GEOLOGY OF THE PITCHBLENDE DEPOSITS OF PORT RADIUM, GREAT BEAR LAKE, N. W. T.

Thesis by

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ABSTRACT

The geology of the McTavish Arm area of Great Bear Lake, Northwest Territories, Canada, is reviewed and a geologic map is presented. The geology of the Labine Point region is described in detail. Intrusive feldspar porphyry bodies are haloed by contact metasomatic zones in which the lower Echo Bay cherty sediments have been enriched in Ca, Al, Mg and Fe by the development of ferromagnesian minerals. The sediments have been locally severely deformed by intrusion of the porphyry bodies. A body of massive crystalline tuff in the mine area is believed to be the remnant of a volcanic vent.

The ore deposits occur in a lenticular network of northeast-trending shear zones. Differences in wall rock competency have resulted in the development of relatively wide tensional fracture zones at various places along the shear systems. The pitchblende ore bodies occur in these zones of greater than usual dilation.

The mineralization of the Port Radium deposits occurred in five stages: I, hematite-quartz; II, pitchblende-quartz; III, quartz-cobalt nickel arsenides; IV, copper sulphides-chlorite; V, carbonate-silver. Deposition of pitchblende at Port Radium took place in dilated portions of the vein zones in the following manner: release of pressure in dilated zones caused loss of CO_2; loss of CO_2 resulted in drop of bicarbonate ion content and consequent decrease in the solubility of the uranium as a complex with carbonate; the uranium flocculated as the uranium colloid precipitate, pitchblende.

Brecciation and some redistribution of the pitchblende by later solutions is illustrated. Comparison is made between the mineralogy of Port Radium and other pitchblende deposits.

Possible sources of error in the lead isotope age determination of Port Radium pitchblende are discussed. Ages determined are believed to be too great by a factor of about three.

TABLE OF CONTENTS

PART	TITLE	PAGE
I.	INTRODUCTION	1
	Location	3
	Physiography	5
	Climate	8
	History	9
	Geologic work	12
II.	GENERAL GEOLOGY	
	REGIONAL GEOLOGY	15
	"Old Complex" rocks	17
	Gneiss complex	17
	Echo Bay Group	19
	Lower Echo Bay Subgroup	20
	Upper Echo Bay Subgroup	21
	Cameron Bay Group	24
	Eldorado vent	27
	Early intrusive rocks	
	Hypabyssal intrusives	28
	Quartz monzonite	31
	Granodiorite complex	32
	Quartz-eye porphyry	33
	Biotite granite	33
	Hornby Bay Group	35
	Late intrusive rocks	
	Trap dikes	35
	Diabase dikes	36
	Diabase sheets	37

TABLE OF CONTENTS (Cont'd)

Structure	
Folding	39
Fracturing	39
Periods of Mineralization	
Early mineralization	43
Giant quartz veins	43
Late mineralization	45
LOCAL GEOLOGY	
Geologic setting	48
Wall-rock units	50
Lower Echo Bay Sediments	52
Mine Series	
Cobalt Island Formation	54
Mine Formation	57
Tuff Series	
Transition Formation	64
Tuff Series	67
Massive crystalline tuff, Eldorado vent	73
External structures	74
Internal structures	78
Lithology	79
Origin	
Sedimentary	83
Intrusive	84
Volcanic vent	85

TABLE OF CONTENTS (Cont'd)

Lithology	86
Structure	89
Summary	90
Intrusives	
Feldspar porphyry	93
Mode of emplacement	95
Petrology - Crystalline variety	100
Aphanitic variety	102
Alteration	104
Granite and aplites	108
Diabase	111
Metamorphism	114
Zoning	116
Facies	121
Textural changes	122
Chemical changes	128
Progressive metamorphism	130
Thermal stage	130
Metasomatic stage	131
Retrograde stage	134
Changes in competency	135
Structure	137
Granite	140
Diabase	140
Feldspar porphyry intrusives	142
Eldorado vent	144
Mine series	145

TABLE OF CONTENTS (cont'd)

III. PORT RADIUM DEPOSITS 151

MAJOR FRACTURE SYSTEM 151

No. 1 Vein 160

No. 2 Vein 166

No. 2A Vein 167

No. 3 Vein 167

Western section 170

Central section 170

Upper east section 171

Lower east section 171

Mineralization 172

No. 5 Vein 172

No. 6 Vein 173

No. 7 Vein 173

No. 8 Vein 178

Silver Island Vein 178

No. 4 Vein 179

No. 9 Vein 179

Bear Bay Shear 179

Tensional opening of vein zones 180

Minor fractures 183

ORE DEPOSITION 184

Stage I

Hematite-quartz 188

Stage II

Pitchblende-quartz 189

TABLE OF CONTENTS (Cont'd)

Stage III	
Quartz	201
Cobalt-nickel arsenides	202
Stage IV	
Copper sulphides	206
Chlorite-clay	209
Stage V	
Carbonate-silver sulphides	214
Silver	220
Surface oxidation	221
Paragenesis	223
Chemistry of pitchblende deposition	225
Comparison with other deposits	229
Mineralogy	229
Texture	229
Radiocolloids	231
Age determinations	233
WALL ROCK ALTERATION	260
Red alteration	261
Influence on host rocks	263
Distribution	264
Other occurrences	265
Argillic alteration	266
Influence on host rocks	269
Distribution	271
Other occurrences	272

TABLE OF CONTENTS (Cont'd)

Chlorotization	275
Influence on host rocks	276
Distribution	277
Carbonatization	278
Influence on host rocks	279
Distribution	279
Minor alterations	
Silicification	280
Sulphidization	281
Sericitization	283
Zoning of alterations	283
Relation of alterations to mineralization stages	285
Chemistry of alterations	
Red alteration	286
Argillic alteration	287
Chloritization	289
Carbonatization	289
Silicification	290
Summary	290
<u>FACTORS INFLUENCING ORE LOCALIZATION</u>	292
Description of orebodies	
No. 1 Vein	292
13 Orebody	293
Lower 14 Orebody	295
Upper 14 Orebody	296
11 Orebody	296

TABLE OF CONTENTS (Cont'd)

No. 2 Vein	296
Western orebodies	297
24-26 "	297
No. 3 Vein	299
No. 4 Vein	300
No. 5 Vein	300
No. 7 Vein	301
No. 6 - 8 - 9 Veins	302
Physical factors	302
Structural control at other deposits	304
Chemical factors	305
Principal agent for the precipitation of pitchblende	308
Regional control	309
SUMMARY AND CONCLUSIONS	
Regional geology	311
Local geology	312
Port Radium deposits	314
REFERENCES	317

LIST OF ILLUSTRATIONS

FIGURE	TITLE	PAGE
Frontispiece	Photograph of Port Radium	
1	Index map; showing location of Port Radium	2a
2	Geological map of McTavish Arm area, Great Bear Lake, N. W. T.	Pocket
3	Geological map of Echo Bay area, Great Bear Lake, N. W. T.	47
4	General geological map of Labine Point-Weiner Bay area	Pocket
5	Detailed geological map of Labine Point	Pocket
6	Diagram of stages of tensional deformation of formations in McTavish Arm area	44
7	Photograph of Labine Point, looking south-west from No. 2 Shaft	47b
8	Photograph of Crossfault Lake, looking east from No. 2 Shaft	47b
9	Photograph of Cobalt Island Formation cherts and Eldorado vent	72
10	Photograph of Mine Formation cherts	72
11	Structural contours of Eldorado vent	75
12	Contact features of Eldorado vent	76
13	Photomicrograph of non-sutured variety of massive crystalline tuff	82
14	Photomicrograph of sutured variety of massive crystalline tuff	82
15	Structures of some vents and calderas	91
16	Photograph of contact of massive crystalline tuff and Mine Series cherts. Labine Point	97
17	Photograph of contact of intrusive feldspar porphyry. North shore of Labine Bay	97
18	Photograph showing folding of cherts near porphyry contact. Labine Point	98

19	Photograph showing deformation of sediments near porphyry contact. No. 2 Shaft area	98
20	Photomicrograph of crystalline variety of intrusive feldspar porphyry. No. 1 Body, north shore of Labine Bay	105
21	Photomicrograph of typical aphanitic variety of intrusive feldspar porphyry. Labine Point	105
22	Paragenesis of late hydrothermal minerals in some Colorado sills and in Great Bear Lake porphyritic intrusives	107
23	Variously digested massive crystalline tuff xenoliths in granite near contact. Northwest shore of Labine Point	112
24	Granitized xenoliths, detail of Fig. 23	112
25	Map showing location of porphyritic intrusives and related metasomatised zones. Labine Point	118
26	Photomicrograph of metasomatic minerals in chert	126
27	As Fig. 26, with crossed nicols	126
28	Paragenesis of metamorphic minerals at Port Radium	130b
29	Photograph showing hornblende along bedding planes of chert. Labine Point	136
30	Photograph showing veining and brecciation of sediments by late metasomatic assemblages. No. 2 Shaft area	136
31	Cross-section showing the location of porphyry intrusive bodies and the deformation of the Mine Series. Labine Point	147
32	Map illustrating deformation of Mine Series	148
33	Aerial photograph of Port Radium area. (With overlay.)	150a, 150b

LIST OF ILLUSTRATIONS (Cont'd)

34	Map showing fracture pattern on Labine Point	155
35	Vertical cross-section through the Eldorado Mine	156
36	Vertical cross-section of principal vein zones	157
37	Legend for vein zone illustrations	162
38	No. 1 Vein. Wide section. Plan 1" = 20'	163
39	No. 1 Vein. Typical barren sections	164
40	No. 1 Vein. Typical ore section	165
41	No. 2 Vein. Typical barren sections	168
42	No. 2 Vein. Typical ore section	
	No. 2A Vein. Typical section	
43	No. 3 Vein. Typical central and upper east section	174
44	No. 3 Vein. Typical central section	175
45	No. 3 Vein. Typical western and upper east section	176
46	No. 3 Vein. Typical lower eastern section	177
	No. 5 Vein. Typical ore section	
47	Vein zones open during each stage of mineralization	187
48	Photomicrograph showing pitchblende and quartz in situ	194
49	Photomicrograph showing rhythmic layered quartz and pitchblende	194
50	Photomicrograph showing replacement of loose pitchblende spherules in late ore quartz	195
51	Photomicrograph showing late ore-quartz breaking pitchblende and occupying cracks	195

LIST OF ILLUSTRATIONS (Cont'd)

52	Photomicrograph showing pitchblende fragments in ore-quartz but not in later quartz	198
53	Photomicrograph showing flow orientation of pitchblende fragments in ore-quartz	198
54	Camera lucida showing replacement of pitchblende by cobalt-nickel arsenides	205
55	Camera lucida showing replacement of quartz around pitchblende by cobalt-nickel arsenides	205
56	Camera lucida showing typical association of bornite with pitchblende in chalcopyrite	207
57	Camera lucida, as Figure 56	207
58	Photomicrograph showing pitchblende bands in quartz replaced by chlorite	211
59	Photomicrograph showing pitchblende fragments in chlorite veinlet cutting earlier quartz	211
60	Photomicrograph showing brecciated pitchblende and quartz in chlorite	212
61	Photomicrograph showing pitchblende replaced pseudomorphically by chlorite	212
62	Photomicrograph showing pitchblende relicts in carbonate-chlorite	217
63	Photomicrograph showing pitchblende replaced by chlorite and both by carbonate	217
64	Photomicrograph showing carbonate replacing pitchblende	218
65	Photomicrograph showing quartz brecciating pitchblende and replaced by carbonate	218
66	Photomicrograph showing carbonate dendritically replacing pitchblende	219
67	Photomicrograph showing carbonate dendritically replacing pitchblende	219

LIST OF ILLUSTRATIONS (Cont'd)

68	Paragenesis of primary vein minerals at Port Radium	223b
69	Photograph of massive pitchblende	240
70	Photograph of "bubble" pitchblende in argillic gangue	240
71	Photograph of relict pitchblende bands in banded carbonate, clay and chlorite	241
72	Photograph of relict pitchblende, niccolite and apatite in dolomite	241
73	Autoradiograph (with overlay) of primary pitchblende	243, 243b
74	Autoradiograph (with overlay) of massive pitchblende	244, 244b
75	Autoradiograph (with overlay) of rhythmic banded quartz and pitchblende	245, 245b
76	Autoradiograph (with overlay) of rhythmic banded quartz and pitchblende	245, 245b
77	Autoradiograph (with overlay) of simultaneous quartz and pitchblende	246, 246b
78	Autoradiograph (with overlay) of pitchblende and quartz along fracture in jasperized rock	246, 246b
79	Autoradiograph (with overlay) of dendritic pitchblende	247, 247b
80	Autoradiograph (with overlay) of pitchblende and quartz being replaced by chlorite and carbonate	247, 247b
81	Autoradiograph (with overlay) of pitchblende being replaced and ghosted by late carbonate	248, 248b
82	Autoradiograph (with overlay) of moderately brecciated pitchblende in dolomite	248, 248b
83	Autoradiograph (with overlay) of brecciated wall rock in pitchblende	249, 249b

84	Autoradiograph (with overlay) of pitchblende around fragments of quartz in chlorite vein	250, 250b
85	Autoradiograph (with overlay) of primary pitchblende around red altered porphyry fragments	250, 250b
86	Autoradiograph (with overlay) of "breccia ore"	251, 251b
87	Autoradiograph (with overlay) of typical "breccia ore"	252, 252b
88	Autoradiograph (with overlay) of "chlorite ore"	253, 253b
89	Autoradiograph (with overlay) of pitchblende fragments in clay-chlorite-chalcopyrite	254, 254b
90	Autoradiograph (with overlay) of pitchblende fragments in chalcopyrite and minor chlorite ("sulphide ore")	254, 254b
91	Autoradiograph (with overlay) of massive pitchblende and "diffuse ore"	255, 255b
92	Autoradiograph (with overlay) of very "diffuse ore" (chlorite-clay)	256, 256b
93	Autoradiograph (with overlay) of radiocolloids in brecciated ore	257, 257b
94	Autoradiograph (with overlay) of undisturbed, brecciated, and diffused pitchblende	258, 258b
95	Autoradiograph (no overlay) of undisturbed pitchblende (Detail of Fig. 94)	259, 259b
96	Autoradiograph (with overlay) of brecciated pitchblende (Detail of Fg. 94)	259
97	Photograph of No. 3 Vein (North Branch). Ore section. Photo, courtesy R. Lasby	291
98	Photograph of No. 3 Vein (North Branch). Barren section. Photo, courtesy, L. Jory.	291

LIST OF ILLUSTRATIONS (Cont'd)

99	No. 1 Vein orebodies. Longitudinal vertical section	Pocket
100	Contours on No. 1 Vein. Longitudinal vertical section	Pocket
101	No. 2 Vein, western and upper orebodies. Longitudinal vertical section	Pocket
102	No. 3 Vein, central orebodies. Longitudinal vertical section	Pocket
103	No. 5 Vein, western orebodies. Lontitudinal vertical section	Pocket

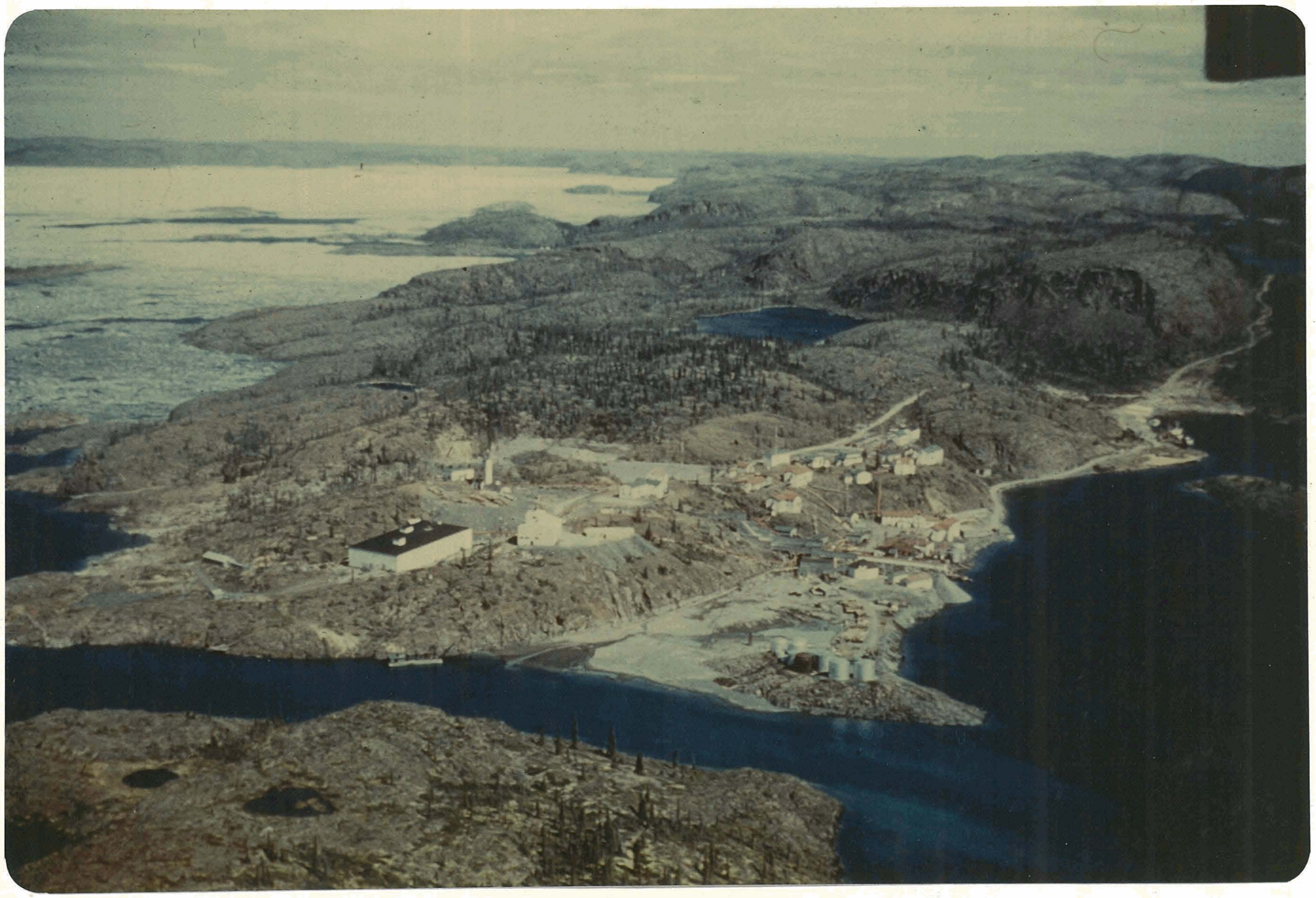
LIST OF TABLES

TABLE	TITLE	PAGE
1	Table of formations; McTavish Arm area	18
2	Table of formations; Eldorado Mine area	51
3	Recent and fossil calderas	87
4	Analyses of Port Radium pitchblende	192b

Port Radium Northwest Territories Canada

Frontispiece

Photo courtesy H. E. Lake



Port Radium Northwest Territories Canada

Photo courtesy H. E. Lake

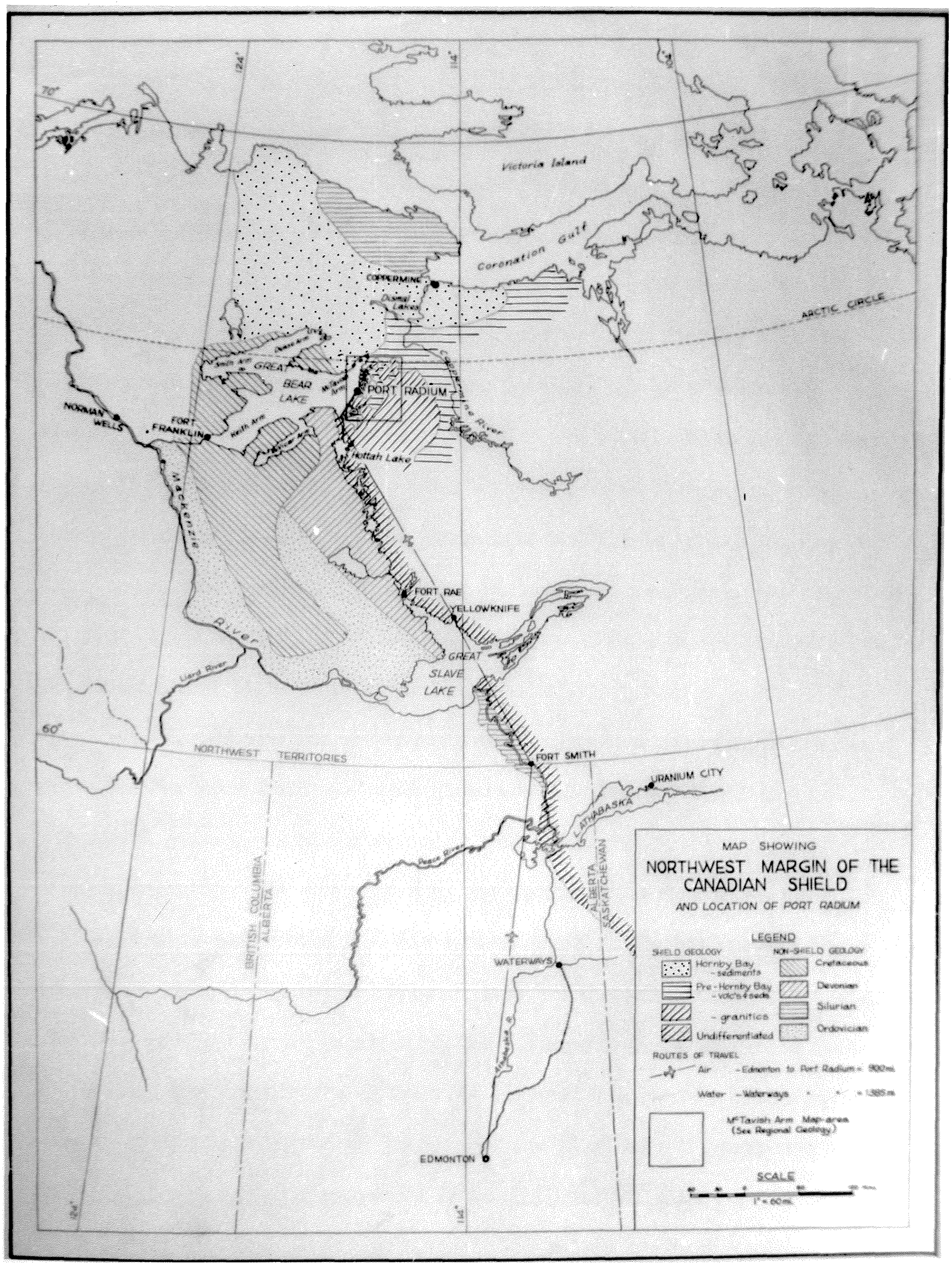
INTRODUCTION

J. MacIntosh Bell, a Canadian Survey geologist, exploring Great Bear Lake during the summer of 1899, noted that "In the greenstones, east of MacTavish Bay, occur numerous interrupted stringers of calc-spar containing chalcopyrite and the steep rocky shores which here present themselves to the lake are often stained with cobalt-bloom and copper-green."(1)

The publication of this sentence produced effects seldom equalled by many such routine observations for, thirty years later, it excited the interest of prospector-promoter Gilbert Labine who, upon investigation, found the stained cliffs noted by Bell. There Labine developed the Eldorado Mine. In 1944, the first atom bomb, using uranium products from Port Radium pitchblende, was exploded in New Mexico, ushering in the Atomic Age.

Until other sources of uranium in Canada, U.S.A., and elsewhere had been brought into production in the early fifties, the Eldorado Mine at Port Radium was one of the two sources of radioactive products for the western nations. At the present time when many new deposits are being discovered and developed it is of special value and interest to examine in detail the geologic features peculiar to the Port Radium deposits.

The dominant results of five years' detailed geologic investigation of the Port Radium Mine and vicinity are presented here with the hope that answers derived at Port Radium will facilitate understanding of similar uranium deposits elsewhere. A fairly comprehensive account of most of the geologic features is presented, but definite emphasis is placed on those features known, or believed, to have been important in the control of deposition of uranium ore. It is planned that features not discussed in detail in this report will be dealt with in later reports.


MAP SHOWING
NORTHWEST MARGIN OF THE CANADIAN SHIELD
AND LOCATION OF PORT RADIUM
LEGEND
SHIELD GEOLOGY
NON-SHIELD GEOLOGY
Hornby Bay - sediments
Pre-Hornby Bay
- granitics
Undifferentiated
Cretaceous
Devonian
Silurian
Ordovician
ROUTES OF TRAVEL
Air
Water
SCALE
Victoria Island
Coronation Gulf
COPPERMINE
ARCTIC CIRCLE
GREAT BEAR LAKE
PORT RADIUM
NORMAN WELLS
FORT FRANKLIN
Hottah Lake
Mackenzie River
FORT RAE
YELLOWKNIFE
GREAT SLAVE LAKE
Liard River
NORTHWEST TERRITORIES
FORT SMITH
URANIUM CITY
LATHABASKA
Peace River
BRITISH COLUMBIA
ALBERTA
SASKATCHEWAN
WATERWAYS
EDMONTON

LOCATION

Great Bear Lake lies on the Arctic Circle one hundred miles east of the Mackenzie River in the Northwest Territories, Canada. The lake has an area of approximately 12,000 square miles. It is the fourth largest lake on the North American continent and the largest completely within Canadian territory. It lies in a sparsely-timbered lake-dotted wilderness on the edge of the treeless Barren Lands, which cover Northern Canada to the east. This lake is very irregular in shape and is essentially made up of five large arms, three pointing southwest, one northeast and the largest, McTavish Arm, pointing east. Port Radium lies on Labine Point, the western tip of a large peninsula midway up the east shore of McTavish Arm. (Figures 1 and 2).

Aircraft are the most practical means of passenger transportation to Port Radium, and Eldorado Mining and Refining Ltd. transport planes maintain summer and winter service to the mine from Edmonton, 950 air miles to the south. Charter aircraft on floats or skis are based 270 air miles south at Yellowknife. In winter the wheel-equipped aircraft land on the lake ice at the mine; in summer they fly to an airstrip on the south shore of Great Bear Lake, and the remainder of the trip to Port Radium is made by boat. Heavy freight is shipped on barges of the Northern Transportation Co., a subsidiary of Eldorado, from railhead at Waterways, Alta., down the Mackenzie River system 1,380 miles to Port Radium. Water transport operates from about July 10 to October 20. All transportation to and from the mine is suspended during freezeup, (November) and breakup (June).

PHYSIOGRAPHY

The western edge of the Canadian Shield extends across the end of McTavish Arm of Great Bear Lake and lies about 20 miles west of the east shore of the Arm. Generally there is a marked contrast between the physiographic expression of the pre-Cambrian rocks to the east and that of the Mesozoic and Paleozoic rocks which underlie the rest of the lake basin to the west. The slightly folded soft Mesozoic and Paleozoic rocks form rolling hills, cuestas and plateaus and produce long smooth shores whereas the resistant highly folded pre-Cambrian rocks form rugged scarp-faced hills, ridges and lake-filled gullies, and produce the very complex shoreline of east McTavish Arm, replete with bays, islands and fjord-like inlets. Labine Point, a low rocky promontory, forms the southwest tip of an eight-mile-long peninsula that lies between Lindsley Bay to the north and Echo Bay to the south (Fig. 3). Labine Point is low-lying relative to the lake-level, and a 300 foot scarp one mile northwest separates the point from the more rugged topography of the main peninsula where the highest peak is about 650 feet above Great Bear Lake. Topographically, the Echo Bay area is at the abrupt western edge of a rugged range of hills that extends about twenty miles inland. To the east the hills grade into uplands which farther east grade into the Barren Lands. This range of high hills rises abruptly along the east shore of McTavish Arm with the highest peaks (about 1500 feet above lake-level), near the southeast corner of the lake and the lowest relief, (about 700 feet), around Hunter Bay in the northeast corner. Thus the range declines gradually to the north and around Echo Bay rises to about 1,000 feet. The topography near the lake shore is very rugged. Vertical cliffs, hundreds of feet high, fringed with extensive talus slopes, are numerous. Many hills have rounded tops, gentle slopes to the east and abrupt west-facing scarps. This physiography suggests a westward flow of the continental glaciers that crossed this region.

Glaciers have stripped and scoured the east shore area to such an extent that about 50 percent of the ground is outcrop. Smoothly planed outcrops and glacial striae, striking about S 70° E, are very widespread. Thus much of the upland is largely devoid of soil cover, and the valleys and depressions are usually floored with detrital material, talus and drift or filled by lakes. This seriously affects prospecting because most of the veins underlie drift-filled breaks. Outcrops are generally extensively covered with lichen and stains. Weathering has not proceeded far enough to reflect differentiation of most rock types. Forests are not dense but are widespread and consist predominantly of white spruce, with local white birch, willow, alder and aspen. Trees measuring 20 inches in diameter at the base are not uncommon in sheltered regions.

Glacial deposits are not widespread. They consist of boulder clay and morainal material scattered in hollows and some valleys. Erratic boulders of granite gneiss up to 10 feet in diameter are common on flat hills. By far the most extensive post-glacial deposits are raised lacustrine boulder gravel and sand beaches and plains. Because of the rugged topography such beaches are not extensive, being confined to valleys and embayments in hillsides; however, one beach near Hornby Bay at the north end of McTavish Arm is nine miles long, 1/4 mile wide and has a top elevation 500 feet above the present lake-level[2]. These cobble beaches are often terraced and represent successive lowerings of an ancestral Great Bear Lake. Such beaches have been found considerably south and east of the present Great Bear Lake and at elevations well above the height of land between the Great Bear Lake and Great Slave Lake watersheds[3]. At some time after the retreat of the ice, a single waterway reached about 300 miles between the two present lakes. The maximum extent of this post-glacial lake cannot be accurately determined until topographic maps of the region become available.

Isolated lakes are abundant and lie at various elevations, as high as 1,000 feet above Great Bear Lake.

CLIMATE

The climate is sub-arctic. The annual mean temperature at Port Radium is about 20°F; January and February temperatures average about -20°F. In contrast to the below-zero temperatures of the winter months are the high summer temperatures that on some days reach above 90°F. Annual precipitation seldom exceeds 10 inches and comes as heavy rainstorms in the spring and late summer and very light snowfall in the winter. With good living quarters and suitable clothes, inhabitants of the region find living comfortable and enjoyable in all seasons.

Ground in the Port Radium vicinity is frozen all year to depths of 200 to 300 feet. In bedrock within the frozen zone open fractures and shears contain ice. In upper mine workings water freezes if it is not circulated.

The permafrost blanket is not found beneath the larger lakes and can be driven away from mine workings in a few years by circulation of mine air. At Port Radium where the inflow of water to the mine via the vein systems presents a serious problem, the permafrost zone is in some ways a desirable horizon for underground exploration by drilling or drifting, for within the zone the water problem is nullified.

Heated air is blown into the upper levels during the winter months. At 1,000 feet below the surface the mine workings maintain a fairly constant temperature of about 42°F and at 1,500 about 52°F.

HISTORY

As noted earlier J. Macintosh Bell was the first recorded observer of the Port Radium veins[1]. He was on a reconnaissance canoe trip for the Geological Survey and had travelled from Great Slave Lake down the Mackenzie River to Bear River, up the Bear into Great Bear Lake and from Fort Franklin had followed the shore in a clockwise circumnavigation of the lake. His many side-trips included a journey down the Coppermine River nearly to its mouth, then a return across Dismal Lake and resumption of the trip down the east coast of Great Bear. Thus it was late in the season when he touched at Labine Point, and he still had to traverse the then uncertain route through the Hottah Lake system to Fort Rae on Great Slave Lake, some 300 miles away; therefore, he spared only enough time to the Port Radium showings to make cursory observations on some of the minerals present and enter the one significant sentence in his journal.

Gilbert Labine and E. C. St. Paul investigated these outcrops and late in 1930 sent a shipment of specimens to the Mines Branch of the Canadian Survey in Ottawa, where the major mineral was identified as pitchblende, a high-grade ore of radium[4].

High concentrations of silver were discovered in the pitchblende veins in the summer of 1931, and before the end of summer there were nearly 300 prospectors in the district, and 3,000 claims had been staked. The discovery of silver was an interesting development insofar as Gilbert Labine was first attracted to the cobalt-stained showings described by Bell on the possibility that silver would be associated with the cobalt as at Cobalt, Ontario. The property was brought into production in 1934 under the name of the Eldorado Gold Mining Company, a company which Labine had previously organized to develop a gold property in Manitoba [5]. Later the name of the company was changed to Eldorado Mining and Refining Limited. A plant for radium extraction was built in Port Hope, Ontario.

Late in 1933, a mill began operation at Port Radium and by June, 1934, the Port Hope refinery had treated 58 tons of pitchblende from which $5\frac{1}{2}$ grams of refined radium had been isolated. By-products of this operation were 35,000 pounds of uranium salts and 30,000 ounces of silver[6]. Production of radium from the Eldorado mine effectively broke the monopoly by Belgian Congo of the world market. The Belgian Congo uranium deposits at Shinkolobwe had been discovered in 1915 but had not begun production until 1921[7]. Initially the Shinkolobwe ore had produced 1 gram of radium per 10 tons of concentrate but by 1934 the grade had dropped to 1 gram in 30 to 40 tons; therefore the Eldorado production, at a 1 gram per 12 ton ratio, coupled with high silver production, overcame the economic difficulties imposed by the isolation of the mine and tumbled the 1932 price of radium from $70 per milligram to $25 per milligram[8]. Ore running 10-40°/o U_3O_8 would yield 26-104 milligrams of radium on a 97°/o extraction.

At the mine, first production came in 1931 from two veins, one lining the bluffs along the south shore of Labine Point and the other parallel to the first and 400 feet north. These were designated No. 1 (Discovery) vein and No. 2 vein. Of the first 28 tons of pitchblende concentrate shipped to Waterways in 1931, eight tons came from a pit on No. 1 vein and the remainder from several pits on No. 2 vein[4]. Because pits on No. 1 vein continually filled with water, work was concentrated on No. 2 vein. An adit was collared on the No. 1 vein cliff-face and a cross-cut driven over to No. 2 vein, intersecting it about 100 feet below the outcrop. By the end of 1933, 1,150 feet of drifts, cross-cuts, and raises had been completed[6]. A townsite had been established at Cameron Bay about 5 miles southeast of the Eldorado Mine. The Cameron Bay townsite was later abandoned and activities were concentrated at the mine site which became Port Radium.

By 1940 the rich silver ore-shoot was mined out at Eldorado and the radium market was negligible; so the mine closed down. Early in World War II, advances in the development of atomic bombs emphasized the need for a source of uranium in North America, and in 1942 the Eldorado Mine was reopened without publicity. As a security measure all shares of the Company were purchased by the Canadian government in 1944, and Eldorado Mining and Refining Ltd. became a Crown Company.

GEOLOGIC WORK

After Bell's initial reconnaissance in 1899, no further geologic work was done in the Great Bear Lake area until D. F. Kidd[9] published a brief account of mineral deposit examinations he had made in 1931. In 1932 Kidd mapped 3,000 square miles of the east shore of McTavish Arm, and the results of this work[10], a reconnaissance map (1 inch = 4 miles) and a report, were published in 1932 by the Canadian Survey. This map is today the principal source of general geologic information for the area. In 1934, Kidd[3] extended the reconnaissance mapping in a 20 mile-wide strip south from Great Bear Lake to Fort Rae on Great Slave Lake. In 1947, W. H. Parsons[11], carrying the (1 inch = 2 miles) mapping of the Great Slave area northward, overlapped some of Kidd's work southeast of McTavish Arm and effectively correlated with Kidd's geology.

Two theses, one in the Lindsley Bay area[2], and the other at Contact Lake[12], by geologists working for mining companies produced some detailed information on the rock-types in those areas.

The latest extended mapping of the McTavish Arm region by the Canadian Survey was done by M. Feniak[13] in the MacAlpine Channel area.

In the mine area the Survey and Eldorado Mining and Refining Limited cooperated to map the Labine Point-Cross Fault Lake-Glacier Bay region on 1 inch = 400 feet using aerial photos as a base. These maps were restricted in accordance with security policies. The outlines of these various projects are shown on Figure 2.

At the mine, geological mapping was done during the late thirties and early forties on the surface at Labine Point and underground in parts of the upper four levels by Richard Murphy, the company geologist. When Murphy transferred to the Exploration branch of the company, some geologic work was continued at the mine by A. W. Estey.

In 1932, Kidd and Haycock[7] made a mineragraphic study of the surface ores of No. 1 and 2 veins. The publication of their study has remained the classic reference for this type of ore.

Late in 1949, the author joined the staff of Eldorado Mining and Refining Limited and began detailed remapping of the mine and vicinity. By 1953, over 22 miles of underground workings had been mapped at 20 feet to the inch and nearly 3 square miles of surface had been mapped at 100 feet to the inch.

This detailed study will help in correlating previous works on the regional geology. For this reason much of this paper is devoted to a resume and discussion of the general geology of the McTavish Arm pre-Cambrian area.

As a result of the detailed studies it was found that several structures have directly controlled the emplacement of the pitchblende ore bodies; therefore, following the discussion of the regional geology this report deals extensively with the detailed structural geology of the mine area.

The accumulation of data and observations at the mine along with the results of laboratory investigations carried out at the California Institute of Technology (1953-55) have provided much information on the characteristics of pitchblende mineralization, and discussion of this information makes up the last major portion of this paper.

Certain data, pertaining principally to grades, tonnage and ore reserves, are considered classified material and must remain restricted. For this reason some geologic information is not included in this paper. This is particularly the case in the section on Ore Control.

It is felt that all pertinent geologic features have been adequately illustrated and described despite the restriction of some data.

GENERAL GEOLOGY

REGIONAL GEOLOGY

General

The geology of the region adjoining the east shore of McTavish Arm, Great Bear Lake, has been mapped in different degrees of detail in separate areas by several geologists. The region encompasses the entire east shore of McTavish Arm and extends about 50 miles inland. The total area, about 3,500 square miles, is shown on Figure 2.

A reconnaissance of the whole area was made in 1932 by D. F. Kidd. He subsequently mapped the Echo Bay region on 2 miles to the inch(10). During the same period H. S. Robinson(15), G. M. Furnival(12) and C. Riley(2) mapped small areas in the vicinity of Echo Bay. No further work was done in the area until 1944, when a program of detailed mapping on a scale of 1" = 400' was conducted by the Geological Survey in the immediate vicinity of the Eldorado mine. This program was carried out by A. W. Jolliffe and J. D. Bateman in 1944, by J. B. Thurber(17) in 1945, by Y. O. Fortier(18), in 1946, and by M. Feniak(19) in 1945-46. A large section of the area in the south and east was mapped by W. H. Parsons(11) on a scale of 1" = 2 miles in 1948. At the same time Feniak(13) mapped the MacAlpine Channel area on a scale of 1" = 2 miles.

The interpretations of many geologic relations differ considerably between these workers, principally because each was confined to the limited evidence available in his own area. Tables of formations have differed with each geologist and have been expanded considerably from Kidd's first reconnaissance. Work done in the region in recent years by Eldorado geologists and information made available by extensive development of the mine provide a basis for the constructive correlation of all previous works and the compilation of a new table of formations. Most of the descriptions and interpretations of the formations given here are based on information gained by the detailed mapping in the mine area as well as reconnaissance by Eldorado geologists.

The entire area at the end of McTavish Arm lies within the Canadian Shield, and the rocks present are all pre-Cambrian. Over half the area is underlain by granitic intrusives. The non-granitic rocks are in the form of extensive patches, pendants and screens, generally interconnected. The rocks thus represented consist of a variety of clastic, argillaceous and cherty sediments, a thick sequence of volcanics and a widespread network of andesitic hypabyssal intrusives. The majority of the rocks in the map area are probably late pre-Cambrian in age.

The principal problems encountered by geologists mapping in this region usually involve seemingly anomalous relations of intrusives to hosts. There is strong evidence that much of the confusion in interpretation is attributable to the existence of multiple intrusions of both the granitic rocks and the hypabyssal rocks. This multiplicity has been suspected by some workers but not considered by others, resulting in several contradictory interpretations. Some of the data made available in the Eldorado mine at Port Radium may serve to clarify the picture.

As mentioned, nearly every geologist who has mapped a portion of the area has compiled a table of formations for that portion. The broad concepts of these various tables are in fair agreement but differences occur in the position of several individual rock units. This is understandable considering the separation of the areas and the variety of exposures available from one area to the next. The modified table of formations presented here (Table 1) for the McTavish Arm pre-Cambrian rocks is the result of a correlation of the data published by each geologist as well as that obtained by Eldorado geologists in the course of their work in the mine vicinity and their explorations in various parts of the area. Major differences between this table and those of previous workers are noted in the following descriptions of the rock units and their interrelations.

"OLD COMPLEX" ROCKS

The term "Old Complex" was used by Kidd[10] to designate all rocks older than the various granitic intrusives. They represent the majority of the non-granitic outcrops in the areas. Kidd and Robinson[15] later divided the non-intrusive rocks of the "Old Complex" in the vicinity of Echo Bay into two groups, designated the Echo Bay Group and the Cameron Bay group.

<u>GNEISS COMPLEX</u> - Granitic gneiss, granitized sediments and allied rock-types are exposed east of the Calder River and were mapped by Parsons. Because mapping ended along the fringe of

TABLE 1

TABLE OF FORMATIONS

East Shore of McTavish Arm, Great Bear Lake, N. W. T.

AGE	FORMATION	ROCK TYPE	DESCRIPTION
RECENT PLEISTOCENE		Terraced gravel and cobble beaches. Unconsolidated boulder clay.	Glacial erratics.
	Erosional Unconformity		
PROTEROZOIC		DIABASE TRAP DIKES	Dikes, sheets and (Coppermine) flows.
	Intrusive Contact - Faulting		
	HORNBY BAY SERIES (Et-Then Series) (Epworth Series)	Sediments	Sandstone, quartzite, conglomerate Sandstone, quartzite, conglomerate Quartzites and limestone
	Erosional Unconformity		
ARCHEAN(?)		BIOTITE GRANITE (Teshierpi granite; Coppermine)	Major batholith and related aplite dikes
	Intrusive Contact - Tilting and Folding		
		GRANODIORITE COMPLEX	Includes: quartz-eye porphyries, quartz monzonites latites and aplites
	Intrusive Contact		
		HYPABYSSAL INTRUSIVES	Feldspar-hornblende porphyries
	Intrusive Contact - Local Folding		
	CAMERON BAY GROUP	Sediments + 1000 ft.	Pebble-cobble conglomerate with some arkose and volcanics
	POSSIBLE DISCONFORMITY		
	UPPER ECHO BAY SUBGROUP (Snare)	Volcanics + 5000 ft.	Intermediate flows; interbedded tuffs and pebble conglomerates. Some shallow-water argillites and arkoses.
		ELDORADO VENT	At least two tuff-filled vents
	Extrusive and Intrusive Contacts		
	LOWER ECHO BAY SUBGROUP Tuff Series Mine Series	Sediments $\pm$ 4500 ft.	Bedded tuffs, fragmentals, conglomerate and some flows Cherts, quartzites; locally calcareous and ferruginous
	Relation Unknown		
		EARLY BIOTITE GRANITE GNEISS COMPLEX	Boulders in Cameron Bay conglomerate Granite gneiss, granitized sediments. (Southeast of area.)

this complex, little is known at the present time of its character or its age relative to the other formations.

ECHO BAY GROUP

In 1948 Parsons, extending the geologic mapping north from Great Slave Lake, tied in with the geology done by Kidd near Great Bear Lake. The similarity of the Echo Bay Group rocks to the Snare Group rocks of the Great Slave region was so obvious in most respects that Parsons placed the two groups into the same age division. Also, about 30 miles southeast of Clut Lake a belt of Echo Bay rocks converges from the northwest with the belt of Snare rocks that extends north into the McTavish Arm map-area. The two belts of rocks are separated by about 10 miles of granite in that region and are so similar in character and structure that their correlation is very reasonable. In 1948 J. F. Henderson[20], working in the Hottah Lake region between Great Bear and Great Slave Lakes, traced Snare rocks into Kidd's area of nearly identical Echo Bay rocks.

Division of the Echo-Bay and Snare Group into upper and lower sub-groups was suggested by Feniak and Parsons. Thurber sub-divided it into three sub-groups, all easily distinguished in the Glacier Bay area but not so distinct elsewhere. The Feniak-Parsons subdivisions are in fair agreement and are distinct over most of the map-area; therefore they are adopted here with slight modification. Because the name Echo Bay preceded the name Snare in the designation of this group of formations, it will be used in this report with the understanding that it includes Snare rocks.

Lower Echo Bay Sub-Group

Outcrops of the Lower Echo Bay rocks are not widespread in the map area and are identified only on Labine Point, Dowdell Point and (as the Lower Snare) in a belt 20 miles east of Calder River (Fig. 2). They may outcrop near the mouth of the Camsell River on Conjuror Bay, for this area of Echo Bay rocks has not been mapped in detail.

The base of the sub-group is not exposed, and at all localities the older beds are truncated by intrusive granite to the west. A maximum of 4,500 feet of stratigraphic thickness lies above the granite contact. The rock types differ only in minor details from one locality to another. The predominant rock types are finely banded red, maroon, green and grey cherts, cherty argillites, quartzites and tuffs. These rocks occupy the lower and major part of the series and include at least two limestone beds near the base of the exposed section. The limestone beds range up to 20 feet in thickness on Dowdell Point and on Cobalt Island near Labine Point. In the southeast part of the McTavish Arm map-area the rocks are mostly phyllites and greywackes with interbedded finely banded cherts.

The finely banded cherty rocks are locally channelled and ripple-marked with symmetric ripples but seldom show any grain gradation. They grade upward to mudcracked, asymmetrically ripple-marked, graded and scoured argillites, tuffs, arkose, a pebble conglomerate, and occasional fine grained andesitic flows and breccias. The pebble conglomerate is a distinctive marker bed and occurs in the section throughout the entire area with minor variations. The pebbles usually range from $\frac{1}{2}$" to 2" (boulders exceeding 2 feet in diameter occur locally), are well rounded, and include not only all rock-types described in the lower part of the section but also feldspar porphyry and vein quartz. The conglomerate has a dense cherty matrix, and when broken it fractures through the pebbles. This is contrasted to Cameron Gay group conglomerates that fracture around the pebbles. The presence of andesitic feldspar porphyry pebbles in the Echo Bay conglomerate indicates the existence of extrusives or intrusives that are not now visible in Lower Echo Bay rocks but which are lithologically identical with post-Echo Bay intrusive and extrusives.

A brecciated cherty argillite near the top of the Lower Echo Bay sequence is overlain by a dense porphyritic andesite flow which is in turn overlain by interfingering tuffs, argillites and thin flows and finally a thick sequence of alternating andesitic flows and pyroclastics. The first dense andesite flow above the brecciated chert constitutes the base of the Upper Echo Bay series.

In contrast to the steeply dipping, folded oldest beds of the Lower Echo Bay group the youngest beds are relatively undeformed with dips seldom exceeding 30 degrees.

Upper Echo Bay Sub-Group

The gently-dipping volcanics of the Upper Echo Bay subgroup are widely distributed in the Echo Bay region, less so near Conjuror Bay and only in isolated patches elsewhere in the map-area (Fig. 2). A total stratigraphic thickness of about 4,800 feet is exposed east of Hoy Bay from the base of the sub-group to its contact with the overlying Cameron Bay group (Fig. 3).

The sub-group consists of relatively coarse textured porphyritic andesite flows and interbedded tuffs and sediments. This thick sequence is divisible into three series. The lowest is about 2,300 feet in thickness, the next is from 200 to 400 feet in thickness and the highest is about 2,200 feet in thickness. The middle series consists of interbedded quartzites, argillites, and tuffs. In the Hottah Lake region Henderson[20] reports this middle series of sediments to consist of about 400 feet of quartzites. In the Echo Bay area it is about 250 feet thick and is predominantly argillite-greywacke with minor interbedded breccia and conglomerate. The other two series of the sub-group consist predominantly of flows, only 15 percent of these series being sediments and tuffs. The individual flows seldom exceed 100 feet in thickness and are generally uniform in character not only throughout the map area but also south to Hottah Lake. The flows are coarser textured than those in the Lower Echo Bay sub-group and although the size of the phenocryst differs considerably from flow to flow it becomes successively smaller toward the top of the series. The phenocrysts do not differ in size within individual flows and are as large in thick flows as in thin ones. Therefore it seems probable that the phenocrysts in the flows are about the same size as they were in the source magma and that with the larger phenocrysts being tapped off in the first flows the growth of phenocrysts in the source failed to attain such a degree again.

The porphyries consist of a dark grey, purple or red, almost cherty matrix with white, pink or colourless plagioclase laths that give the rocks a light spotting on weathered surfaces. Quartz in amygdules and phenocrysts is not uncommon in some flows. The microphenocrysts are predominantly oligoclase, occasionally orthoclase, and are usually less than 2 millimeters in length. In some amygdaloidal tops phenocrysts are nearly two centimeters in length. Hornblende phenocrysts usually accompany the plagioclase phenocrysts in the porphyries in various amounts. Vesicles and flow breccias are common. Pillows were reported by Parsons[11] in the Snare flows.

Because these flow-rocks are identical in lithology with intrusive rocks common in the area and because many of the flows are devoid of flow structures it is important to realize that many of the units mapped as massive flows may be intrusive.

The principal rock-type is andesite. Basalts and dacites make up the remainder.

The tuffs are red or pink fine to medium grained crystalline aggregates with occasional color banding. The grains are generally less than 1 millimeter in maximum dimension. Oligoclase, (An_{15}) is the predominant constituent of the tuffs. In some localities, orthoclase is the main constituent.

The Upper Echo Bay volcanics in the Echo Bay area strike about due north and dip about 20 degrees to the east. This simple structure is modified locally by gentle flexures.

CAMERON BAY GROUP

The Cameron Bay Group rocks comprise a sedimentary sequence that overlies the Upper Echo Bay volcanics more or less comformably. They constitute a large percentage of the non-intrusive rocks in the Camsell River and Echo Bay areas and from Lindsley Bay north to Hornby Bay, they are the only exposed non-intrusive rocks and underlie much of the shoreline and many of the off-shore islands (Fig. 2).

The exact relation of the Cameron Bay group to the underlying volcanics is not known. The one reported exposure of the contact is believed to be a fault contact[19]. However, in view of the fact that the attitudes of the Cameron Bay rocks so closely parallel those of the underlying volcanics the existence of a major unconformity is doubtful.

A maximum of 1,000 feet of stratigraphic thickness of the Cameron Bay group has been measured near Cameron Bay by Kidd[10]. Throughout the map-area the top of the group is an erosion surface; therefore the actual thickness that was deposited cannot be determined.

The lower 500 feet of the group is made up of deep red and maroon interbedded boulder and cobble conglomerates and ferruginous arkoses. These conglomerates grade upward to pebbly sandstones, greywackes and grits that comprise the next 300 - 500 feet of the group. The uppermost part of the group consists of a capping of interbedded red greywackes and tuffs with some agglomerates. Parsons reports tuffs and agglomerates interbedded with the sandstones etc. in the middle members of the group.

The conglomerates of the lower Cameron Bay Group are poorly sorted, poorly cemented, and differ widely throughout the map-area in the types of cobbles. The cobbles and boulders are well-rounded to sub-angular and range up to 2 feet in diameter with an average diameter of about 8 inches. Parsons[11] reports angular boulders and breccias within the group in the vicinity of Conjuror Bay and suggests the possibility that they represent pre-Cambrian talus slopes. Two-foot boulders in beds with two-inch pebbles are common and give an indication of the poor sorting. Arkose beds up to 2 feet in thickness commonly separate conglomerate beds. Pebble beds several feet thick in places lens out within a hundred feet along strike. As noted previously the Cameron Bay Group conglomerates differ from the Echo Bay conglomerates in that they break around and not through the pebbles and cobbles.

In general the rock types represented in the cobbles are those of the underlying formations in the near vicinity. In the MacAlpine Channel area the cobbles are predominantly porphyritic andesites of the Upper Echo Bay volcanics[2]. In the type section at Cameron Bay about 50°/o of the cobbles are brown-grey volcanics and the remainder are green cherty argillites and quartzites similar to Lower Echo Bay rock-types[19]. Occasional pebbles of vein quartz and jasper are found in the Cameron Bay conglomerates in the Echo Bay area. The nature of the cobbles is markedly different in the Conjuror Bay area where

Parsons[11] reports the rock-types represented in the cobbles to be 50°/o biotite granite, 30°/o feldspar porphyry, 15°/o greenstone and 5°/o vein quartz.

The matrix of the conglomerates is generally red-brown arkose consisting of about 30°/o quartz and 70°/o red feldspar. The angularity of the particles in the gritty matrix indicates that wear has not been great.

The Cameron Bay conglomerates represent a period of erosion following Echo Bay time, but the character of the conglomerate suggests rapid disintegration and deposition with little decomposition. Also, near Bay 66 the Upper Echo Bay volcanics are interbedded with cobble conglomerates very similar to lower Cameron Bay Group conglomerates. The evidence strongly indicates that the change from a period of volcanic activity to one of rapid erosion and deposition was transitional.

At Cameron Bay, Conjuror Bay and in the MacAlpine Channel area the conglomerates are intruded by andesite porphyry[19][13]. At MacAlpine Channel they are intruded by biotite granite and near Contact Lake they are cut by quartz veins[12]. As noted above, granite and vein quartz pebbles and cobbles are widespread in the conglomerates in the southern part of the map-area. Therefore, this is definite indication of pre- and post-Cameron Bay biotite-granite intrusion and quartz-jasper mineralization.

The Cameron Bay Group strata form flat-topped hills and gently dipping terraces. Dips seldom exceed 20°.

ELDORADO VENT

In the Eldorado Mine and on the surface on the northwest flank of Labine Point is exposed a formation of massive tuffaceous rock that appears on the surface to comprise the base of the Echo Bay group. Outcrops of these tuffs occur along the shore of Great Bear Lake from Labine Point to Corregidor Bay, two miles to the northeast. There are no other exposures reported within the McTavish Arm map-area of this type of tuff complex.

Lithologically the complex is a massive finely crystalline aggregate of orthoclase-plagioclase crystals, locally fused or re-crystallized, with gradations into a rock type not unlike the feld-spar porphyry volcanics of the Upper Echo Bay sub-group. Structurally, the rock formation is in the form of an elliptical bowl whose long axis runs northeast and whose eastern lip is exposed along the shore of the lake. Immediately off-shore the bowl has been truncated by biotite granite intrusion.

Underground and on the surface this massive tuff body not only cuts across Echo Bay rocks but also, locally, lies uncon-formally on top of them and in some places appears to grade into them. These paradoxical relationships of the massive tuff body coupled with its lithology and shape, suggest the possibility of its being a caldera-type structure.

In space and lithology this possible caldera can be readily correlated with the Upper Echo Bay volcanics and later tuffs. Considering this and considering also that it cuts Lower Echo Bay rocks, it has been placed in the geologic time table before and with the Upper Echo Bay sub-group. For convenience it has been designated the Eldorado Vent. Details of the vent are presented in the discussion of the mine geology later in this paper.

INTRUSIVE ROCKS

Hypabyssal Intrusives

Echo Bay and Cameron Bay rocks, and the Eldorado Vent, are intruded by a series of porphyritic andesitic hypabyssal dikes, sills, laccoliths and stocks. The general belt of intrusive porphyries is 40 miles wide in the southern part of the McTavish Arm map-area but narrows sharply, going northward, to an apex at Hunter Bay. East of Clut Lake the wide part of the belt is represented only as pendants left in the granite (Fig. 2). Outlying small intrusive porphyry bodies crop out in the non-intrusive rocks along the borders of the main belt.

These porphyries comprise over 50 percent of the outcrop area of the "Old Complex" rocks in the McTavish Arm map-area.

The distinctive lithology of these intrusive rocks facilitates their correlation through the separate map-areas of the geologists who have mapped from Great Slave Lake to Great Bear Lake. The areal extent of the porphyries is therefore easily compiled. Parsons[11] traced them south to the vicinity of Hottah Lake. Kidd[2] traced them from Hottah Lake south to Great Slave Lake and later Lord recorded them as a map unit in a belt about 10 miles wide extending from Beaverlodge Lake near Hottah to a point about 50 miles northwest of Fort Rae on Great Slave Lake. In addition Stockwell[22] reports similar intrusive porphyries in the east arm of Great Slave Lake 100 miles southeast of Fort Rae. The porphyries thus form a somewhat discontinuous belt, up to 40 miles in width but nearer 10 miles as an average, of tabular intrusive bodies extending for over 300 miles along the edge of the pre-Cambrian shield from Great Bear Lake to Great Slave Lake.

The linear configuration of these intrusives for a distance of over 300 miles and the tendency for that configuration to parallel the structure of older volcanics and sediments indicate the existence in pre-Cambrian time of a major structural feature parallel to the axis of the intrusive belt. The extensive vulcanism of Upper Echo Bay time, the uplift and resultant rapid erosion of Cameron Bay time, and the following stage of hypabyssal intrusion along the 300 mile belt suggest that the structural feature was probably an orogenic belt.

It is of interest to note that such a belt of orogeny extending from Great Slave Lake to Great Bear Lake crosses an orogenic belt recently proposed by Collins, Farquhar and Russell[23]. Their belt trends northeast from Fort Rae on Great Slave Lake for about 300 miles and intersects the line of hypabyssal intrusives at Fort Rae at an angle of about 30 degrees. Collins et al have based their presumption of the existence of this northeast trending belt on differences in ages of radioactive vein-material found between Great Slave and Great Bear Lake. The vein mineralization post-dates the widespread granitic intrusives that came after the porphyry intrusives; therefore the belt suggested by them could be an expression of much later orogeny than the one indicated by the belt of porphyries. Because their conclusions regarding orogenic belts depend solely on radiogenic age determinations, the problems and dependability of such determinations are important. This is discussed more fully under "Ages".

As noted earlier the lithology of the hypabyssal intrusives is distinctive throughout large areas. The porphyries of the Great Slave area differ only slightly from those of the Great Bear area. In general the hypabyssal intrusives have a fine-grained to aphanitic matrix that may differ widely in colour within small areas. Commonest colours are shades of grey, red-brown and purple. Phenocrysts seldom exceed three millimeters in length. They are white or grey stubby feldspar and black-green hornblende laths. Rounded quartz phenocrysts occur locally and in various quantities. The feldspar phenocrysts are predominantly oligoclase and orthoclase. The matrix is composed of tiny laths of plagioclase and usually comprises about 70 to 80 percent of the rock. Flow lineation is common.

Texture, alteration and proportions of constituents change, often considerably, from one area to another. For this reason the porphyries have been variously designated as syenite porphyry, granite porphyry, feldspar porphyry, feldspar-quartz porphyry, rhyolite porphyry, and diorite porphyry by different geologists. Considering that the matrix is for the most part fine-grained, that the phenocrysts are predominantly feldspar and that quartz may or may not be present, a more correct general term for these rocks would be "feldspar porphyry". Further designation as "intrusive" is useful in view of the fact that most of the lavas of the Upper Echo Bay series are also "feldspar porphyries" and almost identical in appearance with the intrusives. In this discussion they will be called "intrusive feldspar porphyries".

These porphyritic hypabyssal rocks are characteristically blocky jointed in outcrop and form most of the higher prominences in the McTavish Arm area. The difference in shades of red or grey of the matrices is a function of the variation of hematite dusting of the feldspars and has no obvious relation to variations of the principal mineral components.

In the Echo Bay and MacAlpine channel areas the porphyritic hypabyssal rocks are cut by both granodiorite and biotite granite. In addition they are cut by dikes of compositions identical to their own. Parsons[11] and Feniak[13] report these dikes cut biotite granite. This indicates either a very late stage of porphyry (dike) intrusion or possibly intrusion of porphyry into the early biotite-granite which is inferred from boulders in the Cameron Bay conglomerate but which in mapping has not been differentiated from the more widespread later granite.

In the Echo Bay area, intrusion of the porphyritic hypabyssal rocks has been accompanied by intense local metasomatism and deformation of the host rocks. It is not unlikely that the scattered recrystallization and metasomatism evidenced in many of the non-intrusive rocks in the McTavish Arm map-area are attributable to the proximity of the broad belt of feldspar porphyry intrusives. The later biotite granites have produced metamorphic effects in host rocks only for a few inches from their contacts.

Quartz Monzonite Intrusive

On Dowdell Peninsula, Feniak[19] mapped a small dike-like body of quartz-monzonite that cuts Echo Bay rocks and is cut by granodiorite. This is the only reported occurrence of this rock-type.

Granodiorite Complex

In the Echo Bay area several elongate bodies of granodioritic composition cut Echo Bay rocks and feldspar porphyry intrusives and are themselves cut by the late biotite granite. The bodies are about a mile in width, up to 5 miles in length and trend northwest across Echo Bay (Fig. 3). The rock is medium-coarse granitoid in texture and is grey-brown or grey in colour. Locally it ranges widely in composition. Feniak(19) reports quartz diorite and quartz monzonite local facies but in general the rock appears to be granodiorite. It contains about 45 percent plagioclase, 20 percent orthoclase-albite, 15 percent quartz and 20 percent biotite, augite and hornblende and accessories, according to analyses by Feniak(19) and Furnival(12).

Accompanying the granodiorite intrusives locally are wide contact metamorphic aureoles extending as much as 1,000 feet into host rocks. Granitization and recrystallization are locally noted, but the aureoles are mostly characterized by the extensive development of chlorite, magnetite, actinolite, epidote and pyrite in host rocks. The chlorite is pennine. The pyrite in the aureoles weathers to form yellow gossans around the granodiorite. Near Wiener Bay there are no obvious contact aureoles around the granodiorite exposures.

The metamorphic minerals listed above are widespread in varying concentrations throughout non-intrusive rocks in the Echo

Bay area. The minerals may have been derived from the granodiorite intrusives or, as noted earlier, from the feldspar porphyry intrusives. The occurrence of pennine and magnetite as late minerals in the feldspar porphyries suggests possible metamorphism of those rocks by the granodiorite.

Quartz-eye Porphyry

Feniak mapped several latite-monzonite porphyry dikes on Dowdell Peninsula. These are about 30 feet in width and are distinctive in that they contain abundant round quartz "eyes". Feniak thought them to be late derivatives of the granodiorite complex.

Biotite Granite

Intruding all rock-types described above, throughout the entire McTavish Arm map-area, are biotite granite stocks. These intrusives underlie about 50 percent of the map-area. The areas mapped as granite may include more than one age of granite, but the majority of the intrusion is later than the feldspar porphyry.

These granites crop out as bodies ranging from 5 to 25 miles in width and are studded with irregular pendants of earlier rocks (Fig. 2).

The granites are quite uniform in appearance throughout the McTavish Arm area. They are massive, medium to rather coarse-grained, locally gneissic or porphyritic, pink weathering, biotite granites averaging about 30 percent quartz, 40 percent microperthite and orthoclase, 20 percent albite-obligoclase and 5-10 percent biotite. Analyses of specimens from widely separated localities are strikingly uniform; e.g. Lindsley Bay,[2] Labine Point, Dowdell Peninsula,[19] Contact Lake,[12], and even Hottah Lake,[20] forty miles south of the McTavish Arm map-area.

This granite is probably the same age as the Teshierpi basal granite that underlies the Epworth Series in the Coppermine area north of Great Bear Lake. The two granites are lithologically alike and occupy the same position in the section if the Epworth Series is the correlative of the Hornby Bay Series to the west (Table 1). The area between the Coppermine River area and the McTavish Arm map-area is unmapped and it is not known whether the granite is continuous across this interval.

Sericitization of the plagioclase, kaolinization of the microperthite and chloritization of the ferromagnesian minerals are common, but differ in intensity at different localities. In general, the granites are fresh-looking rocks.

Contacts are sharp. Schlieren and partly digested xenoliths are widespread along the borders. Contact alteration effects are negligible. Associated pegmatites are extremely rare, but aplite dikes are widespread along the edges of the granite bodies. The aplite dikes cut the granite contact and invade country rocks for short distances (1,500 feet) before dying out. They can be traced into the granite for a few hundred feet before they disappear. They are erratic in strike, dip and shape, and are usually less than 5 feet in width.

Intrusion of the granites has steeply tilted and locally folded host rocks for distances of about 2,000 feet away from present contacts. Less noticeable effects have possibly been broad doming and uplift.

HORNBY BAY GROUP

In the Hornby Bay area a series of flat-lying shallow water sandstones, quartzites and some conglomerates lies unconformably on Cameron Bay Group rocks (Fig. 2). This sedimentary sequence extends westward off the map-area where it is overlapped disconformably by Cretaceous formations to the west and Paleozoic formations to the northwest (Fig. 1). When Kidd[10] first described the Hornby Bay Group rocks he suggested that they could be either late pre-Cambrian or early Paleozoic. They overlie the giant quartz veins that cut the biotite granite and represent deposition after deformation and erosion.

The Hornby Bay Group corresponds closely in lithology and position in the Table of Formations to the Et-then Series in the Great Slave area[22] and the Epworth Series in the Coppermine River area[119]. With the Snare and the Echo Bay Groups correlated the Hornby Bay Group is the northern counterpart of the Et-then Series (Table 1).

LATE INTRUSIVE ROCKS

Trap Dikes

On Dowdell Peninsula Feniak observed many narrow dikes intruding sediments, volcanics and granite. They are less than ten feet in width, dark grey, and composed of a groundmass of fine grained feldspar and chlorite with occasional feldspar and hornblende phenocrysts. One such dike intrudes the biotite granite in the mine at Port Radium, but its extent is not known.

Diabase Dikes

Within the McTavish Arm map-area a multitude of diabase dikes cuts all the formations described above. Few of the dikes are wider than 20 feet and, depending on the widths, they are either fine or medium-grained. They usually have chilled edges and sharp contacts. Variations in appearance and lithology between dikes in different areas are slight. The rock weathers to a distinctive grey-brown and commonly disintegrates to sand or rubble although surrounding rocks are relatively undecomposed.

These dikes are steeply dipping and consistently trend west-northwest, deviating locally along faults, joints, or contacts. Individual dikes have been traced as much as four miles along strike (Fig. 3) but also are often seen to pinch out within a few hundred feet.

The dikes cut the Hornby Bay Group and the giant quartz veins[3]. They occupy mineralized shear zones and are veined by ore minerals in the mine at Port Radium.

These diabase dikes, so common in the vicinity of McTavish Arm, are also found, practically identical in lithology and appearance, in the Coppermine area[119], at Hottah Lake[20], Great Slave Lake[21], and as far south as Lake Athabaska[24]. Everywhere they are assumed to be very late pre-Cambrian or possibly Cambrian in age.

The composition of the diabase dikes is generally the same at all the localities listed above. The rock exhibits ophitic texture with laths of labradorite enclosed in augite. The components are about 45 percent labradorite, 45 percent augite, 5 percent magnetite and variable amounts of quartz and accessories.

Diabase Sheets

In the McTavish Arm map-area one or more gently-dipping diabase sheets, up to 300 feet thick but about 150 feet on an average, intrudes all formations described above. In some exposures the diabase sheet cuts diabase dikes but in others it merges with them. It is apparent that there are at least two ages of diabase; the older appearing as dikes and the younger as sheets with minor dikes. The relation between the diabase dikes and the diabase sheet in the Port Radium area is not yet known. Until an intersection of the two is seen it will not be known whether or not they represent one or two intrusions. The sheet diabase is sill-like in habit where the host rocks are stratified and not excessively folded, elsewhere it cuts across intrusives and tightly folded rocks still maintaining its undulatory low dips. It pinches and swells abruptly in some areas but maintains consistent thicknesses over long distances in other areas.

A diabase sill crops out near the mouth of Gunbarrel Inlet. A similar sill underlies most of the Echo Bay area like a large saucer, (See Figure 3), and discontinuous exposures continue north along the shore to Hunter Bay. The elevations of nearly all the exposures of diabase sill, from Gunbarrel Inlet to Hunter Bay, are about the same; namely, within tens of feet of lake-level. For this reason it is suggested that the diabase sheet is a single, but locally discontinuous, body extending 80 miles along the east shore of McTavish Arm.

The steep cliffs of the columnar-jointed diabase sheet rise abruptly from the lake and are a characteristic feature of much of the shore-line of McTavish Arm. A similar flat-lying diabase sheet caps the Superstition Islands that lie about twenty miles southwest of Port Radium.

The sheet in the Echo Bay area crosses major faults without showing displacement; however it is fractured, veined and altered at such intersections. Therefore, the sheet, like the dikes, came in after the major faulting, but before the final fracturing and mineralization.

The sheet diabase is lithologically the same as the dike diabase, except for local higher concentrations of quartz. It is coarser grained than the dike diabase.

It is of interest that in the Coppermine area the Epworth Series of sediments, presumably corresponding to the Hornby Bay Series, is overlain by the Coppermine Series of extrusive basalt and diabase flows. In relating the diabase dikes and flows Jenney[119] states that many large diabase dikes, perpendicular or near-perpendicular, trend slightly east of north. They have the same composition as the flows. He proposes that the dikes, diabase flows, and basalts are related and are derived from the same magma. The diabase dikes are thought to be feeders for the flows. It is possible that these diabase flows are the counterpart of the McTavish Arm diabase sheet. This would date the diabase as late pre-Cambrian.

STRUCTURE

Folding

The gross structures of the Old Complex formations in the McTavish Arm area are simple. Near intrusive contacts there is local tight folding, but in general the formations trend north-northeast and dip to the east.

Fracturing

A major structural feature in the district is the widespread pattern of northeast-striking fractures and faults. This direction of failure is persistent down to fractures a few hundred feet long. A secondary set of breaks, perhaps tensional, strikes due east. Major northeast-trending shear zones and related fractures are the principal loci for pitchblende ores in the area.

Several major northeast-striking fault zones are known (Fig. 2); one is located along the Fault River northeast of Hornby Bay, another follows the Sloan River between Hunter Bay and McLaren Lake, a third fault passes through Cameron Bay and a fourth follows the Tilchuse River. These faults are roughly parallel and spaced about 12 miles apart. This system of faults probably includes many others as yet undetected, but which can be inferred from the many prominent northeast-trending topographic lineaments.

Detailed work along the Cameron Bay fault has revealed many related faults that form a system extending from Gilleran Lake to Dowdell Point between which the belt of faults attains a maximum width of 3 miles. The major north branch of this system comprises the Port Radium-Failes Bay fault system and contains the richest known pitchblende deposits of the district. The Cameron Bay fault proper has an apparent horizontal right displacement of about 2 miles (Fig. 3). Displacements on other faults of the Cameron Bay system, where known, are normal and seldom exceed a few tens of feet.

Compound branching of the major faults with coalescing of the branches along strike is a common feature of the northeast-trending fault zones in the McTavish Arm area. East-striking tensional fracture systems lying between the northeast-striking branches are common near the junctions of the branches. These structures exhibit abundant brecciation and fracturing of wallrock but seldom show continuous fault planes. They are the loci for the richest ore of the Port Radium deposits.

The northeast-trending faults usually underly drift-filled draws, but their presence is generally suggested by hydrothermal alteration and secondary shearing of the adjacent rocks. Where they are exposed they are shear zones ranging in widths from one foot up to twenty feet. They are commonly filled with vein quartz and carbonate and invariably show extensive chloritization and argillization of country-rock horses and included fragments. At least one fracture in each zone contains gouge.

A prominent fault line in the district extends from Hunter Bay nearly due south beyond Gilleran Lake. It apparently crosses the Cameron Bay fault with no displacement shown by either. No other north-south structure of this nature is known in the district, but several are known in the Coppermine River area further north.

Pertinent to the system of northeast-trending faults in the McTavish Arm area is Jenney's[(119)] description of the fracture pattern in the Coppermine River area. He states, "Prominent tension faults trend for long distances across the country. Some have been traced for over 50 miles and in all probability extend through to faults of a similar nature on the northeast end of Great Bear Lake. Most of these faults trend from slightly east of north to north 45° east, while a second and less prominent pattern is shown by similar faults trending north to northwest. All faults examined were tension fractures with very little movement and no large scale shear or tension movement." There is little doubt that the McTavish Arm system, and type, of failures extends nearly to the Arctic Ocean.

Two additional but less pronounced directions of fracturing occur in the McTavish Arm area; one trending north-northeast and the other east-southeast. Both these systems are inconspicuous, except where they are occupied by vein or dike material. The diabase dikes occupy members of the east-southeast-trending fracture system and the giant quartz veins occupy those of the north-northeast system. Both the dikes and the quartz veins locally occupy zones of the major northeast shears but generally leave these zones via the aforementioned fracture systems. Considerable lengths of giant quartz veins and very minor lengths of diabase dikes are diverted along the major northeast-trending shears.

It is evident that following the major northeast faulting in the district tensional forces opened the shear zones thus formed and provided ingress for diabase magma and quartz-rich solutions. This tensional opening occurred at two separate intervals acting from different directions each time. The tensional forces that formed the north-northeast set of fractures occupied by the giant quartz veins would have had considerable dilatory effect on the northeast-trending main shear zones which are at a slight angle to the north-northeast system. For this reason the giant quartz veins not only preferentially occupy the north-northeast set of fractures but also occupy, to a considerable degree, some of the major northeast-trending shear zones. The tensional forces that resulted in the formation of the east-southeast set of fractures occupied by the diabase dikes were acting nearly parallel to the major northeast-trending shear zones and thus would have minor dilatory effects on them. For this reason the diabase dikes generally cut sharply across the northeast-trending shear zones and occupy them only for short distances and at widely scattered localities. The diabase dikes cut the giant quartz veins, therefore the tensional forces acted first in a NW-SE direction, opening the north-northeast fractures and the major shear zones for occuptation by the giant quartz veins, then acted in a SW-NE direction, opening the east-southeast fractures for occupation by the diabase dikes. At a still later period the tension was again acting in a NW-SE direction and reopened the north-east-trending shears and fractured the diabase dikes that had occupied and crossed them. There is good evidence that the last tensional action that opened the zones was one of relaxation with accompanying dip-slip on some of the faults.

From the foregoing discussion it is apparent that, following the initial northeast shearing, the formations in the McTavish Arm area were subjected to at least three periods of tension and that the directions through which the tensional forces acted varied from one period to the next. The northeast-trending fault zones that comprise the initial major deformation are right-hand normal faults. They were probably the result of north-south acting tensional forces.

The stages of tensional deformation described above are illustrated in Fig. 6. The pitchblende mineralization occurred during the fourth stage, when the northeast-trending zones were opened and the giant quartz veins and the dikes were fractured. Pitchblende is therefore found not only in the northeast-trending vein zones but also in northeast striking fractures in both the diabase dikes and the giant quartz veins in the vicinity of the major zones.

PERIODS OF MINERALIZATION

Early Mineralization:

The existence of vein quartz pebbles in Echo Bay and Cameron Bay conglomerates indicates the existence of hydrothermal veins before Echo Bay time.

Giant Quartz Veins:

Occupying many of the northeast-trending faults and fractures are giant quartz veins. Thirty-six veins were mapped by Kidd[10] in the McTavish Arm map-area, and single veins have been traced for over ten miles (Fig. 2). They are known as far south as Great Slave Lake and as far north as the mouth of the Coppermine River[3].

The veins are composite stockworks from 50 to 500 feet in width that show extensive evidence of replacement of wall rock.

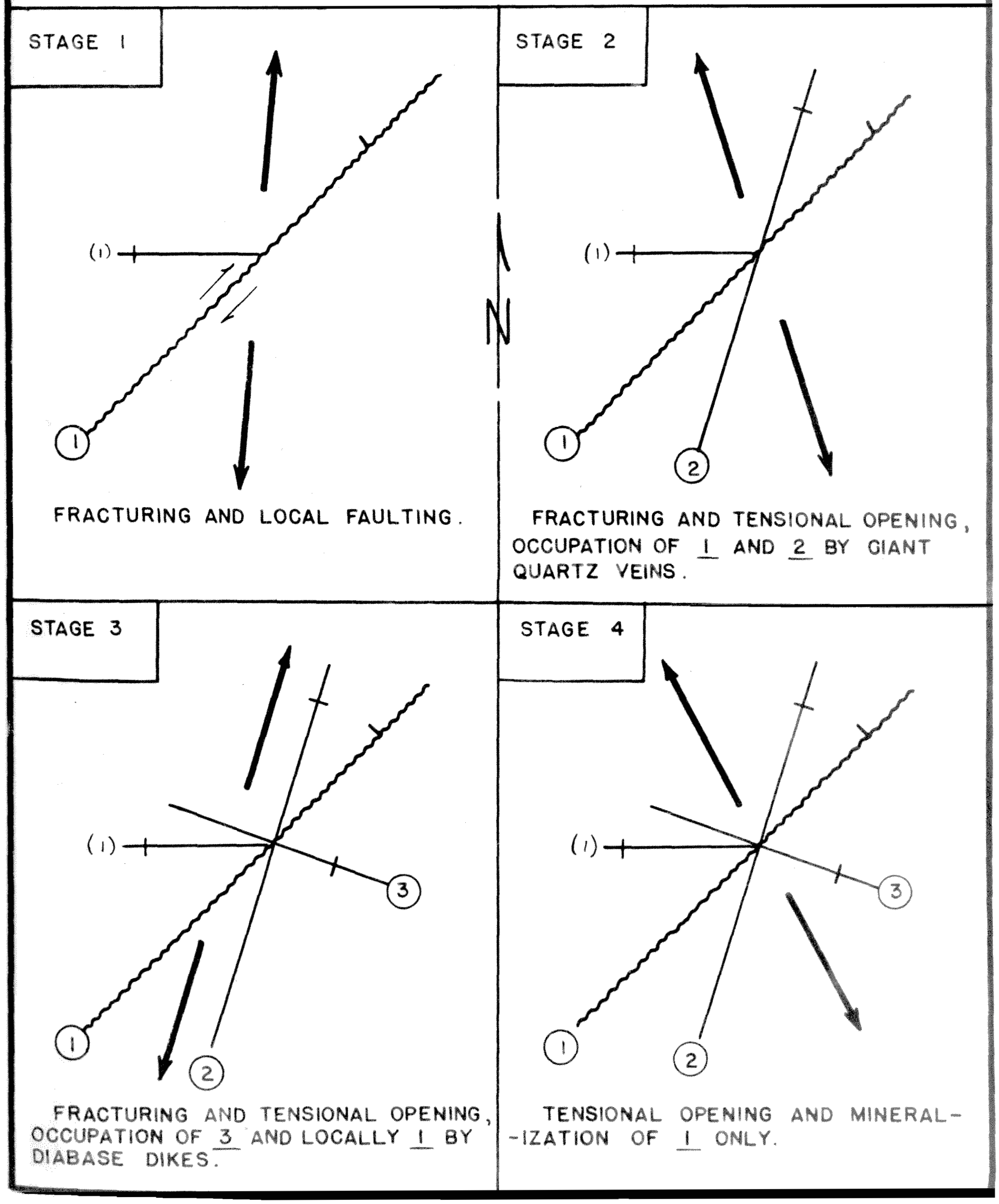
FIGURE 6

DIAGRAM ILLUSTRATING

STAGES OF TENSIONAL STRESS

ON

FORMATIONS IN MCTAVISH ARM AREA



The walls of the stockworks are generally ragged due to interfingering of quartz and country rock. The grey, cherty replacement quartz forms about 70 percent of the vein material. Most of the remainder is made up of milky quartz veinlets and bands that cut the cherty quartz. Cutting across this assemblage are small, glassy, vuggy quartz veinlets that commonly contain clear quartz crystals and rosettes of specularite and hematite, but only locally contain copper minerals and pitchblende. This latter phase of mineralization may well be a correlative of the metal mineralization at Port Radium.

Kidd[10] and Feniak[13] report exposures in the vicinity of Hornby Bay in which the Hornby Bay conglomerate and sandstones unconformably overlie the cherty quartz portion of the giant stockworks, but the later networks and veins of milky quartz lace the stockwork and cut the sediments above.

Late Mineralization:

The last stage of mineralization in the McTavish Arm map-area was in all probability related to the final quartz veining of the giant quartz veins and was definitely extensive in space and in duration. It is itself divisible into at least five separate stages of mineralization based on marked changes in the compositions and paragenesis of the metallic minerals. To the late mineralization belong all the metal-bearing quartz and quartz-carbonate veins. They not only occupied new openings, but also shared old fissures with previous quartz veins and replacements. In the Port Radium veins early massive hematitic quartz has been followed by at least three stages of quartz and carbonate, each with a different suite of metallic minerals. Metal-bearing siliceous mineralization occurs in veins and mineralized shear and fracture zones that are exposed in various deposits from Hornby Bay to Camsell River. The range in time between the beginning and final stages of this mineralization may have been considerable, and, because the first stage did not begin until post-Hornby Bay time, i.e. very late pre-Cambrian or possibly Cambrian, the metal deposition in the McTavish Arm deposits could very conceivably be later than pre-Cambrian. This conclusion is in sharp disagreement with the results of age determinations for the pitchblende from Port Radium. A complete discussion of these controversial problems is presented later in the section on Ages of Mineralization.

The principal metals accompanying the last stage of mineralization are, in approximate order of abundance: iron, copper, manganese, arsenic, uranium, cobalt, nickel, silver and gold.

All deposits in the district that have stirred economic interest to date belong to this last phase mineralization of silica-carbonate-metal.

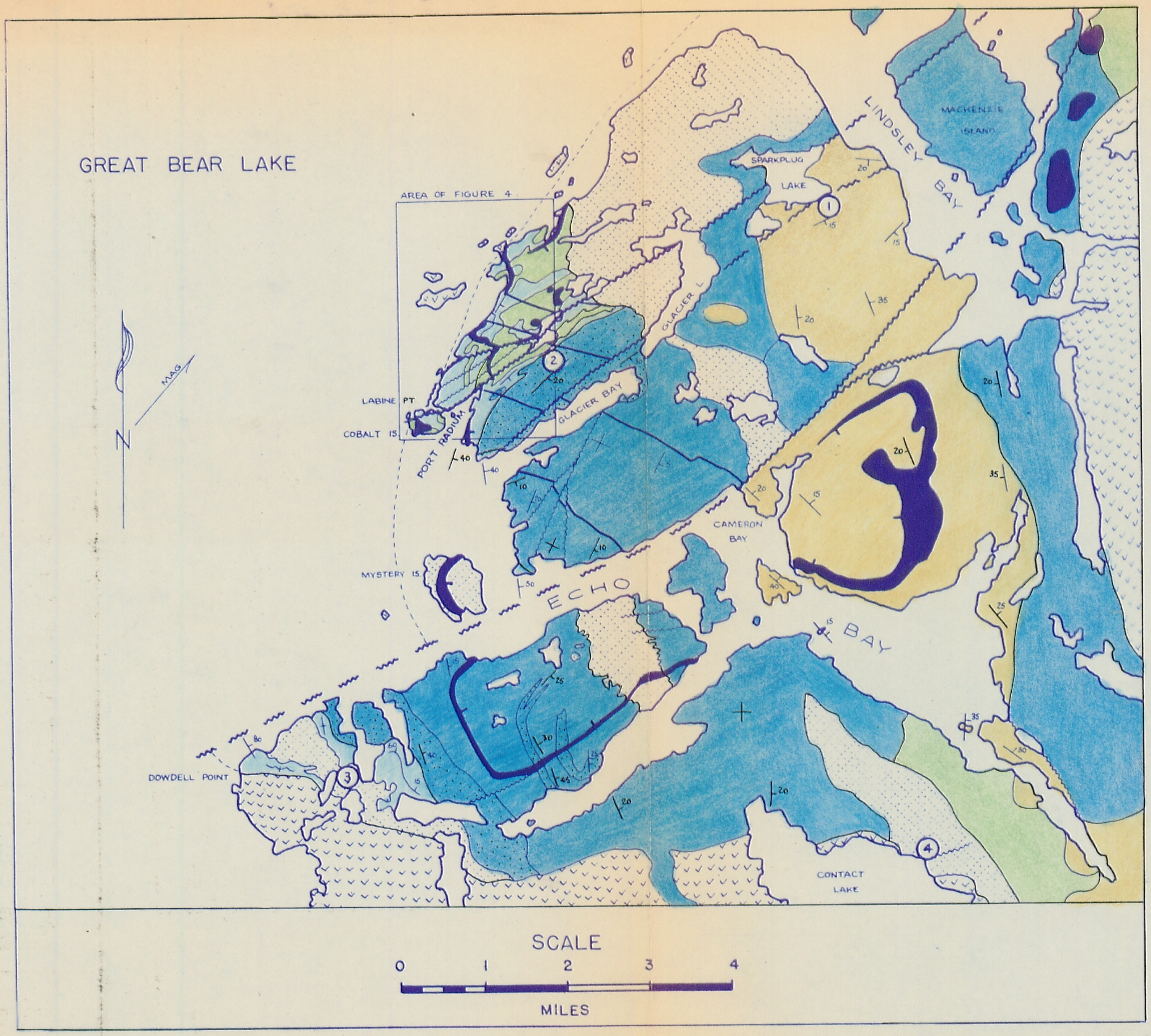
FIGURE - 3 -

GEOLOGY OF

ECHO BAY

AREA

GREAT BEAR LAKE NWT



ORE DEPOSITS

1 BUD GROUP FE CU AU

2 ECHO BAY GROUP FE CU U CO NI MN AG

3 BONANZA FE CU U AG

4 M GROUP FE CU U CO NI MN AG

BEDDING FAULT GRANITE CONTACT

INTRUSIVES

DIABASE - DIKES , SHEET

GRANITE

GRANODIORITE

FELDSPAR PORPHYRY (HYPABYSSAL)

CAMERON BAY GROUP - CONGLOMERATE ; TUFF, S.S.

UPPER ECHO BAY SUB-GRP - ANDESITE FLOWS

" - TUFFS , FLOWS, SEDS.

LOWER " - CHERTS, QUARTZITES.

Figure 7. Photograph of Labine Point, looking southwest from No. 2 Shaft.

Figure 8. Photograph of Crossfault Lake, looking northeast from No. 2 Shaft.

LOCAL GEOLOGY

Geologic Setting

The pitchblende ore deposits of Port Radium occur in vein-filled fractures and shear zones that trend northeast along Labine Point. On Labine Point the vein zones are in Lower Echo Bay strata. Immediately southwest of the point they pass into a biotite granite batholith. Two miles northeast of the point they cross a granodiorite stock $1\frac{1}{2}$ miles in width. From the granodiorite stock northeastward into the Lindsley Bay area the vein zones cut Cameron Bay strata. Pitchblende has been found in the vein zones between the granite in the southwest and the granodiorite to the northeast. No ore has been discovered in these vein zones anywhere else in the Echo Bay map-area (Fig. 3). Ore shoots have been found in other vein zones elsewhere in the map-area but they have proven to be minor compared to the Port Radium deposits. Therefore, the rock formations to be dealt with in detail are those of the Lower Echo Bay sub-group and the intrusives that cut the sub-group in the Labine Point area.

The Lower Echo Bay rocks of Labine Point lie on the western flank of what may be termed the Echo Bay pendant, a roughly triangular area, 80 square miles in size, of older formations within the granite batholith. In the northeast part of this pendant a neck of the older rocks projects northward beyond MacKenzie Island (Figs. 2 and 3).

The formations within the pendant are folded within a mile or two of the contacts with the surrounding granite, but the intensity of the folding greatly diminishes toward the centre of the pendant so that the formations underlying most of the pendant are relatively undeformed. Both the pendant and the granite have been cut by a multitude of fractures and shears. The principal fault systems are the Cameron Bay Fault and the Eldorado Zone, both striking north-east. The Cameron Bay Fault has an apparent right-hand displacement of about 2 miles. Good evidence of displacement on the Eldorado Zone is lacking. Between Crossfault Lake and Cobalt Island the Eldorado Zone splits into two major shear zones that enclose an elongate lens about two miles in length and one half mile in maximum width. The rocks within this lens are entirely Lower Echo Bay strata and accompanying intrusives, most of which are feldspar porphyry bodies. A variety of imbricate fractures and faults traverse the lens between the two major shear zones (Fig. 4). This pattern of breaks within the large lens has been the major locus of pitchblende deposition.

The feldspar porphyry intrusion in the vicinity of the fault lens is in the form of a tabular mass that trends about 20 degrees east of north and dips about 30 degrees to the east. This mass is actually composed of two main coalescing tabular bodies and is flanked by many discontinuous lesser bodies. The flanking intrusives are in some places branches of the main masses, but in most cases they are separate bodies. The whole system of intrusives seldom exceeds one mile in overall width and extends for four miles from Labine Bay northward to Weiner Bay where it is truncated by the granodiorite (Figs. 3 and 4).

The volcanic rocks of the Upper Echo Bay sub-group lie to the southeast of the mine area and are not traversed by the Eldorado Zone. Some pitchblende and metallic minerals occur in fractures in the flows southeast of Crossfault Lake, but so far have not proven to be economic. This sequence of massive volcanics probably overlay the Labine Point area when the Eldorado Zone fracture system was formed and mineralized. Such a thick section of competent rock would have had considerable effect on the character of the shear zones and probably rendered them unfavorable for deposition of vein material. This feature is characteristic of the vein zones in massive rocks throughout the Echo Bay region. The Upper Echo Bay volcanics thus may have acted as a cap to ascending solutions. Such a pinching of the vein zones may have been the cause of the concentration of the ore minerals in this vicinity in the underlying Lower Echo Bay rocks. In this event, deposits of favorable minerals in Upper Echo Bay volcanics, though uneconomic, may portend economic deposits in rocks beneath the volcanics.

A similar theory, in the case of the diabase sheet, is nullified by the fact that, although little ore occurs within the diabase, rich ore occurs both above and below it.

Wall-Rock Units

The formations in the vicinity of the Eldorado Mine include the Lower Echo Bay formations, the Eldorado vent, the feldspar porphyry, the granitic and the diabase intrusives.

A detailed table of formations for the mine-area is given in Table 2.

TABLE 2

TABLE OF FORMATIONS

Eldorado Mine Area, Port Radium, N. W. T.

FORMATION		DESCRIPTION
	Mineralization	Quartz, carbonate, sulfides, arsenides, pitchblende
TENSIONAL FRACTURING		
	Diabase	Dikes and at least one sheet
INTRUSIVE CONTACT		
	Mineralization	Quartz stockworks including giant veins
FAULTING AND FRACTURING		
	Biotite Granite	Generally pink. Coarse grained. Batholithic proportions
INTRUSIVE CONTACT		
	Granodiorite Complex	Elongate stocks. Red to grey. Medium grained.
INTRUSIVE CONTACT		
	Hypabyssal Intrusives	Feldspar-hornblende porphyry tabular bodies.
EXTRUSIVE AND INTRUSIVE CONTACTS		
Eldorado Vent		Tuff-filled pipes and associated caldera.
INTRUSIVE CONTACT		
Tuff Series	Upper Beds Conglomerate Transition Formation	Brown, cherty and silty, bedded tuffs. Section of pebble and cobble conglomerates, generally massive, apparently conformable. Fine fragmentals, cherty tuffs and some flows. Buff coloured. Includes porcelain cherts.
Mine Series	Mine Formation Cobalt Island Formation	Thin banded ferruginous cherts, massive cherts. Mod. thin bedded quartzites and cherts, mostly calcareous. Thick bedded cryptocrystalline cherts.
LOWER CONTACTS ALL AGAINST GRANITE INTRUSIVE		

LOWER ECHO BAY SEDIMENTS

On Labine Point, Cobalt Island and the east shore of Labine Bay about 2,850 feet of stratigraphic thickness of the Lower Echo Bay rocks are exposed. This thickness is measured from the base of the Upper Echo Bay volcanics on the east-shore cliffs of Labine Bay to the feldspar porphyry intrusive next to the granite on Cobalt Island (Fig. 4). In general, the Lower Echo Bay strata in this area trend slightly east of north and dip to the east. This general structure has been locally modified by multiple intrusions of feldspar porphyry and on Labine Point and Cobalt Island such modification is complex. For this reason the determination of the stratigraphic thickness in these regions can only be approximated.

The Lower Echo Bay sub-group in the mine area is divisible into two major units designated the Mine Series and the Tuff Series. The uppermost unit, the Tuff Series, beneath the Upper Echo Bay volcanics, is predominantly bedded tuff with minor fragmentals, cherts, and conglomerate. The lower unit, the Mine Series, underlies most of Labine Point and Cobalt Island and is comprised of cherts, cherty quartzites, calcareous cherts and quartzites and minor tuffs.

Along the west side of Labine Point and the northeast portion of Cobalt Island lies a section of calcareous cherts and quartzites with at least two cherty limestone beds. The bedding ranges in thickness from $\frac{1}{2}$ an inch to 6 inches. The upper beds of this unit are exposed on the extreme western tip of Labine Point. They underlie the narrows between the point and Cobalt Island, and trend southward across the east shore of that island. The lowest beds of the unit are truncated by intrusive feldspar porphyry on the west side of Cobalt Island. The exposed stratigraphic thickness of these calcareous rocks is about 700 feet. The section has been designated the 'Cobalt Island Formation'. A thin bed of conglomerate is exposed locally along the upper boundary of the formation. It suggests the existence of a disconformity between the Cobalt Island Formation and the overlying Mine Formation, but because it is exposed in an area of very intense deformation and widespread intrusion, its true relations cannot be determined with any degree of reliability.

The Mine Formation and the Cobalt Island Formation grade imperceptibly into one another. Some rock types are common to both formations. However, because broad differences do exist and are discernible between the formations they have been separated to facilitate structural work and discussion with the understanding that separation in the mine and on the surface often becomes too arbitrary to warrant the use of these formations as "working" units. The rocks of both units comprise the Mine Series.

Underlying most of Labine Point is a relatively thick section of very thinly bedded cherts. Because this section has been subjected to complex deformation in this area it is difficult to establish an accurate stratigraphic thickness for it. It has been estimated to be about 800 feet in maximum thickness. For purposes of discussion it has been designated the 'Mine Formation'.

The contact between the Mine Formation and the overlying Tuff Series trends north-south across the middle of Labine Point. Comprising the lower 500 stratigraphic feet of the Tuff Series are bedded and massive cherts, tuffs, and fragmentals with scattered thin dacitic flows. These rocks are best exposed in the vicinity of Bear Bay and differ from the overlying remainder of the Tuff Series, in that the rocks are finer grained, more massive and commonly fragmental. They have been designated the 'Transition Formation' in the mine and will be occasionally referred to as such in this report but the distinction as a mappable unit in the field is not dependable enough to warrant the separation of these rocks from the rest of the Tuff Series.

The remaining 800 feet of the Tuff Series is made up of evenly bedded tuffs. The beds range up to a few inches in thickness.

<u>Mine Series</u>

<u>Cobalt Island Formation:</u>

Rocks of the Cobalt Island Formation are best exposed on the northeast half of Cobalt Island (Fig. 4). The beds strike slightly east of north and dip 30-50 degrees to the east. They are exposed in the southwestern mine workings below the 650 Level. A line drive, 601 W., paralleling No. 1 Vein on the 650 Level, cuts through 250 stratigraphic feet of beds that represent the middle of the Cobalt Island Formation.

The Cobalt Island Formation is comprised mainly of moderately coarsely bedded cherty quartzites. Beds range in thickness from about an inch to 6 inches. "Hair banding", a characteristic feature of the Mine Formation cherts, is rare in Cobalt Island Formation rocks. The quartzites are extensively interbedded with cherts that are not as glassy in texture as the Mine Formation cherts. Also common in the Cobalt Island Formation are thick beds of massive, cryptocrystalline to glassy chert. The quartzites and interbedded cherts are usually banded pink, red and grey. The massive cherts are predominantly deep pink, almost red-brown, and, less commonly, grey or white. Emplacement of metasomatic ferromagnesian minerals has added green and black banding to local sections of the rocks.

In addition to the quartzites and cherts the Cobalt Island Formation includes many sections, up to several feet in thickness, of streakily banded grey cryptocrystalline cherty rocks that are highly calcareous. The carbonate content of the specimens studied ranges from 10 to 35 percent and is present as anhedral patches and euhedral rhombs dispersed throughout the chert in irregular bands. The rhombs seldom exceed 0.2 mm. in length. Similar calcareous cherts are described in the literature as being widespread in sedimentary rocks of all ages. Keller[25] states that in tests made on the Rex cherts of Idaho-Wyoming the euhedral rhombs of carbonate have been found to be dolomite, whereas the anhedral carbonate is calcite. Limited investigation of the Cobalt Island Formation calcareous cherts suggests the same textural difference between the calcite and the dolomite. Metamorphism of these calcareous strata at Port Radium has produced large patches of grey-green garnet with some scapolite and diopside. Such minerals are strikingly lacking in similarly metamorphosed non-calcareous rocks. The unmetamorphosed calcareous cherts megascopically so resemble the non-calcareous varieties that distinction in the field of one from the other is difficult. If the carbonate content of the chert is relatively high and predominantly calcite, hydrochloric acid will produce some effervescence. These calcareous cherts occur solely in the Cobalt Island Formation of the Lower Echo Bay sub-group.

The beds of the Cobalt Island Formation weather differentially to a slight but noticeable degree. This is a function of the carbonate content and provides a good field distinction between these rocks and the non-calcareous Mine Formation rocks to the east.

Good horizon markers in the Cobalt Island Formation are two lenticular sections of quartzitic limestone. The average thickness of one section is about ten feet, but extremes of two or twenty feet are common. The other (upper) section seldom exceeds one foot in thickness. Where these limestones are exposed, they provide an excellent trace of the structure of the otherwise featureless sequence of bedded cherts and quartzites (Fig. 5). Unfortunately they pinch out locally, either by lack of deposition or by deformation, and cannot be depended upon to appear in any given place. The Cobalt Island limestone beds are in the same general stratigraphic position as two limestone beds on Dowdell Point and probably represent the same horizons. The thin beds of the limestone units weather differentially to produce a grey-coloured deeply ribbed rock easily recognized in the field. The unweathered rock, however, appears so much like the surrounding quartzites that the megascopic recognition of the limestone horizon underground is virtually impossible.

Underground, two hundred and fifty feet of Cobalt Island quartzites and cherts exposed in 601 West Drive are regularly bedded in strata that average about two inches in thickness. Graded bedding, scour channels and small-scale cross-bedding are clearly evident in some beds and indicate that the beds are right side up with tops facing east. No ripple marks have been found. The sediments appear to be stable shelf deposits.

Mine Formation:

Rocks of the Mine Formation underlie most of Labine Point and encompass a large part of the mine workings (Figs. 4 and 5). At Labine Point the Mine Formation has been extensively intruded by tabular feldspar porphyry bodies. The intrusions of these bodies have truncated, isoclinally folded, arcuately folded and fractured the sedimentary rocks so that local structures are often very complex. However, the general northeast strike and southeast dip of the Lower Echo Bay formations are maintained on a large scale. Metasomatism has also accompanied the porphyry intrusions and has so pervaded the host rocks that few specimens of Mine Formation rocks can be found that do not show its effects. In the vicinity of Labine Point the majority of the exposed Mine Formation possesses at least 20 percent metamorphic minerals. For the most part, the location of these minerals has been strongly influenced by the original bedding so that the principal metamorphic modification on the appearance of the rocks has been one of accentuation of banding and change of colour. In zones of intense metasomatism all traces of the original banding have been destroyed.

The principal rock-type of the Mine Formation, ignoring for the moment the metasomatic products, is thin-bedded chert. The bedding of the chert is apparent in some thin sections as variations in grain size, but in general the thin lamination is megascopically mainly the result of slight variations in hematite colouring. The cherts are normally shades of pink or grey, depending on the hematite content. The hematite is in the form of microscopic dust disseminated throughout the rock and comprises up to 3 percent of the rock. Banding in the cherts ranges in thickness from 2 mm. to 1 cm. This thin banding, usually accentuated by metasomatism, is very characteristic of the Mine Formation rocks and serves to distinguish them from the Cobalt Island and Transition Formation rock types. Thin banding is present in some Cobalt Island Formation rocks but is confined to narrow belts. In many exposures the texture of the banded Mine Formation rocks suggests quartzites rather than cherts. In all such cases where thin-sections were made, the character and sizes of the silica grains were those of chert. The deceptive megascopic appearance of the texture is due mostly to the presence of metasomatic minerals and occasionally to the recrystallization of the original quartz grains.

The other major rock type of the Mine Formation is massive chert. It occurs as lenticular beds that range in thickness from less than one foot to forty feet. The bottoms of the massive chert units usually grade into the bedded cherts within a foot or two. The tops either grade into the overlying bedded cherts or are in sharp contact with them and often show an intraformational breccia of sharp-edged fragments of massive chert in banded chert. The massive chert beds grade into the bedded cherts laterally as well and thus show considerable, and often abrupt, variations in thickness. The massive chert beds are good horizon markers for short distances, but because there are at least three of them all much alike and all known to lens out locally, they do not make dependable horizon indicators for projections much over 500 feet. The denseness and lack of internal structures of the massive chert units has made them poor hosts for metasomatism in most places, and they have retained their primary lithology. The massive cherts of the Mine Formation are generally bright pink, possess a conchoidal fracture, are very hard and characteristically glassy. This glassiness is in contrast to the cryptocrystalline character of the Cobalt Island Formation cherts and the dull, porcellanous character of the Transition Formation cherts. Essentially the massive cherts and the thin-bedded cherts are identical in texture and composition. The difference between them is primarily one of genesis which is discussed below. The present great differences between them are attributable to the differential alterations by metasomatism.

The thin and uniformly bedded cherts of the Mine Formation extend over a strike length of about six miles in the Echo Bay area. Primary depositional features are lacking in the sequence. The series apparently represents cyclic chemical deposition of colloidal silica in fairly deep water. The very thin bedding throughout large thicknesses indicates a control of flocculation and deposition of silica that occurred frequently but for short durations.

Recently geologists working in the pre-Cambrian iron ranges have attempted to apply broad definitions to the term iron-formation(26)(27)(28). A general consensus is that iron-formation is any rock that originated as chemical precipitation of iron as oxide or hydroxide and silica as chert and which was deposited by rhythmic alternations of iron-rich and iron-deficient precipitates. James(26) puts a minimum limit of 15 percent on the iron content. All differences in types of iron minerals, resulting either from metamorphism or from original depositional conditions, are encompassed by this general definition. Thus the major pre-Cambrian iron-rich sediments from the itabirites of Brazil to the complex assemblages of the Lake Superior ranges would be classed as iron-formation. By extrapolation the equally abundant pre-Cambrian iron-rich (a few percent iron) cherts could be considered as being lean iron-formation(27). This general type of rock would be akin to the banded ferruginous cherts of the Mine Formation at Port Radium.

Numerous studies have shown that iron and silica can be transported in rivers either as colloids or in true solution, and that they will be precipitated soon after contact with sea water(29). If limonite were the original iron mineral deposited then regional metamorphism could expel the water and produce hematite or possibly magnetite. James(26) favours original precipitation of magnetite in some of the Biwabik formation where it is found interlayed with chert far from any igneous intrusives. The Mine Formation cherts are banded with both magnetite and hematite, but because the magnetite attains its maximum in the vicinity of the feldspar porphyry intrusives its origin is probably more metasomatic than sedimentary. The thick beds of massive chert, gradational with underlying thin beds, and in sharp contact with overlying thin beds, represent periods of deposition during which conditions changed considerably from those prevailing for the usual thin-bedded deposition. This change of conditions may have been either a sharp increase in the silica concentration of the source rivers or a moderate local change in the factors causing flocculation of the silica. Because the massive chert beds interfinger laterally into bedded cherts, and because the upper sharp contacts suggest rather abrupt termination of conditions, a local change of flocculation factors is favoured as the cause of the deposition of chert in massive lenses. The change necessary to affect the source of the silica would be one of a radical change in weathering and erosion that subsequently sharply reverted to previous conditions. The changes necessary to alter the flocculation could be more easily attained. Either the local introduction of a different flocculating agent for a short period, or a slight change in the agent already operating would suffice to precipitate an abnormal amount of silica. Colloidal silica in solution can be precipitated by very slight changes or additions of electrolytes or colloids of opposite charge[30]. A slight change in salinity of the sea water would be enough to cause deposition of massive chert beds.

Sampson[31] suggests a mechanism whereby iron, transported in the ferrous state, is oxidized by ocean water to ferric hydroxide. The positive charge of the ferric ion neutralizes the negative charge of the silica and causes coagulation. The iron appears in the chert as hematite dust. The Port Radium cherts are almost identical to the Newfoundland cherts described by Sampson. The massive cherts of the Mine Formation are generally bright pink or red and contain much more hematite dust than the banded varieties. This higher hematite content of the massive cherts may be correlative with the coagulation of the thick bands of silica.

The silica in the least metasomatized cherts is in the form of a dense mosaic of interlocking non-clastic lobate grains whose dimensions range from less than 0.02 mm to 0.10 mm. In most sections studied, most grains are considerably smaller than the largest grains. Occasional thin-sections show slight sorting of grains by sizes, but such examples are rare. One specimen exhibited bands of 0.2 mm-sized particles interbedded with larger bands of 0.02 mm-sized particles. Metamorphism of these rocks has resulted in a progressive recrystallization of the quartz and growth of grains. With increased recrystallization the silica grains exceed 0.1 mm in size and are distinctly sutured. These grains have the optical properties of quartz and show undulatory extinction.

Many thin sections of chert, both banded and massive, show contents of plagioclase ranging up to 25 percent. The plagioclase is intimately dispersed throughout the rock in grains similar in size and shape to those of the quartz. In very fine grained chert, recognition of plagioclase in thin section is nearly impossible. Some of the feldspar may be indigenous to the chert, but in general the feldspar content of the chert increases with increasing recyrstallization. Also, the specimens with highest feldspar contents are in zones of most intense metamorphism. In all cases the plagioclase, where determinable, is oligoclase. It is concluded that the majority of the plagioclase observed in thin sections so intimately associated with the silica is a product of metasomatism and not original deposition. Rocks previously described from this formation as being arkosic are in effect pseudoarkosic meta-cherts.

Occasional small quartz clasts are dispersed through the chert. They seldom exceed 0.5 mm in size. Cherts with pebble-sized sub-angular clasts are very common in the Transition Formation but are absent from the Mine Formation.

The distinctive thin and even bedding of the Mine Formation banded cherts can be observed in some thin sections as slight variations of particle size. It is most obvious, however, as colour differences. The differential colouring of thin beds is imparted in the unmetasomatized sediments by the disposition of hematite and in the metasomatized rocks by the location of metasomatic minerals along preferred bands. The latter characteristic is discussed later under Metamorphism, however, it is important to note here a significant misconception that has arisen because of it. These banded cherts have been designated by some geologists as argillaceous cherts or cherty argillites. Very thin grey green and black fine grained bands interspersed through pink or cream chert have the appearance of argillaceous beds. In thin section these bands show up as crystalline aggregates of metasomatic minerals that have selectively replaced bands of chert.

Replacement textures are abundant, and no evidence of argillaceous derivation can be found in any of the specimens. Type, grain-size and quantity of these metasomatic minerals emplaced in the cherts change in direct relation to the proximity of intrusive feldspar porphyry bodies. It is concluded that the chemical components of the metasomatic minerals, with the exception of silica, have been added to relatively pure cherts, and little or no material has been derived from indigenous clay. Therefore, in the Port Radium area at least, the Mine Formation contains no argillaceous rocks, although some appearances in the field belie the fact.

Tuff Series

Transition Formation:

Immediately overlying the Mine Formation, and cropping out on Labine Point between Dumpy Lake and Radium Lake is a forty foot sequence of thin tuff beds. Between these tuff beds and the other beds of the Tuff Series to the east, is a thickness of about 500 feet of interbedded cherts, tuffs and fragmentals. This sequence has been designated the Transition Formation. The rocks were so named originally in the mine where they appeared to be transitional between the Mine Formation cherts and the massive crystalline tuff body, the Eldorado Vent. Subsequently it has been found that the Eldorado Vent truncates the Transition beds and that the latter represent the part of the stratigraphic sequence above the Mine Formation and at the bottom of the Tuff Series to the east.

The transition of the Mine Formation cherts to the overlying tuffaceous rocks is gradational. The boundary between the two sequences has been placed at the top of the uppermost thin-bedded cherts. This boundary is not easily defined in outcrops because of the similar appearance of the cherts and the tuffs. By thin section study the boundary between cherts and tuffs is easily fixed. The abundance of fragmental beds in the Transition Formation provides an additional distinction between it and the underlying rocks.

The Transition Formation differs from the Mine Formation in that it has cherty tuffs and coarsely fragmental tuffs interbedded with minor cherts. By the same token it differs from the rest of the Tuff Series in that it has cherts interbedded with tuffs, whereas cherts are uncommon in the rest of the Tuff Series. The differences between the Transition Formation and the overlying rocks are slight and the position of the boundary between the two is arbitrary. It has been placed at an horizon above which the predominant rock type is fine grained tuff and below which the predominant type is coarsely fragmental tuff. The position of the boundary is open to doubt where exposures are meagre; however, in general, the Transition Formation rock types often constitute separable map units, so for local convenience the differentiation is retained. Where there is doubt, the designation Tuff Series is used.

The Transition Formation is comprised mostly of fragmental and cherty tuffs, generally poorly banded. In addition, it has bedded coarse-grained tuffs, cherts and some thin discontinuous flows. The cherts are similar to the massive varieties of the Mine Formation but are not as glassy in texture and are coloured more dull brown than pink. Banding is common but uneven and often not continuous. Limits of beds are not always sharply defined. Dull grey brown is the predominant colour of all the Tuff Series rocks, including those of the Transition Formation.

Beds range in thickness from 0.5 inches to over a foot. The tuffs are hard, buff coloured and generally cherty in appearance. On close inspection a fine granular texture may be seen, but in general the texture is megascopically like that of the cherts. In thin-section the tuffs appear as unsorted aggregates of subangular plagioclase grains and very minor amounts of quartz. The plagioclase, where determinable, is oligoclase. Comprising the basal 40 feet of the Transition Formation are bedded coarse-grained ($\pm$0.5 mm) tuffs. Rocks of this type are not common in other parts of the Transition section but comprise the majority of the overlying Tuff Series. This rock is distinctive from the surrounding cherts in that it is slightly thicker banded and has a crystalline texture. Unfortunately the neighbouring cherts are heavily recrystallized and metasomatized, as are the tuffs, so the megascopic differences between the rock types are often masked. These tuffs are hard, peppery grey or pink coloured and fine sugary crystalline. Plagioclase grains are often recognizable megascopically. In thin section the rock is a jumble of subrounded feldspar grains interstitially packed with finer grained feldspar grains. The matrix material comprises about 20-25 percent of the rock and is about 0.02 mm in grain size. The larger grains are about 0.50 mm in size. Fifty to seventy-five percent of the feldspar is oligoclase, the remainder is albite and orthoclase.

Sorting is absent, and bedding is only moderately well developed in these tuffs, indicating possible subaerial deposition.

Scattered through the Transition Formation in the vicinity of McDonough Lake are beds of fragmental rocks. These are similar to the surrounding fine-grained tuffs, except for the presence in them of rather thinly distributed angular cherty fragments. The matrix of the fragmental rock is fine-grained tuff, essentially the same as the fine-grained tuff described above as the principal Transition Formation rock type. The fragments seldom exceed one inch in largest dimension and are comprised mainly of green, grey, brown or pink felsite, tuff and chert. Chert fragments appear to be the most common and in at least one horizon seem to be the sole constituent. The sequence of fragmental beds is very poorly defined, and individual sections range up to 40 feet in thickness with no signs of bedding. Fragment concentrations range from no fragments to 80 percent fragments within distances of a few feet. The best exposures of the fragmental tuffs are underground and west of Weiner Bay (Fig. 4). At the time of writing their distribution is not well known.

Tuff Series:

The Tuff Series, above the Transition rocks, is composed predominantly of unevenly, thinly bedded relatively coarse-grained tuffs. Individual beds are usually about one inch in thickness, but beds as thin as 0.25 inches are not uncommon. Monotonous sequences of very fine and even beds, so characteristic of the Mine Formation, are lacking in the Tuff Series. The tuffs are hard, dull pink and brown, fine crystalline or cherty and unevenly bedded. Metamorphism has locally developed ferromagnesian minerals and recrystallized the feldspar. In general, these bedded tuffs closely resemble arkoses in hand specimen.

In thin section the tuffs are about the same as the coarse-grained tuffs described above under Transition Formation. The fine-grained varieties, described as cherty tuffs, are composed of bands of poorly sorted, jumbled and intergrown fine plagioclase grains. Grain sizes range from 0.1 mm to 0.01 mm and do not show perceptible sorting in or within bands. The principal mineral constituent is oligoclase. Quartz usually constitutes less than 10 percent of the rock.

Interbedded with the tuffs are abundant thin beds of pale pink chert. The exact proportion of chert to tuff in the sequence is not known but from the data available the tuffs constitute probably more than 75 percent of the rocks.

In the upper part of the Tuff Series there is at least one pebble-cobble conglomerate composed of rounded cherty and felsitic pebbles scattered moderately thickly through a dense silty matrix. This conglomerate crops out near Talus Lake and between Diamond Lake and Bruce Lake (see Fig. 4). The Lower Echo Bay rocks exposed northwest of Crossfault Lake, where the conglomerate is best exposed, occur as isolated pendants and irregular-shaped strips enclosed by the main feldspar porphyry intrusive complex. The intruded rocks are not highly folded but are locally faulted and occur in such scattered patches that correlation from one pendant to another is not dependable. The location on the map (Fig. 4) of the conglomerate outcrops suggests the existence of more than one conglomerate unit; however, in the field the conglomerate occurrences are so strikingly similar, both in lithology and in stratigraphic environment, that it seems unlikely they do not represent the same unit. Faults that are exposed or inferred will not suffice to account for the dismemberment of the conglomerate unit, assuming there is only one unit. The only other plausible explanation is dislocation of blocks (as pendants) of host rocks by the intruding feldspar porphyry bodies. In view of the fact that extensive forceful intrusion of the porphyry bodies is well illustrated in the mine vicinity this explanation is a likely one for the erratic distribution of the conglomerate exposures.

The conglomerate generally conformably overlies and is overlain by bedded tuffs, locally fragmental or cherty, of the Tuff Series. The basal contact is sharp but the upper contact is locally gradational into the tuffaceous beds. As nearly as can be determined, the conglomerate lies about 800 feet below the top of the Tuff Series, which is overlain by the first flow of the Upper Echo Bay sub-group. The conglomerate unit maintains a stratigraphic thickness of between 100 and 150 feet.

The cobbles of the conglomerate constitute about 50 percent of the rock and are generally pebble-sized (± 1 inch) in the upper part of the unit but increase in size downward in the unit so that boulders over two feet in diameter are not uncommon in some exposures of the lower layers. This general sorting is the only principal primary structure apparent in the conglomerate. Bedding, small scale sorting and interbedding by sandy layers occur only rarely. The pebbles of the top part of the conglomerate are predominantly pink and cream coloured cherts; however, deeper in the unit the cobbles are predominantly grey, green and brown porphyritic felsites and finely banded cherts and the boulders at the bottom are usually porphyritic felsites. Cobbles of granitic rocks are not uncommon. The boulders and cobbles are always well-rounded but the pebbles range from well-rounded to subangular in shape.

Southeast of Crossfault Lake the upper beds of the Tuff Series interfinger with and are locally truncated by lava flows of the Upper Echo bay sub-group (Fig. 4). The overall thickness of the Tuff Series therefore changes east of the mine and may be expected to do so elsewhere.

The Tuff Series has been exposed underground in the No. 2 Shaft area.

Figure 9.

Cobalt Island Formation calcareous cherts and Eldorado Vent. Looking north along west shore of Labine Point.

Mine Formation cherts, Labine Point.

Figure 10.

MASSIVE CRYSTALLINE TUFF - ELDORADO VENT

Along the northwest side of Labine Point is a body of massive rock that both cuts through and unconformably overlies bedded rocks of the Cobalt Island and Mine Formations. Northward, beyond Dumpy Lake and beyond Bear Bay, the contact of this body strikes parallel to the Transition Formation beds but dips into them to the east (Figs. 4 and 5). Because of the near-parallelism of the sediments with the contact of this massive tuff body it was assumed that the two were more or less conformable and that the tuff formed the base of the Lower Echo Bay section. This was further suggested by apparent transitional relations exposed in some mine workings. Subsequent work has shown the massive tuff to be in angular unconformity with the sedimentary formations and to be sharply truncating them along its southern contact. Detailed surface mapping has revealed several places where the tuff truncates the sediments. There is also at least one locality where the tuff clearly lies on top of vertical beds of the Cobalt Island Formation. There are no discernible metamorphic effects in any rocks adjacent to the massive crystalline tuff contact. Most of the contact explored underground is occupied by a vein zone, and the primary contact relations are largely obliterated.

The massive crystalline tuff crops out along the northwest flanks of Labine and Flat Points for a distance of 6,000 feet northward from the mine. It crops out again in the Corregidor Bay area (Fig. 4). The size, lithology, complete homogeneity and structural relations of the body, when considered together, define a formation that is rather unique in the district. There is a strong probability that this massive tuff body is a remnant of a caldera-type formation.

At the mine the massive crystalline tuff has been conveniently and non-commitally named MCT. For consistency and convenience the designation MCT will be used in this paper when referring to the rock type, but where connotation of the structure is desired the term "Eldorado Vent" will be used.

Considerable work has been done in an effort to establish the true nature of the massive tuff body. An account of this work, and the conclusions drawn therefrom, are presented here in some detail. The existence of such a structure in the pre-Cambrian has not been reported heretofore, therefore it is felt that a rather detailed description is warranted.

External Structures:

As shown in Fig. 4, the main body of the tuff lies astride Bear Bay, and additional bodies crop out in the vicinity of Corregidor Bay. The Corregidor Bay bodies appear to be pipes, but data on them are meagre, therefore this discussion is concerned mainly with the Bear Bay tuff. The general shape of the Bear Bay massive tuff body is shown by subsurface contours in Fig. 11 and by cross-sections in Fig. 12.

The intrusion of the granite locally tilted and folded Old Complex formations. The granite intruded the massive tuff body, and as extensive faulting has antedated the granite, it is probable that the original shape of the massive tuff body has been somewhat

p. 75 Cumpbell - dd - 1955

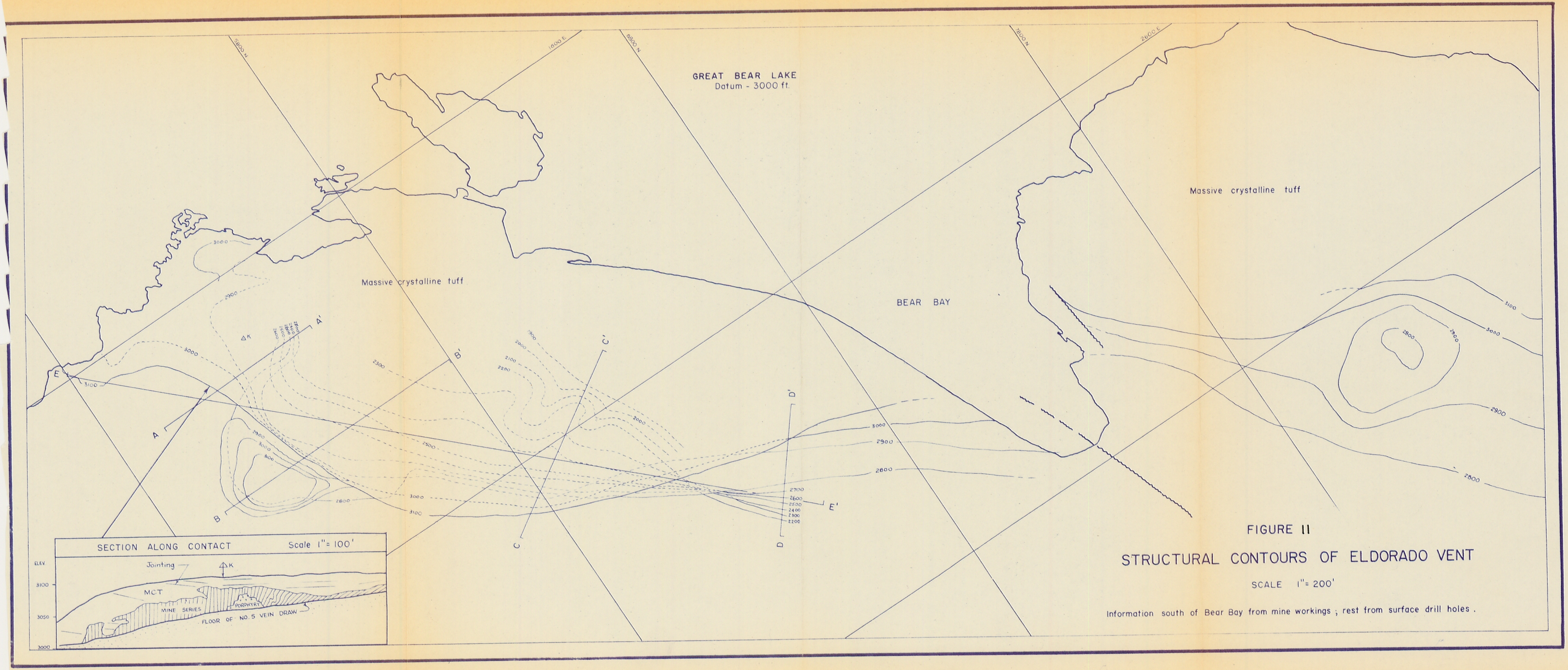


FIGURE 11

STRUCTURAL CONTOURS OF ELDORADO VENT

SCALE 1"= 200'

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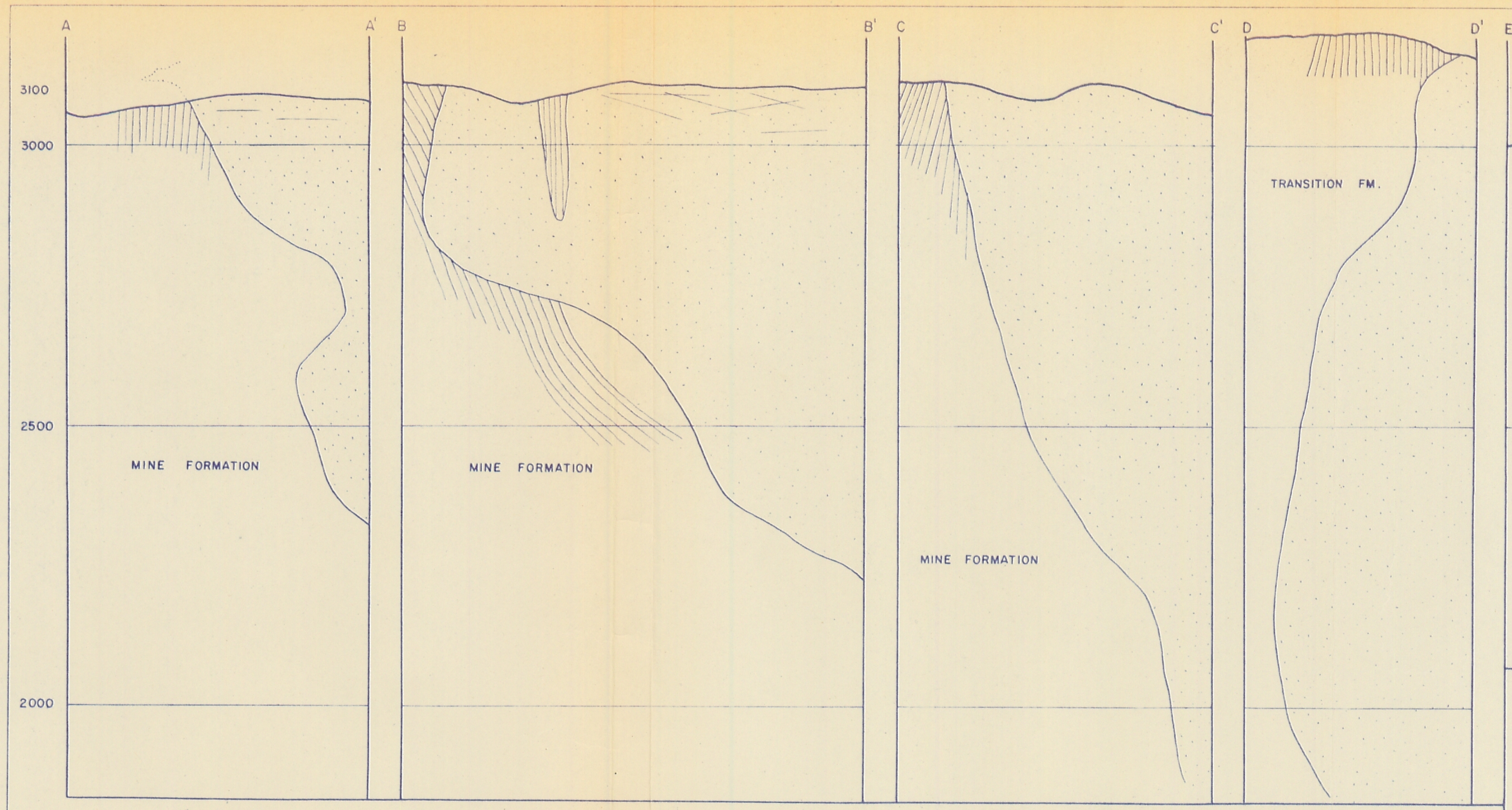


FIGURE 12 A

CROSS SECTIONS OF CONTACTS OF ELDORADO VENT

SCALE 1" = 200'

LEGEND

MCT (Vent)
Bedded sediments
Massive cherts
Jointing
Bedding
Drill holes

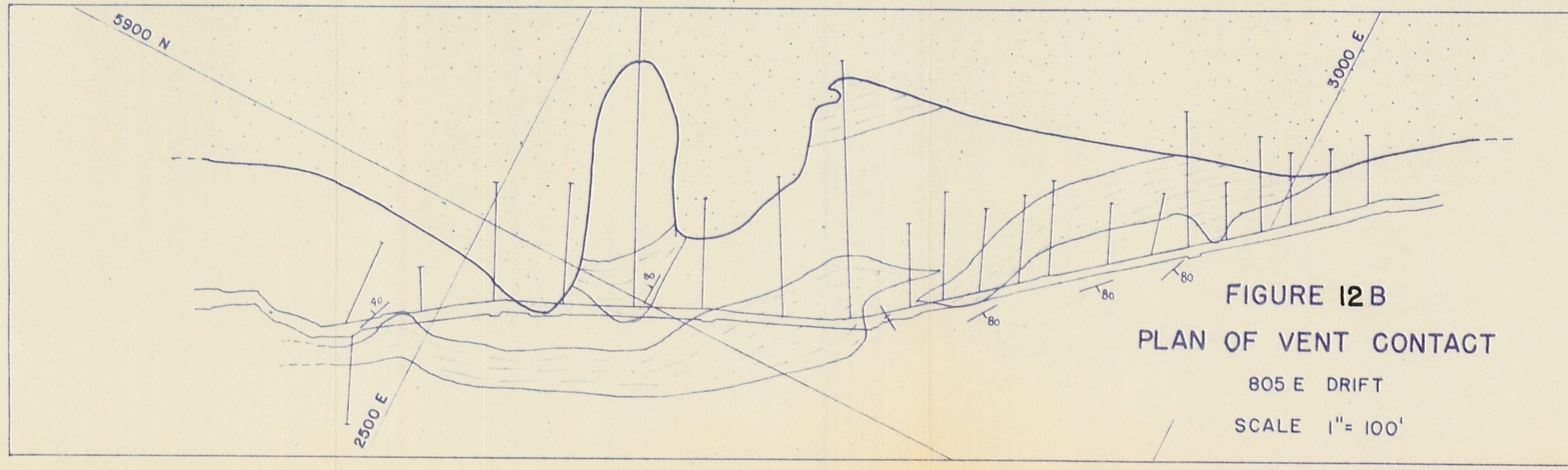


FIGURE 12 B

PLAN OF VENT CONTACT

805 E DRIFT

SCALE 1" = 100'

modified. No. 5 Vein (shear zone) was deflected from its general strike when it reached the massive tuff body and angled along the contact of the tuff. Smaller veinlets, shears and fractures, common in the surrounding sedimentary rocks, are also deflected at the tuff contact where they meet it at low angles or on penetration of the tuff die out in it within short distances. These features suggest that the tuff body acted as a relatively immovable massif during diastrophism and consequently has not suffered radical changes in its original shape. There is the suggestion that the surrounding sedimentary formations were folded against the tuff massif so that they locally assumed rough conformity with the tuff contact. It seems reasonable to assume that the present shape and position of the tuff body are not unlike the originals in gross aspects, and that the tuff body was emplaced in much the same position as we see it now.

The body appears to be a segment of a steep-sided plug with an overhanging lip or bulge to the south. The walls bulge and roll locally, but the general steep dips and curvilinear plan are maintained. The overhang on the south side is where the tuff unconformably lies on top of vertical sedimentary beds. This is shown in Fig. 12A, Section E-E', and in Fig. 11. (Insert).

The cross-cutting relationships of the tuff body to the Mine Formation is shown in Fig. 11 and in Fig. 12A cross-sections A-A', B-B' and E-E'. Local near-conformable relationships are shown in Fig. 5 near the contact of the Mine Formation and the Transition Formation, and in Fig. 12A cross-sections C-C' and D-D'. Because the eastern contact of the massive tuff body trends almost parallel to the strike of the Transition Formation the beds of that formation appear to be conformable with the tuff along that part of the contact. Underground exposures showing this pseudo-conformability resulted in the original conception that the tuff was the base of the sedimentary section and that the Transition Formation bedded tuffs represented a transition to the sedimentary rocks of the Mine Formation. In many places this would seem to be the case, but in others (Fig. 12B) it has been revealed to be erroneous.

Internal Structures:

Internal structures are rare in the massive crystalline tuff body. The rock is monotonously massive and uniform. At scattered places along the margins of the body the tuff is coarsely, unevenly and discontinuously bedded. Wedges of well bedded chert, up to 100 feet in length and several feet in width, are found near the margins of the tuff either wholly enclosed by tuff or connected at some point to the adjacent sedimentary rocks. These wedges resemble elongate xenoliths within an intrusive, but nowhere near them or within them are there any evidences of metamorphism, digestion or other contact actions.

At a few localities, one in 305 E. Drift, another on the surface near Diamond Lake and another at the water's edge on the south shore of Bear Bay, the massive tuff is brecciated along its contact. The breccias are made up of relatively large subangular and rounded fragments of tuff in a gritty tuffaceous matrix. They grade imperceptibly into the massive crystalline tuff but are in sharp contact with the adjacent sediments. The fragments range in diameter generally from 6 inches to one foot. One of the breccias occurs in a protuberance of tuff into the surrounding sediments. The breccia zones seldom extend more than ten feet into the tuff body.

A distinctive feature of the outcrop of the massive tuff is a well developed near-horizontal jointing. Viewed from a distance, especially when the sun is low, the massive tuff outcrops appear to be distinctly layered, an illusion imparted by the flat joints. One set of jointing in tuff-filled volcanic pipes is commonly flat[32], in contrast to a similar set in intrusive plugs that is usually convex upward. Along No. 5 Vein Draw, 300 feet east of Great Bear Lake, the tuff lies across vertical chert beds of the Cobalt Island and Mine Formations (Fig. 5). This contact has several irregular humps and reentrants, but for the most part it is flat-lying, and the contacts are sharp. There is local rustiness and fracturing along the contact, but in general no evidence of primary thermal or dynamic activity.

Lithology:

The massive tuff is generally uniform in appearance in all exposures. Differences are usually in colour, seldom in texture. The rock is hard, uniformly fine crystalline (often sugary), characteristically black peppered and massive. Its colour is grey-buff or brownish grey, usually with light or dark streaks. Locally the rock is pink or nearly black, with or without the fine black peppering. Feldspar faces are commonly megascopically distinguishable. White feldspar phenocryst-like grains are rarely present and if so are widely scattered. It is difficult to tell a specimen of massive crystalline tuff from some of the finer-grained intrusive porphyry rocks, and if the field relations are obscure this difficulty becomes acute in mapping.

Twenty-five specimens were collected from the outcrop area of the massive crystalline tuff between Bear Bay and No. 5 Vein and studied in thin sections. They represent a moderately uniform sampling of a 1600 x 900 foot area of the massive tuff. The samples covered a vertical range of about 100 feet as well. They all exhibited a remarkable uniformity in lithologic character. Compositionally the tuff is identical over the whole area studied. It is generally monomineralic, the main constituent being oligoclase. In a few specimens quartz constitutes up to 10 percent of the rock and more rarely andesine, orthoclase and secondary albite may accompany the oligoclase in nearly equal proportions to it. All sections showed that the original rock had been modified in different degrees by both hydrothermal and metamorphic actions. New minerals from such actions occupied nearly 45 percent of some slides, but in general they seldom exceeded 30 percent. The metasomatic minerals are fine-grained, are disseminated thinly throughout the tuff and impart the peppered appearance to the rock. They all clearly replace the feldspar grains. The peppering increases directly as the amount of metasomatic minerals present and is not a primary characteristic. The added minerals are mostly magnetite, hornblende and chlorite.

Texturally the massive tuff ranges between two types. One type is a fresh tuff consisting of jumbled stubby broken plagioclase subhedra with grain sizes ranging from 0.1 mm to 0.5 mm and showing no sorting or discernible common orientations. The grains are abundantly twinned, only slightly sericitized and are tightly intergrown with incipient suturing. The other type of tuff is by far the predominant type in the massive body. It resembles the fresh type of tuff, in that it is a jumble of unsorted irregular-shaped stubby plagioclase laths. The grain sizes are similar, averaging about 0.3 mm, but in this type of tuff there is more finer grained feldspar between the larger anhedra and the texture has a "fused" appearance. The "fused" type of tuff differs from the fresh type in the following properties: (1) Twinning is obscure and sericitization of the plagioclase is heavy, especially in the larger grains; (2) the grain boundaries are moderately sutured throughout and secondary feldspar growth is common around rims of grains and in interstitial pockets; the secondary feldspar is albite and is generally not sericitized; (3) phenocryst-like grains as large as one millimeter are not uncommon and are sutured to surrounding grains. They are apparently relatively larger fragments and are not metacrysts. They are all very heavily sericitized.

Boundaries between the two types of tuff, or any systematic distribution of them, could not be found. The massive crystalline tuff body apparently was subjected after formation to conditions causing incipient recrystallization and some sericitization in all but a few local areas. These conditions were probably brought about by the retained heat (presuming the original tuff

Figure 13. Nonsutured massive crystalline tuff. Photomicrograph x 50.

Figure 14. Sutured massive crystalline tuff. Photomicrograph x 50.

had acquired some heat before expulsion) and the inherent compaction of so large a body of loose material. There are no indications that this slight metamorphism was induced or accompanied by solutions, but the possible presence of moisture cannot be disregarded.

Microscopically the massive crystalline tuff is not dissimilar from some specimens of intrusive feldspar porphyry. A few points of distinction are noteworthy. The distinct phenocrysts characteristic of most of the intrusive porphyry are not present in the tuff, although scattered large fragments of feldspar in the tuff may megascopically appear to be phenocrysts. Ferromagnesian minerals are present in the intrusives as primary phenocrysts and matrix grains. They are absent as primary minerals in the tuff. The oligoclase grains in the intrusive are usually narrow uniformly sized laths. In the tuff they are stubby poorly sized subhedra. The plagioclase grains in the porphyry matrix are generally about 0.05 mm in size, whereas the grains in the tuff groundmass usually exceed 0.3 mm. The anorthite content of the oligoclase is generally the same in both rock types.

Origin of Massive Crystalline Tuff:

Sedimentary Origin

The lithology of the massive crystalline body is that of a fused tuff. The position of the tuff relative to the Echo Bay sediments, and the relations seen underground suggested that it was a basal tuff. Detailed mapping disclosed the truncation of the Mine Formation by the main body of the tuff and the unconformable overlap of the southern lip of the tuff on Cobalt Island Formation rocks.

Therefore, the concept of the tuff forming the base of the sedimentary section was discarded.

An alternative explanation, that the tuff was laid unconformably on Lower Echo Bay Formations, was then investigated. The lack of this type of tuff formation in the entire McTavish Arm terrane, except for the very small area near Port Radium, makes this seem doubtful. In addition, the formations from the Lower Echo Bay group through to the Cameron Bay group represent an essentially continuous and conformable series with no indication of a major angular unconformity as would be necessary if the massive tuff were to fit into the series with its existing relationships. In detail, the contacts of the massive tuff show no evidence characteristic of an erosional unconformity. The shape, the extreme thickness, and the massiveness of the tuff body are incompatible with a theory of an origin as a depositional formation.

Intrusive Origin

Lithology and textures of the massive tuff are only locally like those characteristic of intrusive rocks and are generally characteristic of tuff. This feature would be difficult to explain if an intrusive origin was advocated. Nonetheless it could be argued that the fragmentation and the local "fused" character of the feldspar that makes up the rock may be due to mylonitization and recrystallization of a compositionally unusual intrusive. The forces necessary to so completely granulate this body would show some similar effect on the surrounding formations, or at least result in local development of dynamic metamorphic structures. Such features are entirely lacking. Further, the "unfused" tuff is essentially identical compositionally and lithologically to the bedded tuffs of the Tuff Series and Upper Echo Bay sub-group. There are no primary igneous structures either within the main mass of the body or along its margins. There is no evidence of any thermal effects on neighbouring rocks, either along the walls or around included wedges. The feldspar porphyry intrusives intrude the massive tuff and generally differ from it lithologically, therefore it is not logical to relate the tuff to them. Although the gross structural relationships of the massive tuff body are those of an intrusive body, the many features contradictory to this mode of origin become too difficult to account for to make the theory tenable.

Volcanic Vent

Another theory of origin for the massive crystalline tuff body is that the tuff body represents the filling of an explosive vent or caldera.

The literature is replete with controversial theories concerning the genesis and details of caldera-type structures, however there is fair agreement on the gross features of the structures. The general features of calderas include the following: (1) volcanic clastic deposits, (2) shallow bowl-like shape, flat-floored and surrounded by low rims, (3) circular or elliptical in general plan, (4) up to several miles in diameter, (5) have one or more, relatively small in diameter, vertical diatremes either connected to them or penetrating through them from below. Many modifications of these features are known.

The principal controversy on the subject of calderas concerns the processes by which the final configuration of the formation is attained. The theory that calderas are products of explosive volcanic vents is widely accepted, but recent workers, particularly Williams[33], are strong advocates of an origin by collapse over a magma chamber. It is not within the scope of this paper to evaluate the many aspects of each of these theories, nor is it pertinent to this discussion to do so. The physical characteristics of all calderas are generally alike, regardless of the mode of origin proposed.

Lithology

Of the many recent calderas Williams[33] describes very few that differ in lithology from a general volcanic breccia rock-type. In the majority of calderas the predominant breccia is tuff. Lavas are rare either in the saucer portions of the calderas or in the diatremes. The tuff is generally unstratified and in many cases is as fine as dust. One composition of tuff usually prevails in each occurrence.

In Table 3 are listed the dimensions and rock-types of four active and three inactive calderas. Many other examples are available but these few represent most of the varieties that have been reported. Attention is drawn to the repeated occurrences of massive tuff bodies and tuff vents not unlike the Port Radium massive tuff occurrences. The lithology of the Port Radium body is in extremely good agreement with those found in known calderas and associated necks. Masses of structureless tuff, fused and

TABLE 3

RECENT AND FOSSIL CALDERAS

LOCATION	SIZE	ROCK TYPES
	ACTIVE (33)	
Valles caldera, New Mexico	16 miles in diameter	About 1000 ft. of flat tuff beds all about the same composition and thickness (12 ft.)
Aira caldera, Japan	15 miles in diameter	Crystalline tuff and pumice in vent surrounded by plateaus of lavas and tuffs.
Niuafoou Island, So. Pacific	$\frac{1}{2}$ mile in diameter	Neck of tuff surrounded by basin of tuff 3 miles across.
Lake Toka, Sumatra	20,000 sq. miles	Unstratified, massive rhyolite tuff, 2000 ft. thick. No lavas. Probably came from several vents.
	INACTIVE (FOSSIL)	
Vesuvius (Ancient)	3 miles in diameter	Volcanic dust. (34)*
Cerro de Pasco	1 mile in diameter	Pyroclastic agglomerate + bedding in vent. (35)
Cripple Creek, Colorado	2x4 miles ellipse	Unstratified tuffs, some breccia; intrusives. (32)

*Numbers in brackets refer to the references as listed in the bibliography.

unfused, are typical.

The formation of such bodies is of interest. Most writers are in fair agreement on the initial phases of caldera formation, and the information available seems to bear out the following consensus:

When volcanic activity begins, gases escaping from rising lava take advantage of weak zones in the cover and as they approach the surface escape with explosive force and produce vents whose upper parts flare considerably or only slightly, and whose lower parts are steep-walled. Debris is scattered and much falls back into or immediately around the vent. Successive explosions will clear the vent of crustal material if the initial one fails to do so. Effects on surrounding rocks will be slight, possibly upturning in the immediate vicinity; the action, especially if repeated, is one of reaming out of the vent. In general, the explosion breccia ranges from dust to fragments a few inches in size. Larger fragments may result from:

(1) One explosion that does not clear the vent of crustal breccia.

(2) Re-explosion of consolidated previous breccia or tuff.

(3) Subsidence of wall-rock into unconsolidated breccia.

In general, the breccia will consist of isolated crystals or parts of crystals derived from the partially solidified lava. Unsolidified material will be carried away from the neck as pumice.

Vents a few miles apart may continue to explode and, by reaming their collars and depositing ejecta, eventually form a coalesced surficial deposit fed by several vents. A common feature of some vents[32][35] is the intrusion into the breccia-filled neck of later felsitic rocks of essentially the same composition as the tuff or breccia. In many places the texture of the massive crystalline tuff at Port Radium closely resembles that of a fine-grained igneous rock but this feature can only be determined by microscopic examination; therefore outline of possible intrusive bodies is practically impossible.

Structure

The internal structures of known calderas are similar to those found in the massive tuff body at Port Radium. Scattered discontinuous layering of the tuff, particularly near the margins of caldera bowls, is common and may be due to settling in air, resorting by wind, or rolling down slopes. This phenomenon would account for the isolated layered portions of the Port Radium body. Wedges of country rock within caldera or vent breccias are common, especially along the margins, and would be analogous to the chert slabs in the Port Radium body. Breccias of tuff fragments in tuff matrix as in the Port Radium massive tuff are also not uncommon in vents.

Known vents cut across surrounding formations but do not, as a rule, deform them. The surficial deposits and the flaring lips of the vents will lie unconformably on the enclosing rocks. The vents themselves, while steep-sided, may split, coalesce, bulge or constrict and may or may not flare out at the top. Most of these features occur in the Port Radium massive tuff body.

One of the most comprehensive reports of a caldera is that by Loughlin and Koschnann[32] on the Cripple Creek complex explosive crater. The many underground workings at Cripple Creek have provided data at depth. It is significant to note that much of the most informative data on diatremes and calderas has been derived from mines located within such structures. The best examples: Cripple Creek[32], Cerro de Pasco[35], San Juan[34] and Kimberley, S.A.[34]. The configurations of the Cripple Creek and other vents and calderas are shown in Fig. 15 to facilitate comparison with the known parts of the Port Radium body. The similarities are striking even though the amount of information on the Port Radium body is small. Comparison of features shown in Fig. 15 with those shown in Figs. 11 and 12 reveals:

(1) Similar elliptical shape in plans of the vents and the lobate plan of the caldera as a whole.

(2) Similar bulging and narrowing of the vents and flaring at the collars.

(3) Similar flat and near-flat jointing.

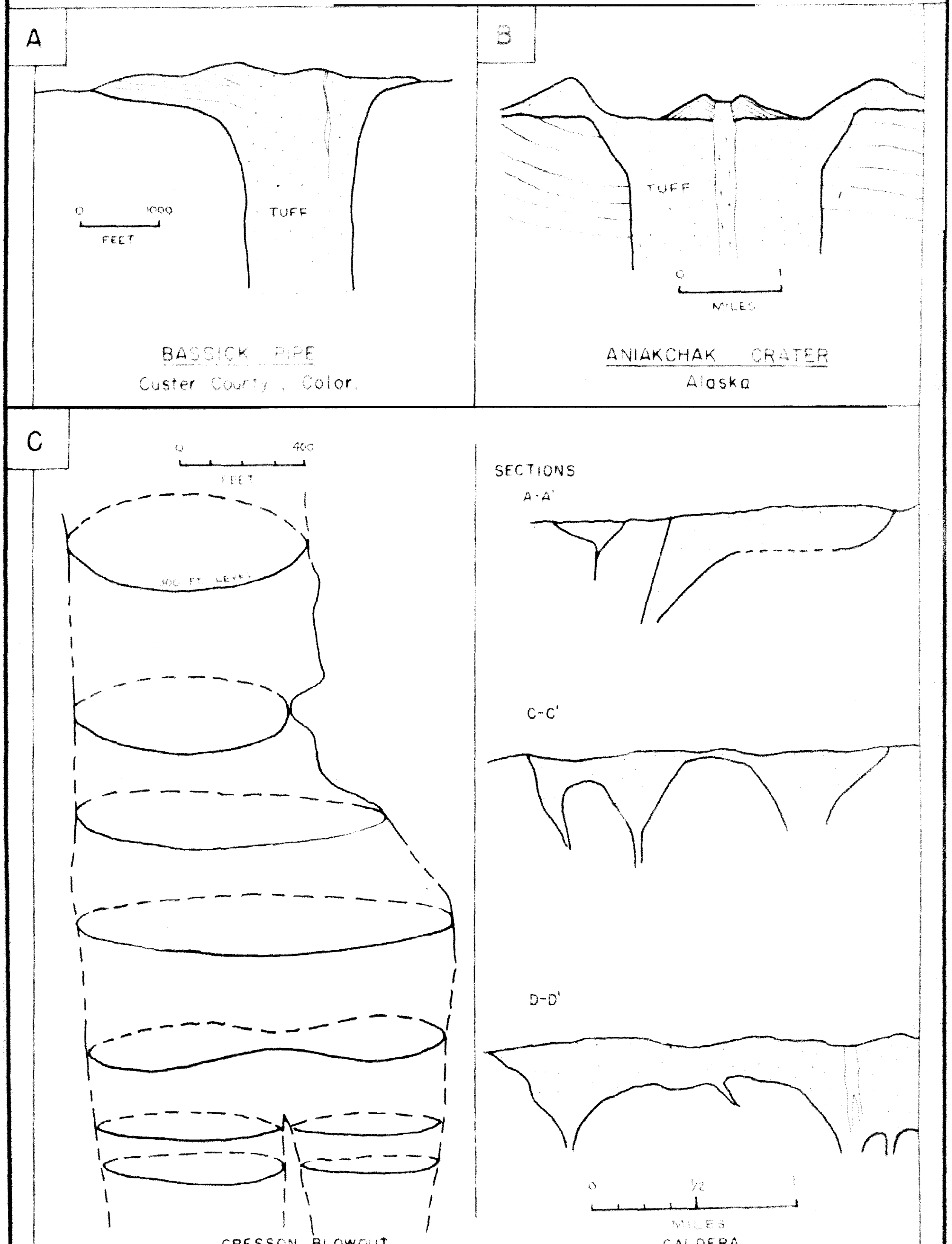
(4) Similar overlap of the caldera and the irregular dips of its edges.

Summary and Conclusions: Eldorado Vent

When size, shape, lithology and relations to surrounding rocks are all considered, the Port Radium massive crystalline tuff body more closely resembles known caldera-type structures than other types of formations.

FIGURE 15

STRUCTURES OF TYPICAL VENTS AND CALDERAS



BASSICK PIPE
Custer County, Color.

ANIAKCHAK CRATER
Alaska

CRIPPLE CREEK, COLO.
Ref. (45), Figs. 2 & 9

In addition, the Port Radium tuff body can be fitted well in time and space to a related volcanic sequence of widespread tuff effusions of identical lithology. This sequence is that of the bedded tuffs immediately underlying the Upper Echo Bay sub-group volcanics.

Although the data are not conclusive, the indications are that the Port Radium massive crystalline tuff is a caldera or explosive vent. It is proposed that possibly two vents existed, one underlying Flat Point north of Bear Bay, and the other underlying the Corregidor Bay region, and that the remainder of the tuff body is the remnant of the caldera or the flared lips of the vents. Because the unfused crystalline tuff is identical to the bedded tuffs of the Tuff Formation it is suggested that the vent or vents exploded in late Lower Echo Bay time and ushered in the volcanism of Upper Echo Bay time. The tuff explosion preceded the extrusion of the Upper Echo Bay flows, hence the possibility exists that the feldspar porphyry intrusive found within the massive crystalline tuff body was a feeder for the flows and rose through the vent of the caldera. Because of lack of data to do with the porphyry intrusive within the massive tuff this hypothesis is no more than conjecture.

To the writer's knowledge there is no other occurrence yet known of an explosive volcanic vent in the Canadian Shield. The recognition of such a structure in deformed terrane would be difficult and is probably the principal reason others have not been reported in the pre-Cambrian rocks. The formations at

Port Radium are relatively undeformed, and enough of the tuff body has been preserved to enable recognition of features strongly suggestive of an explosive vent.

INTRUSIVES

FELDSPAR PORPHYRY:

A large sheet of intrusive feldspar porphyry crops out as a long irregular strip extending from Labine Bay northeast to Norman Lake (Fig. 4). This body is flanked to the west by several very irregular smaller bodies, and to the east by a few apophyses. The main body averages about 600 feet in thickness and dips from 20 to 30 degrees to the east. The outlying bodies range in thicknesses from a few tens to a few hundreds of feet and seldom maintain consistent strikes or dips. The outliers in the footwall of the main body have a general eastward dip, often very steep, and extremely irregular shapes. They are predominantly tabular but this form is commonly modified by erratic twists, branches, pinches, swells and abrupt ends. Since the feldspar porphyry intrusives have been important structural factors in the ore control their principal features and effects warrant considerable attention.

General Features:

Riley[2] made a detailed study of the lithology of similar porphyry intrusives in the Lindsley Bay area. Although some differences exist in details of composition between the Lindsley Bay and the Labine Point porphyries, Riley's descriptions are generally applicable to the Labine Point bodies. The following descriptions are of the Labine Point rocks.

The feldspar porphyry intrusives are resistant rocks and usually form prominent outcrops and rugged hills where other formations are topographically subdued. In all of the porphyry bodies two or three sets of joints are strongly developed. One set is usually nearly flat and the other two are near-vertical at wide angles to one another so that the overall effect on hills of porphyry is a stairlike or piled-block appearance. These joint sets are well exposed in the mine and consist of dominant and persistent joints, spaced ten or more feet apart, between which are sundry minor joints. The larger joints are generally healed with quartz and carbonate which are hematitic in some places.

Texturally and, to a lesser extent structurally, the porphyries are divisible into two broad categories, aphanitic and crystalline. The crystalline variety makes up about 90 percent of the exposed porphyry. It has a fine-grained porphyritic texture and occurs in bodies ranging from thick extensive tabular plugs to dikelets. The aphanitic variety occurs usually as dikelike bodies less than 100 feet in width, or as border phases of bodies of the crystalline variety. The aphanitic variety is rarely porphyritic, is dense, dark grey in colour and microcrystalline in texture. It often resembles some metasomatized cherts and is practically identical in appearance to flow rocks of the Transition Formation.

The crystalline varieties of the porphyry may differ markedly in appearance in different localities and often differ widely from place to place in one body. These differences are principally in colour and, less so, in texture. Lithologically all the crystalline feldspar porphyries show a similarity under the microscope that is remarkable considering the wide differences in appearance in hand specimens. Although the crystalline porphyry occurs in a number of textural and colour phases a general description can closely characterize them all. The crystalline appearance is imparted by clustering of phenocrysts, therefore the term "crystalline variety" is used here merely as a description of the megascopic appearance of the rock.

The rock is coloured dull grey, shades of brown, purple or brick red. White and/or black fine phenocrysts are common. The white phenocrysts are altered feldspar and the black are platy ferromagnesian minerals. Quartz phenocrysts are rare. The phenocrysts are 2 to 3 mm in length and are imbedded in a dense aphanitic or finely crystalline groundmass. Local variations in the concentration of the phenocrysts are common. The groundmass weathers grey or pink, the feldspar phenocrysts weather white and the ferromagnesian phenocrysts tend to weather out and leave pits. The porphyry is generally cross-hatched by narrow closely-spaced bands of red stain flanking joints and microfractures. Under the microscope these bands are seen to be concentrations of hematite dust and within the bands the ferromagnesian minerals are partially or completely chloritized.

Mode of Emplacement:

Most contacts of the intrusive porphyries are diffuse and obscure and are traced with difficulty but sharp contacts are not uncommon (Fig. 16). The porphyry magma penetrated all host rocks in an extremely pervasive manner. Contacts are commonly zones up to 10 feet in width of ramifying tongues of porphyry, isolated masses of porphyry and intensely recrystallized host rock. In many places the contact zone consists of boulder-shaped masses of crystalline porphyry packed in a mesh of coarsely crystalline magnetite, apatite, epidote and amphibole (Fig. 17). Such effects are fully discussed under Metamorphism. It is apparent that the porphyry melt was one of low viscosity and hence highly mobile. In many places in tuffaceous rocks porphyry can be seen to form a network matrix to tuff grains; apparently it seeped among the coarse grains of the tuff.

The merging erratic contacts described above are by far the commonest for the porphyry bodies, however, sharp contacts, particularly along the footwalls of the major masses, are not uncommon. Sharp slickensided contacts of porphyry against Mine Formation sediments are exposed in the mine and suggest possible forceful injection of some of the porphyry in a semi-solid state. The slickenside surfaces are not subsequent fault planes, they are confined to the porphyry contacts.

Although the detail of many of the porphyry contacts indicates pervasive local intrusion, the gross relations of the porphyry bodies and the intruded sediments indicates emplacement predominantly by forceful intrusion. The sediments of the Mine Formation bend around porphyry bodies in wide arcuate folds with many local bends and drag folds (Fig. 18). Small-scale isoclinal folding of sediments in the region of the porphyry intrusives is

Figure 16. Contact of massive crystalline tuff and Mine Series cherts.

Figure 17. Contact of feldspar porphyry with masses of porphyry in mesh of coarse metasomatic minerals. North shore of Labine Bay.

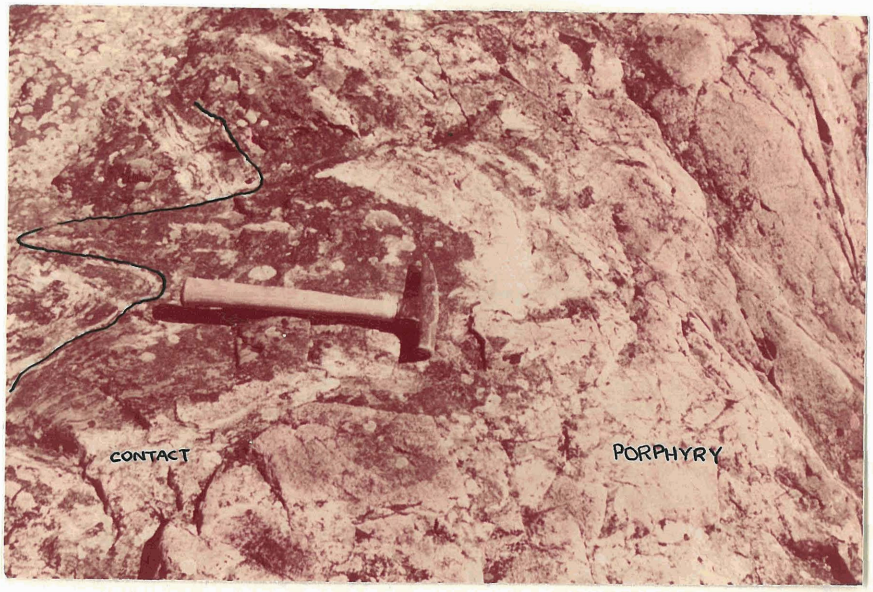


Figure 18. Folding of cherts near porphyry contact. Labine Point.

Figure 19. Deformation of sediment near porphyry contact. No. 2 Shaft area.

exposed in mine workings and on the surface. In addition to being folded, the sediments are everywhere cut by slip fractures of displacements ranging from a few inches to several feet (Fig. 19). These fractures are not related to the later vein-fracture patterns. This intense folding and breaking of the sedimentary rocks is found only in the vicinity of porphyry intrusives. North or south along the strike of the Lower Echo Bay sediments, and away from the area of porphyry intrusion, the sedimentary beds assume their regional simple monoclinal structure. One porphyry tongue in the vicinity of No. 1 Shaft terminates about 50 feet below the surface and the banded cherts directly above it clearly illustrate the complex folding caused by the porphyry intrusion (Fig. 5, southwest of No. 1 Shaft).

Clearly the feldspar porphyry intrusives made room for themselves by forcing aside and upward the pre-existing sediments. This action may have been facilitated by soaking of the intruded rocks by metasomatic fluids, but more likely the metasomatic fluids did not escape until the porphyry was already emplaced. This is born out by the fact that the metasomatic minerals in the sediments show no signs of strain, deformation or breaking. By the time they were emplaced the host sediments were already deformed. Apparently the dilation caused by the folding of the sediments provided channelways for metasomatizing fluids along bedding planes and fractures where the metasomatic minerals are now most abundantly emplaced.

Most of the folding of the bedded rocks in the Labine Point area was caused by the intrusion of the feldspar porphyry bodies. The Eldorado Vent may have been somewhat deformed at this time but it seems to have acted more as an immobile mass against which the sediments were pushed and folded. The later intrusion of the granite resulted in broad uplifts and tilting.

Various examples of the deformation of the sediments by the intrusion of porphyry bodies are shown in Figs. 31 and 32.

Petrology - Crystalline Variety:

Phenocrysts - In the specimens studied the phenocrysts make up, on an average, 35 percent of the rock. In individual specimens the concentration of phenocrysts may be as high as 55 percent or as low as 15 percent. The phenocrysts are most commonly oligoclase-andesine (an 30) and hornblende, less commonly albite and orthoclase. Feldspar phenocrysts usually exceed the hornblende phenocrysts in number, and in many specimens, especially the fine-grained varieties, the hornblende phenocrysts are absent.

The feldspar phenocrysts are stubby subhedra or, occasionally, several individuals grown together. The edges of the phenocrysts are usually slightly corroded. Twinning is usually well developed. Zoning is very rare. Inclusions of primary minerals such as hornblende and plagioclase occur occasionally within the feldspar phenocrysts. The feldspar phenocrysts are characteristically clouded by hematite dust and partly altered to sericite. Many phenocrysts are almost completely replaced by fine-grained sericite and others nearby are hardly touched. On an average about 10-15 percent of each phenocryst is replaced by sericite. The sericite is concentrated in the centres of the feldspars and thins out toward the edges of the grains, leaving only a rim of feldspar surrounding a mass of sericite flakes in some specimens. The feldspar phenocrysts may be replaced by penninite or carbonate. These alteration minerals usually attack the edges of the phenocrysts.

The hornblende phenocrysts are not as well developed as the feldspars and occur as skeletal or splintery blades, equant grains or clusters of fibres. In some specimens hornblende occurs in grain sizes gradational from that of phenocrysts to that of the matrix. Hornblende is invariably accompanied by fine euhedral grains of magnetite which may occur as inclusions in the hornblende or as clusters around the edges of the hornblende. Hornblende phenocrysts are commonly completely replaced by penninite. They are less extensively replaced by carbonate, biotite and leucoxene.

Isolated clusters of euhedral grains of magnetite occasionally form aggregates of phenocryst dimensions.

<u>Matrix</u> - The groundmass of the crystalline porphyritic rock is comprised predominantly of oligoclase-andesine (an 40-an 20). Fibrous grains or flakes of hornblende and, occasionally, biotite are dispersed as minor constituents through the matrix. The plagioclase grains are usually intergrown well twinned fine

laths. The size of the grains ranges from less than 0.01 mm to 0.2 mm from one specimen to another but is usually constant in any one specimen. Orientation of matrix laths into flow patterns along contacts and around phenocrysts is very common.

Apatite and titanite occur in the groundmass as tiny anhedral grains or as relatively large clusters of subhedral grains. The large clusters of apatite are probably products of late alteration. They seldom make up more than a few percent of the rock. Magnetite is widespread as fine euhedral grains scattered throughout the matrix and clustered in or around hornblende. It makes up from one to eight percent of the rock. Zircon is a rare constituent.

Petrology - Aphanitic Variety:

The aphanitic varieties of the porphyry occur as dikelike bodies flanking the main porphyry masses and as ends of the smaller bodies of porphyry. They are massive, moderately hard or soft, uniform dark brownish grey, aphanitic to finely crystalline rocks. Occasionally they are faintly speckled by feldspar phenocrysts. In places the rock is noticeably biotitic, and in such cases the biotite often occurs as dim brownish fine spots. Streaky flow banding and alignment of biotite are common.

Petrologically there are sharp differences between the aphanitic and the crystalline varieties of the porphyry. Phenocrysts rarely make up more than 10 percent of the rock and generally comprise less than 3 percent. All the phenocrysts are stubby oligoclase subhedra or clusters less than one millimeter in length. There are no ferromagnesian phenocrysts. The groundmass grains are fairly uniform in size and generally measure about 0.20 mm. This is more than five times the size of the usual matrix grains of the crystalline variety of the porphyry and suggests that the aphanitic bodies cooled more slowly than did the crystalline bodies. A major difference between the two varieties of porphyry is the higher content of ferromagnesian minerals, particularly biotite, in the aphanitic rock. Biotite, hornblende and magnetite together constitute from 30 to 50 percent of the rock, all in the groundmass, and account for the dark colour of the rock. The local differences in the biotite content result in the local differences in the hardness of the rock. The biotite occurs as fine flakes and occasional clusters generally oriented parallel to the plagioclase laths of the groundmass. It makes up about 20 percent of the rock. The biotite content of the crystalline porphyry is negligible. Apparently the biotite concentrated at the advancing aphanitic fronts of some of the porphyry bodies, possibly because of relatively high water and potash concentrations at those places. The hornblende content varies inversely as the biotite content often to the exclusion of one or the other. In rocks with both minerals present biotite accompanies and occasionally partially replaces the hornblende. Magnetite occurs as fine euhedral grains disseminated uniformly throughout the aphanitic porphyry and generally constitutes about ten percent of the rock. In some specimens magnetite is absent.

Late hydrothermal alteration minerals so common in the crystalline porphyry are practically absent from the aphanitic varieties. A few specimens show about 5 percent penninite. The other alteration minerals occur as traces in occasional specimens.

Alteration:

The alteration minerals related to the porphyry intrusives are generally restricted to the crystalline varieties of the porphyry and to the metasomatic haloes around the porphyry bodies. These minerals are probably indigenous to the feldspar porphyries and represent an alteration subsequent to consolidation. A few of the same minerals are present locally in the granite but these are in zones related to the hydrothermal alteration emanating from the vein zones. In general, in the porphyritic rock, the alteration of the groundmass is less intense than that of the phenocrysts, but the products are the same.

Sericitization of the feldspar phenocrysts has been described. Chloritization by the introduction of penninite is the most pervasive alteration, attacking all phenocryst and matrix minerals, but particularly the ferromegnesian minerals. The penninite occurs as tiny flakes or fibrous aggregates dispersed throughout the rock and may constitute as much as 20 percent of the crystalline porphyry. Where it occurs in such large amounts it is usually pseudomorphic after hornblende phenocrysts. Accompanying the penninite flakes, but in lesser amounts ($\pm$ 10 percent), is carbonate. In addition to irregular replacement masses, carbonate occurs as occasional late veinlets with quartz. Leucoxene is a common alteration of

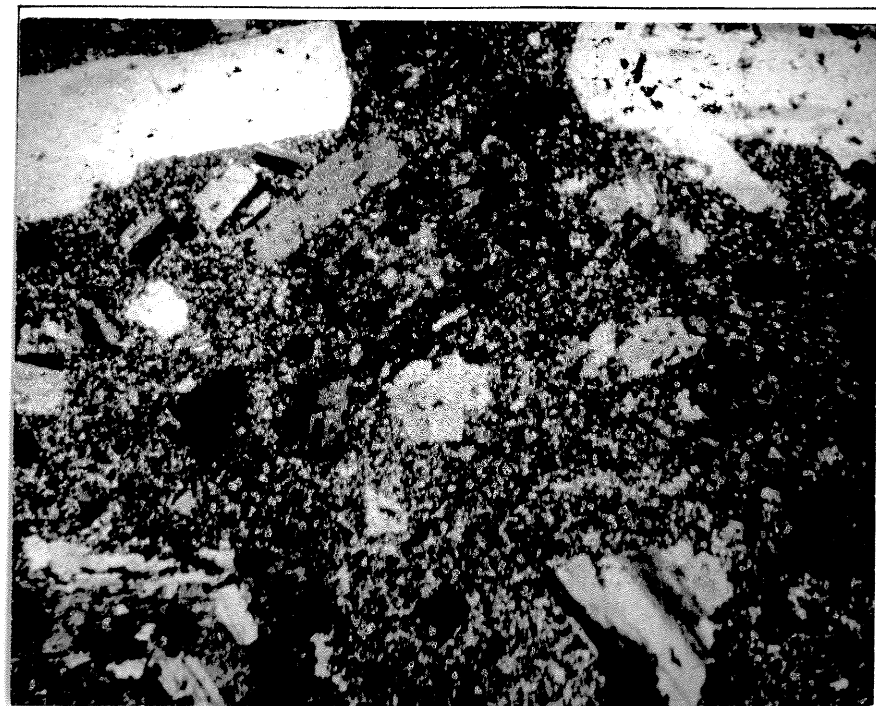


Figure 20. Photomicrograph of typical crystalline variety of feldspar porphyry. North shore of Labine Bay, No. 1 body. x25.

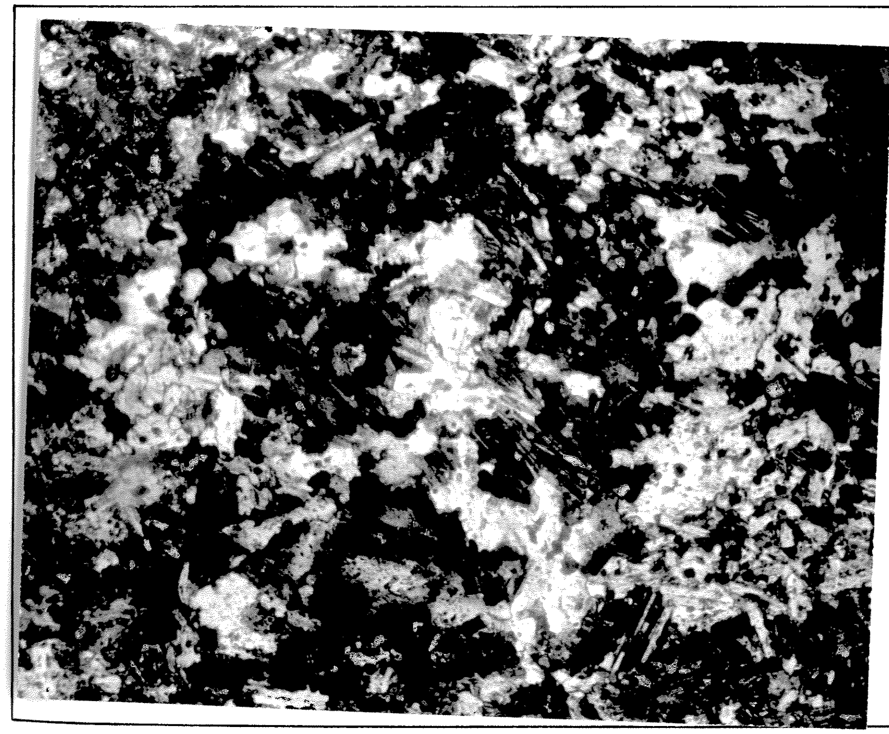


Figure 21. Photomicrograph of typical aphanitic variety of feldspar porphyry. Labine Point. x50.

the magnetite and the hornblende.

The following table summarizes the distribution of the late alteration minerals in the feldspar porphyry (crystalline variety).

	Feldspar Phenos	Hornblende	Magnetite	Matrix (Feldspar)
Extent Altered	Heavily	Heavily	Slightly	Moderately
Always Present	Sericite	Pennine, Leucoxene	Leucoxene	Carbonate, Pennine
Occasionally Present	Carbonate, Pennine	Carbonate	Pennine	Sericite, Quartz Hematite

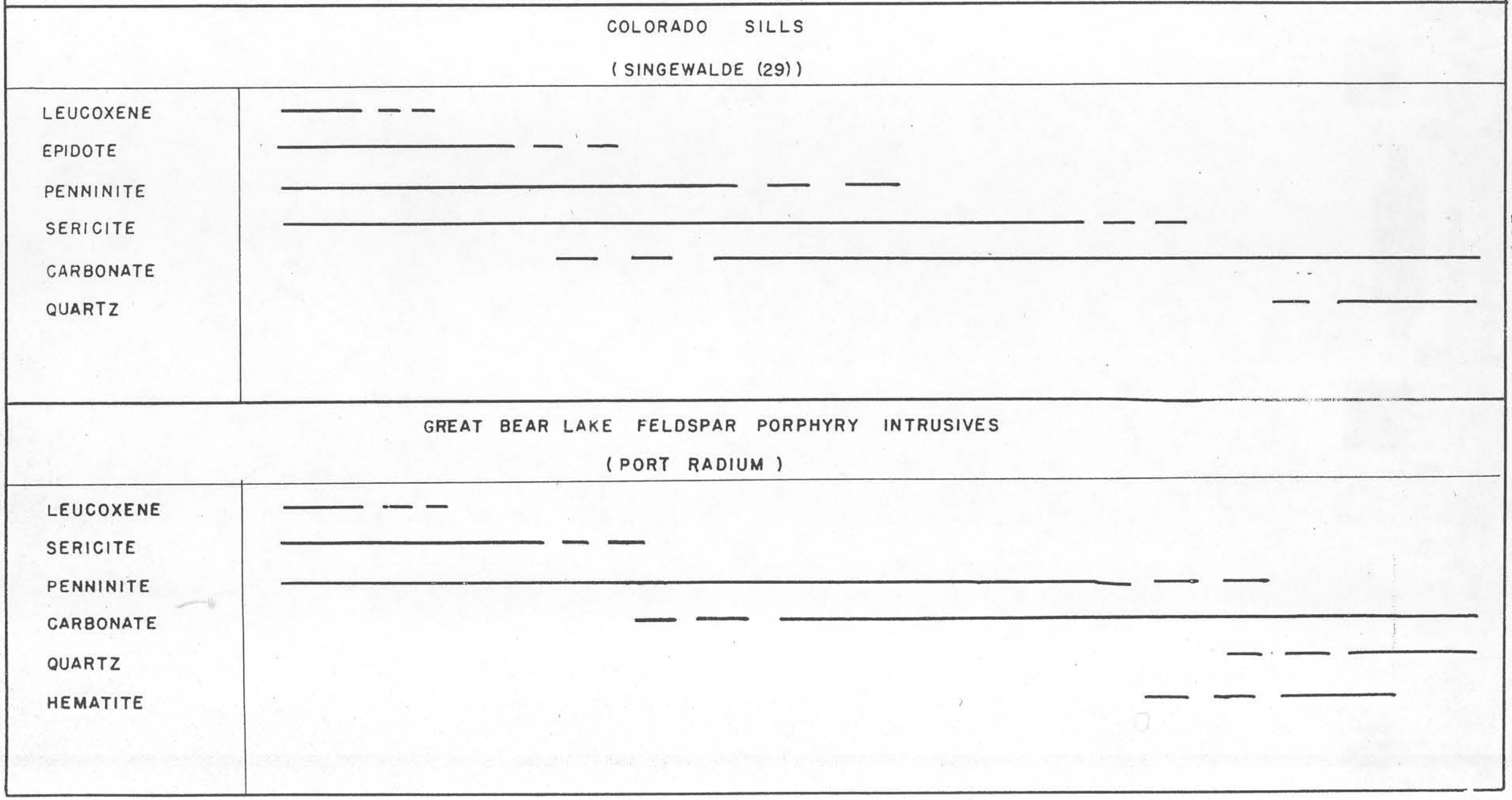
The late alteration minerals in the feldspar porphyry intrusives are not related to veins or shear zones. The penninite variety of chlorite is distinctive of the late feldspar porphyry alteration.

A similar type of alteration of hypabyssal intrusives is described by Singewald(36) as occurring in sills in Colorado. Singewald describes the alteration as an end phase of igneous intrusion of sills. In the locality he describes there are no other igneous intrusives, nor are there fracture zones that could have acted as sources for the hydrothermal alteration; the only sources are the sills themselves. The Colorado sills differ slightly in composition from the Port Radium feldspar porphyries. Biotite is a major constituent of the Colorado sills, and the plagioclase is always andesine. The alteration products and their habits are the same in the Colorado and the Port Radium intrusives, except for the presence of rutile, epidote and zoisite in small amounts in the Colorado sills. A comparison of the paragenesis of each alteration suite is shown in Fig. 22.

FIGURE 22

COMPARISON OF PARAGENESES

OF LATE HYDROTHERMAL MINERALS IN SOME COLORADO SILLS AND GREAT BEAR LAKE PORPHYRITIC INTRUSIVES



Singewald divides the sequence of the late stage alteration into two early high temperature phases and one final medium-low temperature phase. The first phase includes sericite, zoisite, (rare) epidote and penninite, and it principally attacked the feldspar. The second phase is mostly penninite, some sericite and leucoxene, and it principally attacked the hornblende. The final low temperature phase includes veining by quartz and carbonate. Although relative age relations between the first and second phases are not always apparent in the Port Radium porphyries the general relation of all phases seems to agree fairly well with Singewald's interpretation. Singewald concludes that because the systems concerned are open, this late phase alteration should be termed hydrothermal and not deuteric.

The lack of late phase hydrothermal alteration minerals in the aphanitic variety of the porphyry is probably a function of permeability. The aphanitic porphyry is much denser than either the crystalline porphyry or the metasomatized haloes and apparently excluded all but small amounts of the altering solutions.

GRANITE AND APLITES:

Intrusive into all the formations described above in the Port Radium area is a biotite granite body with related aplite dikes. The granite underlies Great Bear Lake immediately west of Labine Point and crops out on a few points and islands along the shore (Figs. 4 and 5). This contact of the granite strikes northeast and dips about 75 degrees to the southeast. In the lower levels of the mine there is a large bulge in the otherwise regular granite contact; this shoulder of granite represents the only irregularity in the exposed contact.

Aplite dikes are common and generally strike at right angles to the granite contact. They are irregular in habit and only penetrate the Echo Bay rocks for several hundred feet from the granite (Fig. 5). They disappear in the granite within a few hundred feet of the contact. Dikes two or three feet wide and dipping steeply north predominate, but flat dips and widths from a few inches to 20 feet are not uncommon.

Lithologically the Labine Point granite is about the same as the general case described under Regional Geology. In the mine area the granite consists of the following:

Orthoclase with some microperthite	45°/o
Quartz	25°/o
Albite-oligoclase	20°/o
Hornblende and biotite	10°/o
Apatite, zircon and magnetite	Trace

The feldspars are locally heavily sericitized and the ferromagnesian minerals are locally completely chloritized, especially near the vein zones. Normally the granite is medium to coarse-grained and dappled red. The red coloration is caused by staining of the feldspars by hematite dust. As the concentration of the dust changes from place to place the colour of the rock changes. Commonly chlorite and/or epidote alter the feldspars to such an extent that the rock is dappled pale green and grey instead of red. Such colour variations occur within short distances in the same body and do not signify separate intrusions.

The aplites differ considerably in composition from one to another and from place to place in the same dike. General ranges in composition are as follows:

Quartz	35-60%
Albite and orthoclase with minor microcline	35-60%
Oligoclase	0-10%

Chlorite and epidote are not common but locally may form 5 percent of the rock.

Contact phenomena along the edges of the granite are negligible. The contacts with all rock are sharply defined and locally show a few inches of pegmatite within the granite. Some contacts are slickensided for short distances. Metamorphism of host rocks is observable only as slight recrystallization of the massive crystalline tuff and porphyry within a few inches of the granite. Local concentrations of xenoliths and schlieren occur along the border of the granite. Near Powderhouse Island xenoliths of massive crystalline tuff in various stages of digestion are strewn in bands about ten feet in width in the granite along and near the contacts (Fig. 23). Progressive digestion of the xenoliths is marked by rounding of the fragments and by the different stages of granitization of each fragment (Fig. 23). The first stage of the granitization is one of recrystallization of the plagioclase and growth of orthoclase metacrysts. The further growth of feldspars is accompanied by development of coarse-grained ferromagnesian minerals, mostly biotite and hornblende. Quartz is the last mineral to develope large crystals in the granitized xenoliths. Different stages of this process are illustrated in Figures 23 and 24.

Small scale indications of stoping by the granite can be seen along its contact, but in general the contact is featureless.

DIABASE:

Two steeply dipping diabase dikes and one low dipping diabase sheet crop out in the Labine Point area. Innumerable aphanitic chilled diabase dikelets erratically occupy joints, fractures and shear zones in the vicinity of the larger dikes. They range in width, often abruptly, from a fraction of an inch to several feet.

Lithologically the dikes and the sheet are identical with the general case described under Regional Geology, namely ophitic textured labradorite and augite with about 5 percent magnetite and some quartz. The sheet diabase tends to be coarser grained than the dike rock, but essentially they are lithologically identical. The diabase is a medium or coarse crystalline, uniform dark grey-green rock. It weathers to a pale brownish grey colour.

No intersection between the dikes and the sheet has been exposed, but near McDonough Lake a diabase dike tapers and disappears within a few hundred feet above and below its intersection with the sheet. The actual intersection is covered with overburden but the implication is that the sheet was a feeder for the dike. It is felt that the diabase sheet was contemporaneous with the discontinuous dikes but somewhat later than the regionally pervasive dikes.

The sheet crops out along the base of the bluffs lying across

Figure 23. Variously digested massive crystalline tuff xenoliths in granite near contact. Labine Point near Powder-house Island.

Figure 24. Granitized xenoliths as in Figure 23.

the northeast end of Labine Point (Fig. 4). It strikes roughly due north and dips 20 to 30 degrees to the east. The outcrops show gross columnar jointing with joint faces several feet in width. The sheet changes in strike and dip gently and changes in thickness both gradually and abruptly. On the point due east of Cobalt Island the sheet, well exposed on the bluffs, pinches from about 100 feet in thickness to about 20 feet within 100 feet along the strike. The thickness of the sheet at Labine Point ranges from one hundred to two hundred feet.

The diabase dikes average about 25 feet in width. They are medium to fine crystalline, depending on the width of the dike, and generally have chilled margins. Regionally the dikes occupy a fracture system with a northwest trend and a steep southwest dip. However, where they intersect the Labine Point vein zone system, they occupy some of the zones for distances of over 1000 feet before continuing their usual trend. The southern-most dike in the area, striking northwest from the bluffs southeast of the mine, intersects No. 1 Vein at the north end of Labine Bay (Fig. 5). There it turns and lies along the footwall of the vein zone, striking southwest, for 850 feet where it abruptly crosses the vein zone, and is cut by it, and, with a slight jog, re-assumes its regional northwest trend, crossing No. 2 Vein with little deviation. At No. 3 Vein the dike turns and strikes due west along the vein zone for about 1300 feet before turning north once more. The diabase dike is chilled against the shear zones and is itself locally much brecciated and is veined by some of the gangue and most of the metal minerals. It has not been favourable for vein deposition insofar as the veins within it are constricted relative to the same veins in other rocks. It is clear that the fracture and shear zones existed prior to the intrusion of the diabase and that some movement, brecciation and mineralization occurred after the emplacement of the dikes. A diabase dike about two feet in width occurs within No. 1 Vein zone on the 1300 Level. It has been completely converted to an argillic, chloritic schist.

The aphanitic diabase dikelets are widely distributed throughout the mine between the main vein zones as well as along the zones. The rock is usually dense, hard and dark grey but if widths increase to two feet or more the rock becomes a normal diabase in texture and appearance. About one-half inch of the margins of the dikelets is usually chilled and pale green. The emplacement of the dikelets was haphazard, for they occupy joints, fractures and vein zones and switch from one to another with sharp deviations in strike, dip and width.

METAMORPHISM

GENERAL:

Metamorphism of the Lower Echo Bay strata has been locally intense in the mine area. In some places the metamorphosed rocks have been important in controlling the location of the pitchblende ore shoots.

Large areas of the Cobalt Isle, Mine and Transition Formations have been subjected to contact metasomatism. In these metasomatized zones calcareous cherts have been converted to aggregates of pyroxene and garnet; fine banded cherts have been converted to aggregates of pyroxene, amphibole, feldspar and magnetite. In many places the changes have been so complete that no vestiges of the original rock remain. Transition from metasomatized and metamorphosed rocks to unaltered rocks is gradational. The metasomatism accompanied the intrusion of the feldspar porphyry bodies and is spatially and genetically related to them.

Metamorphic effects resulting from the intrusion of igneous rocks other than the feldspar porphyry are apparently negligible in this area. Contact phenomena are noticeable for only a few inches from the granite contact. The widespread recrystallization and metasomatism of the cherts and tuffs underlying Labine Point are in no way related to the adjacent granite. Kidd(7) related the metasomatism to a granodiorite stock which he said was exposed on the surface as a small outcrop 100 feet in diameter on the east shore of Labine Bay, about a half a mile southeast of the mine. This exposure could not be located by Eldorado geologists.

Exposures of granodiorite near Crossfault and Explorers Lake do not exhibit extensive contact aureoles. The granodiorite in the Contact Lake area is reported by Furnival(12) to be bordered by granitized and metamorphosed haloes that exceed 1000 feet in width. The metamorphic minerals comprising these zones are mostly chlorite, actinolite, epidote, magnetite and pyrite. This suite is distinctly different from that surrounding the feldspar porphyry intrusives at Labine Point. Although the intrusion of granodiorite may have had some effect on the Labine Point rocks, no granodiorite is exposed within a mile radius of the mine and it is doubtful that there could be any effect unless there is granodiorite within the area not yet exposed.

ZONING:

The contact metasomatism of the rocks underlying Labine Point is most pronounced around the relatively small tongues of feldspar porphyry that lie west (in the footwall) of the main intrusive. These tongues invade the Mine Formation for the most part, and therefore the thin-banded cherts are more intensely metasomatized than are the tuffs to the east or the quartzites and calcareous cherts to the west.

Zoning is not well developed, but where present it is expressed as changes in amounts and types of metasomatic minerals at various distances from the parent porphyry body. The most intensely metasomatized zones are directly above the tops of the porphyry bodies. Rocks adjacent to the flanks of the tabular masses are only moderately altered by metamorphism. Within the areas of general moderate metasomatism, which comprise most of the southwest end of Labine Point, the principal minerals developed have been hornblende and magnetite. A few hundred feet away from the areas intruded by the porphyry tongues the amount of metasomatic minerals in the cherts becomes negligible.

One intrusive porphyry tongue strikes north-south near No. 1 Shaft and dips almost vertically. It is about 200 feet in width and ends abruptly about 50 to 100 feet below the surface. The rocks directly above this body are intricately folded and brecciated. A tunnel passes through the top contact of this body and provides excellent exposures of the phenomena attending the metamorphism immediately in front of the intrusion. In this restricted area diopside and some garnet have been developed. On the surface, patches of diopside and garnet occur in the rocks along the trace of the porphyry tongue that lies directly beneath. A few tens of feet away from this locus the garnet and diopside are absent and the metasomatic minerals are predominantly hornblende and magnetite (Fig. 25).

Compositions of the different host rocks have also been important in determining the types of metamorphic products formed. On the western tip of Labine Point the calcareous cherts of the Cobalt Island formation have been metamorphosed by contact action of one porphyry intrusive which lies a few hundred feet to the east and another which lies directly south and whose top dips down beneath the rocks on the point (Fig. 25). Here the predominant metamorphic minerals, in order of abundance, are diopside, garnet and scapolite. Other metamorphic minerals are present in minor amounts.

With the exception of the two areas described above, namely the area of Cobalt Island formation and the area directly over the porphyry body near No. 1 Shaft, the sediments underlying most of Labine Point have been converted to hornblende-magnetite-biotite assemblages differing locally in amounts, grain size and proportions. Thus a hornblende-rich zone has been developed in the silicate rocks and a diopside-garnet zone has been developed in relatively calcareous rocks. In addition, narrow diopside-garnet zones have been

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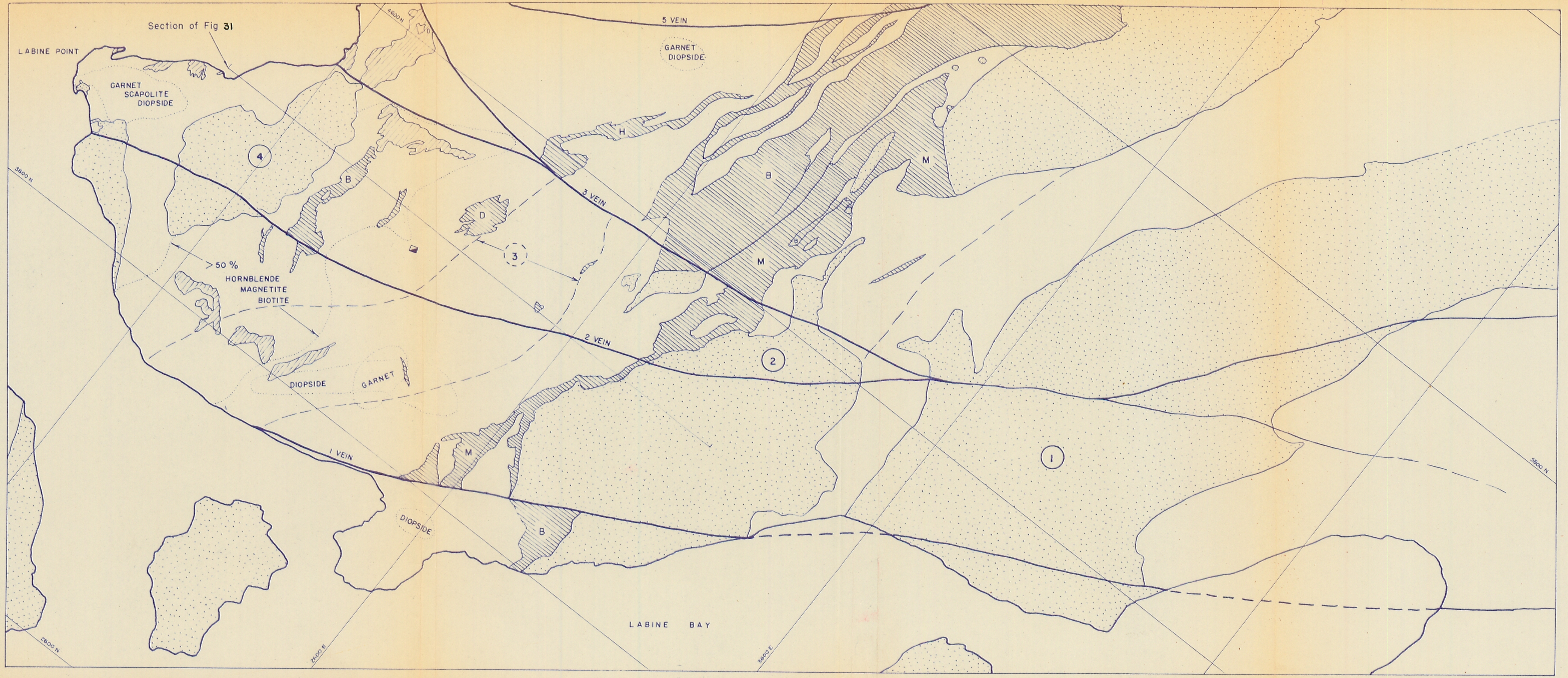


FIGURE 25

PORPHYRITIC INTRUSIVES
and
RELATED METASOMATISED ZONES

LABINE POINT
Great Bear Lake , N.W.T.

SCALE 1"=200'

LEGEND

FELDSPAR PORPHYRY INTRUSIVES
Crystalline variety

FELDSPAR PORPHYRY INTRUSIVES
Aphanitic variety

SEDIMENTS and TUFFS

APHANITIC METASOMATISED CHERTS
Principally : Biotite (B), Magnetite (M), Hornblende (H), and/or Diopside. Minor relict chert.

AREAS OF VARIOUS METAMORPHIC MINERALS
Generally medium crystalline

OUTLINE OF PORPHYRY BODY LYING BELOW SURFACE
Projected from 125 Level

VEIN ZONE

developed in relatively calcareous rocks. In addition, narrow diopside-garnet zones have been developed in the immediate vicinity of top ends of porphyry bodies. These constitute the principal zones developed by metamorphism in the Labine Point area.

One further crude type of zoning occurs adjacent to the footwall of the main porphyry intrusive bodies to the east. This zone consists of discontinuous tabular masses up to 50 feet in width that lie beneath and parallel to the footwall of the porphyry and up to a few hundred feet from it (Figs. 5, 25 and 31). These masses are fine-grained assemblages of magnetite and biotite with minor amounts of hornblende. They are similar to those rocks described previously as fine-grained tops of some porphyry tongues. They are fine-grained, dark grey, hard or soft and often show sharp intrusive contacts. The amount of relict chert in these rocks is less than 50 percent and in many places less than 25 percent. The intrusive-like contacts of these masses suggests mobility during the peak stage of the soaking by metasomatic fluids. Where the contacts are gradational they seldom exceed two feet in width. Some of these masses grade into aphanitic porphyry at depth but others do not. In general, the zone of fine-grained biotite-magnetite rocks is continuous along the footwall of the main porphyry body, but any individual unit is not. On the 1175 Level in the mine, in the vicinity of the main footwall porphyry body, one such mass of fine-grained magnetite lies within recrystallized and metasomatized sediments. It is a lens at least 200 feet in length, about 20 feet in width and at least 50 feet in vertical extent and is essentially all magnetite. Such aphanitic monomineralic assemblages are common and represent remarkable phases of the contact metasomatism connected with the intrusion of the porphyries. They also occur to a lesser extent above the porphyry tongue in the No. 1 Shaft area. In that region they are gradational into aphanitic porphyry which in turn grades into crystalline porphyry below (Fig. 31). Directly north of the surface intersection of Numbers 2 and 3 veins the top of the westernmost main porphyry intrusive lies below the surface. In this region the fine-grained biotite-magnetite rocks have been most widely developed and merge with similar bodies that lie along the footwall of the underlying porphyry (Fig. 25). Here again it would seem that such metasomatic bodies are directly related to the front of the intruding porphyry magma.

Between the two main porphyry intrusive bodies, Nos. 1 and 2, south from McDonough Lake a thickness of about 200 feet of bedded tuffs has been only moderately metasomatized (Fig. 25). Recrystallization of plagioclase and quartz has been considerable, but pyroxene and garnet are absent. Therefore, although these rocks are flanked above and below by massive crystalline porphyry bodies they have not been subjected to the intense grade of metasomatism that has developed at the ends of the smaller porphyry bodies.

As should be expected in contact metasomatic environments, the metamorphic zoning in the mine area is very local. No overall delineations of zones can be made other than those surrounding the areas of porphyry intrusives. The Eldorado Vent was apparently relatively impervious and chemically unreceptive to the metasomatic solutions for metamorphic effects are minor in it.

FACIES:

The metasomatism of the Labine Point rocks is equivalent to the amphibolite facies of metamorphism as far as mineral assemblage is concerned. Turner(37) describes a garnet-amphibolite facies occurring in many pre-Cambrian terranes for which the assemblage almandine-diopside-hornblende is critical. This he assigns to the amphibolite facies. Magnetite-diopside-andradite-tremolite is a common assemblage of contact metamorphism in dolomites and is roughly analogous to the contact zones in the Cobalt Island Formation rocks.

The minerals developed by the metasomatism in the Port Radium area are, in order of abundance, hornblende, diopside, magnetite, plagioclase, biotite, apatite, garnet, scapolite, epidote and sphene. Rarely present are chloritoid, idocrase and clinozoisite.

Where quartz and calcite were present in the original rock they have reacted under metamorphic conditions to form garnet and/or scapolite and diopside but not wollastonite. This, according to Ramberg(38), indicates temperatures of metasomatism below 500°C. It might also indicate original dolomite rather than calcite. The proposed temperature for Eskola's amphibolite facies is about the same as suggested by Ramberg. In the immediate vicinity of the porphyry intrusives a somewhat higher grade occurs. Turner(37) states that in contact zones of shallow-seated hypabyssal intrusives, especially if the magma is basic in composition, a high temperature is likely to be reached rapidly, maintained for a short time and then followed by rapid lowering of temperature. This would account for the garnet-pyroxene assemblages immediately next to the tops of the porphyry tongues as well as the very limited extent of these assemblages.

TEXTURAL CHANGES:

It has been common practice in the Port Radium area to describe the metasomatized cherty rocks as recrystallized. Actually the action has been more one of replacement of the chert grains than recrystallization of them. The recrystallized appearance is due mostly to the development of crystalline plagioclase that is evenly distributed throughout the chert. In some places plagioclase occurs as bands cutting across chert aggregates, but in most cases it has developed as separate grains from individual nuclei in the chert. In the metasediments throughout most of the area the plagioclase seldom exceeds 10 percent of the rock and contributes little to the general appearance; however, in places of intense metasomatism the plagioclase content increases sharply to 30 percent or more and is relatively coarsely crystalline. In such places it imparts a decided recrystallized appearance to the rock, but actually this is feldspathization.

The quartz of the chert is coarsely recrystallized in the vicinity of coarsely crystalline metamorphic minerals. In bands that may contain as little as 20 percent hornblende the quartz is recrystallized to grains of 0.2 mm or more in size, whereas in adjacent bands containing no hornblende the quartz grains are the usual 0.02 mm in size. Where the content of coarsely crystalline metasomatic minerals increases to major percentages then the relict quartz is often completely coarsely crystalline. If the metasomatic minerals are fine grained the host chert grains are essentially unrecrystallized even though the amount of metasomatic minerals present may exceed 50 percent.

In almost all cases, where the quartz is recrystallized, it is clear of hematite dust that clouds the quartz of the chert. The metamorphic plagioclase may or may not be dusted by the hematite, but the unrecrystallized plagioclase of the tuff always is. None of the other metamorphic minerals appears to be dusted by hematite. Apparently the rocks were hematitic before metasomatism, and one result of metasomatism has been the disappearance of hematite dust from all minerals except the plagioclase. Of course, it is possible that the colours of the metasomatic minerals may mask any hematite dust that is present in these minerals.

There is ample evidence in the metasomatic rocks that the original quartz has been recrystallized, but the recrystallization is obviously related to the growth of nearby metasomatic minerals. Schistosity, granulation and other evidences of dynamic metamorphism are lacking in the Labine Point rocks. The metasomatic minerals occur along minute fractures and along tightly folded bedding planes yet show no strain or preferred orientation. Clearly the deformation preceded metasomatism. The metasomatic fluids favoured fractures and dilation openings that had resulted from deformation, and these surfaces of readiest migration also became surfaces of greatest ease of post-tectonic crystal growth. This preferential permeation by the emanations along bedding planes has resulted in the preservation of the original sedimentary structures even though a high degree of metasomatism may be reached and the bulk composition of the rock greatly changed.

Close to the porphyry bodies the grain size of the metasomatic minerals is as large as five centimeters. In places of less intense metasomatism the grain sizes of the new minerals generally range up to one centimeter in largest dimension. Throughout most of the metasomatised zones the new minerals seldom exceed one or two millimeters in grain size. Dense dispersions through the chert of microscopic subhedral grains of metasomatic minerals are common and tend to alter the colour of the chert without appreciably changing the texture. This applies particularly to the plagioclase, diopside, hornblende and the biotite and indicates that the chert was homogeneous enough so that favourable centres of nucleation were evenly distributed, and hence the resulting rock is also homogeneous. Two types of diffusion of metasomatic material through the chert were prominent. The first was the invasion along fractures, bedding planes and permeable beds that resulted in banded, patchy and brecciated-appearing non-homogeneous rocks containing coarsely crystallized metasomatic minerals. This stage was probably a high temperature phase. The second type of ingress was a pervasive soaking of the host rock resulting in a homogeneous, massive product. The fineness of grain of the metasomatic minerals associated with this phase suggests that temperatures were not high enough for long enough time and/or that the diffusion of material to growing crystals was too low to result in large crystals being formed.

A common phenomenon, particularly near the immediate contact of the porphyry bodies, is the occurrence of veinlets of coarsely crystalline ferromagnesian minerals, although the rock adjacent to the veinlets is markedly deficient in these minerals. These veinlets apparently represent a late phase leaching action whereby metasomatic minerals in the rock have migrated to a fracture that may or may not have existed at the time of original metasomatism. Ramberg[38] explains such phenomena as the result of the introduction of a low pressure zone into the area by the opening of a fracture in a late stage of metasomatism. The cracks fill with liquid and, under impetus of the pressure differential, the minerals slowly disintegrate and constituents diffuse toward the low pressure zone and precipitate there. This is a plausible explanation for the widespread occurrences in the Labine Point area of magnetite-filled cracks whose adjacent wallrocks are visibly deficient in magnetite.

The hornblende, diopside, magnetite and plagioclase have tended to replace beds of the host rocks preferentially, so that these minerals markedly accentuate bedding. Banding otherwise not noticeable in the cherts becomes sharply delineated with the emplacement of these minerals (Fig. 29). The unrecrystallized chert and often the new plagioclase are coloured red by hematite dust, therefore, with the introduction of various metasomatic

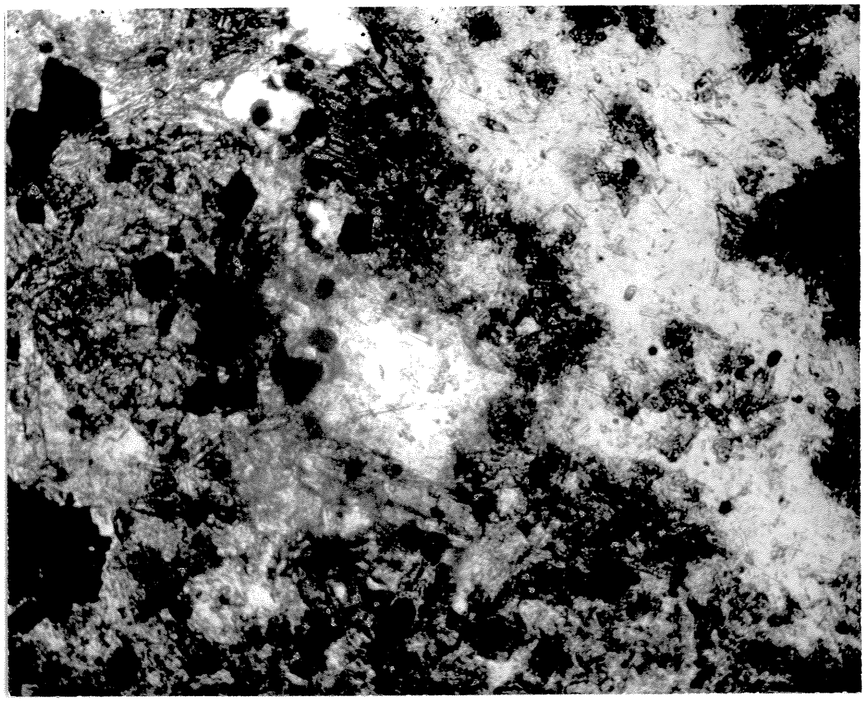


Figure 26. Typical metasomatic hornblende, magnetite and apatite in bedded cloudy (hematite dust) chert. x50.

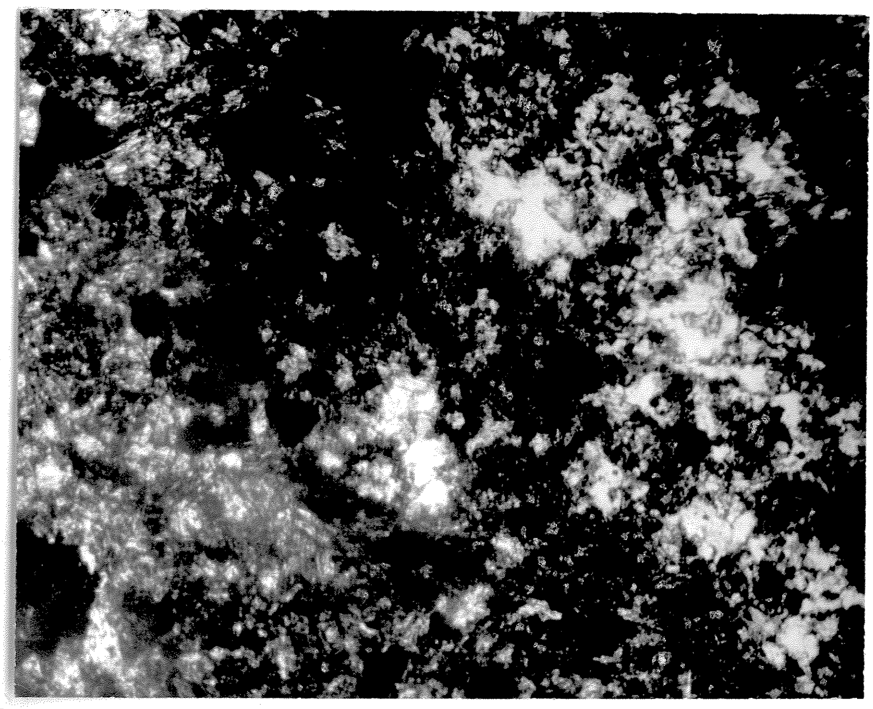


Figure 27. As Figure 26 with crossed nicols. Showing texture of chert.

minerals in bands the rocks become distinctively banded red and black (magnetite), red and dark green (hornblende) or red and pale green (diopside). With differences in the hematite dust content the red will give way to pink or cream. Where metasomatism has resulted in total replacement the rock is usually dark green with pale green and/or black bands. In many places the metasomatic minerals are so fine grained that bands of them resemble argillaceous partings.

In contrast to those metamorphic minerals whose emplacement has conformed to the original bedding there are some minerals whose emplacement generally tends to obliterate the bedding. Biotite, garnet and scapolite usually occur as massive finely crystalline mats that may or may not reflect the original bedding. The biotite forms a dark brownish-green or green-grey rock wherein banding is very indistinct and is usually in the form of thin seams of magnetite. Such rocks have been commonly termed massive sediments. This is erroneous, for the lack of banding is a function of the metasomatism, not the primary deposition. Similarly, the garnet and scapolite tend to form light grey and pinkish brown patchy massive rocks. The vitreous lustre of such rocks is very distinctive. Not uncommonly diopside or hornblende may occur as masses independent of original bedding and thus produce a massive rock, but such occurrences are of minor extent compared with the massive garnetiferous rocks.

CHEMICAL CHANGES:

The compositions of the different host rocks have been important in determining the degree of metasomatism and the types of products formed. The occurrences of garnet, scapolite and idocrase are confined almost entirely to the Cobalt Island formation rocks, many of which are calcareous. Optical properties and modes of occurrence indicate that the garnet is probably grossularite. The implication is that the calcium present in these minerals was derived from the carbonate already present in the host rock. The magnesium of the dolomite has gone into diopside which commonly accompanies the garnet. This being the case, the garnet-scapolite zones probably represent as much thermal metamorphism as metasomatism. Without chemical analyses this can only be surmised.

The tuffs, including the massive crystalline tuff, have been less hospitable to metasomatism than the cherts. Hornblende has formed in quantities comprising up to 10 to 40 percent of the rock and locally occurs as pseudomorphs after oligoclase. Diopside and biotite are less common. Magnetite occurs in very small amounts but is widespread throughout the tuffs. Recrystallization of the plagioclase fragments seems to have been the most prominent effect of the metamorphism of the tuffs. Local suturing, mortar textures and bent twinning are not uncommon in the tuffs and possibly represent some dynamic effects of the intrusion of the porphyry.

Pure cherts have been completely converted to amphibolite facies mineral assemblages. The bulk composition and the specific gravity of the rocks have been changed by the addition and subtraction of material.

Without chemical analyses it cannot be determined what compositional changes the cherts have undergone. Harker[39] states that thermal metamorphism of pure sandstone and chert initially produces minute flakes of biotite and possibly epidote. Higher grade metamorphism produces coarse biotite and quartz and some feldspar. If the original cementing material is sericite, chlorite and limonite metamorphism will produce biotite. Calcite and kaolin cement will produce epidote; chlorite, calcite and quartz produce augite whereas a ferruginous cement, limonite or hematite, will produce magnetite as strings of little octahedra or scattered granules. Only one of these products, magnetite, is found in the Port Radium metacherts. Harker also states that metamorphism of a feldspathic sandstone generally produces recrystallization of the feldspar to oligoclase as well as the formation of biotite and possibly cordierite. Examples of metamorphosed cherts are rare in the literature but the foregoing suggest that the hornblende-diopside-magnetite-feldspar metacherts at Port Radium were produced from metasomatism of ferruginous, possibly feldspathic, cherts. The principal elements added were Ca, Mg, Al, and possibly some Fe and Na depending on the amounts of impurities in the original chert.

The products of metamorphism of cherty dolomites and dolomitic cherts, somewhat similar to the Cobalt Island Formation sediments, are generally well known. Metamorphism of dolomite in an excess of chert causes the silica to react with the Mg to produce diopside and some tremolite. In a system rich in Al grossularite or idocrase will appear with the diopside. If Al is deficient wollastonite is produced instead of garnet. If the calcareous cherts of the Cobalt Island Formation had alumina impurities then thermal metamorphism would have produced the present diopside garnet rock with addition of little or no material.

Since most of the metacherts at Port Radium are non-calcareous, they fall into the hornblende-diopside, magnetite-feldspar type and hence are products of metasomatism. This type of metasomatism corresponds to the process of "basification" as described by Ramberg and others. Certainly in the Port Radium rocks such a process of the introduction of the basic elements Ca, Mg, Al and Fe has been the major agent of metasomatism. It is of interest that these elements all possess small ionic radii and low charges which favour diffusibility.

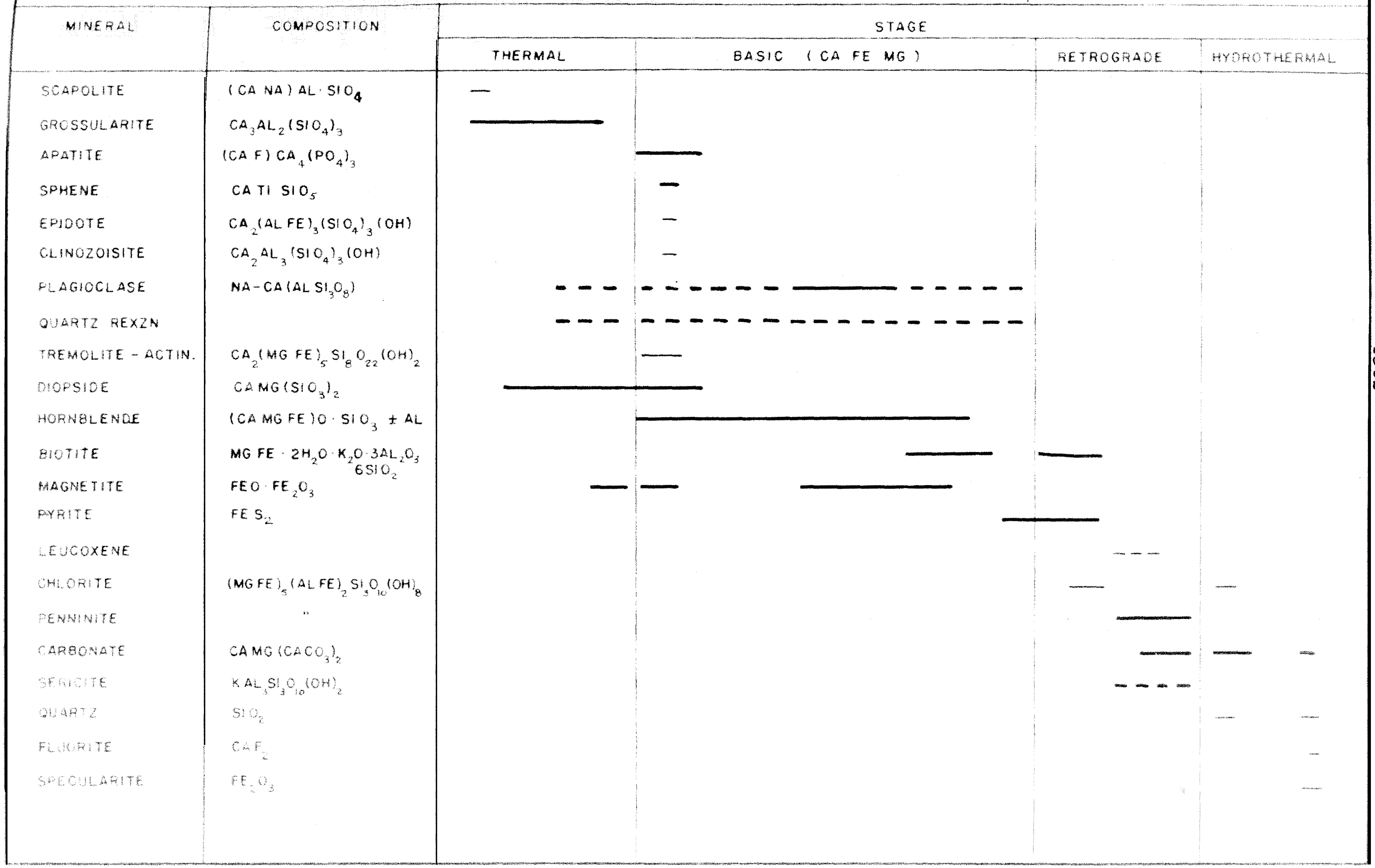
PROGRESSIVE METAMORPHISM:

Although metamorphism differed from host to host and from one porphyry intrusive to another, it is possible to reconstruct a rough sequence of events. A schematic paragenesis is shown in Fig. 28. Four stages of metamorphism can be postulated from the distribution and relations of the minerals involved. Without a doubt these stages overlapped considerably in time and space but their general individuality was clearly discernible in the study of some 200 thin sections of rocks from Labine Point.

Thermal Stage: The initial phase involved only the reaction of the host rocks to heat and, possibly, some liquid but with

FIGURE 28

PARAGENESIS OF METAMORPHIC MINERALS DEVELOPED IN ROCKS AT PORT RADIUM, N.W.T.



no addition of new cations except perhaps Al. Thus in calcareous cherts grossularite and scapolite developed first and, growing from evenly distributed nucleii, formed massive rocks. These two minerals are typical products of the metamorphism of siliceous rocks in a calcareous environment. Assuming that considerable calcium was present in the original rock, the introduced cations need only have been Al and Na. If the chert was impure initially, the amounts of these elements needed to produce the metamorphic minerals may have been already present in the rock. Microscopic study of thin sections did not reveal any obvious clay impurities in the chert.

In the non-calcareous cherts the first phase of metamorphism is represented by some recrystallization of the chert to distinct quartz grains and simultaneous growth of plagioclase. The growth of the plagioclase exactly parallels that of the recrystallizing quartz in all cases insofar as the sizes of the grains are considered; however, with increased recrystallization of the cherts the quantity of the plagioclase generally increases. Here again, the only cations introduced, assuming an original pure chert, were Na^{+}, Al^{+++} and Ca^{++}. The feldspathization and recrystallization continued into the second stage of metamorphism and attained their best development at that time.

Metasomatic Stage: The second phase of the metamorphism involved the basification proper. The basic cations Ca^{++}, Fe^{++} and Mg^{++} with some Al^{+++} were introduced in large enough amounts to replace extensive areas of chert with amphibole-pyroxene-magnetite assemblages. The presence of potash during this phase is indicated by the development of small amounts of biotite. Disseminated apatite and sphene and veinlets of coarsely crystalline amphibole, magnetite and apatite developed near the close of this phase of metamorphism.

Included in the second phase of metamorphism was the development of the large masses of fine-grained biotite-magnetite-hornblende. These masses generally merge with aphanitic varieties of the porphyry, which in turn grade into crystalline varieties. The high ferromagnesian content and identical fineness of grain of the aphanitic porphyry and the fine-grained metasomatic assemblages make the two rocks difficult to distinguish megascopically. Bedding is inconspicuous in the metasediments and closely resembles in appearance the flow banding in the aphanitic porphyry. In places where the two rock types merge, the changes in the metasediments as the aphanitic porphyry is approached involve gradual decreases in quartz content; sharp decreases in the magnetite content; and sharp increases in plagioclase, until finally an aphanitic porphyry rock-type is attained. This rock grades into the crystalline porphyry through increases in phenocryst content and sharp decreases in biotite content. A comparison of the fine-grained massive metasediments with the aphanitic porphyry is tabulated below:

Rock	Grain Size of Ferromags.	Qtz.	Biotite	Hornblende	Magnetite	Plagioclase	
Aphanitic Porph.	$\pm$ .10 mm	4	19	11	5	60)	%
F.G. Metased.	" "	22	35	15	21	3)	

(Averages from 5 specimens of each type)

These fine-grained metasediments are commonest near the upper ends of porphyry bodies and are generally absent from the flanks of the bodies. They apparently represent not only basic fronts of iron and magnesium concentrations, but also a water and potash concentration as well. Biotite is relatively rare in the metasediments along the flanks of the porphyry bodies. The water and potash were apparently concentrated in the vicinity of the tops of the bodies. The fineness of grain of these rocks suggests a lower temperature than the preceding phases. The implication is that an initial high temperature was reached rapidly near the upper extremities of the porphyry body but was only maintained for a short time. When the porphyry stopped advancing, cooling was rapid and the assemblages in the immediate vicinity of the tops crystallized in a fine-grained state. This process implies that the hypabyssal intrusives were relatively shallow-seated. This type of environment agrees with the resulting metasomatism as seen at Port Radium. During the crystallization of the porphyry intrusives, especially under low pressures which would not favour entry of water into the crystallizing silicates, progressive crystallization of the non-volatile constituents may have raised the concentration of substances of high vapour pressure sufficiently to cause the remaining liquid to boil. This would form a gaseous phase capable of penetrating the surrounding rocks and taking with it the available small-ionic-radius elements. Turner[37] points out that in such cases the elements introduced into the surrounding rocks are often those in which the parent magma itself is strikingly deficient. This phenomenon Turner terms as the principle of polarity. It reflects the contrasting compositions of the dilute aqueous solutions and the silicate magmas from which they separate. This adequately fits the conditions found around the Port Radium intrusive feldspar porphyries. The porphyry bodies are surrounded by haloes of Ca-Fe-Mg-rich minerals and are themselves only moderately supplied with these elements.

Retrograde Stage: The third phase of metamorphism evident in the Labine Point formations may possibly be one of retrogression. Minor amounts of late-forming minerals occur everywhere, generally as alterations of the metasomatic minerals. These late minerals are biotite, pyrite, chlorite, carbonate, penninite and rarely chloritoid. Because a hydrothermal phase followed the formation of these minerals it is conceivable that the so-called retrogressive phase may actually have been a preliminary stage of the hydrothermal phase. Pyrite, chlorite and biotite occur extensively as pseudomorphic replacements of most of the metamorphic minerals, particularly hornblende and magnetite. Pyritic banding is a striking characteristic of the more completely metasomatized rocks. Penninite and carbonate tend to occur as flakes and mats indiscriminantly overlapping grain boundaries. Late biotite is itself locally replaced by chlorite. Penninite replaces chloritoid and cuts earlier chlorite. Leucoxene occurs as an alteration of late biotite and chlorite. The biotite, chlorite, pyrite and chloritoid may be products of retrograde metamorphism, but the penninite, carbonate and sericite are identical in habit with the same minerals in the porphyry bodies. These minerals in the porphyry have been suggested as representing a late deuteric or hydrothermal alteration phase of the porphyry intrusion. If this proposal is valid then the same minerals occurring in the metasomatic haloes around the porphyry bodies would seem to be a part of that late phase and are not retrograde metamorphic products.

The final phase of the development of the metamorphic rocks involved the veining of all the above-mentioned minerals by quartz, carbonate, chlorite, fluorite and hematite. This phase is probably related to the mineralization of the shear zones, but because microveinlets occur in rocks well removed from the shears and veins, it is included as a phase in the development of the rock. Veinlets of chlorite, carbonate and quartz cut all the metasomatic assemblages and are in turn cut by later veinlets of quartz, carbonate, hematite and, rarely, fluorite.

CHANGES IN COMPETENCY:

A significant characteristic of the metasediments and metatuffs is their competency. By recrystallization and metasomatism the banded and folded original cherts have been converted to rocks more like the porphyry intrusives in competency. Shear zones cutting these rocks have attained much the same form in them as in the porphyry bodies. Because some pitchblende has deposited in the vein zones at places determined by differences in manner of fracturing the fact that some metasediments fractured in an identical manner as did the porphyry is important in the search for ore.

Figure 29. Hornblende along bedding planes of chert. Labine Point.

Figure 30. Veining and brecciation of sediments by late metasomatic assemblages. No. 2 Shaft area.

STRUCTURE

The generalized structural geology in the vicinity of the Eldorado Mine is relatively simple, but in places the detailed structure is very complex. Except for some anomolous structures in the formations immediately adjacent to the Eldorado vent, practically all the structural complexities in the mine area occur relatively close to feldspar porphyry intrusive bodies.

Most pitchblende production comes from an area between the northeast arm of Crossfault Lake and the tip of Labine Point. This area can be roughly represented as a northeastward trending block of Lower Echo Bay formations bounded on the southeast by the Upper Echo Bay volcanics and on the northwest by the granite (Fig. 4). The northeastern and southwestern limits of the productive area are the edges of the Eldorado fracture system which crosses the block in a northeast-southwest direction. This fracture system is a wide belt of mineralized shear zones described earlier as being related to the Cameron Bay fault zone (Fig. 3). The distance on the surface between the granite and the Upper Echo Bay volcanics is about 4400 feet. This width increases with depth because the granite dips about 75 degrees to the southeast, whereas the volcanics dip about 40 degrees. The formations within the delineated block consist of:

1. Sections of all the Lower Echo Bay rocks.

2. Multiple, irregular shaped, intrusive feldspar porphyry bodies.

3. At least one diabase sheet and several diabase dikes.

Although bodies of intrusive feldspar porphyry are to be found anywhere between the granite and the volcanics the major concentration of them occurs in a belt about $\frac{1}{2}$ mile in width dividing the Lower Echo Bay rocks of the above described block into two elongate segments. The western segment, between the granite and the porphyry belt, is about twice as wide as the segment between the porphyry belt and the volcanics (Fig. 4). The belt of porphyry intrusives roughly parallels in strike and dip the footwall of the Upper Echo Bay volcanics. The belt is comprised of one or two principal tabular bodies, sinuous and irregular in outline, that are flanked, and in some places joined, by smaller, more discontinuous, branching and coalescing intrusive bodies. The central portion of the belt extends from Dog Island in Labine Bay northeastward across the west end of Talus Lake. Strips and pendants of Lower Echo Bay formations occur in many sizes and shapes throughout this main belt of intrusives. Underground exploration has revealed the intrusive belt to be a more massive zone than is indicated on the surface. Apparently many of the pendants are shallow-seated.

A diabase sheet crops out along bluffs that cross the block from Labine Bay to Great Bear Lake west of Diamond Lake (Fig. 4). This sheet dips 10 to 30 degrees to the east and traverses across the host formations from the upper beds of the Tuff Series, east of Labine Bay, across the porphyry belt and down to the Transition Formation beds on Great Bear Lake. In detail, the trends of its contacts are erratic. In some places the sheet branches to form two layers lying one above the other. There is evidence that, when being emplaced, it effected abrupt changes in elevation by moving, dike-like, up or down available fracture zones. In the vicinity of No. 2 shaft the diabase sheet crosses the No. 1 Vein zone and on the north shore of Crossfault Lake it crosses the Bear Bay shear zone. At both these places the vein zones are extensively sheared and mineralized, in widths up to 20 feet, above and below the diabase sheet but are only sparsely mineralized fractures and gouge-filled slips, a few inches in width, within the diabase itself. Similarly, pitchblende occurs as rich shoots in the vein zones above and possibly below the diabase but not within the diabase. Apparently the final tensional opening of the vein zones just managed to fracture the diabase sheet that had earlier crossed the pre-existing zones.

The strip of Lower Echo Bay rocks lying between the main porphyry belt and the Upper Echo Bay volcanics is comprised entirely of Tuff Series tuffs and conglomerates. These formations strike generally northeastward and dip 10 to 30 degrees to the southeast. At the present time the ore deposits at Crossfault Lake and No. 2 shaft, all of which lie within this eastern part of the block, are incompletely developed. Data on ore controls in these areas are fragmentary but are, to date, consistent with those found for deposits of the western part of the block in the mine proper. An abundance of detailed information is available on the deposits within the western part of the productive block; therefore, the discussion that follows will concern that area, the mine proper, with but occasional references to the eastern part of the block. This will be done with the understanding that the eastern portion, between the porphyry belt and the volcanics, though not included in the discussion, is no less important as favourable environment for the occurrence of pitchblende.

The major part of the Eldorado Mine is located between the granite to the northwest and the porphyry belt on the southeast; hence the structural geology in this vicinity will be described in detail. All production has come from vein zones within this block of ground. Development to the northeast and southwest continues and is governed by the discovery of favourable vein zones in those directions.

Granite

The outcrop of the contact of the granite body to the west approximately follows the shoreline of Great Bear Lake along Labine Point. This rather regular trend is interrupted at depth by occasional minor apophyses, some of which grade into aplite dikes, and by one large bulge, most pronounced on the 1300 Level.* But for these protuberances, the contact maintains a regular north-northeast strike and a 75 degree southeast dip. The vein zones dip to the north and strike at an angle of about 50 degrees to the granite contact; therefore, the trace of the granite contact on longitudinal sections of most of the veins is as flat as 40 degrees.

The erratic habit of the aplite dikes and their occurrences, limited to the vicinity of the granite contact, have been described above.

Diabase

The diabase sheet lies above the hanging wall of the main

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*All mine levels are numbered in feet measured from a datum 22 feet above the level of Great Bear Lake.

porphyry belt well east of the mine area; therefore, it is not included in this discussion of the structural geology of the mine.

Two major diabase dikes traverse the rocks of the mine area. Both are about 15 to 20 feet in width, both usually strike about N60°W and both dip over 70 degrees to the north. One dike crops out on the southeast shore of McDonough Lake but does not reappear on the surface to the northwest (Fig. 5). It is irregular in strike and shape and has many branches and reentrants. It forms the footwall of No. 2 Vein zone for about 100 feet on the cliffs west of Gib Lake and parallels No. 5 Vein zone for a few feet before it crosses it. The dike is chilled against some fractures of the No. 5 zone and is itself cut by others. It is probably contemporaneous with the diabase sheet.

The other diabase dike lies in the centre of the mine area. This dike is generally regular in width and attitude and shows variations in these only where it intersects certain vein zones. It strikes into the mine area from the southeast, following west along No. 1 Vein for about 800 feet, then resumes its regional trend to the northwest to cut across No. 2 Vein with minor deviation and within a short distance intersects No. 3 Vein, which it follows west for over 1500 feet before resuming its regional northwest strike (Fig. 4). Where it follows No. 3 Vein the dike generally forms the footwall of the vein; however, below the 600 Level the dike crosses and recrosses the vein zone, often enveloping the zone for tens of feet, along hundreds of feet of strike and dip before finally leaving it both at depth and along strike. In this locale the diabase has been chilled against some fractures and shears, has been cut by others, and in many places is extensively brecciated to form wide zones of diabase fragments in vein material. The intersection of the diabase with the vein zone developed many local controls of ore deposition.

In addition to these two relatively large diabase dikes there are numerous small, usually chilled, dikes or dikelets scattered throughout the mine area. These have been described earlier. Only in rare instances have they been of any consequence in the control of the pitchblende deposition.

Feldspar Porphyry Intrusives

One large sill-like body of porphyry lies to the east of the mine. This mass forms the main part of the porphyry belt of intrusives in the mine area and has been designated No. 1 Porphyry body. It strikes northeasterly, dips about 35 degrees to the east, and has many local irregularities along its contacts. The true width of the body seldom exceeds 400 feet. The footwall crops out in a line striking northeast and southwest from the southwest corner of McDonough Lake (Figs. 4 and 25). The footwall has been explored down to the 1300 Level and shows no major deviations; however, below that level the dip appears to flatten to less than twenty degrees.

West of this main porphyry body lies a parallel body of major dimensions, No. 2 Porphyry. It is about 200 feet in true thickness and is separated from the larger body by a band of bedded tuffs about 150 feet in true width (Figs. 5 and 25). This porphyry body appears as a series of irregular shaped outcrops on the surface southwest of McDonough Lake. A hundred feet beneath the surface these separate cupolas coalesce to form a continuous tabular body. The mass extends down dip to the 1175 Level where it terminates in a zone of aphanitic porphyry and porphyritized sediments, similar to the zone that overlies it at the surface. Not only is this mass extensively capped and underlain by these rock-types, but it is also flanked by them along its footwall. As postulated earlier, this association of rock-types probably typifies the tops of the porphyry intrusives, where water and potash were concentrated in an environment of high but short-lived initial temperatures. This particular body of porphyry does not extend north of No. 5 Vein, except as small tongues and lenses, whereas near Labine Bay and south of the mine it is in the form of a large stock; therefore, it is assumed that the porphyry magma entered from depth to the south and terminated approximately beneath the present surface southwest of McDonough Lake (Fig. 25). The tabular body exposed in the mine is terminated at top and bottom and is surrounded by rock-types typical of the upper ends of the porphyry bodies. It represents the tip of a larger mass which lies deeper and to the south.

Between the porphyry bodies described above and the granite contact to the west three additional tabular porphyry masses have intruded the Mine Series sediments. These bodies are essentially identical in lithology with the main masses to the east but are considerably less extensive and far more irregular in shape. The easternmost body of these three, No. 3 Porphyry, is the largest--about 300 feet in maximum thickness. It strikes almost due north and dips about 60 degrees to the west. It does not crop out but terminates about 100 feet below the surface near No. 1 shaft (Figs. 25 and 31). It is about 300 feet in maximum thickness. Most of it is composed of the crystalline variety of porphyry but near its ends it grades sharply upward and laterally into aphanitic porphyry and finally fine-grained intensely metasomatized metasediments. This body of porphyry has produced one of the most important controls of ore localization in the area.

West of this porphyry body are two small tabular tongues, one, No. 4 Porphyry, dipping vertically and the other, No. 5, the westernmost, dipping to the west (Fig. 25). Both these bodies are extensive in the southern part of the mine block but terminate to the north short of the Eldorado vent.

A few smaller bodies of aphanitic porphyry in dike form occur erratically distributed between the major bodies described. In addition, to the south and west of the mine another large body crops out against the granite on Cobalt Island.

Eldorado Vent

The Eldorado vent occupies the northwest corner of the mine block and delimits the area favourable for ore occurrence. The configuration and location of the vent have been described in detail in the discussion on the origin of the body. It is important in this discussion on structure to re-emphasize the effect of the competency of the tuff body. Joints and fractures within the body are tight and very limited in extent. The vent has acted as a massive bulwark resistant to fracturing; therefore several fracture zones failed to penetrate it but were deflected along its edges. An example is No. 5 Vein.

Mine Series

The absence of dependable marker beds within the Mine Series has impeded attempts to determine the structure of the sedimentary rocks in the mine area. The massive chert beds have served as local markers, but they are so lenticular that projection of them for distances exceeding a few hundred feet is undependable.

Several features indicate that the general structure of the Mine Series is one of a homocline with complex deformation in the vicinity of the porphyry bodies (Figs. 31 and 32). This structure is suggested by:

(1) a correlation of the massive chert beds from the lower levels of the mine to the surface, assuming that the massive cherts are confined to approximately the same horizon in the Mine Series (Fig. 31);

(2) the undisturbed eastward dip of the beds underlying Cobalt Island to the west and the beds of the Tuff Series to the east (Figs. 4, 5 and 31);

(3) generally constant strikes to the northeast and dips to the southeast of beds throughout the mine;

This homocline has been modified in the vicinity of the large bulge in the granite in the lower levels of the mine. The dips of the beds change, with depth, from east to west around this granite protuberance. Apparently the intrusion of this apophysis caused the sediments to fold around it.

Large scale arcuate bends and tight folds have been imposed upon portions of the homocline by the intrusion of the feldspar porphyry bodies (Figs. 31 and 32).

In detail, the structure of the Mine Series sediments is considerably more complex than the general structure would suggest. The complexity is at a maximum in the immediate vicinity of feldspar porphyry intrusive bodies, particularly directly above their ends. In these regions the beds are so intricately folded and dislocated that structurally the geology is chaotic. This is graphically illustrated on the surface south of No. 1 shaft headframe, directly above the top of one of the main porphyry intrusives (Fig. 5).

In addition to the structural complexities near intrusive bodies many small scale deformational features occur within the sedimentary series far removed from any intrusives. Open and isoclinal folds with amplitudes of a few feet are common in the sediments. These features suggest the existence of similar larger structures, but because of the absence of marker beds within the monotonous sequence of thin banded cherts such structures cannot be detected. A second type of deformation occurring throughout the sediments is small scale faulting on jointlike slip planes. This is best seen along contacts of the massive chert where the differences in rock types make the displacements easily detectable. The faults causing these displacements belong to three general sets. Faults of the most dominant set strike northeast to east and dip about 60 degrees to the northwest. This set roughly parallels the general attitude of the tabular bodies of porphyry. A less abundant set is represented by faults striking northeast and dipping very steeply to the southeast. Faults of the third set are still fewer in

FIGURE 31

LOCATION OF THE PRINCIPAL PORPHYRY INTRUSIVE BODIES

ELDORADO MINE

Port Radium, NWT

SCALE 1" = 200'

LEGEND

FELDSPAR PORPHYRY INTRUSIVES
Crystalline variety
(Numbered as in text)

FELDSPAR PORPHYRY INTRUSIVES
Aphanitic variety

SEDIMENTS and TUFFS

APHANITIC METASOMATISED SEDS. and TUFFS

GRANITE

MASSIVE CHERT BEDS (Mine Fm.)

ATTITUDE OF SEDIMENTS
Known and projected

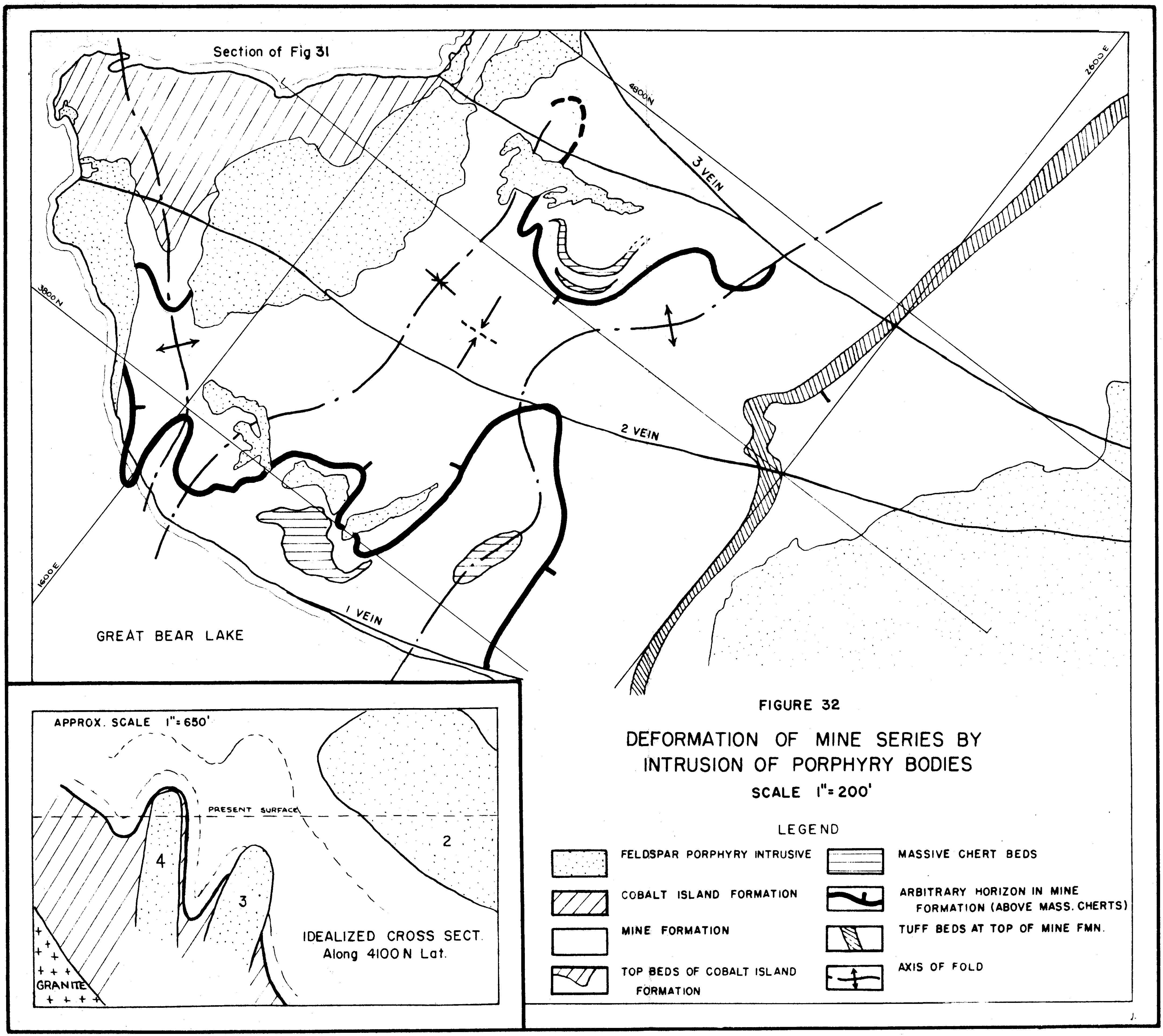


FIGURE 32

DEFORMATION OF MINE SERIES BY INTRUSION OF PORPHYRY BODIES

SCALE 1" = 200'

number. They strike about due east and dip 65 degrees to the south. The largest displacements are on the first, most dominant, set and are usually normal dip-slips. Displacements seldom exceed ten feet. All these faults are found only within the sedimentary rocks and are clearly related to the intrusion of the porphyry bodies. Although their individual displacements are small, in aggregate they probably account for much of the deformation that was necessary to provide room for the intrusives.

All the above mentioned structures preceded the main shearing and subsequent mineralization. Many of the small faults are healed by vein carbonate and quartz.

The principal deformation at Labine Point of the regional homoclinal structure of the sediments is folding produced by the intrusion of No's. 3 and 4 porphyry bodies. Both bodies domed the sediments above them into contorted anticlines whose limbs flank the intrusive bodies. The sediments between the two porphyry bodies are folded into a crude U-shaped syncline. These structures can be roughly traced by projecting the exposures of massive chert beds and the attitudes of the thin-bedded cherts throughout the mine (Fig. 31). The two anticlines and the intervening syncline trend generally north but are complicated greatly by local cross and drag folding as well as truncation by the porphyry bodies (Fig. 32). The complexity of the deformation of the Mine Formation cherts above and around No's. 3 and 4 porphyry bodies is illustrated particularly in the 100-scale map of Labine Point (Fig. 5). Figure 32 represents an interpretation of the structure of the sediments at the surface.

The insert on Figure 32 illustrates the draping of the sediments over the porphyry bodies. This isoclinal-like folding of the Mine Formation in the Labine Point area has more than doubled the usual width of the belt of Mine Formation cherts.

An important structural feature of the Mine Formation is that it represents an integral unit possessing uniform competency and physical characteristics regardless of internal structures. With the exception of the massive cherts, there are no beds or sequences of beds within the Mine Formation that are different enough in competency or large enough in size to seriously affect the form of the shear zones passing through the series.

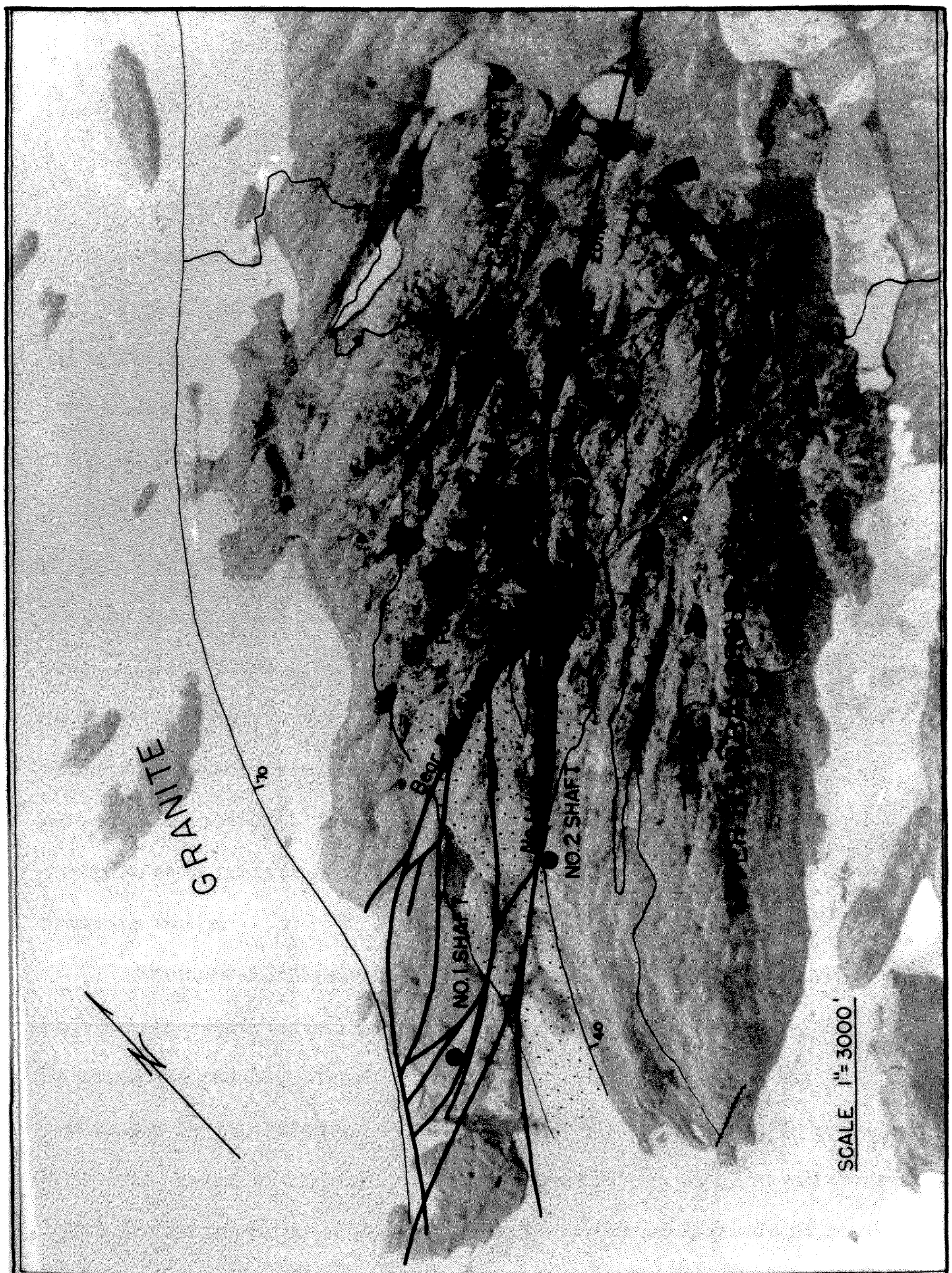


FIGURE 33

Aerial photograph of Port Radium area. From RCAF photo.

PORT RADIUM DEPOSITS

MAJOR FRACTURE SYSTEM

The pitchblende deposits of Port Radium and vicinity occur as open-space fillings in shear and fracture zones which are inter-related in a common regional system of faulting, the Cameron Bay-Eldorado system. Despite their close spatial and genetic relationship the zones differ from one another considerably in size and character. The main fault of the system, the Cameron Bay or Reid Fault, exhibits a right-hand displacement of about 2½ miles (Figs. 2 and 3). There is some local normal displacement on No. 1 Vein, No. 2 Vein, and the Bear Bay Shear in the Port Radium area. The evidence indicates however that most of the zones are fracture structures with little or no displacement and that many pronounced lineaments in the area show no displacement of structures or formations. The fissures in the mine are flanked by many tension fractures that have no correlative fractures on the opposite walls.

Fissure-fillings along fracture zones constitute the major ore-bearing structures. Replacement of wall rock of the zones by some gangue and metallic minerals is not uncommon, but replacement by pitchblende, silver, and arsenide minerals is non-existent. Veins of simple single fracture fillings are however rare. Successive reopening of the fracture zones during periods of mineralization are indicated by the complexity of the vein fillings. At least five separate periods of vein deposition are identifiable, pitchblende deposition being probably the second in the sequence.

Most of the major and minor fractures in the area exhibit some filling by quartz, calcite, and hematite. The mineralized zones range from large barren quartz veins, tens of feet in width, to shatter areas or breccia zones in which fragments of country rock are cemented by a matrix of quartz, calcite, and other vein minerals, to very narrow cracks locally filled with vein material.

The principal members of the Eldorado system of fracture zones at Port Radium are the No. 1 vein zone and Bear Bay Shear (Figs. 4 and 33). These structures converge near the north shore of Cobalt Island and beneath the center of Crossfault Lake and are 3/4 mile apart, the greatest separation, at the mine. The lenticular area they encompass is extensively broken by secondary shear and tension zones that comprise the major loci for the Port Radium pitchblende deposits. Veins and tensional cracks occur in most outcrops, and topographic expressions of fracture zones are to be seen in many places.

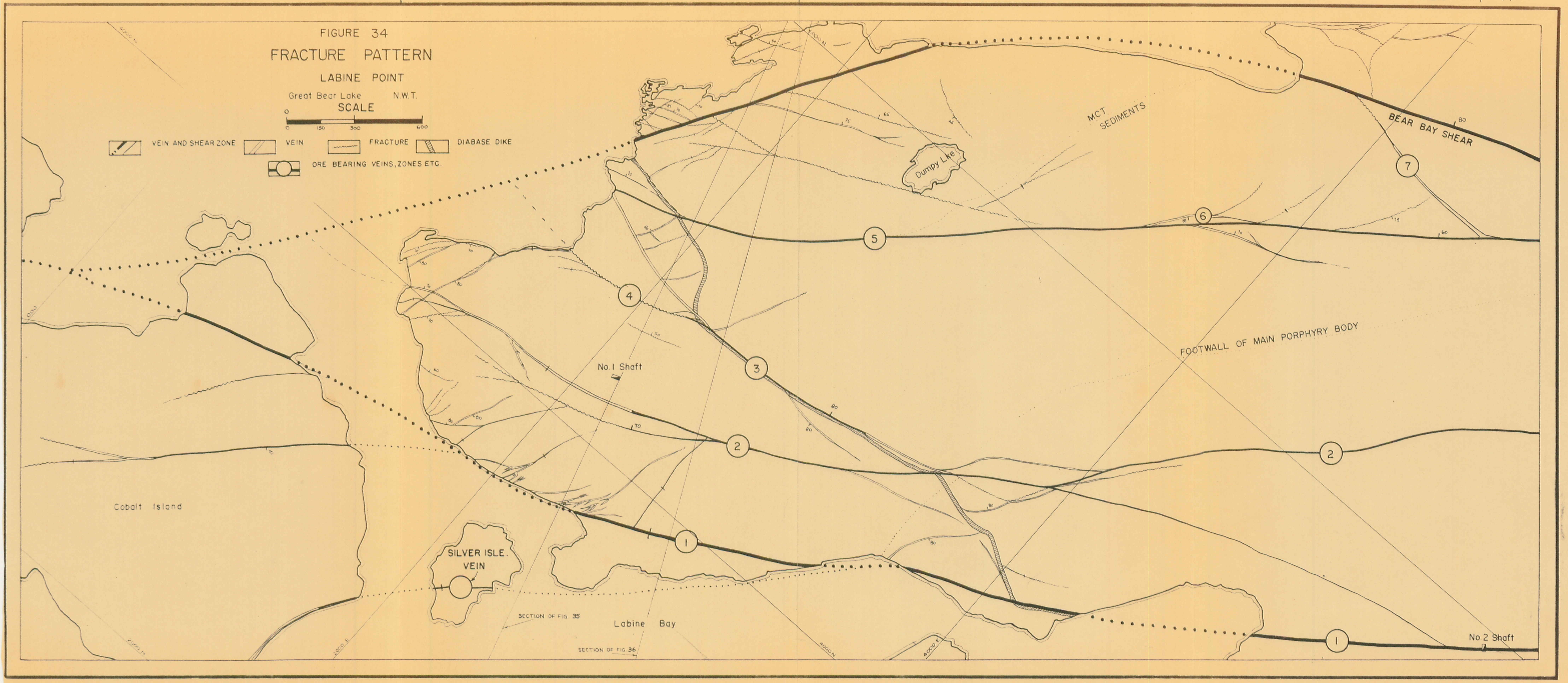
Both the Bear Bay Shear and the No. 1 vein zone, the principal members of the Eldorado fracture system, exhibit displacement in some localities but none in others. They both traverse the quartzitic limestone band of the lower Mine Series on Cobalt Island but do not offset it (Fig. 4). On No. 1 Vein, 2500 feet to the east of the limestone band, positions of porphyry bodies on either side of the zone indicate a downdrop of the hanging wall side by about 200 feet. Although the porphyry bodies are not usually dependable markers for this type of correlation because of their very irregular outlines, in this particular place an unusual cross-section shape of one porphyry body serves as a distinctive identification of the body on either side of the vein zone (see porphyry body # 3, Fig. 99). From this evidence it is postulated that the Eldorado fracture zone system originated as a set of tensional fractures related to movement on the Cameron Bay Fault. Later relaxation resulted in gravitational downdropping of the large lenticular block encompassed by the Bear Bay Shear and No. 1 vein zone. This movement was greatest at the widest part of the lens but was negligible where the two faults converged, at Cobalt Island and Crossfault Lake. This would explain the contradictory displacements observed along No. 1 vein zone. Displacement on No. 2 Vein is not more than ten feet in the area of maximum subsidence. No evidence was found to indicate displacement on any of the other fracture zones in the system.

With few exceptions, all fracture and shear zones in the area dip steeply to the north. A general constancy of dips is maintained 1500 feet below the surface; data at greater depths are not yet available. From about the 500 Level to the surface all the vein structures steepen in dip so that at the surface most of them are nearly vertical (Fig. 35).

The ore-bearing structures at Port Radium are so diverse in individual characteristics that no one term or description could adequately fit them all. Generally speaking, the structures are complex mineralized shear and fracture zones. At the mine they are called veins; therefore, in this paper the terms "No. 1 Vein", etc., will be used in compliance with familiar nomenclature. "Vein zone" will be used as a descriptive term.

The fracture pattern of the Eldorado system is shown in Figs. 33 and 34. No. 1 Vein and the Bear Bay Shear are the principal members of the system. They are complex shear zones ranging in widths from one foot to 40 feet. Gouge-covered slickensided fracture planes are common and usually form the footwalls of both zones throughout most of their exposed lengths. No. 2 and No. 5 veins are zones of fracturing subsidiary to the Bear Bay Shear and truncated to the northeast and southwest by it. They are roughly parallel to No. 1 Vein. Secondary fractures cross from No. 2 Vein to No. 1 Vein and to the Bear Bay Shear, particularly where No. 2 Vein converges with these structures. Similar secondary structures connect No. 5 Vein to the Bear Bay Shear (Fig. 34). Slickensided planes, with and without gouge, are common in the No. 2 and No. 5 vein zones but are not as continuous as those in the No. 1 and the Bear Bay shear zones. The other major vein zones within the lens are No. 3, 4, 7 and 8 Veins. No. 4 and No. 8 Veins are narrow sparsely mineralized fracture zones comprised of parallel slip planes, some of which may have up to a half an inch of gouge and ten inches of vein material. They are relatively minor structures. No. 3 and No. 7 Veins are major tension zones that are transverse between shear members. No. 3 Vein joins No. 2 and No. 5 Veins; No. 7 Vein joins No. 5 and the Bear Bay Shear. They are both wide zones of fracturing, brecciation, vein-filling and intense wall-rock alteration that grade, within short distance, to narrow fracture zones

p. 155 Campbell-Ag-1955



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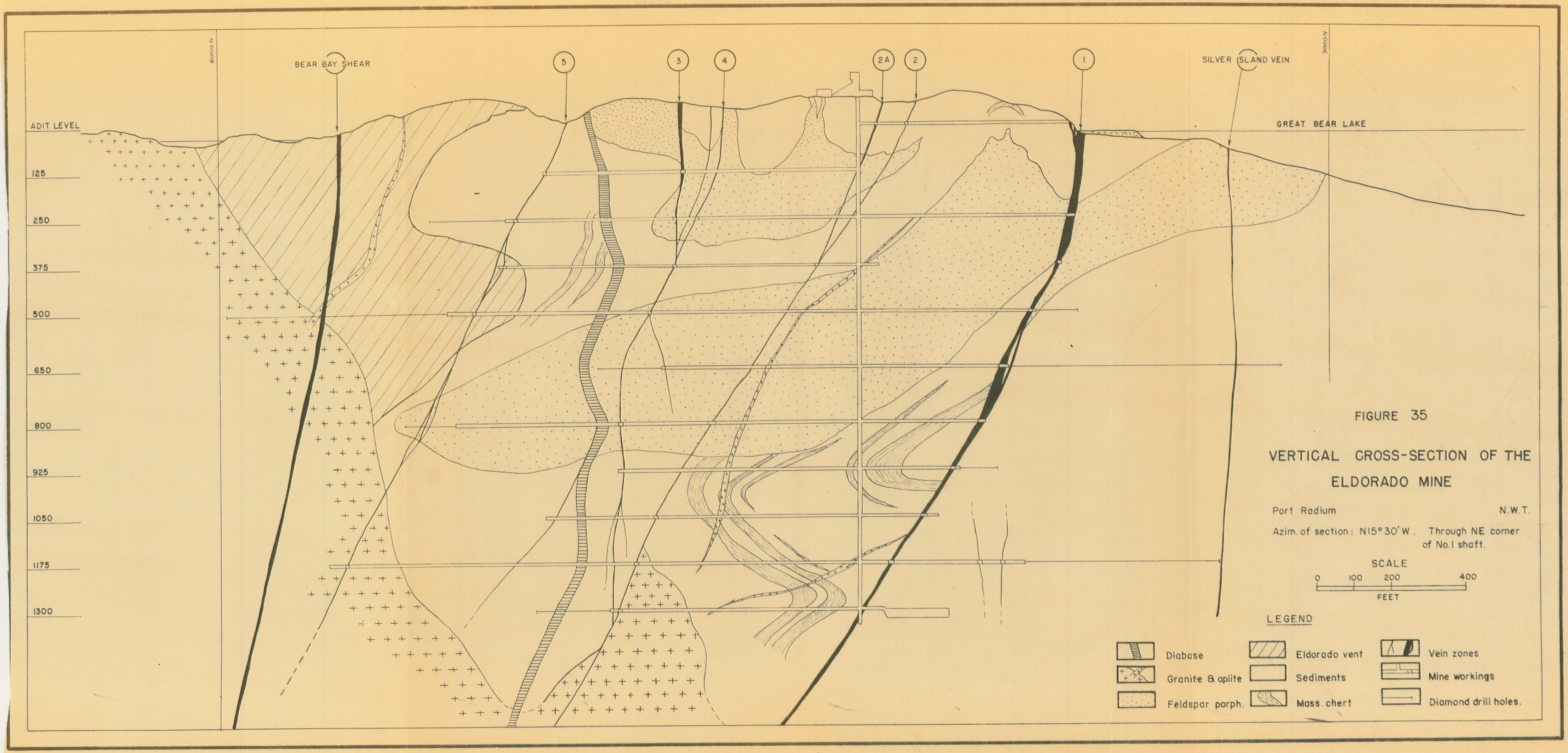

FIGURE 35

VERTICAL CROSS-SECTION OF THE ELDORADO MINE

Port Radium N.W.T.

Azim. of section: N15° 30' W. Through NE corner of No. 1 shaft.

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FIGURE 36

VERTICAL CROSS-SECTION OF THE PRINCIPAL VEINS

Eldorado Mine Port Radium N.W.T.

Azim of section: N25°W. 400' E. of No. I shaft on baseline bearing N65°E.

typical of the previously described vein zones. In general, 3 and 7 Veins maintain east-west strikes and vertical, or steep north, dips; however, strikes and dips may show many local irregularities. Continuous gouge-filled fractures are rare in both these tension zones.

In addition to the vein structures between No. 1 Vein and the Bear Bay Shear there are several important vein zones located outside the main lens of shearing. The Silver Island Vein branches from the footwall of No. 1 Vein near the narrows of Labine Bay and strikes southwest across Silver Island. It is a vein-filled fracture zone much like No. 2 Vein in character and size but has a vertical dip (Figs. 34-36). North of the Bear Bay Shear, and possibly related to it, is a system of wide quartz veins and fracture zones of which only No. 9 Vein carries pitchblende (Fig. 4).

In the vicinity of Crossfault Lake the major shear zone of the Eldorado System is flanked by a number of parallel and transverse fracture zones similar in character to those occurring in the mine area.

The major fracture pattern in the Port Radium area was probably imparted mainly by compressional stresses for extensive slickenside and gouge were formed on all major fractures. The compression was followed by tension that opened the fracture system for mineralization. The principal movement on the Cameron Bay-Eldorado fault system occurred along the Cameron Bay Fault. The Eldorado Zone is essentially a north branch of the Cameron Bay Fault and exhibits no great strike displacement but locally does exhibit considerable normal dip-slip displacement. From the point where it branches from the Cameron Bay Fault, near Failes Bay, southwestward to Crossfault Lake, the Eldorado Zone is ostensibly a single zone. From Crossfault Lake to Cobalt Island it branches into two units which re-converge at Cobalt Island and which are connected by secondary branching fractures (Figs. 4 and 33). This is the "lens" of fracturing that is host to the pitchblende deposits of Port Radium. The lens of fracturing lies adjacent to the east contact of the granite (Fig. 33) suggesting that, when the fracture zones were formed, the marked difference in regional competency between the granite and the Echo Bay rocks resulted in the formation of a wide zone of fracturing adjacent to the granite mass. Later relaxation allowed normal adjustment on the various fracture planes within the lens, so that normal movement occurred on several zones near the wide part of the lens but no movement occurred near the constricted ends of the lens.

The tensional zone represented by the large lens of fracturing provided the best regional channelway for pitchblende-bearing solutions and became the locus for the principal Port Radium deposits. This feature of the occurrence of pitchblende deposits along major fracture zones at points of maximum tensional opening is reflected by the deposits at Failes Bay (Fig. 2), northeast of Port Radium along the Eldorado zone. Similarly the same type of control is repeated on a smaller scale along the individual vein zones within the lens of fracturing at Port Radium.

Of the many and diverse vein structures at Port Radium, the most important are shown in Figs. 33 and 34. The principal ore-bearing zones are Nos. 1, 2, 2A, 3, 5, 6, 7 and 8 Veins. Also of interest, either mineralogically or tectonically, are No. 4 and No. 9 Veins, the Silver Island Vein and the Bear Bay Shear.

No. 1 VEIN

No. 1 Vein is a strong fracture and shear zone extending for a little over two miles from Cobalt Island to Crossfault Lake, joining the Bear Bay Shear at both places. It ranges in dip from vertical to 60^{o}, average in the mine being about 65^{o}, and in width from one foot to forty feet, the average being between 5 and 10 feet. The displacement is normal and is as much as 200 feet where determinable.

The vein zone is characterized by a strong gouge-covered footwall shear plane which is always present and in some places constitutes the entire zone. The gouge on the footwall ranges in thickness from one-half inch to a foot. Generally, this shear plane is accompanied by parallel and diverging complementary fractures which form the zone of weakness that has been host to alteration and several vein depositions. These branching fractures may form local expansions of the zone, usually in the hanging wall for ten to forty feet, consisting of large lenses of vein material or wall rock apexing either upward or downward or both. In the productive areas the ore widths seldom make up more than 30 percent of the total width of the zone, especially in the very wide portions.

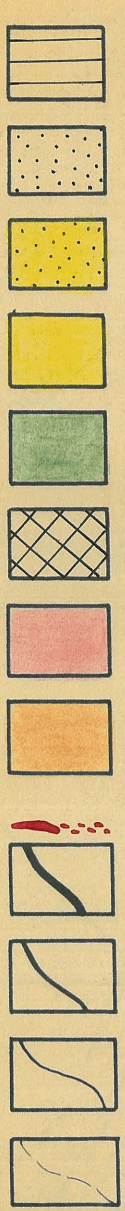
The character of No. 1 Vein is unpredictable for any distances beyond about 20 feet, and selective mining is necessary to obtain the ore without excess dilution by barren vein zone material. The multiple fracturing in the vein zone and in the hanging wall make for unstable ground and necessitate cut-and-fill stoping.

The vein zone is a chloritized fracture zone occupied by a wide variety of quartz veins of different ages. The pitchblende and the metallic minerals are generally associated with particular ages of quartz veins. In general the ore-bearing quartz veins are near the footwall of the zone and barren hematite-quartz veins of the giant quartz vein type occupy the hanging wall. In many places the hanging wall veins grade into sheared chlorite and altered wall rock with no sharp cut-off. The hanging wall is rarely straight, and is usually comprised of short horsetail fractures in altered rock. The vein zone almost everywhere has some quartz veins and heavy gouge on a relatively straight footwall shear. Mineralization beneath the footwall has been meagre. Where quartz filling is absent the zone consists of sheared chlorite. Breccias of country rock or quartz in matrices of late quartz are common. Branches from the footwall are infrequent but where present are strong (i.e., the Silver Island Vein), whereas branches from the hanging wall are many but are weak and short.

The vein zone changes very slightly in widths and mineralogy from one wallrock type to another, except in the diabase sill where the vein zone is seldom more than a narrow zone of fractures.

LEGEND

For plans of vein zones shown in Figures 38 to 46.



Diabase.

Argillic alteration of wall rock.

Quartz-hematite vein.

Quartz. and/or carbonate

Chlorite.

Massive chalcopyrite (sulphidization).

Red alteration (J = Jasper).

"Ore vein": Ore quartz with pitchblende $\pm$ carbonate, chalcopyrite, Co-Ni arsenides.

Visible pitchblende.

Fracture or fault with more than $\frac{1}{2}$" of gouge.

Fracture or fault with less than $\frac{1}{2}$" of gouge.

Fracture or fault with no gouge.

Contact

Scale of all plans

1" = 20'

Figure 37

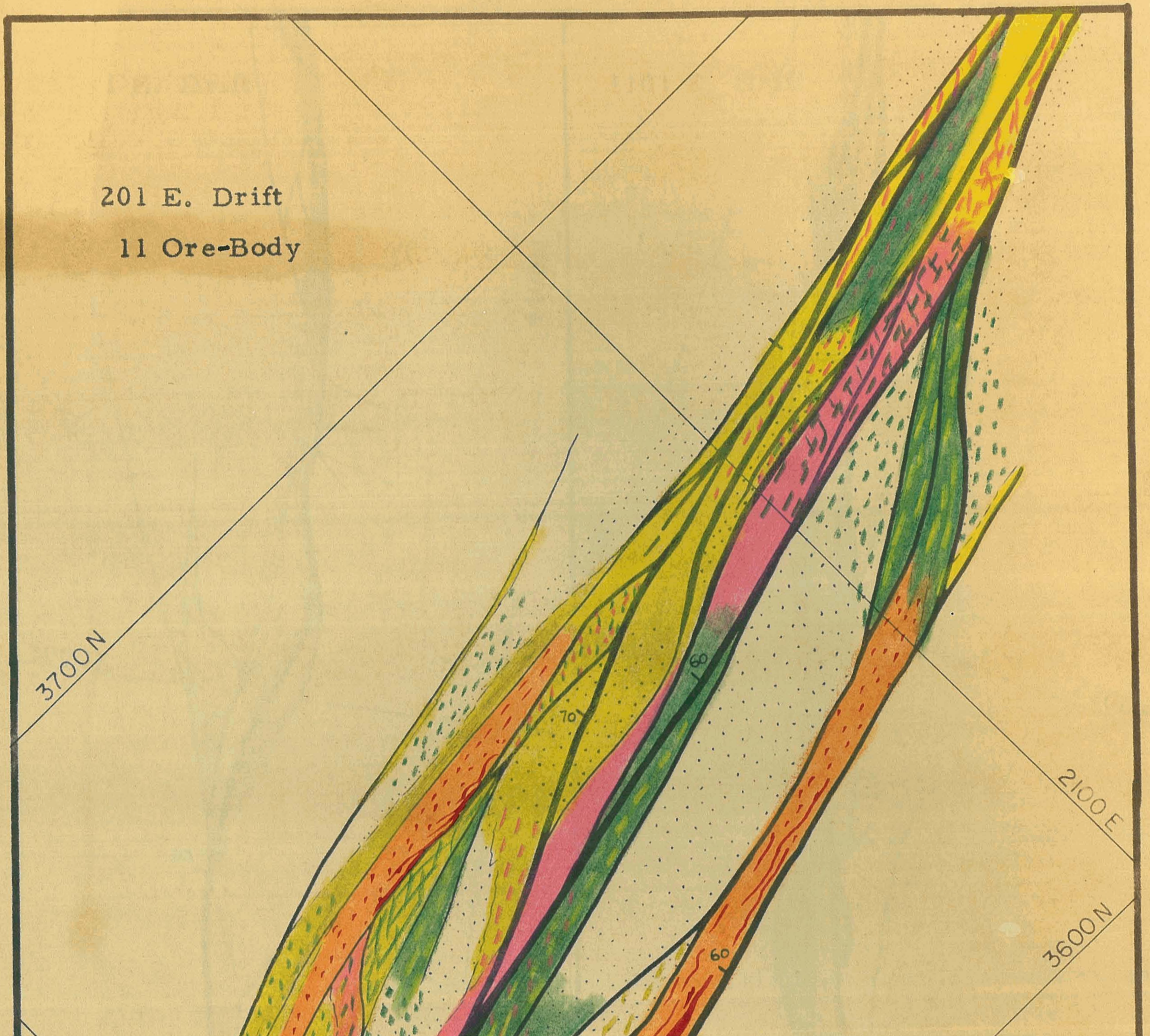


Figure 38. No. 1 Vein - Wide Section.

Figure 39. No. 1 Vein. Typical Barren Sections.

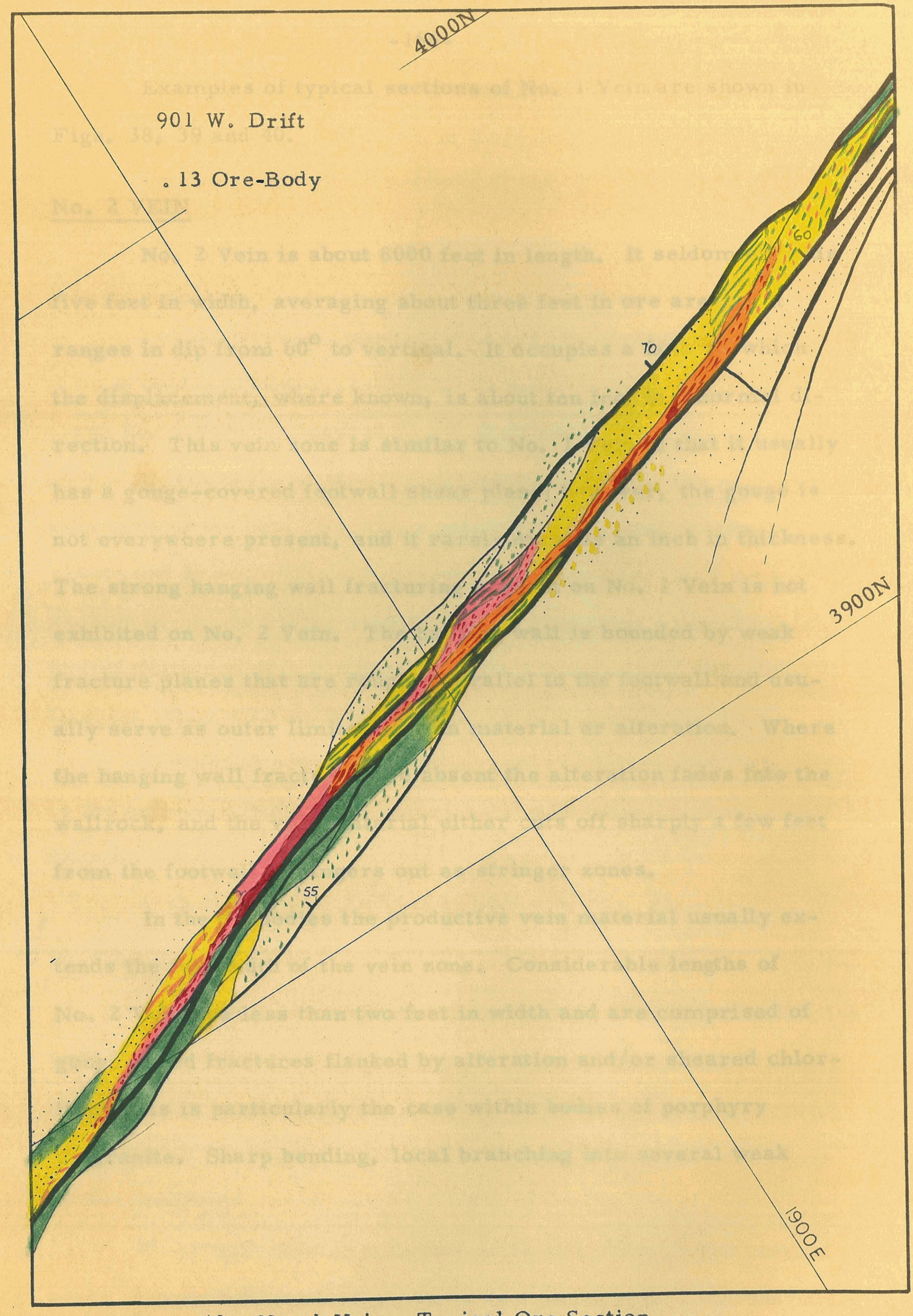


Figure 40. No. 1 Vein - Typical Ore Section.

Examples of typical sections of No. 1 Vein are shown in Figs. 38, 39 and 40.

No. 2 VEIN

No. 2 Vein is about 8000 feet in length. It seldom exceeds five feet in width, averaging about three feet in ore areas. It ranges in dip from 60° to vertical. It occupies a fault on which the displacement, where known, is about ten feet in a normal direction. This vein zone is similar to No. 1 Vein in that it usually has a gouge-covered footwall shear plane; however, the gouge is not everywhere present, and it rarely exceeds an inch in thickness. The strong hanging wall fracturing present on No. 1 Vein is not exhibited on No. 2 Vein. The hanging wall is bounded by weak fracture planes that are roughly parallel to the footwall and usually serve as outer limits for vein material or alteration. Where the hanging wall fractures are absent the alteration fades into the wallrock, and the vein material either cuts off sharply a few feet from the footwall or fingers out as stringer zones.

In the orebodies the productive vein material usually extends the full width of the vein zone. Considerable lengths of No. 2 Vein are less than two feet in width and are comprised of gouge-filled fractures flanked by alteration and/or sheared chlorite. This is particularly the case within bodies of porphyry or granite. Sharp bending, local branching into several weak fractures, and abrupt ending of veins are common along No. 2 Vein and make the vein zone difficult to trace in many places.

Examples of typical sections of No. 2 Vein are shown in Figs. 41 and 42.

No. 2A VEIN

No. 2A Vein is a hanging wall vertical branch of the No. 2 Vein occurring between the 500 Level and the surface. It splits from No. 2 Vein just east of No. 1 Shaft and extends almost parallel to No. 2 Vein to the westward, eventually becoming the principal vein zone of the two. For the most part it lacks gouge-coated slip planes and is more like a single vein in character. It is a quartz-carbonate-jasper fracture-filling and replacement vein with fairly well-defined and stable walls and little accompanying shearing. Breccia zones with wallrock fragments are common.

The initial production of the mine came from this vein. It is the only vein from which commercial quantities of silver have been mined.

A section of No. 2A Vein is shown in Fig. 42.

No. 3 VEIN

No. 3 Vein is terminated to the east by No. 2 Vein and to the west by No. 5 Vein. Its dip is generally vertical, and therefore it terminates at depth on No. 2 Vein. Tectonically it is a vertical hanging wall tensional branch of No. 2 Vein, essentially the same as No. 2A Vein.

No. 3 vein zone is a system of partially integrated tension zones that form four principal types of vein zones in different parts of the mine.

Figure 41. No. 2 Vein - Typical Barren Sections

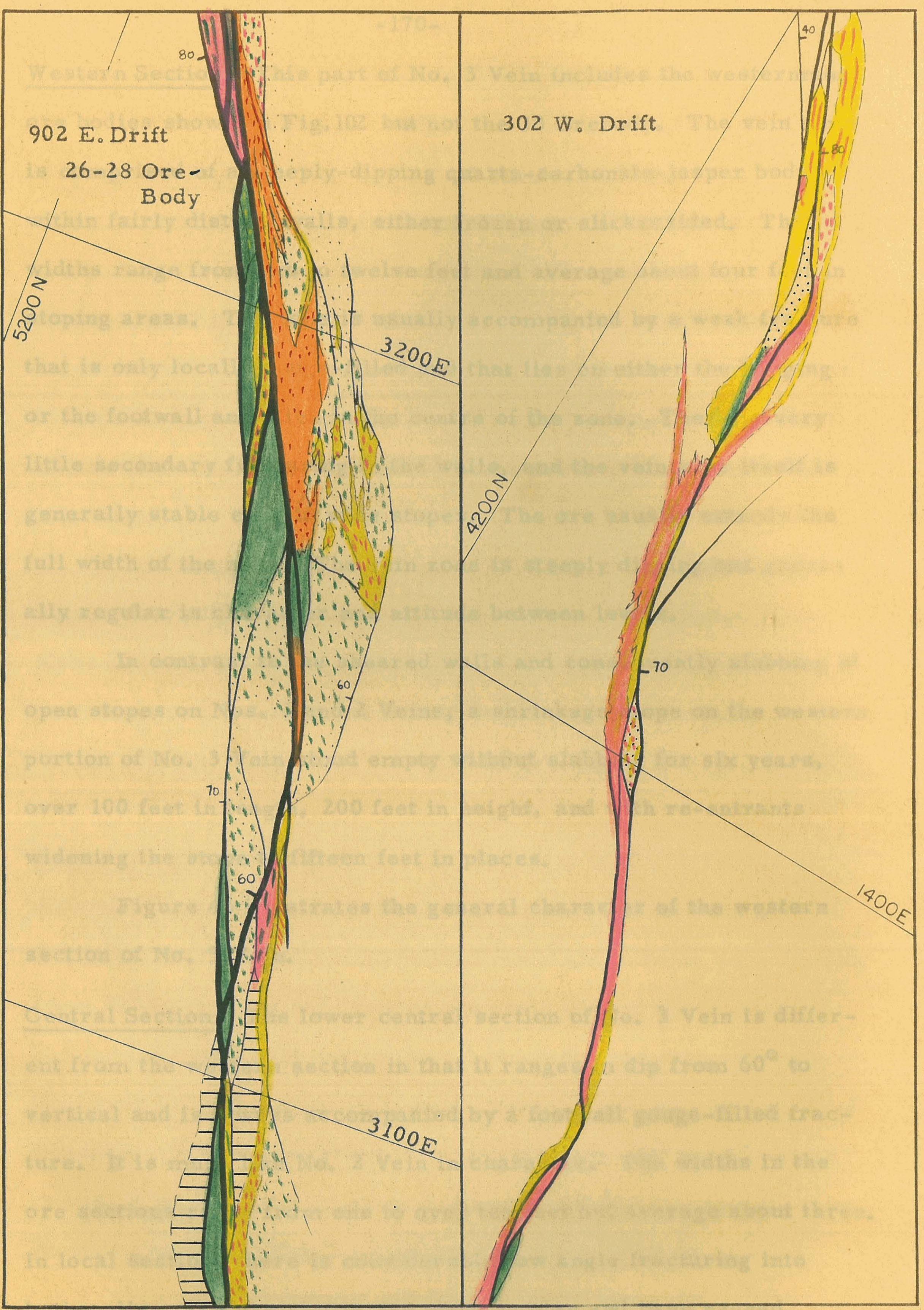


Figure 42. No. 2 Vein - Ore Section.
No. 2A Vein - Typical Section.

Western Section: This part of No. 3 Vein includes the westernmost ore bodies shown on Fig. 102 but not the 30 Orebody. The vein zone is comprised of a steeply-dipping quartz-carbonate-jasper body within fairly distinct walls, either frozen or slickensided. The widths range from two to twelve feet and average about four feet in stoping areas. The zone is usually accompanied by a weak fracture that is only locally gouge-filled and that lies on either the hanging or the footwall and often in the centre of the zone. There is very little secondary fracturing in the walls, and the vein zone itself is generally stable even in wide stopes. The ore usually extends the full width of the zone. The vein zone is steeply dipping and generally regular in character and attitude between levels.

In contrast to the sheared walls and consequently slabbing of open stopes on Nos. 1 and 2 Veins, a shrinkage stope on the western portion of No. 3 Vein stood empty without slabbing for six years, over 100 feet in length, 200 feet in height, and with re-entrants widening the stope to fifteen feet in places.

Figure 45 illustrates the general character of the western section of No. 3 Vein.

Central Section: The lower central section of No. 3 Vein is different from the western section in that it ranges in dip from 60° to vertical and is always accompanied by a footwall gouge-filled fracture. It is much like No. 2 Vein in character. The widths in the ore sections range from one to over ten feet but average about three. In local sections there is considerable low angle fracturing into both walls. The ore shoots are short in plan and have ragged boundaries. The 30 Orebody is in this section of No. 3 Vein. (Fig. 102. Parts of the central section are shown in Figures 43 and 44.

Upper East Section: The upper east section of No. 3 Vein includes the 32 - 36 orebodies and consists of a mineralized fracture zone lying along the hanging wall of a diabase dike and ranging in dip from vertical to 60°. It is characterized by a strong gouge-filled fracture on the footwall, next to the diabase, and by the dispersion of the vein material from the footwall into the hanging wall for distances from one to fifteen feet. Widths average about three feet in stopes.

In some sections the hanging wall bulges out under curving fractures which allows slabbing of the vein zone, although these slabs are usually ore in this zone. The hanging wall rocks are sediments and aphanitic porphyry, the foot wall is diabase.

Typical portions of this section are shown in Figs. 43 and 45.

Lower East Section: The lower east section of No. 3 Vein is very different in character from the foregoing parts of the vein zone. It is a compact, heavily mineralized, vein and breccia zone dipping from 70° to vertical and lying on the north side of the diabase. It joins the upper east section as a branch and is connected with the lower central section by a weak, narrow, sparsely mineralized fracture. It averages about four feet in width, and the full width is ore. There is little adjacent fracturing outside the tight fractures on either wall. Wallrock alteration is markedly slight.

The 34 - 36 Orebodies are on this portion of No. 3 Vein. (Fig. 102).

A typical section of this vein is shown in Figure 46.

Mineralization on No. 3 Vein: The predominant vein minerals are different for each of the different sections of No. 3 Vein. The western section is predominantly quartz-jasper; the lower central section is quartz-chlorite; the upper eastern section is quartz-carbonate-chlorite; and the lower eastern section is quartz-chalcopyrite-carbonate-arsenide. Within porphyry bodies, No. 3 Vein is reduced to a narrow zone of fractures with or without gouge and adjacent alteration.

No. 5 VEIN

No. 5 Vein is a narrow fracture zone about one mile in length, bounded at both ends by the Bear Bay Shear. It dips about 70° to the north, steepening to vertical near the surface at the mine. Wide vein-filled, tight-walled sections are not uncommon and are generally ore-bearing in the mine area. These sections commonly exhibit brecciated wallrock enclosed by vein quartz. There is little or no shearing on or in either wall except for a tight slip plane on the footwall.

Only a small percentage of the explored portion of No. 5 Vein contains pitchblende ore bodies. The productive portions occur to the west, near the Eldorado Vent, and to the east, near No. 7 Vein. The vein zone has not been explored east of No. 7 Vein.

The intervals between the wide quartz-filled parts of the fracture zone are composed predominantly of sheared chlorite mineralized by quartz and/or carbonate. In many places the vein zone is no more than a zone of fractured altered rock.

A typical ore section is shown in Fig. 46.

No. 6 VEIN

No. 6 Vein has had little development. Its structure apparently is similar to No. 2A Vein. It branches from the hanging wall of No. 5 Vein at about the 125 Level beneath the southwest end of McDonough Lake. The width ranges from one foot to three feet, being widest near its junction with No. 5 Vein. It is a vertical zone of jasper replacement and quartz veining. Despite the limited extent, the vein appears to be rich in pitchblende.

No. 7 VEIN

Information on No. 7 Vein at present is gained from one drift, one raise, and several diamond drill holes. The ore zone is a jasper zone that is extremely irregular in outline and width. The edges of the zone are generally gradational, hence ore limits must be established by assay boundaries. There is little continuous fracturing and no shearing along the zone. The pitchblende and other vein minerals are scattered throughout the zone in discontinuous fractures. The zone dips from 70° to vertical. It averages about five feet in width, but widths of 20 feet are common.

Away from the ore-bearing sections No. 7 Vein consists of a winding gouge-filled fracture flanked by red alteration and discontinuous quartz veins.

No. 7 Vein merges abruptly with No. 5 Vein to the east and merges with the extensive hematitic alteration zone of the

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Figure 43. No. 3 Vein – Junction with No. 4

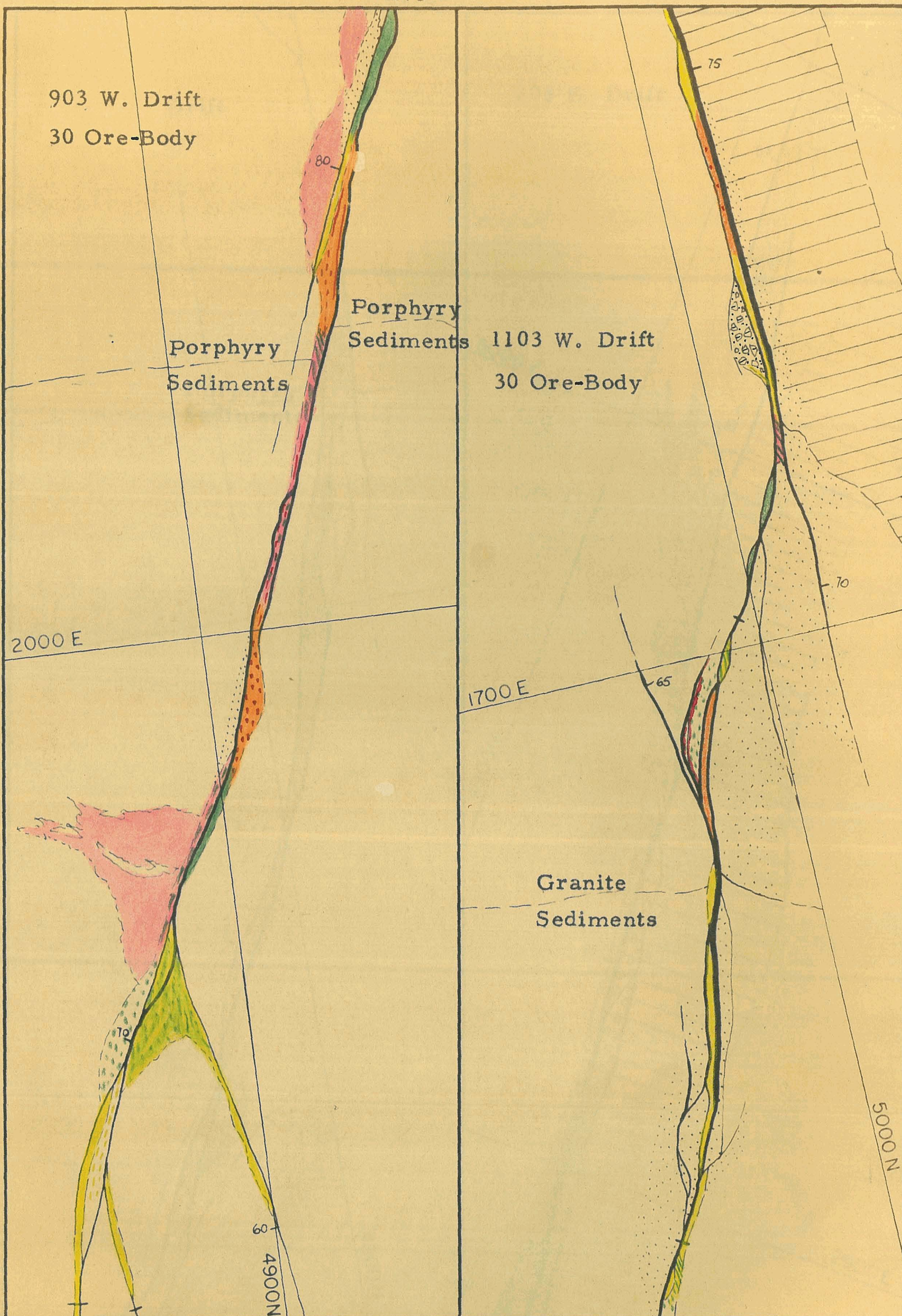


Figure 44. No. 3 Vein. Central Section.

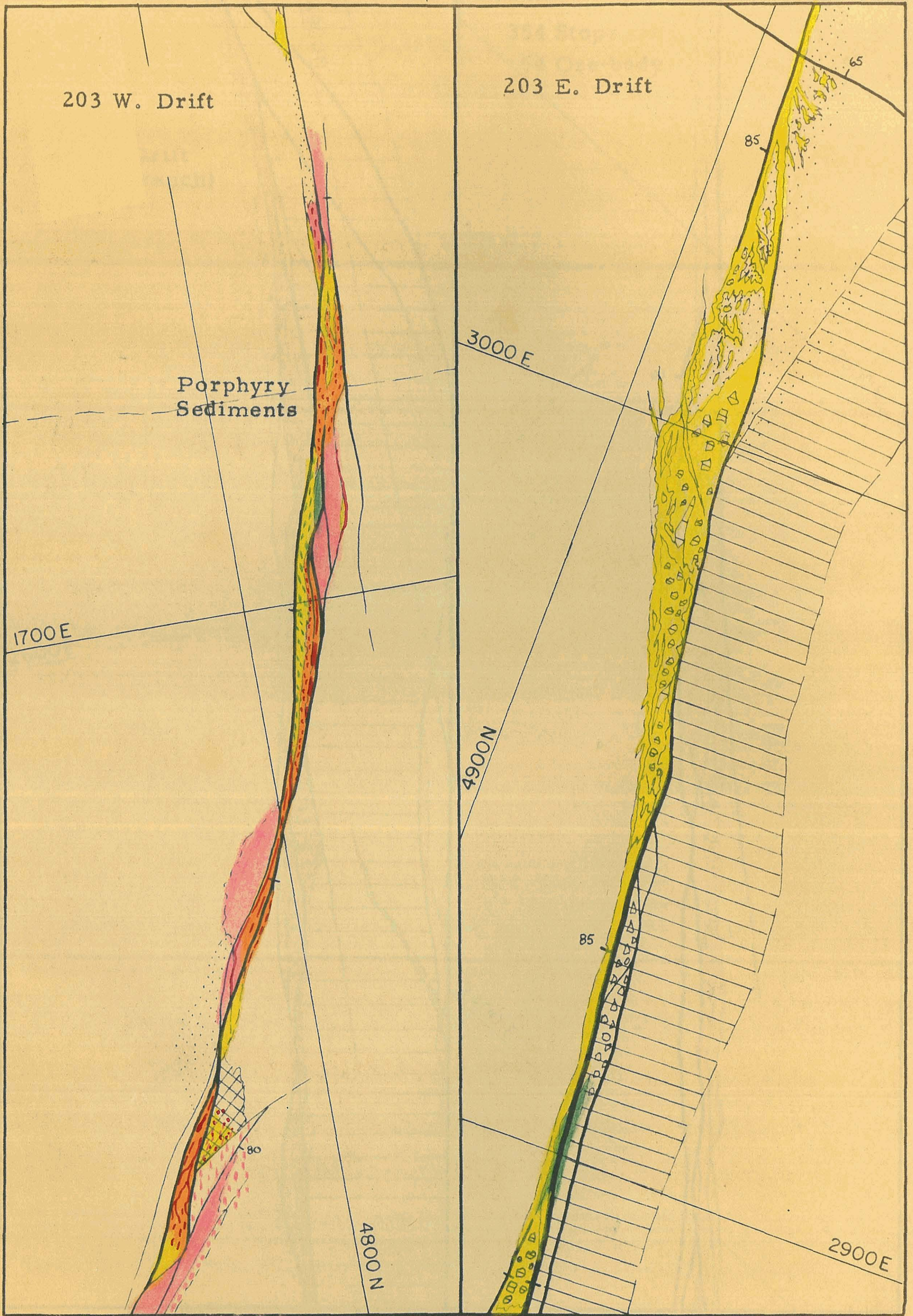


Figure 45. No. 3 Vein. Western and Upper East Sections.

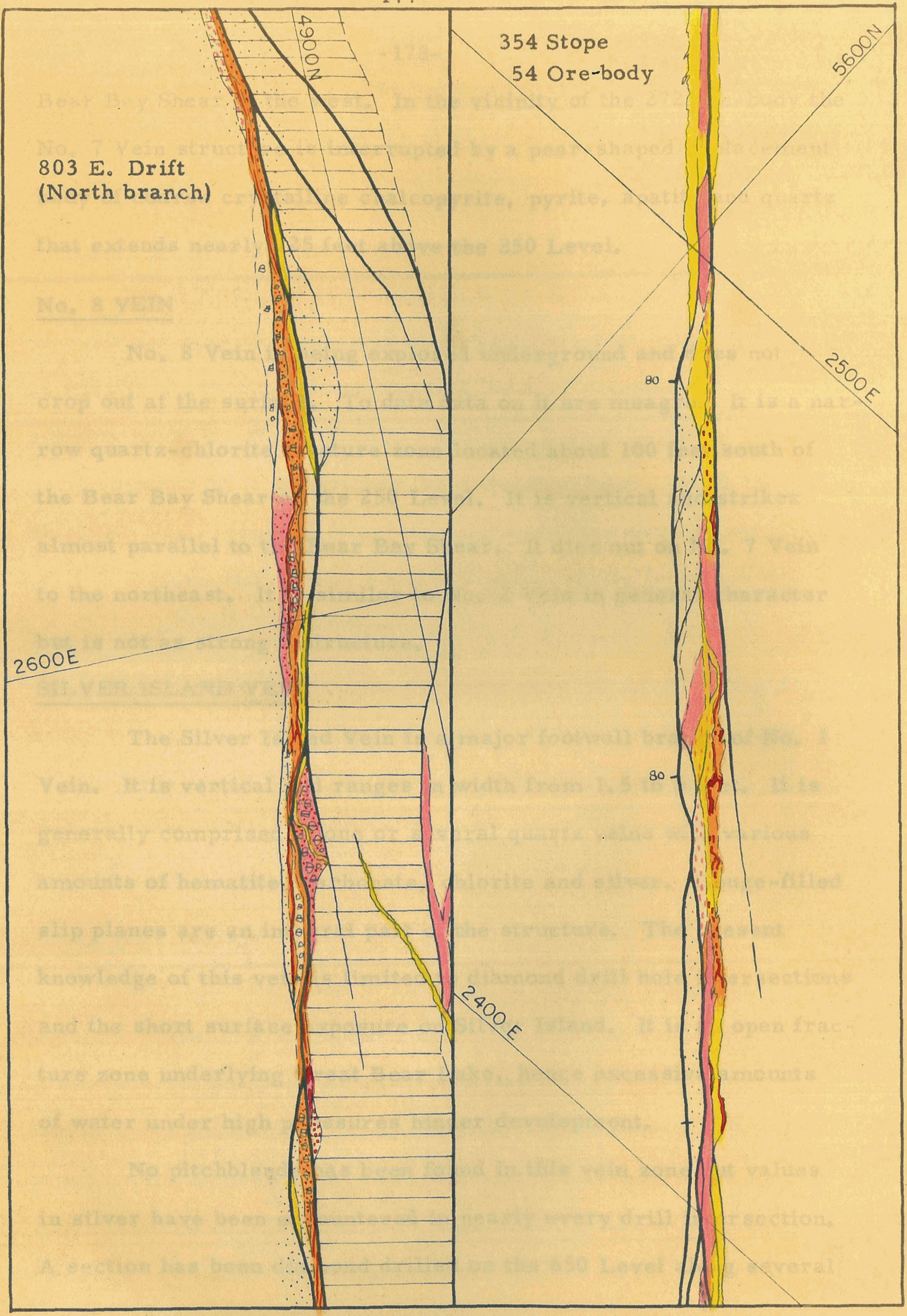


Figure 46. No. 3 Vein
Lower east section.

No. 5 Vein.
Ore section.

Bear Bay Shear to the west. In the vicinity of the 272 ore-body the No. 7 Vein structure is interrupted by a pear-shaped replacement body of coarse crystalline chalcopyrite, pyrite, apatite and quartz that extends nearly 125 feet above the 250 Level.

No. 8 VEIN

No. 8 Vein is being explored underground and does not crop out at the surface. To date data on it are meagre. It is a narrow quartz-chlorite fracture zone located about 100 feet south of the Bear Bay Shear on the 250 Level. It is vertical and strikes almost parallel to the Bear Bay Shear. It dies out on No. 7 Vein to the northeast. It is similar to No. 2 Vein in general character but is not as strong a structure.

SILVER ISLAND VEIN

The Silver Island Vein is a major footwall branch of No. 1 Vein. It is vertical and ranges in width from 1.5 to 5 feet. It is generally comprised of one or several quartz veins with various amounts of hematite, carbonate, chlorite and silver. Gouge-filled slip planes are an integral part of the structure. The present knowledge of this vein is limited to diamond drill hole intersections and the short surface exposure on Silver Island. It is an open fracture zone underlying Great Bear Lake, hence excessive amounts of water under high pressures hinder development.

No pitchblende has been found in this vein zone but values in silver have been encountered in nearly every drill intersection. A section has been diamond drilled on the 650 Level along several hundreds of feet, and all cores have contained abundant wire silver in grey quartz, with an average of about 200 oz. Ag/Ton over widths of three feet.

No. 4 VEIN

No. 4 Vein is a south branch from No. 3 Vein and consists of a narrow zone of fracturing with very little vein filling. Gouge is usually present on one or more of the fracture planes. The zone roughly parallels No. 2 Vein and like No. 2 Vein becomes progressively weaker as it approaches the Bear Bay Shear. Near the junction with No. 3 Vein the No. 4 vein zone carries some pitchblende.

The junction of No. 3 and 4 Veins is shown in Figure 43.

No. 9 VEIN

No. 9 Vein is a narrow fracture zone occupied by one or more quartz-hematite veins. It rarely exceeds two feet in width. It lies north of the Bear Bay Shear and strikes west from it. It is the only structure north of the Bear Bay Shear that has been found to carry pitchblende.

BEAR BAY SHEAR

The Bear Bay zone of shearing is probably the principal member of the Eldorado fault zone in the vicinity of Port Radium. It dips steeply to the north and ranges between 5 and 20 feet in width. It is essentially a zone of closely-spaced gouge-filled slip planes with the intervening rock brecciated and heavily altered to clay, chlorite and/or hematite. Vein material is not extensive and is usually hematitic quartz of the giant quartz vein type. The zone is flanked by wide areas of secondary fractures and very intense hematitization and argillization so that in many places the total width of the zone of shearing and alteration is as much as 100 feet. The Bear Bay Shear persists strongly through the diabase sill, whereas all the other vein zones, including No. 1, pinch down to practically nothing where they traverse the sill.

Although the Bear Bay Shear appears to be the dominant shear zone in the area, it does not carry pitchblende in commercial quantities in the rather limited length it has been explored. Further exploration along this structure may indicate the existence of ore bodies in it. At present it appears that the tensional opening necessary to allow passage of hydrothermal solutions existed along the fracture zones south of the Bear Bay Shear but was lacking or limited on the shear itself.

The open character of all the vein zones described above is further illustrated by the fact that every zone is host to disconnected networks of water courses along the entire exposed lengths to depths of at least 2000 feet. The amounts and pressures of the water encountered in the vein zones differ greatly from place to place. Even structures that do not underly Great Bear Lake are saturated with water. Such structures eventually run dry when they are opened in mining. In the permafrost zone the water in the vein zones occurs as veins of ice interspersed throughout the openings in the zone.

TENSIONAL OPENING OF THE VEIN ZONES

All the vein zones at Port Radium exhibit some differences in characteristics in different wall rocks. Within the porphyry bodies and the granite, Veins No. 2, 3, 4, 5 and 7 and the Silver

Island Vein pinch to narrow quartzose chloritic fractures, but No. 1 Vein and the Bear Bay Shear show only slight constrictions and some simplification of mineralogy. The indications are that No. 1 Vein was affected by differences in wall rock in the early stages of its mineralization and development, but that successive stages of re-opening and mineralization tended to even out the early variations in such a way that the zone is now generally uniform in width and character throughout all rock types. The zone is very constricted within the diabase sill because the diabase sill was emplaced after most of the re-opening and mineralization had occurred.

Most of the vein zones, if they are constricted within the porphyry, widen and branch sharply at the edge of the porphyry to form bulged sections within the sedimentary rocks adjacent to the porphyry. These relatively wide zones gradually become more narrow further into the sedimentary rocks, and the vein zones assume uniform widths until a new rock formation is intersected. These zones of branching fractures and breccias are reflections of the differences in competency between two adjacent rock types. The greater the strength differential between the rock types, the more intense would be the zone of tensional fracturing in the weaker formation at the time of failure. The original tension would possibly impart a network of fractures in the weaker rock while the adjacent stronger formation would remain unbroken. When the competent formation would finally rupture the single or few planes then formed would remain the only zones of weakness in that rock during further stresses. This has apparently been the case at Port

Radium. The zone of multiple fractures in the weaker formations adjacent to the porphyry bodies remained as the most open parts of the fracture zones. This feature of difference in fracture openings from one rock type to another is most pronounced between the porphyry and the least metasomatized and/or recrystallized sedimentary rocks. It is very great between the granite and all other rock types. It is the predominant structural feature controlling the deposition of the pitchblende.

In addition to the tension zones set up along the vein zones where they traverse competency differences in the wall rocks, tension zones attributable to other causes are fairly common along most of the vein zones. These are:

(1) Bending and "horse-tailing".

At many places where the vein zones change sharply in strike branch or "horse-tail" fractures occur, usually in the hanging wall of the zone. These "horse-tail" features seldom continue for more than 50 feet.

(2) Zones of tension were also formed near the junction of major fracture zones such as Veins No. 2 and 3 or branches of major fractures. Transverse fractures across the apex of the triangle of the junction form fracture zones that are locally ore-bearing.

(3) Steepening and flattening.

Changes in the dip of the vein zones, combined with normal dip-slip movement, in a few places have served to open the steep parts of the structures relative to the flat portions. This type of opening has controlled the emplacement of at least one main ore body. This type of control is, however, not common.

MINOR FRACTURES

Minor fractures, where not related directly to the major fracture zones, have been unimportant factors in the localization of ore. Minor transverse fractures, crossing between the major zones, (Fig. 34), are often host to quartz, chlorite, hematite and copper minerals, but the veins are seldom over 9 inches in width and do not carry pitchblende. Ore-bearing sections are wider on some major vein zones where secondary fractures intersect them. One such intersection on No. 3 Vein, 132 Stope, widened the ore-bearing zone to thirty feet from the usual 3 to 5 feet (Fig. 43).

The relation of minor fracturing to the major pattern of the Port Radium fault lens between No. 1 Vein and the Bear Bay Shear is shown in Fig. 34.

Joints in the porphyry, the massive crystalline tuff and the granite are generally healed by narrow quartz-carbonate veinlets. Similarly, the fractures in the Echo Bay rocks that were caused by the intrusion of the porphyry bodies are also locally healed. Slight red alteration or chloritization usually flanks these secondary fractures where they are vein-filled. No pitchblende has been found in these fractures.

ORE DEPOSITION

The mineralogy of the Port Radium vein zones is complex in that at least five principal stages of mineralization are represented, and the effect of each stage of mineralization has been different for each vein zone and even for different parts of each zone. Over forty metallic and nine nonmetallic minerals have been identified in specimens from the different veins, hence a thorough study of the mineralogy of one stope represents a fair amount of work. A thorough study of the mineralogy of all the vein zones is a major research endeavour in itself and will be carried on by others. In the present study an outline will be given of the mineralogy of each stage of mineralization, with emphasis on the pitchblende mineralogy.

Haycock and Kidd[27] studied 232 polished sections of specimens from twenty localities on No's. 1, 2A and 3 Veins, mostly from the surface and from No. 2A Vein. These specimens were a very limited representation of the Port Radium deposits; nonetheless, they were found to contain forty metallic and six nonmetallic minerals. Most of the study was made on specimens of the carbonate-silver type of ore, peculiar to No. 2A Vein.

The two most abundant components of the Port Radium vein zones are quartz and chlorite, which occur separately and together. The quartz is divisible into at least four varieties, each occurring in a separate phase of mineralization.

Changes in the composition of the mineralizing solutions appear to be generally progressive, but definite time-breaks separate the five main stages of mineralization. Each time-break involved re-fracturing of the vein zones, hence brecciation of wall rocks and early minerals and veining by later minerals are common relationships throughout all vein zones. While solutions were depositing a given suite of minerals in parts of some vein zones the remaining parts were tight, and so no deposition took place. Additional fracturing caused the available openings on a vein to shift with time, resulting in the formation of disconnected lenses of given suites of minerals along each vein zone. The original fracture zones owed their local configuration to the differences in breaking characteristics of the rock formations, but subsequent clogging of the openings, alteration of the wall rocks, and re-fracturing of the zones nullified the effect of wall rock differences on later stages of mineral deposition.

The five stages of mineralization are as follows:

STAGE I - Hematite-quartz:

(A) Red alteration of wall rock.

Hematite deposition and replacement; minor quartz.

(B) White replacement quartz; minor hematite.

Brecciation of red altered wall rock.

White comb quartz (minor)

Translucent quartz (minor)

STAGE II - Pitchblende - quartz:

(A) Medium grey, cream or translucent quartz $\pm$ hematite.

Brecciation of early quartz and red altered wall rock.

(B) Pitchblende)
Rhythmic deposition.
(C) Quartz

(D) Quartz - Late surge brecciates and strews pitchblende.

STAGE III - Quartz - arsenides of Co and Ni:

(A) Quartz, creamy grey. Contains dark fragments of jasper, pitchblende, and dark grey and brown quartz. Second brecciation of pitchblende.

(B) Cobalt-nickel arsenides - followed by quartz.

STAGE IV - Copper - chlorite:

(A) Copper sulphides $\pm$ dolomite, galena, sphalerite.

(B) Chlorite. Third brecciation of pitchblende.

STAGE V - Carbonate - silver:

(A) Dolomite, rhodochrosite.

Copper and silver sulphides and quartz.

(B) Silver, bismuth, carbonate, $\pm$ hematite, quartz, chalcopyrite.

Minerals deposited during stages I, II and IV constitute the bulk of the material in the Port Radium vein zones.

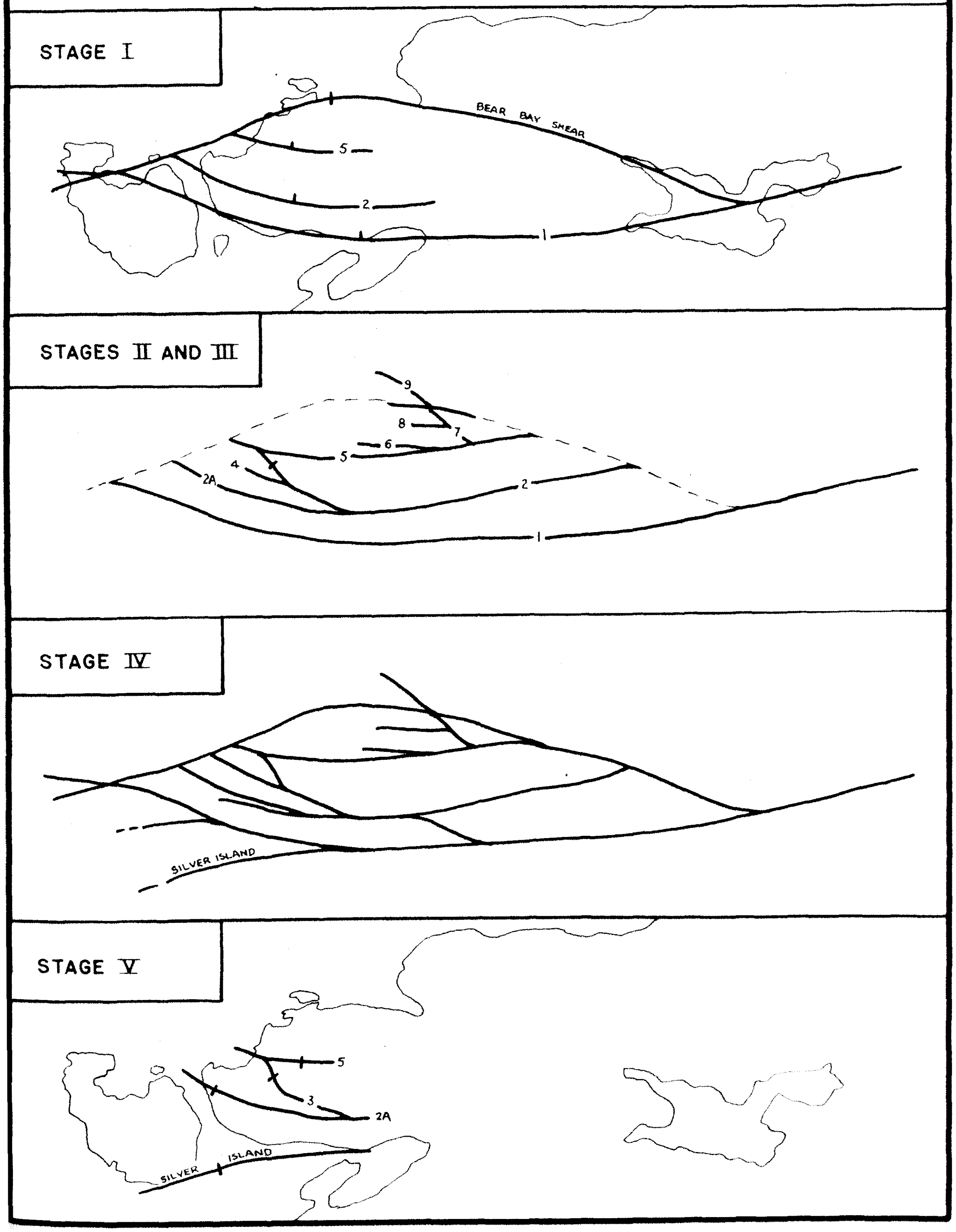
A study of distribution of the minerals of the various stages suggests the following fracture openings during mineralization:

Stage I is represented extensively in No. 1 Vein, in the Bear Bay Shear, and in the western parts of No's. 2 and 5 Veins. Diagramatically the openings available for filling were as shown in Fig. 47.

FIGURE 47

VEIN ZONES OPEN DURING
EACH STAGE OF MINERALIZATION

SCALE 1" = 3000'



Stages II and III are represented in No's. 1 to 9 vein zones in various places, but not in the Bear Bay Shear (Fig. 47).

Stage IV is represented in practically every fracture in the area (Fig. 47).

Stage V is represented principally in the vertical members of the system; Silver Island Vein, No. 2A Vein and locally along No. 3, 5 and 7 Veins (Fig. 47). Small amounts of quartz, hematite, bismuth and chalcopyrite of this stage of mineralization occur in nearly all the principal vein zones.

These changes suggest a progressive opening of the system through stages I to IV, followed by a reduction of available openings during Stage V, either by tectonic forces or by deposition of vein material.

There is some indication that the vein material changes with depth from predominantly quartz to predominantly chlorite.

STAGE I

Hematite-quartz: The oldest principal veins in the area are massive white hematitic quartz, apparently related to the regional giant replacement quartz veins. One giant quartz vein is exposed near the mine area, just west of Corregidor Bay. Extensive sections of the Bear Bay Shear and No. 1 Vein have the same type of replacement hematitic quartz stockworks ranging up to 20 feet in widths. The quartz is characteristically very fine grained, almost chalcedonic, chalky white to greyish white and is rather ornately embellished with hematite rosettes, rings, concentric bands, irregular patches and dendritic laceworks. Solid lenses of rouge and botryoidal specularite are not uncommon. In many places the hematite is so concentrated that it is the major constituent, and the vein material is hematite flecked with quartz stringers. Where other vein material is present, these wide hematite-quartz veins occupy the hanging wall of the vein zone, and their outside edges usually show evidence of replacement of the wallrock. Fragments of wall rock, up to one foot wide and rimmed by comb quartz, are common along the edges of the hematite-quartz veins.

This type of mineralization is present on No's. 2 and 3 Veins but is very local and rarely attains widths exceeding a few feet. White quartz of this age is extensive along No. 5 Vein, but the hematite is generally very minor.

The hematite-quartz veins characteristically have druses and vugs lined with an early white comb quartz and sealed with translucent quartz. These veins are extensively brecciated and sheared in the vein zones and are replaced and cut by later minerals.

This stage of mineralization antedated the diabase dike intrusion.

STAGE II

Pitchblende-quartz: Mineralizing solutions of Stage II were still siliceous but utilized new openings and now carried the constituents for the deposition of pitchblende.

The quartz of this period is characteristically much coarser crystalline than that of Stage I and is translucent brownish grey or cream. It contains very minor amounts of hematite, usually as disseminated dust. Quartz of the youngest phases of this stage is generally dark brown or buff in colour with a distinctive greasy or vitreous lustre and carries the name "ore quartz" at Port Radium.

Red alteration of the wall rock (to be described later) had occurred before the introduction of the ore quartz, for this quartz contains abundant fragments of altered red wall rock as well as earlier vein quartz.

In places several inches of quartz were deposited before the first pitchblende was precipitated, but in other places the pitchblende was deposited directly on the walls of the openings; examples are most abundant along the edges of the diabase dike on No. 3 Vein and along some sections of No. 2 Vein. Even in these occurrences, quartz was deposited interstitially among the fine pitchblende spherulites and in the syneresis cracks of the botryoidal pitchblende.

Cyclic precipitation of pitchblende and quartz was common at the peak of the pitchblende deposition. This pitchblende precipitated in botryoidal forms with lobate surfaces facing the solution cavity. Comb quartz formed on the lobate pitchblende with crystal points facing the cavity. In one occurrence this cycle was repeated at least three times.

Veins of the ore type of quartz are usually about fifteen inches in thickness but widen to as much as three feet and pinch to a few inches. The veins are now in the form of lenses, up to one hundred feet in length, that have been sheared and brecciated, then veined and replaced by later vein material. They generally lie close to the footwall of the vein zones but also step across to the hanging wall in many places. They are usually, but not always, ore bearing. Some pitchblende is usually visible in or near the ore quartz as fragments, clots, bands or lenses. Along No's. 2 and 5 Veins the ore-quartz type of vein occupies the entire vein zone in many places but is absent in others. Considerable lengths of ore quartz along these vein zones are not ore-bearing, although they generally grade into ore. Ore-type quartz occurs along No. 3 and 7 Veins in very discontinuous lenses that invariably merge with breccia zones up to 20 feet in width. Where the ore-quartz becomes vuggy, coarsely crystalline and clear the pitchblende content becomes negligible.

Occurrence of undisturbed cyclic banded pitchblende and quartz are fairly difficult to find in the Port Radium deposits. Generally later quartz has brecciated the early quartz and pitchblende. Also chlorite and carbonate extensively replace the quartz and dissipate the pitchblende. Even the later phases of the ore quartz have broken the pitchblende into large fragments and crystallized around them. Nonetheless, simultaneous deposition of pitchblende and quartz is suggested by occasional examples of undisturbed cyclic precipitation, by unbroken ringlets and spheres of pitchblende around euhedral quartz crystals or clusters of crystals, and also by the constant association of quartz with pitchblende even though the later ore-quartz commonly has brecciated the pitchblende.

In some literature, particularly from the U.S.A. previous to 1950, the terms uraninite and pitchblende have been used interchangeably to describe any black uranium oxide minerals. This has resulted in some confusion. The use of the two terms as synonyms should be avoided. Both terms represent very definite minerals which differ in occurrence, form, and composition.

Uraninite occurs as a component of igneous rocks, particularly granites and pegmatites, and, rarely, in some high temperature veins. One uraninite-bearing vein near Hazelton, B.C.[63], contains as gangue minerals hornblende, quartz, feldspar, apatite and scheelite which suggests unusual conditions for hydrothermal deposition. Pitchblende is restricted to hydrothermal deposits. Uraninite is crystalline, whereas pitchblende is amorphous and exhibits forms of gel precipitates. Uraninite contains from 2 to 14 percent ThO_2 and rare earths[5], and the U_3O_8 content ranges from 65 to 85 percent. Pitchblende contains less than one percent rare earths and practically no thorium but may contain small amounts of Fe, Mn, Al, Ca, Mg, Si, etc. The U_3O_8 content of pitchblende ranges from 50 to 80 percent. Uraninite was probably originally pure UO_2; the sexivalent uranium forms from subsequent oxidation. Pitchblende probably had a composition close to U_3O_8 even when first formed because of immediate oxidation from UO_2 while in hydrothermal colloidal suspension[41].

Several analyses of Port Radium ore are available, and are tabulated in Table 4 (p. 192b). Numbers in brackets indicate the source of the analysis. Analyses without numbers were those made in the course of this investigation.

Specimens 10 and 11 were picked samples of jet black pitchblende with high lustre and negligible megascopic impurities. The other specimens represent types of pitchblende ore but have no

Table 4

Analyses of Port Radium Pitchblende

	Location	Level	% U_3O_8	% Pb	% SiO_2	Other Impurities over 1 %	Description	Reference
1	No. 2 Vein	Surface	39.6-56.8	7.23-10.62	19.9-40.7	S, CO_2, Ag(3-10oz/T), Fe	Siliceous ore	(40)
2	"	"	32.4-45.94	6.88-10.62	1.76-3.26	S, CaO, SO_3, $BaSO_4$, CO_2, Ag(300-360oz/T)	Carbonate ore	(40)
3	Various specimens	"	28-84	5.5-11.25	< 45			(4)
4	132 Stope	125	14	3	>10	Cu, Fe, Ca	Copper breccia ore	
5	4 Vein	250	19	>10	>10	Fe, Zn, Mg		
6	834 Stope	800	2	-	5	P, As, Bi, Fe, Cu, Zn, Ni, Co	Sulphide ore	
7	914 "	925	18	1	>10	Fe, Cu	Ore quartz	
8	1015 Sub drift	1050	56	11.83	-	-		
	"	"	52.4				2 ft. channel sample	
9	1028 Stope	"	42.75	>10	>10	Fe, Mn		
10	1131 "	1175	68.6	12.3	-		In granite	
11	1328 Dr.	1300	66.25	>10		Cu, Ca		

significance in relation to the stopes or levels. The relation of the different impurities to grade is however, significant. Some of the lead reported in the analyses is from galena but most is daughter lead from disintegration of the pitchblende.

The pitchblende in the Port Radium deposits ranges from gross mammillary clusters to compact fine grained massive lenses. All the ore is botryoidal, although the spherules may be microscopic and the ore look megascopically massive. Forms include: colloform structures with knobs over an inch in diameter; botryoidal narrow bands; rounded compact masses; sinuous veinlets with or without botryoidal faces; microscopic cellular ringlike structures; dendritic growths; spherulitic clusters with individuals as small as 50 microns; and fragments of all the foregoing forms in any shape or size. The only obvious difference between the pitchblende occurring at the surface and that at the 1500 Level is a difference in size of mammillary lobes. Specimens of pitchblende with lobes exceeding $\frac{1}{2}$" in diameter are found more commonly above the 500 Level than below although even above the 500 Level they are not widespread. There is no apparent difference in the character or occurrence of the pitchblende from one vein zone to another.

Syneresis cracks are present in all the pitchblende and attest to the colloidal nature of the precipitation. Considerable water must be present in suspensoid flocculates to permit their surfaces to be rounded by surface tension. The escape of this included water results in shrinking and development of syneresis cracks. Most of these cracks in the Port Radium pitchblende are filled with quartz

Figure 48. Pitchblende and quartz in situ. No. 1 Vein, 1015 sub-drift. Photomicrograph. x25

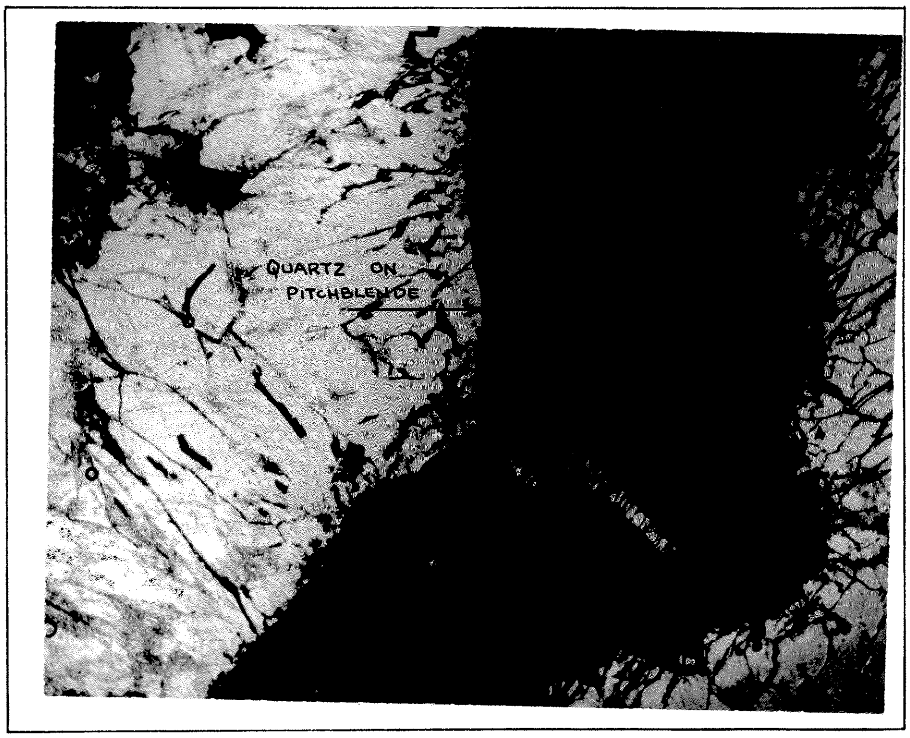


Figure 49. Rhythmic layered quartz and pitchblende. No. 2 Vein, 123 stope. Photomicrograph. x 25

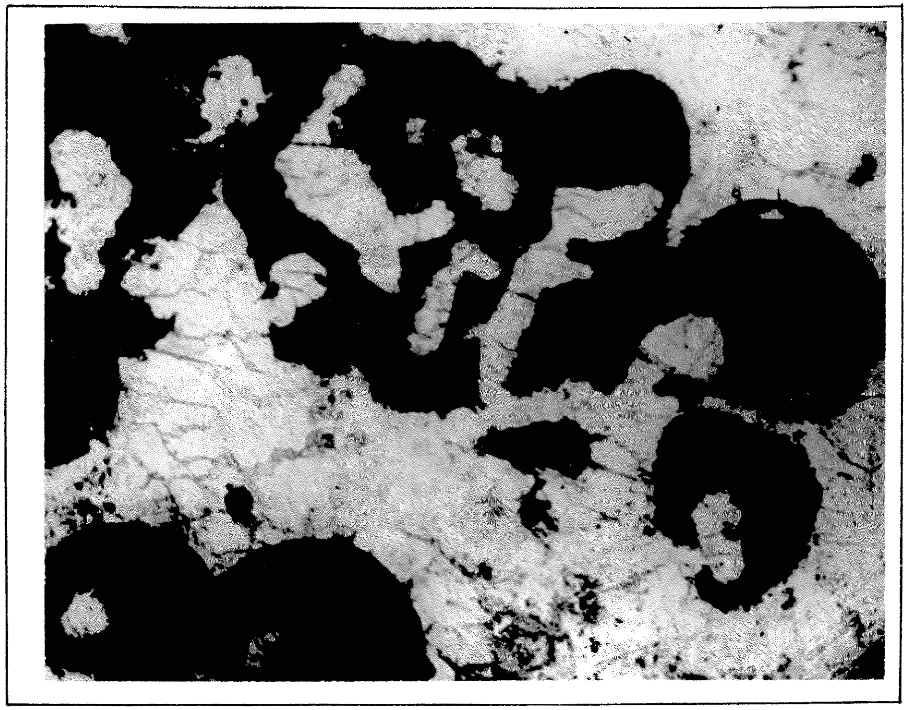


Figure 50. Replacement of loose pitchblende spherules in late ore-quartz.
No. 1 Vein, 913 stope. Photomicrograph. x50

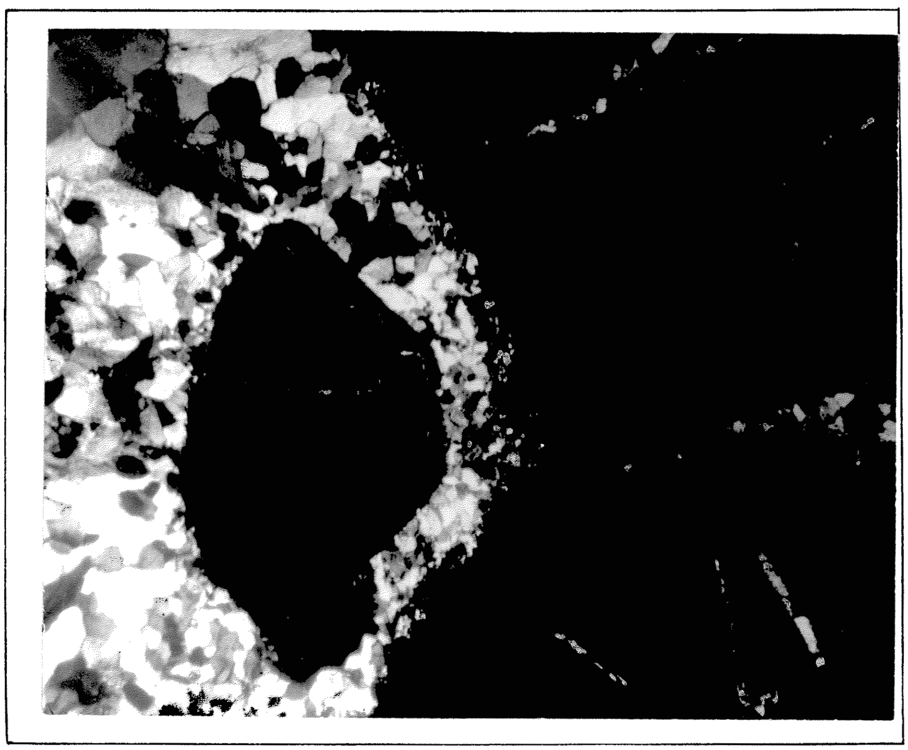


Figure 51. Late ore-quartz breaking pitchblende and occupying cracks.
No. 1 Vein, 613 subdrift. Photomicrograph .x25
Crossed nicols.

that was cyclic in deposition with the pitchblende. This same quartz occasionally contains microspherulites of pitchblende that probably developed through nucleation and coagulation during late stages of mineralization when the pitchblende concentration in the solutions was low and both the quartz and the pitchblende were in a gelatinous state. Occasionally the microspherulites form clusters that merge into larger botryoidal structures.

In the vein zones the pitchblende masses occur in the following forms:

(1) Seams up to an inch in thickness whose outer surfaces show convex colloform habit but whose inner surfaces conform with the surface on which deposition took place.

(2) Massive pitchblende veins and lenses up to two feet in width. These are invariably heavily fractured by two sets of fractures, one parallel to the vein walls, the other perpendicular to the vein walls and flat. This fracturing is almost characteristic of Port Radium pitchblende, especially the larger bodies. In many places it looks like cleavage.

(3) Strung out pods and lenses in quartz or chlorite shears.

(4) Discrete massive patches in barren vein material.

(5) Zones of fragments in quartz, chlorite or sulphides.

(6) Isolated fragments in vein material.

(7) Rims around earlier quartz or wallrock fragments.

In the closing phases of the Stage II mineralization the solutions became depleted in uranium, and pitchblende precipitated only as scattered microscopic spherulites strewn through the quartz. Movement of the silica solutions after the deposition of the pitchblende is indicated by local brecciation of the solid pitchblende (syneresis cracks had formed), and a strewing through the quartz of fragments of pitchblende (Figs. 52 and 53). This represents the first of at least three brecciations and redistributions of the pitchblende by post-pitchblende solutions. The actual brecciation of the pitchblende was probably brought about by the development of syneresis cracks in the mineral and by tectonic stresses on the zones. Later solutions apparently had little difficulty in transporting the fragments. This phenomenon was so widespread that brecciated pitchblende is the commonest type of ore at Port Radium. The late quartz of Stage II has generally broken the pitchblende into relatively gross units with very little comminution or solution and in some places has even aligned the fragments into a flow orientation (Fig. 53). This feature of transport, with minor decomposition, of the pitchblende by quartz is in contrast to the disturbance by the chlorite-clay and carbonate. The chlorite-clay solutions transported the pitchblende but at the same time tended to comminute and dissolve the fragments. The carbonate solutions generally caused replacement of the pitchblende with very little transportation.

Irrespective of the types of occurrence, the pitchblende is always in definite zones or ore shoots.

Ore shoots:

Ore-bearing portions of the vein zones in the Port Radium deposits comprise a minor percentage of the total vein areas. No.

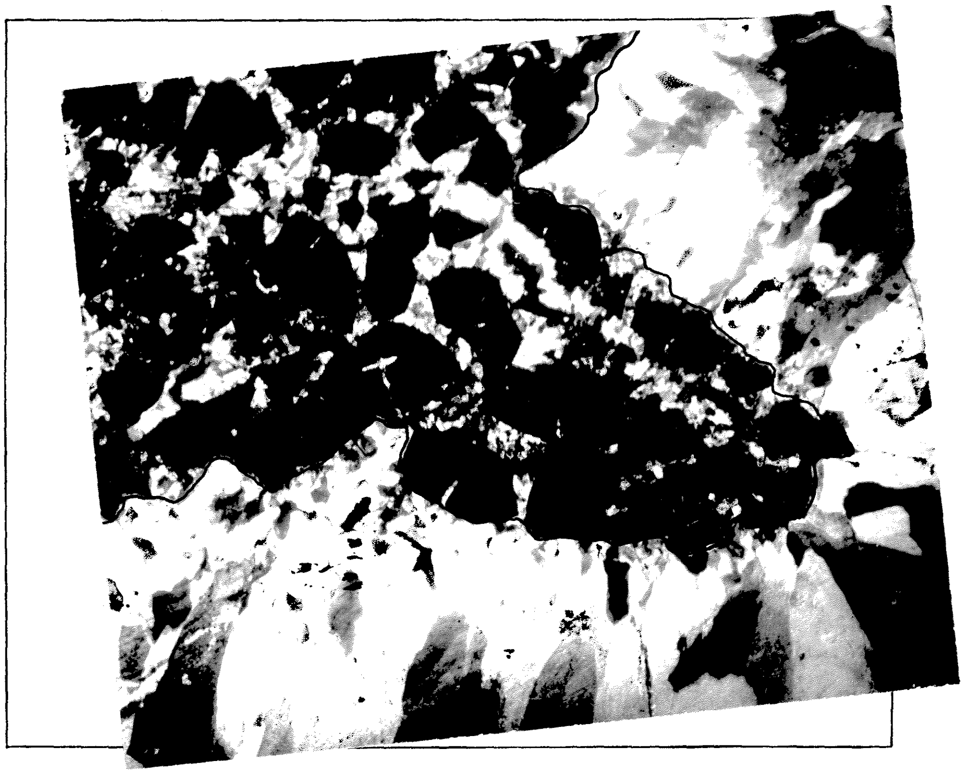


Figure 52. Pitchblende fragments in ore-quartz but not in later quartz. Crossed nicols.
No. 1 Vein, 913 stope. Photomicrograph. x25

Figure 53. Flow orientation of pitchblende fragments in ore-quartz.
No. 1 Vein, 913 stope. Photomicrograph. x25

3 Vein with approximately 30 percent of the vein area ore-bearing shows the highest ratio of productive to non-productive longitudinal area east of the granite. In general the ore shoots on all the vein zones are sharply defined and range from short lenses to elongate shoots extending from the bottom levels of the mine to the surface. Horizontal lengths of continuous ore range from less than 100 feet up to an extreme of 600 feet.

The fracture zones are generally occupied by vein quartz wherever pitchblende occurs. Exceptions generally consist of pitchblende veins in sheared chlorite or diabase, with variable amounts of minor quartz or carbonate. Throughout all the ore-bodies, pitchblende is usually megascopically visible, if only in very small amounts. Marginal ore is rare; values in U_3O_8 invariably drop to trace quantities outside the areas of visible pitchblende, even though the remainder of the vein material may continue unchanged.

The pitchblende occurs in vein zones grading from single narrow veins to composite zones of as many as six or more different veins. In the complex areas the pitchblende is invariably associated with the ore-quartz described earlier. The ore-quartz is cut, terminated and brecciated by later quartz, carbonate and chlorite and, although it does not always carry pitchblende, its presence in drift faces or drill core usually indicates favourable ground for further exploration. The pitchblende-bearing parts of the vein zones generally lie close to the footwall sides of the zones, although in many places they step across the zones in en echelon lenses. In zones of en echelon lenses the grade of the entire zone is generally high enough to mine. Where the ore-bearing portions hug the footwall they are often mined selectively, leaving the rest of the vein zone intact.

Many secondary fractures, such as horsetails and complementary shears directly related to the major vein zones, may contain pitchblende for distances up to several feet from the main zone.

Common types of ore sections are shown in Figs. 38, 40, and 42 to 46 inclusive.

Hydrothermal Oxidation:

Haycock and Kidd(7) reported finding two types of pitchblende in the Port Radium deposits:

(1) Pitchblende I; a hard, dense type in the siliceous ores. 77% UO_2 + 17% UO_3

(2) Pitchblende II; a relatively soft type with a greenish powder. 9% UO_2 + 90% UO_3

This sooty type (pitchblende II) has since been shown to be the result of oxidation by hydrothermal solutions or, under certain conditions, mine water. Pitchblende is readily soluble in HCl and H_2SO_4, so that hydrothermal alteration produces variations both in physical appearance and chemical composition. Kerr(45) showed that such hydrothermal alteration is the cause of the differences in lattice constants of pitchblende from different localities. Sooty uraninite from Shinkolobwe has a cell edge, (a), measuring 5.411 Å, whereas well crystallized material has an edge of 5.453 Å. Cell edges of Port Radium pitchblende range from 5.39 Å (64) to 5.475 Å(65), indicating considerable alteration by late solutions. Kerr also showed that the variations in cell edges were not related to either the admixture of radiogenic lead or to the disintegration of uranium (metamictization). This was shown by a total lack of correspondence between various edge measurements and the PbO contents or the ages. Although pitchblende is amorphous, enough order is present to obtain measurable X-ray diffraction patterns for determination of cell dimensions. Best reflections are obtained from steel-grey, hard material. With increased oxidation of the pitchblende, reflections become weak, and finally no pattern is obtained[64].

It is of interest in this regard that pitchblende from the Colorado Plateau[66] ranges in unit cell edge from 5.38 Å to 5.44 Å, indicating probably alteration by late solutions.

<u>STAGE III</u>

<u>Quartz</u>: The quartz veins representing the major phase of the third stage of mineralization form the bulk of the vein material in the zones at Port Radium. New openings were occupied, and the new quartz veins cut across, brecciate and replace the earlier vein materials. The veins belonging to this quartz phase range up to five feet in width and contain an abundance of fine fragments of earlier vein quartz, altered and unaltered wall rock, and locally pitchblende. The quartz is creamy grey with local reddish colouring by hematite. The veins are characteristically greenish white to green in colour and often grade into vein chlorite. Some chlorite is contemporaneous with the quartz, but most of it is later and has impregnated and replaced the quartz along microfractures and imparted a green colour to much of the quartz. This quartz and the closely related chlorite

are found in all vein zones everywhere, very frequently where all other vein material is absent.

Where the Stage III quartz veins occupy parts of the vein zones in which pitchblende occurs they often contain enough pitchblende fragments to constitute ore. This stage represents the second time that pitchblende was brecciated and picked up by later solutions. The brecciation and strewing of pitchblende by the chloritic quartz is locally extensive, but transport has not been more than a few tens of feet from the source. This limit to the distance of pitchblende fragments from pitchblende in place may be a function of the solubility of the pitchblende.

The quartz of Stage III is much more coarsely crystalline than any preceding quartz and is generally clearer.

Cobalt-Nickel Arsenides: Following the deposition of the chloritic quartz came precipitation of cobalt-nickel arsenides along the same general openings as well as along new fractures in the vein zones. The deposition of the arsenides was accompanied by deposition of limited amounts of quartz and locally hematite. This hematitic quartz separates two major periods of arsenide precipitation. The first group of arsenides are rich in Fe and Ni; the second are rich in Co and S.

The identification of the cobalt-nickel arsenides is difficult, and the paragenesis is often subject to some conjecture. Further work is necessary to adequately cover the mineralogy of this suite of minerals, but the data derived to date will serve as an outline of the sequence. The following minerals have been identified:

Oldest	Niccolite	NiAs	Group A
	Loellingite	$FeAs_2$	
	Safflorite-loellingite	$(CoFe)As_2$ (&7)	
	Safflorite-rammelsbergite	$(CoNi)As_2$	
	Gersdorffite	NiAsS	
	Polydymite	Ni_3S_4 (&7)	
Quartz	________________		
	Smaltite-chloanthite	$(CoNi)As_2$ (&7)	Group B
	Skutterudite	$CoAs_3$ (&7)	
	Glaucodot	(CoFe)AsS	
	Cobaltite	CoAsS	
	Corynite	Ni(AsSb)S	
	Loellingite	$FeAs_2$	
Youngest	Niccolite	NiAs	

(&7) - Identified by Haycock and Kidd only.

The principal minerals are underlined; the others occur rarely or in very minor amounts. Group A are the Fe-Ni rich arsenides; Group B are the Co-S rich arsenides. Minerals of Group A comprise the great bulk of the arsenides in the Port Radium deposits.

The most abundant arsenides occur in the following forms:

Niccolite - Coppery pink veinlets and large masses of irregular grains, usually rimmed by safflorite-loellingite minerals.

Safflorite-loellingite - White metallic masses, patches and veins.

Gersforffite - Dull grey replacement dendrites, ringlets and lacy patches.

The cobalt-nickel arsenides are fairly widespread in the Port Radium vein zones, although heavy concentrations are very local. Their distribution is roughly the same as the pitchblende but more extensive. In some places the arsenides occur in the absence of pitchblende, but few ore sections lack some arsenides. The arsenides are somewhat more abundant than the pitchblende, although observation underground would suggest them to be less abundant, because the arsenides are often finely disseminated and inconspicuous in the complex vein zones. Chemical analysis of monthly composites of mill heads for 1950 give a good indication of the proportion of pitchblende to arsenides. With U_3O_8 arbitrarily taken as 100 the ratios are: U_3O_8: 100; As : 48.5; Co : 60; Ni : 29. These analyses are excellent representatives of all the pitchblende-bearing zones in the Port Radium area.

The arsenides clearly cut the pitchblende and generally replace it but show no evidence of having transported it. They have extensively replaced the quartz in and around the concentrations of pitchblende before they have begun replacement of the pitchblende (Figs. 54 and 55). The gersdorffite and safflorite-loellingite are extensively disseminated throughout the preceding quartz veins as patches as well as narrow rims around quartz crystals, or series of crystals and mineral or rock fragments, in cellular and pseudo-dendritic forms. They also occur in the quartz in true dendritic forms. Fragments of the arsenides are strewn extensively through later chlorite-clay vein material.

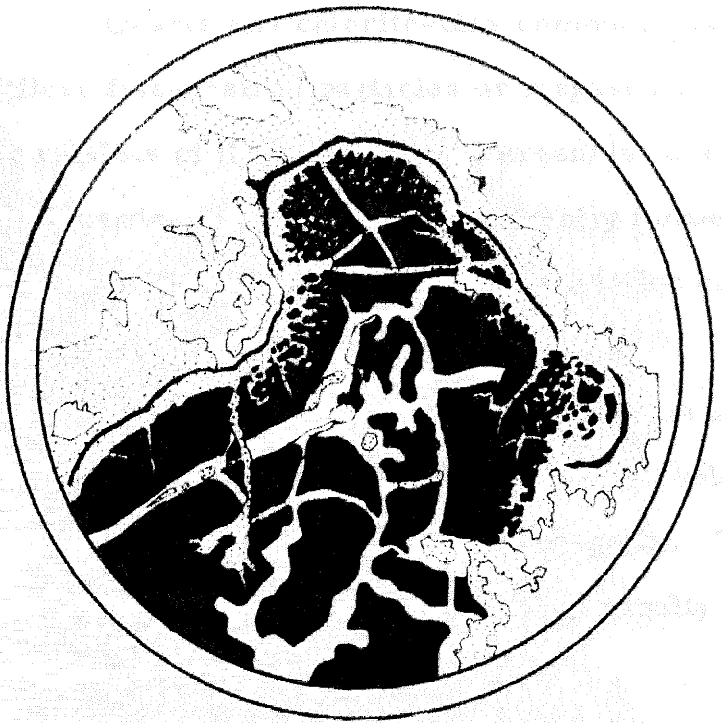


Figure 54

Extensive replacement of quartz and limited replacement of pitchblende by cobalt-nickel arsenides (mostly gersdorffite and safflorite-loellingite).

Camera lucida, x20

Pitchblende | Cobalt-nickel arsenides | Quartz

Figure 55

Cobalt-nickel arsenides replacing quartz around pitchblende fragments. Also as fine fragments in late chlorite-clay veinlet.

Camera lucida, x20

Pitchblende | Chlorite-clay

Quartz and chlorite-clay commonly carry pitchblende as diffuse fine-grained particles or megascopic fragments, but masses or veinlets of the cobalt-nickel arsenides are invariably barren of pitchblende. The arsenides apparently formed as static replacement and deposition products with no brecciation and transport of earlier minerals.

The cobalt-nickel arsenide minerals are locally brecciated and replaced by coarse crystalline cream coloured quartz that represents the last mineralization of Stage III. This quartz occurs as discontinuous relatively small veins, usually in the vicinity of the arsenide minerals.

STAGE IV

Copper sulphides: The most abundant and ubiquitous metallic mineral in the Port Radium deposits is chalcopyrite. It was deposited during two widely separated periods of mineralization, one at the beginning of Stage IV, and the other at the end of Stage V. The earlier chalcopyrite forms large masses and veins in the vein zones, particularly in the ore sections, and is distinctive in its rather dull yellowish grey colour. The dull colour is due to fine pyrite and quartz inclusions. The later chalcopyrite accompanied the carbonate stage of mineralization and fills cracks and vugs and crystal interstices in all vein material in the area. It is generally crystalline in form and bright yellow in colour.

Tetrahedrite is much less abundant than the chalcopyrite but it is widespread in the ore sections and is clearly the last mineral of the main copper mineralization. It extensively replaces the

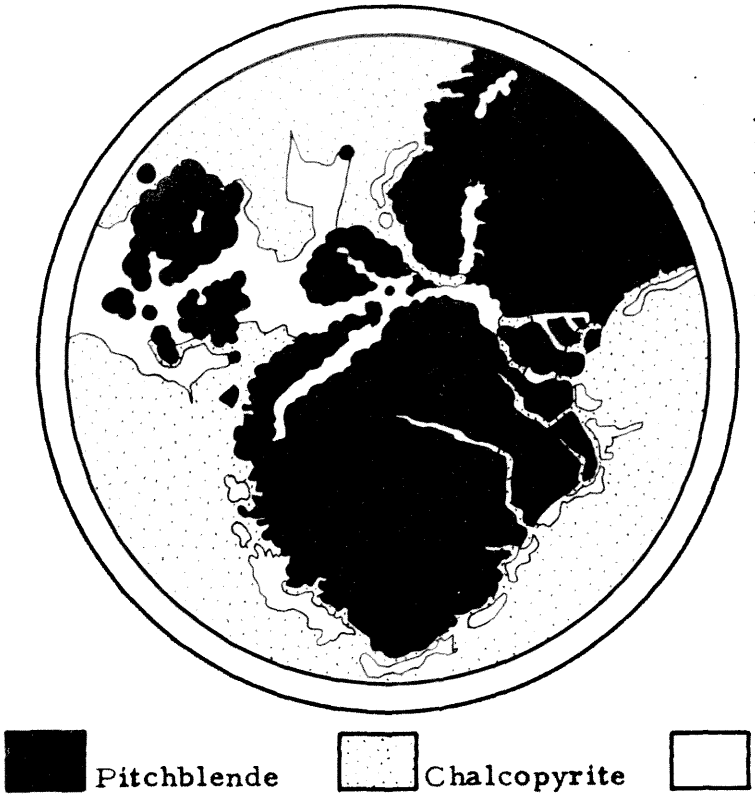


Figure 56

Typical association of bornite with pitchblende fragments in chalcopyrite.

Camera lucide. x20

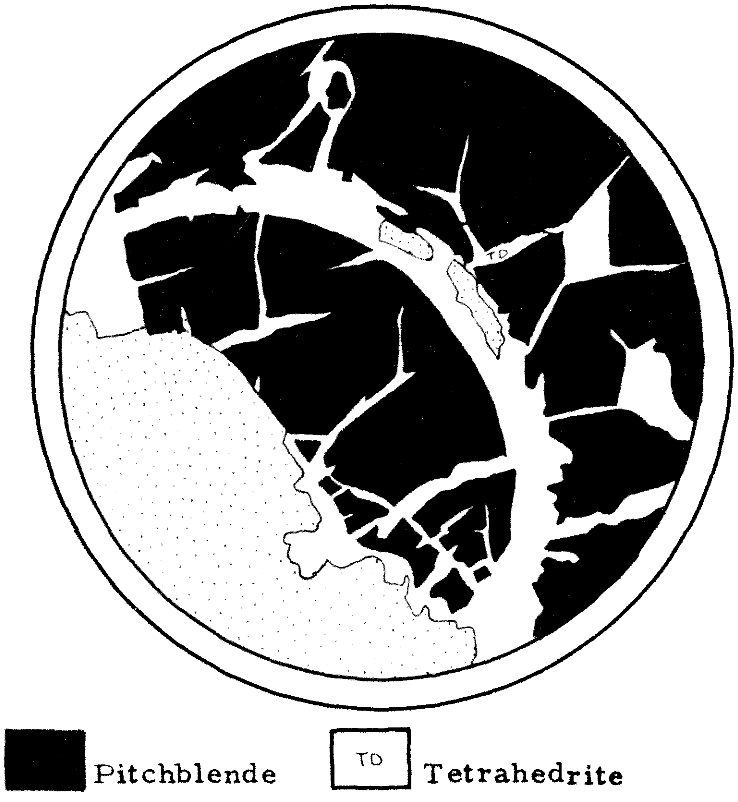


Figure 57

As Figure 56.

Co-Ni arsenide minerals as disseminated "islands" in the arsenides.

Bornite occurs in very heavy concentrations in widely scattered places along various vein zones. It is not common at Port Radium. It appears to have had an affinity for pitchblende, for wherever it occurs it partially or wholly envelopes fragments of pitchblende that may be residual in chalcopyrite (Figs. 56 and 57).

Other copper minerals occur in comparatively minor amounts and are usually associated with tetrahedrite or chalcopyrite. The copper minerals occurring in the Port Radium ores are:

Oldest	<u>Chalcopyrite</u>	$CuFeS_2 \pm$ Pyrite FeS_2
	Cubanite	$Cu_2S \cdot Fe_4S_5$
	<u>Chalcocite</u>	Cu_2S
	Chalcostibite	$Cu_2S \cdot Sb_2S_3$
	Tennantite	$5Cu_2S \cdot (CuFe)S \cdot 2As_2S_3$
	Chalcocite	Cu_2S
	Aikinite	$Cu_2S \cdot 2PbS \cdot Bi_2S_3$
	<u>Bornite</u>	Cu_5FeS_4
	<u>Tetrahedrite</u>	$5Cu_2S \cdot (CuFe)S \cdot 2Sb_2S_3$
Youngest	Covellite	CuS

Malachite and some azurite occur on surface exposures.

The principal minerals are underlined, the others are uncommon or rare.

The only gangue minerals deposited with the copper sulphides were dolomite and quartz. Both occur in very small amounts in scattered localities.

The invasion of copper solutions was a vigourous emplacement and replacement that extensively obliterated and cut all previous vein minerals including the arsenides. Chalcopyrite commonly rims pitchblende fragments in breccias. Large fragments of pitchblende were moved along vein openings, particularly by the solutions depositing chalcopyrite and tetrahedrite. This represents the third brecciation and transport of the pitchblende. It was not as extensive as the two previous disturbances by quartz.

The extensive chalcopyrite replacements are commonest in the ore areas of No's. 1, 2, 3, 7 and 8 Veins and are less common in the non-pitchblende-bearing sections and along the other veins.

With U_3O_8 represented by 100 the mill head analyses for 1950 give the following ratios for the elements of the copper suite: U_3O_8:100; Cu:95; Fe:650; S:217. The copper minerals are in considerable abundance over the pitchblende. Also associated with the copper stage of mineralization, and probably slightly preceding it, are the following minerals:

Sphalerite (Marmatite)	ZnS (Fe)
Galena	PbS
Stibnite	Sb_2S_3
Molybdenite	MoS_2

These minerals are generally uncommon at Port Radium relative to the other metallic minerals.

Chlorite-clay: Following or possibly simultaneous with the copper deposition there was extensive emplacement of a late gangue mineral assemblage of chlorite, montmorillonite and various amounts of sericite and/or iddingsite. This gangue replaced preceding gangues and cut all preceding minerals. It usually occurs as a network of veinlets in the vein zones and contains very small fragments of nearly all the minerals that it encountered. It apparently tended to pulverize the pitchblende and carry it along as almost submicroscopic disseminations that register on autoradiographs as "wisps" or clouds. On a small scale it carried pitchblende into areas that were previously barren (Fig. 59). This represents the fourth brecciation and transport of the pitchblende.

The chlorite-clay mineralization extensively replaced and locally redistributed minerals, particularly quartz. The chlorite is generally somewhat more abundant than the clay but the two are commonly intimately mixed in very fine-grained aggregates ranging in composition from all chlorite to all clay. The chlorite is younger than the clay but the spatial correspondence of the two suggests a very close time relation. Chlorite-clay veins, ranging in widths from less than a tenth of an inch to over two feet, invariably carry fragments of all earlier vein minerals and occasional fragments of wallrock. Quartz veins everywhere are more or less chloritized and in many places completely replaced by the chlorite-clay minerals. In addition, wallrock fragments in quartz veins are commonly partially or wholly replaced by chlorite which also occupies interstitial spaces between the quartz crystals surrounding the fragments. In banded veins the chlorite generally selectively replaces bands of particular minerals, e.g., in banded quartz and pitchblende the chlorite preferentially replaces the pitchblende (Fig. 58). Replacement of all minerals by the chlorite and clay tends to be pseudomorphic, whereas replacement by later carbonate is generally in the form of mats or rhombs that are irrespective

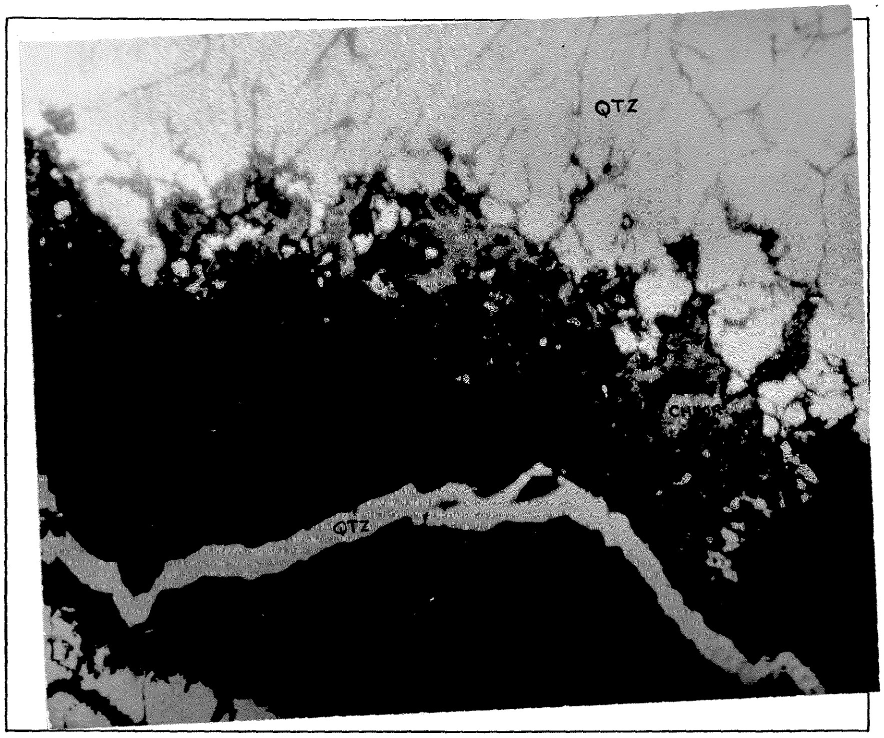


Figure 58. Pitchblende bands in quartz selectively replaced by chlorite. No. 0 Vein, 1175 Level. Photomicrograph. x25.

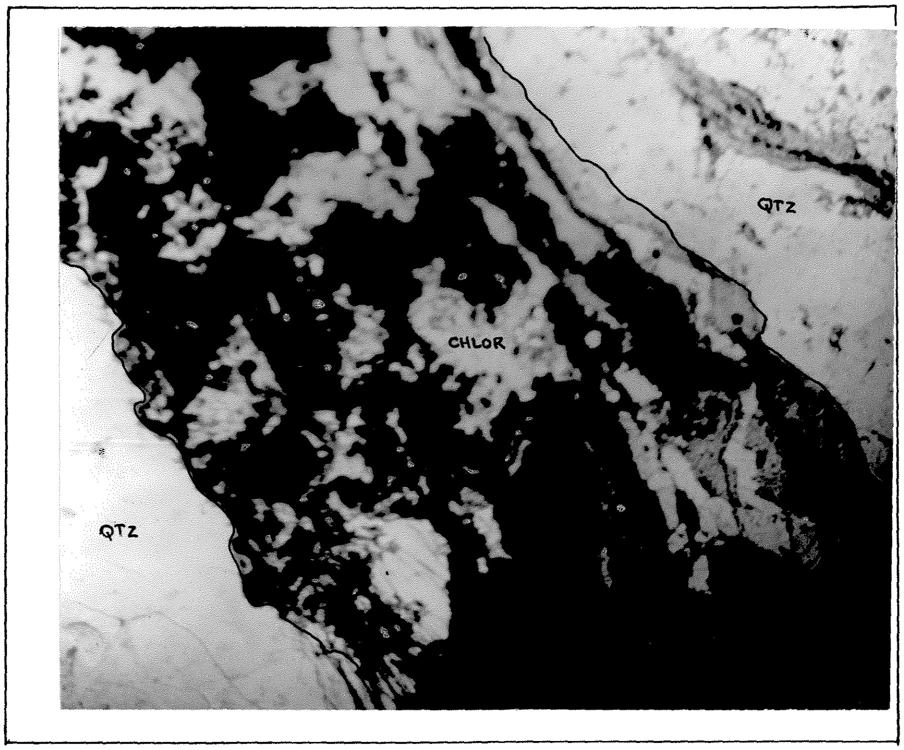


Figure 59. Pitchblende fragments in chlorite veinlet cutting earlier quartz.
No. 1 Vein, 914 stope. Photomicrograph. x25.

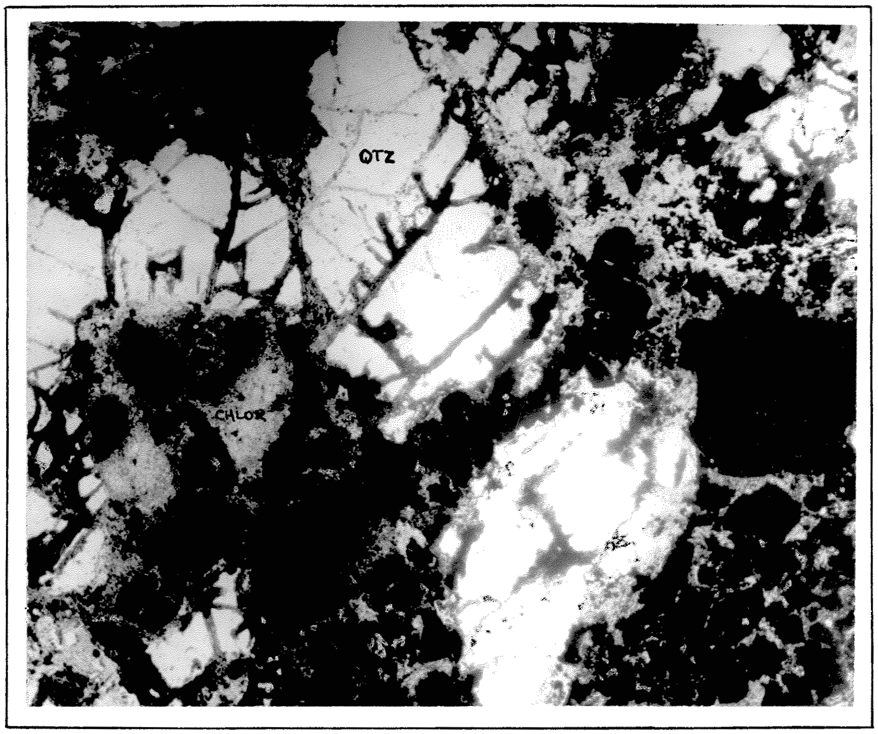


Figure 60. Brecciated pitchblende and quartz in chlorite.
No. 3 Vein, 136 stope. Photomicrograph. x50.

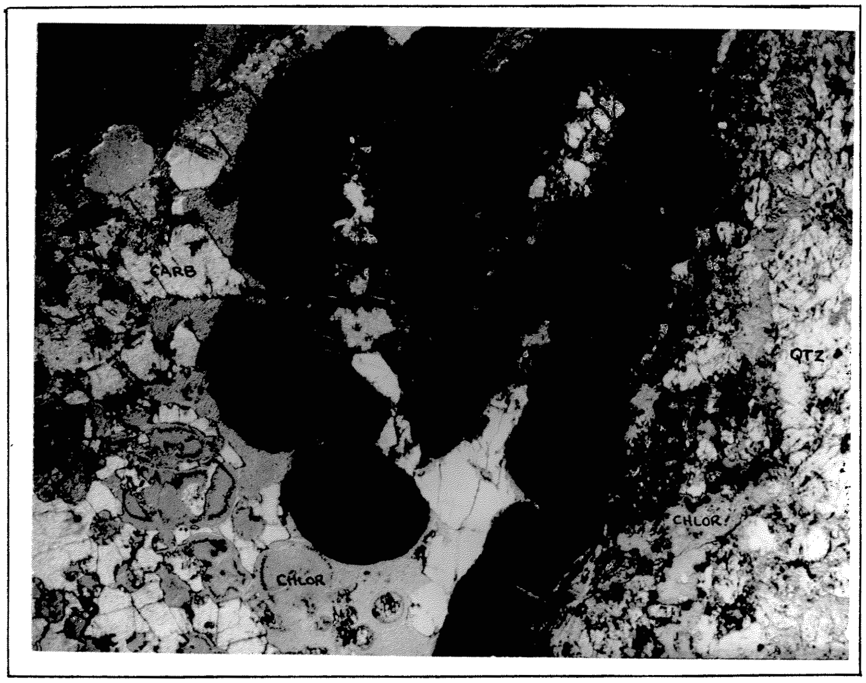


Figure 61. Pitchblende (on f.g. quartz) replaced pseudomorphically by chlorite.
No. 3 Vein, 136 stope. Photomicrograph. x25.

of grain boundaries of the host. The two commonest types of chlorite-clay veins are: sinuous branching narrow greenish-grey veins, seldom exceeding a few inches in width, composed principally of chlorite and/or clay with minor tiny fragments of earlier minerals; massive brownish grey veins, up to two feet in width, composed principally of quartz relicts in a matrix of chlorite and/or clay that is often megascopically inconspicuous. The latter variety is commonly ore by virtue of its content of fragments, often microscopic, of pitchblende. Fragments in the chlorite-clay are principally quartz but also include pitchblende, Co-Ni arsenides, pyrite, apatite and wallrock. In wide veins of chlorite-clay the fragment content often decreases to nil toward the centre of the vein.

Disseminations of chalcopyrite and bornite are widespread throughout the chlorite-clay material but it is difficult to tell if they are relicts or primary bodies. Some veins of tetrahedrite cut chlorite-clay assemblages. It is suggested that the chlorite-clay mineralization was simultaneous with the copper mineralization, later than the chalcopyrite and bornite but earlier than the tetrahedrite. It is possible however that the chlorite-clay preceded all the copper minerals.

On encountering pitchblende the clay generally transported fragments without destroying them. The chlorite, in contrast, accompanied the transport of the pitchblende with vigorous comminution and dissolving of the fragments. The finely pulverized pitchblende in the chlorite is not visible megascopically but registers on autoradiographs as clouds or wisps. The presence of pitchblende in the chlorite-clay matrices constitutes ore divisible into two general categories, diffuse ore and fragment ore. The diffuse ore contains considerable microscopic pitchblende as wisps in a chlorite-clay matrix with occasional megascopic fragments of quartz, pitchblende or arsenides. The fragment ore, or chlorite ore, is comprised of masses of chlorite-clay with abundant large and fine fragments of jasper, quartz, pitchblende, arsenides and wallrock strewn haphazardly throughout. This type of ore invariably grades into the diffuse type and also into vein material in situ with minor chloritization.

Autoradiographs of all these types of ore are shown in Figs. 73-96.

STAGE V

Carbonate - Silver sulphides: The change from predominantly quartz to predominantly carbonate gangue is clearly discernible both megascopically and microscopically. Pink and white coarsely crystalline carbonate minerals form lenses, veins, laceworks of veinlets, and vug fillings along all the vein zones, but the wide extensive carbonate veins occur only in the Silver Island Vein, No. 2A, and No. 3 Veins.

The commonest carbonates are dolomite, rhodochrosite and calcite. The dolomite and rhodochrosite are common as linings of vugs and open seams in nearly all the veins. They are invariably associated with native bismuth, specularite, clear crystal quartz, hematite, and crystalline chalcopyrite, all lining single vugs in spectacular mineral assemblages.

In most places the dolomite is earlier than the rhodochrosite, and relations suggest that the dolomite began depositing in small amounts during the copper sulphide phase of Stage IV. The rhodochrosite is entirely confined to Stage V. Chemical analyses reported by Kidd[2] and several done by chemists at the mine have established the identity of the two carbonates. The rhodochrosite is generally ferruginous (Fe = $\pm$ 9°/o).

The calcite usually occurs as very late, white crisscrossing networks of veinlets and lenses that represent the final mineralization in the Port Radium deposits.

There is some indication that minor amounts of primary pitchblende were deposited either in the closing phases of Stage IV or early in Stage V. Relation of this pitchblende and carbonate are not clear, and the pitchblende could belong to a late phase of Stage II. With the introduction of sulphide solutions, especially if they contained unoxidized S and were actively depositing sulphides, the solid pitchblende could easily be reduced and returned to solution. Re-precipitation of this pitchblende would result in a late hypogene stage of pitchblende.

The principal minerals of the carbonate phase of Stage V are:

Oldest	Dolomite	(MgCa) CO_3
	Rhodochrosite	(MnFe)CO_3
	Quartz(xl)	SiO_2
	Hematite	Fe_2O_3
	Chalcopyrite	$CuFeS_2$
Youngest	Native bismuth	Bi

All these minerals are widespread and common in all vein zones. Haycock [7] reports argentite in this sequence, but this mineral is not common except in the silver veins, and its paragenetic relations are not clear.

Fine crystalline dolomite is the principal component of the wide carbonate veins at Port Radium. It not only filled open fissures but also very extensively replaced earlier vein minerals, particularly in No. 0, 2A, and Silver Island Veins. Fragments of earlier minerals strewn in the carbonate are rare because the carbonate tended to replace all minerals with negligible transportation. Chlorite was less favourable to replacement by carbonate than any other minerals and often occurs as relicts in the carbonate veins. Whereas the chlorite preferentially replaced the pitchblende bands before the quartz bands, the carbonate generally replaced the quartz then the pitchblende. In many places the pitchblende remains as relatively undisturbed antecedent bands and clusters in carbonate that has entirely replaced the surrounding quartz. Wherever the carbonate is in contact with pitchblende a characteristic brown halo about 1/10 mm in width colours the carbonate. It is probably a result of radiation of the pitchblende. A characteristic feature of the replacement of pitchblende by carbonate is the formation of strings of rhombs in dendritic patterns through the centres of the pitchblende masses. When taken to extremes this lends the pitchblende a dendritic appearance (Figs. 66 and 67). The same feature is common in the replacement of pitchblende by silver.

Botryoidal hematite commonly accompanies the carbonate and gives it a characteristic brown or rose tint.

Native bismuth commonly lines vugs in all vein zones and extensively replaces the Co-Ni arsenides and tetrahedrite in the silver-carbonate veins.

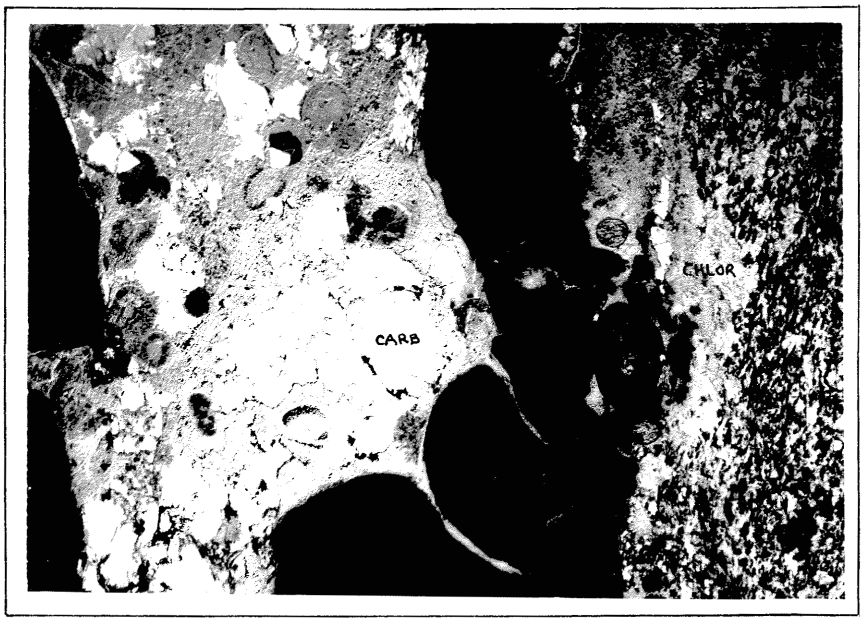


Figure 62. Pitchblende relicts in carbonate-chlorite. Carbonate veinlet dissolving pitchblende walls.
No. 1 Vein, 814 stope. Photomicrograph. x25.

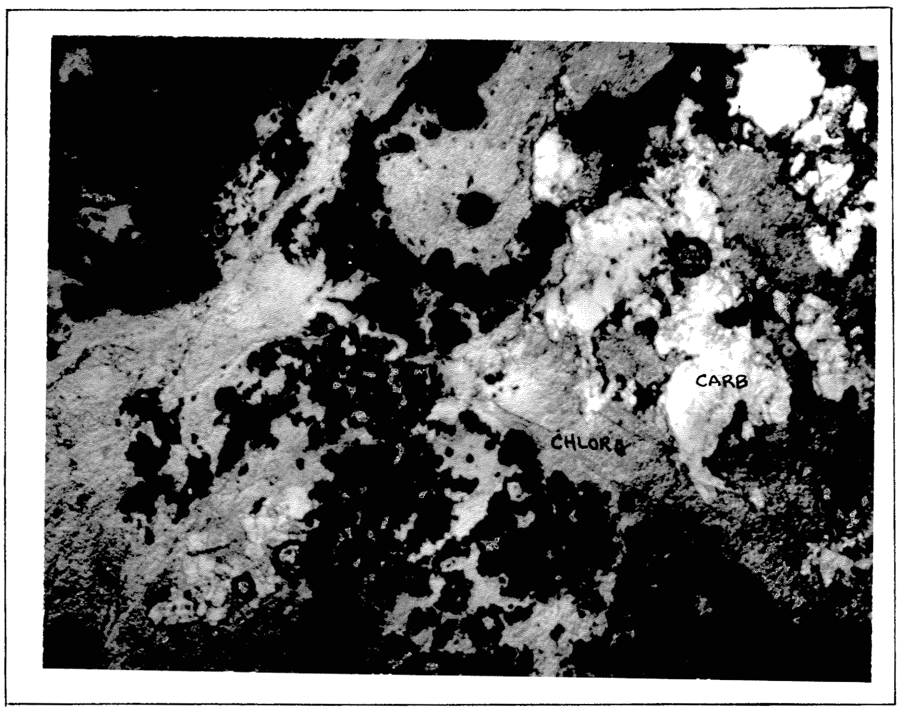


Figure 63. Pitchblende replaced by chlorite and both by carbonate.
No. 1 Vein, 914 stope. Photomicrograph. x25.

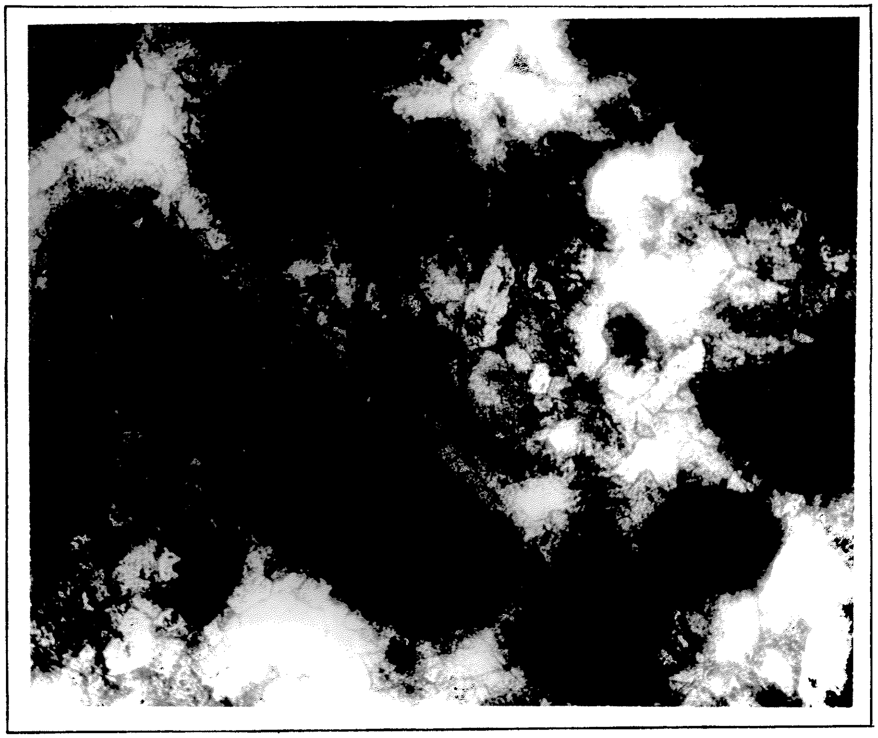


Figure 64. Carbonate replacing pitchblende.
No. 2A Vein, 320 stope. Photomicrograph. x50.

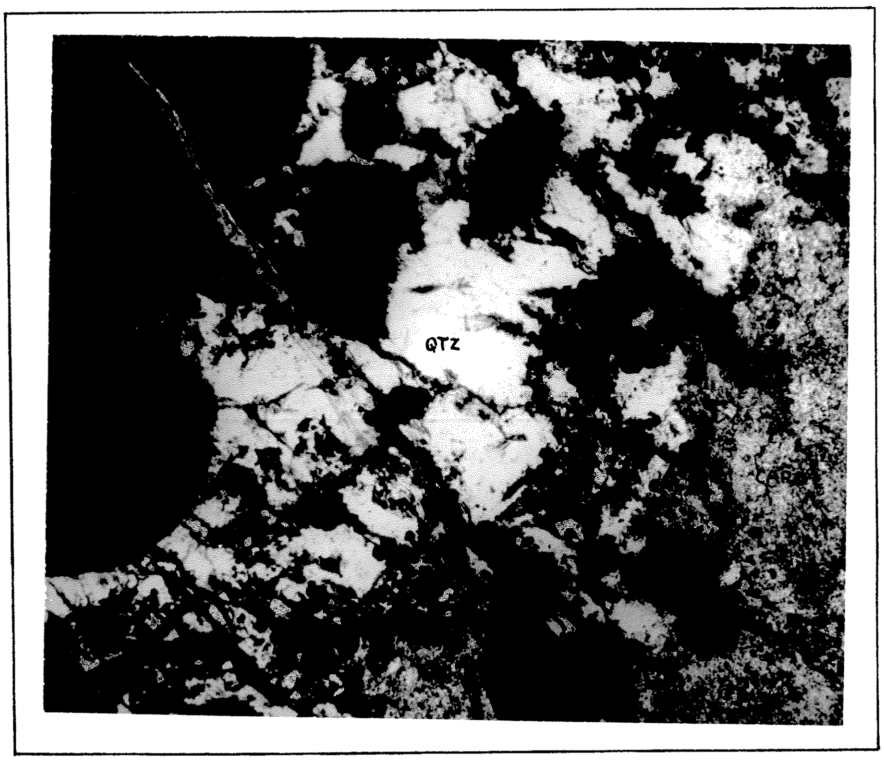


Figure 65. Quartz brecciating pitchblende and replaced by carbonate.
No. 1 Vein, 650 Level. Photomicrograph. x50.

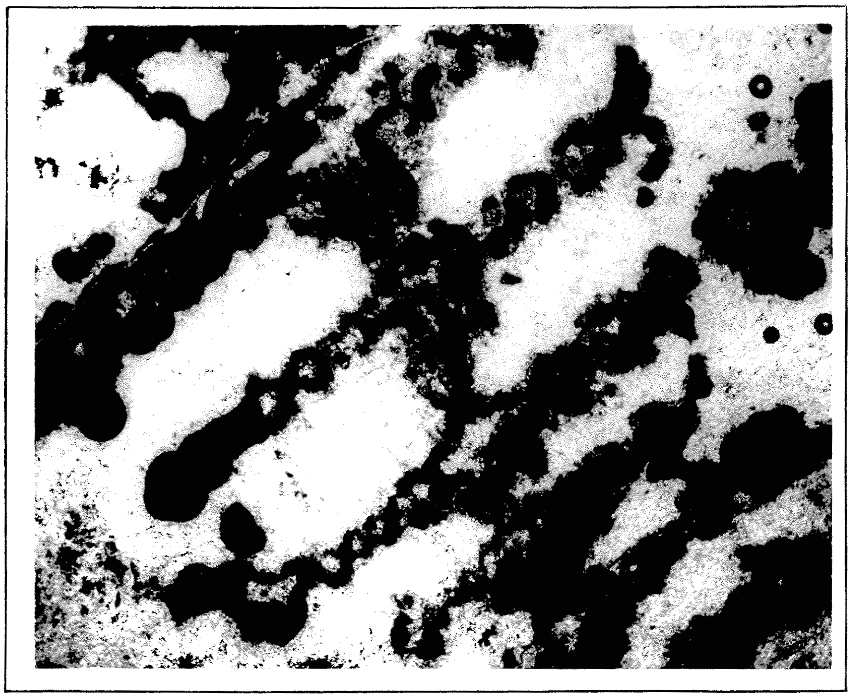


Figure 66. Carbonate dendritically replacing pitchblende. No. 1 Vein, 650 Level. Photomicrograph. x 50.

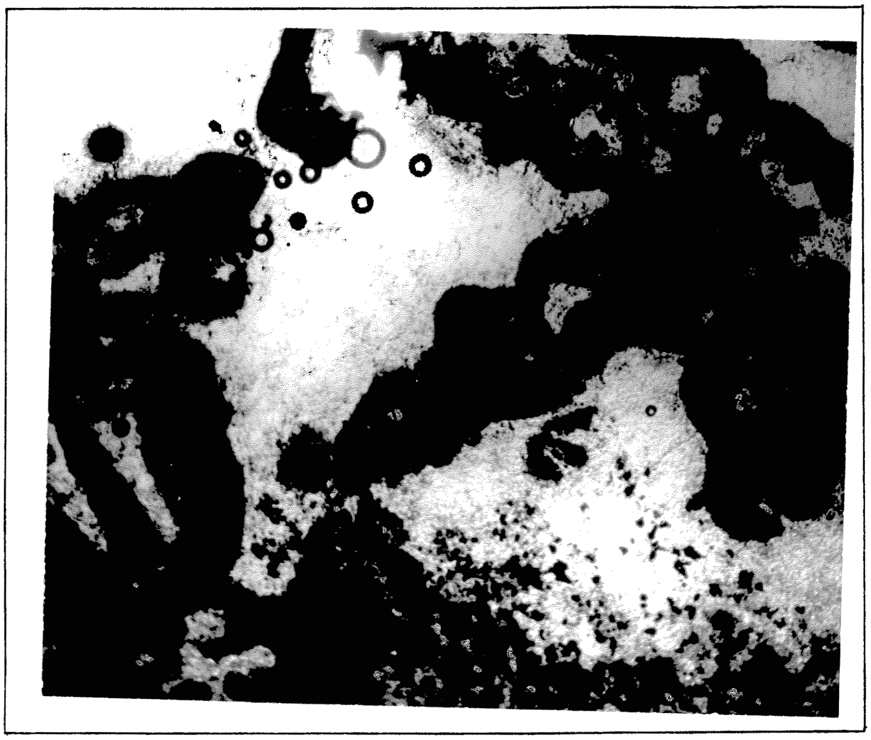


Figure 67. As Figure 66.

Silver: The final stage of mineralization at Port Radium was the deposition of large amounts of native silver in restricted vein zones. The silver occurs in three principal forms:

(1) Masses of wire and fine laceworks intimately impregnating medium crystalline rose-coloured carbonate-barite veins that range in thickness from a few inches to 30 inches.

(2) Leaves and films on joints or fracture surfaces, usually near the walls of the vein zones.

(3) Wires and films in brecciated pitchblende.

The silver-bearing carbonate veins are major components of only two veins, the Silver Island and No. 2A vein zones. In addition, silver and carbonates occur in discontinuous veinlets and lenses a few inches in width along the upper levels of No. 5 Vein, in a tight fracture on the 1175 Level called 0 Vein, and as small lenses along No. 7 Vein. The leaves and films of silver occur only on the Silver Island, No. 2A, No. 3 and No. 5 Veins. The masses of silver and pitchblende occur only on No. 2A Vein. The tectonic relation of all these vein zones probably had a direct bearing on the emplacement of the silver. They are all vertical tension fractures and, since they are the sole recipients of the silver mineralization, they were probably the only members of the fracture system open during Stage V.

During the early years of mine, production came almost exclusively from No. 2A Vein, and profits were obtained mostly from the silver before the radium extraction was perfected. This emphasis on silver production is illustrated by old assay plans and by good uranium ore left unmined because of low silver content.

Where the gangue in No. 2A Vein is predominantly quartz instead of carbonate there is no silver.

The silver content of the Silver Island Vein was not realized until 1954, when development on the 650 Level disclosed a length of 200 feet assaying over 200 oz Ag/ton across 3 feet of width.

The minerals comprising the silver phase of Stage V are:

Oldest	Stromeyerite	$Ag_2S\ Cu_2S$	
	Argentite	Ag_2S	
	Rhodochrosite	$(FeMn)CO_2$	) Age uncertain
	Barite	$BaSO_4$	) Age uncertain
	Hessite	Ag_2Te	
Youngest	Silver	Ag	

Only the silver, argentite and gangue minerals occur in appreciable quantities, the argentite as veinlets cutting chalcopyrite, and the silver in the forms described above as well as in complex replacement relations with pitchblende, copper sulphides and the arsenides.

SURFACE OXIDATION

Surface exposures contain the following secondary minerals:

Mn	Pyrolusite	MnO_2	Pitchblende	Gummite
	Psilomelane	" $+Ba, K, H_2O$ etc.		Uranophane
	Polianite	MnO_2		Zippeite
Cu	Malachite	$CuCO_3Cu(OH)_2$	Co.	Erythrite $Co_3As_2O_8 \cdot 8H_2O$
	(Azurite)	2 " "	Ni	Annabergite Ni_3 " "

The cobalt-nickel blooms appear in undisturbed drifts and stopes usually by a year from the time of opening and increase steadily to masses which are brilliant when moist but fade when dry.

Surface exposures of pitchblende deposits at Port Radium are generally inconspicuous. Yellow and orange stains of secondary uranium minerals are found along some vein zones, but they are often masked by iron oxide, manganese stain or malachite derived from the minerals present in the zone. Pitchblende weathers very readily and is soon leached away under anything but very dry conditions. The initial orange decomposition products alter still further in atmosphere to a pale yellow-grey powder that is easily removed by surface waters. It is only on cliff faces or sheltered clefts and cracks that the secondary uranium minerals remain conspicuous. The stains that attracted McIntosh Bell to the No. 1 Vein bluffs in 1899 were malachite and the nickel-cobalt blooms.

Oxidation and hydration of pitchblende results in the formation of a number of waxy green, brown, orange, red or yellow hydrated oxides of uranium, of indefinite composition, that are grouped under the generic name gummite. The weathering process oxidizes the U_3O_8 to red UO_3 and then combines it with water to form the gummite[41].

At Port Radium the secondary minerals consist of gummite stains, minor uranophane (yellow green crusts of minute needles), and zippeite (yellow crystals of hydrous uranium sulphate)[42].

The rhodochrosite content of the vein zones at Port Radium is usually high, particularly near the pitchblende shoots. The decomposition of this carbonate forms manganese dioxide which coats the outcrops as black stain or crust and effectively masks the pitchblende stains.

The open nature of the vein zones to depths of over 2000 feet and the circulation of ground water through the zones have lined fractures and vugs in the vein material near the ore with gummite.

PARAGENESIS

The parageneses of the vein minerals have been outlined above for each stage of mineralization and is shown graphically in Fig. 68. Relations are quite clear except in the case of some of the arsenides and the overlapping ages of quartz. In addition, there are some corroded relict crystals of pyrite and arsenopyrite in the early quartz of Stage II. This suggests an early sulphide stage. Early pyrite in the wall rocks could have been the origin of the relict grains of that mineral but not the arsenopyrite.

The interesting feature of the paragenesis of the Port Radium deposits is the change of composition of the mineralizing solutions and the definite time breaks between the stages of mineralization, as shown by the brecciation of earlier minerals and the formation of new openings. The sequence of deposition was, in general:

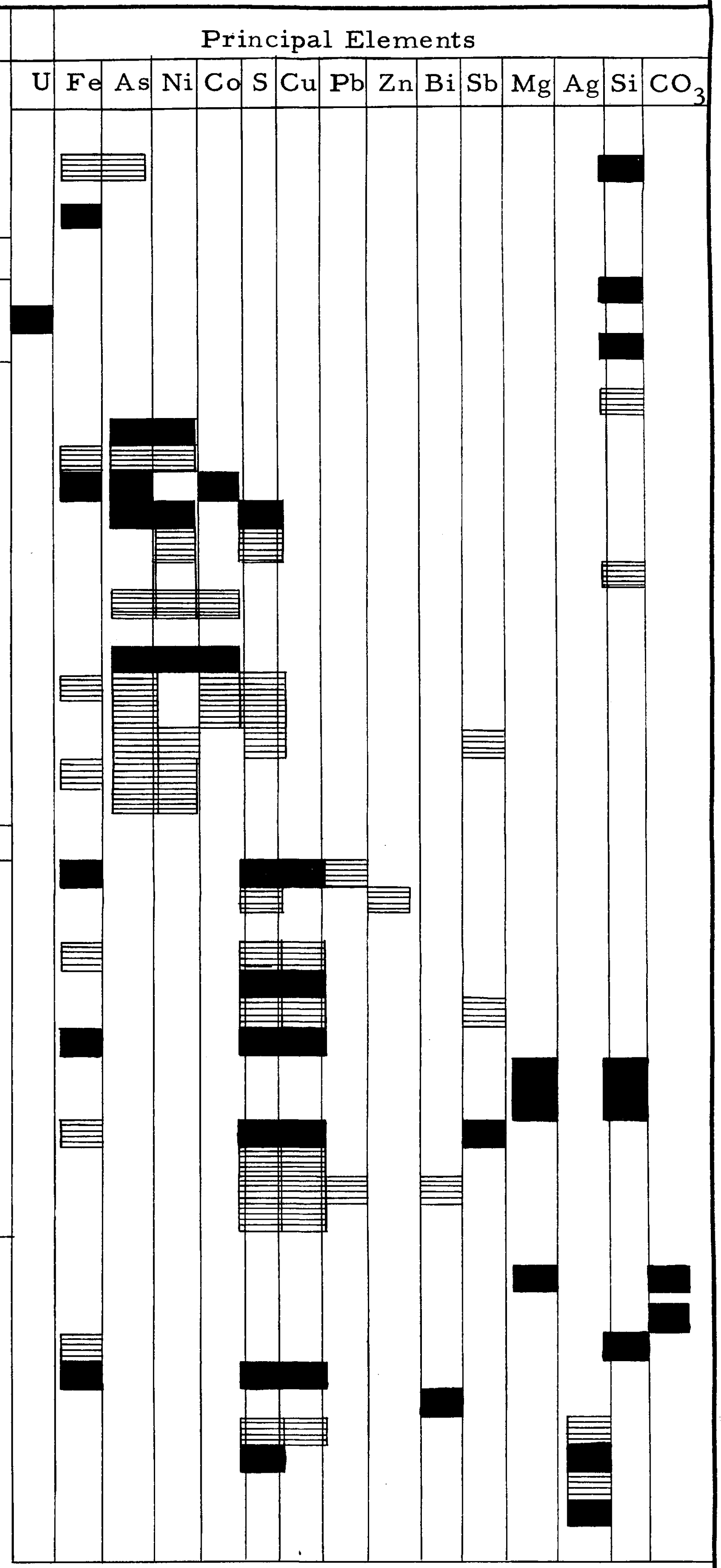
(1) Oxides.
(2) Arsenides.
(3) Sulphides.
(4) Carbonates.
(5) Native metals.

The oxide pitchblende is thus not directly associated with any of the sulphophile elements. On the other hand the spatial association of pitchblende with these sulphophile elements is worldwide and cannot be due to coincidence. Probably the metals had a common source

Figure 68

PARAGENESIS OF PRIMARY VEIN MINERALS AT PORT RADIUM

Stage	Major Minerals	Minor Minerals
I Oxides	Quartz Hematite	Pyrite, arseno-pyrite (?)
	Brecciation	
II	Quartz Pitchblende Quartz	
III Arsenides	Niccolite Safflorite-loell. Gersdorffite Skutterudite	Quartz Loellingite Polydymite Quartz Smaltite-chloanthite Glaucodot Cobaltite Corynite Loellingite Niccolite (?)
	Brecciation	
IV Copper sulphides (Silicates)	Chalcopyrite Chalcocite Bornite (Montmorillonite) (Chlorite) Tetrahedrite	Galena Sphalerite (Marmatite) Cubanite Chalcostibite (Sericite) Tennantite Chalcocite Aikinite Covellite
V Carbonates Silver	Dolomite Rhodochrosite (Quartz) (Chalcopyrite) (Bismuth) Argentite (local) Silver (local)	Hematite Stromeyerite Hessite



in a crystallizing magma but different times of expulsion.

The crystallochemical properties of certain elements (the rare earths, Zr, Th, Hf, Cb, Ta, W, Sn, Li, Be, B and U) do not favour the entry of those elements into the lattices of the early forming minerals in crystallizing silicate magmas. These elements concentrate in the final portions of the liquid magma and generally appear in minerals in pegmatites, which are formed from the residual silicate magma. If an aqueous fraction forms in this final liquid magma, most of the remaining elements (S, Se, Te, Fe, Mn, Cu, Zn, Cd, Pb, Ge, As, Sb, Bi, Co, Ni) will concentrate in the aqueous solutions. Most of its compounds being highly water soluble[41], uranium, although it is an oxyphile element, in the presence of aqueous solutions will concentrate with the sulphophile elements. When these solutions form hydrothermal deposits, the uranium becomes associated with the metals. Because of its chemical properties the uranium is precipitated as an oxide[41]. Presumably the first vein-forming solutions to escape would be predominantly water, possibly in gaseous form, and the water soluble elements. This would concentrate the uranium in the early solutions, to deposit, as at Port Radium, early in the sequence of minerals.

Precipitation of elements may have been influenced by a rising pH of the solutions. Experimentally the elements of interest can be precipitated as hydroxides by a change in the pH[43]. Precipitation will be as follows:

pH	0-3	3-5	5-7	7-9	9-12
Element	Fe^3	U^6	Cu, Fe^2, Pb, Ni, Co	Ag	MgCa
	Acid				Alkaline

Changes in mineralogy and wallrock alterations point to the fact that the mineralizing solutions at Port Radium changed from initially acid to finally alkaline with major deposition-breaks after the pitchblende and after the sulphides. This corresponds to the divisions of the groups in the above table of pH's.

Silica, appreciably soluble in acid solutions, would tend to precipitate as quartz along with hematite as the pH increased. By the time the pH had passed 5 there would be little likelihood of any more uranium remaining in solution.

It has been suggested that the botryoidal forms of the pitchblende necessitate deposition at low temperature, but gels are more likely to be coagulated at very high temperatures. Moreover, it has been found that artificial U_3O_8 can be formed from ignition of suitable components and will be either moss green or black in colour[41]. The green variety forms if the temperature of ignition is below 800°C. The black variety forms if the temperatures are from 900-1000°C. Though not strictly analogous to hydrothermal conditions, this suggests that the black pitchblende may indicate high temperatures.

Types of Ore

Autoradiographs of specimens of all the types of pitchblende ore found at Port Radium are shown in Figs. 74 to 98 at the end of this chapter. Textures peculiar to each type of ore are clearly illustrated in these autoradiographs.

CHEMISTRY OF PITCHBLENDE DEPOSITION

Pitchblende is a colloidal precipitate and so its deposition is governed by colloidal rather than ionic phenomena.

Gels consist of either myriads of tiny crystals or gelatinous clusters of ultramicroscopic particles, each surrounded by an envelope of water[44]. From microscopic observation and X-ray evidence it is clear that pitchblende is not a crystalline variety of gel. Dehydration of the pitchblende gel results in shrinkage and hardening and the consequent formation of syneresis cracks. This process is usually irreversible, therefore chemical peptization and redispersion by the parent solutions can only be effected before dehydration. However, dispersion of the gel can also be accomplished by mechanical disintegration; the brecciation and comminution of the pitchblende at Port Radium is an example of this type of dispersion. The gel tends to show signs of crystallization during the dehydration stage, and for this reason some pitchblende gives an X-ray pattern.

Rapid coagulation forms a gelatinous precipitate such as pitchblende whereas slow coagulation forms a jelly of solution and sol which will not develop syneresis cracks[44].

Kurbatov et al[48] investigated the precipitation of uranium and thorium from solutions and found that these elements as well as some complexes of them invariably form colloids in aqueous solutions over wide ranges of temperature and pressure. Coagulation of the colloids can be brought about by introduction of a proper amount of an electrolyte, change in pH, or decrease in carbonate content. Change of temperature is not a major factor in the coagulation of the uranium colloids.

<u>Introduction of an electrolyte</u>: An electrolyte bearing a charge opposite to the charge of the particles in the solution causes

neutralization of the colloid, destruction of the dispersive property of the colloid, and deposition. There is no evidence that this phenomenon has caused the precipitation of pitchblende in natural occurrences.

Changes in pH: At $25^{\circ}C$ and a given concentration of uranium there is a regular increase in coagulation with increasing pH, reaching an optimum at about 4.5 at which value most of the uranium has precipitated[48]. This relation is important in the natural precipitation of pitchblende because it sets a possible limit on the character of the solutions from which pitchblende precipitates. If the solution changes from acid to alkaline, all the pitchblende will precipitate before the solution reaches the alkaline stage. At pH 8 the uranium sol may begin to reform, but alkaline hydrothermal solutions that have evolved from originally acid solutions would be depleted of the uranium sol, pitchblende.

Decrease in carbonate content: Uranium ions react with carbonate or bicarbonate ions to form soluble complexes. In acid solution an increase in carbonate content directly increases the amount of uranium held in solution[46][48]. In an aqueous solution containing bicarbonate, carbonate and oxygen, uranium is in the hexavalent state as the complex $UO_2\,(CO_3)_3^{-4}$ [46]. The CO_3^{-2} and HCO_3^{-} ions regulate the solubility of the uranium in the solutions and under high pressures will increase the solubility greatly. In solution the carbonate and bicarbonate ions will be in equilibrium with CO_2 in accordance with their equilibrium constants and the partial pressure of the CO_2. If CO_2 is suddenly subtracted from the solution the equilibrium is shifted causing dissociation of the uranium-carbonate complex and coagulation of uranium colloid as uranous hydroxide at relatively low temperatures[50]. Dissociation of the uranous hydroxide gel takes place immediately after or during precipitation to uranous oxide and water[41].

$$U(OH)_4 \xrightarrow{\text{dissociation}} UO_2 + 2H_2O \quad \text{(gel.)}$$

Gronvold[62] found that UO_2 takes up oxygen at temperatures from 200-250°C to form $UO_{2.43}$, i.e., U_3O_8. Decrepitation work on quartz associated with the Port Radium pitchblende gave temperatures of possible crystallization of the quartz ranging up to 400°C. Delepine and Lebeau[45] found that, under oxidizing conditions in an electric furnace, Shinkolobwe uraninite breaks down to U_3O_8 at about 300°C. These data on possible temperatures of the formation of pitchblende strongly suggest precipitation at relatively low temperatures and consequently in the form of $U(OH)_4$. As stated earlier, this would instantly dissociate and oxidize in hydrothermal environment to form U_3O_8[41][62].

Forward[46] has applied the reverse reaction of dissociation of the uranium-carbonate complex to leach pitchblende ores. This reaction, applied to the precipitation of pitchblende is as follows:

$$UO_2(CO_3)_3^{-4} + 3H_2O \rightleftharpoons \underset{\downarrow \text{Coagulation}}{3U(OH)_4} + 3CO_3^{-2} + \left[6HCO_3^- \rightleftharpoons 6CO_2\uparrow + 3H_2O\right] .$$

As described earlier, the uranous hydroxide colloid further breaks down under oxidizing hydrothermal conditions as follows:

$$U(OH)_4 \longrightarrow UO_2 + 2H_2O.$$

and $$3UO_2 + O_2 \longrightarrow U_3O_8 \quad \text{(Pitchblende).}$$

It is evident that release of the CO_2 pressure in uranyl-carbonate solution will cause instantaneous precipitation of the uranium as pitchblende. If the solution is acid the CO_2 will come off strongly through release of pressure(47) and the described reactions will be that much more rapid and effective.

COMPARISON WITH OTHER DEPOSITS

Mineralogy: A number of deposits have pitchblende in association with complex suites of metallic minerals similar to those at Port Radium. These deposits are listed in Table 5. In the list the similarity of mineral suites is broken in the cases of Joachimsthal and Cornwall by differences in parageneses. Except for these two localities, the general mineral groups and parageneses are remarkably similar. The above list, plus Port Radium, includes three of the world's five principal known pitchblende deposits.

The simplest explanation for the U-Co-Ni-As association in widely separated parts of the world is that certain magmas are particularly rich in these metals and give rise to this type of deposit in the course of their crystallization. The ages of the above listed deposits range from pre-Cambrian to Tertiary.

Texture: The brecciation of the pitchblende at Port Radium is not peculiar to that deposit. All the pitchblende ores in the Great Bear Lake district, with the exception of Hottah Lake ores, exhibit this feature. It is not uncommon in some of the deposits near Lake Athabaska, Saskatchewan, and Robinson(54) refers to

TABLE 5

Mineralogy of Some Pitchblende Vein Deposits

				Ref.
1.	Echo Bay Group	- South of Crossfault Lake, N. W. T.	- Identical with Port Radium	
2.	M Group	- Contact Lake, N. W. T.	- Identical with Port Radium	(10)
3.	Caribou Mine	- Colorado	- Quartz, gersdorffite, pitchblende, chalcopyrite, sphalerite, pyrite, argentite, proustite, silver.	(51)
4.	Nicholson Mine	- Saskatchewan	- Pitchblende, thucholite, niccolite, Co-Ni, arsenides, gold, platinum.	(24)
5.	How Group	- Camsell River, N. W. T.	- Dolomite, pitchblende, pyrite, niccolite, chalcopyrite, sphalerite, galena, bismuth, silver.	(52)
6.	Shinkolobwe	- Belgian Congo	- Quartz, uraninite, pyrite, Co-Ni, sulphides, chalcopyrite.	(53)
7.	Joachimsthal	- Czechoslovakia	- Quartz, Co-Ni, sulpharsenides, pitchblende, pyrite, sphalerite, galena, silver minerals.	(53)
8.	Cornwall	- England	- Chalcopyrite, arsenopyr., pyrite, galena, sphalerite, Co-Ni, sulpharsenides, pitchblende.	(53)
9.	Carrizal Alto	- Chile	- Chalcopyrite, hematite, pitchblende, Co-Ni, sulpharsenides, bornite, chalcopyrite, calcite.	(53)

"wisps" of pulverized pitchblende in late chlorite gangue from deposits near Athabaska. Kerr[45] reports textures in many specimens from pitchblende deposits that suggest plucking from earlier formed pitchblende. In addition, the writer has noted the same texture in specimens from the Boulder Batholith deposits, Marysvale, and Joachimsthal.

A possible explanation is that the development of syneresis cracks in the dehydrated pitchblende so weakens the mineral that it becomes susceptible to fragmentation by slight disturbances.

RADIOCOLLOIDS

Autoradiographs of Port Radium specimens of brecciated pitchblende veined by late gangue minerals show fine dots and clusters of dots of extremely high specific activity concentrated in the late gangue veinlets. These dots are jet black on the prints, whereas even the highest grade pitchblende registers only grey-black for the same exposure time. (See Fig. 93). Employing special emulsions for studying X-ray tracks and calibrating ranges in the emulsions of X-rays originating from various radioactive sources, Yagoda[55] identified the spots in the Port Radium ore specimens as containing RaC^1, Ra, Radon, RaA and Polonium. The composition of the radioactive material was determined to be predominantly $RaSO_4$. Since the specific activity of equilibrated $RaSO_4$ is $5 \times 10^8/sec/cm^2$ and that of primary pitchblende is $338/sec/cm^2$, the reason for the more intense registration of the dots on the autoradiographs is obvious.

Laboratory studies by Starik and Segel[56], [57] have shown that in acid, alkaline and neutral solutions, over a wide range of temperatures and times, radium is preferentially removed from uranium minerals. The probable reason for the ease of removal, relative to uranium, is that the radium is contained in intercrystalline spaces whereas the uranium is in the crystal lattice. The leaching of the radium is not affected by temperature. The more highly altered a specimen is the more radium is missing. It is evident then that the working over of the Port Radium pitchblende by hydrothermal and ground water solutions probably resulted in considerable leaching of radium and solution of uranium. In acid solutions containing sulphate ions, the radium would form a radiocolloid of acid insoluble $RaSO_4$ and precipitate in tiny clots along fissure walls.

The present total composition of the radioactive clots is, according to Yagoda[55], $Pb^{206}SO_4$ associated with about 0.003 percent $RaSO_4$ (150 times the concentration of radium in pitchblende). Assuming an original composition of $RaSO_4$, it is calculated that the time interval since the deposition of the clots is about 20,000 years. There is no way to determine whether or not the original $RaSO_4$ precipitate included some Pb from the leached pitchblende; therefore, the age determined by Yagoda, 20,000 years, must be taken as a maximum and the true age of the precipitation of the $RaSO_4$ may be much less. If the radioactive clots were due to hydrothermal leaching the conclusion must be that there has been hydrothermal activity at Port Radium since the Pleistocene! An alternative explanation is that the $RaSO_4$ was formed by ground water activity during a pre-glacial and pre-permafrost period when conditions were favourable for the formation of sulphate solutions in the vein zones. But if this is the case, why are the clots in quartz and chlorite veinlets near brecciated pitchblende? Is their apparent distribution a function of sampling? The problems posed by the radiocolloid clots are not yet answered. Further investigation is necessary before definite conclusions can be made.

AGE DETERMINATIONS

Some of the first age determinations of uranium minerals were made from Port Radium ore. A great many determinations have since been made on this ore, mainly by methods now known to be undependable, but only in recent years has the more dependable lead isotope method been used. This involves the determination of the ratio of Pb^{207} to Pb^{206} in the end product of the radioactive disintegration of pitchblende. Theoretically, ages determined in this manner should be accurate in spite of disturbances to the mineral since its deposition, because the calculations are based on isotope ratios and not on amounts of different elements which can be naturally fractionated.

Seven lead isotope age determinations have been made on samples of Port Radium ore. The results are not entirely in agreement with each other, nor are they in agreement with the age, late pre-Cambrian, indicated by the geologic setting of the deposit. With the present knowledge of the complex history of the pitchblende at Port Radium it is possible to analyse the validity of age determinations made from it. This subject constitutes a separate investigation which will be dealt with in a subsequent paper; however, it will be briefly discussed here because the age of the Port Radium ore is important in concepts of the geology of the western Canadian Shield.

The most pertinent geologic age relations are these: pitchblende occurs in fractures in late diabase dikes; these dikes cut the latest pre-Cambrian formation, the Hornby Bay Group; this formation is composed of flat-lying sediments which are overlain disconformably by Cambrian rocks. This would suggest that pitchblende mineralization occurred in the very late pre-Cambrian. There is no evidence in the study of Port Radium ores of more than one age of pitchblende, but also there is no evidence that the pitchblende in different vein zones could not be of different ages. The only feature that suggests a common age for all the pitchblende deposits in the Great Bear Lake area is that they are all in late pre-Cambrian rocks.

Nier's age determination (1939) for a specimen from Port Radium was 1420 mill. yrs. Three specimens from the same surface pit were analysed at Toronto(58) and gave ages of 1430$\pm$40, 1410$\pm$60, and 1460$\pm$70 mill. yrs. Two other specimens from a different ore shoot in the same vein were analysed at Toronto and gave ages of 1330$\pm$40 and 1350$\pm$50 mill. yrs. All these ages are by the Pb isotope method. One other age has been determined. This was by the Carnegie Institute of Technology, and the only record we have of it is a letter that stated the age to be "..... about 1000 million years." The specimen used was from a different vein and from a deeper level in the mine. The significant point about these ages is the apparent separation of average ages between ore shoots: 1470 million years in one ore shoot at and near the surface; 1380 million years in another ore shoot on the same vein but 200 feet below the surface; and a possible 1000 million years in a different vein 600 feet below the surface. Regardless of the ages selected, they place the mineralization in Archean time and not in late pre-Cambrian, as the geology suggests.

If the Archean age is correct for the Great Bear deposits, then the western Canadian Shield is completely devoid of Proterozoic rocks. Not only are such rocks missing but the relatively simple disconformity separating the pre-Cambrian and Paleozoic rocks represents a hiatus of roughly a 1000 million years during which there was no deformation.

Additional confusion arises from the fact that a Pb isotope determination on a specimen of pitchblende from Hottah Lake, 40 miles south of Port Radium, gave an age of 460 million years (Nier, 1939) and another gave an age of 580±60 million years, (Toronto, 1953), both early Paleozoic. This pitchblende occurs with hematite and quartz in veins in diabase dikes identical with the veins at Port Radium. This mineralization is single-stage and undisturbed, whereas the Port Radium deposits exhibit at least three stages of mineralization later than the pitchblende. A possible explanation for the apparent discrepancies in age is that the Hottah Lake ages represent the true ages of the undisturbed pitchblende and the apparently older Port Radium ages represent changes brought about by disturbances through continued hydrothermal activity.

The evidence suggests an erratic factor in the age determinations. Further undependability is inferred when it is realized that the age determinations have been made on a few specimens representing zones that comprise a tiny fraction of the complete deposits.

Presence of older radiogenic lead: If, at the time of deposition by hydrothermal solutions, older radiogenic lead was trapped with the pitchblende, an isotope age determination of that mineral would give an age older than the actual age of the mineralization.

In such a case there are too many unknowns, and age determination becomes impossible. The supposition of such contamination is valid. The pitchblende from the solutions must have been derived from an older system at depth, and the uranium mineral in the parent system had been decaying prior to its redistribution. Norton[59], Starik[56] and others have established that the daughter products from radioactive decay of UO_2 remain in the crystal lattice and the lattice remains that of UO_2 even though radiogenic lead may constitute high percentages of the mineral. Yagoda[55] found that in dilute solutions of radioactive salts the solutes exist not only as individual ions but also as discontinuous aggregates which he calls radiocolloids. Kurbatov et al[48] determined by experiment that such radiocolloids could be precipitated under different conditions but always formed a colloidal precipitate. It is evident that partition of old radiogenic lead, from the undecayed uranium trapped in the UO_2 lattice, is not only a function of the relative solubility of the elements but also of the degree of destruction of the UO_2 units. If aggregates of greater than crystal lattice unit size move off in solution and in a short time are incorporated in colloidal particles, the retention of some radiogenic lead is almost assured. Further, it is obvious that under the varying conditions of dissolution and hydrothermal transport the retention of lead would vary in different localities and result in different isotope ages for samples from the same deposit. Such results would be interpreted as representing different ages of mineralization even though all the ore was emplaced at the same time.

If it is assumed that complete ionic solution of the uranium from the old UO_2 is attained in the magma generating the hydrothermal solutions and all the lead is liberated, then the concept of the lead remaining in the UO_2 lattice vestiges would not apply. However, another mechanism is a likely possibility, namely, if the hydrothermal solutions are carrying uranium and lead, as elements or complexes, as soon as conditions are reached whereby radio colloidal suspension will form, some lead may be trapped in the new UO_2 aggregates.

A sample of galena from a vein at Port Radium was analysed by Nier and found to have a lead isotope ratio of 1 ; 15.93 ; 15.3 and 35.3 for Pb^{204}, Pb^{206}, Pb^{207}, and Pb^{208} respectively. It is thus evident that the mineralizing solutions were carrying radiogenic lead from an earlier decay system. That some of this lead could contaminate the pitchblende is a possibility.

Leaching by hydrothermal solutions: At Port Radium it is obvious that the pitchblende has undergone extensive disturbances by successive mineralizing solutions. Nier and Collins et al have devised a correction factor for ages by crosschecking Pb^{207}/Pb^{206} ages with Pb^{206}/U^{238} and Pb^{208}/Th^{232} ages to determine the extent lead or uranium have been leached from the mineral. Bakken, Gleditsh(60), Yagoda(55) and others have shown that selective leaching of the members of the decay series in uranium minerals is easily accomplished with a wide variety of solutions. Those who use the Pb isotope method of age determinations argue that such leaching, whether lead or uranium, would not appreciably alter the lead isotope ratio because fractionation of the lead isotopes by leaching is unlikely. Recently Grant[61] has shown that isotopic fractionation of silicon occurs in natural geologic processes. Similar fractionation of lead isotopes in continual hydrothermal recirculation may be feasible.

However, if leaching took place at some time after the uranium decay series reached equilibrium, intermediate products, radium in particular, would be selectively leached. The presence of $RaSO_4$ concentrations proves that this has happened to the Port Radium pitchblende. The exact effect of such leaching and redistribution of radium on age determinations would be difficult to evaluate without knowing the times and quantities involved. One point of interest in this evidence of leaching of radium is that the solutions which deposited the $RaSO_4$ did so a maximum of 20,000 years ago[55]. If such solutions were hydrothermal it would indicate an extremely long time interval, pre-Cambrian to Pleistocene, between mineralizations of the same deposit. This in itself is a vitally interesting feature, but unfortunately in the case of Port Radium we cannot be certain whether the leaching was by hydrothermal or by groundwater solutions.

It is evident that the dependability of the age determinations made on Port Radium ore is open to considerable question, mainly because of the complex geologic history of the pitchblende. This problem is to be further investigated by making age determinations on all types of pitchblende from all the veins. If any correlation exists between the amount of disturbance or the distribution of the pitchblende and the lead isotope age determinations this survey should illustrate it. The dependability of the age determinations will then be better evaluated.

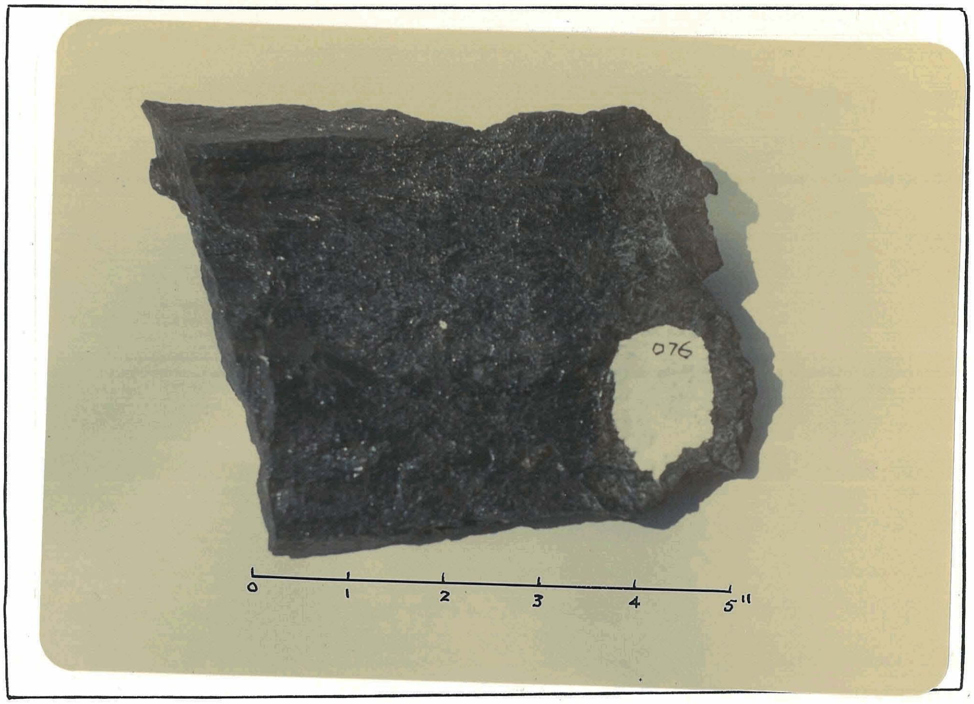


Figure 69. Massive pitchblende. No. 3 Vein. 1050 Level. x$\frac{1}{2}$

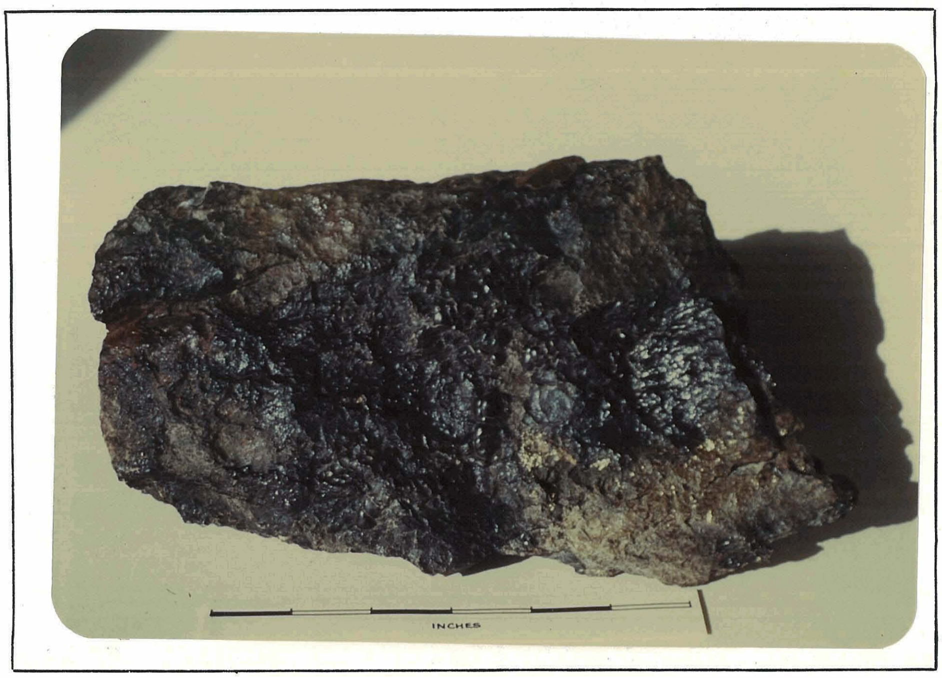


Figure 70. "Bubble" pitchblende in argillic gangue.
No. 7 Vein. 250 Level.

Figure 71. Relict pitchblende bands (high lustre) in banded carbonate, clay and chlorite. No. 3 Vein. 125 Level.

Figure 72. Relict pitchblende (black), niccolite (silvery) and apatite (rust red) in dolomite.
No. 2 Vein. 375 Level.

AUTORADIOGRAPHS

The following autoradiographs (Figs. 73-96) were made from specimens of Port Radium ore and illustrate all the common forms of pitchblende occurrences. The dark areas within the specimen outlines are areas of pitchblende as registered on enlarging paper.

Paper = No. 3, glossy, enlarging paper.

Exposure time = Nine days for maximum density, two days for good register.

LEGEND

Pbe	- Pitchblende. All the black areas in the autoradiographs.
Qtz	- Quartz.
I, II, III	- Stage of mineralization.
Chlor	- Chlorite.
Carb	- Carbonate.
Rac	- "Radiocolloid" spots.
Wrk	- Wallrock in situ.
Wrkf	- Wallrock fragment.
Cp	- Chalcopyrite.
Bn	- Bornite.
Ars	- Cobalt-nickel arsenides.

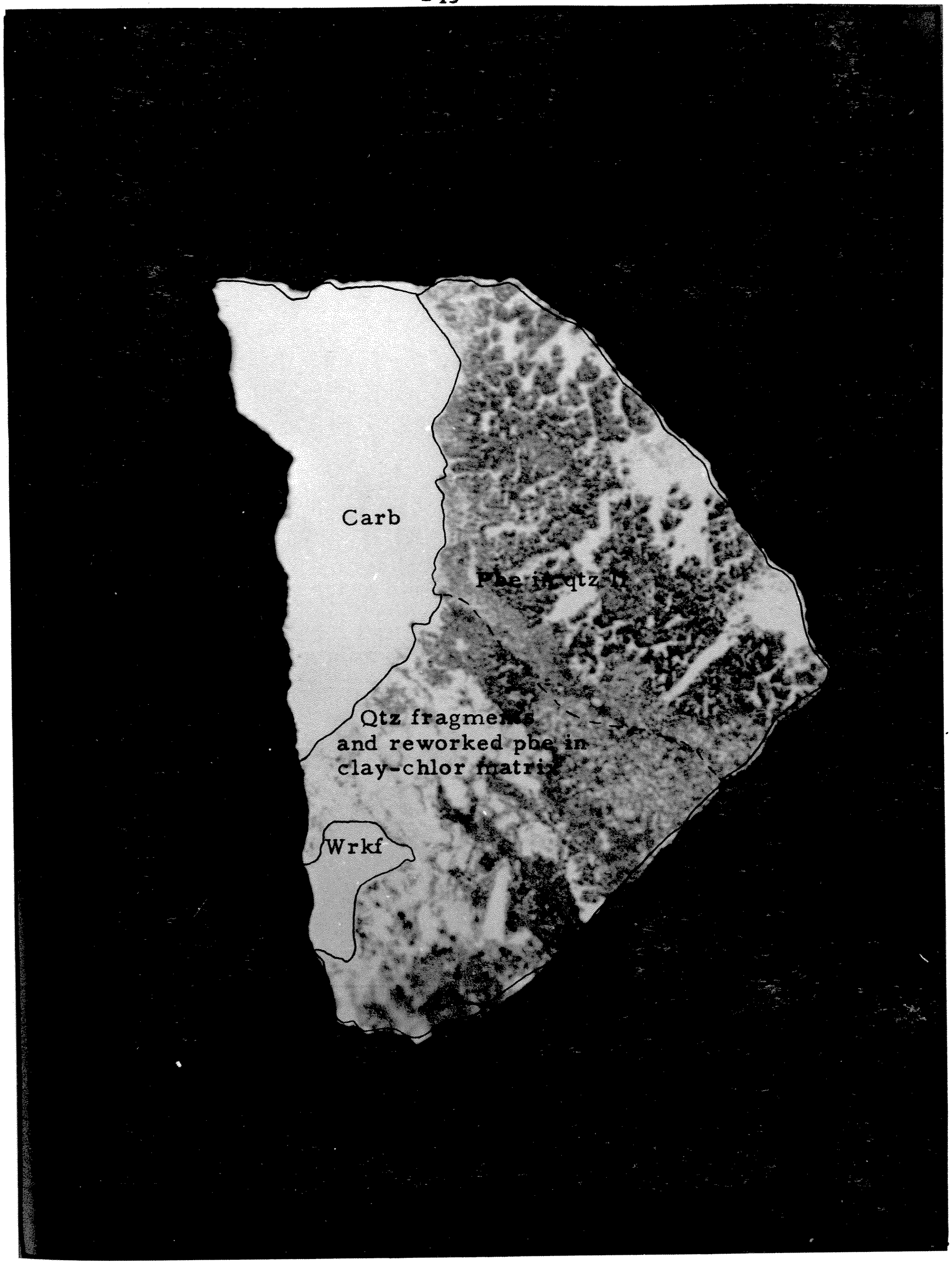
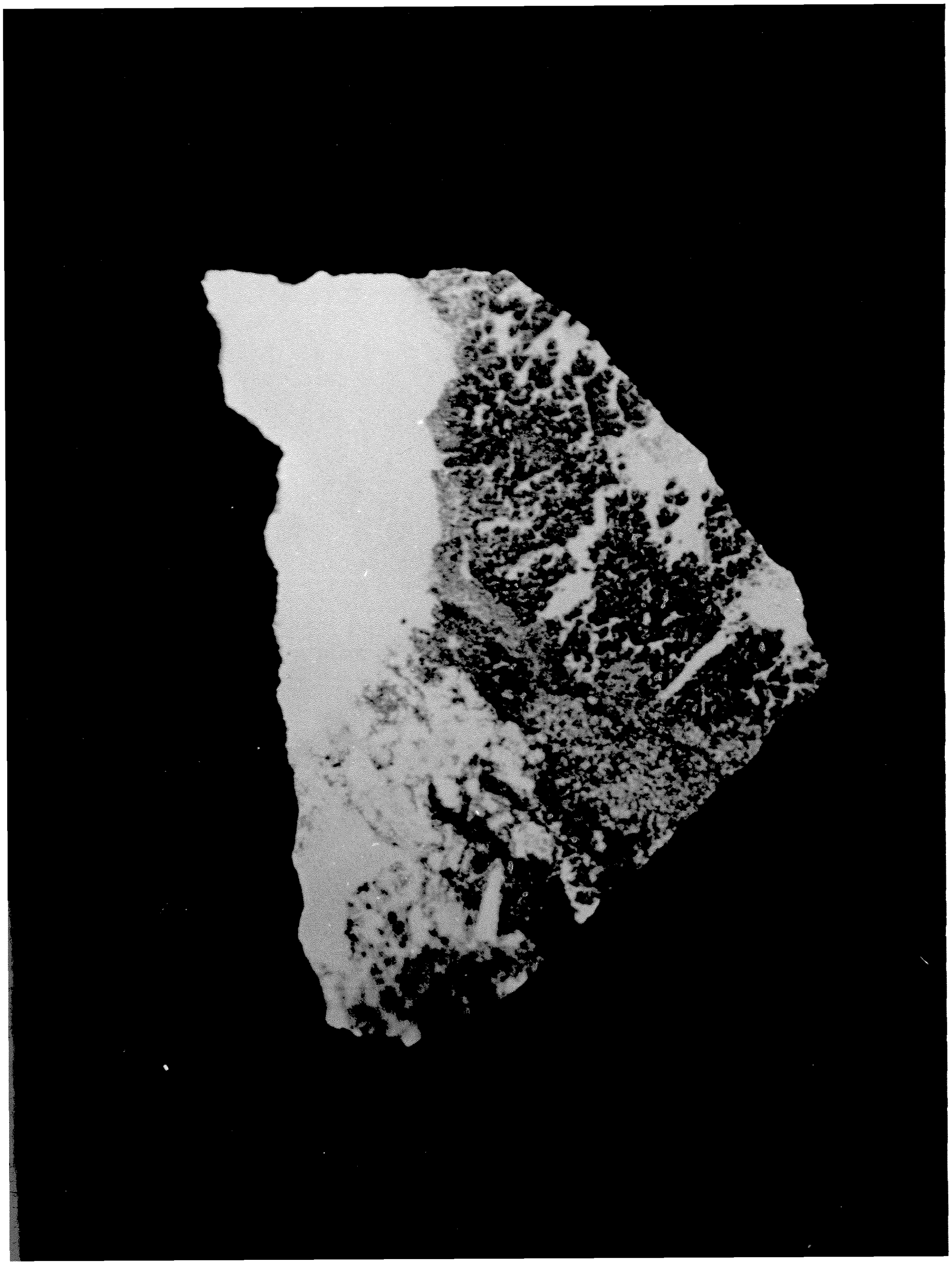


Figure 73. Primary pitchblende



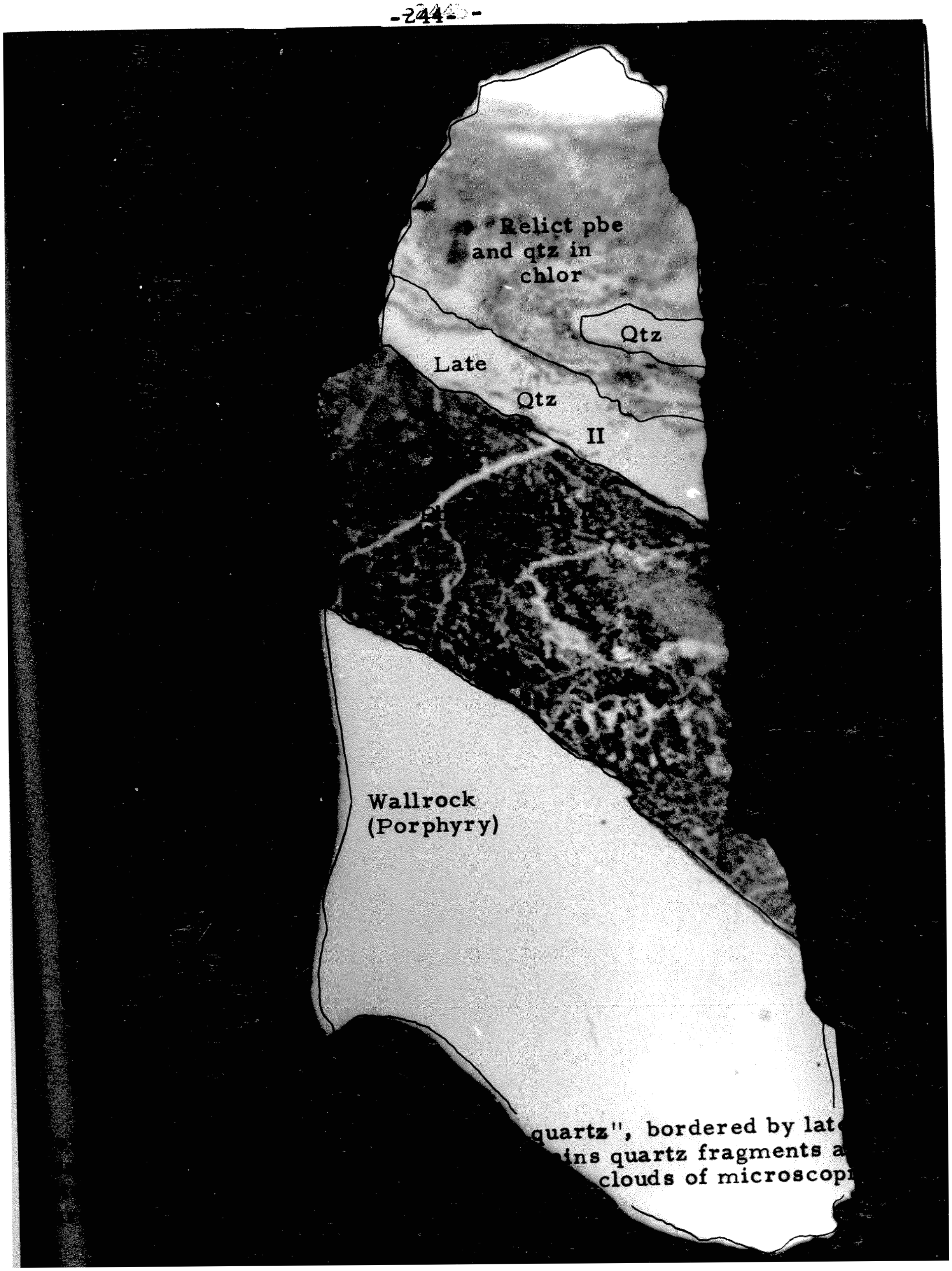


Figure 74. "Massive" pitchblende.

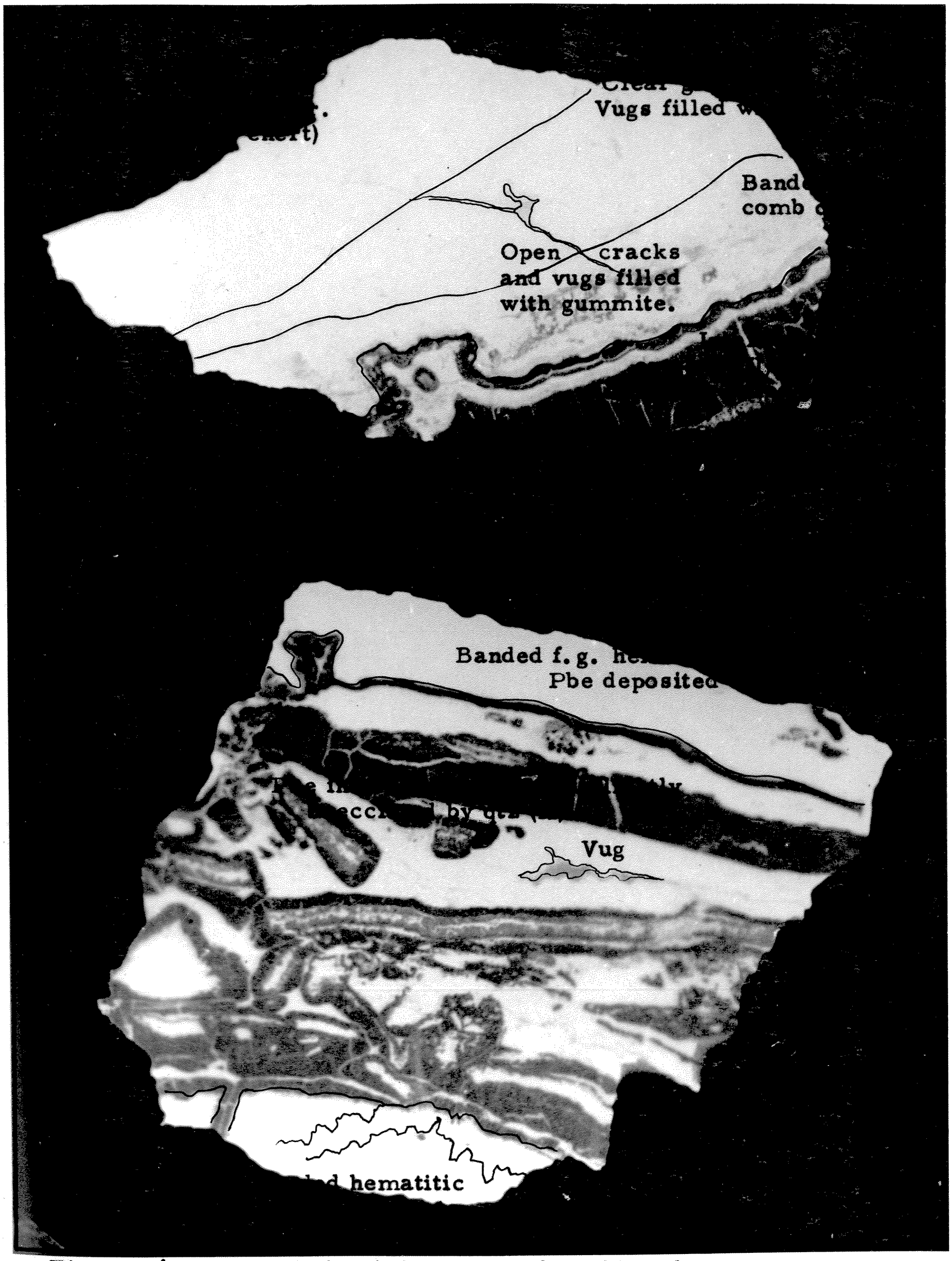


Figure 76. Rhythmic banded quartz and pitchblende.
No. 1 Vein. 613 Stope. x2

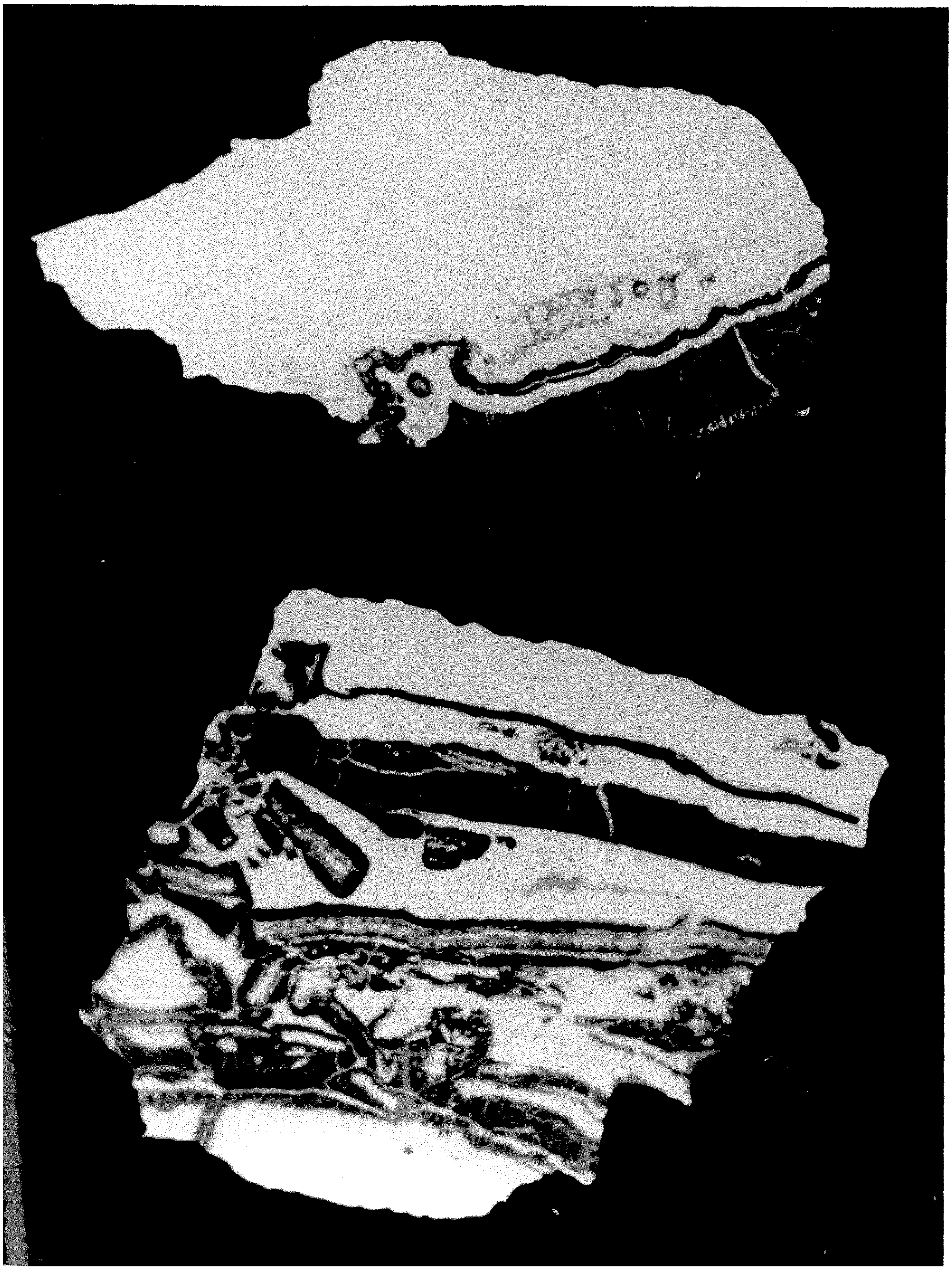


Figure 77: Simultaneous quartz (II) and pitchblende.
No. 1 Vein. 1015 Subdrift. x1

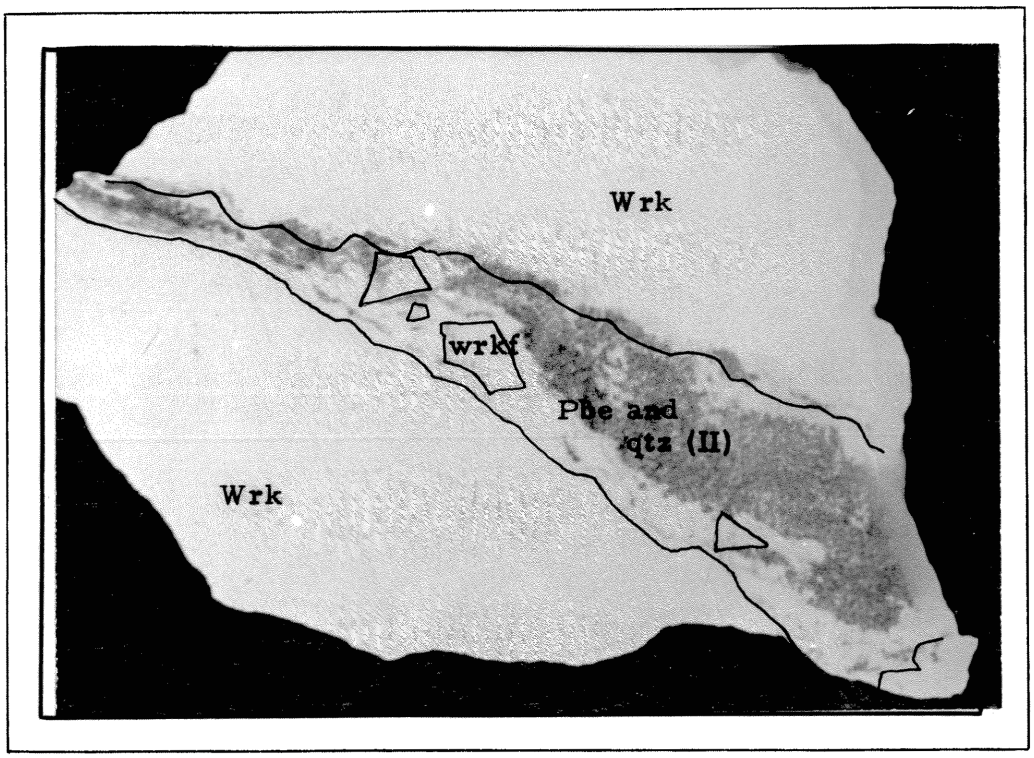


Figure 78. Spherules of pitchblende in simultaneous quartz (II)
occupying fracture in red altered porphyry.
No. 3 Vein. 1050 Level. x1

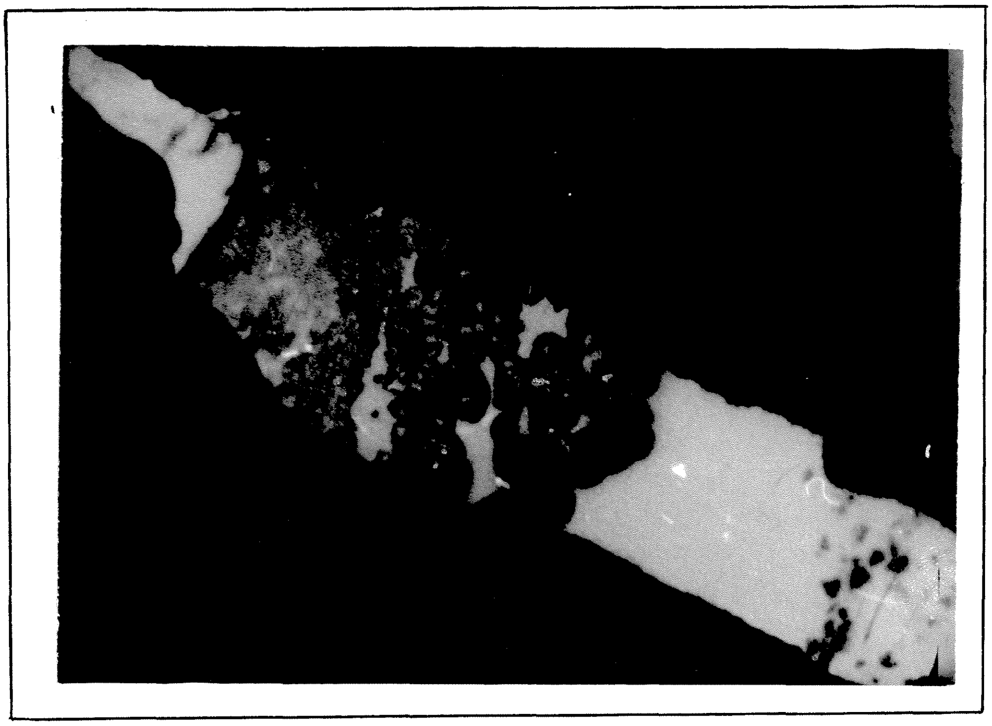


Figure 77: Simultaneous quartz (II) and pitchblende.
No. 1 Vein. 1015 Subdrift. x1

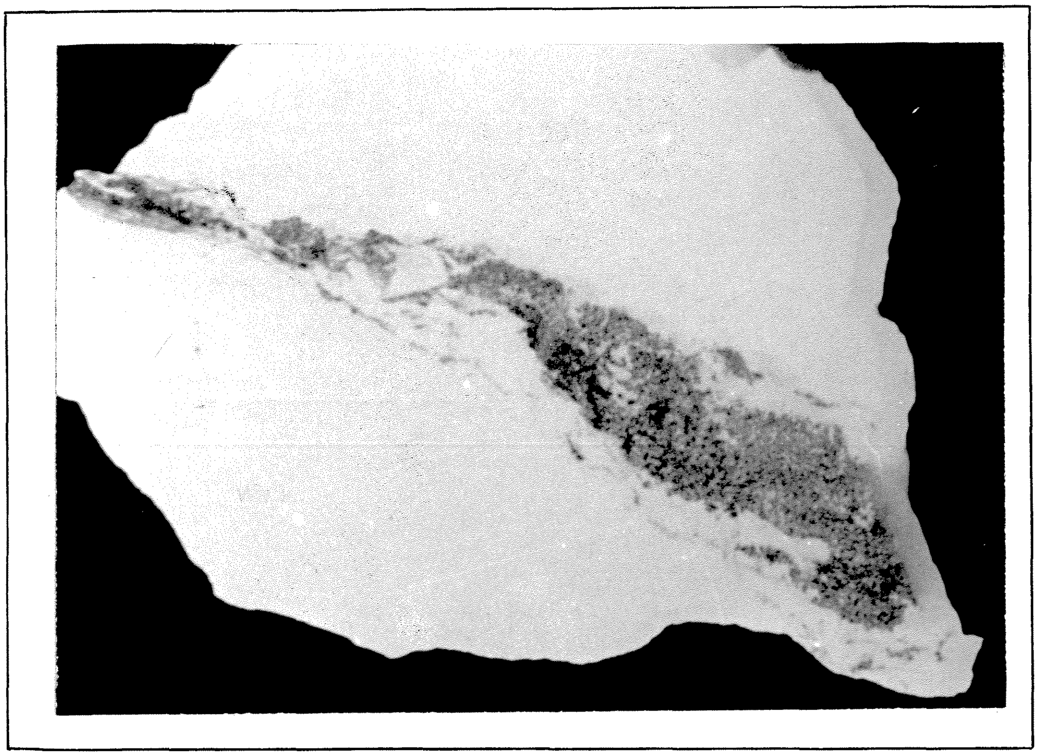


Figure 78. Spherules of pitchblende in simultaneous quartz (II) occupying fracture in red altered porphyry.
No. 3 Vein. 1050 Level. x1

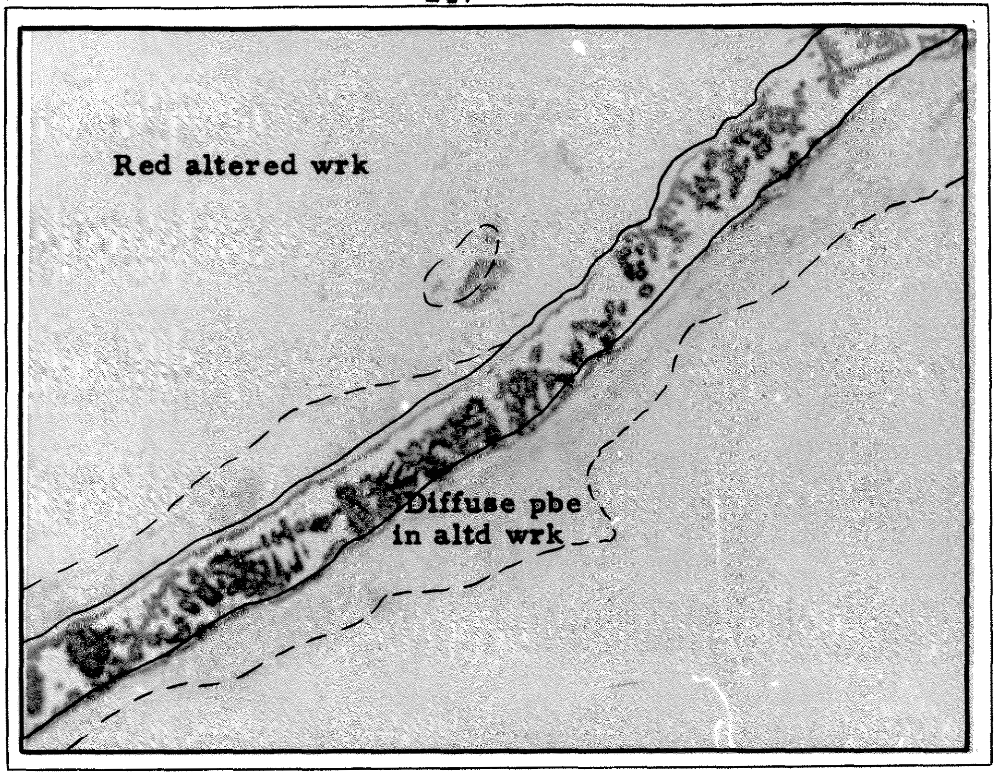


Figure 79. Veinlet of dendritic pitchblende partially replaced by carbonate. No. 7 Vein. 250 Level. x 1.6

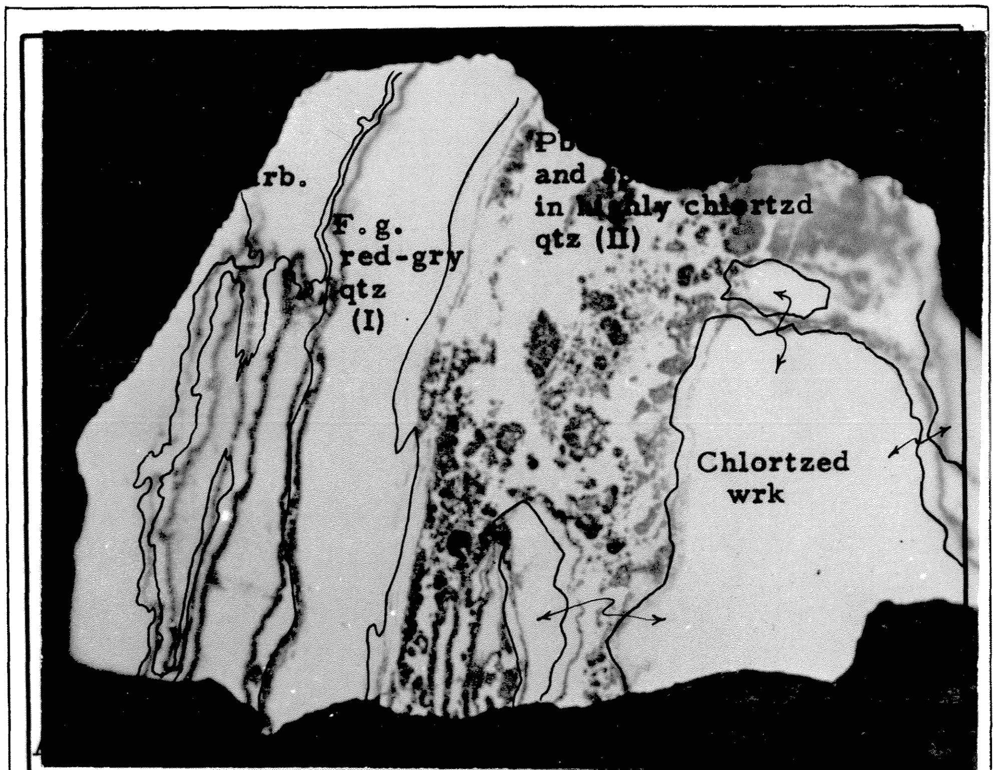


Figure 80. Pitchblende and quartz partially replaced by chlorite and carbonate. No. 3 Vein. 136 Stope. x 1.5

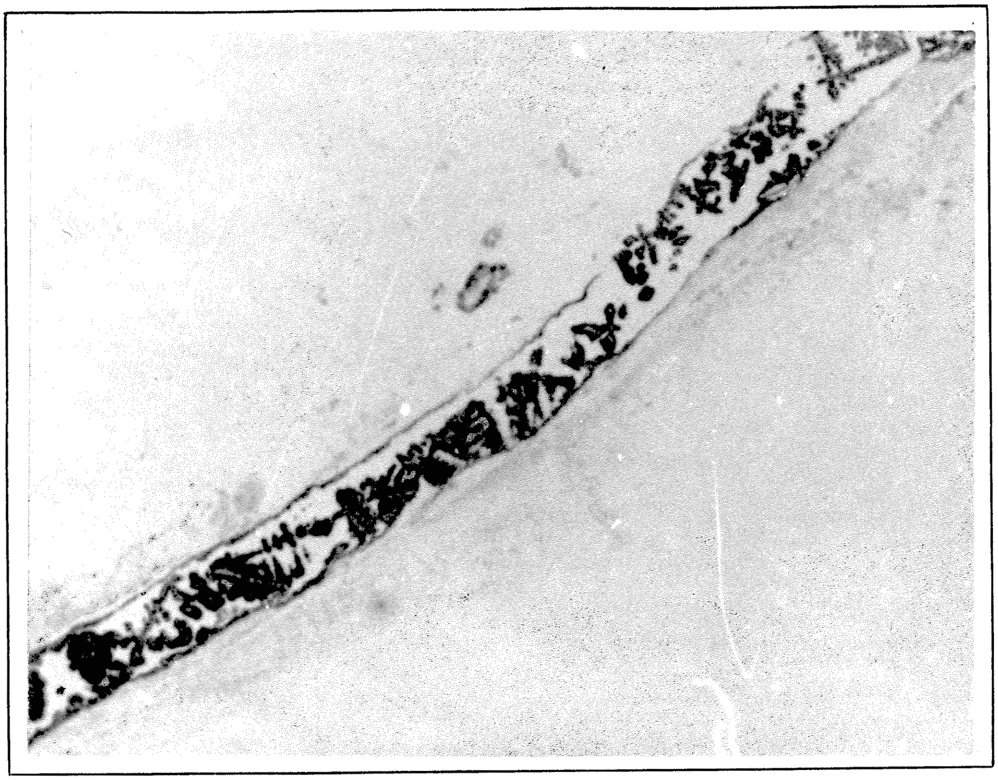


Figure 79. Veinlet of dendritic pitchblende partially replaced by carbonate. No. 7 Vein. 250 Level. x 1.6

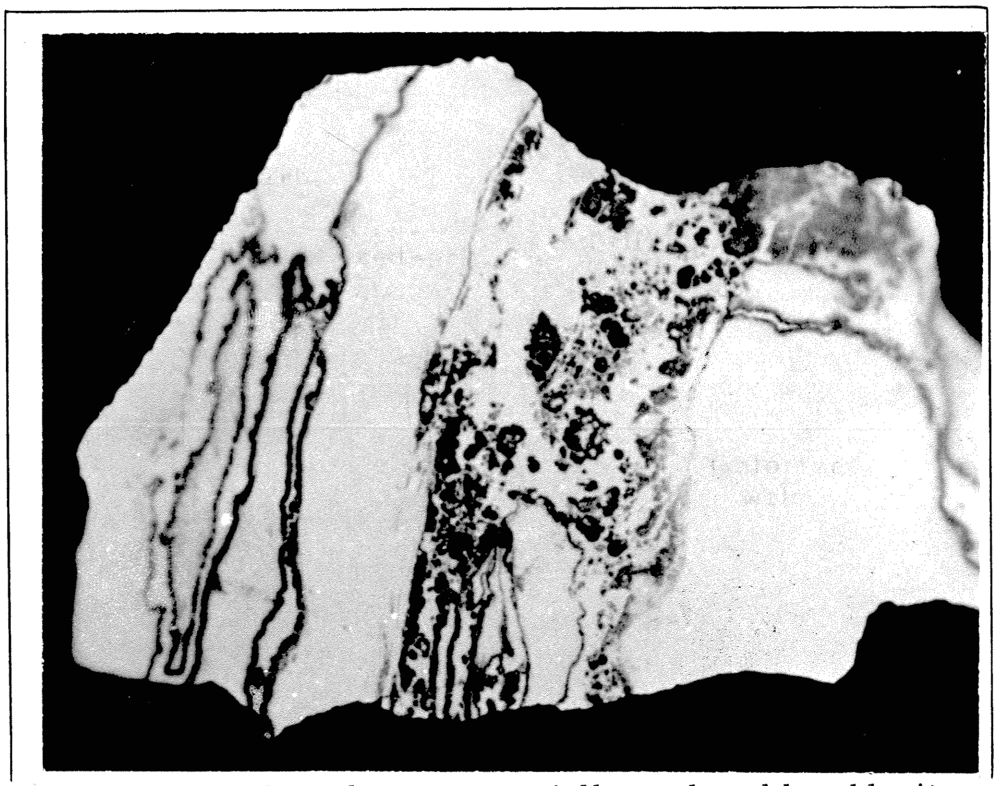


Figure 80. Pitchblende and quartz partially replaced by chlorite and carbonate. No. 3 Vein. 136 Stope. x 1.5

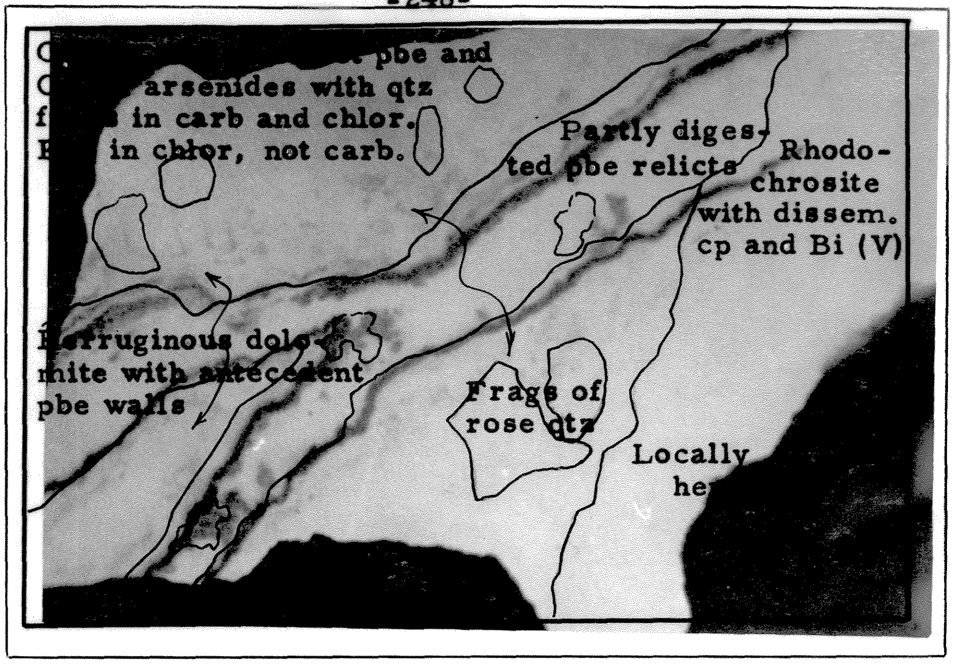


Figure 81. Relict pitchblende in late carbonate.
No. 1 Vein. 814 Stope. x 1

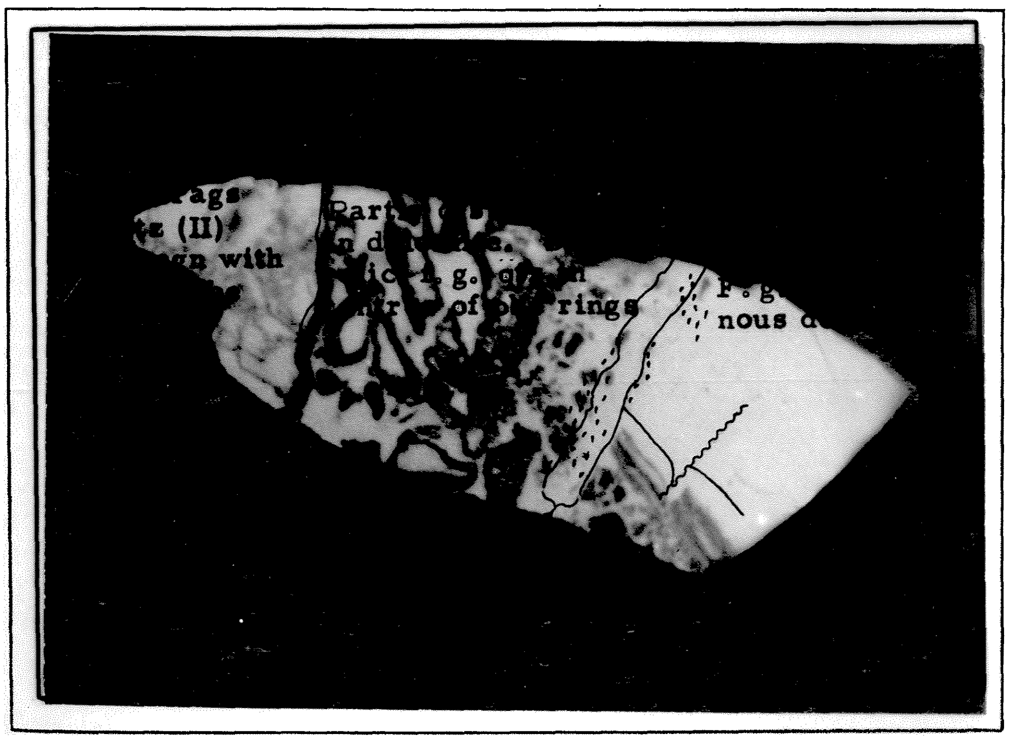


Figure 82. Moderately brecciated pitchblende in dolomite.
No. 2 Vein. 320 Subdrift. x 1.4

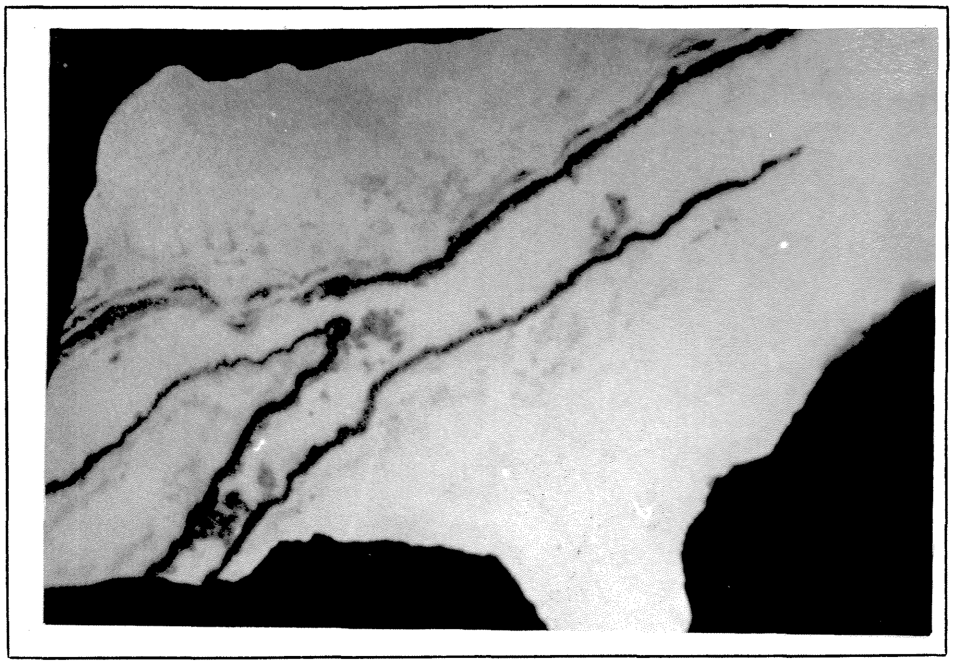


Figure 81. Relict pitchblende in late carbonate.
No. 1 Vein. 814 Stope. x 1

Figure 82. Moderately brecciated pitchblende in dolomite.
No. 2 Vein. 320 Subdrift. x 1.4

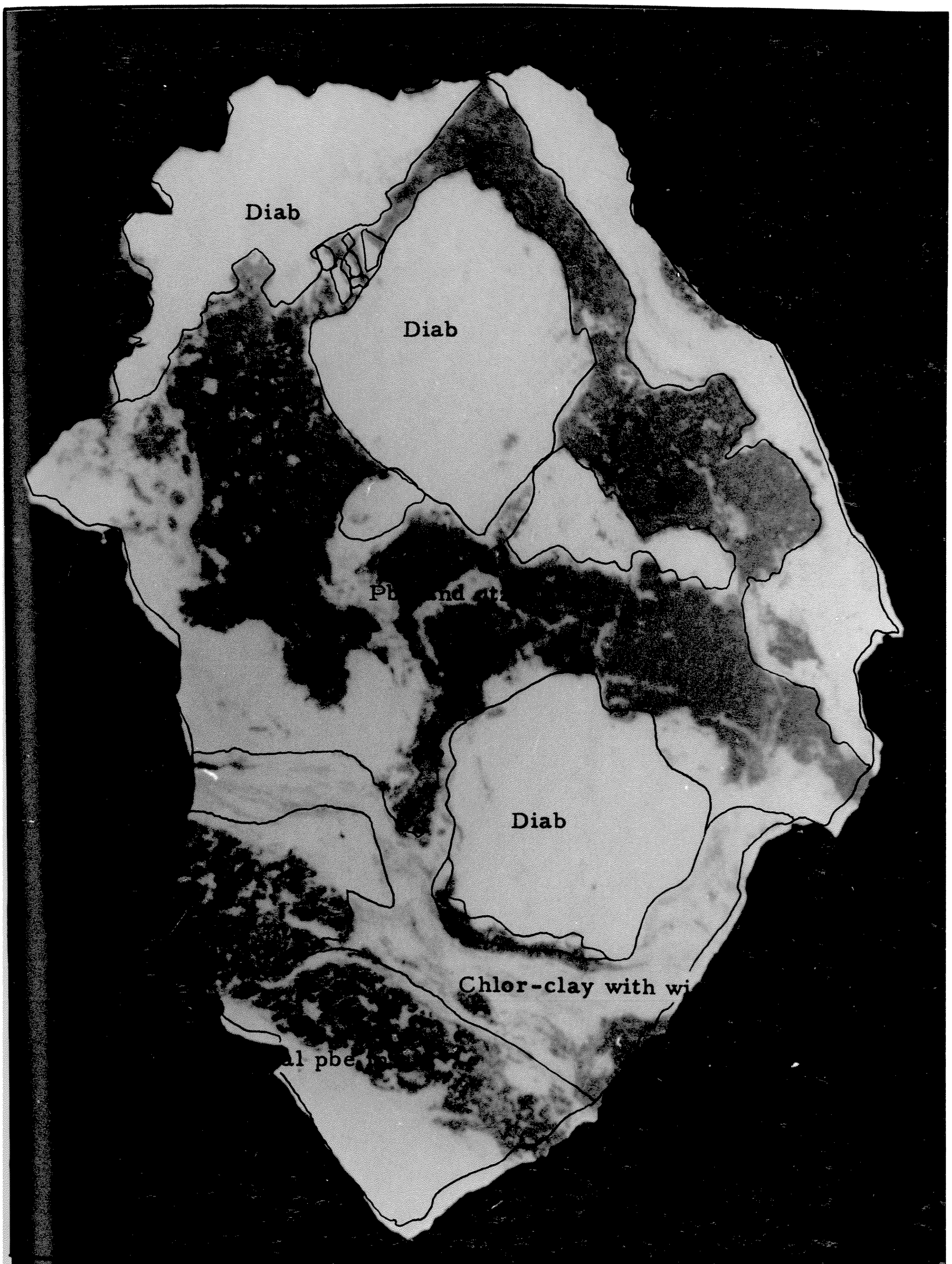
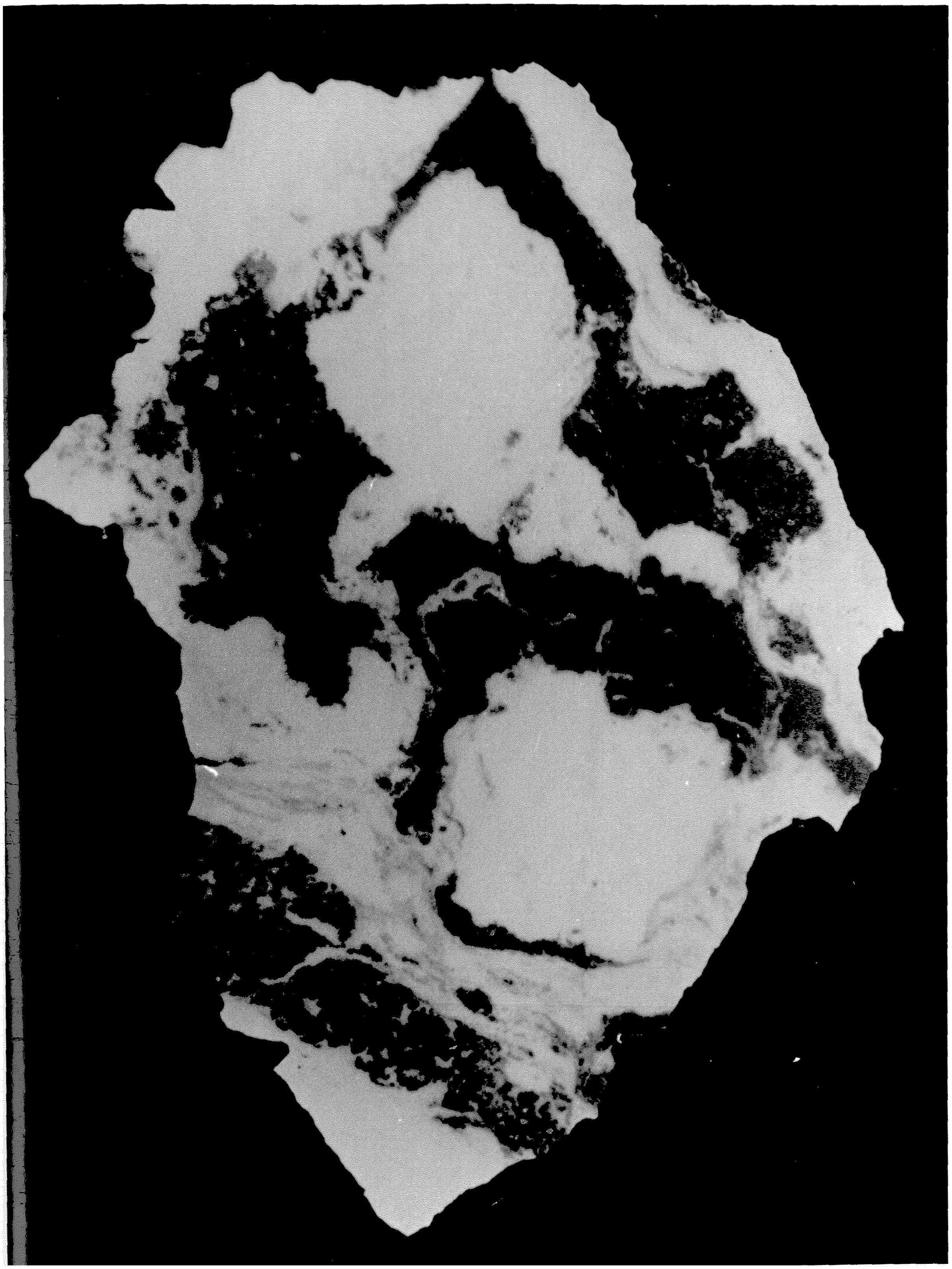


Figure 83. Brecciated wallrock in pitchblende. No. 3 Vein. 800 Level. x1.3



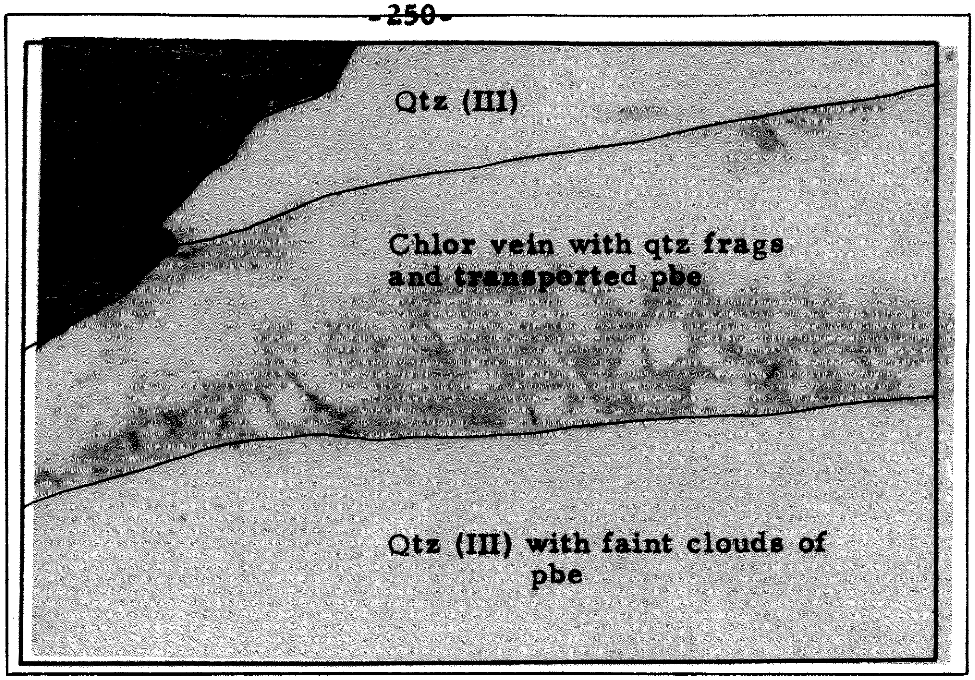


Figure 84. Relict pitchblende around quartz fragments in chlorite vein.
No. 5 Vein. 154 Stope. x 1.5

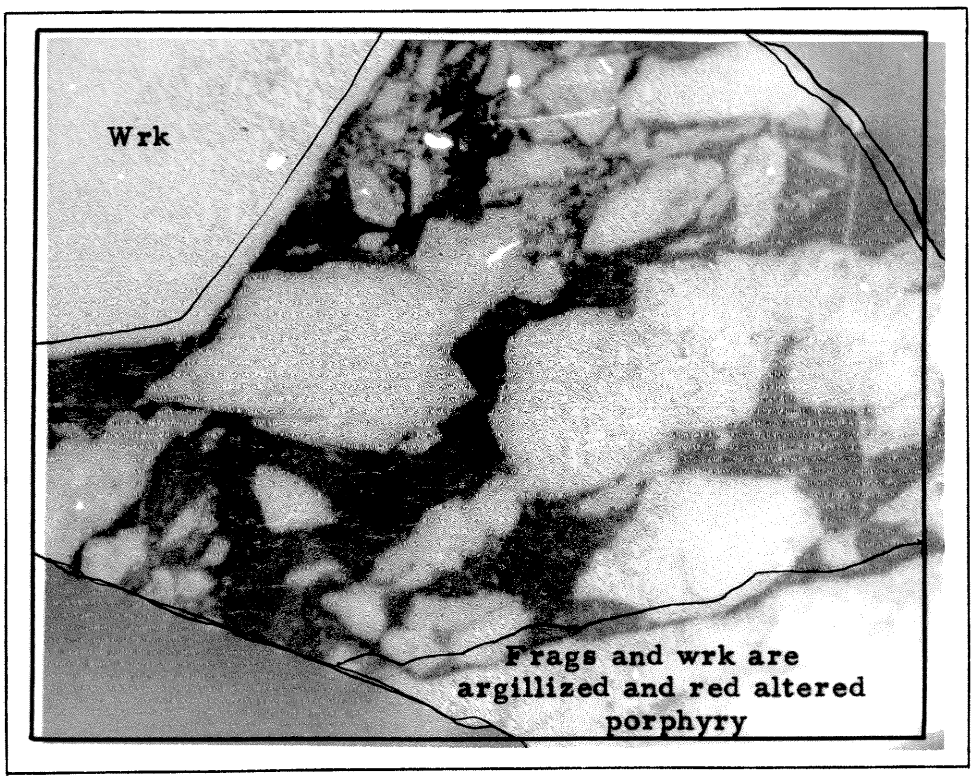


Figure 85. Primary pitchblende around fragments of altered porphyry.
No. 3 Vein. 1050 Level. x 1.5

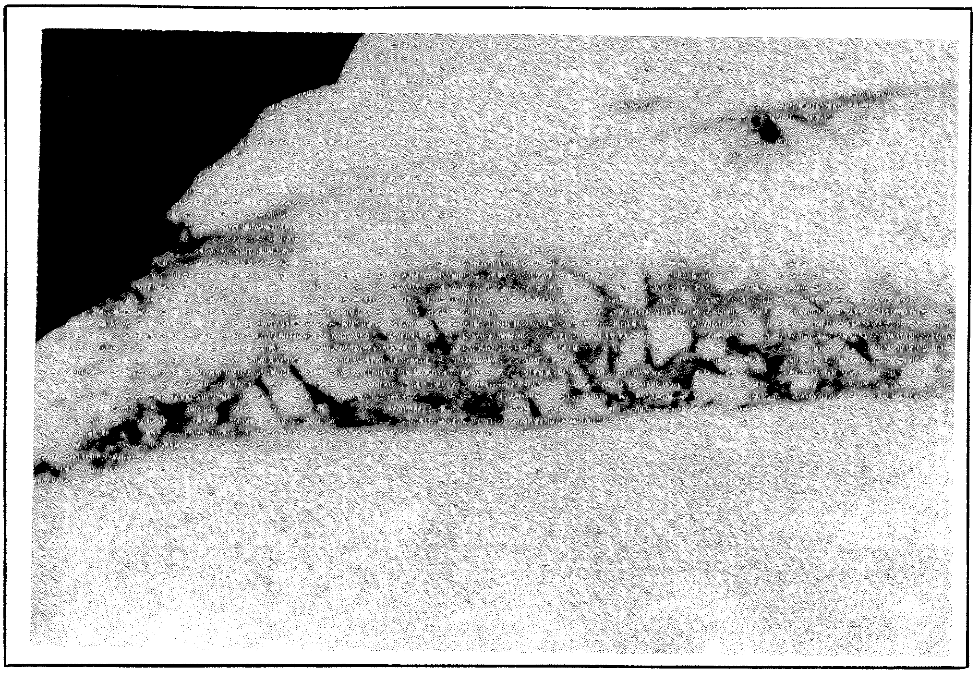


Figure 84. Relict pitchblende around quartz fragments in chlorite vein.
No. 5 Vein. 154 Stope. x 1.5

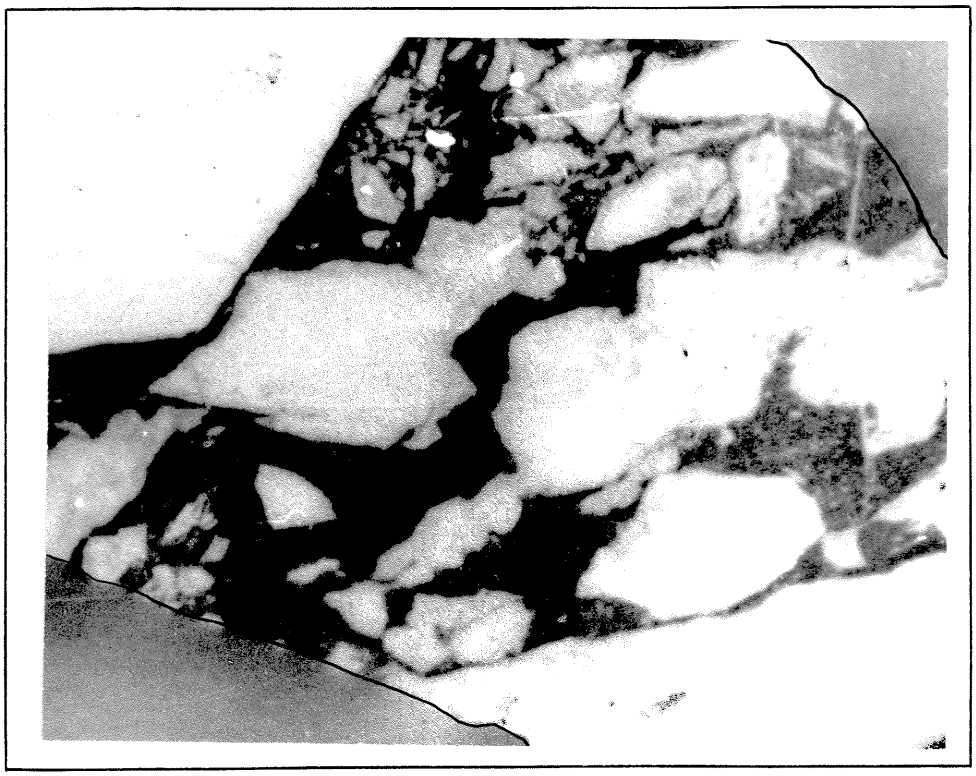


Figure 85. Primary pitchblende around fragments of altered porphyry.
No. 3 Vein. 1050 Level. x 1.5

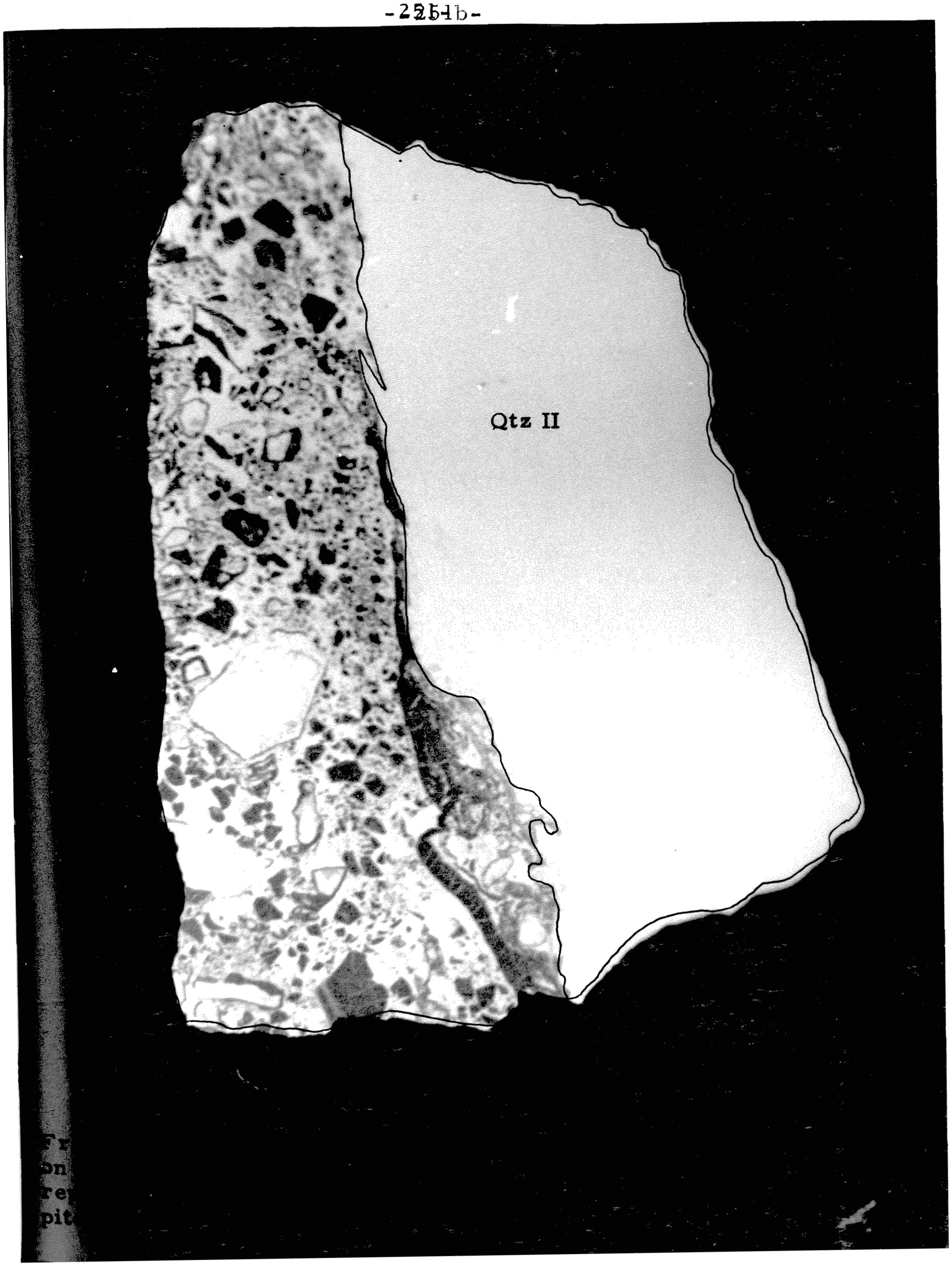
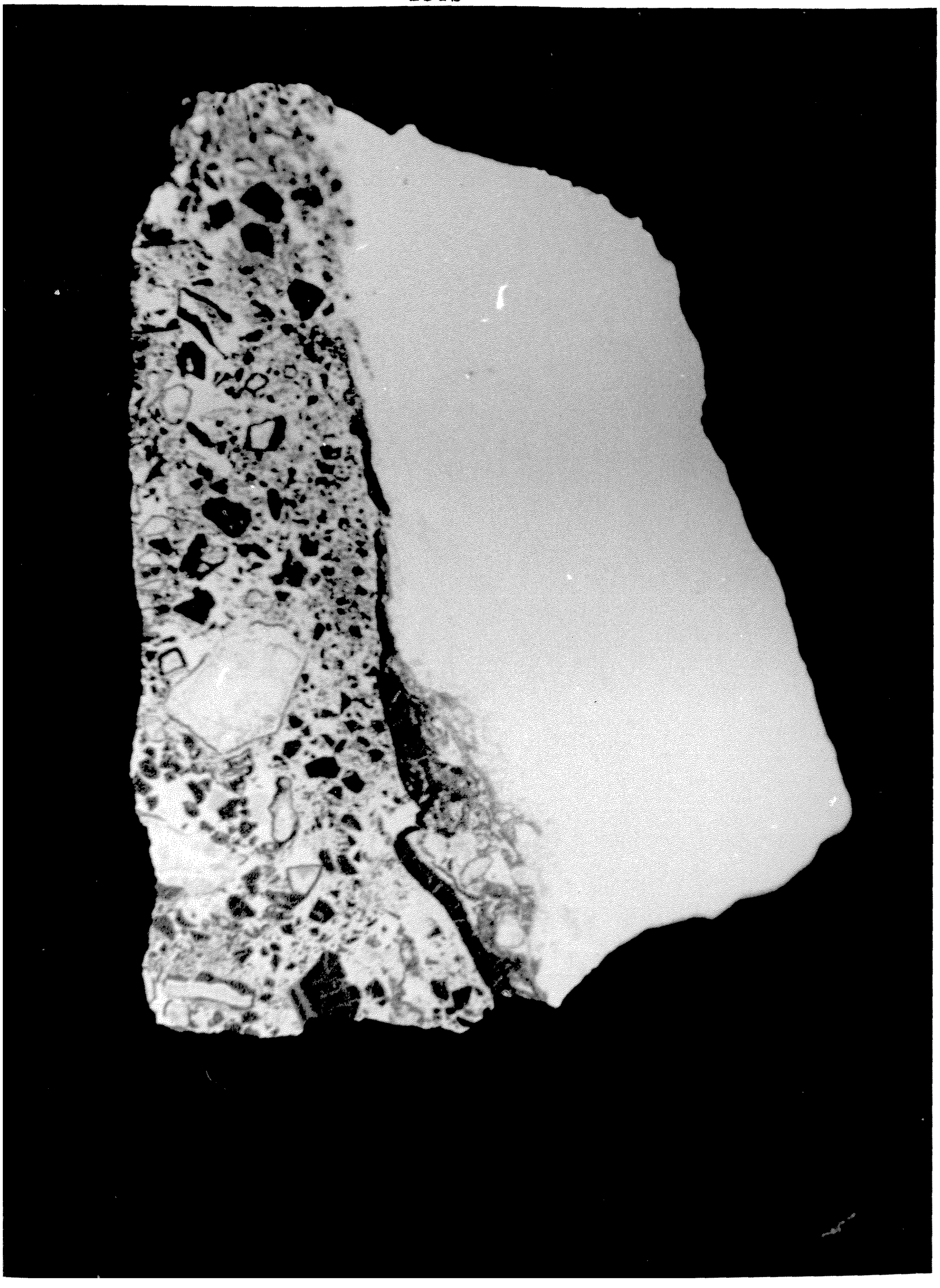


Figure 86. "Breccia ore".



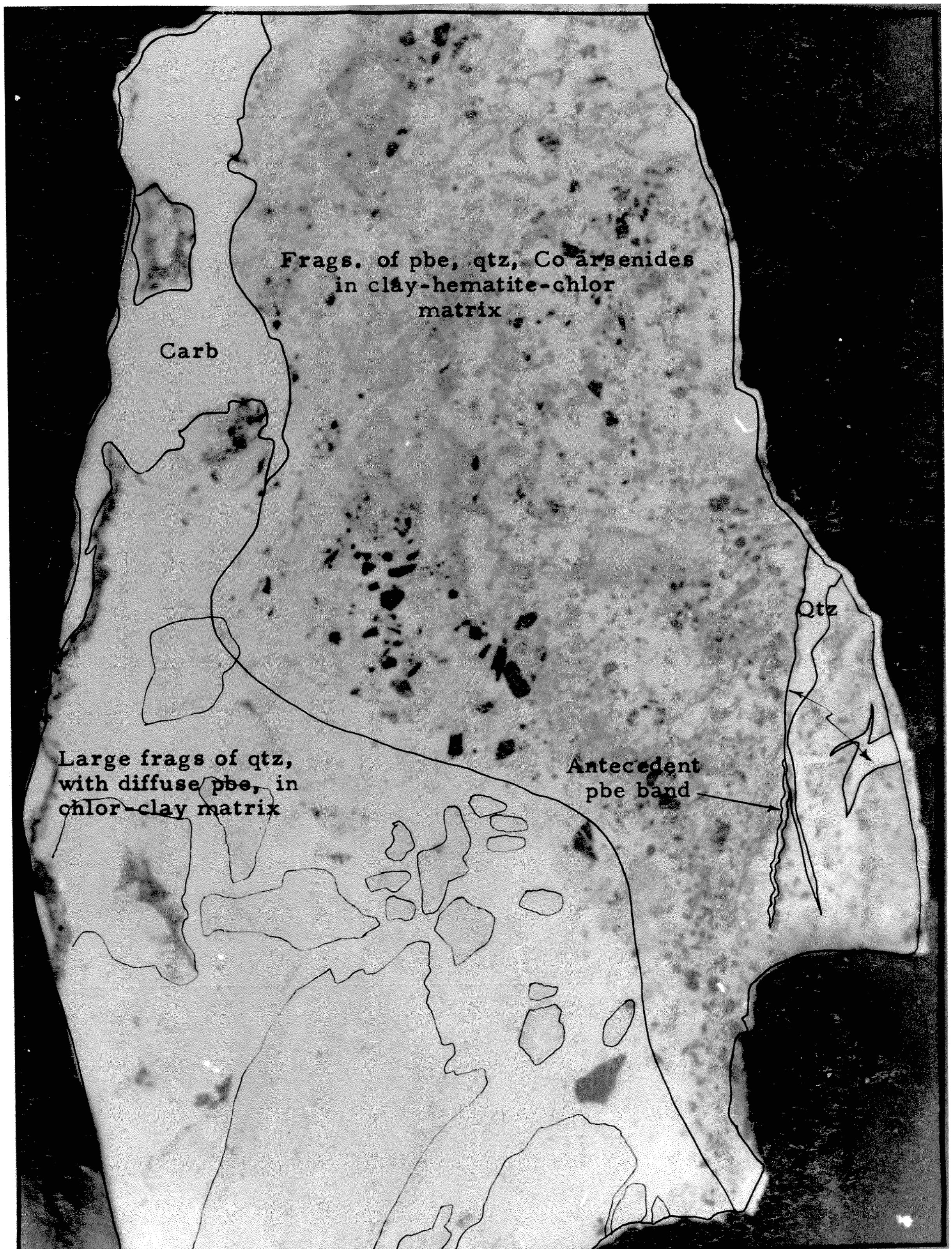
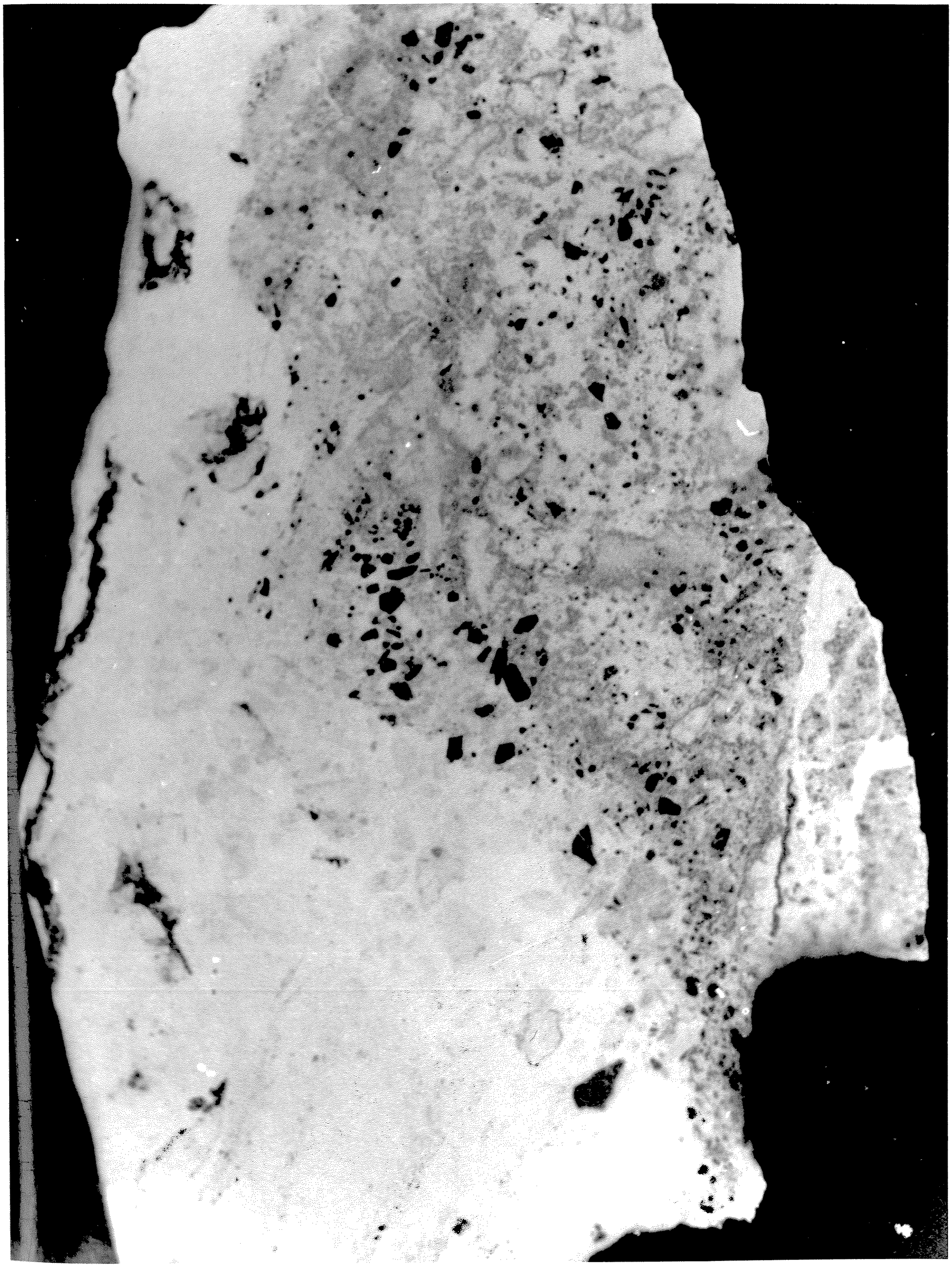


Figure 87. Typical "breccia ore". No. 3 Vein. 333 Stope x1.



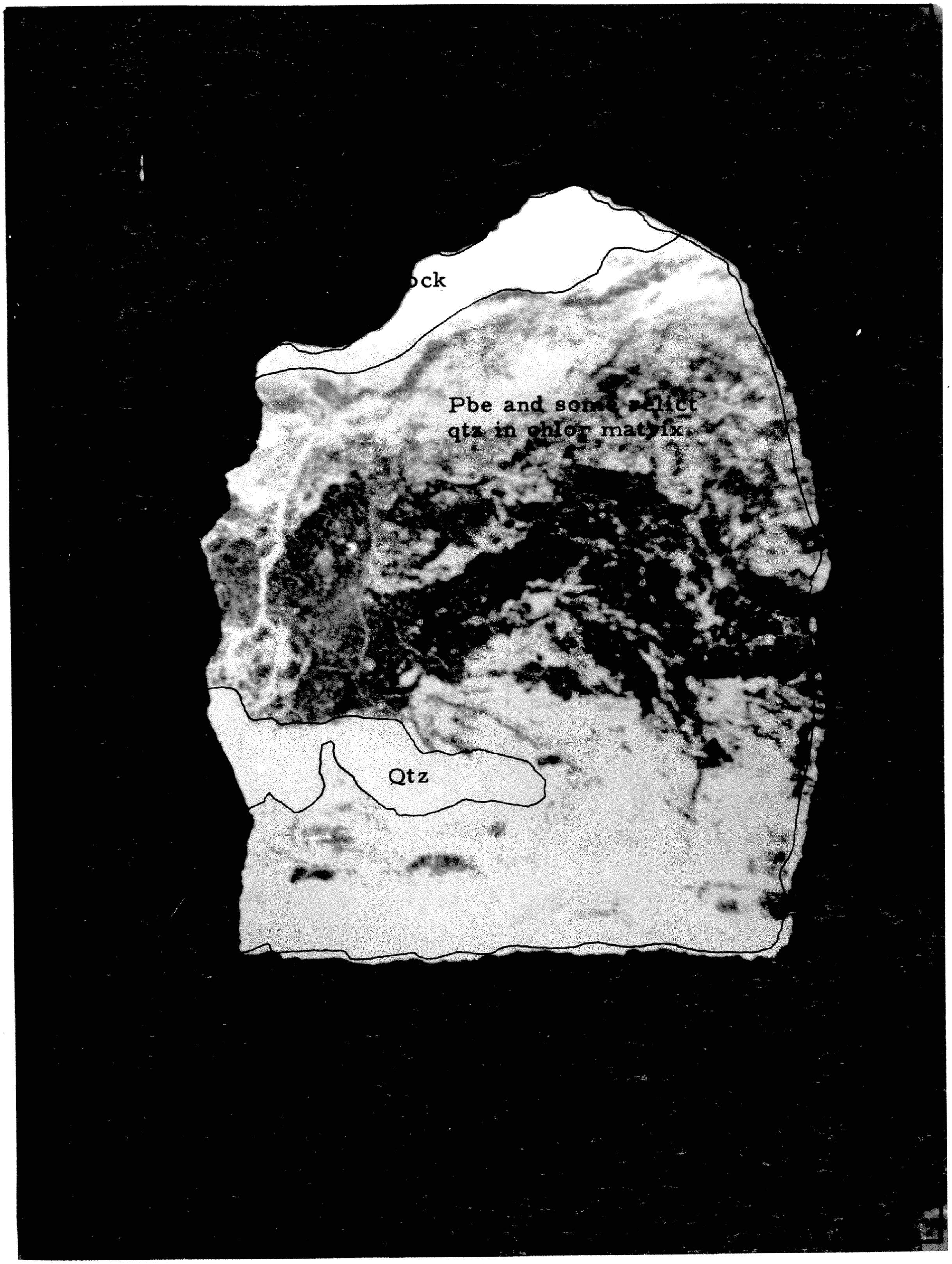
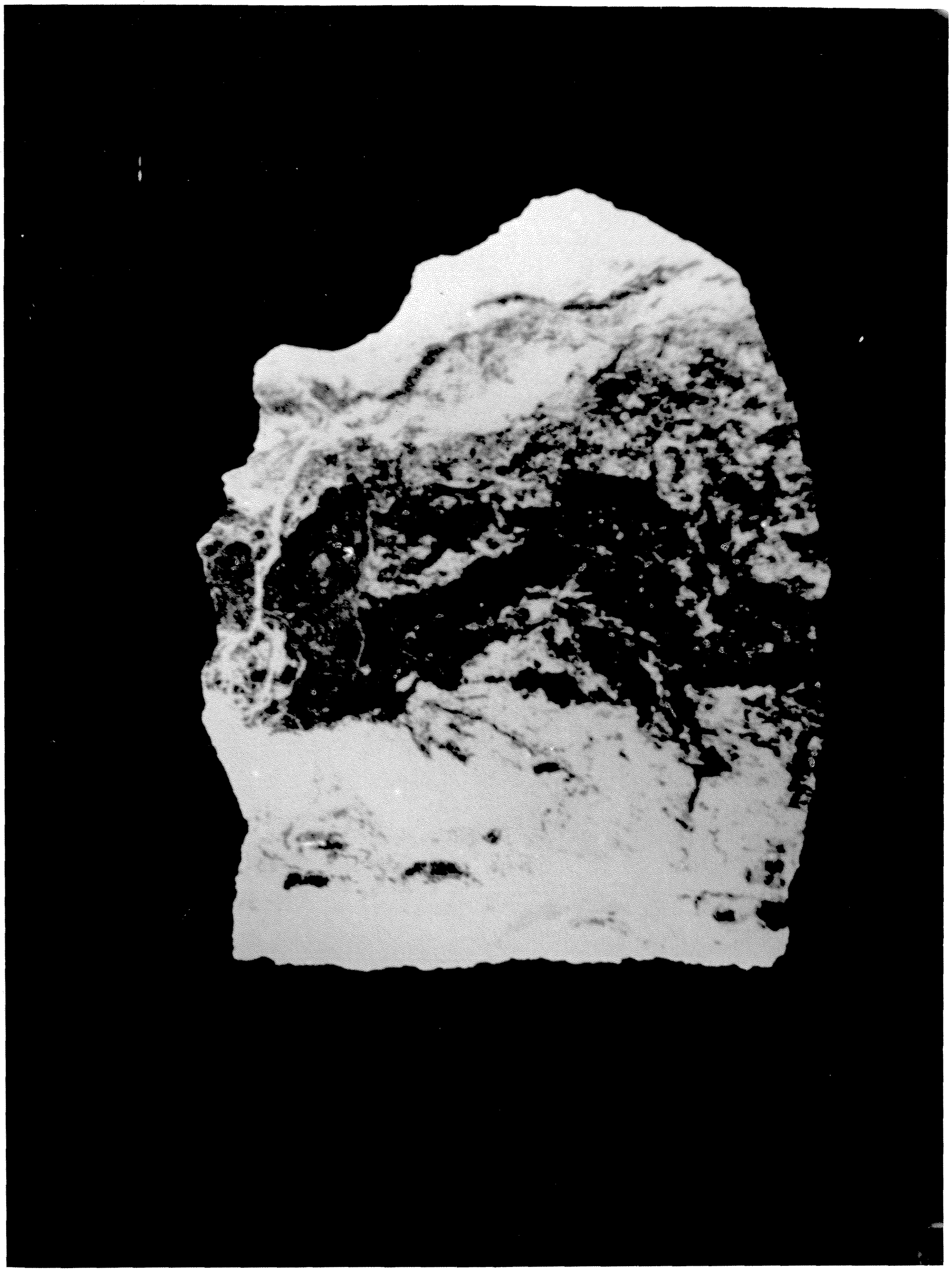


Figure 88. "Chlorite ore".



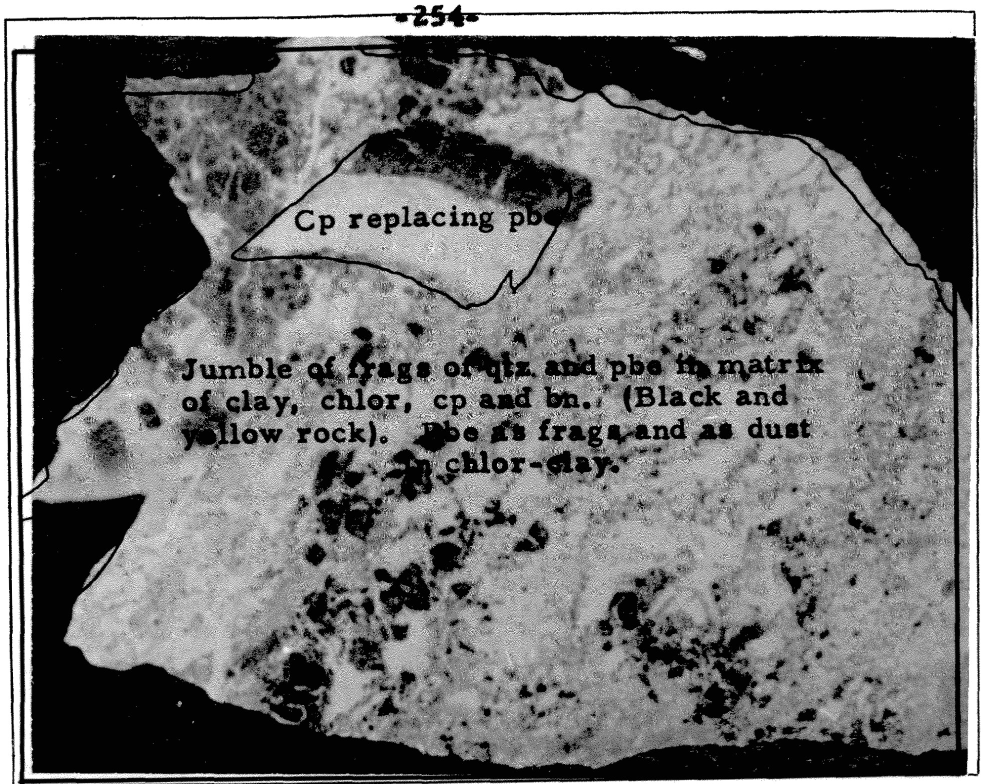


Figure 89. "Breccia ore", clay-chlorite-chalcopyrite matrix.
No. 3 Vein. 132 Stope. x 1.3

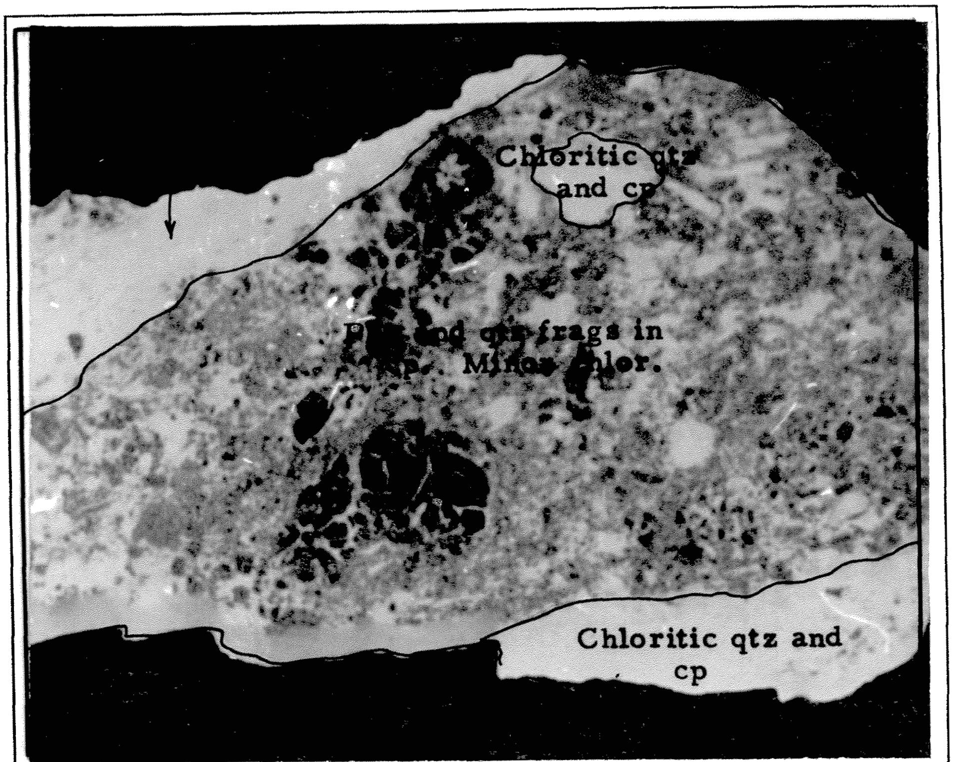


Figure 90. "Sulphide ore", pitchblende fragments in chalcopyrite.
No. 3 Vein. 132 Stope. x 1.3

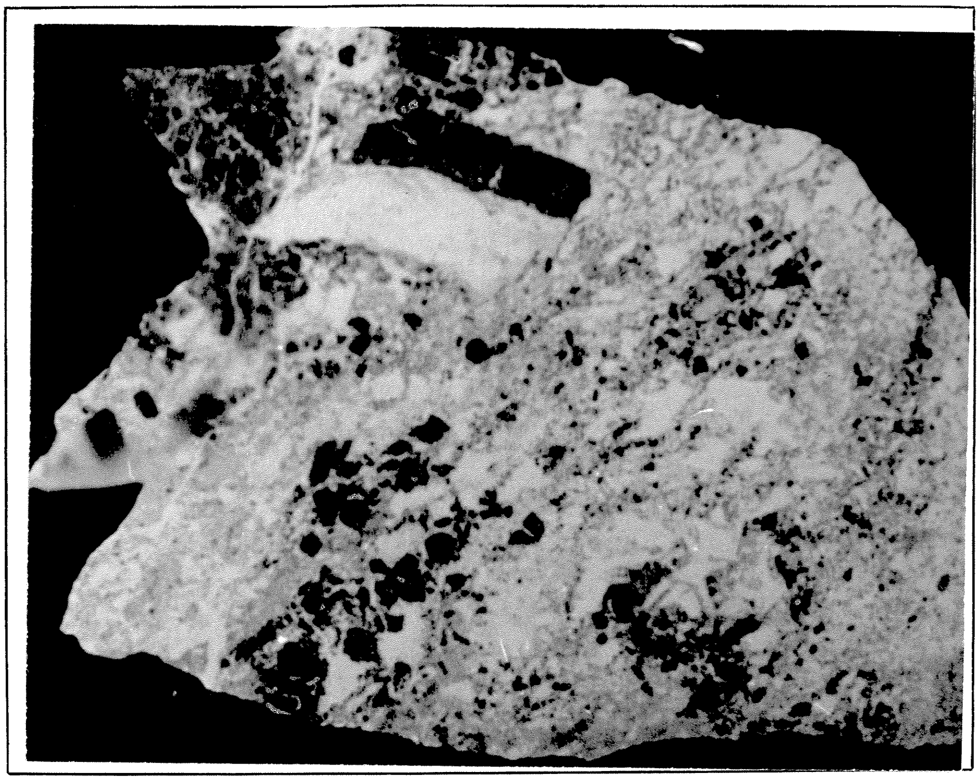


Figure 89. "Breccia ore", clay-chlorite-chalcopyrite matrix.
No. 3 Vein. 132 Stope. x 1.3

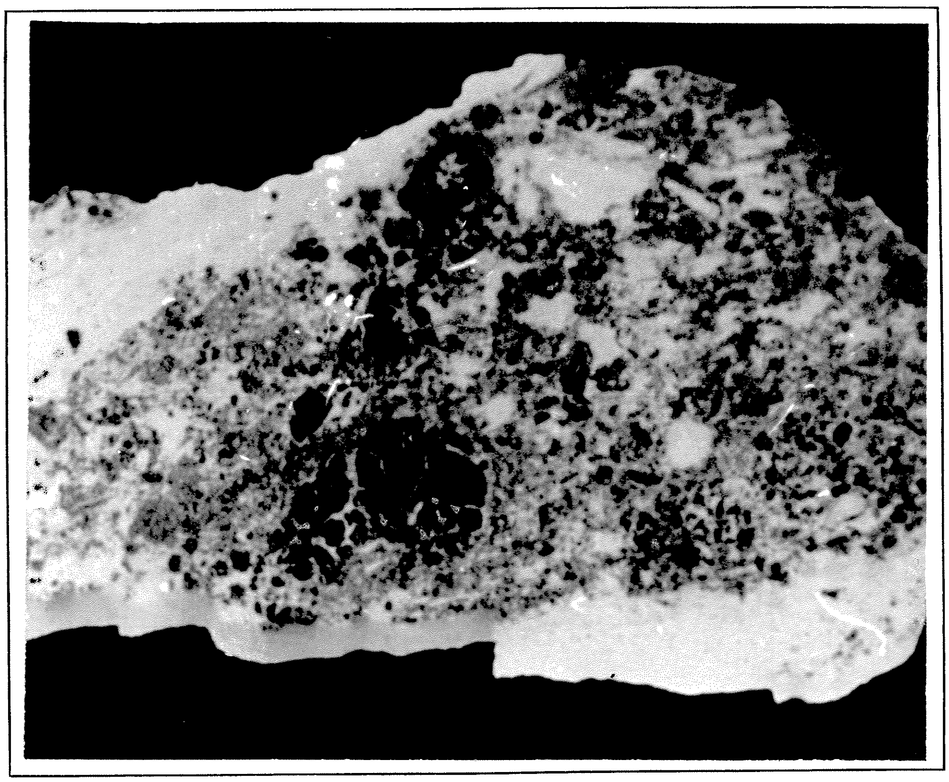


Figure 90. "Sulphide ore", pitchblende fragments in chalcopyrite.
No. 3 Vein. 132 Stope. x 1.3

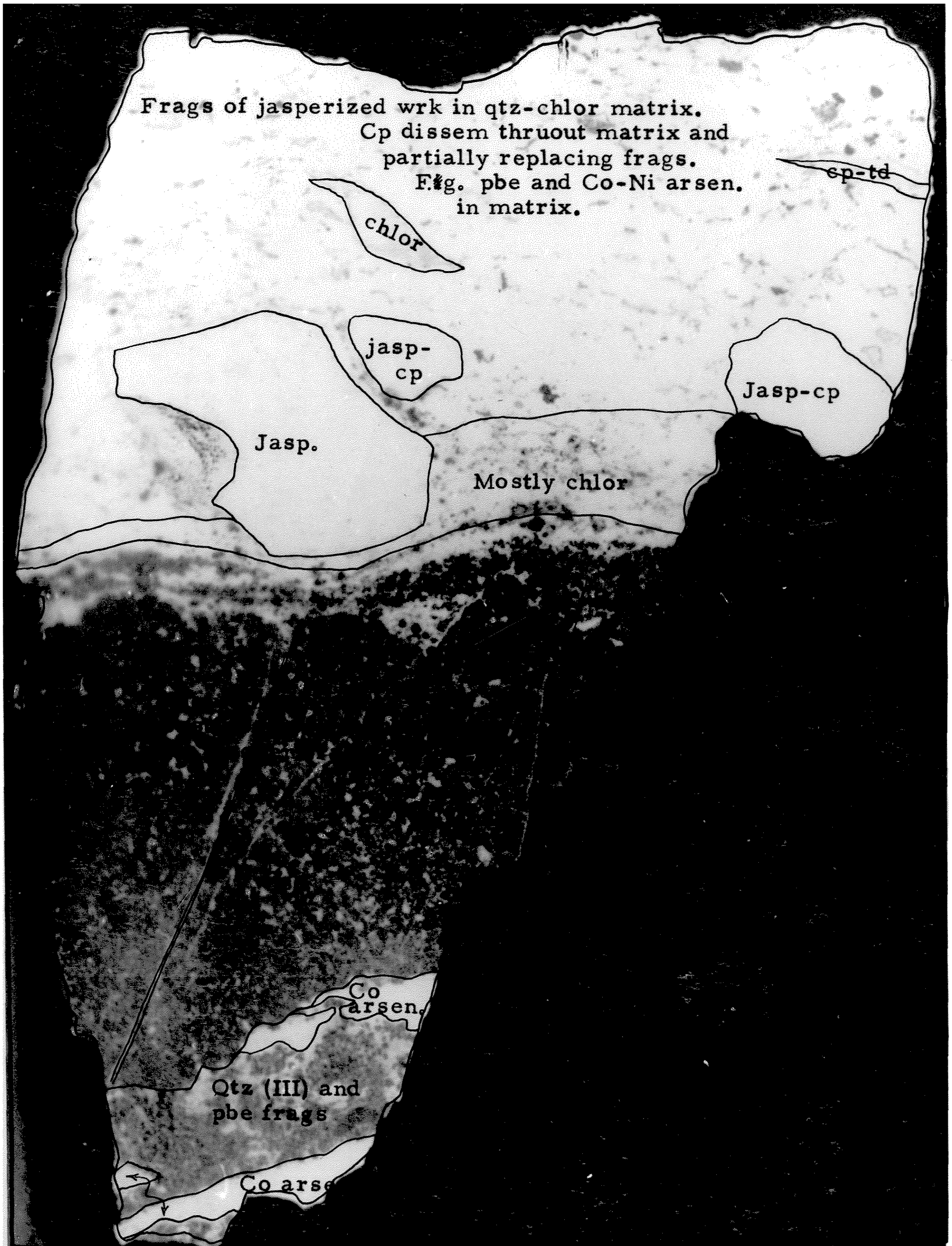
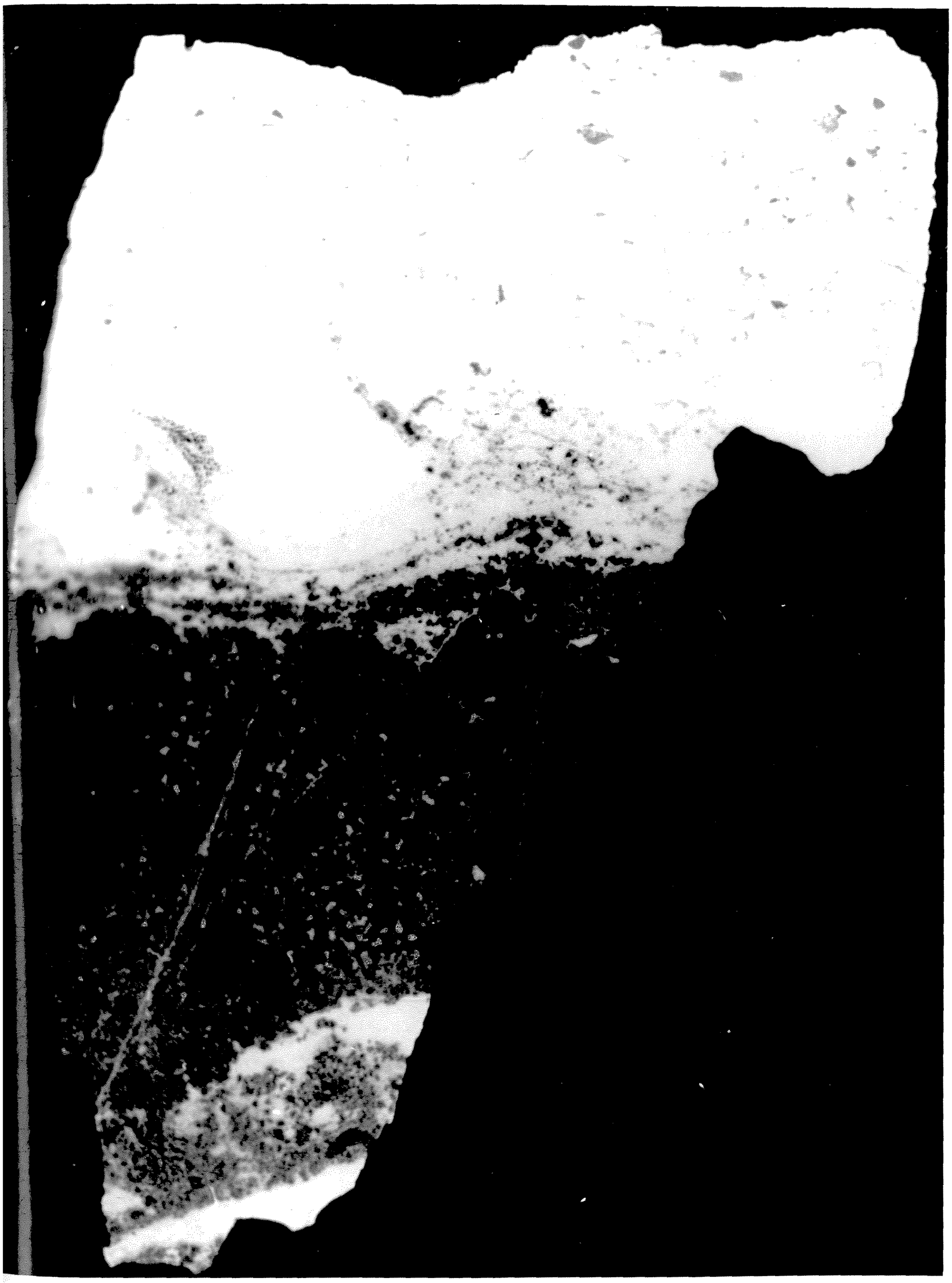


Figure 91: Massive pitchblende and "diffuse ore".
No. 3 Vein. 1050 Level. x1



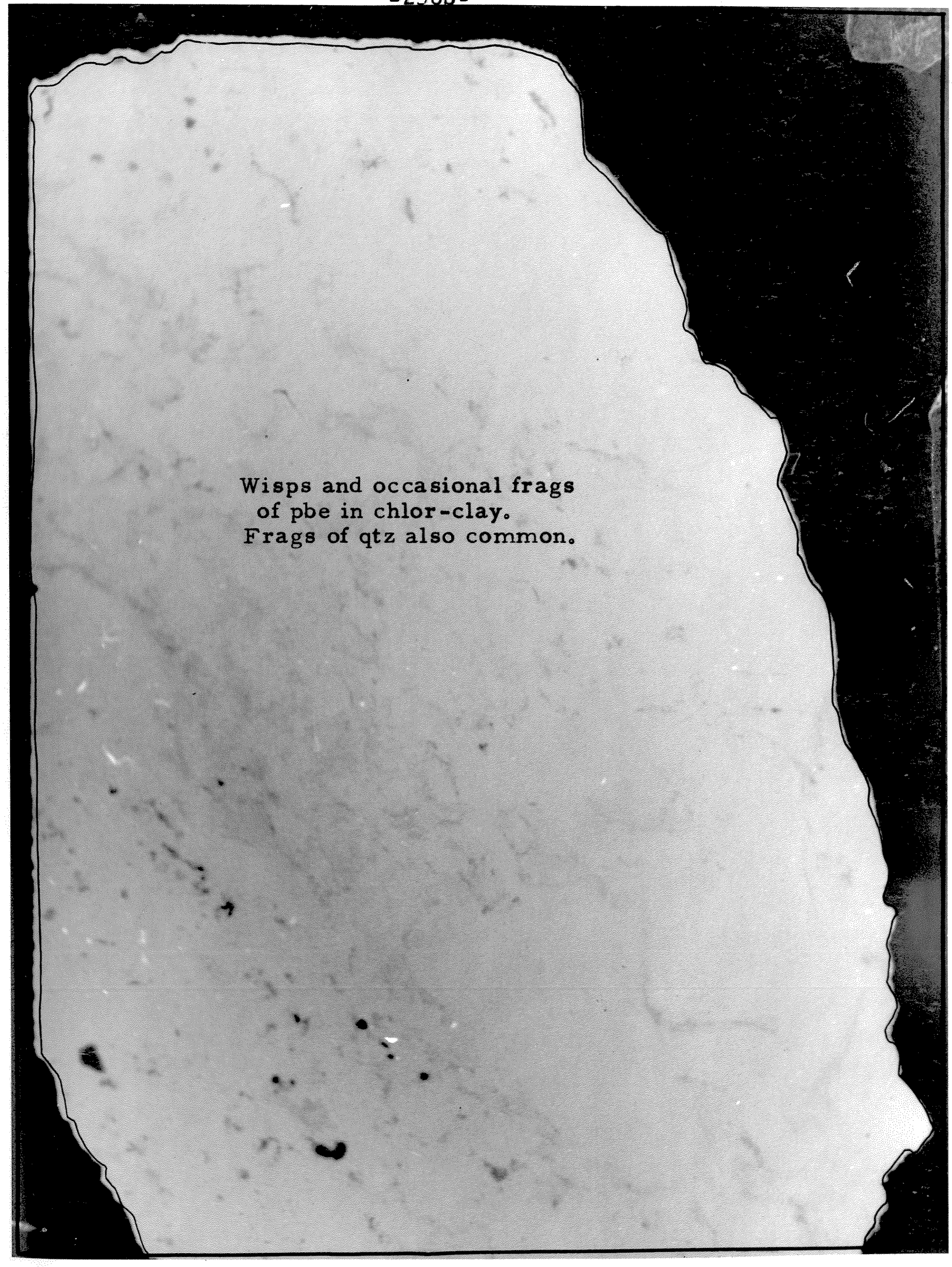
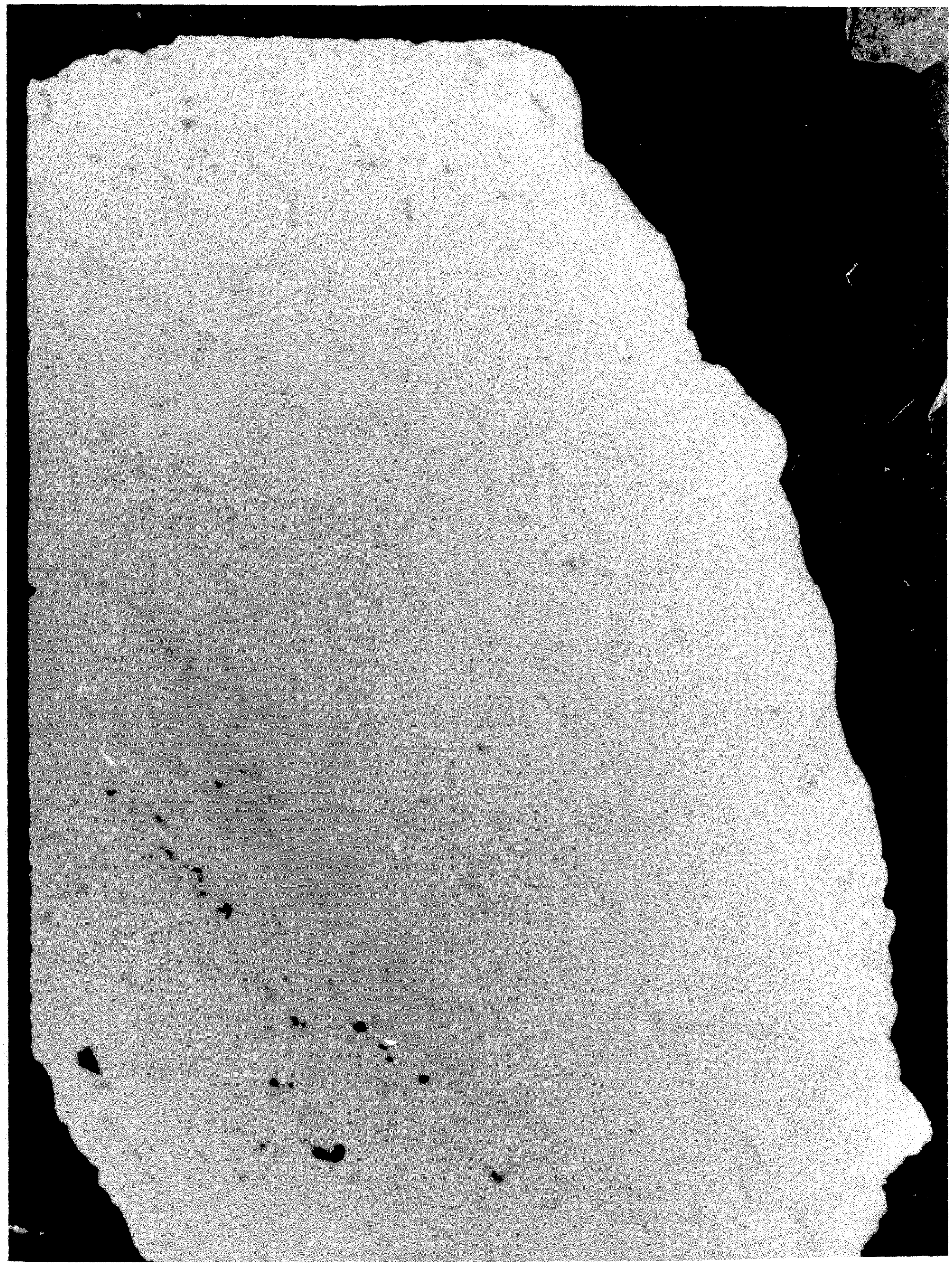


Figure 92. Very diffuse ore. No. 3 Vein. 1050 Level. x2



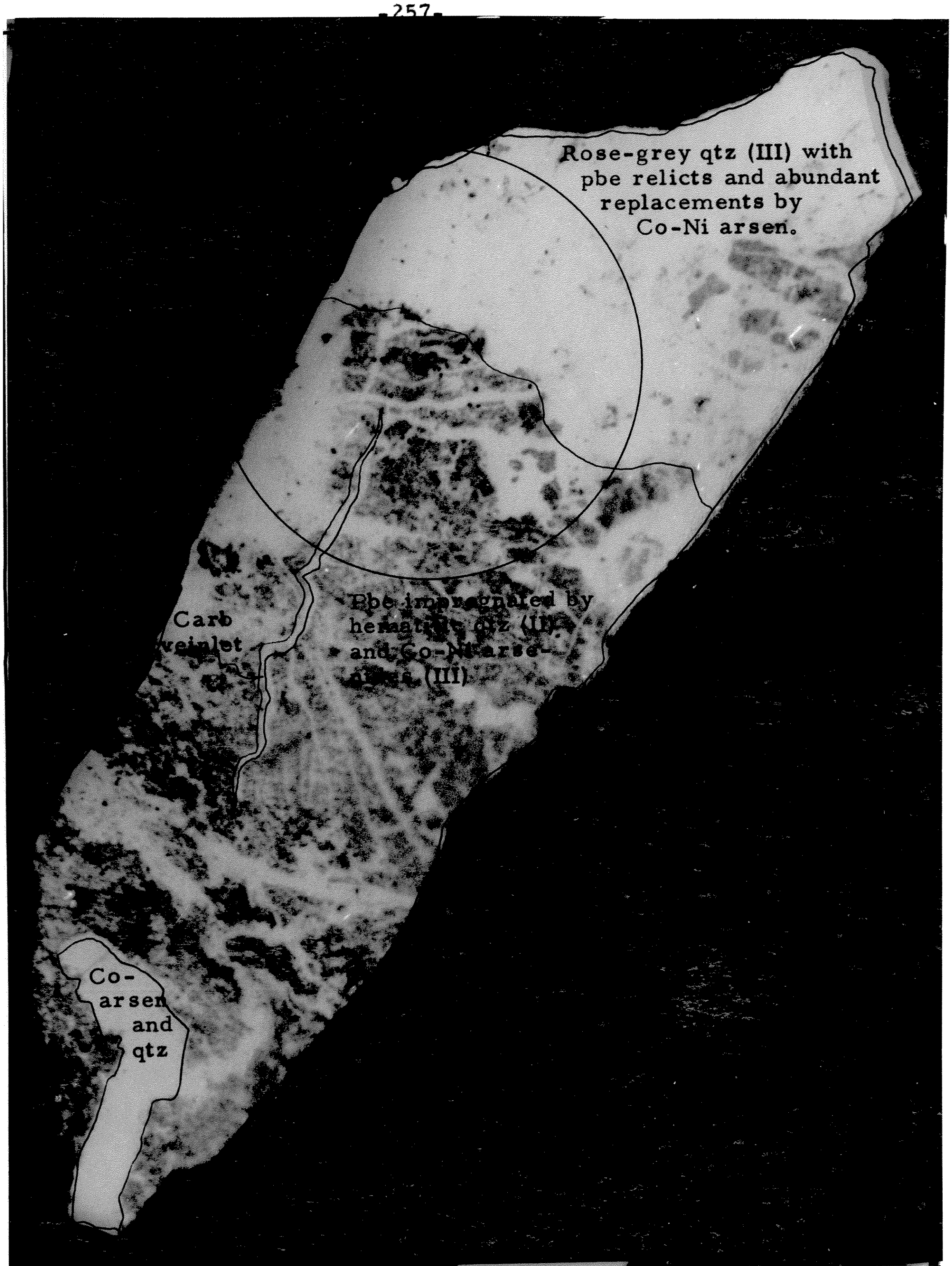


Figure 93. Radiocolloids in "breccia ore". No. 1 Vein. 814 Stope. x1.5

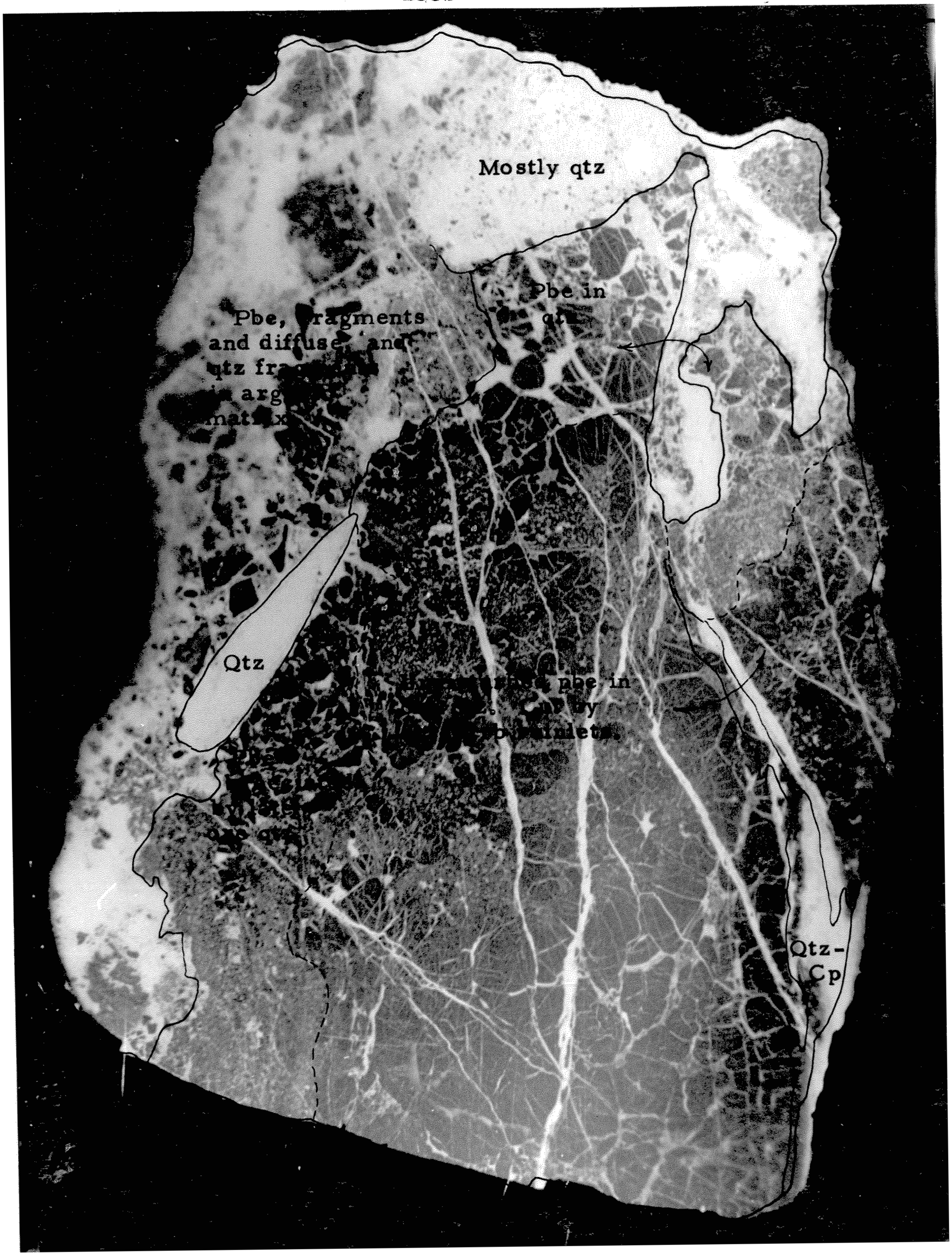


Figure 94. Undisturbed, brecciated and diffused pitchblende.

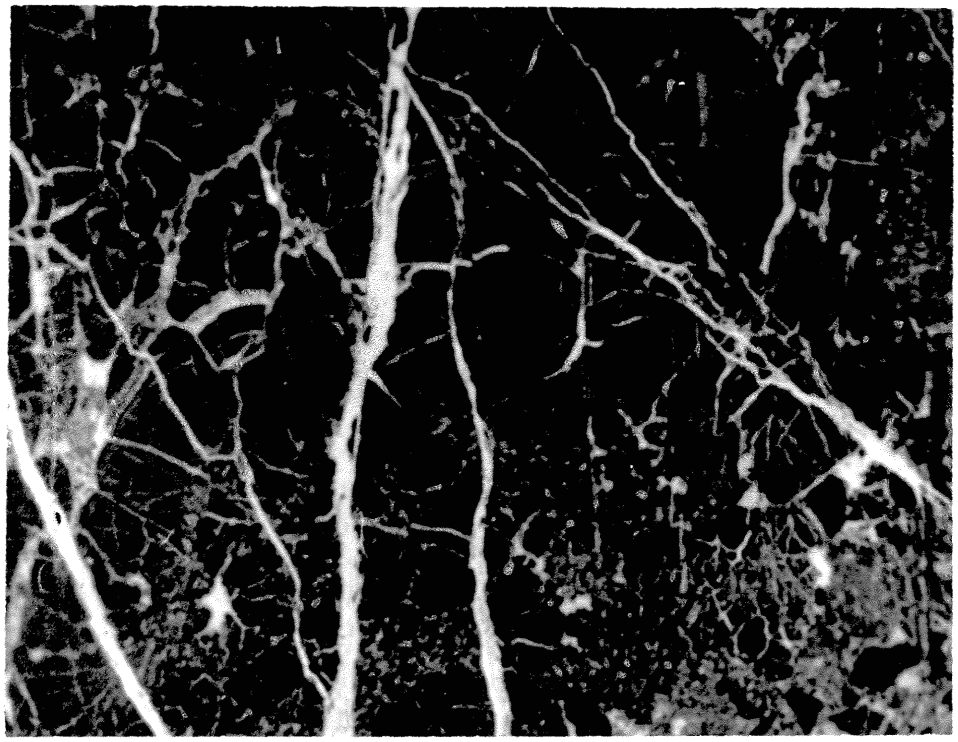


Figure 95. Pitchblende in situ. (Detail of Fig. 94).

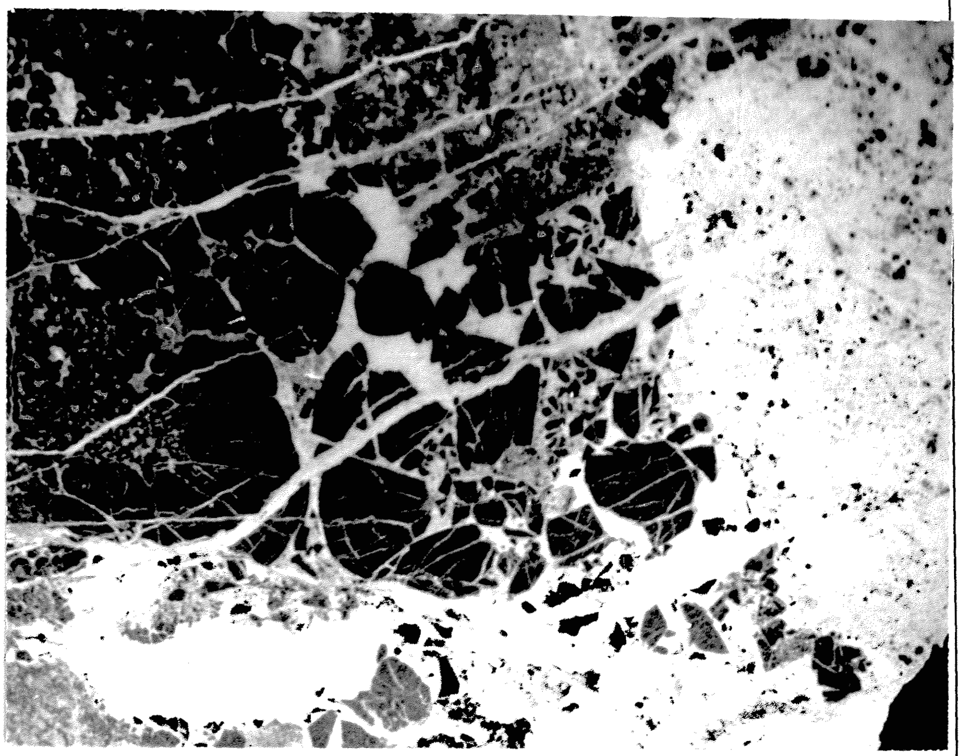


Figure 96. Brecciated pitchblende. (Detail of Fig. 94).

WALL ROCK ALTERATION

Hydrothermal wall rock alteration is common along all the major vein zones at Port Radium; nevertheless, no one type nor any combination of types is associated with the pitchblende occurrences closely enough to be used as an ore indicator. Locally, certain alterations partially envelop pitchblende ore shoots, but generally may occur elsewhere without pitchblende. This lack of spatial correspondence between ore and any particular alteration is due to the fact that the alterations and ore periods were separated in time. Replacement textures, both microscopic and megascopic, and differences in distribution indicate that the main types of alteration were separated from one another in time and are not the products of advancing waves evolving from a constant solution.

Wall rock alteration in the Port Radium area is extremely variable in distribution and intensity. A zone of alteration may be less than one inch in width at one place and over 50 feet in width at another place on the same vein zone in the same country rock. The walls of most of the main Port Radium vein zones are altered to some extent by at least one type of alteration. In non-vertical vein zones the alterations are extensive on the hanging wall but are meagre or non-existent on the footwall.

Contrary to previous conceptions, jasperization is neither widespread nor closely associated with the Port Radium pitchblende deposits, although portions of a few of the richest orebodies are flanked by this alteration. It was fortuitous that the original mining was done on No. 2 and No. 3 Veins at places where they are flanked by extensive jasperization. The apparent association of red alteration and pitchblende thus suggested has since been disproved by the exposure of many equally rich orebodies which are devoid of red alteration.

The principal alterations, from earliest to latest, are:

1. Red alteration
2. Argillic alteration
3. Chloritization
4. Carbonatization

Minor alterations include silicification, sericitization, sulphidization, and concentration of apatite.

There is very slight correlation in spatial distribution between the separate alterations and the metal mineralizations described in the previous section.

RED ALTERATION

The term "red alteration" is used in preference to hematitization or jasperization because it denotes the general effect on the rocks without being restricted by composition. Red alteration of wall rocks is very intense and extensive along portions of some vein zones at Port Radium but is not as widespread as the clay or chlorite alterations. It is a red coloration of the rock imparted by impregnation by hematite in dust-like particles. In thin section the altered mineral grains appear cloudy and covered with patchy smears of dust which in reflected light can be identified as hematite. The original texture of the rock is not destroyed even though the hematite may constitute 50 percent of the rock.

The red alteration occurs in three general types at Port Radium; red staining; jasperization; and hematitization. The red staining is no more than a light dusting of quartz and feldspar grains by hematite so that the rock is essentially unaltered except for the change in color to dull or bright red. Jasperization is essentially the same process, but the host is cherty rock and the impregnation by hematite dust converts it to fine grained red silica or jasper. At Port Radium the silica in the so-called jasper zones is derived from the original chert and little if any is a hydrothermal addition to the rock. Replacement by hematite is an end phase of the impregnation by hematite as dust-like particles and becomes so intense that the original minerals are unrecognizable, megascopically or microscopically, and in many instances the end product is very fine grained deep red or maroon hematite, usually cut by fine veinlets or lenses of specularite.

Influence on Host Rocks: Red alteration affects all rock types at Port Radium but is most intense and extensive in the banded chert and the feldspar porphyry. In its most intense development it changes the cherts to a massive, hard, bright orange-red jasper, commonly flecked with small white lenses of quartz derived from silicification. This extreme jasperization is, however, very local, and confined to the cherts and in most places vestiges of the original sedimentary banding are clearly preserved in the red altered rock. Moreover, later argillic and chloritic alterations usually modify the jasper zones by replacement along original bedding planes, re-emphasizing banding that the jasperization had obliterated.

The red alteration of the metasediments is like that of the cherts except that the hematite dust does not impregnate or is not visible on the ferromagnesian minerals. This results in red and black or red and green banded rocks.

Red alteration of the feldspar porphyry is locally intense and is so widespread that the porphyry for hundreds of feet from vein zones is generally cross-hatched by narrow red-stained bands that flank joints and fine fractures. The red alteration of the feldspar porphyry is an impregnation of the matrix feldspar grains by hematite. The feldspar phenocrysts are generally sericitized, and the ferromagnesian minerals may be chloritized, but are not usually altered red except along cleavages and microfractures. The altered porphyry is generally very fine grained, deep red and speckled with black and white altered phenocrysts. All gradations from this extreme red alteration to unaltered porphyry occur along the vein zones and at the outer fringes of the red alteration. The commonest type of feldspar porphyry in the Port Radium area has a slightly hematitic groundmass that imparts a brown or purple cast to the rock.

The effect of red alteration on the tuffaceous rocks is identical with that found in the porphyry except that the spotting by phenocrysts is absent.

Diabase is stained red in local patches near vein zones. The hematitization may be intense in the rocks flanking the diabase but negligible in the diabase. The alteration is one of dusting of the feldspar grains and a faint clouding of the augite by hematite.

Red alteration of the granite is locally intense and consists of red dusting of the feldspars and quartz with no appreciable change of the texture. The end product is essentially a red granite. Red alteration of aplite is generally less intense than that of the granite, the dusting of the feldspars being much lighter. Aplite near vein zones commonly shows evidence of granulation and in such rocks intergranular finely crushed material is extensively replaced by hematite.

Hematite dusting gives the pinkish cast to most of the rocks throughout the Echo Bay area. Most of this alteration cannot be related to the fracture zones in the area. The occurrence of red rocks is widespread in the western Canadian Shield and is everywhere due to hematite dusting. A commonly held explanation of this phenomenon is that the hematite originated in the pre-Cambrian iron-rich sediments and subsequent intrusive, metamorphic and hydrothermal processes caused it to be redistributed and/or concentrated in other rocks as well as the original sediments.

Distribution: Zones of red alteration have been overlapped and locally obliterated by later argillization, chloritization and carbonitization. Vestiges of the red alteration can be seen as patches in later alterations or, more often, as microscopic clots of hematite among the clay and chlorite mats and as local dusting of clay minerals. This type of hematitic argillic alteration is widespread throughout the Eldorado Mine and is evidence that the red alteration zones were at one time much more pronounced than they are at present.

Areas of intense red alteration, generally jasperization, of wall rocks, occur along the central and western portion of No. 3 Vein and No. 4 Vein; along some portions of No. 2A Vein and western No. 2 Vein; as patches along the western portion of No. 5 Vein; extensively, as jasperization, along No. 6 and 7 Veins; along No. 1 Vein as local extensive patches of maroon hematitization; and everywhere along the Bear Bay Shear as a wide zone of maroon hematitization.

Red alteration is found where there is no pitchblende in the adjacent vein zone and, conversely, most orebodies in the mine are not flanked by red alteration; nevertheless, it is striking that some of the richest concentrations of pitchblende at Port Radium are enveloped by intense jasper alteration zones, particularly on Nos. 3 and 7 Veins.

<u>Other Occurrences</u>: Types of red alteration of wall rocks occur in some degree in most of the known pitchblende deposits in the world. Invariably the habit is identical with that at Port Radium, namely an impregnation by microscopic hematite dust. Differences in host rocks result in many variations in appearance of the red alteration, but the feature of impregnation by dust-like hematite is the same.

Kerr[(45)] relates the more intense red jasper zones at the Sunshine Mine directly to the greater concentrations of pitchblende. He also proposes that the silica of the jasper was introduced and not derived from the host quartzites. These conclusions were drawn from very limited exposures along the one, very weak, pitchblende-bearing vein in the mine. This writer, in a cursory examination of the Sunshine Mine pitchblende vein, did not observe the close correspondence between red alteration and ore that is suggested by Kerr.

Red-stained vein dolomite in the Erzegebirge deposits of Czechoslovakia is reported to be used as a guide to ore[53].

Hematite staining of wall rocks also occurs in the Carrizal Alto deposits in Chile[53]; in the Montreal River deposits in Ontario[5]; and in the Prospector Mine of the Marysvale deposits[67].

Many types of hematitization occur with some of the pitchblende deposits in the extensive Lake Athabaska uranium province of northern Saskatchewan. Direct spatial relation of red alteration to pitchblende occurrences is evident in many places in the Athabaska area; however, both pitchblende deposits and red alteration occur independently.

In pegmatite deposits of Ontario[5] the rock surrounding some crystals of the uranium minerals is altered to a bright red colour.

Although the correspondence between red alteration and pitchblende occurrences can seldom be demonstrated conclusively in detail, the widespread general association of pitchblende and red alteration in the same deposits or districts is probably more than coincidence. There is a strong suggestion of a common origin for the two.

ARGILLIC ALTERATION:

Argillic alteration of the wall rocks at Port Radium is later than the red alteration which it extensively overlaps and replaces along the central and eastern sections of the vein zones. It is itself superseded by chlorite and carbonate alterations. Argillic alteration is the most widespread and the commonest alteration associated with the vein zones. Included in this alteration are variable amounts of carbonate and minor amounts of chlorite. In some places the carbonate and/or the chlorite become major constituents. These "soft" alterations are most extensive along the hanging wall of the vein zones and in the fine-grained metasomatized cherts. It is practically impossible to determine megascopically the relative proportions of clay, carbonate and chlorite in the soft alteration; therefore, the term argillic alteration is used for any type of soft, (green)-grey alteration. Argillic alteration zones are widest and most extensive along Nos. 1, 2 and 3 Veins, particularly in the eastern section of the mine. The zones are narrow or patchy along the Silver Island Vein, Nos. 5, 6 and 7 Veins and the Bear Bay Shear. Argillization affects all rock types in the area and tends to reduce them to a common product, a fine or silty grained, grey to greenish aggregate of clay, regardless of original composition or texture. The alteration ranges from a very slight softening and discolouring of the rock to complete destruction of original texture and minerals. The first evidence of the alteration is the destruction of the red colour of the rocks by reduction of the hematite dust. The argillized rock is commonly flecked by fine pyrite or chalcopyrite.

Microscopically the alteration appears as scattered patches or solid masses comprised of extremely fine shard-shaped grains or, occasionally, splintery flakes. The length of the individual grains rarely exceeds 0.10 mm and is usually much less than 0.01 mm. In areas of intense argillization, particularly where associated with chlorite, the clay minerals are coarsely fibrous. The mats or patches of the microcrystalline grains are colourless or very slightly green in colour, generally non-pleochoric, and exhibit interference colours up to middle second order. Where large grains were tested, indices of refraction were invariably lower than Canada balsam. The form, birefringence and index of refraction are characteristic of the montmorillonite group of clays.

Microscopically the clay is not difficult to distinguish from the chlorite on the basis of optical properties. Megascopically the two mineral types can be distinguished by the difference in the colour of the streak, if one mineral is sufficiently dominant; the argillic alteration gives a white streak, whereas the streak of the chloritic alteration is green. Chemical tests on the clay are complicated by the difficulty of isolating a pure sample; however, several fairly good samples were tested with the p-amino phenol reagent procedures as outlined by Hambleton and Dodd[68]. Good to doubtful reactions were obtained for the montmorillonoids; fair to negative for the illites or hydromicas; and slight to negative for the kaolin group. The presence of sericite was expected from the microscope work, but relative amounts are difficult to judge. Occasionally the kaolin minerals were distinguished in thin sections.

It is concluded that locally kaolin is intimately interspersed with the montmorillonite, but generally the predominant component of the argillic alteration is montmorillonite. Sericite occurs with the clays in minor quantities, but where the flakes are fine and interspersed with the montmorillorite shard-shaped grains the sericite is difficult to distinguish.

Influence on Host Rocks: Rock types are altered by argillic alteration in decreasing order of intensity as follows: fine banded cherts, diabase, porphyry, metasediments, granite, massive crystalline tuff, massive chert, and aplite. Intensity of alteration has been influenced as much by permeability as by composition, for the alteration invariably occurs along and out from bedding planes, joints and fractures. Argillic alteration is also common in horses or fragments of country rock within the vein zones. Intense argillic alteration zones are consistently wider in the sedimentary rocks than in the other rock types. The zones are generally narrow and discontinuous in the massive crystalline tuff, narrow but continuous and locally extensive in the porphyry and diabase, and relatively uncommon in the granite and aplite.

In homogeneous fine-grained cherts the argillic alteration replaces the rock more or less evenly. Near the outer fringes of the alteration zone the clay is scattered in patches of fine grains. These patches coalesce closer to the immediate locus of the altering solutions, and the chert becomes relict islands in a clay groundmass; ultimately no chert remains. The transition zone from relatively unaltered rock to a rock predominantly clay is rarely more than a foot wide and is knife-edge sharp in some places. This may be the case even where the argillic zone is 50 feet or more in width. Complete argillization of the wallrock occurs only immediately adjacent to the vein zones, regardless of the total width of the argillic zone.

Where the chert is partially or wholly recrystallized, the initial stages of clay alteration are represented by patches of clay interstitial to the host grains.

In metasediments the clay alteration preferentially replaces pyroxenes, amphiboles, magnetite and feldspars before attacking the quartz. A common product of partial argillization of metasediments is a rock comprised of clay and chert, all the metamorphic minerals having been destroyed.

In feldspathic rocks the clay appears first in the centers of the larger feldspar grains and progressively increases until each grain is a solid mat of clay. Generally the matrices of such rocks are replaced before the final vestiges of the large grains are gone. In the granitic rocks the feldspars are argillized completely before the quartz is attacked.

The pyroxene and magnetite of the diabase are the first minerals to be replaced by the clay minerals and may be completely destroyed many feet beyond the main zone of alteration. The feldspar is replaced in the same manner described for the feldspathic rocks. Argillic diabase is distinctively flecked with fine white specks which are clusters of leucoxene developed from the magnetite. The ferromagnesian minerals in the diabase and the granite are generally converted to either penninite or other chlorite apparently after the feldspars have been replaced by montmorillonite. In addition, sericitization of feldspars is common but merges with the montmorillonite. The quartz of the Port Radium granite is usually untouched by alterations, and the most extremely altered granite is a coarsely crystalline, mottled black-green and white, quartz-clay (chlorite) rock. The original coarse texture is rarely destroyed.

Distribution: Argillic alteration commonly occurs adjacent to the pitchblende ore bodies, although often in minor patches. Extensive argillization also occurs along barren sections of vein zones.

Since the pH of solutions of clay minerals ranges from 6 to 8[(49)], and since at Port Radium the clay alteration probably followed the pitchblende deposition, it would follow that, by the time of the clay alteration of the wall rocks, all the pitchblende had been precipitated. (See page 227). In most places the argillic alteration is in direct contact with the vein zones and seldom extends more than five feet, generally less than two feet, from the vein. Commonly, the argillic zone is absent or just a few inches wide. Its distribution along the vein zones throughout the mine is very discontinuous and patchy. In many places the vein zone itself consists of nothing but fractured argillized rock, and the unfractured wall rock is unaltered. Commonly, vein-zone chlorite grades out into wall rock argillization with no distinct demarkation between the chlorite and the argillization.

The components of the argillic zones, as mapped, are generally the same throughout the Port Radium deposits, i.e., clay, carbonate, and some chlorite, but local differences are common and include a considerable range of secondary components. Pyrite is a constant component,although in small amounts,[redacted] as disseminated fine grains. Hematitic argillic rock is very common, and the hematite content is great enough in many localities to impart a red streak to the rock. The hematite occurs as clots and interstitial networks among the argillic mats and appears to be remnants of earlier hematitization of the rock. Epidote occurs in megascopic quantities in the argillic zones only in isolated localities. Similarly, there are local areas of very high concentrations of penninite and a chrome mica.

A very widespread and locally abundant component of the argillic alteration is apatite. It occurs as disseminated microscopic grains, as patches up to several inches across or as partially replaced fragments. Apatite also occurs occasionally as a vein mineral at Port Radium. Apparently the apatite in the alteration zones and in the veins is metamorphic apatite that has been dissolved from the altered rock, redistributed, and concentrated by the argillizing solutions. It lies in an argillic groundmass and is invariably veined and partially replaced by chlorite. It occurs in concentrations in all argillic alteration in consistent spatial relation to the vein zones or source fractures. The amount and grain size of the apatite progressively increase in the argillic alteration from the outer fringe of the alteration zone inward to the immediate locus of alteration and reach a maximum development one or two feet from the fracture or vein. Closer to the locus the apatite is extensively replaced by chlorite and clay and within six inches of the locus there is none left.

<u>Comparison with Other Occurrences</u>: Argillic hydrothermal

alteration has been extensively investigated by Lovering[69] and Sales and Meyer[70] for the Tintic and Butte districts respectively, but literature concerning its association with pitchblende deposits is scarce.

Argillic alteration occurs in zones ranging in widths from a few inches to ten feet along pitchblende-bearing vein zones of Marysvale, Utah[67], Urgeirica, Portugal[53], and the Caribou Mine, Colorado[51][71][72]. It is of interest that, of the world's known vein-type pitchblende deposits, these three most resemble the Port Radium deposits in other features such as mineralogy and vein structure as well as alteration. The host rocks in these three deposits are granitic; therefore, alterations in them are similar to alteration of the granite in the western part of the Eldorado Mine at Port Radium.

Progressive alteration at Marysvale is described by Gruner et al[73] as occurring in stages, as follows:

1. Feldspar clouded
2. Feldspar converted to argillic minerals
3. Biotite converted to chlorite
4. Original texture destroyed.

The alteration at Urgeirica is described by Everhart and Wright[53] as occurring in three zones:

1. Altered granite, quartz, pink potash feldspar, unaltered muscovite, and a green sericite mineral near the veins.
2. Biotite and plagioclase progressively replaced by green sericitelike mineral, 6" - 10' from vein.
3. Argillization of feldspar.

This is analogous to the Marysvale alteration but differs from that at Port Radium in having well defined zones.

At the Caribou Mine, Colorado, Wright[51][72] described zones of alteration similar to the above zones, with the addition of a zone of bleaching (sericitization and silicification) a few inches in width, adjacent to the wall of the vein. Beyond this bleached zone lie an argillic zone, a sericitic zone, and a chloritic zone, each zone being less than one foot in width. This is essentially the same as the Butte zonal sequence of alteration. This series of zones, in such orderly arrangement, occurs only very locally at Port Radium.

At Port Radium, as at the porphyry copper deposits[74], the sericite and quartz alterations are superimposed upon the earlier argillic alteration but in many places are absent. Consistent widths of the different zones, such as those at the Caribou Mine, do not occur at Port Radium. The zones described by Wright pertain to one section of a vein exposed in a drift 40 feet in length, a very limited exposure on which to base generalizations regarding alteration zones. King[71] describes the alteration on both this and other veins at the Caribou Mine as argillic zones ranging in total width from a few inches to ten feet. This more nearly corresponds to the conditions found at Port Radium. Along the 20 miles of drifts at Port Radium zones like those described by Wright occur at intervals, but so do many variations of these zones. No one alteration or combination of types of alterations is typical of all vein zones, of one vein zone, or even of the ore-bearing portions of the vein zones, at Port Radium.

At Port Radium it is evident that argillic wall rock alteration is not closely related to the pitchblende orebodies. Taylor and

Anderson[67] also cite the lack of close relation in the case of the Marysvale deposits.

CHLORITIZATION

Chloritization is slightly less widespread than argillization at Port Radium. Although these two types of alteration are closely associated, one seldom occurring without at least small amounts of the other, the chlorite is more generally and more intimately associated with carbonate alteration. The chlorite occurs in three forms, each representing a different stage and type of chloritization but all later than Stage III of the mineralization sequence.

The earliest chlorite is the most widespread and constitutes a major hydrothermal alteration. Microscopically, it is in very fine-grained flaky mats and fretted patches generally associated with the clay minerals, but younger than them. It is bright green, pleochroic, and has low first order interference colours.

The second most abundant type of chloritization is a veining and replacement by penninite. This variety of chlorite is widespread and locally in large quantities. It occurs as late veinlets, lattices and patches composed of fine or coarse flakes or plates, averaging 0.10 mm in width. In thin section it is greenish-grey in colour and has distinctive grey-blue interference colours. The penninite is later than the chlorite mats. In the feldspar porphyries, an earlier age of penninite is cut by later hydrothermal chlorites. This very early penninite is probably related to the late fluids in the porphyry magmas (see page 104).

The third and least abundant type of chlorite is in the form of microscopic veinlets with quartz. These veinlets are found everywhere along the vein zones but seldom comprise more than a fraction of one percent of the rocks. They represent the last phase of chloritization.

In the vein zones chlorite is a widespread constituent and locally is the only hydrothermal mineral. In these places it is relatively coarsely crystalline in solid aggregates of sheaflike grains that completely replace the rock. It is present in various amounts in the argillic alteration and is often concentrated at the outer fringe of the argillic zone. Locally it replaces extensive sections of wall rock, and, in such places, is usually directly related to secondary shears. The chlorite is easily distinguished when it is a major constituent by its greenish streak. Where chlorite is a major constituent the rock is invariably enveloped by slickensided fractures.

Sometime before or during the stage of chlorite formation in the vein zones, Stage IV, the extensive chloritization of the wall rocks was brought about.

Influence on Host Rocks: All types of chlorite preferentially replace ferromagnesian minerals before attacking feldspar or quartz. This replacement is either pseudomorphic or as ragged patches overlapping the surrounding minerals. In the diabase, tuffs and porphyry the chlorite pseudomorphically replaces the feldspar grains, but in the cherty sediments it spreads as fine-grained aggregates haphazardly distributed among the silica grains or heavily concentrated along microfractures and larger cracks. As an alteration of ferromagnesian minerals it always extends well beyond the outer fringe of the argillization.

The chloritization is found in all rock types but is most widespread and intense in those rocks with the highest ferromagnesia content. Thus diabase, dark bands of the metacherts, and the ferromagnesian phenocrysts in the porphyry are the first to be chloritized. Otherwise, the chloritization extends along available fractures or other openings.

A common alteration of the granite near and in the Port Radium shear zones consists of granulation of the feldspar and quartz grains and a disappearance of the biotite, followed by dendritic veining of the mylonitized aggregate by chlorite. The feldspars and quartz are practically untouched by alteration.

Distribution: Chloritization occurs along all vein zones, particularly in the hanging walls. It is heaviest along Nos. 1, 2 and parts of 5 Veins. It is the most consistent of the alterations in distribution in the various zones. Where it occurs in a vein zone or between secondary fractures next to a vein zone it constitutes from 50 to 100 percent of the rock. Where it is an alteration of the wall rock within ten feet of the vein zone it seldom exceeds 20 percent of the rock and is usually about 10 percent, particularly when it occurs with argillic alteration. Beyond the argillic zone, or about ten feet from the vein if the argillic zone is narrower, the chlorite content consistently drops sharply to about two percent and gradually diminishes from that.

The chlorite is definitely later than the argillic alteration. It superimposed itself on the clay zones and extends beyond them.

CARBONATIZATION

Carbonatization of wall rocks at Port Radium is intense along certain parts of certain veins and at such places constitutes the major and often the only hydrothermal alteration. It is also found throughout the chlorite and argillic alteration zones, often as a major constituent. It is widespread in all rock types. The carbonate is difficult to distinguish megascopically, therefore it is mapped with the argillic alteration.

Carbonatized cherty rocks may contain as much as forty percent carbonate and still be hard to scratch and appear to be unaltered. Where it is the principal alteration the carbonate occurs as haphazardly distributed mats of formless fine-grained flakes. The mats may be connected by networks of microscopic veinlets that diffuse into the mats and have indefinite boundaries with the host rock. In dense masses of carbonate, anhedral grains or rhombs up to one millimeter in size begin to appear, and the original chert remains only as isolated islands. The carbonate occurs in small amounts for tens of feet from veins, in rock otherwise unaltered by hydrothermal solutions. In such cases it invariably replaces chert in the vicinity of diopside and/or magnetite, possibly because of greater permeability around the coarse grains relative to the dense chert. Where carbonate is the only alteration it may constitute up to 60 percent of the rock, but where it occurs with other alterations it rarely exceeds 20 percent and is usually five to ten percent. Where it is the only alteration it pseudomorphically replaces hornblende and at the same time replaces the chert around other ferromagnesian minerals, then replaces all of the ferromagnesian minerals and the rest of the chert.

In addition to the dense fine-grained mats, the carbonate occurs as late microscopic veinlets that cut all other alterations as well as the carbonate mats and even late quartz-chlorite veinlets.

In the chlorite or argillic zones the carbonate is intimately intermingled, as fine-grained flaky fretted patches, with the other alteration minerals. It replaces the clay and chlorite minerals and in most thin sections appears to be more closely associated with the chlorite. Carbonate extensively replaces the jasper alteration and in such places is commonly accompanied by pyrite or apatite. Close to the vein zones the carbonate alteration replaces pyrite and chalcopyrite but further out from the source it occurs with the sulphides showing no evidence of replacement.

The carbonate, as a minor constituent, extends for greater distances from the veins than do any of the other alterations.

Influence on Host Rocks: In all rock types that it alters the carbonate pseudomorphically replaces the amphiboles and pyroxenes before replacing any other minerals. It next replaces the spinels and works out from them in coalescing patches and mats.

Carbonatization is absent or rare in the diabase and is not common in the granite and aplite. It is more extensively and intensively developed in the metacherts than any of the other rocks. Its presence is extremely difficult to detect megascopically.

Distribution: Carbonatization is widespread along the vein zones that possess abundant carbonate mineralization, such as Veins

No. 2A, Silver Island, etc., especially where other alterations are absent and is the most abundant alteration of the massive crystalline tuff along No. 5 Vein. It is erratically distributed. It may range from nearly zero to 50 percent of the rock within ten feet and may be more abundant 30 feet from the vein than adjacent to the vein. It occurs in small or moderate amounts throughout most of the argillic zones but is also absent from extensive areas.

The carbonatization is spatially related to the pitchblende in the cases of some orebodies, and at such places as No. 2A Vein it is the only alteration adjacent to the ore. In general, however, its distribution is not related to that of the pitchblende. If, as is believed, the argillic alteration came after the pitchblende mineralization, then the carbonate alteration is even farther removed in time from the pitchblende.

MINOR ALTERATIONS

Silicification: Silicification is widespread in the Port Radium deposits but in very minor amounts. It is found in two forms: a narrow zone of chalcedonic silica immediately adjacent to the veins; and small white blebs of quartz disseminated through other alterations.

The chalcedonic zones occur mostly along Nos. 1 and 5 Veins and very locally along the other vein zones. They seldom exceed a foot in width, are usually in the hanging wall and are essentially replacement veins in some places. They bear no obvious relation to the pitchblende.

The disseminated type of silicification is very common throughout the jasper zones, occasionally in the argillic and carbonate zones, and in the altered granite. The silica is in the form of clear fine-grained quartz in blebs and lenses from 0.5 mm to several centimeters in length. Some is later than the red alteration but spatially related to it. This silica was probably derived from the hematitization of the chert. Other disseminated silica occurs along the vein zones and is simultaneous with or later than the carbonatization and is probably residuum from that alteration.

Sulphidization: Chalcopyrite is a principal vein mineral in many of the Port Radium vein zones. In addition, it is widespread in the wall rocks where it occurs as disseminated fine grains, as lenses several inches in length, and as large replacement bodies with quartz, pyrite, and less commonly, apatite and arsenides.

The disseminated chalcopyrite usually occurs in evenly distributed anhedral grains, about 0.10 mm in width, which locally coalesce to relatively large solid masses. Large replacement bodies of chalcopyrite are extreme developments of the disseminated type. The chalcopyrite is usually accompanied by quartz, some of which has been formed by recrystallization of chert and some by introduction of silica.

The age relation of the chalcopyrite to the other alterations is not clear, but it is definitely earlier than the carbonate and apparently simultaneous with, or perhaps later than, the clay and chlorite.

The chalcopyrite replacement bodies favour the sedimentary and metasedimentary rocks. They are not common in the porphyry and are generally absent from all other rock types. The chalcopyrite replaces all mineral constituents without any consistent preferences.

Chalcopyrite patches are scattered along the hanging walls of Nos. 2 and 3 Veins. Smaller bodies and disseminations occur within a foot or two of parts of Nos. 1, 5 and 8 Veins. Large replacement bodies are commonest along Nos. 3 and 7 Veins. The two largest areas of replacement are near the junction of Nos. 3 and 4 Veins (Fig. 43), and across and along No. 7 Vein between the 125 and 250 Levels. The latter body contains about 10,000 tons of rock containing more than 60 percent chalcopyrite. It overlaps part of No. 7 Vein and appears to be the product of late hydrothermal solutions.

Pyrite is also common as local disseminations in unaltered or altered wall rock. Most of the pyrite is probably from the very early regional alterations but some appears to have been formed during hydrothermal alteration related to the vein zones. Although it is widespread in distribution, the pyrite in the alteration zones rarely exceeds one percent of the rock, but local concentrations constitute as high as 20 percent.

The pyrite invariably occurs as discrete cubes and clusters of subhedral grains, ranging in width from 0.10 to 1.0 mm. In the metasediments it is concentrated in bands which are reflections of the original bedding. This type of pyrite is a product of early regional alteration and is extensively replaced and veined by all the later hydrothermal alterations. The original chert grains surrounding the pyrite are recrystallized to relatively coarse, clear quartz. The late hydrothermal pyrite is much less common or concentrated and appears to be associated with the argillic alteration but is replaced by the chlorite and carbonate alterations.

Sericitization: Sericite occurs in the argillic alteration in trace to minor amounts and appears to be later than the clay minerals but earlier than the carbonatization. It is also extensively developed in the feldspars of the intrusive rocks, often at great distances from any vein zone. It is a minor and early component of the silicification zones. Other than in these occurrences, sericitization is not a principal alteration at Port Radium. Discrete zones of sericitization are absent, and the alteration is rarely a principal component of the altered wall rock.

ZONING OF ALTERATIONS

Zoning of the wall rock alterations at Port Radium is not well defined but is generally consistent everywhere. Small-scale well defined zoning of the different alterations occurs only very locally. Alterations are usually better developed in the hanging wall rocks of the vein zones. Silicification is generally confined to the first foot immediately adjacent to the vein. Chloritization is a principal vein constituent and is locally concentrated along the walls in the vicinity of secondary fracturing. It occurs with the argillic alteration and generally extends beyond the outer fringes of the argillization. The carbonatization is well developed in scattered places, generally where other alterations are negligible or absent. Red alteration is very patchy in distribution and has been locally obliterated by the clay and chlorite alterations.

Because the different wall rock alterations were formed at separate times and in many instances at separate places, well defined zonal relations between them are lacking; however, a general spatial relation does exist where two or more alterations overlap. A generalized sequence of all the alterations occurring together in porphyry or metacherts would be as follows:

> Adjacent to the vein - Dense, fine-grained montmorillonite with local patches of silicification and considerable amounts of disseminated coarse pyrite and chalcopyrite. Very minor amounts of apatite.
>
> About two feet from vein - Montmorillonite with superimposed fine-grained carbonate and some coarse-grained chlorite. Abundant coarse apatite and patches of pyrite. Local areas of hematite intimately mixed with clay.
>
> About five feet from vein - Heavy concentrations of carbonate and fine-grained chlorite with very minor montmorillonite and scattered fine-grained apatite. Abundant relict red altered chert or feldspar patches. Some disseminated silicification and quartz-chlorite-carbonate veinlets.
>
> About five to ten feet from vein - Original rock, locally red altered, with ferromagnesian minerals partially replaced by chlorite. Abundant patches of carbonate and penninite scattered throughout. Cut by fine quartz-carbonate veinlets.
>
> Beyond ten feet - Original rock, not red altered, some ferromagnesian grains chloritized. Scattered microscopic, but fairly abundant, patches of carbonate. Locally abundant fine carbonate veinlets.

The above distances and relations represent an idealized compilation of a multitude of combinations of alterations observed at Port Radium and are not to be considered as being typical.

A crude regional zoning of the alterations in the Port Radium deposits is suggested by the general distribution of the types of alterations. Red alteration occurs extensively along vein zones in the western and northern fringes of the mine area and above the 800 Level. Argillic and chloritic alterations are sparse in these parts of the mine but increase sharply toward the central and eastern parts and are most intense and widespread along the vein zones east of the shaft and in the lower levels. Because the red alteration preceded the soft rock alterations and is replaced by them, extensively in the upper central parts of the mine but hardly at all in the upper western parts, the suggestion is that the altering solutions rose from a source lying to the east and that the final argillic solutions did not reach as far west as the earlier, red altering, solutions.

Examples of the occurrences of the different wall rock alterations are shown in Figs. 38 to 46 inclusive.

RELATION OF ALTERATIONS TO MINERALIZATION STAGES

The wall rock alterations can be divided into four main stages, and the vein minerals into five stages. Relations between the vein minerals and the wall rock alterations are difficult to establish, but on the basis of chemical similarity and the texturally and structurally determined time breaks the stages of mineralization are correlated with the alteration phases as follows:

	Mineralization stages:	Alteration stages:
I	Quartz-hematite	Red alteration
II	Pitchblende-quartz	
III	Co-Ni arsenides	Argillization and sulphidization
IV	Copper sulphides-chlorite	Minor chloritization Major chloritization
V	Carbonates and native metals	Carbonatization

At the Caribou Mine, Wright(51) related the argillic alteration directly with the pitchblende mineralization. He based this conclusion on the fact that the argillic zone has a radioactivity higher than background, but decreasing with distance from the vein and ending at the edge of the alteration. This suggested to him a diffuse permeation of the porous altered rock by uranium-bearing solutions. At Port Radium some argillic zones adjacent to orebodies are radioactive but others are not. The later age of the argillic alterations makes the diffusion theory untenable. A more probable explanation for the slight radioactivity of the argillic zones is that the alteration solutions dissolved small quantities of the earlier pitchblende from the vein zones and re-deposited it in the walls. This process is suggested by the many examples of chlorite and clay veinlets bearing brecciated pitchblende, as well as by the high solubility of pitchblende.

CHEMISTRY OF ALTERATIONS

Red Alteration: No chemical analyses of red altered rock are available from Port Radium, but several from rocks in the Athabaska area show that the percentage of total iron in the altered rock is about the same as that in the unaltered rock, whereas the ratio of ferric to ferrous oxide increases with the amount of red alteration. A minor number of analyses of Athabaska specimens indicate an increase in total iron in the red altered zones. It is suggested that iron already available in the rock has been oxidized and isolated as hematite dust. In some material there has been a definite increase in the iron content in the red altered zones, and apparently this iron was introduced and distributed by solutions that had little else to contribute but perhaps silica.

At Port Radium the red alteration commonly decreases immediately adjacent to the vein zones, suggesting a reducing environment in the veins at some time after the formation of the hematite. The pyrite occurring in the clay and chlorite zones also indicates a change in oxidation-reduction potential from the earlier hematite-depositing solutions.

Krumbein and Garrels[29] have shown that the form in which iron is precipitated from solution is more strongly dependent upon the oxidation-reduction potential (Eh) than the pH. The presence of widespread early hematite in the wall rocks of pitchblende deposits indicated an oxidizing environment. The apparent general coincidence in time between red alteration and pitchblende mineralization at Port Radium and other localities suggests a relation between the two whereby the pitchblende-bearing solutions were the source of the oxidizing conditions that resulted in the red alteration of the wall rock, with or without the addition of iron.

<u>Argillic Alteration:</u> The chemistry of argillizing solutions has been investigated by many geologists. The general conclusions are that the solutions were probably acid or neutral and were reducing.

The presence of pyrite in the argillic zones at Port Radium, Tintic[75], Wairakei, N. Z.[76] and elsewhere indicates reducing conditions. Lovering[75], largely from a study of the pH of the solutions in the natural formation and artificial synthesis of the clays and sericite, postulates a gradual change in character of the altering solutions from acidic to alkaline. To form the argillic zones from the Port Radium rocks there must be a leaching of some silica, probably some alumina, and the bases K, Na and Ca. The removal of these base and alkali metals reflects their inability to form stable compounds in the new environment which therefore was probably acidic.

Evidently the hydrothermal solutions changed from oxidizing and acidic of the red alteration-pitchblende phase to reducing and possibly neutral of the argillic-metalliferous phase.

An excess of magnesia is an essential condition for the formation of the montmorillonite type of clay.

Analyses of montmorillonites from seven different deposits show the following ranges in composition[77]:

SiO_2	49-58	CaO	0.5-3.3
Al_2O_3	15-20	K_2O	0-0.6
Fe_2O_3	0- 6.5	Na_2O	0-1.2
FeO	0- 0.95	TiO_2	0-0.3
MgO	2.5-6.5	H_2O	8-25

From these compositions it is evident that to argillize the Port Radium cherts magnesia, alumina and water must have been added and considerable silica removed. These changes would be modified by the degree of metasomatism of the sediments. In porphyry, tuffs and granite, the main changes were probably removal of the alkali metals and addition of water and magnesia.

The formation of the kaolin would require no magnesia and more alumina. This may have been effected by differences in the solutions or in the original rocks, although there is no relation at Port Radium between wall rock types and the amounts of kaolin in the zones.

Chloritization: The chlorite is closely related in time and space to the argillic alteration and would require few changes if any in the altering solutions, possibly only minor increases in the ferrous iron and magnesia content. Replacement of chert or earlier clay would require removal of some silica.

From a study of the vein minerals it is clear that a minor stage of vein zone chlorite follows the Co-Ni arsenides and a major stage follows the copper minerals. In many places on all veins the vein zone chlorite grades out into wall rock chloritization. Therefore, it is reasonable to assume that most of the wall rock chloritization was later than the Co-Ni-Cu mineralizations. The chloritization, both in the vein zones and the wall rock, possibly represents a high iron and magnesia phase of the earlier argillizing solutions. This is further borne out by the close spatial relation between the two types of alteration.

Carbonatization: The carbonate alteration was the last major alteration of the sequence and was separated from the chloritization by time, as suggested by its replacement of the chlorite and the differences in distribution of the two alterations. The last major vein mineralization is represented by carbonate with native Ag and Bi and quartz. The extensive carbonate alteration zones are generally alongside vein zones that are rich in the late carbonate phase minerals. It is reasonable to relate the carbonate mineralization to the carbonatization of the wall rocks.

In the red altered rocks the carbonate flakes and patches are surrounded by bleached zones where the hematite has been reduced. The evidence suggests that the final major altering and mineralizing solutions were reducing and alkaline.

Silicification: The microscopic and megascopic lenses and patches of silica in the alteration zones appear to have formed by redistribution of silica indigenous to the wall rocks. This process was accomplished to a limited extent during the metasomatism and later during the red alteration. Zones of total silicification of the wall rocks are not common but often occur with the argillic alteration. Probably this silica was removed from the wall rocks during argillization.

SUMMARY

Structural and textural relations give good evidence that the different stages of mineralization were separated by time and tectonic events and probably occurred as separate surges rather than one continual flow. There is also strong indication that the altering and mineralizing solutions changed from acidic to alkaline and from oxidizing to reducing during their progress through the Port Radium vein zones.

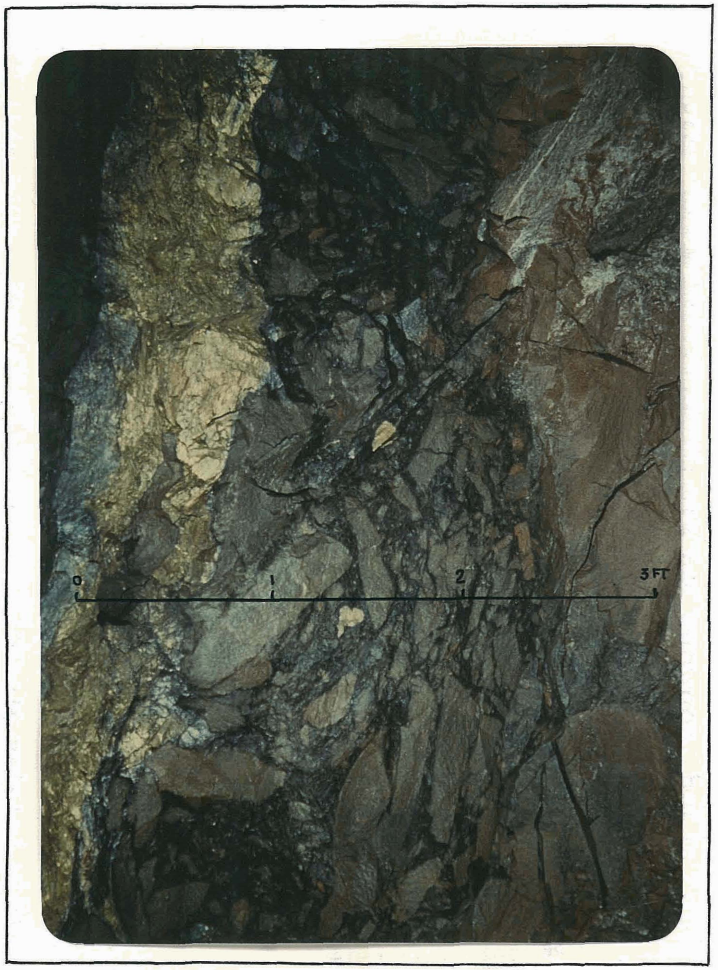


Fig. 97. No. 3 Vein (North Branch)
Ore section: Co-Ni arsenides (silvery), chalcopyrite (yellow), pitchblende (black), and brecciated diabase. 800 Level.

Fig. 98. No. 3 Vein (North Branch)
Barren section: Quartz, carbonate, chlorite, hematite, clay, some Co-Ni bloom. 800 Level. Scale= As Fig. 97.

FACTORS INFLUENCING ORE LOCALIZATION

Definite controls governing the emplacement of the pitchblende have been deduced for most of the major ore shoots in the Port Radium deposits, but for some orebodies the controls are still not clear.

The orebodies at Port Radium have sharply defined boundaries. There is very little low-grade ore material along the fringes of the ore shoots; one or two rounds in a drift and one lift in a stope will usually be the difference between good ore and completely barren vein material. This is not a function of arbitrary assay boundaries but of the actual absolute presence or absence of pitchblende. Pitchblende is nearly always visible in some amount in orebodies.

The largest body of solid pitchblende seen by the writer in the mine measured 30 inches in maximum width and about 15 feet in length. Such occurrences are not common, but in comparison with most of the other known pitchblende ore deposits in the world, the Eldorado Mine at Port Radium is exceptionally high in grade.

DESCRIPTION OF OREBODIES

NO. 1 VEIN:

Four of the principal ore shoots on No. 1 Vein are designated the 11, 13, Upper 14 and Lower 14 Orebodies. They are shown in longitudinal section in Fig. 99. It will be noted on Fig. 99 that the orebodies all occur within sections of the vein zone flanked by Mine Formation wall rocks. This feature is common to all the orebodies on this vein. Some orebodies are clearly related to the porphyry-sediment contact on the footwall of the vein zone, but others are not.

In most places on No. 1 Vein the post-pitchblende stages of mineralization have deposited vein material so liberally throughout the zone that original fluctuations in width and fracture pattern along the vein zone have been erased. Although it is believed that differences in widths at the time of the pitchblende mineralization were important in controlling the precipitation of the ore, contours of widths of No. 1 Vein show only vague anomalies corresponding with the positions of the orebodies.

13 Orebody: (Fig. 99). The 13 Orebody lies beneath the No. 3 Porphyry contact and ranges between 100 and 300 feet in horizontal length. The width of the vein zone ranges between 5 and 20 feet, but not all is ore (Fig. 40). The ore generally hugs the footwall side of the vein zone and is flanked on the hanging wall side of the vein zone by thick barren veins of quartz-hematite-chlorite. The orebody rakes to the west at an angle of about 45 degrees conforming in general with the very irregular contact of a porphyry body on the footwall side of the vein zone. It does not conform with the contact of the displaced portion of the same porphyry body on the hanging wall. Probably there was no displacement on the vein zone before the introduction of the pitchblende, and the opening of the zone in the sediments adjacent to the porphyry in some way favoured the precipitation of the pitchblende.

Reasons for the termination of the 13 Orebody at the 650 and 1050 levels are also related to rock structures in the footwall. As shown in Fig. 99, the extent of the orebody conforms exactly to the underside of the re-entrant in the porphyry-sediment contact, suggesting a possible influence of a directional introduction of solutions. Contours of values of pitchblende in stopes, particularly on No. 2 Vein, suggest that the pitchblende-bearing solutions probably rose up the vein openings from an eastward direction. The solutions probably approached the porphyry re-entrant of the 13 Orebody upward from the east.

There was no deposition along the porphyry contact that forms the lower side of the re-entrant. This portion of the vein is flanked by massive cherts and quartzites of the Cobalt Island Formation that have been moderately recrystallized by the intrusion of the underlying porphyry. These rocks are only slightly less competent than the porphyry and slightly more competent than the fine banded sediments of the Mine Formation; therefore, there is no sharp change in competency of the wall rocks in the area below the 1050 level west of Section 0-00 (Fig. 99), and consequently there was no sharp change in the physical characteristics of the fracture zone where it traverses this area. Evidently the rising solutions found no zone favourable for deposition of pitchblende until they encountered the contact between the porphyry intrusive and the Mine Formation.

Apparently the position of the massive chert of the Mine Formation that lies almost parallel to No. 1 Vein between the 650 and 375 levels has influenced the pitchblende deposition. The vein zone passes through this large lens of massive chert just east of the porphyry contact. The 13 Orebody ends where the chert and the porphyry converge. The chert apparently controlled the fracturing in much the same manner as did the Cobalt Island Formation rocks below the

13 Orebody, as its competency is somewhere between that of the fine banded sediments and the porphyry.

Lower 14 Orebody: The Lower 14 Orebody is divided into an upper and a lower half by a horizontal strip of barren vein zone at the 800 Level. In general character it is similar to the 13 Orebody except that it lies on a steeper part of the vein zone and the vein zone is generally narrower, ranging from 5 to 12 feet in width. There are no changes in the type, character or structure of the wall rocks in the immediate vicinity of the 14 Orebody. The only significant differences are the near proximity of the edge of the recrystallized, heavily metasomatized sediments and a tongue of porphyry, both to the east, and a steepening of the vein zone in the ore area (Fig. 100). The net effect of the steepening and the changes in wall rock has been to form a pocket in the general vein structure. The pocket was probably accentuated by early relaxation which tended to open the steepened portion more than the surrounding parts of the vein zone. This pocket was then favourable for pitchblende deposition.

Scattered orebodies (not illustrated) occur in the vein zone between the edge of the recrystallized sediments and the east contact of the small body of porphyry that lies down dip to the east of the Lower 14 Orebody. This area was not as favourable for ore deposition as that existing where the Lower 14 Orebody occurs because the uniform dip of the vein zone failed to form openings during the displacements.

Upper 14 Orebody: The Upper 14 Orebody lies wholly within fine banded Mine Formation sediments between porphyry bodies No. 2 to the east and No. 3 to the west. It also lies in a nearly vertical section of the otherwise north-dipping vein zone (Fig. 100). Normal movement on the zone has widened the vertical portion relative to the sloping portion as that the vein zone throughout most of the Upper 14 Orebody is unusually wide, ranging from 7 to 40 feet. Below the 375 Level the flattening of the vein zone, together with the appearance of the massive chert as wall rock, apparently restricted the downward extension of the favourable area for pitchblende deposition.

11 Orebody: The 11 Orebody lies in the vein zone within an area of fine banded Mine Formation sediments that is encompassed on both sides and the top by a porphyry body. This structural control is supplemented by a split in the vein zone, forming a loop in plan, above the 375 Level (Fig. 38), and a steepening of the zone. The added opening of the zone induced by these features favoured precipitation of pitchblende in the vein zone farther into the porphyry than is usually the case in the area.

NO. 2 VEIN:

The locations of the major orebodies on No. 2 Vein in the upper levels of the central part of the mine are shown in Fig. 101; No. 2A Vein is projected onto the same longitudinal plane as No. 2 Vein. The configuration of the orebodies in this portion of the vein zone is typical of those in the rest of the vein, not illustrated.

Western Orebodies: The western orebodies on this vein zone are mostly on the No. 2A Vein. The position of these bodies is clearly related to the location of the porphyry intrusive bodies (Fig. 101). The orebodies lie in a structural trough of wall rocks between Nos. 3 and 4 porphyry bodies and are separated by smaller porphyry masses. The sedimentary rocks in the lower part of the trough have been metasomatized to a crystalline rock whose competency is more like that of the porphyry; hence the vein zone in this part of the trough was not favourable for pitchblende deposition.

24-26 Orebody: The upper portion of the 24-26 Orebody is shown in Fig. 101. Here again the relation to the porphyry-sediment contact is obvious throughout most of the ore shoot. No reason is known for the termination of the orebody just below the present surface. Possibly the No. 2 porphyry body flattened and lay parallel to and immediately above the present surface, forming a boundary that is now not apparent. It is also possible that the recrystallization of the sediments above the nose of the No. 3 porphyry body changed the competency enough to make the subsequent fracture of No. 2 Vein unsuitable for pitchblende deposition.

The 24-26 Orebody pinches out between the 650 and 800 Levels where the diabase dike crosses the vein zone. The constriction of the vein zones in the diabase is clearly visible in many places underground (Fig. 43). This damping effect, although only local, was enough to cause a near-horizontal barren section in the 24-26 Orebody 50 feet in width.

The 26 Orebody continues below the 800 Level, but instead of following the sediment-porphyry contact, it follows the contact between recrystallized sediments and unmetamorphosed sediments and lies on the unmetamorphosed sediment side of the contact. This is one of the few places in the mine where a favourable zone is found along this type of contact.

The barren area on No. 2 Vein beneath the No. 3 porphyry body is a puzzle. A few hundred feet to the north, beneath the same contact of the same porphyry body, No. 3 Vein is host to an extensive orebody, yet the same general situation on No. 2 Vein has resulted in negligible pitchblende ore. In fact, eastward from this porphyry to the junction with No. 3 Vein there is very little vein material of any type in No. 2 Vein. The vein is generally a narrow zone of gouge-filled fractures and lenses of chlorite. A possible explanation for this paucity of ore and vein material may be that the No. 3 Vein structure, branching vertically off No. 2 Vein relieved all the tensional stress in the area. No. 3 vein zone, being a vertical tension zone, would open more easily under relaxation or tension than the inclined fractures of No. 2 vein zone. West of the porphyry body, No. 3 Vein lies several hundreds of feet north of No. 2 vein zone, which is here abundantly filled with ore and vein material. In this area there was no nearby structure to take up the tension, and so No. 2 vein zone was opened far wider than it was further east near No. 3 Vein. In the vicinity of the 24-26 Orebody this effect of the proximity of No. 3 vein zone was not so important because of the additional open tension zone developed along the porphyry-sediment contact.

No. 2 Vein has received much less vein material than has No. 1 Vein; hence the character of the original fracture patterns is still visible. In the porphyry, diabase and granite the No. 2 zone is clearly constricted, and the number of fractures is less. In fine banded sediments adjacent to more competent rocks the zone bulges to widths generally greater than usual for the sedimentary rock environment.

NO. 3 VEIN:

The principal orebodies, 30, 31, 33 and 36, on the main branch of No. 3 Vein are shown in Fig. 102. Considerable ore also occurs on a north branch of No. 3 Vein which follows the north wall of the diabase dike. This branch is not shown.

As is clearly shown in Fig. 102 the deposition of the pitchblende has been strongly influenced by the greater amount of fracturing in the sedimentary rocks than in the porphyry. The diabase dike is also shown to be generally unfavourable for ore deposition.

The zone of increased tensional fracturing that lies beneath the No. 3 porphyry body extends for a short distance into the granite and has been host to pitchblende deposition there. Recrystallization of the sediments at the bottom of the trough between No. 3 and 4 porphyry bodies caused the vein zone to be unfavourable for pitchblende deposition; hence the 31 Orebody bottoms near the 650 Level.

No. 3 Vein (North) (Not illustrated): Ore deposition on the north branch of No. 3 Vein has been influenced mainly by the diabase dike. For a distance of 400 feet west of the junction of No. 2 and 3 Veins, the diabase dike lies on the footwall of No. 3 Vein (North). Parallel to the junction with No. 2 Vein and about 400 feet horizontally from this junction, the diabase crosses to the hanging wall of No. 3 Vein (North). Between this crossing of the dike and the junction with No. 2 Vein, No. 3 Vein (North) is ore-bearing (Fig. 46).

NO. 4 VEIN:

In general, No. 4 Vein is a barren zone of fracturing with little vein filling. However, between the 375 and the 125 Levels, between the wide zone of fracturing near the junction with No. 3 Vein to the east and a west-dipping porphyry tongue to the west, for a distance of about 100 feet No. 4 zone is ore-bearing.

NO. 5 VEIN:

The pitchblende ore occurs on No. 5 Vein in the vicinity of the Eldorado Vent and in the vicinity of No. 7 Vein.

The deposition of the principal orebody, the 54, in the vicinity of the Eldorado Vent was influenced by two factors: the contact between the vent and the sedimentary rocks; and a steepening of the usual 60 degree dip of the vein zone in the vicinity of this contact. The position of the orebody with respect to these features is shown in Fig. 103. The major influence on ore deposition was probably the shallow trough formed in the shear zone by the steepening. Tensional relaxation opened this steep trough, and pitchblende deposition was favoured. The steepening of the fracture zone is adjacent to the vent and was probably caused by buckling against this relatively competent mass. This is one of the best examples at Port Radium of the opening of a vein zone and subsequent ore deposition being controlled by the differences in the dip of the vein zone. The vein zone is very definitely wider in the steep ore section.

The 53 Orebody is being developed and from the data available it appears that it lies in a wedge of sediments between the Eldorado Vent below and a porphyry body above and to the west. The fracturing has been more favourable for pitchblende deposition in the relatively incompetent sediments than in the adjacent porphyry and massive crystalline tuff (Fig. 103).

The orebodies on No. 5 Vein in the vicinity of No. 7 Vein have not yet been developed sufficiently to disclose the ore controls.

NO. 7 VEIN:

No. 7 Vein zone has not been extensively developed, hence little additional information on ore control is available from it. It is a nearly vertical tension zone occupied and flanked by wide zones of red alteration and mineralized throughout by metallic minerals and pitchblende. Pitchblende occurs as fine fracture fillings and large lenses throughout the zone in much the same fashion as it does in the upper western portions of No. 3 Vein. The orebody developed at present on No. 7 Vein lies beneath the contact of an eastward dipping porphyry body and is analogous to the orebodies on No. 3 Vein in structural control.

NO. 6 - 8 - 9 VEINS:

Development on these veins has not progressed far enough to provide definite information on the principal ore controls.

PHYSICAL FACTORS

It is evident that areas of relatively greater tensional opening on the fracture zones were the most favourable ones for the deposition of pitchblende. The springing or bulging of the fracture zones in less competent rock adjacent to the contact with more competent rock is the major reflection of these differences in tensional failure. Thus favourable zones have been developed in Mine Series banded sediments along contacts with porphyry bodies, diabase, massive crystalline tuff, and recrystallized, metasomatised sediments.

Areas of increased tension have also developed open fracture systems favouring ore deposition in the vicinity of major bends or branches of the vein zones. This is illustrated by orebodies occurring in the vicinity of the junction of 3 and 4 Veins, 5 and 7 Veins, and, to a limited extent, along No. 3 vein zone in the vicinity of the diabase dike, where branches of the vein zone cross from one wall of the dike to the other.

Tensional openings favourable for ore deposition have also occurred on relatively steep portions of the vein zones that opened wider than adjacent less steep portions. Examples of this feature are the Lower 14 Orebody on No. 1 Vein and the 54 Orebody on No. 5 Vein. The increase of tensional openings on vertical structures probably also accounts for the fact that Nos. 2A, 3 and 7 vein zones are the richest in the mine.

The presence of breccias consisting of fragments of wall rock and early vein minerals in the vicinity of nearly every orebody at Port Radium is further evidence of the dilational nature of the favourable zones. Brecciated wall rock is cemented by vein material of several ages. Occurrences of pitchblende (Fig. 83) and comb quartz around many fragments points to deposition in open, tensional fissures. Characteristic textures in the Port Radium ores (banding of vein minerals; comb and euhedral quartz crystals; colloform crusts of pitchblende, hematite and some metallic minerals; and abundant vugs occupied by many different minerals) all are evidence of the dilational nature of the vein zones during deposition.

In the granite, diabase and massive crystalline tuff the vein zones at Port Radium are generally reduced to tight zones of shears with discontinuous lenses of quartz, carbonate and chlorite. The competency of these rocks has so hindered the development of wide tensional fracture zones that little mineralization of any type occurred along zones within them.

Small bodies of porphyry were somewhat more hospitable than the diabase, but for bodies over 100 feet in thickness the relation of fracturing to wall rock is about the same as for the granite.

Secondary fracturing along the shear zones was extensively developed in Mine Formation rocks but not in the Cobalt Island Formation. This secondary fracturing was accentuated at the edges of more competent masses; thus, the most favourable areas for the development of wide fracture zones has been in nonrecrystallized Mine Formation rocks near the contacts with more massive rock bodies.

Structural Control at other Deposits: The importance of the physical character of the fracture system in the deposition of pitchblende has been noted in many other deposits. The writer has observed almost identical controls (fracture intersections, porphyry-sediment contacts, etc) at several deposits in the Great Bear Lake area, e.g. Hottah Lake, Workman Island, Crossfault Lake, Camsell River and Contact Lake. The same controls were also reported by Henderson[20] for Hottah Lake and by Feniak[13] for Workman Island.

These same structural controls are also common in many deposits in the Athabaska area of Saskatchewan. The writer has observed a great many examples of intersections of fractures and the differential dilation of fractures in different wall rocks favouring pitchblende deposition. Robinson[54] also stressed these features of tensional environment as being important to ore control in the Athabaska deposits. Allen et al[78], reported at Martin Lake that "vertical rolls in the shears have opened cymoidally-curved lenses and pods which have become filled with ore." For the Black Bay deposits, Hale[79] noted, "where a fracture crosses rocks of different physical characteristics a deflection in the strike of the fracture is apparent." He further notes that the fracture is usually more open along one leg of the deflection, and pitchblende deposition has favoured these zones. Such controls by deviations of strike or dip are widespread in the Athabaska area.

In many of the vein deposits of pitchblende in the United States the structural controls are well established. Gruner[73] states that the most important deposits at Marysvale, Utah, are associated with the quartz-monzonite intrusive at the contact with the overlying, relatively more competent, volcanics. In the Prospector Mine at Marysvale it was noted by Taylor et al[67] that brecciated areas occur where branching fractures intersect the walls of a main shear zone, and on curves of the branching fractures. The richest concentrations of pitchblende occur in these situations. The authors also report that the intersection of two veins, No. 1 and No. 3, is the site of an excellent ore shoot. King[71] reports that the ore deposits of the Caribou Mine, in Colorado, are found at or near the intersection of the eastward-trending and northeasterly-trending veins.

In the Joachimsthal deposits[53] the north trending "Midnight" veins produce ore where they intersect the east-west "Morning" veins. In the "Midnight" veins the open vertical portions have ore whereas the tight flatter portions are barren.

In the deposits at Urgeirica, Portugal[53], fault intersections have been conduits for ore-bearing solutions. Orebodies are largely within straight parts of veins where fissures were most open. In tight segments orebodies are lacking.

CHEMICAL FACTORS

It has been shown that the argillic and chloritic wall rock alterations were formed after the deposition of the pitchblende, hence they could not have controlled the deposition of the pitchblende. Further, the soft alterations bear no relation in distribution to the structural features that apparently have influenced the ore deposition. It is concluded that the deposition of pitchblende was in no way influenced by chemical effects of the soft rock alterations.

On the other hand, it is believed that the red alteration was closely related in time to the pitchblende deposition. The wall rocks were altered either shortly before or during the early stages of the pitchblende deposition, for fragments of wall rock in "ore quartz" are generally in various stages of being altered. However, there is no close correspondence between the pitchblende orebodies and red alteration of the wall rock. There are many more orebodies without associated red alteration than there are with it. More important, there are nearly as many examples of red alteration without ore as there are with it, although admittedly the spatial correspondence is usually much closer than in the case of the soft alterations.

It is difficult to see how the presence of hematite dust could have any chemical influence on hydrothermal solutions in such a way as to promote pitchblende deposition. The red alteration is more likely a common effect than a cause. In general, it is safe to say that there was no chemical influence exerted on the pitchblende-bearing solutions by the red alteration.

It has been argued by several geologists that at Port Radium and other localities the deposition of the pitchblende was influenced by the chemical character of certain wall rocks. In most instances further investigation has indicated that it has been the physical differences of the wall rocks, not the chemical differences, that have produced favourable areas of deposition. Rock types unfavourable for pitchblende deposition in one locality may be favourable in a different locality, depending on the physical environment.

Exceptions to this principle of chemical inertness of wall rock occur where the host rocks are calcareous or carbonaceous, both types having the power to induce precipitation of pitchblende through chemical actions. There is also some evidence suggesting that rocks high in alumina may influence the deposition of pitchblende.

At Port Radium and in the Athabaska area the occurrence of pitchblende in such a wide variety of rocks as granites, chert, andesitic hypabyssal rocks, argillites, and diabase, though admittedly not in the same amounts, suggests that the host has influenced deposition in some way other than chemically. In the foregoing discussion on the orebodies of Port Radium it was shown that rock types favourable for pitchblende deposition in one locality are not favourable in other localities because of differences in physical environments. It is apparent at Port Radium and at many other localities that the pitchblende has been localized along the relatively more dilatant portions of the fracture zones, regardless of the composition of the host rocks.

In deposits as complex as those at Port Radium the possible influence of earlier vein minerals on the precipitation of the pitchblende must be considered, but study of the ores shows that the pitchblende was the earliest metal mineral to be deposited in the vein zones. Moreover, it has been found that there is only very local spatial correspondence between other metallic minerals and the pitchblende at Port Radium.

PRINCIPAL AGENT FOR THE PRECIPITATION OF PITCHBLENDE

The foregoing data indicate that the widespread control of pitchblende deposition by zones of greater than usual dilation, which may have been induced by a multitude of conditions, is probably the most important key to the precipitation of pitchblende from hydrothermal solutions. The precipitation of pitchblende in zones of relatively low pressure is analogous to the precipitation of uranium colloids experimentally by the subtraction of carbonate from high-pressure solutions[48]. In natural hydrothermal solutions the precipitation by this means could be accomplished by a loss of CO_2 from solution.

In a reaction involving expulsion of CO_2, the influence of pressure is equally important whether the CO_2 is in the form of a gas or is held in aqueous solution[80]. Sudden reduction in vapour pressure of the solution would allow release of CO_2 and resultant precipitation of pitchblende. At Port Radium the occurrence of pitchblende in loci of greater than usual dilation in the fracture zones is in accordance with this concept. Solutions ascending the relatively uniform and tight fracture (shear) zones entered the areas of highly brecciated and fractured rock and suffered sudden reduction in pressure and consequent loss of CO_2, whereupon pitchblende was precipitated.

$$\underset{\text{(colloid in solution)}}{\text{Pitchblende}} \xrightarrow[\text{pressure}]{\text{Decrease in}} CO_2\uparrow \xrightarrow{\text{Flocculation}} \underset{\text{(solid)}}{\text{Pitchblende}}\downarrow$$

As each dilated zone was reached and occupied the conditions of the system would be changed by the loss of CO_2 and pitchblende but, with continuous flow, equilibrium would tend to be restored

(Le Chatelier's principle) and the solutions passing to higher zones would retain enough uranium colloid to form ore deposits at other favourable locations in the same manner.

Thus the tension fracture zones induced by differences in wall rocks at Port Radium were the loci for precipitation of pitchblende ore.

REGIONAL CONTROL

The possible source of the pitchblende mineralization in the McTavish Arm area along the east shore of Great Bear Lake is not indicated by the exposed geology. The biotite granite is the youngest and most extensive intrusive in the area that could have generated hydrothermal solutions. Pitchblende occurs in shear zones in the granite in several widespread localities. The Cameron Bay fault, to which the pitchblende-bearing fracture zones are related, displaces the granite several miles; hence the granite was solidly in place before the pitchblende mineralization. Possibly the giant quartz veins and the later metal minerals were the final expression of the granite intrusion in fracture zones in the outer crust of the granite body. If the biotite granite was not the source of the hydrothermal mineralization in the McTavish Arm area, the source is not apparent.

All the pitchblende and precious metal deposits in the McTavish Arm area occur in fracture systems spatially related to the major northeast-trending fault systems. This is true for the Achook Island, Failes Bay, Echo Bay and Camsell River deposits (Fig. 2). It is also generally true that the known deposits all occur in Old Complex rocks near the edges of granite bodies. In the Mc-Tavish Arm area, fault and fracture zones are invariably expressed on the surface as depressions filled by alluvium and lakes. This blanketing makes the discovery of new deposits of pitchblende in these most likely places extremely difficult. There is no reason to assume that Port Radium is the only pitchblende bonanza in the district. If other orebodies do exist in the area they probably occur in the vicinity of northeast-trending fracture zones in Old Complex rocks. In particular, the northeast continuation of the Cameron Bay-Eldorado fault system holds the best possibilities for ore discovery. Similar faults in the Camsell River area also have good possibilities. Further mapping of the undifferentiated Old Complex rocks northeast of Hunter Bay may also reveal the existence of geologic environments similar to those at Port Radium.

If another deposit of pitchblende is found, a study of the fracture pattern, with particular emphasis on zones of dilation, will be of great assistance in finding orebodies. The features of pitchblende ore control contained in this thesis would apply probably equally well in districts other than Great Bear Lake.

SUMMARY AND CONCLUSIONS

REGIONAL GEOLOGY: A geologic map has been compiled from all the information available on the McTavish Arm area of Great Bear Lake. The table of formations used by early geologists in the district (Kidd, Fenick et al) has been modified somewhat in detail, but the general outline is the same. One noteworthy change has been made. The body of massive crystalline tuff located near Port Radium is not a basal formation of the Echo Bay Group but is probably a volcanic vent younger than Lower Echo Bay rocks.

The bodies of hypabyssal feldspar porphyry intrusive rocks that are widespread in the McTavish Arm area are part of a belt about forty miles in maximum width that extends from Great Bear Lake to Great Slave Lake. These porphyry bodies comprise over 50 percent of the Old Complex rocks in the McTavish Arm area and are younger than all the sedimentary rocks except those of the Hornby Bay Group but are older than the granite.

The youngest sedimentary rocks in the area, the Hornby Bay Group, are analogous to the Epworth Series at Coppermine and the Et-then Series at Great Slave Lake.

Diabase dikes and sheets are the youngest rocks in the district and are also younger than the giant quartz veins. They are older than the pitchblende mineralization.

The major structural feature in the district is the widespread system of northeast-trending strong fault and shear zones. The Port Radium pitchblende deposits occur on the Cameron Bay-

Eldorado Zone of this system. The fracture pattern was in existence before the diabase intrusion, for diabase dikes locally occupy the northeast-trending shear zones. The same dikes were later fractured and mineralized in the shear zones. Formations in the McTavish Arm area were subjected to at least three periods of tension, each period giving rise to a new set of openings in the rocks. Pitchblende mineralization followed the final tensional opening of the shear zones.

LOCAL GEOLOGY: The major locus for pitchblende deposits is the Eldorado system of shear zones where it forms a complex lens of fracture zones between Crossfault Lake and Cobalt Island. A belt of east-dipping coalescing tabular bodies of feldspar porphyry crosses the middle of the lens of fracturing, and the richest pitchblende deposits occur in the shear zones to the west and beneath this belt. Most of the production of the Eldorado Mine is derived from this area west of the porphyry belt.

The predominant wall rocks of the ore deposits are the cherts of the Mine Formation and the tuffs and fragmentals of the Transition Formation.

Rocks of the Mine and Transition Formations are truncated against a pipelike body of massive crystalline tuff. Lithologic and structural features of this body strongly suggest that it is a remnant of a volcanic vent. Its age is probably between Lower and Upper Echo Bay time. It is a massive body that has been unfavourable for the development of open fracture zones and, consequently, has been unfavourable for pitchblende deposition.

Several tabular bodies of intrusive feldspar porphyry occur in the mine vicinity between the main belt of porphyry intrusives to the east and the granite to the west. These porphyry bodies are of two textural types, crystalline and aphanitic. The crystalline variety comprises most of the bodies. The aphanitic variety occurs in small outlying bodies and at the ends of the bodies of crystalline porphyry. The intrusion of the porphyry bodies has locally intricately deformed the Mine Series rocks and has been accompanied by contact metasomatism.

The metasomatism of the cherty rocks around the porphyry bodies consisted principally of the addition of Al, Fe, Mg and Ca, to form ferromagnesian minerals in aggregates and bands. Garnet has been formed in the calcareous Cobalt Island Formation rocks. Feldspathization and recrystallization of quartz are also widespread in the metasomatized rocks. The metasomatized rocks are medium to coarsely crystalline. Zoning of the metasomatism exists only as rather indefinite zones of different mineral assemblages flanking the various porphyry bodies. Metasomatism has reached its maximum development in rocks surrounding the ends of aphanitic porphyry bodies. The most important feature of the metasomatism, in regard to ore control, has been the change of competency it has imposed on the sedimentary rocks. It has made them more like the porphyry bodies in competency and this has been reflected in the fracture pattern of the vein zones.

The rocks of the Mine Formation represent a unit of homogeneous competency despite deformation by the porphyry intrusion. In some instances the massive chert beds may exert a separate influence on the fracture pattern of the shear zones. The metasomatized Mine Formation rocks and the rocks of the Cobalt Island Formation are more competent than the unmetasomatized Mine Formation rocks and affect the fracture pattern of the shear zones accordingly.

PORT RADIUM DEPOSITS: Between Cobalt Island and Crossfault Lake, the Eldorado Zone of shearing splits into two members, the Bear Bay Shear and No. 1 Vein. Within the lenticular area enclosed by these principal shear zones occur at least seven supplementary fracture zones that comprise the loci for the pitchblende deposits. The members of this fracture system that carry pitchblende orebodies are designated: No. 1 Vein, No. 2 Vein, No. 2A Vein, No. 3 Vein, No. 4 Vein, No. 5 Vein, No. 6 Vein, No. 7 Vein and No. 8 Vein. Principal producers are Nos. 1, 2, 2A, 3, 5 and 7 Veins. The fracture zones range between one and 40 feet in width and average about 3-5 feet. They consist of zones of parallel fracture planes one or several of which may be gouge-filled. Several ages and types of alterations and mineralization have left their effects along the shear zones, which are now vein zones of complex mineralogy flanked by various types of alterations.

The vein zones are generally narrow in competent rock formations and relatively wide in incompetent formations, such as the Mine Formation.

The mineralization of the Port Radium deposits occurred in five separate stages:

Stage I	Hematite-quartz
Stage II	Pitchblende-quartz
Stage III	Cobalt-nickel arsenides-quartz
Stage IV	Copper sulphides - chlorite - clay
Stage V	Carbonate-silver

Products of Stage II represent a small percentage of the total vein zones, and their deposition was more dependent on the original fracture pattern of the fracture zones, as determined by the different competencies of the wall rocks, than were the products of later stages. Successive vein materials, particularly quartz, contain abundant fragments of pitchblende. This brecciation of the pitchblende has been extensive, but transport of the fragments has rarely gone beyond the limits of the areas of original deposition. Textures and mineral associations of the pitchblende at Port Radium are very similar to the other major known vein deposits of pitchblende in the world.

The most widespread wall rock alteration is argillization, accompanied, in many places, by chloritization and carbonatization. The principal clay mineral is montmorillonite. Carbonatization came after the argillization and locally replaced the clay as well as unargillized wallrocks. Red alteration of the wall rocks occurred before the clay alteration and probably before any mineralization. The wall rock alterations at Port Radium are not indicators of pitchblende orebodies.

Mineralizing and altering hydrothermal solutions that formed the Port Radium deposits began as acidic oxidizing solutions depositing pitchblende and ended as alkaline reducing solutions depositing carbonate and silver.

Most of the orebodies at Port Radium occur at loci of greater than normal dilation along the vein zones. These loci may be breccia zones, zones of sharp increase in width of the shear zones, steep portions that have opened by normal relaxation, or junctions of shear or fracture zones. Most of the dilational portions of the shear zones are directly related to the differences in competency of the various wall rock formations. Porphyry, diabase, massive chert and granite are relatively competent, and the shear zones in them are constricted. Unmetasomatised fine banded Mine Formation cherts are relatively incompetent and provide the most favourable environment for pitchblende deposits in the shear zones. The ore control has been entirely physical, dependent on the structure of the wall rocks.

Precipitation of the pitchblende was caused by sudden losses in CO_2 from the solutions. The bicarbonate ion forms a soluble complex with uranium in hydrothermal solutions, particularly under pressure. Release of pressure results in loss of CO_2 and decrease in bicarbonate ion concentration, and subsequent flocculation of the uranium colloid, pitchblende. At Port Radium this action took place wherever the pregnant solutions entered relatively dilated, low pressure portions of the vein zones.

Several age determinations have been made on Port Radium ore, but they may not be dependable because of the complex history of disturbances the pitchblende has undergone since its original deposition.

Many localities in the Great Bear Lake area are worthy of further investigation in the search for pitchblende deposits.

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