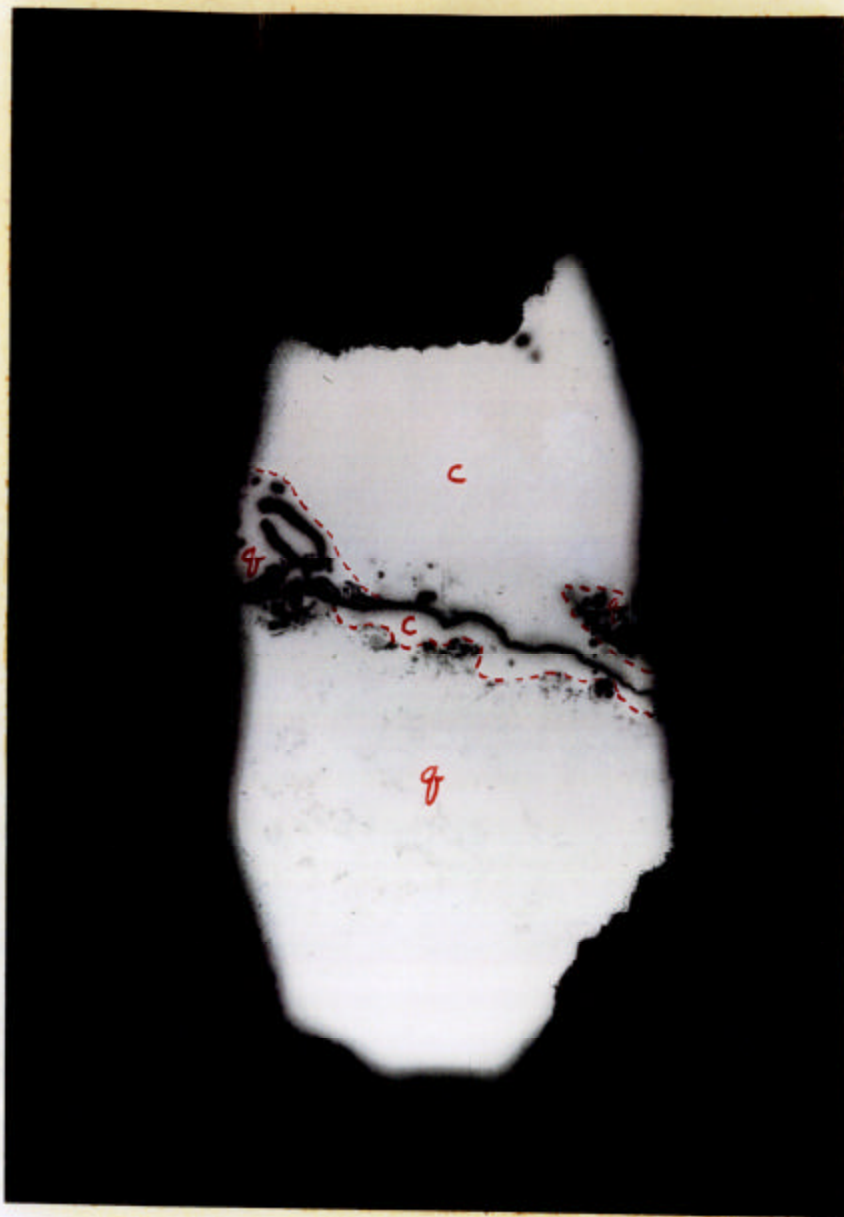
Autoradiograph of spherulitic pitchblende (black) in hematitic laminated quartz gangue (white). No. 1 vein, 13 ore shoot. xl



Autoradiograph of brecciated pitchblende (black) in chloritic, chalcopyrite "ore" quartz gangue (white). No. 2 vein, 21 ore shoot. xl



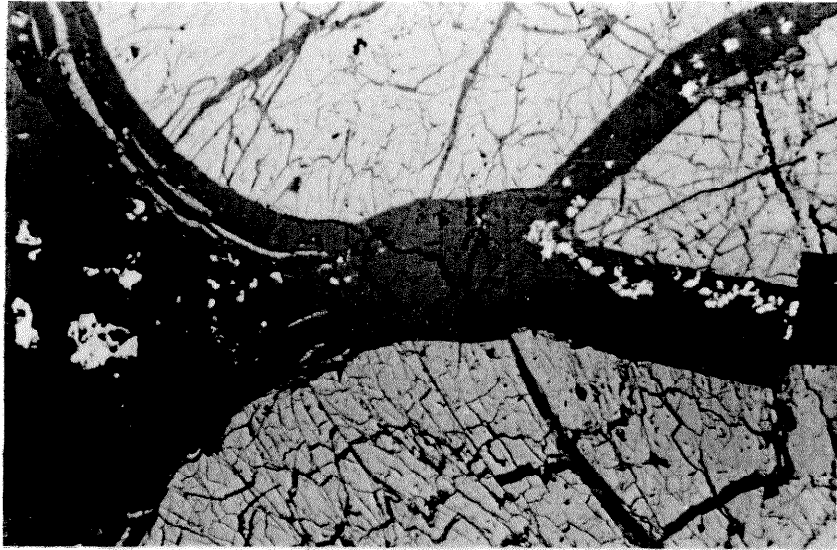
Autoradiograph of "diffuse" pitchblende (black) comminuted and replaced in chloritic quartz (white). No. 5 vein, 54 ore shoot. xl



Autoradiograph showing possible second generation pitchblende veinlet (black) in carbonate (c). Remainder of pitchblende (fragments and diffuse radioactivity) occurs in arsenide bearing quartz (q) which is permeated by replacement carbonate. No. 2 vein, 21 ore shoot. xl



Autoradiograph of dendritic pitchblende (black) in hematitic quartz gangue (white). No. 3 vein, 31 ore shoot. xl



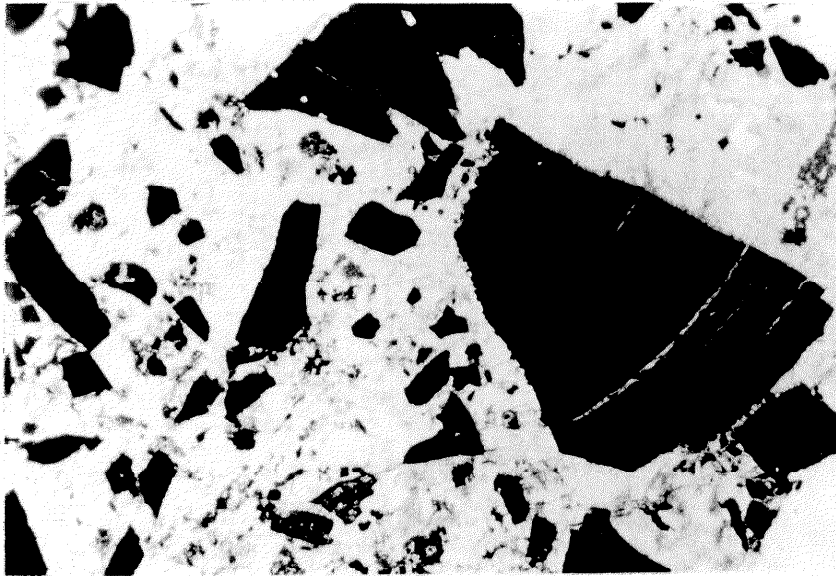
14A



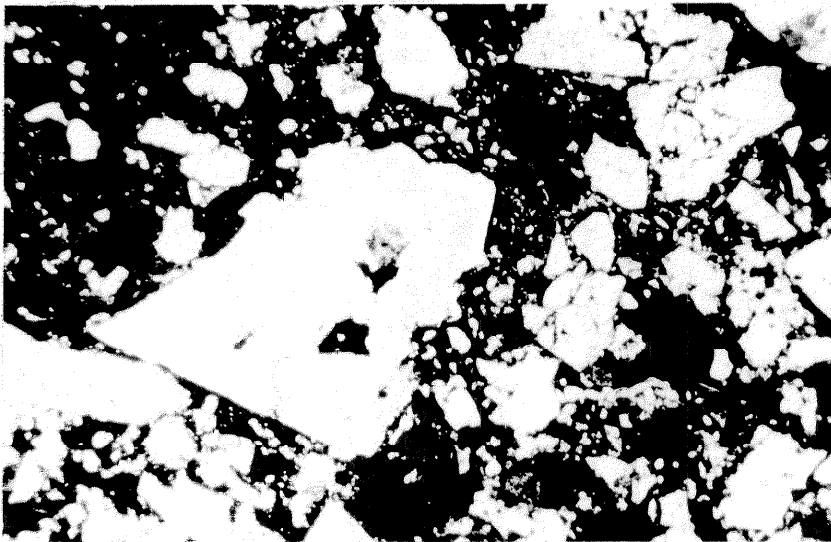
14B

14A. Botryoidal pitchblende (medium grey) in quartz (dark grey) containing minor pyrite and chalcopyrite (white). Note quartz in syneresis cracks and offset of main quartz band. No. 1 vein, 13 ore shoot. x33

14B. Brecciated pitchblende (medium grey) healed by quartz (dark grey) containing minor rammelsbergite. No. 2 vein, 22 ore shoot. x80



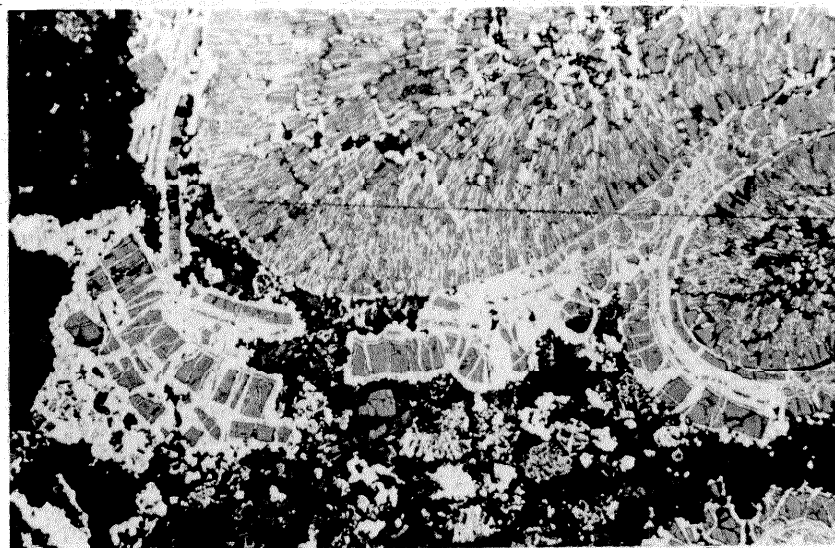
15A



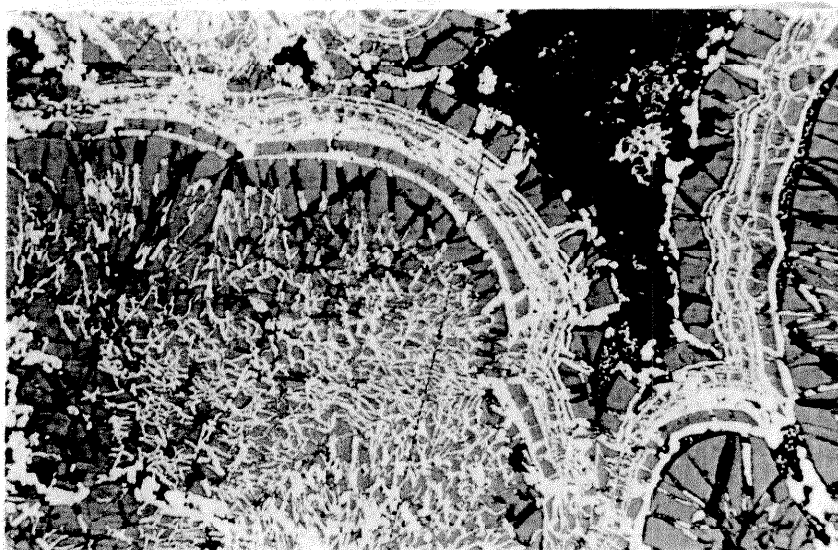
15B

15A. Brecciated pitchblende (black) in fine crystalline quartz (white) with minor interstitial chlorite (grey). Fractures in pitchblende fragments are filled with carbonate. No. 2 vein, 23 ore shoot. x10

15B. Brecciated quartz (white) healed by pitchblende (black). No. 3 vein, 32 ore shoot. x10



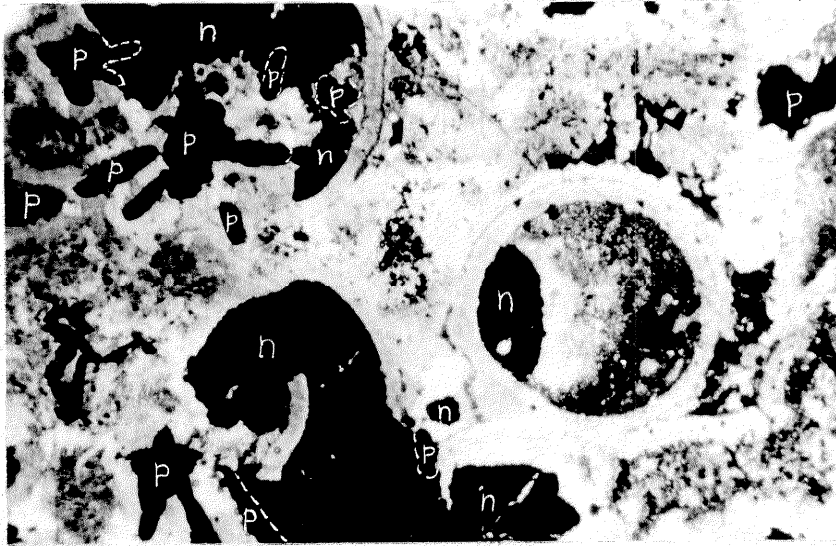
16A



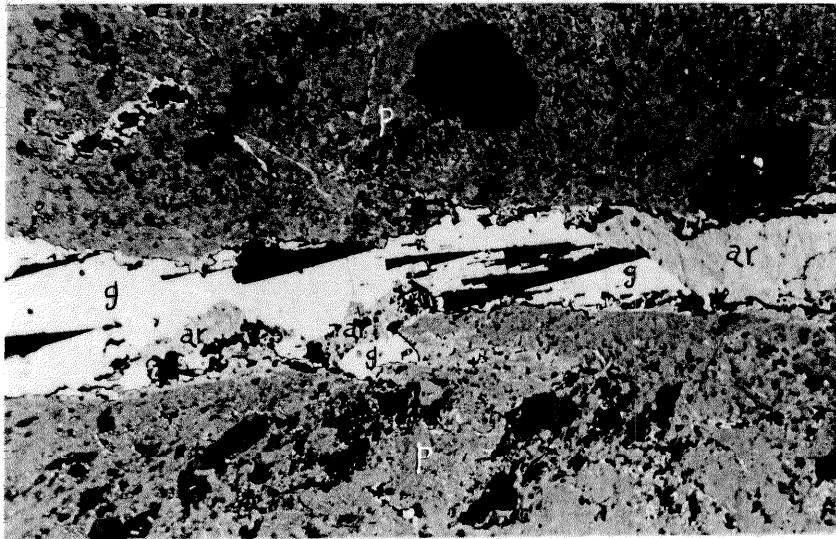
16B

16A. Botryoidal pitchblende (medium grey) replaced radially and concentrically by arsenides (white) in chloritic quartz gangue (dark grey). No. 5 vein, 54 ore shoot. x33

16B. Same polished section as plate 16A. x80



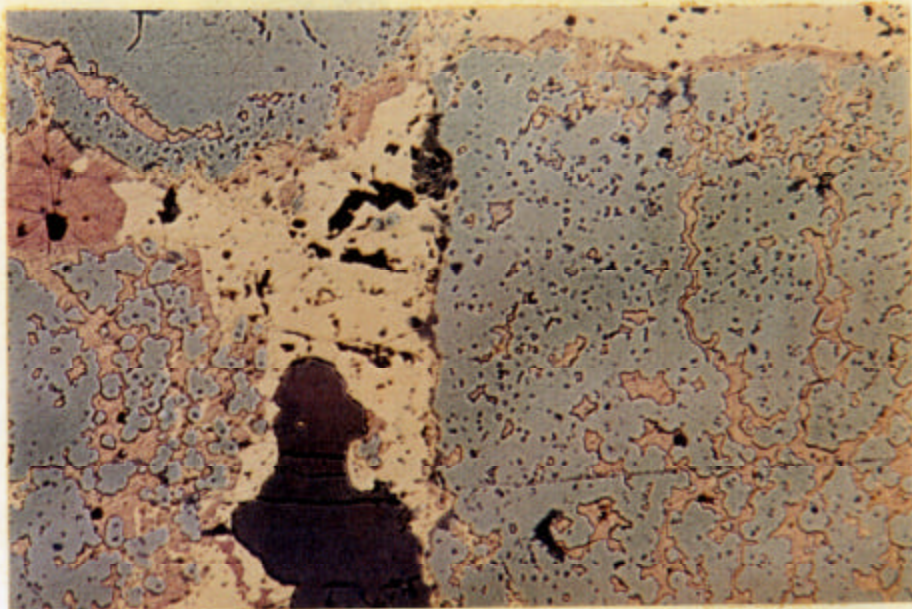
17A



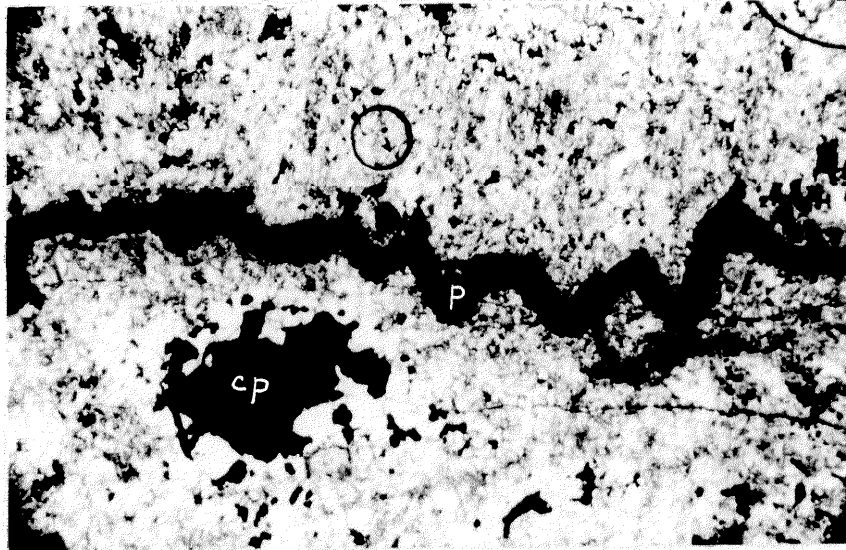
17B

17A. Clusters of pitchblende dendrites (p) with native silver cores and grossly botryoidal niccolite (n) in hematitic carbonate (remainder of field). Niccolite younger than pitchblende but age relative to carbonate rings not established. B vein, 1175 level. x10

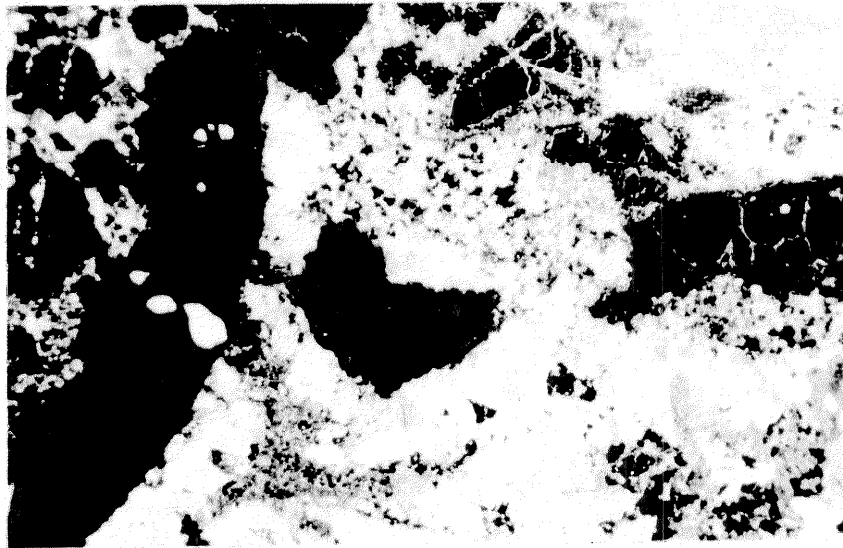
17B. Pitchblende (p) pitted with gangue (dark grey) and veined by galena (g) and argentite (ar). No. 2 vein, 21 ore shoot. x80



Pitchblende (blue-grey) replaced by chalcopyrite (yellow) and bornite (purple). Chalcopyrite and bornite locally finely intergrown. Dark grey is quartz gangue. No. 3 vein, 32 ore shoot. x90



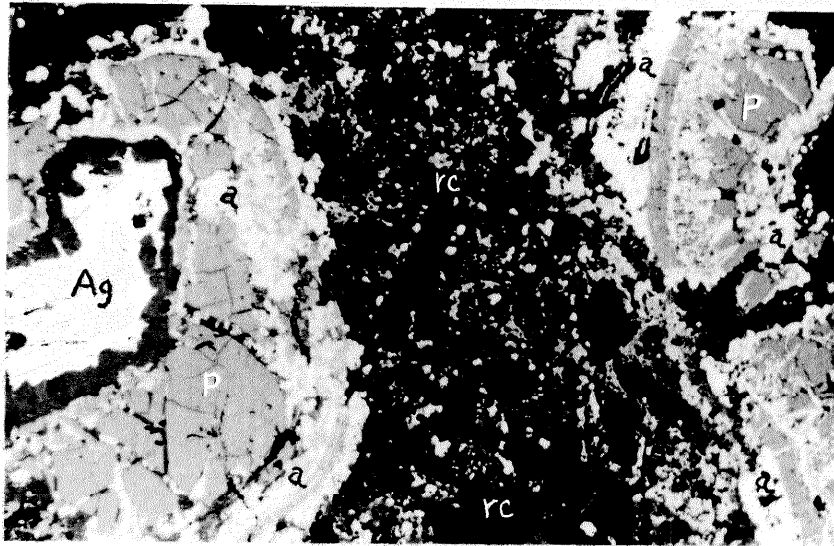
19A



19B

19A. Narrow, sharply defined zone of pitchblende (p) in hematitic rhodochrosite (most of section) which also contains some chalcopyrite (cp). Appears to be second generation pitchblende but vein may be antecedent. B vein, 1175 level. x33

19B. Zones of pitchblende (black) breached and replaced by hematitic rhodochrosite (remainder of field). Same specimen as Plate 12. No. 2 vein, 21 ore shoot. x10

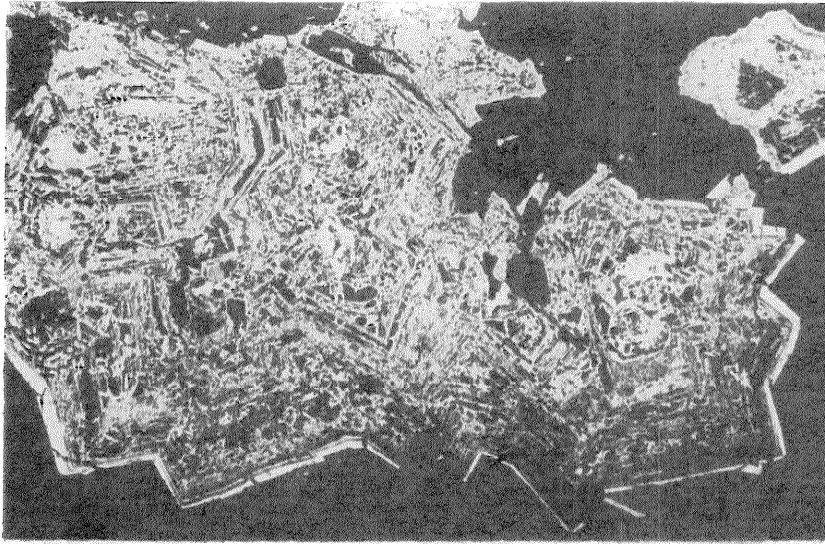


Pitchblende (p) replaced by arsenide minerals (a) and hematitic rhodochrosite (rc, much of section). Pitchblende on left is dendritic and has a native silver core (Ag). Pitchblende on right is a sinuous veinlet and appears to be second generation in hand specimen. It has obviously been replaced by both arsenides and rhodochrosite. White grains in rhodochrosite are chalcopyrite and galena. B vein, 1175 level. x80

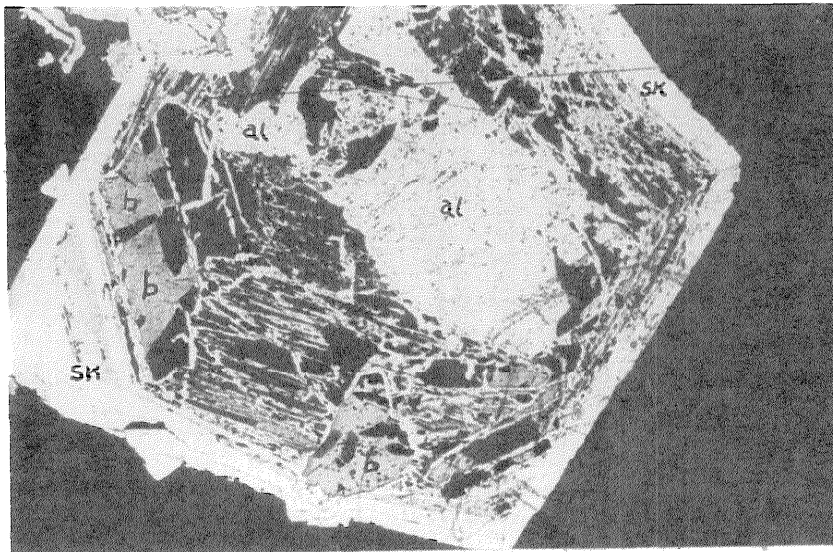
- 237 -

PLATES 21 TO 26

ARSENIDE MINERALS AND ASSOCIATES



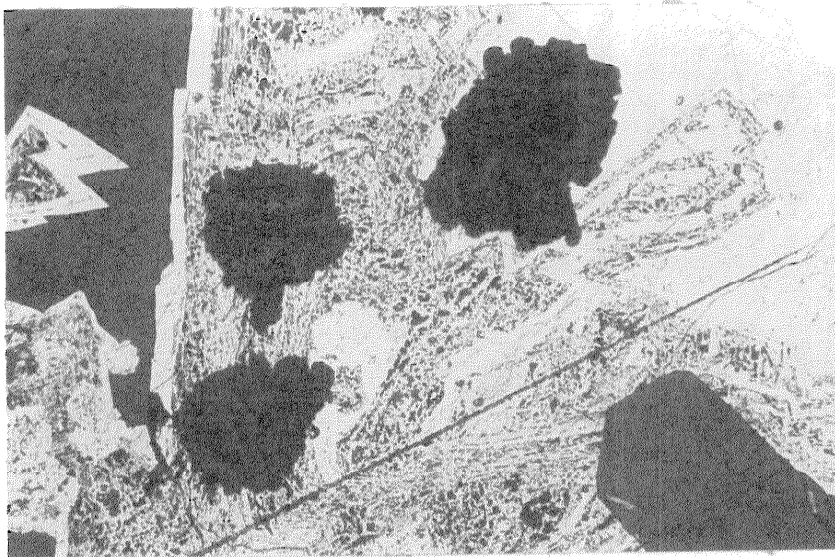
21A



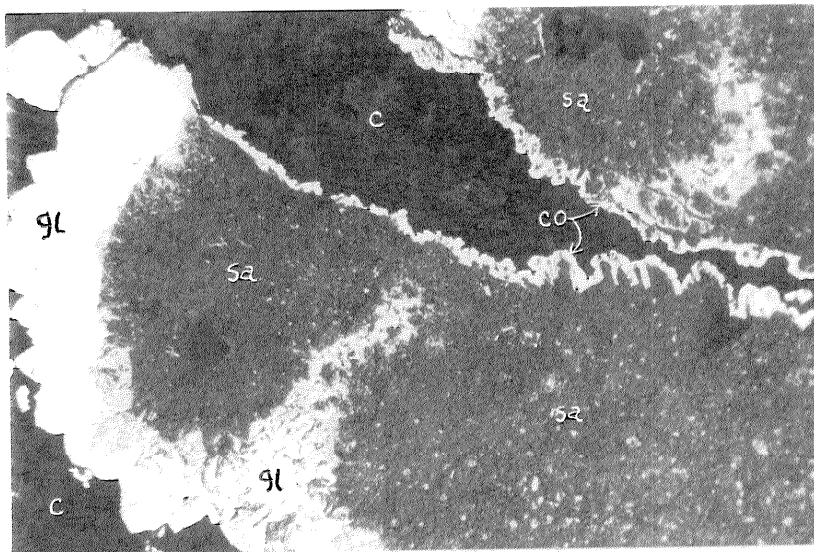
21B

21A. Aggregate of zoned skutterudite crystals containing quartz (dark grey) and other white arsenides. Texture probably in part the result of contemporaneous deposition. No. 7 vein, 72 ore shoot. x33

21B. Crystal of skutterudite (sk) replaced by alloclasite (al) and bismuthinite (b). Dark grey mineral is quartz. Same specimen as Plate 21A. x80



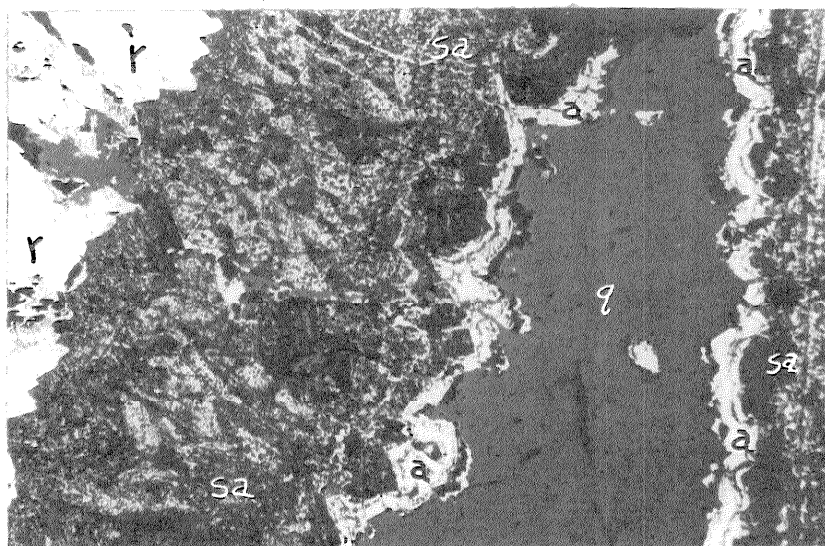
22A



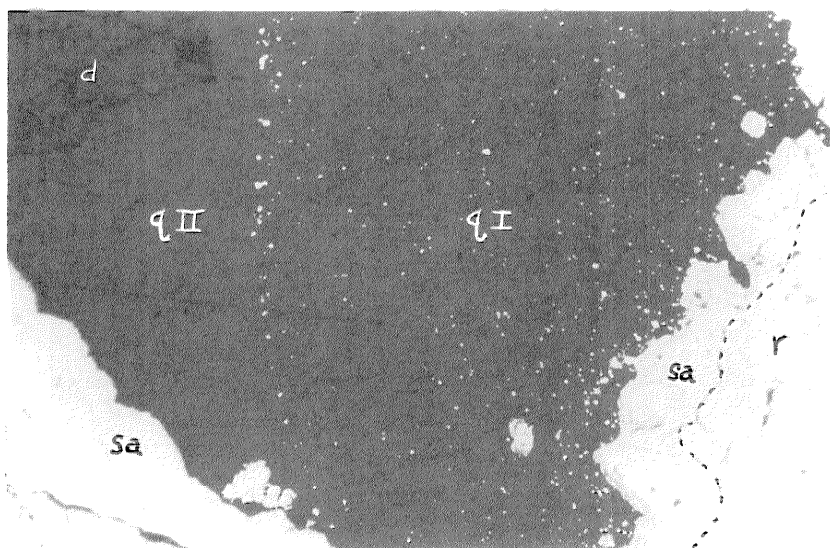
22B

22A. Crystals of skutterudite (light grey) and quartz (dark grey). Round black areas are sample drill holes. X-ray powder photograph of one in upper center gave skutterudite doublet. Same specimen as Plate 21A. x33

22B. Etched with FeCl_3 . Safflorite (sa) with broad rim of glaucodot (gl), veined by carbonate (c) which is bordered by cobaltite (co). No. 5 vein, 54 ore shoot. x80

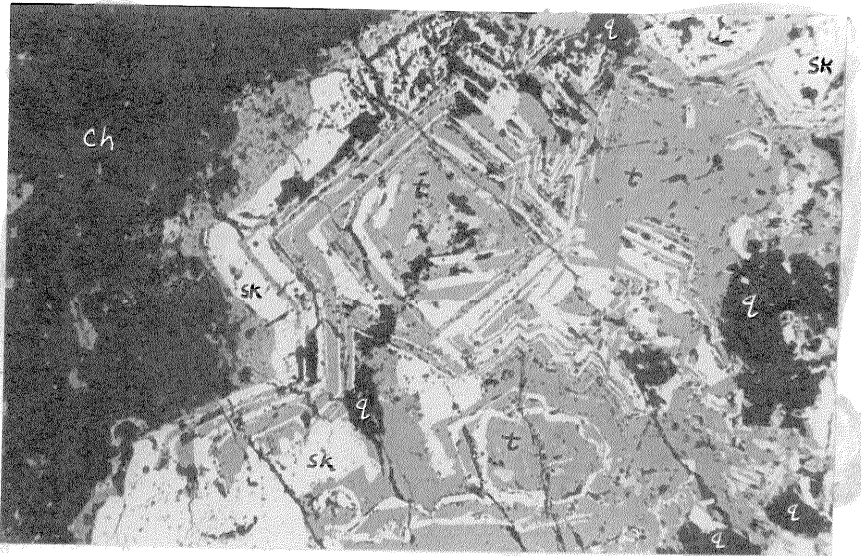


23A

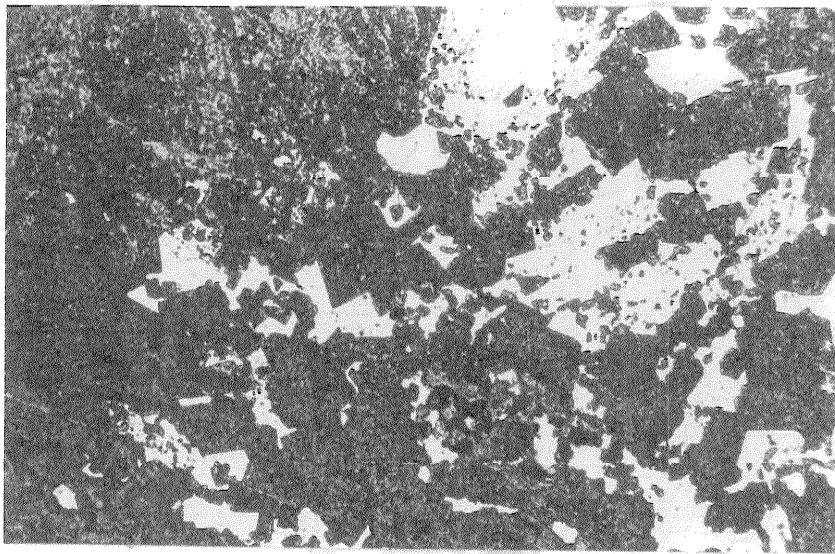


23B

- 23A. Etched with FeCl_3 . Large area of rammelsbergite (r, mainly out of field to left) with overgrowth of safflorite (sa, etched) on which was deposited thin rims of other, unknown arsenides (a). Quartz (q) filled central vug. No. 2 vein, 22 ore shoot. x80
- 23B. Open space deposition of rammelsbergite (r) and safflorite (sa) followed by: quartz (q I) with disseminated arsenide grains; clear quartz (q II); and dolomite (d). Texture possibly due to gravity settling. See text, p. 78. No. 7 vein, 72 ore shoot. x33



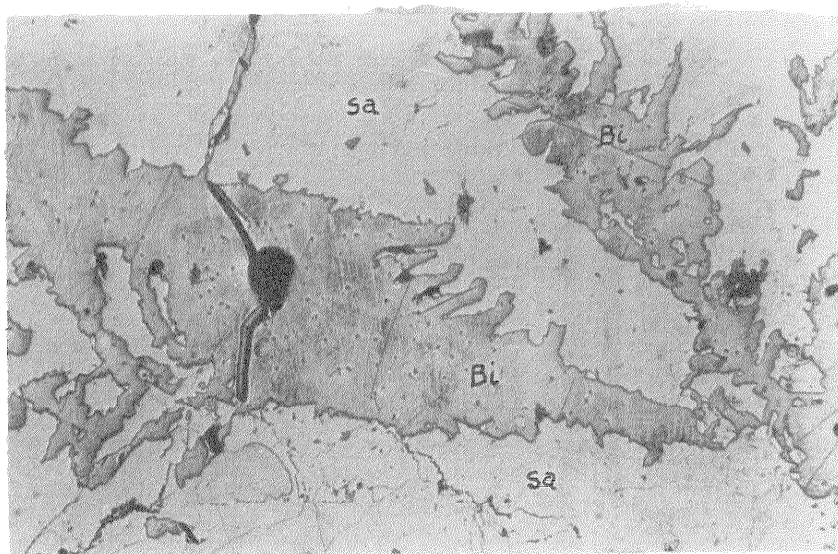
24A



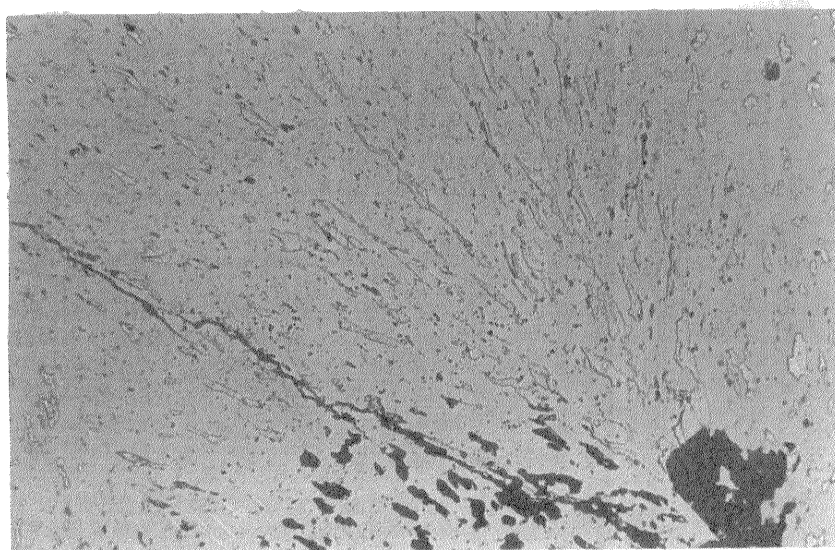
24B

24A. Skutterudite (sk) replaced zonally by tetrahedrite (t). Gangue is quartz (q) and chlorite (ch). No. 3 vein, 34 ore shoot. x80

24B. Air tarnished gersdorffite (dark grey) showing cubic form in niccolite (white). Niccolite possibly younger than gersdorffite. No. 3 vein, 34 ore shoot. x80

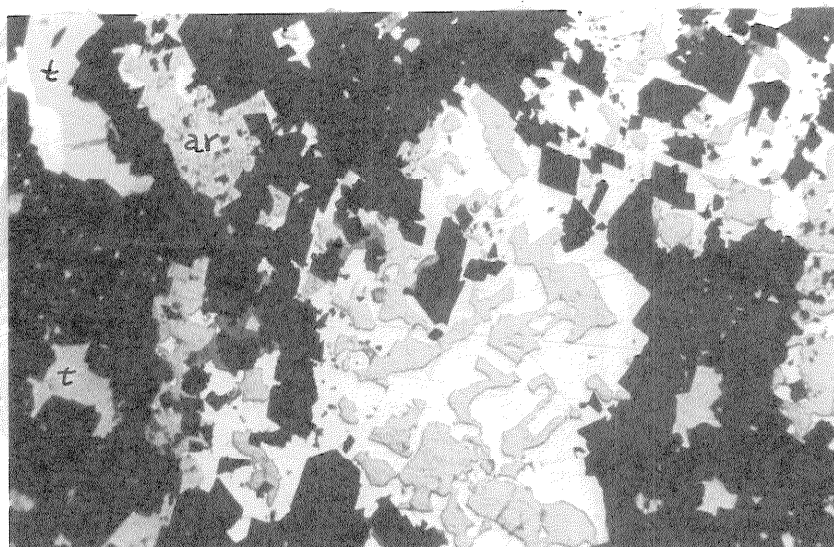


25A



25B

- 25A. Native bismuth (**Bi**) replacing safflorite (**sa**). No. 5 vein, 54 ore shoot. x33
- 25B. Characteristic radial replacement of rammelsbergite by small blebs of native bismuth (light grey). Black grains are quartz. No. 7 vein, 72 ore shoot. x80

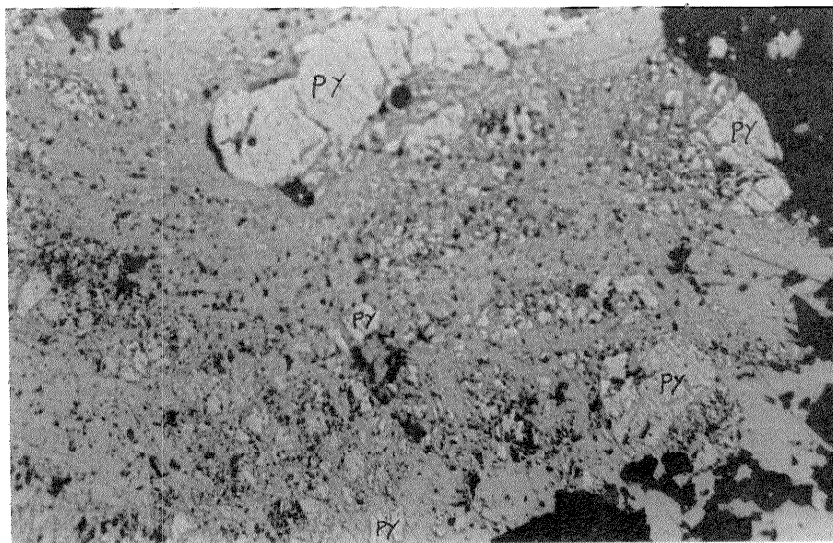


Replacement of gersdorffite (light grey) and carbonate (dark grey) by native silver (white). Minor tetrahedrite (t) and argentite (ar) on left side. No. 2 vein, 21 ore shoot. x80

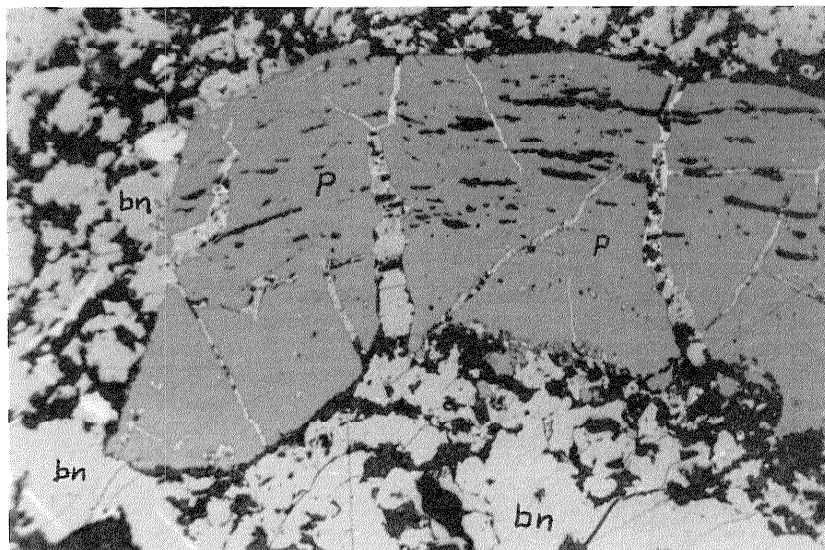
- 244 -

PLATES 27 TO 32

SULPHIDE MINERALS AND ASSOCIATES



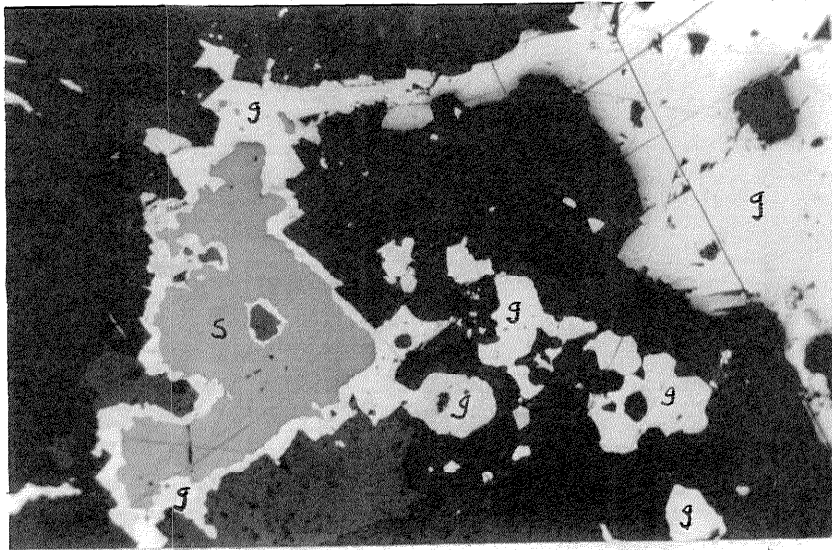
27A



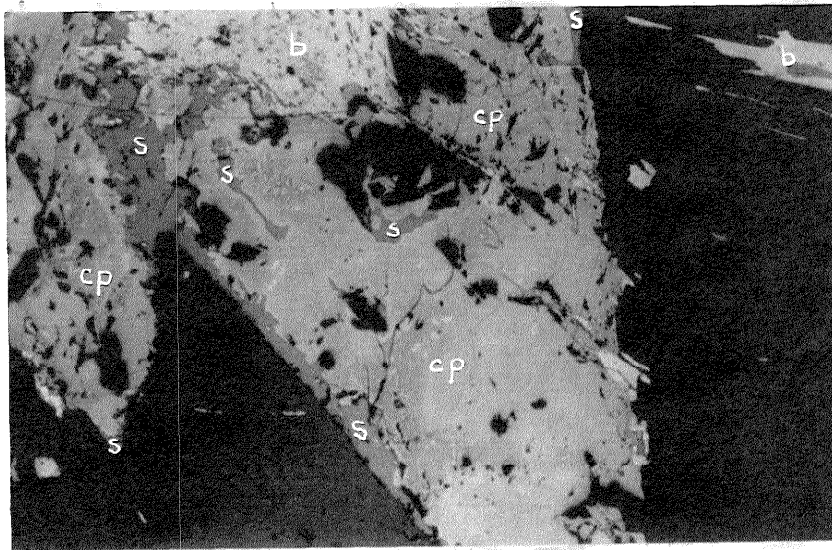
27B

27A. Remnant pyrite (py) in a field of other sulphides, predominantly galena. No. 3 North vein, west of 34 ore shoot. x200

27B. Pitchblende (p) replaced by bornite (bn). Minor chalcopyrite (white) and chlorite (black). No. 3 vein, 32 ore shoot. x80



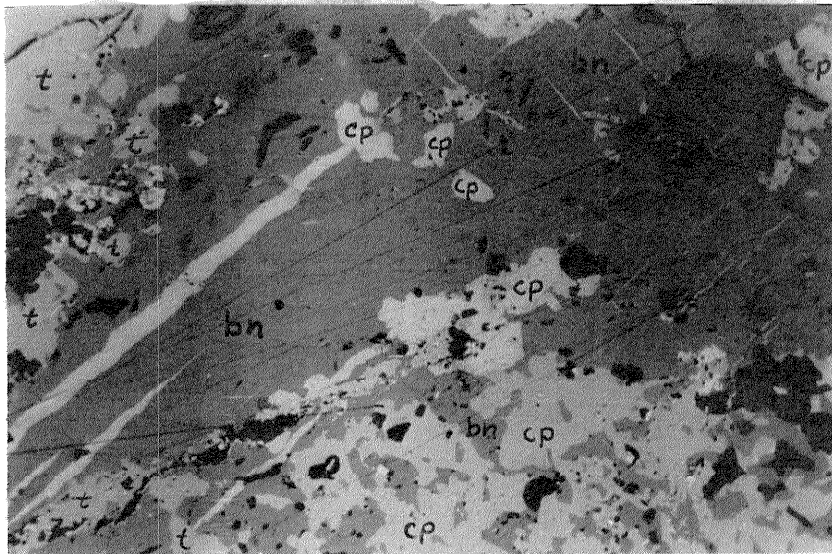
28A



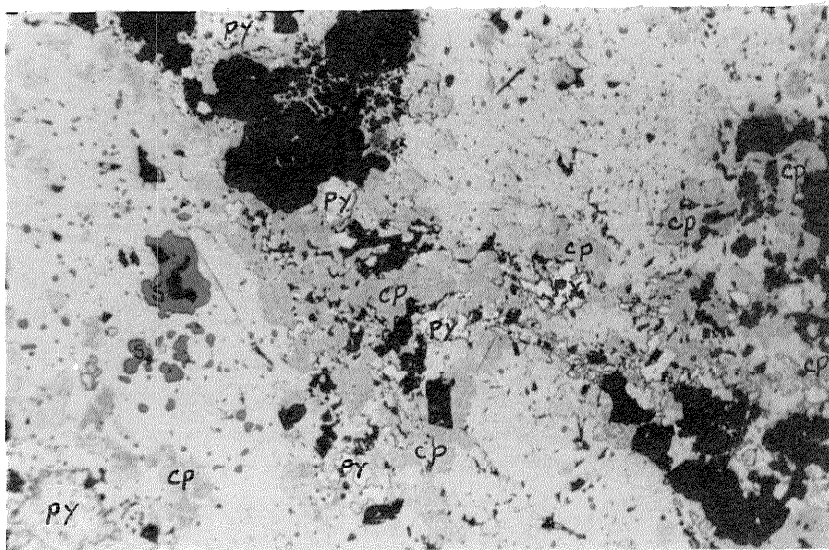
28B

28A. Sphalerite (s) and dolomite (dark grey) replaced by galena (g). Minor chalcopyrite (light grey) in galena. Galena probably J-type. No. 5 vein, 500 level east. x80

28B. Possible sphalerite (s) - chalcopyrite (cp) age reversal with sphalerite replacing chalcopyrite along contact with dolomite (dark grey). Light grey mineral is bismuthinite (b). Location unknown. x33

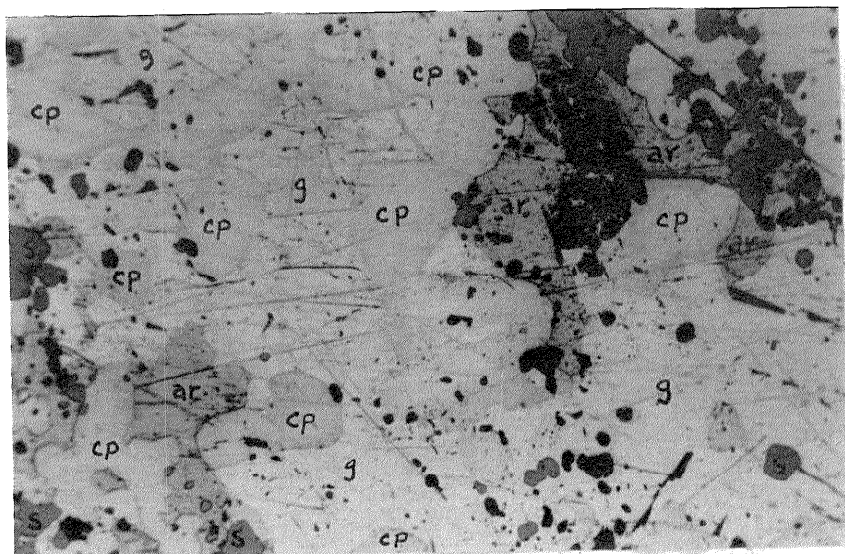


29A

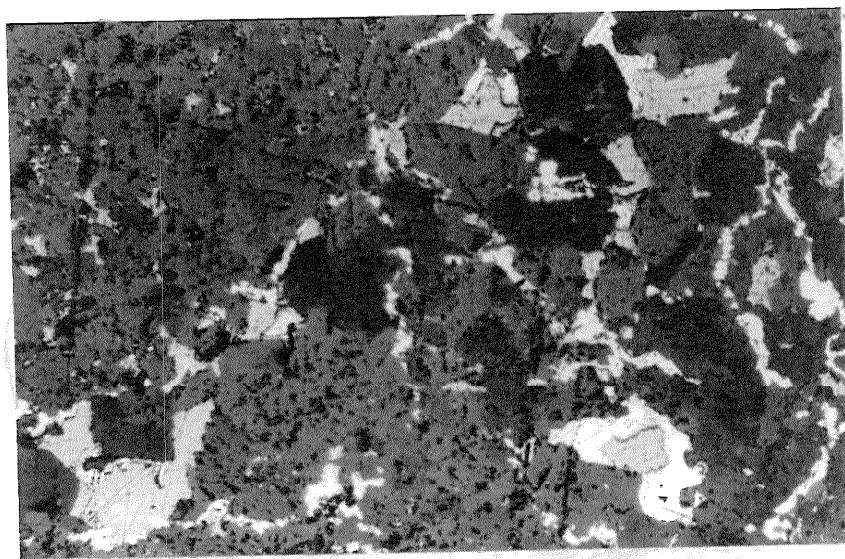


29B

- 29A. Bornite (bn), chalcopyrite (cp), tetrahedrite (t), probably deposited in that order. No. 8 vein, 81 ore shoot. x80
- 29B. Galena (light grey, much of field) containing "islands" of pyrite (py), chalcopyrite (cp) and sphalerite (s). Galena probably J-type. Black is dolomite. No. 5 vein, 500 level east. x80



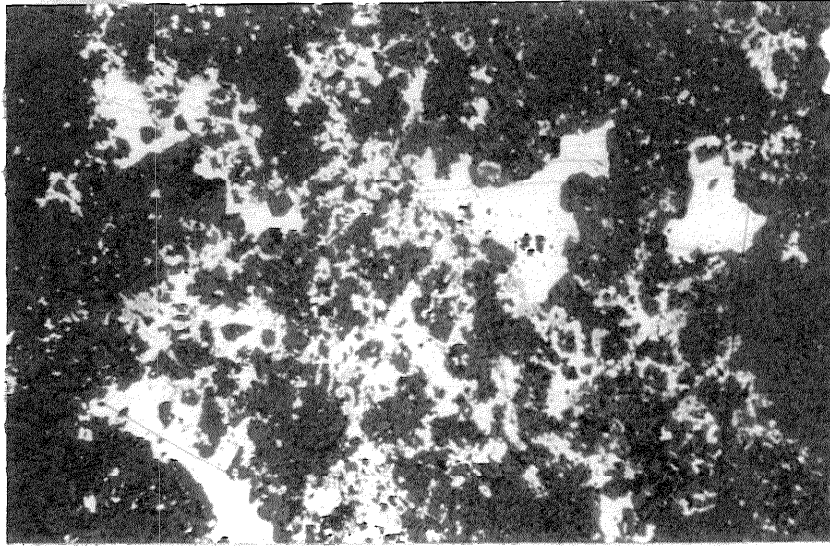
30A



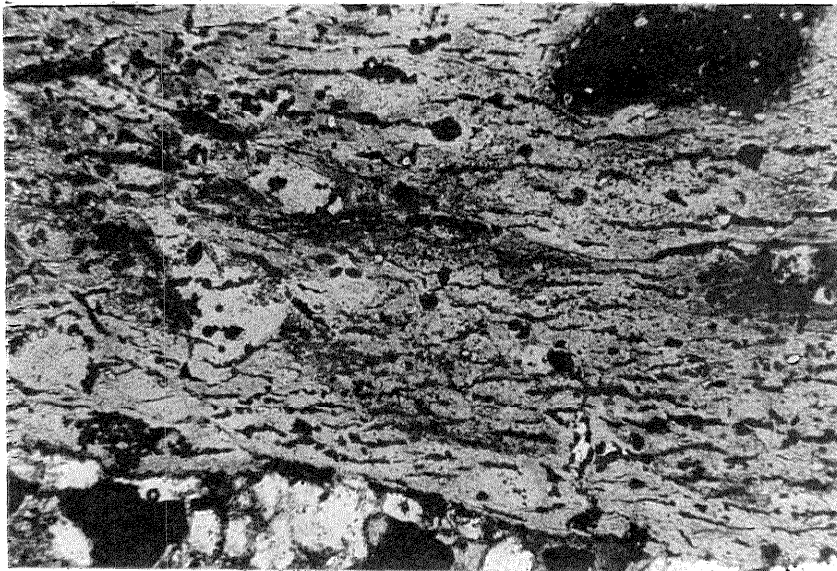
30B

30A. Showing typical mutual boundaries of sulphides. Probable order of deposition is sphalerite (s), chalcopyrite (cp), galena (g), and argentite (ar) but relative ages cannot be determined from this type of association. Galena is isotopically ordinary. No.2 vein, 21 ore shoot. x80

30B. Dolomite (dark grey) replaced by argentite (light grey) and native silver (white). No. 2 vein, 21 ore shoot. x80



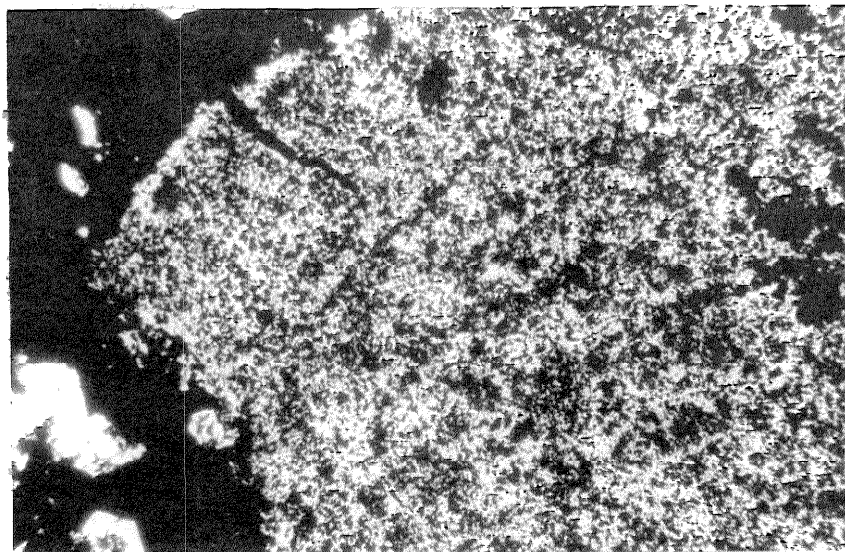
31A



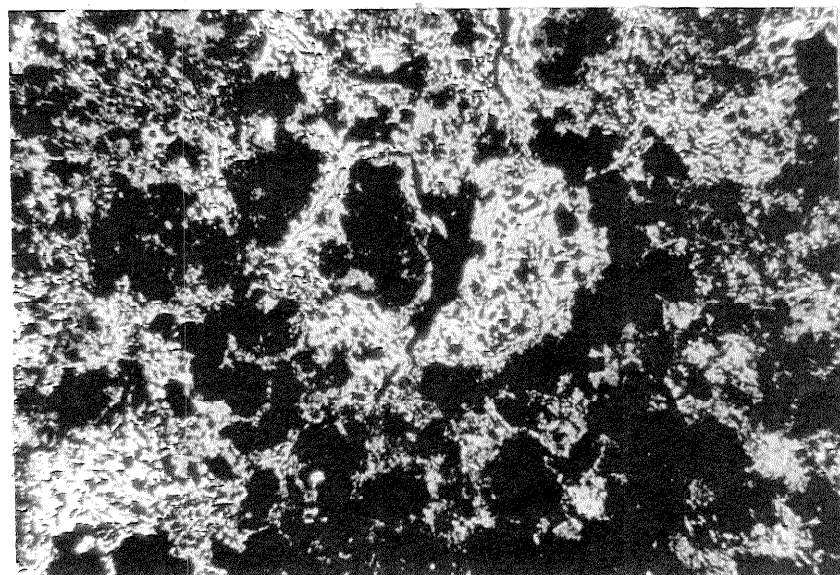
31B

31A. Typical form of replacement of dolomite (dark grey) by native silver (white). Note absence of dendritic forms. No. 1 vein, 13 ore shoot. x33

31B. Elongate blebs of chalcopyrite (black) interleaved with white mica (light grey)(most of field). No. 3 vein, 35 ore shoot. x33



32A



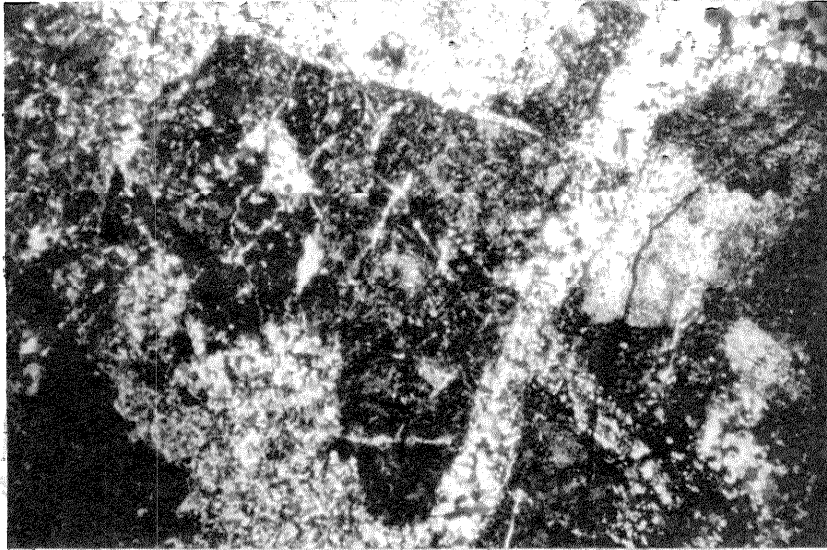
32B

32A. Chalcopyrite and bornite (black) disseminated in chlorite and white mica (white) and in massive patches. No. 3 vein, 32 ore shoot. x33

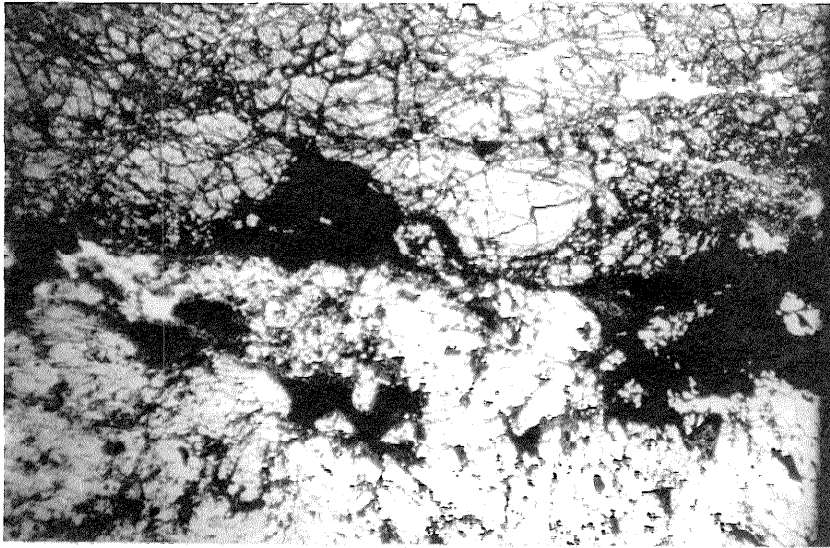
32B. Chalcopyrite and bornite (black) in white mica (white). Note tendency of white mica to wrap around sulphide grains. No. 3 vein, 32 ore shoot. x33

PLATES 33 TO 35

NON-OPAQUE VEIN MINERALS



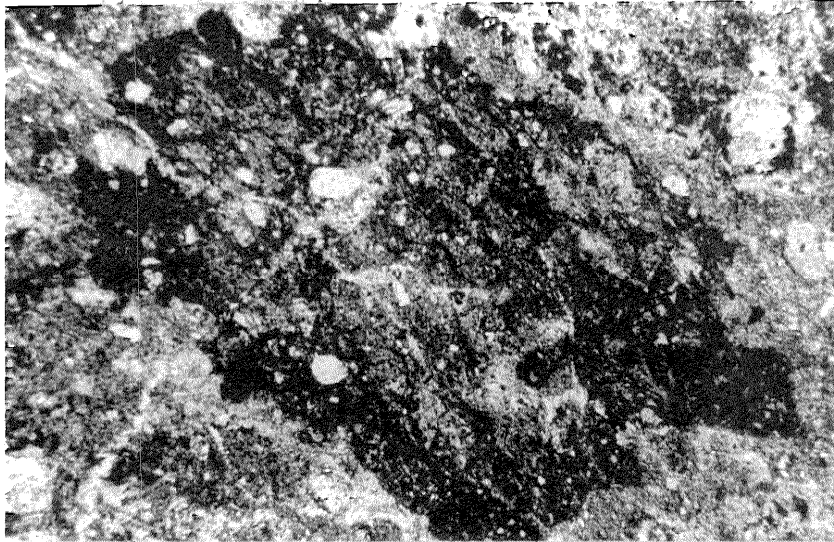
33A



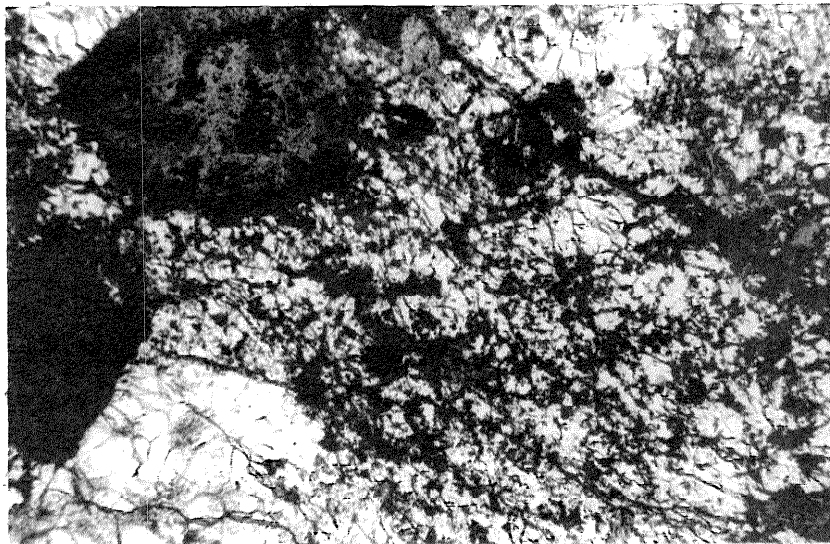
33B

33A. Microclinized wall rock fragments (dark grey) fractured and healed by quartz (light grey to white). Crossed nicols. No. 2 vein, 25 ore shoot. x10

33B. Apatite (top half of field) and early generation quartz (bottom half) fractured and replaced by chalcopyrite (black). No. 2 vein, 22 ore shoot. x10

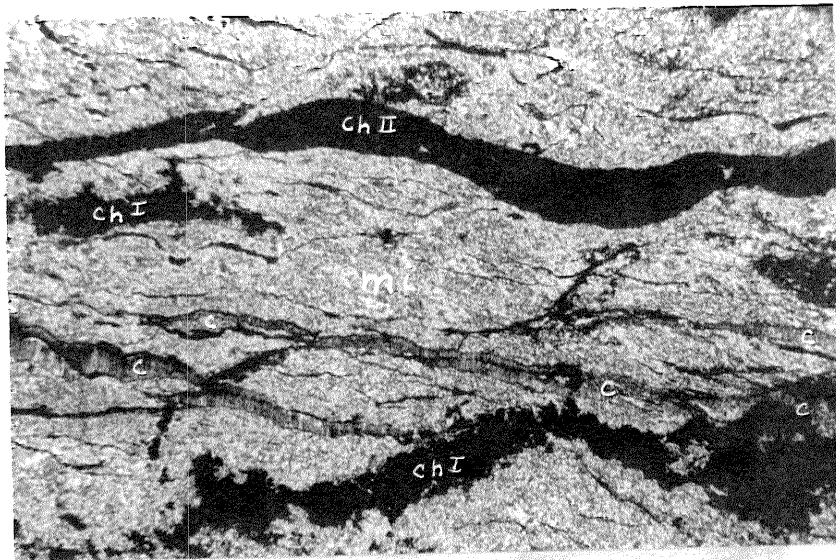


34A

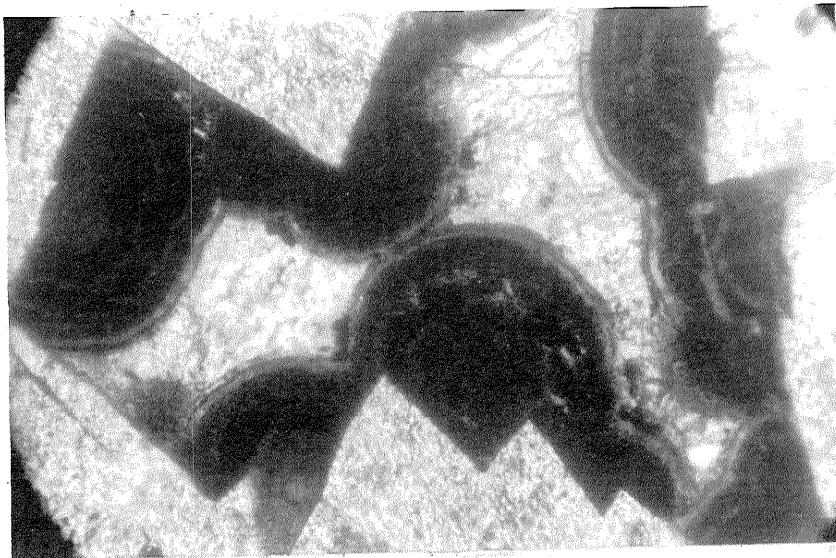


34B

- 34A. Pitchblende fragment (dark outline, most of field) almost completely replaced by chlorite and white mica. Typical of "ghost" or "diffuse" ore. No. 5 vein, 54 ore shoot. x33
- 34B. Quartz (light grey) and pitchblende (black), fractured and healed with chlorite (dark grey). Pitchblende was brecciated and mechanically transported into the quartz during deposition of the chlorite. No. 2 vein, 25 ore shoot. x33



35A



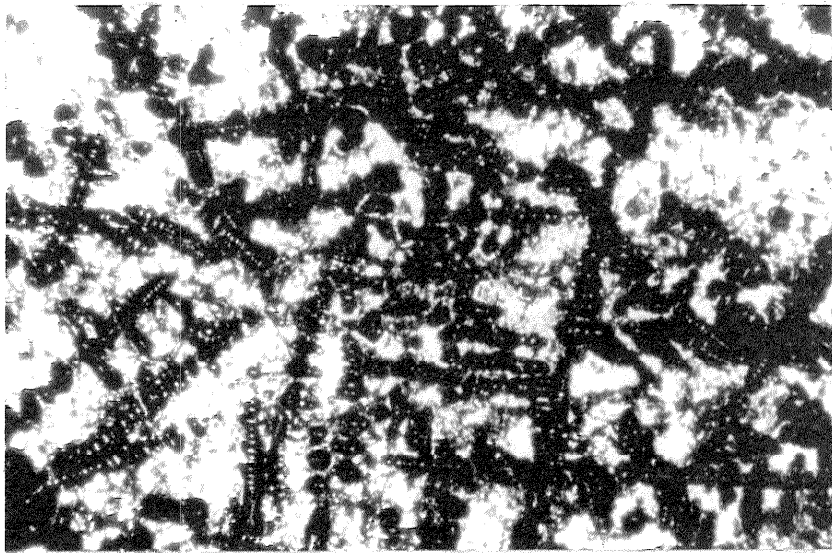
35B

35A. Diffuse zones of chlorite (ch I) replaced by white mica (mi, most of field) which is veined by later chlorite (ch II). Veins of carbonate (c) can be observed in the thin section intersecting all the above minerals. Crossed nicols. No. 3 vein, lower 31 ore shoot. x33

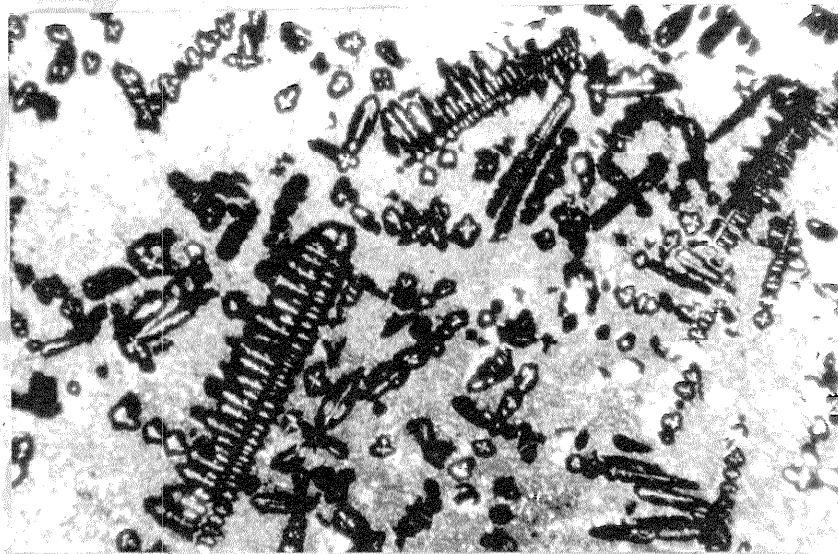
35B. Botryoidal hematite (dark grey) deposited on coarser crystalline dolomite. Interstices (center of field) filled with fine crystalline dolomite. Probably represents essentially contemporaneous deposition of hematite and dolomite. B vein, 1175 level. x10

PLATES 36 TO 42

DENDRITIC STRUCTURES IN THE ORES

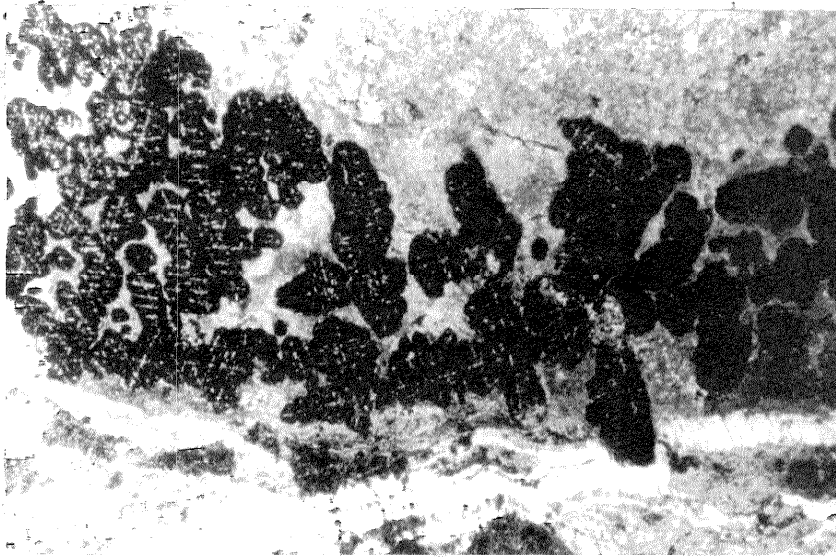


36A

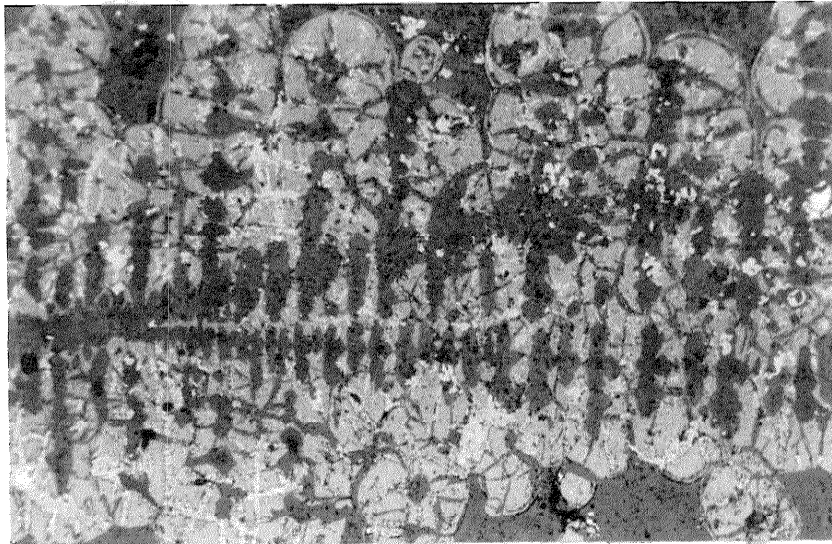


36B

- 36A. Pitchblende dendrites (black) in hematitic quartz (white). Dendrites are up to one inch long. No. 3 vein, 31 ore shoot. x10
- 36B. Safflorite dendrites (black) up to 0.75 inches long in fine crystalline carbonate (light grey). Dendrites have rims of cobaltite or glaucodot deposited on the safflorite. No. 5 vein, below 54 ore shoot. x10



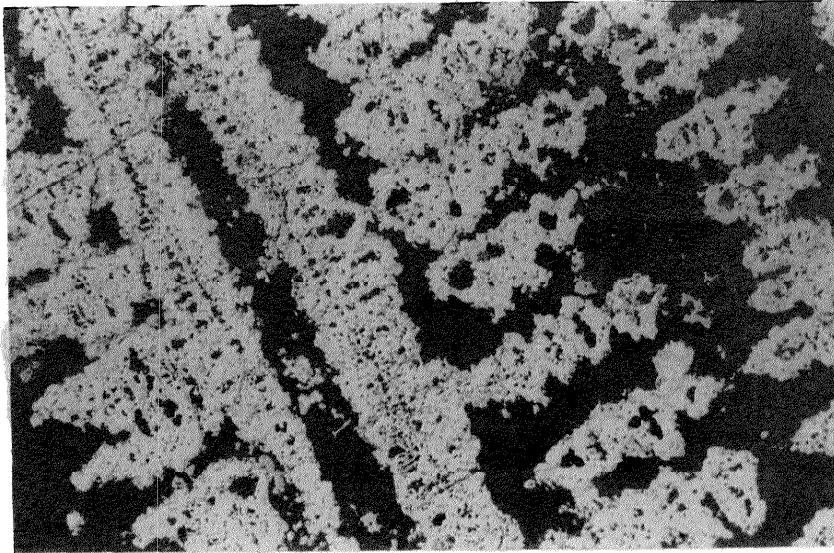
37A



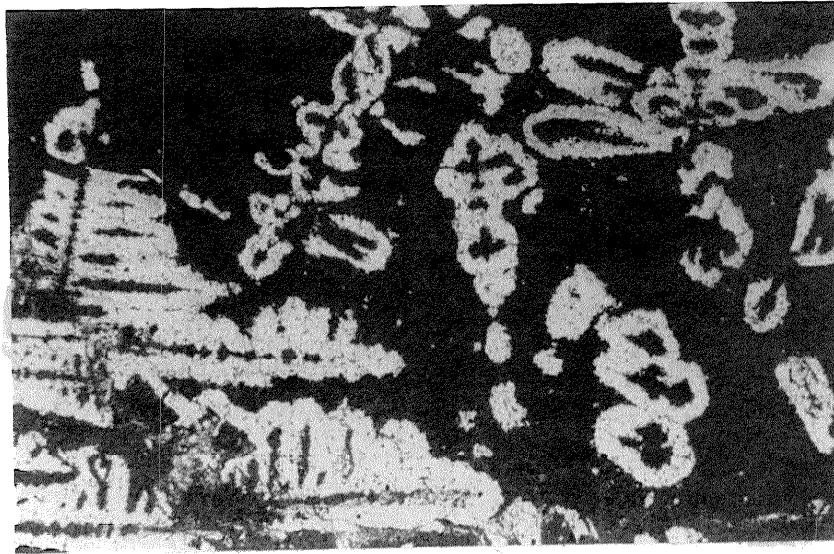
37B

37A. Pitchblende dendrites (black) in dolomite (grey). Veined along bottom by second generation carbonate (white). Dendrites average about 0.25 inches in length. No. 7 vein, 72 ore shoot. x10

37B. Same specimen as Plate 37A but in reflected light. Pitchblende (light grey), carbonate (dark grey) and chalcopryite (white). x80



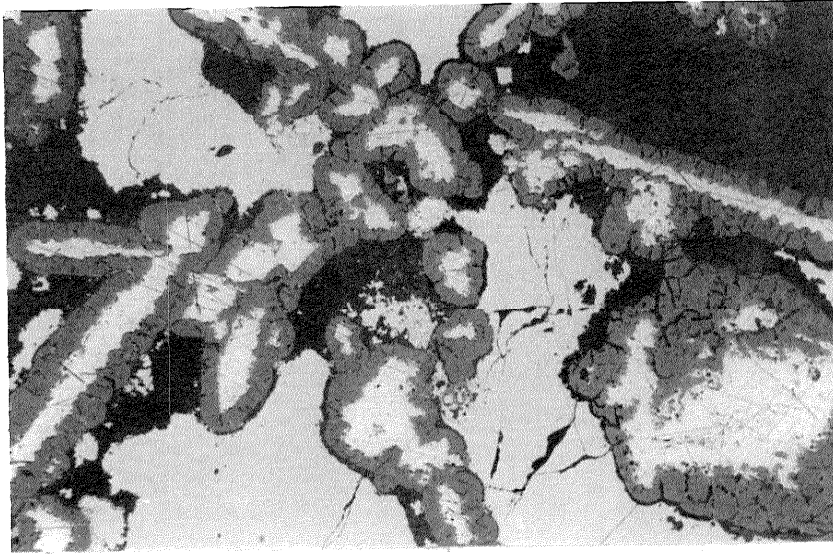
38A



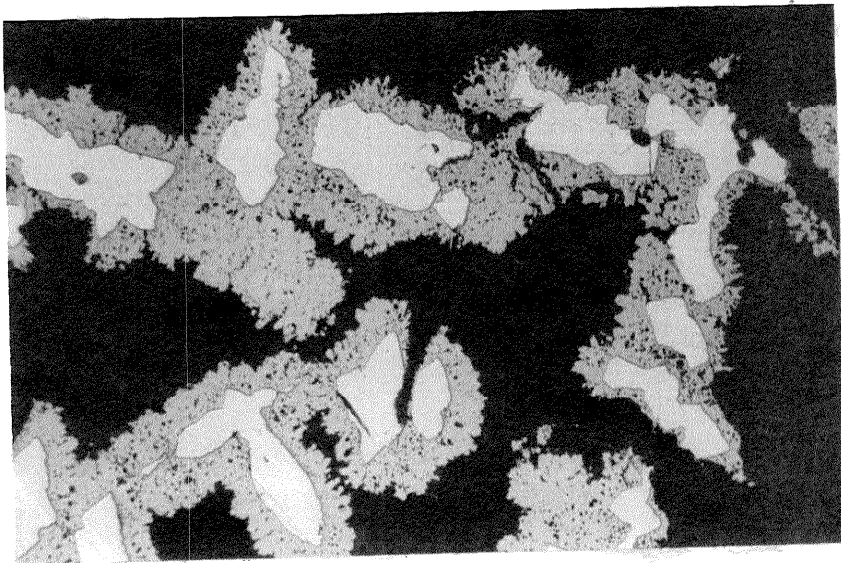
38B

38A. Safflorite (white) dendrites in dolomite (dark grey). Dendrites up to 0.25 inches long. Location unknown. x33

38B. Same specimen as Plate 36B but in reflected light. Safflorite dendrites and petals (white) in carbonate (dark grey). Safflorite walls are rimmed on both sides with minute, euhedral grains of a second arsenide. No. 5 vein, below 54 ore shoot. x33

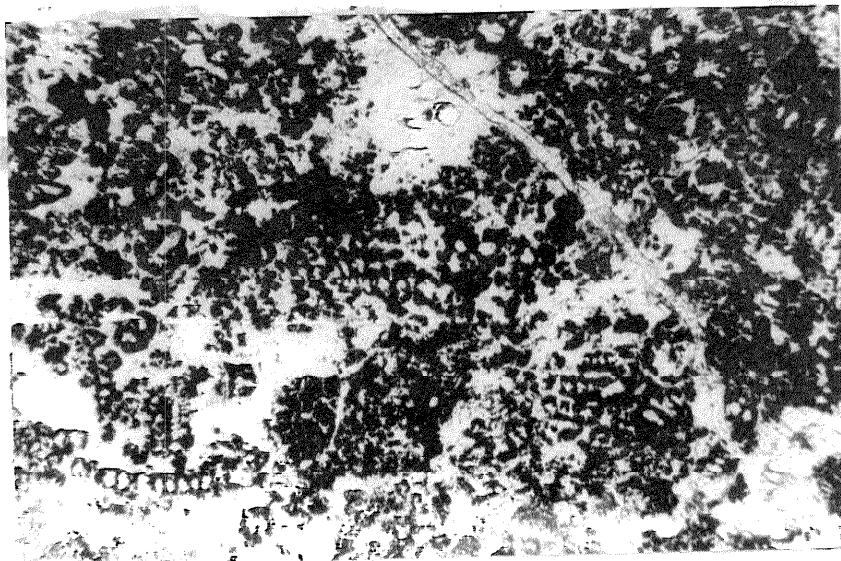


39A

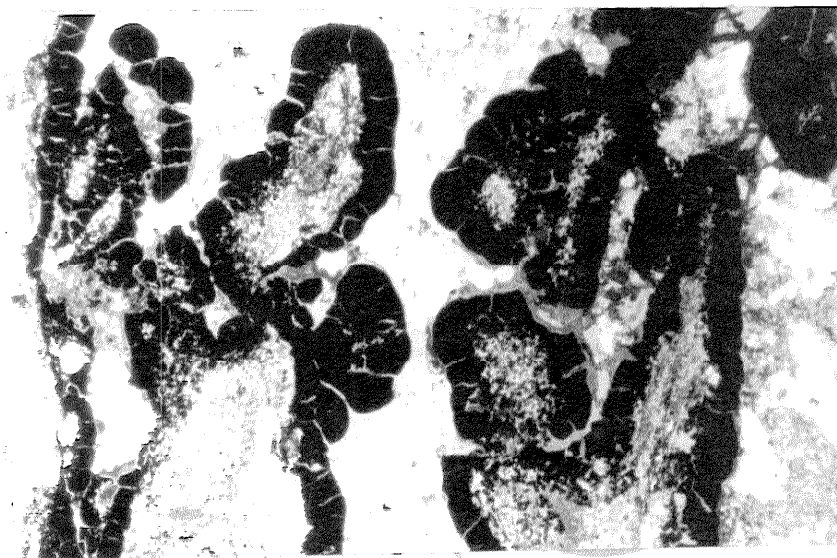


39B

- 39A. Pitchblende dendrites (medium grey) with native silver cores (white) surrounded by niccolite (very light grey) and carbonate (dark grey). Dendrites up to 0.25 inches long. B vein, 1175 level. x33
- 39B. Dendrites of grey, anisotropic arsenide (light grey) with native silver cores (white) in carbonate (dark grey). Dendritic structure not pronounced in plane of section. Dendrites up to 0.5 inches long. Reflected light. Silver Island vein, 650 level. x33

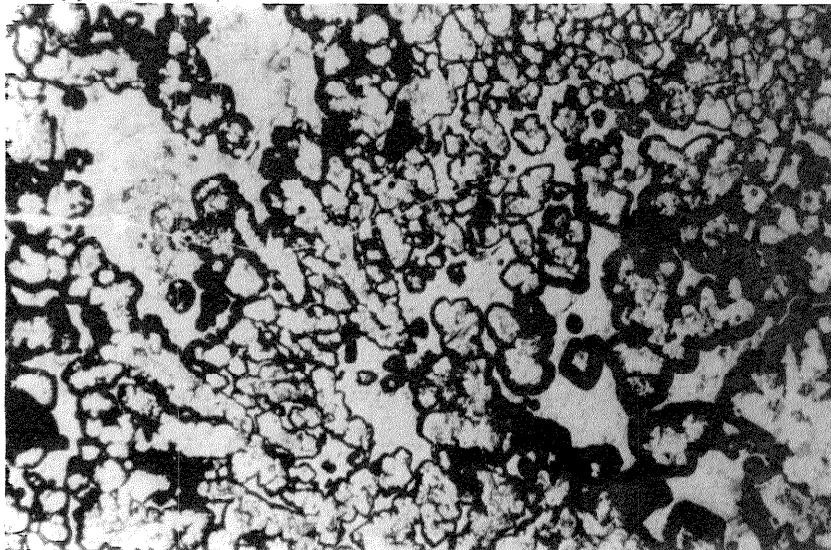


40A

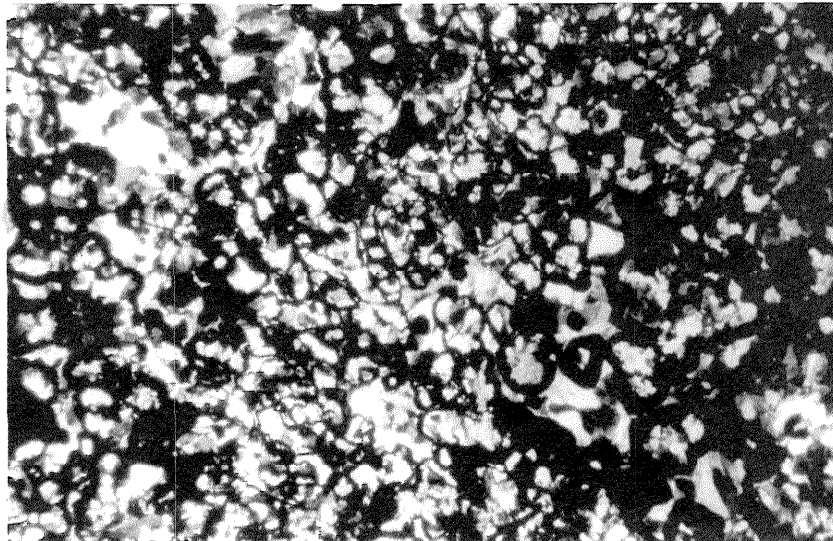


40B

- 40A. Unusual example of pitchblende dendrites (black) in chlorite. Dendrites are not well developed. Veinlet near upper right is of carbonate. No. 2 vein, 28 ore shoot. x33
- 40B. Thick rings of pitchblende (black) in a matrix of chlorite and minor quartz and carbonate. No. 3 vein, 32 ore shoot. x10



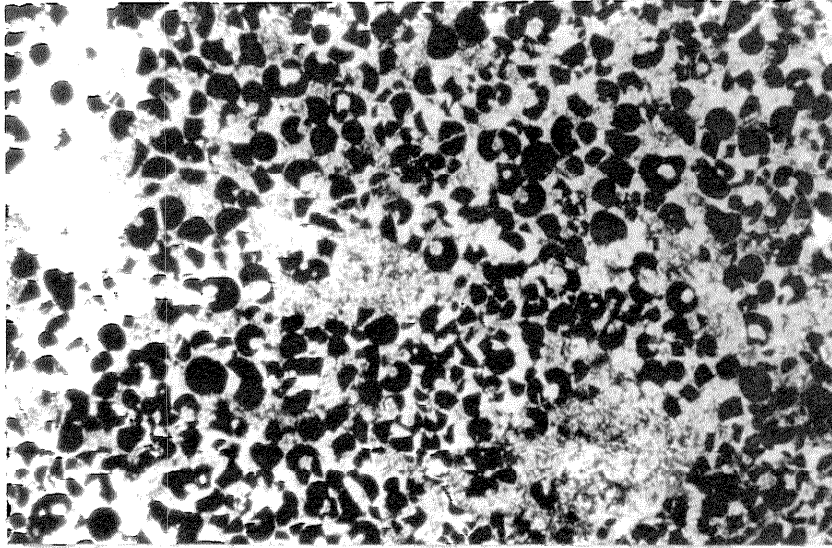
41A



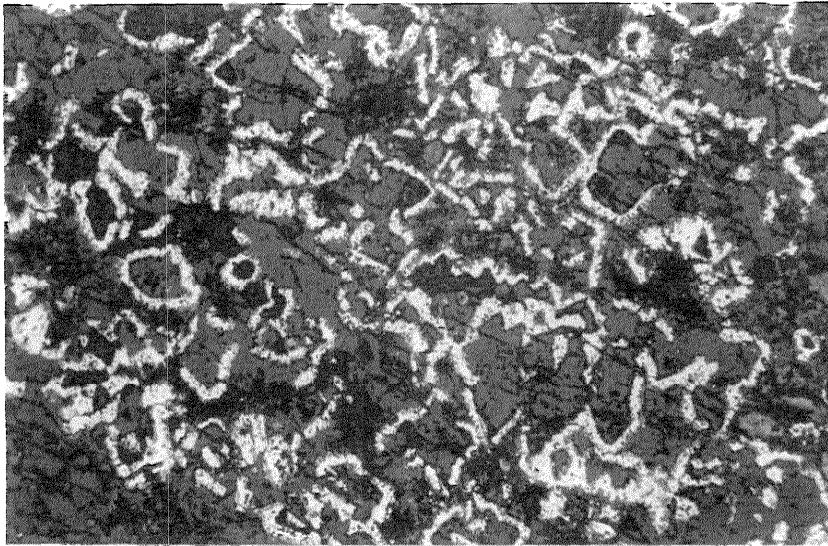
41B

41A. Pitchblende rings (black) in quartz (light grey). Rings do not appear to be gradational with dendritic forms. No. 1 vein, 13 ore shoot. x10.

41B. Same field as above but with crossed nicols. Pitchblende rings enclose aggregates of quartz grains and in some places cut through single quartz grains. x10



42A



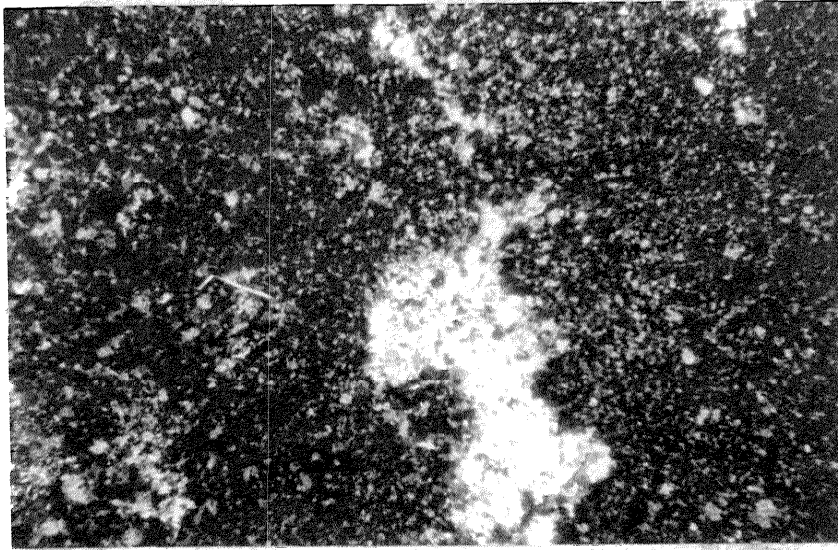
42B

42A. Pitchblende spherulites (black), in part broken, in fine grained quartz (light grey and white). Spherulites do not appear to coalesce to form dendrites. Same specimen as Plate 9 (autoradiograph). No. 1 vein, 13 ore shoot. x10

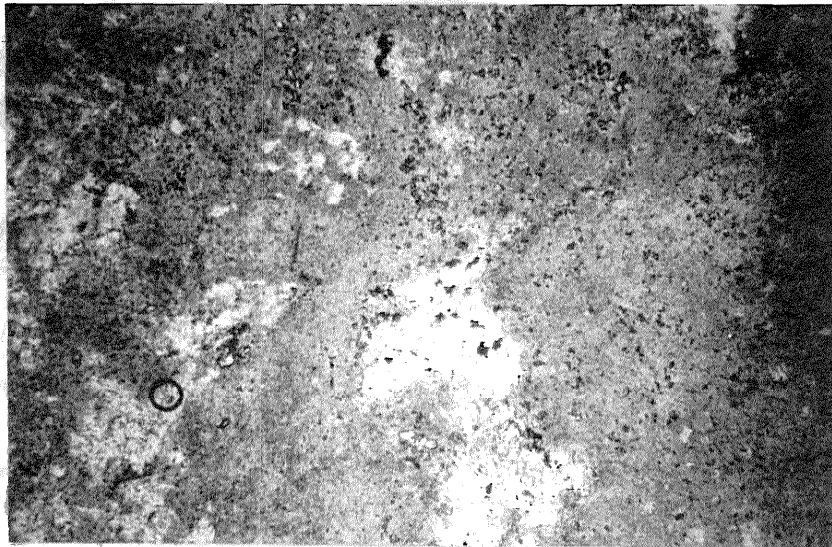
42B. Rings and poorly formed dendrites of zoned safflorite and allouclasite (white) in chloritic quartz gangue. The same specimen contains well formed arsenide dendrites and a few poorly formed pitchblende dendrites. No. 5 vein, 54 ore shoot. x33

PLATES 43 TO 48

WALL ROCK ALTERATION MINERALS



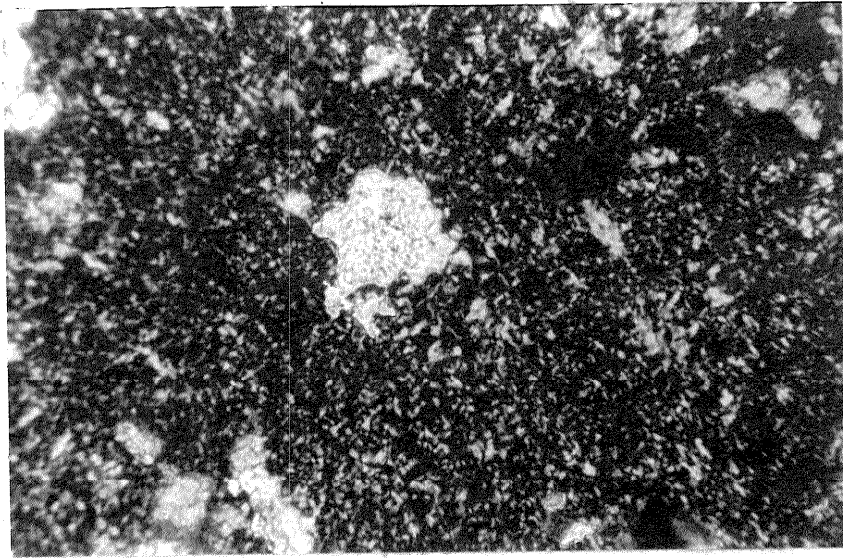
43A



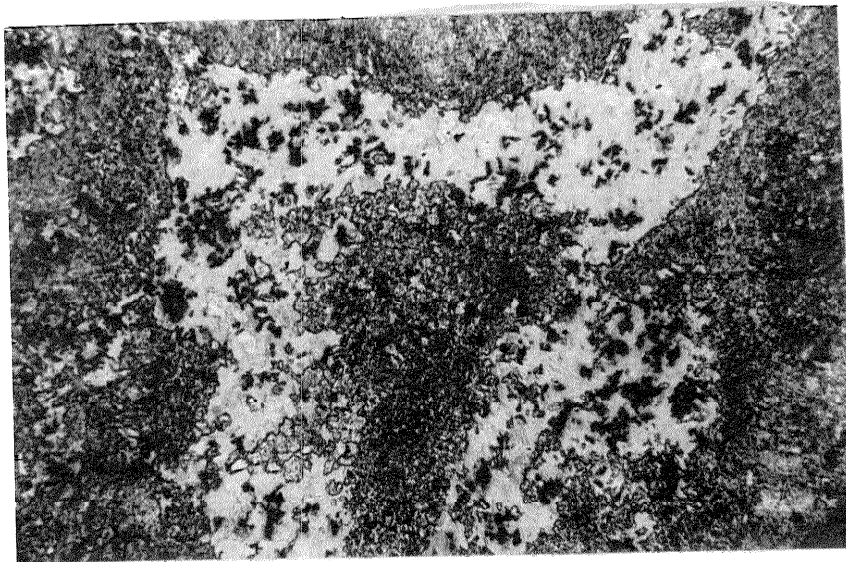
43B

43A. Fine grained albite completely altered to microcline (most of field). White grains are aggregates of residual quartz grains. Mine series tuffs 45 feet in hanging wall of 32 ore shoot, No. 3 vein. Crossed nicols. x33

43B. Same field as above but in plane polarized light. The microcline is very dark because of contained hematite dust.



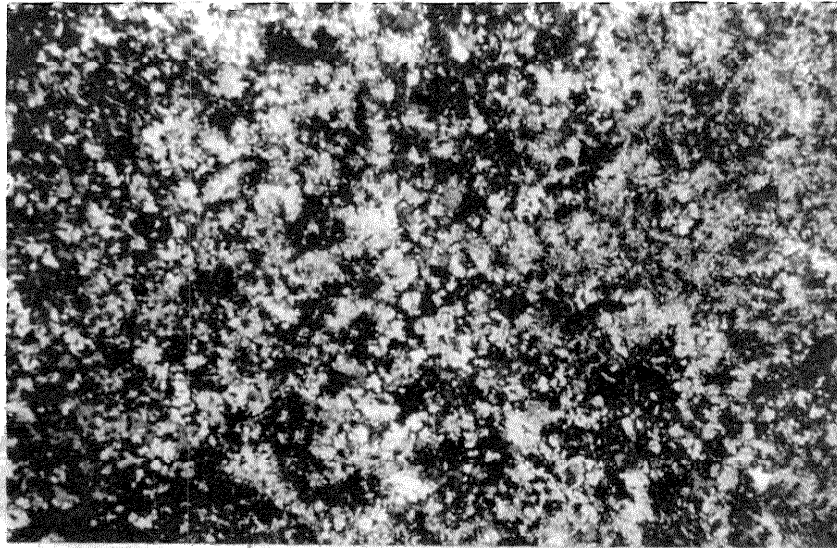
44A



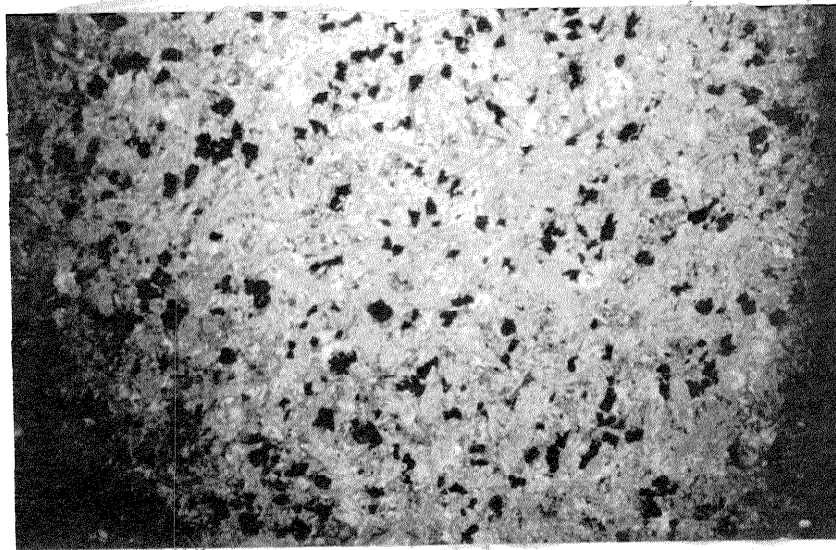
44B

44A. Typical texture of hydrothermal chlorite. Larger grains are carbonate. Crossed nicols. Location unknown. x135

44B. Patches of chlorite (medium grey) in field of fine-crystalline albite (dark grey). Note characteristic disseminated leucoxene (opaque grains) in chlorite. Mine series tuffs, footwall of 54 ore shoot, No. 5 vein. x33

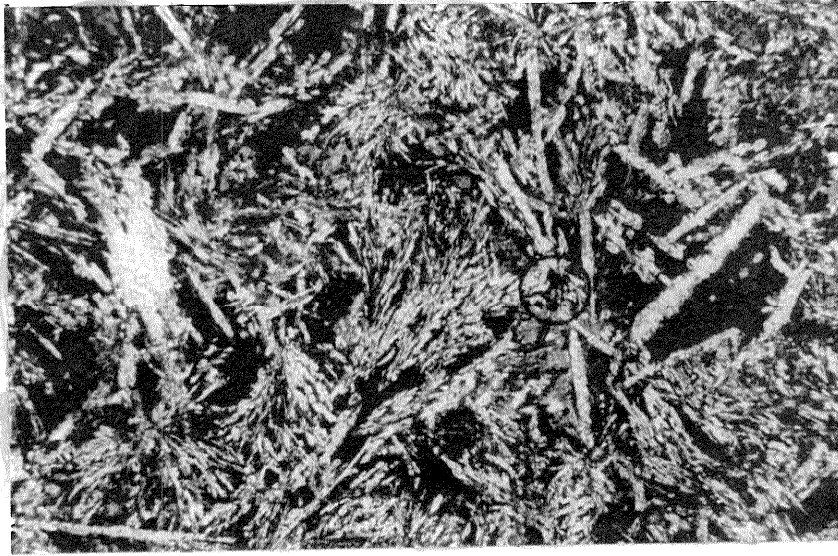


45A

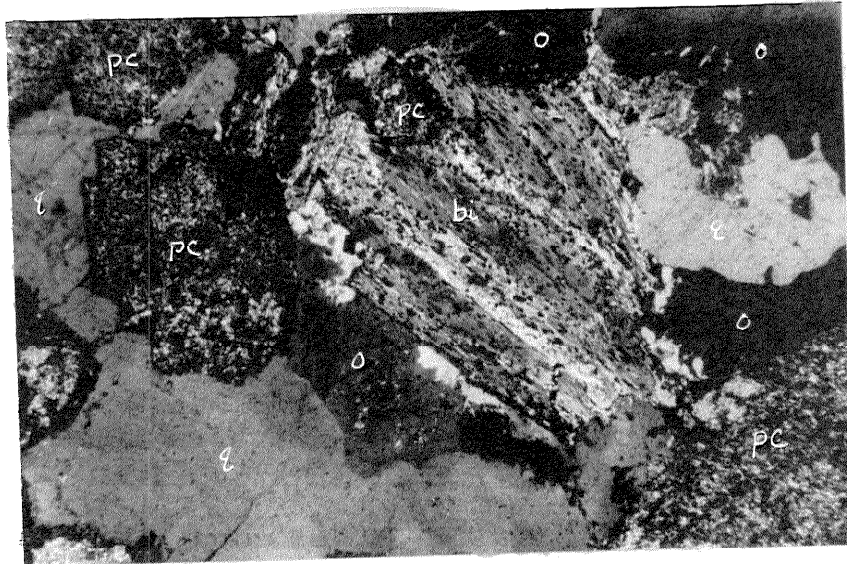


45B

- 45A. Mine series tuff completely altered to carbonate (light grey to white) and chlorite (black). Crossed nicols. Two feet in footwall, 21 ore shoot, No. 2 vein. x33
- 45B. Disseminated magnetite completely altered to leucoxene (opaque grains) in diabase dyke. Fifteen feet in footwall, 32 ore shoot, No. 3 vein. x10



46A



46B

46A. Plagioclase laths altered to fine-grained white mica (white) in diabase dyke. Pyroxene grains and groundmass are chloritized (dark grey to black). Crossed nicols. Hanging wall, 34 ore shoot, No. 3 vein. x33

46B. Granite in which biotite (bi) is completely altered to coarse-grained chlorite (grey) and white mica (white). Plagioclase (pc) is altered to fine-grained aggregates of the same minerals. Orthoclase (o) and quartz (q) essentially unaltered. Hanging wall of lower 31 ore shoot, No. 3 vein. Crossed nicols. x33

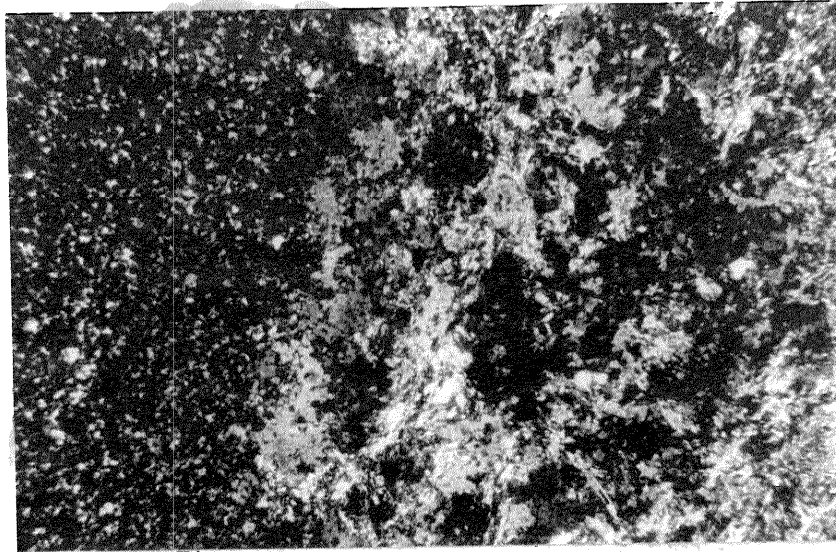
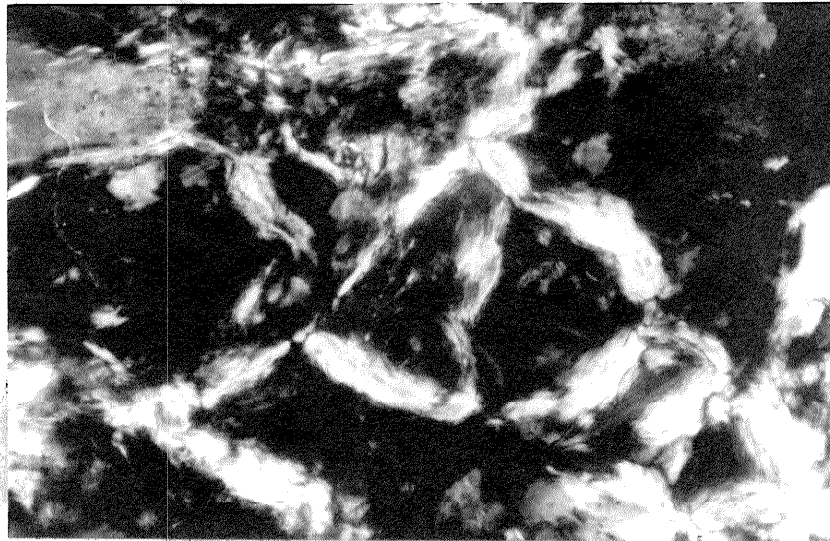
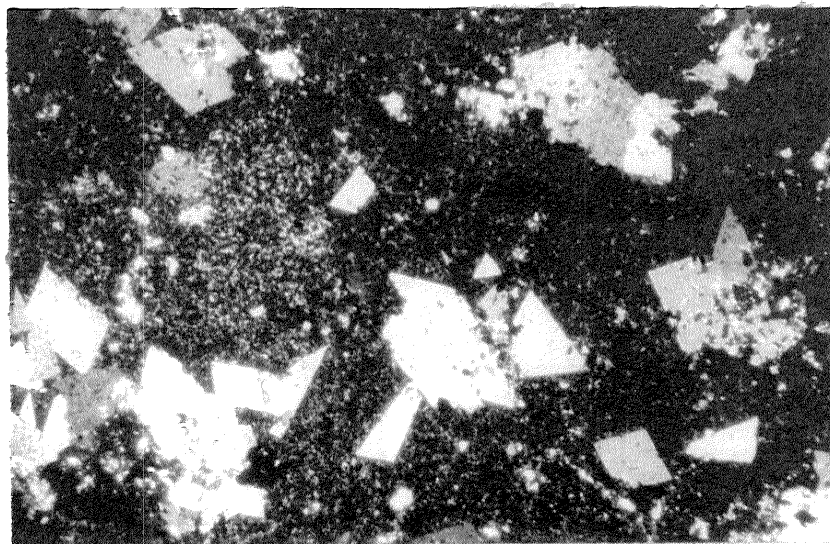


Plate 47A

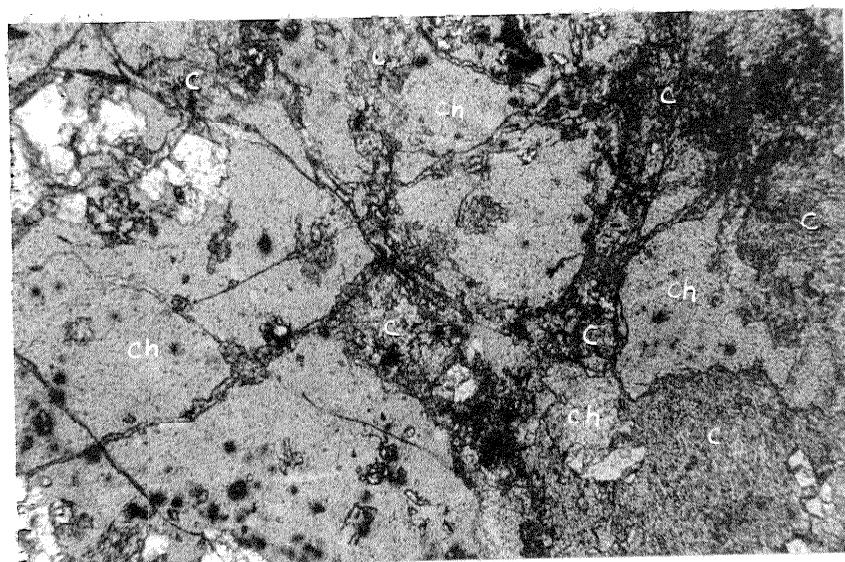


47B

- 47A. Completely microclinized, microcrystalline albite on left and fine-crystalline albite on right. Note that white mica (white) preferentially replaced the coarser grained microcline. Mine series tuff, footwall of No. 32 ore shoot, No. 3 vein. Crossed nicols. x33
- 47B. White mica (white) rimming fine-grained aggregates of chlorite (dark grey). The white mica is possibly younger than the chlorite. Footwall of 13 ore shoot, No. 1 vein. Crossed nicols. x600



48A



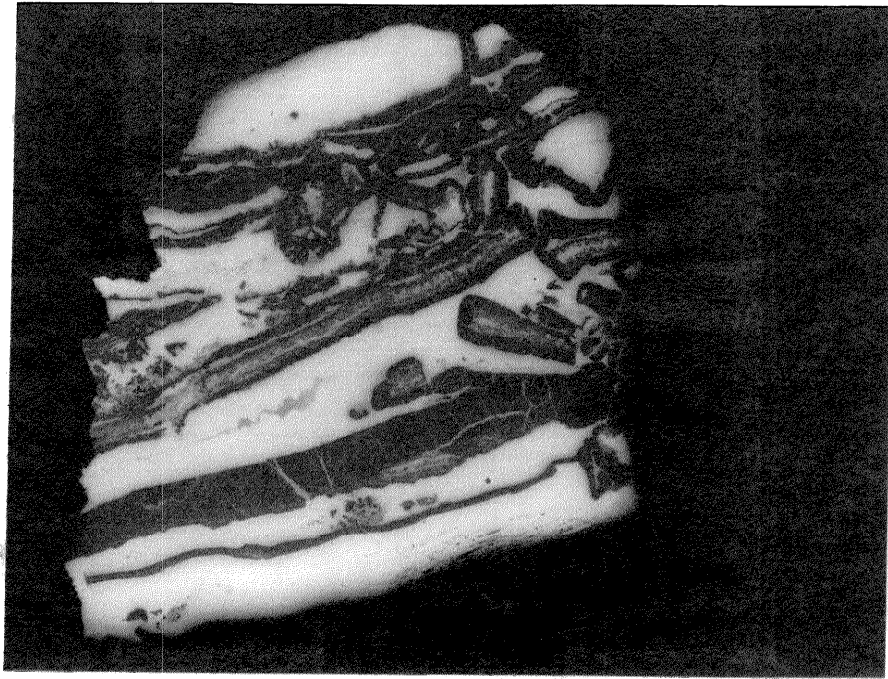
48B

48A. Replacement of microcline by euhedral carbonate. Mine series tuff, hanging wall of 32 ore shoot, No. 3 vein. Crossed nicols. x10

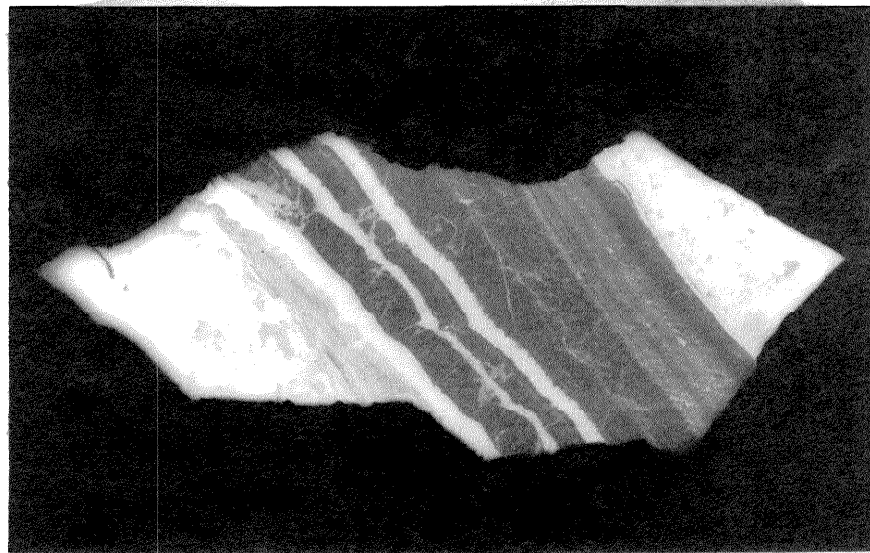
48B. Chlorite (ch) veined by carbonate (c). White grains are apatite. Location unknown. x33

PLATES 49 TO 53

SPECIMENS ANALYSED ISOTOPICALLY



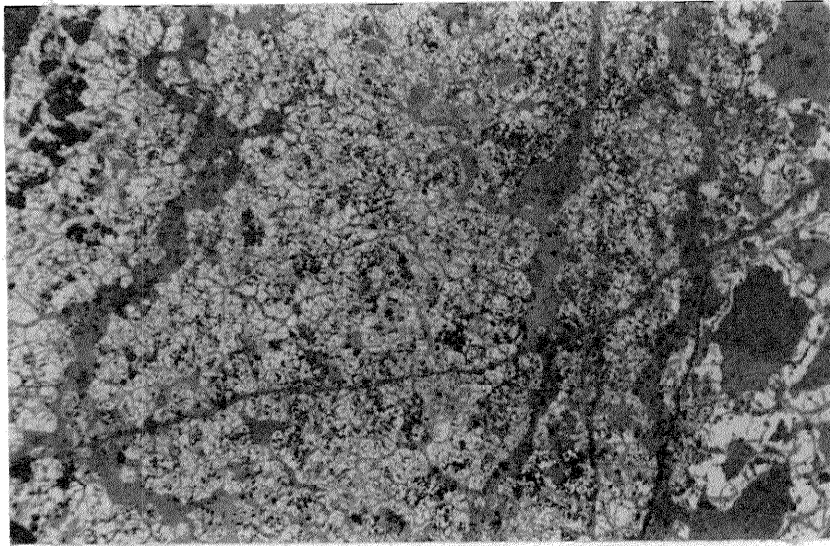
49A



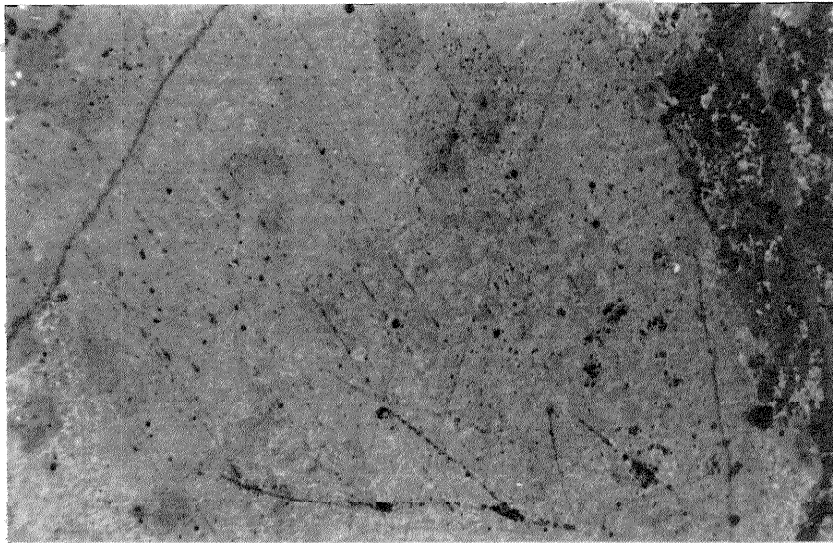
49B

49A. Autoradiograph of interbanded pitchblende (dark grey) and quartz (white). Spec. O13, No. 1 vein, 11 ore shoot. xl

49B. Autoradiograph of pitchblende (dark grey) in dolomite gangue. White zones, with weak radioactivity, on either end of specimen contain quartz and arsenide minerals. Spec. P.R. 33, No. 7 vein, 72 ore shoot. xl

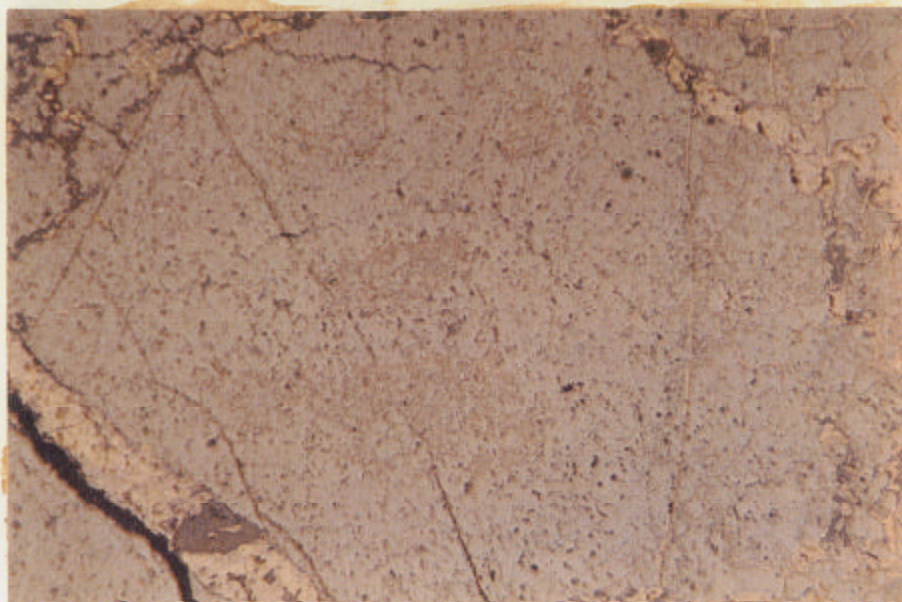


50A



50B

- 50A. Pitchblende (light grey) in dolomite (medium grey). Photograph is of the dense pitchblende zone on the left in Plate 49B. Spec. P.R. 33. x80
- 50B. Similar to Plate 50A but pitchblende apparently extensively replaced by dolomite. Photograph is of a less dense pitchblende zone near the right side of Plate 49B. Spec. P.R. 33. x80



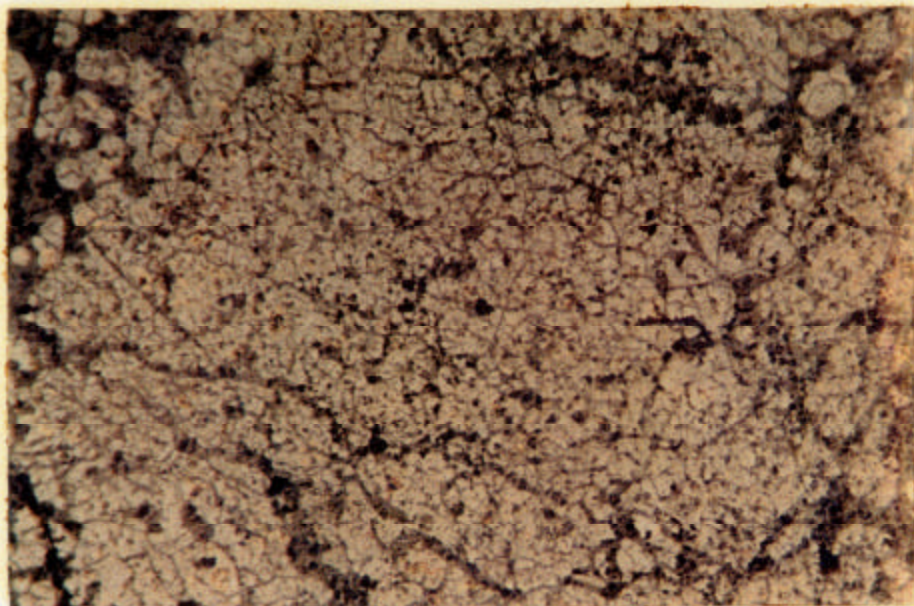
51A



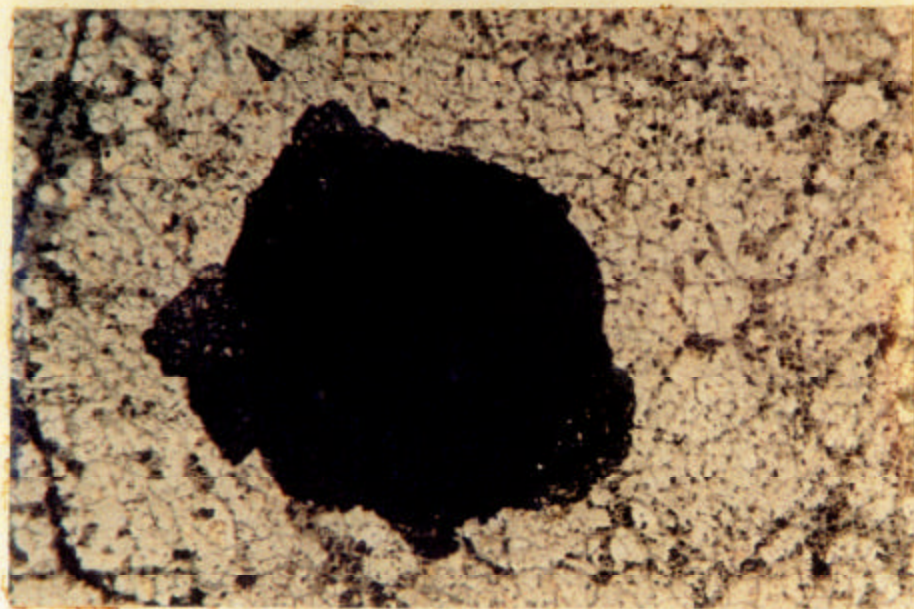
51B

51A. Veinlets and disseminations of chalcopyrite and bornite (yellowish) in pitchblende (medium grey). Spec. 013, No. 1 vein, 11 ore shoot. x90

51B. Same field as above after removal of drill hole sample for spectrometric analysis C-1.

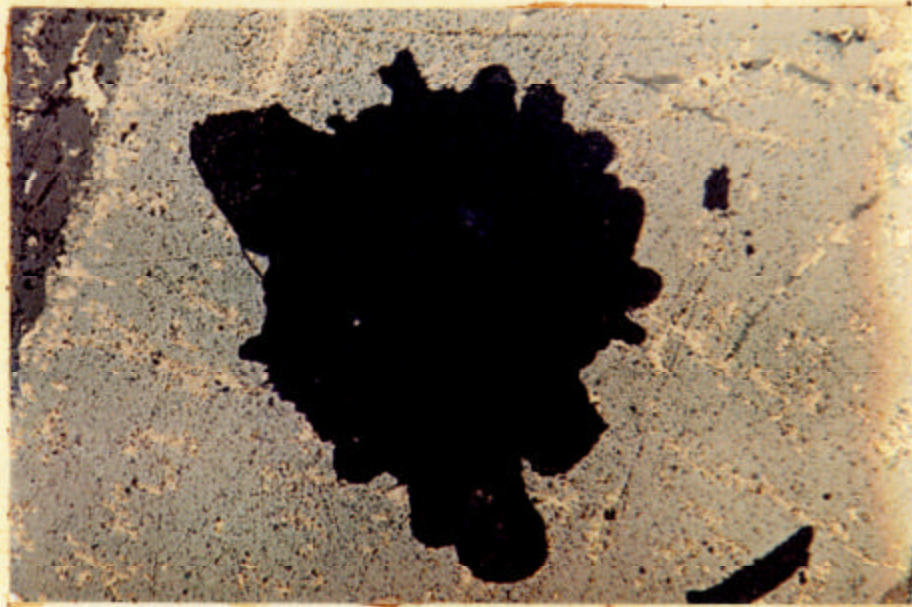


52A



52B

- 52A. Disseminated chalcopyrite (yellow) in pitchblende (medium grey). Dark grey patches and veinlets are dolomite. Specimen P.R.33, No. 7 vein, 72 ore shoot. x90
- 52B. Same field as above after removal of drill hole sample for mass spectrometric analysis C-3.



Pyrite and chalcopyrite (yellow) in fractures and disseminations in pitchblende (blue-grey). Drill hole sample (center of field) weighed 87 micrograms. Spectrometric analysis C-2. Spec. P.R. 85, 1 - 22 ore shoot, No. 1 vein. x90

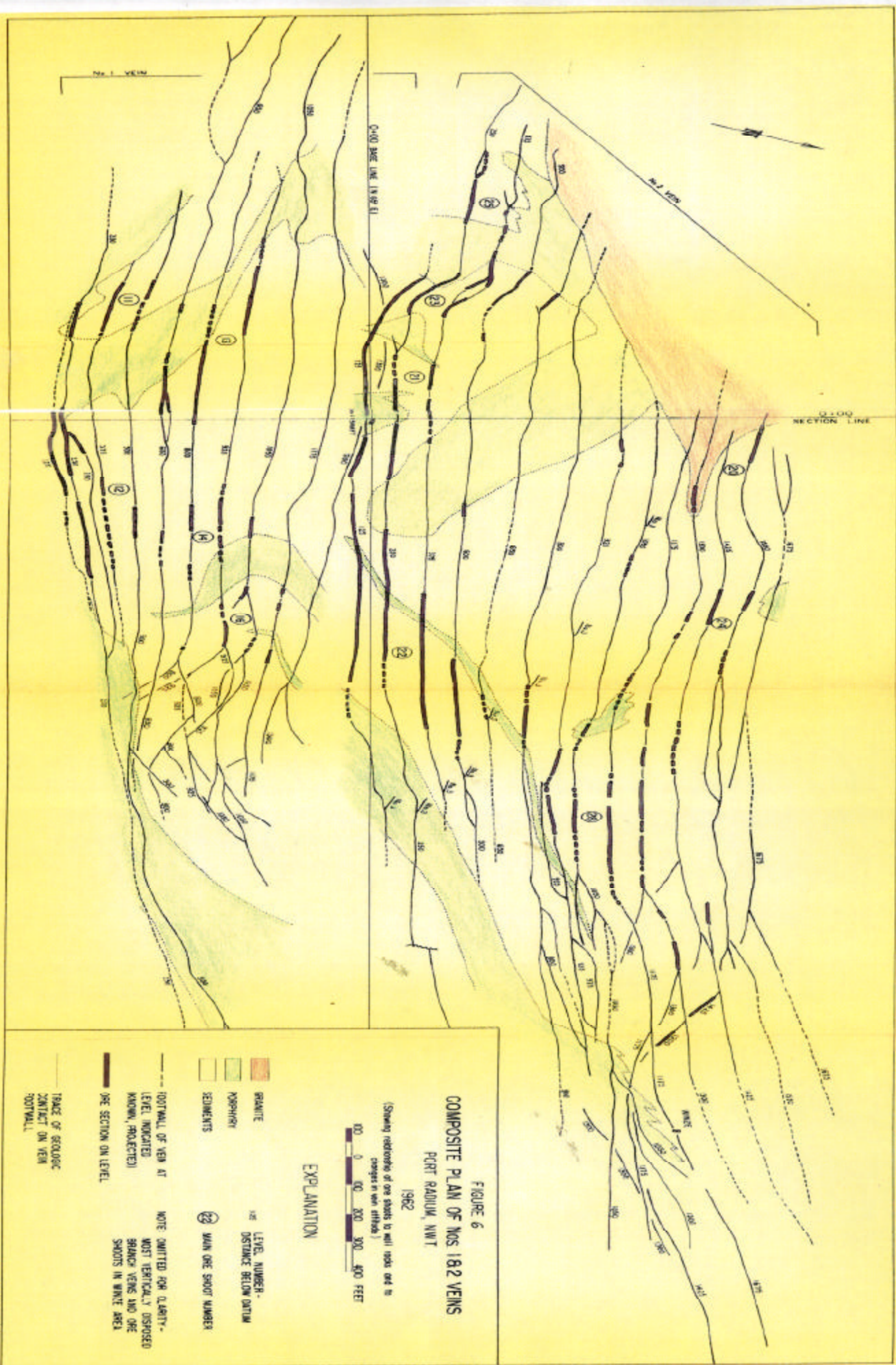


FIG 6

FIG. 4

