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CANADA

DEPARTMENT OF MINES AND TECHNICAL SURVEYS

GEOLOGICAL SURVEY OF CANADA
BULLETIN 31

MINERALOGY OF URANIUM DEPOSITS, GOLDFIELDS, SASKATCHEWAN

BY
S. C. Robinson

EDMOND CLOUTIER, C.M.G., O.A., D.S.P.
QUEEN'S PRINTER AND CONTROLLER OF STATIONERY
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PREFACE

The discovery of numerous uranium deposits in the Goldfields region of northern Saskatchewan during the past 10 years has attracted widespread attention to this field as an important source of uranium. Many deposits have been explored by surface trenches and diamond drill-holes and eight by underground workings, one deposit to a depth of 800 feet. One mill is producing and a second is expected to go into operation in the near future.

The present report describes the results of an investigation conducted during the period 1949 to 1953 of the precise nature and mode of occurrence of the uranium-bearing minerals. All uranium minerals recognized and other associated minerals are described in detail, and forty-eight excellent microphotographs are included. Thirty-eight deposits were selected to illustrate the mode of occurrence of these minerals, and the rocks and structures of these deposits are described. Particular emphasis is placed on data useful to prospectors and operators.

The report presents significant new determinations of the age and history of the deposits, based on their lead-uranium ratio, and also describes new minerals known only from this region. A list of references to papers dealing specifically with uranium ores and minerals is included.

GEORGE HANSON,
Director, Geological Survey of Canada

OTTAWA, June 30, 1954

MINERALOGY OF URANIUM DEPOSITS, GOLDFIELDS, SASKATCHEWAN

CHAPTER I

INTRODUCTION

Investigation of the mineralogy of the uranium-bearing deposits of the Goldfields region was undertaken as part of a general program being carried out by the Geological Survey of Canada to provide data on the occurrence and geological environment of uranium in Canada. Because this region contains many uranium deposits, some of which are expected to be of economic interest, much of the work has been centred in it.

As part of this program: A. M. Christie, D. A. W. Blake, and J. A. Fraser have completed preliminary geological mapping of parts of the area on a scale of 1 mile to 1 inch; W. E. Hale is completing this work in the western part of the region; L. P. Tremblay has begun detailed mapping of part of the region on a scale of 1,000 feet to 1 inch; K. R. Dawson has completed a study of wall-rock alteration in the region; and A. H. Lang has compiled data in the field of economic geology.

The studies of the writer are intended to supplement these other investigations so as to provide: a survey of all uranium and associated minerals that have been recognized in the area; a description of the types of deposit in which they are found; a summary of evidence bearing on the age and genesis of the deposits; and supplementary information that may be of use to prospectors. Because it is necessary to relate distribution of uranium to features of general geology, wall-rock alteration, and types of deposit, brief descriptions of these features are included in this report. For more comprehensive data in these fields reference should be made to Blake (1951, 1952)[1], Christie (1953), Dawson (1951), Hale (1954), and Lang (1952).

Field work for purposes of this investigation was done in the summers of 1949–53, inclusive. Many radioactive deposits were examined on the surface and, where possible, underground. Diamond drill-core also was examined where available. Much of the early work was necessarily devoted to weathered surface exposures. Because pitchblende weathers readily it was difficult to obtain adequate data on the primary minerals. In recent years the increase in underground development has made possible the collection of a more useful suite of specimens for microscopic study, isotope analysis, etc. The present report is based on field examination of 117 individual mineral deposits and on laboratory examination of just over 700 specimens and samples.

Most of the investigation was necessarily done in the laboratory. Where facilities were not available in the Geological Survey of Canada, work was carried out in other specially equipped laboratories.

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[1] Dates, etc., in parentheses refer to Chapter VII.

ACKNOWLEDGMENTS

Field examination of virtually all properties in the area was made possible by the courtesy of the owners and their field staffs. The writer is deeply indebted for permission to examine these properties and to collect specimens and samples and for the generous assistance in transport, housing, and time that greatly facilitated his work. In many instances, too, information was supplied and specimens were collected for him that have enhanced the value of this investigation. It is regretted that the large number of those in the field who have provided this generous assistance, precludes individual acknowledgment in this report.

Lead isotope and/or potassium/argon analyses for age determination were made by C. B. Collins, R. M. Farquhar, and H. Shillibeer at the University of Toronto, J. L. Kulp at the Lamont Geological Observatory, Palisades, New York, R. L. Stieff of the United States Geological Survey, Washington, and by G. J. Wasserburg of the University of Chicago. Palæotemperature determinations of vein calcite were made by H. R. Hoekstra of the Argonne National Laboratories. Decrepitation analyses for palæotemperature determinations of quartz and calcite were made by M. H. Haycock of the Mines Branch, Ottawa. Numerous samples were crushed and concentrated at the Mines Branch, which also made a number of mineral separations on a magnetic separator. Grateful acknowledgment is made to all these collaborators.

The writer has discussed features of the work with many geologists working for various companies in the field. He hereby acknowledges the information and suggestions made orally by the following geologists, who acted for or were employed by mining interests in the area: R. B. Allen, W. W. Archer, L. D'Aigle, W. F. Dix, R. W. Edie, A. Gregory, J. W. Griffith, W. H. Gross, W. Hall, H. G. Harper, F. R. Joubin, B. C. Macdonald, J. R. Macdonald, J. W. MacLeod, J. T. Mandy, G. C. McCartney, L. M. Montgomery, G. W. Moore, H. C. Norman, G. Oliver, J. E. M. Parker, G. Radisics, J. S. Ross, J. F. B. Silman, E. E. N. Smith, E. Walli, and J. R. Walter.

The writer gratefully acknowledges assistance and criticism by colleagues of the Geological Survey of Canada, both in the laboratory and in the field.

LOCATION

For purposes of this report the Goldfields region includes an area on the north shore of Lake Athabasca within a radius of 20 miles of the centre of Beaverlodge Lake. This area includes the villages of Goldfields and Uranium City, Saskatchewan. Beaverlodge Lake itself is the approximate geographical centre of uranium deposits in the district.

HISTORY OF PROSPECTING AND DEVELOPMENT

Interest in the mining potentialities of the Lake Athabasca region was first aroused in a report by J. B. Tyrrell (1896) that described the occurrence of iron-bearing rocks in the vicinity of Fish Hook Bay and elsewhere along the north shore of the lake. Claims were staked in the vicinity of Fish Hook Bay in 1921 but examination of these iron deposits by Allan and Cameron (1922) showed that they were below commercial grade.

Prospecting was next stimulated by the discovery in 1910 of nickel and copper sulphides with some silver in the area east of Fond du Lac. British capital financed drilling for nickel in the Sucker Bay-Dardier Point area and after 2 or 3 years work in the period subsequent to 1914 the properties were abandoned. Interest in copper and nickel was revived by discovery of deposits on Axis Lake, 8 miles north of Stony Rapids, and development work was done in 1929 and 1930. In the past 4 years, these and other deposits extending to the northwest have been again examined.

In 1930 a copper deposit was explored on what is now the property of Consolidated Nicholson Mines Limited. In 1934 gold was discovered northwest of Neiman Bay and a large number of claims were staked on gold and gold-copper showings in the Goldfields district. In the next 3 years a number of shafts were sunk and adits were driven but production was restricted to the Box and Athona mines. Due to the changed economy of the war years the last of these operations ended in 1942. In 1935 prospectors discovered gold in the Sucker Bay area where drilling and some underground prospecting was done until 1938. In this period, too, nickel deposits were found and explored by drilling at Dinty Lake, 24 miles northeast of Goldfields village. Interest in this property has been revived and further exploration was undertaken in 1952.

During development of various properties for gold, pitchblende was recognized in two deposits on what is now the property of Consolidated Nicholson Mines Limited and thucholite was recognized underground at the Box mine. In 1944, the strategic importance of uranium led to the re-examination of the Nicholson property by the Geological Survey of Canada and Eldorado Mining and Refining Limited, a Crown company. As a result, Eldorado initiated an intensive prospecting and development program for uranium in the area, which is being actively maintained. In the spring of 1948 the Federal Government repealed the wartime ban on prospecting for uranium by the general public. Subsequently, in March 1949, the Saskatchewan Government established concessions of 25 square miles each in a large area around Beaverlodge Lake. The exclusive right to prospect these concessions was then sold to companies and individuals for a limited period. As certain of these concessions reverted to the Crown, the ground was thrown open to public prospecting. On August 4, 1952, all areas within the remaining concessions that had not been staked by the concessionaires were thrown open to public prospecting. No concessions remained in force after that date.

Use of instruments that will detect emanations given off during the radioactive decay of uranium has resulted in the location of thousands of radioactive occurrences in the Goldfields region. The more promising of these have been actively developed by stripping, trenching, and diamond drilling. By June 1952, underground development of uranium-bearing deposits included a total of six shafts and two adits. The winter of 1952-53 saw the addition of two more shafts and four more adits. First production from the area was shipped from Eldorado's new mill at its Ace-Fay mine in June 1953. Exploration and development of other properties is being actively carried on.

In 1951 the Saskatchewan Government surveyed a new townsite on the north shore of Martin Lake where Fredette River enters. In the autumn of that year a road was completed from new docks on Black Bay, through the new townsite, to Eldorado's townsite at the north end of Beaverlodge Lake, where a landing strip for passenger aircraft had been constructed during the summer. With the inauguration of daily air service from Edmonton by Canadian Pacific Airlines and a bi-weekly service from Prince Albert by Saskatchewan Government Airlines, construction on the new townsite of Uranium City was started in 1952 and the post office was moved there from Goldfields. Transfer of facilities from Goldfields to Uranium City is now complete, leaving Goldfields a ghost town.

GENERAL GEOLOGY

Rocks and mineral deposits of the district are all of Precambrian age. The oldest rocks are those of the Tazin group, which consist of metamorphosed sedimentary strata, including some volcanic rocks and which Christie (1953) assigns to the Archæan. This group includes quartzites, dolomites, conglomerates, impure sediments and intercalated basic volcanic rocks, and their metamorphic equivalents. Basic sills and dykes that cut the sedimentary and volcanic facies are included in the Tazin group.

Granitic rocks intrude or replace strata of the Tazin group over wide areas. These granites are usually gneissoid and contain relict masses of rocks of the Tazin group. Some areas of massive unfoliated granite that do occur are composed almost entirely of quartz and feldspar, with a notably sparse content of femic minerals. Pegmatites and lamprophyres are probably apophyses of the granites. The lamprophyres are restricted in distribution to small areas in the southeastern part of the district. Pegmatites rarely exhibit sharply defined walls except in the area between Murmac Bay and Mackintosh Bay. Elsewhere, they occur as discontinuous bands in the gneiss or as irregular masses that show crosscutting, but transitional, relationships to the host rocks.

In the Goldfields-Martin Lake map-area, a clearly defined group of intercalated sandstone, andesite, and arkose with a basal boulder conglomerate, comprise the Athabasca series. These rocks, in marked contrast with those of the Tazin group, are fresh and only slightly metamorphosed. The sandstone and arkose members of this series are exposed on islands in Lake Athabasca and over a wide area on the south shore of the lake, which extends eastward almost to Reindeer Lake. The distribution of Athabasca rocks elsewhere and especially north of Lake Athabasca from Goldfields to Fiddlers Point, Alberta, is restricted to remnants lying unconformably on the older rocks. They are also preserved locally on the down-thrown side of major faults. South of Lake Athabasca they appear as a relatively thin, flat-lying series through which large windows of the older rocks are exposed.

Christie (1953) has observed that a series of ubiquitous, small "diabase" dykes, ranging in composition from gabbro to syenodiorite, cut all other rocks in the Goldfields-Martin Lake area. These rocks occur in varying amount throughout the Lake Athabasca region.

Mineral deposits containing pitchblende have been found in fractures that intersect, and are, therefore, younger than, all rock types in the district.

The Archæan granites and Tazin group rocks are much foliated and faulted. Christie (1953) has described certain large structures in these rocks, particularly in the vicinity of Lake Athabasca. Similar structures have been recognized by Hale (1954) in the area of Black Bay and by Blake (1951, 1952) in the Forget Lake and Nevins Lake map-areas. The general trend of rocks and foliation, except in the vicinity of Black, Lodge, Murmac, and Mackintosh Bays near Lake Athabasca, is east of north.

Most folds of the Athabasca rocks are open and simple. Their dominant structure in the region is the Martin Lake syncline. Where these rocks outcrop on the islands of Lake Athabasca and on the south shore of Lake Athabasca dips seldom exceed 20 degrees.

Three major faults have been recognized in the region, which dislocate the Archæan and the Athabasca rocks. The Black Bay fault, striking north 35 degrees east and dipping 65 degrees southeast, is thought to extend from Crackingstone Point a distance of 25 miles to the vicinity of Anne Lake. The St. Louis fault strikes north 60 degrees east and dips 50 degrees southeast and has been traced 7 miles from the north end of Beaverlodge Lake to Raggs Lake. Blake (1951) records evidence that suggests that this fault may extend another 15 miles from Raggs Lake to beyond Alces Lake. The ABC fault trends north 35 degrees west and dips 40 degrees southwest. It cuts off the Athabasca rocks at the north end of the ridge between Martin and Beaverlodge Lakes and probably extends from the St. Louis fault to the Black Bay fault. Christie and Blake have noted that broad bands of fine-grained, cherty, red mylonites are found in the Tazin rocks that flank the major faults. These rocks contain carbonate, chlorite, hematite, and quartz that are probably due to hydrothermal alteration.

CHAPTER II

DESCRIPTIONS OF URANIUM DEPOSITS

In this chapter representative uranium deposits are described to provide a factual basis for a discussion of the general and regional mineralogy. In order to supply a more complete setting for purposes of interpreting discussion of genetic association, brief notes on the types of deposits, their wall-rock alteration, structural features, and distribution in different rock types are also given.

DESCRIPTIONS OF SELECTED PROPERTIES

Properties to be described were chosen: (a) to represent all observed variations in mineralogy; (b) to represent all parts of the region; and (c) to provide maximum vertical extent. Where two or more properties have the same characteristics and occur in the same part of the region, only the one which at the time of the writer's visit provided the greatest variety and least altered mineral specimens is described. Although all deposits are described on which underground development had been undertaken by 1953, inclusion or exclusion of properties for description is not based on the writer's opinion of their economic significance.

Descriptions of each property are dominantly mineralogical, but a brief note on the geological setting of each deposit precedes the mineralogical description. Photomicrographs are used to save words and to illustrate textures and mineral relations. In case of doubt as to the meaning of textural terms, reference should be made to the illustrations.

EXPLANATION OF FIGURE 1

The deposits described in this report, and whose location is indicated by numbers on Figure 1, are as follows:

1. Amax Athabasca Uranium Mines Limited—Showing 49-CC1-11.
2. Athabasca Uranium Mines Limited—Showings GG-1 and GG-2.
3. “ “ “ “ —'That' Lake deposit—Showing FF-10H.
4. “ “ “ “ —Tom Fault showing.
5. Aurora Uranium and Gold Mines Limited—Showing CC2-128.
6. Beaverlodge Uranium Mines Limited—Bar group—zones 2 and 5.
7. Beta Gamma Uranium Mines Limited—Chum group—No. 1 showing.
8. “ “ “ “ “ —White Dog group.
9. Black Bay—deposits in cross fractures northeast of Black Bay (not shown on map).
10. Cinch Lake Uranium Mines Limited—Jam group.
11. Consolidated Nicholson Mines Limited—No. 1 zone.
12. “ “ “ “ —No. 2 zone.
13. “ “ “ “ —No. 4 zone.
14. Eldorado Mining and Refining Limited—Ace and Fay mines.
15. “ “ “ “ “ —Eagle mine.
16. “ “ “ “ “ —Eagle group—selenide deposits.
17. “ “ “ “ “ —Fish Hook Bay—zone A.
18. “ “ “ “ “ —Gil group.

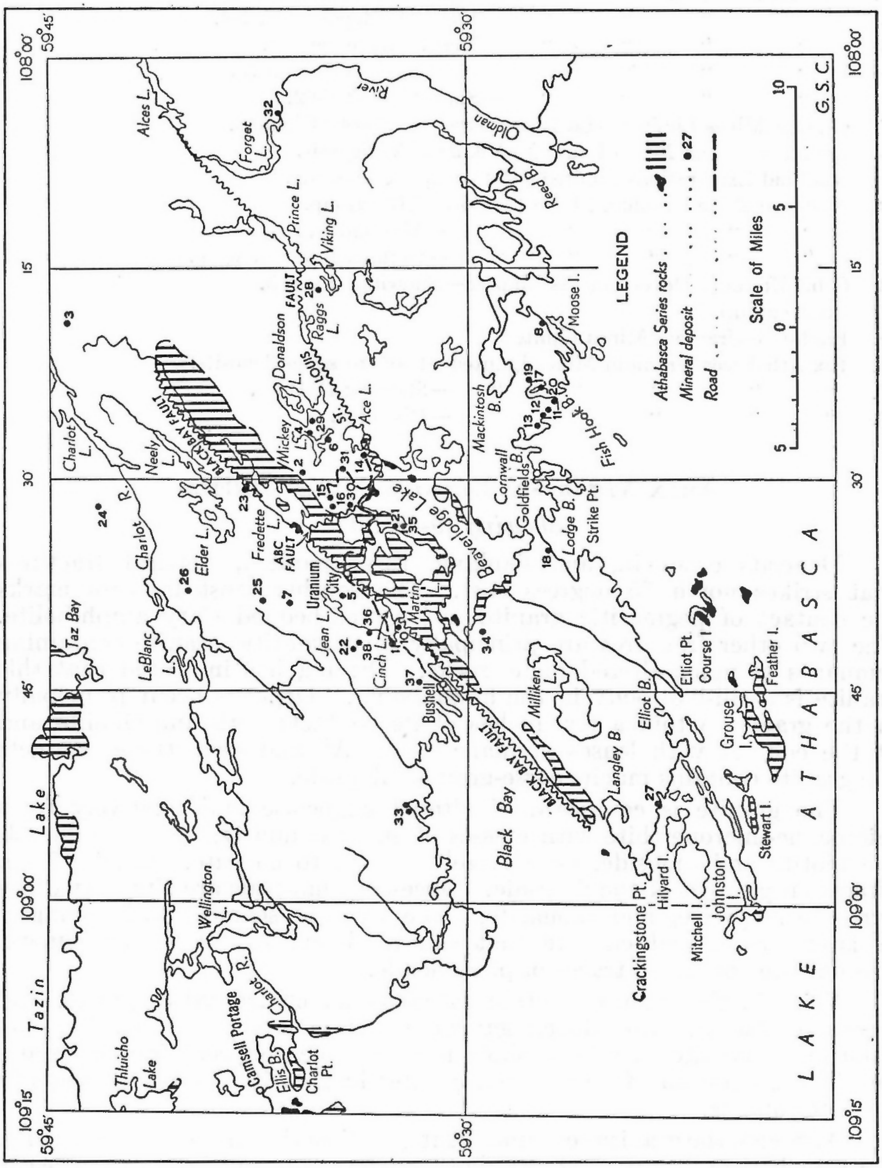


Figure 1. Index map to deposits described in Chapter II.

19. Eldorado Mining and Refining Limited—Hacker zone.
20. " " " " " —Joe showing.
21. " " " " " —Martin Lake mine.
22. Goldfields Uranium Mines Limited—DD1-62 showing.
23. " " " " —Eke Lake deposit—FF1-4.
24. " " " " —Nesbitt Lake deposit.
25. " " " " —Showings NN 70 and 75.
26. " " " " —Showing 50-TT-62.
27. Gunnar Mines Limited—Ed-Bon group—St. Mary's Channel.
28. Lorado Uranium Mines Limited—Viking Lake deposit.
29. National Explorations Limited—Pat group—C showing.
30. Nesbitt-Labine Uranium Mines Limited—ABC group.
31. " " " " " —Maj and Jam groups.
32. " " " " " —Oldman River showing.
33. Orbit Uranium Developments Limited—Showings 2 and 3.
34. Pitche group.
35. Pitch-Ore Uranium Mines Limited.
36. Rix Athabasca Uranium Mines Limited—Leonard series deposits.
37. " " " " " —Showing DD1-58.
38. " " " " " —Rix mine.

AMAX ATHABASCA URANIUM MINES LIMITED

Showing 49-CC1-11

Deposits occur in, and flanking, three parallel, vertical fractures that strikes north 75 degrees east. The southernmost fracture marks the contact of pegmatitic granite and a well-bedded slaty amphibolite. The two other fractures are principally in pegmatitic granite containing remnants of much-altered mafic rocks. Drilling has indicated that this granite is a sill-like body in the amphibolite. Deposits occur principally in the granite within a few inches of its contacts with amphibolite and at the contact with lenses of mafic rock. At and near these contacts the granite contains much coarse-grained diopside.

The granite is composed of altered oligoclase and relatively fresh microcline-microperthite with masses of sutured quartz. Femic minerals are biotite and diopside, both largely altered to chlorite. Calcite is an alteration product of the diopside. Accessory minerals are zircon (variety cyrtolite), apatite, and monazite. The rock is seamed with stringers of later calcite and chlorite that contain hematite. A heavy mineral concentrate contained traces of pitchblende.

Veins in the granite contain pitchblende, chalcopyrite, pyrite, and traces of galena. Introduced gangue minerals are quartz, calcite, and chlorite. The pitchblende is colloform in part, coating rock fragments and an older generation of stained red calcite; in part it remains as wisps in the later quartz.

Although the granite contains slightly radioactive zircon and monazite, the principal radioactive mineral both in the veins and in megascopically massive granite is pitchblende. The granite that appears to be massive in the field has actually been fractured and veined by quartz, calcite, and chlorite as seen under the microscope. The evidence all points to later introduction of pitchblende that has no apparent relationship to the granite.

ATHABASCA URANIUM MINES LIMITED

Showings GG-1 and GG-2

These deposits are in and adjacent to a persistent fault in reddish granite, granite-gneiss, and migmatized mafic rocks. The main fault strikes north 55 degrees east and dips approximately 70 degrees northwest. The best material for mineralogical examination occurs in an east-west structure that is subsidiary to the main fault. Red alteration of the wall-rocks is pronounced around the uranium deposits but there is also much red alteration without uranium.

In the subsidiary fracture, the metallic minerals recognized are: hematite, pitchblende, pyrite, limonite and traces of galena, chalcopyrite, and (?) marcasite. Non-opaque minerals are: chlorite, calcite, quartz, and octahedrite.

The veins are flanked by red, cherty wall-rocks. The vein material consists of scattered quartz fragments with markedly strained extinction set in a matrix of chlorite and calcite. The chlorite with subordinate calcite forms the bulk of the vein material. Calcite, in part coarse grained but in part very fine grained, is intimately mingled with the chlorite and is variably stained by both hematite and limonite; this staining is locally transitional to opaque areas of hematite and pitchblende. Opaque areas in chlorite, by contrast, are usually free from aureoles of this stain. Textural evidence indicates replacement of calcite by chlorite and suggests contemporaneous alteration of hematite to limonite. There is no evidence to suggest that the limonite is a product of surface alteration.

Pitchblende is variable in habit. Commonly it occurs in groups of irregular rounded fragments whose habit suggests that they are residual after replacement by chlorite and calcite. More massive areas of pitchblende are veined by calcite and chlorite and commonly exhibit a halo of discrete grains of pyrite in the gangue around their perimeters. However, in some large areas of vein material that autoradiographs show to be markedly radioactive no pitchblende or other uranium minerals can be recognized.

Massive hematite and dusty red hematite are densely disseminated through the wall-rocks. In the veins hematite is largely euhedral and is also present as the red dusty variety in quartz and calcite. Limonite is associated with red hematite in the calcite.

Traces of a white isotropic mineral in the pitchblende are probably galena grains. Chalcopyrite, in traces, is disseminated as discrete particles in the gangue. In some areas there are concentrations of an acicular, anisotropic, brass-coloured mineral that is probably marcasite.

The significant factor in this deposit is the dispersal of much of the uranium through the gangue in a form that is so finely disseminated it cannot be positively identified. Textural relationships suggest that this dispersal is the result of replacement of earlier pitchblende masses by calcite and chlorite.

'That' Lake Deposit (Showing FF-10H)

This deposit was not visited by the writer. It is reported to be a radioactive pegmatite that occurs along the foot-wall side of a graphitic shear, which strikes north 70 degrees east. The country rock is granite-gneiss.

A group of specimens collected by Mr. J. Kilgour were forwarded to the writer by courtesy of American Canadian Uranium Mines Limited (now Athabasca Uranium Mines Limited).

The specimens represent a rather fine-grained pegmatite or coarse-grained granite. Maximum dimensions of feldspar crystals are of the order of $\frac{3}{4}$ inch. The specimens are composed principally of fresh microcline-microperthite and sutured quartz, with minor amounts of biotite and sericite. Accessory minerals are uraninite, monazite, xenotime, and apatite. These minerals are distributed largely in the microcline and biotite and less commonly in quartz. Pyrrhotite is present in fairly large amount and molybdenite is also present. The pyrrhotite is largely in the quartz gangue and molybdenite is more commonly associated with biotite. An approximate X-ray fluorescence analysis of the uraninite is: U_3O_8, 75 per cent, ThO_2, 5·6 per cent, and PbO, 13 per cent.

Tom Fault Showing

References: Christie (1953, p. 90); Lang (1952, p. 80).

These deposits occur in a prominent fault or shear zone that strikes east-west and dips 70 degrees south. The fault transects granite, chlorite schist, amphibole, and migmatite. Uranium deposition is largely on the foot-wall side and its presence is marked by weak red alteration of the wall-rocks.

Metallic minerals recognized in these deposits are: hematite, pyrite, chalcopyrite, and traces of galena. Non-opaque minerals are: quartz, dolomite, chlorite, and sericite.

Radioactivity of these deposits is difficult to explain on evidence from the specimens available. In the field, traces of uranium stain may be observed but no primary uranium minerals were recognized. Microscopic examination in thin and polished section also failed to produce identification of a primary uranium mineral. Autoradiographs indicate that the radioactivity is restricted to patches of brown cherty material that together with rock fragments are cemented by stringers of comb quartz in which dolomite fills the interstices. This cherty material consists of a granular aggregate of quartz and highly sericitized feldspar with interstitial chlorite and disseminated opaque minerals. The last are in part, pyrite, chalcopyrite, hematite, and traces of galena. The whole is uniformly radioactive and pitchblende is probably disseminated in extremely fine-grained form with the other metallic minerals. Apart from subhedral grains of pyrite and disseminated hematite, the metallic minerals are concentrated in the radioactive areas.

AURORA URANIUM AND GOLD MINES LIMITED

Showing CC2-128

This deposit is of interest because it occurs in fractures in a large diabase dyke whose surface expression is 50 feet wide. The main fracture is approximately parallel with the length of the dyke and lies at least 15 feet from its nearest surface contact with other rocks. Concentrations of pitchblende occur where minor fractures intersect the main one. Red alteration of the diabase is pronounced within 2 to 3 feet of the pitchblende veins.

Metallic minerals recognized in this deposit are: hematite, pitchblende, and chalcopyrite. Non-opaque minerals are: calcite, quartz, rutile, and apatite.

The veins are composed principally of red and white, coarse-grained calcite with a selvage of fine-grained iron-stained quartz along the walls. Pitchblende occurs largely as angular fragments cemented in the calcite. Some colloform rims occur on the quartz of the vein walls. Chalcopyrite as very fine-grained discrete particles is disseminated in the pitchblende. A few euhedral crystals of apatite also occur in the pitchblende of the vein.

The wall-rocks within a few inches of the veins have been intensely altered. Laths of feldspar are almost completely altered to sericite. The femic minerals are wholly altered to chlorite and iron oxides. Calcite and quartz have pervaded the rock to the extent that they form almost 25 per cent of its mineral content. Red, dusty hematite has reddened the rock, and patches of massive to flamboyant hematite (*See* Figure 43) are common. Bladed rutile in rounded patches is a prominent constituent of the wall-rock near the veins. Apatite is quite abundant in euhedral crystals up to 1 mm. long. Pitchblende is found disseminated in the altered wall-rocks up to distances of at least 2 inches from the nearest vein or fracture. It is visible as minute irregular flecks under the microscope, but autoradiographs show that the wall-rock is radioactive even in areas where no pitchblende can be detected under magnifications of the order of 1000 diameters. Grains of chalcopyrite in the wall-rock have the same distribution as the pitchblende.

The relative uniformity of the diabase host rock of this deposit permits some conclusions as to apparent concentrations of different minerals in and near the veins, based on the following analyses by S. Abbey:

Location of sample	TiO_2	Fe
	%	%
Chilled border facies of dyke	2·33	N.D.[1]
Unaltered centre facies of dyke	1·80	7·89
Centre facies 2 inches from vein (red altered)	1·83	8·55
Wall-rock with some vein material	1·45	N.D.

[1] N.D. = not determined.

These results indicate that the only significant concentration of titanium is in the chilled border facies of the diabase dyke. Despite the presence of abundant rutile patches in the wall-rock there is no significant increase in amount of titanium over that of the unaltered part of the dyke; the rutile patches, therefore, are probably due to recrystallization of syngenetic titania. Similarly, it is probable that red coloration of the host rocks is largely due to the oxidation of original iron minerals with only a small amount of iron having been added by the hydrothermal solutions from which the vein was deposited.

BEAVERLODGE URANIUM MINES LIMITED

Bar Group—Zones 2 and 5

Reference: Christie (1953, p. 91).

Deposits of these two zones occur sporadically along a continuous fault system that strikes north 45 degrees west and dips 80 degrees southwest. Country rocks intersected by this fault system strike northeast and their dip varies from 20 degrees southeast at its southeast end to vertical at its northwest end. Principal rocks are: argillites, locally intercalated with narrow quartzite bands, and in one area containing stringers and pods of granite; amphibolite; quartzite; diabase; and chlorite schist and gneiss.

Pitchblende deposits most commonly occur at or close to the contacts of two contrasting rock types. They are usually irregular in shape and conform to dilatant zones. They show a marked preference for argillite, amphibolite, and diabase; only one deposit was observed in granite and none in quartzite.

Red alteration of the wall-rocks is not pronounced in any of these deposits and is lacking in some of them. It is usually confined to the vein material, where it may attain widths up to 1 foot. Alteration of biotite, amphibole, and some feldspar to chlorite is common within 1 inch of the vein.

Metallic minerals recognized in these deposits are: pyrite, hematite, pitchblende, chalcopyrite, galena, clausthalite, bornite, and marcasite. Introduced non-metallic minerals are: calcite, quartz, and chlorite. Garnet occurs locally in vein quartz.

Most of the pitchblende is disseminated through a heterogeneous assemblage of rock fragments, chlorite, iron oxides, and older calcite. Usually, too, younger calcite has veined and partly replaced this older material. In the resulting mixture, relations of pitchblende to other minerals are usually obscure. In some specimens no pitchblende can be recognized among the cloudy iron oxides and other minerals, although autoradiographs show relatively intense but ill-defined centres of radioactivity in them. It is probable, however, that uranium is present as disseminated but very minute particles of pitchblende. Visible pitchblende is usually massive and marked by curving fractures. It appears to be almost transitional to the gangue, through which the fractures also persist. These fractures, moreover, do not occur in gangue free from pitchblende. Chalcopyrite, and to a minor extent galena and pyrite, are rather uniformly distributed through these pitchblende-bearing areas as discrete grains. Locally, chalcopyrite grains are so abundant that they comprise more than 50 per cent of the whole. Massive, pure pitchblende occurs only in chlorite veining earlier quartz, in an area free from calcite and sulphides. Colloform pitchblende was recognized in only one deposit. In large crystals of feldspar, in which alteration to chlorite along cleavage is well advanced, pitchblende with associated iron oxides occurs in the centre of the chlorite veinlets.

Red dusty hematite is disseminated locally through gangue minerals in the vein and marginally in the wall-rock. More commonly hematite occurs in massive, irregular grains. Where the later calcite has replaced earlier gangue minerals the contact is usually marked by a line of specular hematite. Specular hematite has also been observed as a rim around masses of pitchblende. Massive hematite locally veins, and is mixed with, pitchblende. Its texture and spatial distribution suggest that it has replaced pitchblende. Hematite has also been observed mantling pyrite in the wall-rock.

Pyrite is abundant as subhedral crystals in some types of wall-rock. In rounded grains, it occurs sporadically in the vein material and, rarely, it is disseminated as discrete grains in pitchblende and its admixed gangue. Chalcopyrite and galena are most abundant in the pitchblende areas though both occur in adjacent gangue also. Bornite was recognized in areas rich in chalcopyrite. Clausthalite was noted in one deposit only, at the southeast end of the showings, where it is associated with chalcopyrite and pitchblende.

BETA GAMMA URANIUM MINES LIMITED

Chum Group—No. 1 Showing

References: Christie (1953, p. 109); Lang (1952, p. 81).

This complex deposit occurs in a long shear zone that strikes north 75 degrees east and dips 80 degrees south. Diabase occurs almost continuously on the hanging-wall of the shear zone except at the west end. Pegmatite has developed intermittently along the foot-wall over hundreds of feet. A second generation of diabase occurs in fractures "tailing off" on both sides of the main shear. Massive feldspathic quartzite forms the hanging-wall but a variety of paragneisses occur against the foot-wall. In part these have been brecciated in the foot-wall of the shear zone. The breccia has been cemented by quartz, and where brecciation has been intense the resulting rock resembles a granite, marked by pods of chlorite.

Despite the somewhat varied character of the deposit, uranium has been reported fairly consistently over most of its length. The only megascopically visible pitchblende occurs against the hanging-wall where the older diabase has been flexed and brecciated. Calcite with pitchblende and sulphides has cemented the brecciated diabase. Traces of pitchblende have also been recognized along shear planes of the brecciated paragneiss of the foot-wall. Autoradiographs show that pitchblende did not accompany the quartz that sealed this breccia; it appears to have filled cracks developed during a later period of shearing. The pegmatite and diabase are not appreciably radioactive.

Metallic minerals recognized in these deposits are hematite, pitchblende, pyrite, and traces of chalcopyrite. Introduced non-metallic minerals are calcite, quartz, and some of the chlorite.

The walls of fractures in the diabase and in the breccia contain concentrations of hematite and some limonite. Fractures in the diabase are filled with calcite. Autoradiographs indicate that pitchblende occurs principally with the iron oxides; it has not been recognized in the calcite. Pyrite occurs in the diabase, principally in the immediate vicinity of calcite stringers. In the breccia, pyrite is a widespread metamorphic mineral. Red hematitic alteration of the diabase is very noticeable as an envelope around these areas where pitchblende occurs. In and near calcite, specular hematite has developed locally.

In the pegmatite, muscovite, augite, tourmaline, and traces of molybdenite occur. Considerable quantities of zircon and rutile with a few grains of monazite were recovered in a heavy mineral concentrate of the foot-wall granitoid breccia.

It is worth noting that in the No. 2 showing, colloform pitchblende is associated with pyrite, galena, chalcopyrite, and chalcocite. The pitchblende fills fractures in quartz and rims euhedral quartz crystals. Calcite fills the space between the pitchblende rims.

The main deposit is interesting because it shows conclusively that the pitchblende is later than one generation of diabase and probably later than fresh pegmatite. Furthermore, it would appear that the solutions from which pitchblende was deposited followed the same structures that governed emplacement of pegmatite and of two generations of diabase.

White Dog Group

Reference: Lang (1952, p. 105).

The principal radioactive zone on this property occurs in well-banded dolomitic quartzite and amphibolite with some thin biotite-rich bands. These rocks strike north 42 degrees east and dip 50 degrees southeast. These metamorphosed sediments form a narrow band up to $\frac{1}{4}$ mile wide lying between two areas of granite and are remarkably free from folding.

Radioactivity is not continuous for distances of more than 100 feet along the strike, but several such radioactive zones occur in one continuous band over a total strike length of 600 feet. This mineralized zone is composed of well-banded amphibolite, dolomitic quartzite, and mica schist. There is no visible structure to account for the deposit, but there are a few vuggy quartz stringers parallel with the bedding. The zone of highest radioactivity parallels the largest quartz stringer but the others are not radioactive.

The pitchblende-bearing rock is made up largely of hornblende with altered plagioclase feldspar, minor dolomite, and rutile. Metallic minerals appear to have been introduced in local areas where the rock has been granulated on a microscopic scale. In seams where pitchblende occurs the hornblende is largely altered to chlorite and there is a significant increase in disseminated rutile. There is no typical "red alteration" associated with these deposits; hematite is grey and massive and the dolomite present appears to be an original constituent of the rock.

Metallic minerals recognized, in approximate order of abundance, are: hematite, galena, chalcopyrite, pitchblende, pyrite, and sphalerite. There is no introduced gangue mineral in direct contact with these metallic minerals.

Pitchblende occurs as discrete, somewhat angular grains disseminated in seams parallel with the bedding. The sulphides occur in generally rounded to oval grains, very few of which are composed of more than a single mineral. Distribution of sulphides is generally parallel with that of pitchblende and is restricted to the same band, but zones highest in sulphides are not necessarily highest in pitchblende. Grain size of these discrete sulphide particles is usually of the order of 100 mesh or smaller but individual single crystal grains of galena up to $\frac{1}{2}$ inch in diameter do occur. It is only very rarely that grains of two metallic minerals occur in contact; there are no data as to their relative age.

BLACK BAY

Deposits in Cross Fractures

A series of minor fractures that transect a group of gneisses and migmatites in the area extending northeastward from Black Bay contain radioactive minerals. The mineralogy of these deposits as a group is described here. Most of the deposits occur in fractures whose strike varies from east-west to north 70 degrees east. In some instances there are also minor shear zones parallel with the foliation of the host rocks. The dip of the fractures rarely deviates more than 10 degrees from vertical. Red coloration of wall-rocks is usually absent although gangue minerals are locally impregnated by dusty red hematite.

Metallic minerals recognized in all these deposits are pitchblende and hematite; in some of them, chalcopyrite, pyrite, and galena are also present. In some veins introduced gangue minerals appear to be absent; in others quartz, calcite, chlorite, and anatase have been recognized. In veins lacking calcite the pitchblende is massive and cements brecciated rock or quartz (*See* Figure 3). Where calcite is present, colloform pitchblende commonly encrusts the carbonatized rock fragments; in one deposit, outer rims of pitchblende with calcite intervening between them and the colloform pitchblende cores (*See* Figure 35) suggest rhythmic precipitation of calcite and pitchblende. In this and other deposits, colloform pitchblende rims are cut by later calcite in textures indicative of replacement.

CINCH LAKE URANIUM MINES LIMITED

Jam Group

References: Christie (1953, p. 92); Lang (1952, p. 92).

Principal deposits in this property occur on the foot-wall side of the Black Bay fault and within ¼ mile, approximately, of the fault. They occur in two sets of faults and shear zones, the one striking north 80 degrees east and the other north 45 degrees east, approximately. Host rocks are altered mafic sediments, impure quartzite, and aplitic granite that are intersected locally by small basic dykes. Red alteration of the wall-rocks is pronounced within 2 to 3 feet of the veins. There is evidence of some brecciation and shattering of the host rocks over widths of up to 2 feet. Much of the pitchblende occurs in joints and small shears tailing off the main fractures. In drilling, widths of tens of feet of highly altered and kaolinized rocks have been cut, and these are thought to be down-faulted blocks of Athabasca sandstone. This type of alteration is not common in the area and may well have taken place along a major fault following the course now occupied by the stream flowing out of Cinch Lake.

Metallic minerals recognized in these deposits include: hematite, pitchblende, chalcopyrite, pyrite, and tiny flecks of (?) galena. Non-opaque minerals include: calcite, dolomite, quartz, and rutile. Some brecciated feldspar in walls of veins cutting impure quartzite and altered mafic sediments may well be due to hydrothermal alteration preceding uranium and carbonate mineralization.

Occurrence of pitchblende in these veins is of particular interest. An early generation of colloform pitchblende coats fragments of wall-rocks, and of mylonitized feldspar and quartz. In part this pitchblende appears to have been corroded by calcite because under crossed nicols the original colloform outline is visible, but in plane polarized light the pitchblende is mixed with calcite in irregular veinlets and masses. Moreover, calcite has penetrated the rock enveloped by the pitchblende. Much of the pitchblende in the veins occurs as ragged patches of very small size that are interstitial to, or partly enveloped by, the grains of calcite in which they occur. Euhedral to anhedral grains of chalcopyrite and traces of pyrite are disseminated through some of these patches of pitchblende. Some of the patches also show intimate intergrowth with calcite. In a number of sections that are markedly radioactive only very minute traces of pitchblende were recognized. Autoradiographs of these sections indicate that the carbonate areas are distinctly radioactive, particularly where concentrations of disseminated chalcopyrite and (?) galena occur. X-ray powder patterns made of this "radioactive calcite" did not show pitchblende lines. The calcite pattern is identical in spacings and intensities to that of non-radioactive calcite. In thin section, the calcite of these radioactive areas is distinctly cloudy. It is probable, therefore, that uranium-bearing minerals in sub-microscopic form are present.

CONSOLIDATED NICHOLSON MINES LIMITED

No. 1 Zone

References: Alcock (1936, p. 37); Christie (1953, p. 113); Lang (1952, p. 95).

This property was described by Alcock (1936) who visited it when the trenches were opened; it has not been visited by the writer.

The showing, according to Christie (1952), consists of a discontinuous vein-type deposit in dolomitic quartzite close to the contact with ferruginous quartzite breccia. Ellsworth examined specimens collected by Alcock (1936, p. 37) and identified carbonate, botryoidal pitchblende, thucholite, niccolite, grey cobalt-nickel arsenides, erythrite, and annabergite. His partial analysis of a representative specimen of altered radioactive ore is: U_3O_8, 49 (+) per cent; Fe_2O_3, 16 per cent; rare earths, 2 per cent; and silicate silica, 15 (+) per cent. The remainder consists mainly of the following: Pb, Al, Ca, Cu, As, Ni, V, etc. The occurrence of so large an amount of rare earths is unusual for this type of deposit.

Gold, cementing cleavage fragments of calcite, was identified in one trench by Hogarth (personal communication).

No. 2 Zone

References: Christie (1953, p. 113); Lang (1953, p. 95).

This zone consists of a number of discontinuous sub-parallel shears and fractures in quartzite that is locally dolomitic. The zone is in quartzite parallel with, and about 10 feet east of, a body of ferruginous quartzite breccia.

In one surface trench, a vein of carbonate-rich gouge contains the following metallic minerals: pitchblende, native gold, galena, tiemannite, niccolite, pyrite, and chalcopyrite. In other specimens from this deposit, Kaiman (personal communication) has identified the following additional minerals: antimonian silver, dyscrasite, and grey cobalt-nickel arsenides.

Polished sections of this highly weathered material show that pitchblende is colloform in habit and is cemented by dolomite and weathered calcite. Native gold, in grains up to 2 mm. in diameter, occurs largely in the altered calcite, associated with galena, tiemannite, and (?) dyscrasite. In part it occurs in arborescent habit in the gangue that veins and cements the pitchblende. Spectrographic analyses of the gold indicate that it contains important amounts of silver, platinum, palladium, mercury, and antimony. Spectrographic analyses of this gold by Hawley and Rimsaite (1953, p. 467) show that the ratio of platinum metals is Pd:Pt.:Rh = 6:1:0·01. This work also corroborated the suggestion that the platinum metals occur in solid solution in the gold. The cell edge of this gold is 4·089 angstroms as compared with 4·070 for the pure metal.

Principal metallic minerals recognized in veins exposed by the underground workings are: pitchblende, nolanite, galena, chalcopyrite, and pyrite, and traces of bornite and hematite. Introduced non-metallic minerals are: dolomite, calcite, and quartz. Gold in significant quantity has been reported in assays but was not recognized under the microscope.

The quartz along inter-granular boundaries in the quartzite wall-rock has been replaced by dolomite with some massive pitchblende. A bladed boxwork of nolanite and dolomite form a distinct layer on this wall-rock, whose outer surface is in turn mantled by colloform pitchblende (*See* Figure 9). The centre of the vein is filled by coarsely crystalline calcite containing chalcopyrite, pyrite, galena, and traces of bornite. In some specimens spheroids or botryoids of pitchblende have a core of bladed nolanite and dolomite. The sulphides occur sparsely in the nolanite boxwork and in the outer, peripheral layers of the colloform pitchblende. Calcite, which is locally intergrown with a late generation of pitchblende, has cemented syneresis cracks in earlier, colloform, pitchblende (*See* Figure 4).

No. 4 Zone

References: Bowie (1953); Christie (1953, p. 113); Lang (1952, p. 95).

This deposit occurs in interbedded, flat-lying quartzite, dolomitic quartzite, and dolomite, near the contact of a mass of ferruginous quartzite breccia. The ferruginous quartzite breccia is much altered, is saturated by surface waters, and is marked by accumulation of large amounts of limonite. Its contact with the unaltered rocks is roughly vertical but is very irregular in its vertical and horizontal components.

The mineral deposits occur in a series of irregular, sub-parallel shoots in a zone that strikes north 30 degrees west and dips approximately 80 degrees east. This zone is roughly parallel with, and within 200 feet of, the contact with the ferruginous breccia.

Mineralization has taken place largely by replacement as evidenced by: *a*, indistinct vein walls; *b*, discontinuous ribbon-type banding; *c*, lack of evidence of fracturing where introduced minerals are lacking; and *d*, a marked increase in values and in amount of introduced mineral content where ore shoots intersect dolomitic horizons as compared with intersections in quartzite. Vugs, largely in cross fractures in dolomitic horizons and in the ferruginous breccia, are lined with quartz and calcite crystals. Some of the calcite rhombohedra attain dimensions of 4 feet in diameter. Walls of the largest cavity are coated by a thin ($\frac{1}{16}$ inch) deposit of black sooty material that consists primarily of manganese and iron oxides.

The deposits contain an exceptionally diverse group of introduced minerals, many of which exhibit unusual textures. Metallic minerals that have been identified include: pitchblende, thucholite, rammelsbergite, pararammelsbergite, niccolite, cobaltite, arsenopyrite, ullmannite, siegenite, pyrite, marcasite, chalcopyrite, bornite, galena, sphalerite, hematite, goethite, and magnetite. Sporadic gold assays are recorded but no visible gold has been recognized. Non-metallic minerals are: dolomite, calcite, quartz, chlorite, and hisingerite. Annabergite, erythrite, and a diverse group of secondary uranium minerals, including gummite, liebigite, zippeite, and cuprosklodowkite, occur in the surface exposures and upper levels of the mine.

Uranium occurs in: (1) secondary minerals as a result of weathering; (2) thucholite and associated pitchblende; (3) pitchblende that occurs as minute residual blebs in hisingerite; and (4) pitchblende associated with sulphides and arsenides. The thucholite is found in radially shattered rosettes in the surface material and in the upper adit where it occurs in small patches flanking a stringer of pitchblende. Bowie (1953) has shown that much of the pitchblende is enveloped and replaced by rims of thucholite and that the thucholite itself is not appreciably radioactive. This material occurs as dusty black masses in vugs and in softer parts of the ore throughout the mine. The occurrence of pitchblende in hisingerite with hematite in a single ore shoot is a prominent feature of the main ore zone on the first level. The coal-like mass was tentatively identified as uraniferous opal (Robinson, 1950), but subsequently was shown by Bowie (1953) to be hisingerite containing minute inclusions of pitchblende. Hisingerite, in much the same manner as thucholite, appears to have enveloped and replaced pitchblende. Hard, massive to botryoidal, blue-grey hematite is closely associated with hisingerite in this ore shoot. Pitchblende is also associated with a diverse group of sulphides and arsenides of copper, cobalt, nickel, lead, and iron throughout the mine. In many instances such pitchblende is colloform in habit and locally has been shattered. Later massive pitchblende appears to have enveloped some arsenides. Massive rammelsbergite and niccolite, enveloping and replacing pitchblende, are a feature of the lower adit 150 feet south of the main ore zone. In the main ore zone, pitchblende has been replaced by gangue containing various sulphides and arsenides (*See* Figure 5). In many instances, pyrite, ullmannite, and siegenite occur in rosettes in ring-like textures in hollow crystals and in cuneiform-like textures (*See* Figure 6).

The occurrence of the various iron oxides in this mine is worthy of particular consideration. Hematite is present: (1) in red dusty form disseminated through the rock; (2) in hard, blue, massive form, associated spatially with hisingerite; (3) in colloform habit also associated with hisingerite; (4) as specularite, much of which appears to rim concentrations of other types of hematite and may, therefore, be due to recrystallization; (5) as sheaves of specularite with some (?) pseudomorphous sheaves of magnetite (*See* Figure 7). Bowie (1953, p. 6) ascribes the magnetite bodies in hematite to an ex-solution mechanism and concludes that high temperature must have prevailed during deposition of this hematite. The occurrence of most of the limonite of the ferruginous breccia is almost certainly due to supergene processes. Goethite, however, occurs following cleavages of calcite (*See* Figure 8). This calcite, together with sulphides and arsenides, veins and replaces pitchblende (*See* Figure 5).

Various minerals occur only locally in the mine and others are virtually restricted to one or two ore shoots. Moreover, in many instances minerals are found as discrete grains in the gangue and inter-relations are difficult to assess. The following is a general sequence of deposition, to which minor and local reversals are known:

(1) Development of dusty hematite, calcite, and chlorite in the country rock.
(2) Deposition of colloform pitchblende.
(3) Deposition of colloform hematite, specularite, and magnetite.
(4) Development of thucholite in part by replacement of pitchblende some of which was redeposited through later phases ending in phase (7) below.
(5) Deposition of hisingerite, largely by replacement of pitchblende, hematite, and gangue minerals.
(6) Deposition of arsenides and sulpharsenides.
(7) Deposition of sulphides with associated calcite and latest pitchblende.
(8) Deposition of goethite.
(9) Late veining by calcite.
(10) Deposition of calcite, quartz, and hydrated iron and manganese oxides in vugs and cavities.
(11) Supergene development of limonite in ferruginous breccia.

ELDORADO MINING AND REFINING LIMITED

Ace and Fay Mines

References: Allen (1950); Allen, Macdonald, and Smith (1953); Christie (1953, p. 93); Dawson (1954); Lang (1952, p. 77).

Deposits exposed in these interconnecting mines are contained in a length of nearly 6,000 feet along the St. Louis fault, between Ace and Beaverlodge Lakes. They occur largely within 200 feet of the fault and lie principally in the foot-wall rocks.

This section of the fault is singularly uniform in attitude, having a strike of north 66 degrees east and a dip of 50 degrees southeast. Available data suggest that the St. Louis is a normal, right-handed fault with a displacement in excess of 1,000 feet.

Rocks in the hanging-wall are paragneisses of the Tazin series in which local granitic and chloritic facies occur. These are overlain by two shallow synclines of Athabasca conglomerate, in the more westerly of which arkose overlies the conglomerate. Foot-wall rocks are argillaceous members of the Tazin group with intercalated chlorite-epidote facies and bands of quartzite.

The pitchblende deposits are virtually restricted to zones of oligoclase and hematite alteration of the host rocks that have been described by Dawson (1954). This alteration has resulted in two distinctive but transitional rock types. One is red and almost glassy, and resembles jasperoid and the other is massive, red, and retains in part the texture and foliation of the original rock. The jasperoid type (oligoclasite) is made up almost wholly of oligoclase that has been mylonitized, saturated with dusty red hematite, brecciated, and cemented by chlorite, calcite, later oligoclase, and quartz. In the massive type there is evidence of feldspathization and dissemination of dusty hematite but the rock does not appear to have been crushed.

The oligoclasite occurs in two elongate masses against the foot-wall of the fault, which attain maximum widths of approximately 100 feet. It occurs also as an inner envelope enclosing outlying pitchblende veins. The massive type envelopes the oligoclasite except along the fault itself, occurs intercalated with oligoclasite, and is also found as zones in the hanging-wall rocks.

Ore deposits may be arbitrarily assigned to four different categories although each category is transitional to the next in the order described below.

(1) In the main oligoclasite lens adjacent to the fault there is a core, against the fault, made up of oligoclasite breccia cemented by pitchblende and quartz.

(2) In the massive oligoclasite a series of irregular veins of relatively small size contain pitchblende, calcite, chlorite, and other minerals. These veins are branching, close-spaced, usually sub-parallel to the fault, and locally occur *en échelon.* Pitchblende is disseminated in the oligoclasite that intervenes between these veins.

(3) In the zone of intercalated oligoclasite and massive red alteration, deeper in the foot-wall, larger and more widely spaced pitchblende-calcite veins occur that are roughly parallel with the fault. There is relatively little dissemination of pitchblende in the rocks enclosing these veins.

(4) Both in the hanging-wall and in the foot-wall peripheral to the main zones of red alteration, individual pitchblende veins occur. The attitude of these veins is irregular. They are usually enveloped by a narrow rim of massive red alteration. The larger ones have an inner envelope of oligoclasite also.

In order of abundance, introduced non-metallic minerals recognized in these deposits are: calcite, chlorite, some quartz, and traces of apatite and rutile. Oligoclase is possibly of hydrothermal origin at least in part, but its relation to the introduced minerals is largely that of a host rock, called oligoclasite by Dawson.

Oligoclasite in the hand specimen appears to be a hard, vitreous, and virtually homogeneous rock that is distinctly brittle. In thin section, however, it is seen to be made up of dense, very fine-grained feldspar so saturated with dusty hematite that it is virtually opaque. X-ray diffraction patterns of this material indicate that it is composed almost wholly of oligoclase and hematite. In part, this oligoclasite has been brecciated and cemented by relatively clear and coarse-grained oligoclase, by chlorite, and by calcite. Much of this cemented oligoclasite contains irregular areas, stringers, and veinlets of chlorite, calcite, and some quartz, in which rounded to annular segregations of pitchblende occur (*See* Figure 11).

Calcite is the dominant gangue mineral with which pitchblende is intimately associated. At least two, and possibly four, generations of calcite are recognized. Early calcite has permeated the oligoclasite in a manner suggestive of replacement. Irregular areas of such calcite occur in the oligoclasite without any apparent relation to fractures. This calcite is impregnated by dusty hematite and usually exhibits marked development of cleavage planes, relatively wavy extinction, and, locally, bent twinning lamellæ. Similar calcite with chlorite occurs in irregular stringers through, and coats walls of, veins in the oligoclasite. Calcite in the veins themselves is usually little stained by hematite but locally does contain pyrite and other sulphides. It is commonly coarse grained and does not usually exhibit characteristics of deformation. It is possibly calcite of this generation that is intimately intergrown with pitchblende. Finally, stringers of fine-grained clear calcite have been observed intersecting the older calcite, although in many instances the stringers disappear where the younger calcite has been deposited in crystallographic continuity on the older calcite. No dolomite has been recognized in these deposits.

Chlorite is also very intimately associated with pitchblende. It is more common, however, in the oligoclasite than in the veins proper. Occurrence of chlorite in the oligoclasite is similar to that of calcite, but locally chlorite replaces calcite (*See* Figure 12). Where pitchblende is disseminated in the oligoclasite it is very commonly rimmed by a halo of chlorite (*See* Figure 11) or occurs in veinlets of chlorite. Chlorite is also common with calcite along vein walls and is almost always present with calcite that is intergrown with pitchblende. It is only rarely present in the centres of the veins.

Quartz is much less common in the ore deposits than either calcite or chlorite. It occurs principally cementing the brecciated core of the main lens of oligoclasite. In this core it is common to find a rim of pitchblende on the oligoclasite fragments. In part, this pitchblende occurs disseminated as discrete grains (of a few microns in diameter) in brown, cherty quartz (*See* Figure 15). The centre of the cemented space is filled by clear quartz with incipient comb texture. This clear quartz clearly replaces calcite (*See* Figure 10). Barren veins and stringers of cherty quartz with some admixed calcite have been observed flanking the main ore zone.

Rutile has been observed locally in the vein walls and only rarely in the veins themselves. It is usually present in patches made up of submicroscopic grains and was identified only by X-ray diffraction. Apatite was recognized in veins deep in the foot-wall on the sixth level, where it is associated with flamboyant ilmenite and nolanite.

In estimated order of abundance, metallic minerals recognized in these deposits are: hematite, pyrite, pitchblende, chalcopyrite, galena, clausthalite, bornite, nolanite, ilmenite, marcasite, and sphalerite.

Hematite is prevalent as the dusty red variety that permeates the red altered rocks, oligoclasite, and some calcite. In the oligoclasite, hematite is concentrated as haloes of minute crystals about inclusions of pitchblende (*See* Figure 16) and around areas of chlorite or calcite containing pitchblende (*See* Figure 11). Dusty to massive hematite almost always plates pitchblende in the veins. Massive hematite is common along the vein walls. Specular hematite occurs mainly in the calcite veins. Flamboyant ilmenite, associated with nolanite, occurs in some foot-wall veins.

Pyrite is found most commonly as fractured euhedral grains in the wall-rocks, where locally it is veined and mantled by hematite. In the veins it is massive where pitchblende is absent. Where it is associated with pitchblende it commonly occurs both as a rim of discrete grains around the pitchblende masses and disseminated through the pitchblende (*See* Figure 17).

Pitchblende occurs both disseminated through mylonitized oligoclasite and in the calcite-rich veins. In the oligoclasite the pitchblende is in rounded to angular masses and in wisps in irregular chlorite stringers. As noted above, the rounded masses most commonly have haloes of chlorite, some have narrow rims of calcite (*See* Figure 13), and some are marked only by concentration of the disseminated hematite. This pitchblende rarely is contaminated by other minerals.

In the veins, pitchblende occurs coating the vein walls, as partings in the calcite, and as irregular masses in the calcite. Such pitchblende lacks any regular habit, although "ghosts" of colloform habit in which only the hematite rims are preserved are quite common along the walls. This pitchblende is usually admixed intimately with calcite, chlorite, and hematite. In many instances these intergrowths exhibit quite uniform grain size and habit. Through some of these intergrowths subhedral grains of sulphides are evenly distributed. These sulphides may be one or more of pyrite, chalcopyrite, and galena (*See* Figures 17, 18, and 19).

In some few instances euhedral crystals of "pitchblende" have been identified in isotropic calcite and chlorite gangue that has a colloform outline (*See* Figure 16). Pitchblende, as noted above, occurs disseminated as discrete grains in cherty quartz. In one deposit pitchblende exhibits a bladed habit that forms a boxwork pattern (*See* Figure 20). This probable pseudomorphous texture is transitional to massive pitchblende through which pyrite is disseminated. Finally, in some of the minor peripheral veins, pitchblende occurs in true colloform habit, cemented by calcite containing clausthalite and bornite.

Chalcopyrite is remarkably persistent throughout the Ace and Fay deposits. It is a prominent constituent of the ore only in the eastern part of the mine, where it occurs in platy masses up to 2 inches in diameter. More commonly it is disseminated as minute discrete grains in pitchblende intergrowths in the younger vein calcite, and less commonly in the wall-rocks. In some of the peripheral deposits chalcopyrite appears as ex-solution laths in bornite. Many of the chalcopyrite grains in pitchblende are euhedral, having triangular cross-sections (*See* Figure 18). In some instances, with pyrite, it is so thickly disseminated that the pitchblende intergrowth has a metallic lustre and bronze colour in the hand specimen.

Galena is present mainly as minute discrete grains in the pitchblende (*See* Figure 19) and in the adjacent gangue. In one non-radioactive vein in the hanging-wall massive galena is the principal metallic mineral and occurs in a quartz gangue.

Clausthalite is found in massive form and in disseminated grains in a few peripheral veins. In one of these it has cemented colloform pitchblende. It has been recognized also as thin films coating cracks in veins of the foot-wall ore zones. Bornite is associated with clausthalite in the peripheral veins.

Nolanite has been recognized in ores from the fifth and sixth levels only, but spectrographic analyses of pitchblende concentrates show that vanadium is widely distributed throughout the mine. These analyses also show that vanadium increases in amount both with depth and in the foot-wall away from the fault. All vanadium is probably present as nolanite. Nolanite was recognized as minute grains in ores from the fifth level, but in the sixth level it is present in considerable amount in one vein deep in the foot-wall, where it forms part of the matrix for flamboyant ilmenite and colloform pitchblende. The whole forms a narrow replacement along the vein walls.

Ilmenite was recognized only from the above vein on the sixth level where it is the dominant metallic mineral.

Marcasite was recognized in delicate filigree traces and as sheaves of acicular crystals in calcite with pitchblende in two veins in the western section of the mine.

Sphalerite has been recognized only as minute grains in the quartz-rich core of the main ore zone.

The occurrence and texture of minerals in the Ace mine does not facilitate determination of their paragenesis. The following general sequence is based primarily on mineral distribution and to a lesser degree on the few consistent textural relations.

(1) Selective replacement of host rocks by oligoclase.

(2) Crushing and recrystallization of the oligoclasite, followed by intense dissemination of hematite and recementing of the mylonitized oligoclasite.

(3) Brecciation of the mylonitized oligoclasite followed by some recrystallization of oligoclase and possibly addition of fresh oligoclase.

(4) Permeation of the breccia by calcite, chlorite, and pitchblende accompanied by local concentration of hematite in haloes.

(5) Gradual development of tensional veins in the sealed breccia with early deposition of chlorite and red calcite with, probably, colloform pitchblende. This phase appears to have changed gradually with resorption of original pitchblende and its redeposition intergrown with calcite, chlorite, iron oxides, and, locally, sulphides. In isolated instances colloform pitchblende appears to have aged and recrystallized as discrete euhedral grains.

(6) As a late phase in vein-filling, clear calcite containing traces of sulphides filled the centres of the veins.

(7) Replacement of calcite by quartz in the brecciated core of the main ore zone accompanied by solution and redeposition of pitchblende.

(8) Deposition of clausthalite.

Eagle Mine

References: **Allen (1950); Christie (1953, p. 96); Lang (1952, p. 85); Smith (1952).**

Four sub-parallel vein systems are recognized at the surface. Identification of these with underground intersections is, however, difficult. Pitchblende occurs in a series of sub-parallel veins and shear zones whose average strike is approximately east-west. Pitchblende veins are largely confined to chlorite and epidote-rich rocks of the Tazin group and do not extend appreciably into intercalated granite and quartzite bands. Relatively little pitchblende is found in the breccia that marks the main contacts of the chlorite-epidote rocks and the granite. Virtually all the ore shoots are enclosed in an envelope of red, wall-rock alteration.

Although calcite is the dominant gangue mineral in most of the ore shoots, some veins, particularly in the surface exposures, are characterized by comb quartz. Mineralogy of these two types, particularly with respect to textures of the urania, differs significantly.

In the calcite veins, metallic minerals recognized are: hematite, pitchblende, chalcopyrite, bornite, pyrite, and traces of galena. Non-opaque minerals are calcite, chlorite, and quartz.

In these calcite-rich veins, pitchblende of three fairly distinct textural types is recognized, namely: (1) colloform; (2) massive, intergrown with calcite and disseminated sulphides; and (3) pseudomorphous after zoned calcite crystals. Colloform pitchblende is not common in the mine but where it does occur the textures include rims with multi-convex form and a parallel outer rim, and spherules, some of which have outer enveloping rings (*See* Figure 14). The colloform pitchblende is locally brecciated and cemented by calcite in which massive pitchblende intergrown with calcite and sulphides occurs (*See* Figure 21). Massive pitchblende, in which there is admixed calcite, pyrite, chalcopyrite, and galena, is relatively the most common type in the calcite veins. The mixture is so intimate that it appears to be an intergrowth in which the various minerals were deposited contemporaneously. It is notable in many specimens that there is a preferential concentration of pyrite and chalcopyrite in the pitchblende and in some specimens these sulphides are found only in the pitchblende. The pitchblende in the intergrowth appears to be susceptible to replacement by calcite and chlorite; patches of disseminated pyrite and chalcopyrite remain in areas that are virtually isotropic and still radioactive but in which pitchblende cannot be recognized.

The intergrowth itself is relatively late in time of deposition, and in one instance with calcite fills the space between two matching fragments of colloform pitchblende (*See* Figure 21). Perhaps the most interesting of these types of pitchblende occurrence is the preferential replacement of zoned calcite crystals by pitchblende. Such replacement may be completely restricted to certain zonal bands (*See* Figure 23), or it may have gone nearly to completion (*See* Figure 22). Although grains of sulphides may be seen in these replacements they appear to be incidental in occurrence; the pitchblende itself is relatively pure where replacement is complete. One such area of massive pitchblende was observed to have an outer layer (toward the centre of the vein) of colloform pitchblende.

In the quartz-rich veins the common metallic minerals are hematite and pitchblende; chalcopyrite, pyrite, and galena are relatively rare and usually occur in areas of calcite. Non-opaque minerals are principally quartz, with some chlorite and minor calcite. In these veins, where the pitchblende occurs in quartz, free from calcite, it is either massive and interstitial to quartz grains or it is in euhedral crystals growing on quartz crystals and cemented by a later generation of mosaic quartz (*See* Figure 24). The possibility that these apparently euhedral crystals of pitchblende are pseudomorphs after calcite, or some other minerals, appears to be refuted by X-ray data that show that they are in fact single crystals and not massive pitchblende conforming to the outline of an earlier mineral.

In these veins most of the quartz on the walls shows well-defined comb texture, but near the centre of the veins mosaic quartz with some chlorite and calcite occurs. Fragments of wall-rock in the veins usually have a narrow rim of comb quartz on them. The pitchblende occurs in part near the "roots" of the comb quartz interstitial to the quartz grains and in part growing on the euhedral terminations of the quartz crystals. Massive, colloform and pseudomorphous pitchblende is found with calcite and chlorite in these veins.

Eagle Group—Selenide Showings

Reference: Robinson and Brooker (1952).

Three small deposits containing pitchblende with massive selenide minerals occur in an area north of Hal Lake, which is about 1,500 feet west of the Eagle shaft. These deposits occur in small shear zones in granitized mafic rocks. There is no appreciable wall-rock alteration associated with these deposits.

The metallic minerals cement the sheared and brecciated rock; there are virtually no introduced non-opaque minerals, except for traces of quartz, calcite, and chlorite, which are sporadic in occurrence. Metallic minerals identified in these deposits are: umangite, klockmannite, hematite, a Cu-Ni-Co selenide, pitchblende, and traces of berzelianite, clausthalite, and pyrite. Non-opaque minerals are: chalcomenite, and traces of quartz, calcite, and chlorite.

Pitchblende and calcite occur in relatively large amount in one deposit and as traces only in the other two. Cu-Ni-Co selenide (cf. Robinson and Brooker, 1952) is a minor constituent of another deposit and is absent in the two others. In the pitchblende-rich deposit brecciation of the wall-rocks has been cemented by chlorite, hematite, and some calcite, whereas in the other two it is cemented directly by the selenides in which a few euhedral crystals of quartz are embedded. In another similar selenide deposit uranium is absent.

Pitchblende is largely colloform in habit even where the botryoids have coalesced to form nearly solid masses. It is traversed by slightly wedge-shaped syneresis cracks and by tension cracks of uniform width and having matching walls. These cracks are filled by umangite and some calcite in which euhedral crystals of hematite occur. Locally, these minerals have mantled the pitchblende botryoids and in part have replaced them, leaving residual rounded areas of pitchblende in a dominantly umangite matrix (*See* Figure 25). In the two deposits where pitchblende is rare it occurs in residual rounded grains in the umangite.

Hematite is found as ragged grains in the wall-rocks, but in the veins it is euhedral and somewhat rounded by umangite. In some specimens massive hematite has filled cracks in the pitchblende. Euhedral crystals of hematite are veined by umangite.

Of the selenides, umangite in massive form is present in at least ten times the quantity of all the others. The Cu-Ni-Co selenide occurs in equidimensional grains, some of which are rectangular. It is embayed and veined by umangite (*See* Figure 26). Klockmannite occurs around the fringes of the umangite masses and is intergrown with umangite at the contact. Clausthalite and berzelianite occur as occasional grains whose textural relationship to other minerals cannot be interpreted. Pyrite and chalcopyrite with associated chalcocite occur as rounded grains in the selenides and in the gangue. They are locally veined by umangite.

The specimens are all somewhat weathered, and chalcomenite and malachite occur in cracks, traversing the specimens. Chalcomenite also occurs in a remarkable three-directional pattern of laths in the umangite. In some orientations the three directions appear to meet mutually at about 60 degrees. These laths, however, transect grain boundaries of the umangite, and thus appear to have no relationship to its crystal directions (*See* Figure 26).

Fish Hook Bay—Zone A

References: Christie (1953, p. 100); Lang (1952, p. 89).

This zone is exposed in a trench 150 feet long in dolomitic quartzite flanked by ferruginous quartzite. The zone strikes north 30 degrees west and dips 45 degrees west, which is nearly parallel with the strike of the rocks.

The deposit is in a weak vertical shear that transects the banded rocks at a low angle and is transected by numerous short cross fractures. The introduced minerals appear to have been deposited simultaneously in the main shear and in the cross fractures. Distribution and texture of introduced minerals suggest that they filled open fractures and also replaced dolomite bands selectively.

The principal metallic minerals are: hematite, chalcopyrite, pyrite, nolanite (an iron vanadate), sphalerite, galena, marcasite, and pitchblende. Red alteration was noted in four bands parallel with the main shear; radioactivity of these bands is higher than that of the host rock. In the main shear, red alteration occurs as pods up to a foot wide.

Commonly, the metallic minerals are each concentrated in parallel bands, although the order of these bands varies and all of the minerals may occur together in one band.

Nolanite occurs in laths arranged in a boxwork texture in the dolomite and occasionally penetrating chalcopyrite (*See* Figure 27). Pitchblende is rarely visible, due largely to weathering. Autoradiographs show that pitchblende is fairly regularly distributed throughout the shear. Where visible, it is massive and interstitial to grains of dolomite.

Gil Group

References: Christie (1953, p. 102); Lang (1952, p. 90).

Pitchblende deposits of this group occupy narrow but persistent fractures that strike approximately north 70 degrees east. Although the fractures intersect both quartzite and amphibolite, the uranium deposits are sharply restricted to the amphibolite.

Christie (1953) describes the mineralogy as follows:

"The veins show rough banding and in places are vuggy. Brecciation is common, with carbonate and a minor amount of euhedral quartz filling the spaces between the wall-rock fragments. Carbonate occurs in these veins, and is stained deep red-brown, probably due to hematite, wherever pitchblende occurs. The pitchblende may occur as small veinlets cutting the carbonate; in small (up to 5 mm.), rounded or angular masses within the carbonate; or as nodular masses adjoining the carbonate veinlets. It is invariably associated with hematite, and commonly with minor amounts of disseminated chalcopyrite and bornite."

Specimens collected by Christie have been examined under the microscope and the following metallic minerals identified: pitchblende, hematite, chalcopyrite, bornite, chalcocite, covellite, umangite, klockmannite, galena, and native copper. Gangue minerals are: calcite, chlorite, quartz, and finely crushed rock. Angular fragments of wall-rock are cemented in the calcite, chlorite, and quartz.

The pitchblende is dominantly colloform and appears as broken angular fragments cemented in the gangue (*See* Figure 28) in which the sulphides and selenides are distributed. There is some pitchblende intergrown with calcite that shows no residual colloform texture and is probably a later generation, contemporaneous with the sulphides. Although chalcopyrite clearly veins colloform pitchblende, it also appears as disseminated grains in the outer layers of the colloform pitchblende fragments. Sheaves of specular hematite are distributed through the gangue and exhibit no evidence of brecciation. Bornite with ex-solution laths of chalcopyrite (*See* Figure 29) also occurs in this cementing calcite gangue.

It seems evident that colloform pitchblende coagulated in fissures partly filled with brecciated rock and that subsequent movement brecciated the pitchblende. The whole was then cemented by calcite and chlorite with contemporaneous deposition of sulphides. Possibly hematite and the selenides were deposited somewhat later.

Hacker Zone

References: Christie (1953, p. 102); Lang (1952, p. 90).

This deposit occurs in an area of banded dolomitic quartzite, striking north-south and dipping 70 degrees west, that occurs on the west side of Fish Hook Bay toward the north end. A small scarp parallel with the banding of the rocks drops away a few feet west of the radioactive zone.

The radioactive zone is restricted to interbanded biotite-chlorite-quartz schist and amphibolite on the foot-wall of a silicified zone that is about 2 feet wide. Chalcopyrite, arsenopyrite, and hematite are sparsely distributed through the silicified zone, which is not radioactive. Both amphibolite and biotite-chlorite-quartz schist are markedly radioactive over a maximum width of approximately 1 foot. No metallic minerals were visible in these specimens but biotite concentrates are highly radioactive. In thin section rough bands of biotite and chlorite are seen in the quartz. The radioactivity was traced to swarms of minute opaque grains in the biotite, which were proved by X-ray to be uraninite. Similar grains in the quartz and chlorite proved to be hematite and magnetite. Sparse grains of uraninite were also seen in the hornblende, some of which have rough cubic outlines and are marked by bleached haloes. Average grain size of the uraninite is of the order of one micron.

A partial chemical analysis of a biotite concentrate, made by E. J. Brooker, is: U, 6·47 per cent; Pb, 1·63 per cent; Th+ rare earths, 0·19 per cent. Spectrographic analysis of the Th+ rare earth fraction showed presence of the following: Y, Yb, Zr, Si, Th, Ce. These analyses indicate that thorium plus rare earths comprise nearly 2 per cent of the uraninite, a proportion greatly in excess of those given for the pitchblende variety.

Joe Showing

Reference: Lang (1952, p. 89).

This deposit is located on the point at the western entrance to Fish Hook Bay. A long trench exposes a tight vertical fissure in crystalline dolomite. The shear is flanked on both sides by 18-inch bands of red coloration. The deposit itself is distinguished by a marked increase in the grain size of the carbonate and by sporadic occurrences of hematite and pitchblende. Clearly defined vein walls are lacking; vein material appears to be transitional to the host rock.

Principal metallic minerals are: pitchblende, hematite, native gold, chalcopyrite, and traces of pyrite and (?) galena. Principal non-opaque minerals are dolomite and calcite. Two generations of pitchblende may be recognized under the microscope (*See* Figure 30). The more abundant generation is colloform and occurs in botryoids $\frac{1}{16}$ to $\frac{1}{2}$ inch in diameter. The younger, and less abundant, generation is massive and has filled openings along cleavage planes in the dolomite and has replaced the dolomite. Calcite and massive hematite have replaced the older pitchblende, working in from fractures and syneresis cracks. Where replacement is advanced, recognition that the pitchblende is residual is based on shadowy outlines of the original colloform habit and of syneresis cracks (*See* Figure 31).

Native gold occurs principally in the cores of the older pitchblende spheroids, but where the pitchblende has been replaced the gold appears to be concentrated around its original periphery. Gold also appears in cleavage planes of the calcite.

Hematite in blocky massive form rims the colloform older pitchblende and fills syneresis cracks in it. Disseminated, red, dusty hematite occurs in the carbonate as haloes around both generations of pitchblende.

Chalcopyrite appears as small disseminated flecks in the calcite, and (?) galena, also in minute flecks occurs with the younger generation of pitchblende and where the older generation has been replaced.

It seems clear that early pitchblende coagulated in colloform habit with gold as the first metallic minerals. These were followed by hematite and calcite, with late development of pyrite, chalcopyrite, and (?) galena. A late generation of calcite was the last primary mineral to be introduced.

Martin Lake Mine

References: Allen (1950); Christie (1953, p. 104); Dawson (1954); Kerr (1950); Lang (1952, p. 99); Smith (1952).

Mineral deposits of this mine occur in a blocky fault system that intersects intercalated arkose and basic flows of the Athabasca series. Allen (1950) has shown that the main faults are *en échelon* and trend north 68 degrees east, with minor branching spurs striking north 85 degrees east. Ore minerals are rarely found in the faults proper. They occur, according to Smith (1952), in minor shears dipping parallel with the main faults and in a series of cymoid lenses. Later faults, striking north 35 degrees east, and containing chert and calcite only, intersect and offset the ore-bearing structures. Locally, vugs encrusted with crystals of quartz, calcite, and barite are encountered. It is worth recording that vesicles in the flows remote from the ore deposits are commonly filled by quartz, calcite, and chlorite, but not by ore minerals.

Wall-rocks are altered to a characteristic brick-red colour within 1 foot or 2 feet of the vein, and Smith (1952) has shown that carbonatization extends as much as 5 feet out from the vein. Analyses in Dawson (1954) and Smith (1952) indicate that calcite has been introduced but that the total iron is the same as in the unaltered rock. There does not appear to be any quantitative relationship between the degree of wall-rock alteration and the content of uranium in the vein.

Metallic minerals identified in the veins include: hematite, pitchblende, umangite, berzelianite, klockmannite, clausthalite, chalcopyrite, bornite, and native copper. Non-metallic minerals are: calcite with minor amounts of quartz, chert, chlorite, and barite.

Pitchblende is the only primary mineral of uranium recognized in the mine. Two generations of pitchblende are clearly indicated, of which the older generation probably accounts for at least 80 per cent of the uranium present. Commonly, it mantles the wall-rock and wall-rock fragments and euhedral crystals and cleavage flakes of older calcite (*See* Figures 32 and 50). Less commonly it is present as coalescing masses of botryoidal grains in the calcite (*See* Figures 34 and 35). Locally these botryoids are spheres with a core of calcite, or may be made up of a core and outer sphere of pitchblende with a layer of calcite intervening (*See* Figure 35). In both cases the external surfaces show the multi-convex form and the pitchblende is traversed by branching radial and peripheral cracks, both characteristic of colloform texture. Locally this older pitchblende has been brecciated and cemented in younger calcite (*See* Figure 28). The younger generation of pitchblende does not show these characteristics. It is either massive or intimately intergrown with calcite and follows intergranular boundaries of younger calcite, replaces younger calcite along cleavage planes (*See* Figure 36), or cements fragments of older calcite.

The selenides with some hematite appear to be contemporaneous with, or slightly older than, the younger calcite. They mantle and fill syneresis cracks in the botryoidal pitchblende (*See* Figure 37), or occur in the younger calcite. The sulphides commonly appear as disseminated grains in the outer layers of the colloform pitchblende (*See* Figures 32 and 34), or in the older calcite. Native copper occurs in the younger calcite as disseminated rounded grains or as filaments along the cleavage planes. Characteristically, it is isolated from all other metallic minerals.

Hematite dust is distributed through the wall-rocks and older calcite, both dispersed through individual minerals and between them. Hematite occurs as rounded crystals in the rock and as rosettes of euhedral crystals in the younger calcite and in syneresis cracks in the older pitchblende (*See* Figure 37). It is also present replacing the younger calcite along cleavage planes.

Calcite of at least four generations is present. The earliest with chlorite and some quartz is found filling vesicles in the basic flows both near the veins and remote from them. Hydrothermal calcite has permeated the wall-rocks of the veins and has coated the vein walls. It usually contains red dusty hematite and shows strained extinction. Younger, white calcite is generally coarse grained (up to 1 cm. diameter), exhibits sharp extinction, and cements the older pitchblende. In many instances it contains discontinuous rims of older pitchblende that show no relationship to its cleavage. Finally, sharply defined stringers of calcite intersect all the above generations.

Chlorite stringers intersect the altered wall-rock, the older hydrothermal calcite, and the older pitchblende.

GOLDFIELDS URANIUM MINES LIMITED

DD1-62 Showing

References: Christie (1953, p. 106); Lang (1952, p. 82).

This deposit occurs in a fault that strikes approximately south 50 degrees east and dips 55 degrees southwest. The country rocks are quartzite and gneiss that appear to have been granitized, yielding a red, massive, little-foliated rock that resembles a leuco-granite. One small area of carbonate-feldspar rock occurs in the foot-wall. There is an apparent increase in feldspar at the expense of quartz in the immediate vicinity of the deposit. Soft gouge occurs in the fault not only at the surface but also in diamond drill intersections. Uranium occurs principally in the immediate foot-wall of this fault.

Metallic minerals recognized in this deposit are: hematite, pitchblende, and pyrite. Non-opaque minerals, some of which may be original rock-forming minerals, are: albite, quartz, chlorite, and calcite.

This deposit is notable for the fact that pitchblende is virtually restricted to siliceous gangue. In nearly all specimens the dark radioactive material is hard and resembles chert. Microscopic examination indicates that this material is highly comminuted wall-rock, cemented by a siliceous matrix in which hematite and pitchblende are disseminated in very fine-grained form and so densely that thin sections are barely translucent. Only rarely can pitchblende be resolved under magnification of 1,000 diameters. The associated hematite is in part similarly fine grained and in part it is visible in discrete specularite crystals attaining lengths of up to ten microns. In the few instances where massive pitchblende occurs, hematite is distributed through it. The whole is veined by clear quartz stringers having comb texture. Calcite is restricted in distribution to the centre of the veins, where it fills interstices in the comb quartz. Calcite has locally replaced the dark siliceous matrix and only in such replacements is it accompanied by pitchblende; elsewhere it is free of opaque minerals.

In this deposit the paragenesis appears to be:

(1) comminution of wall-rocks, possibly accompanied by addition or recrystallization of albite;

(2) infusion of siliceous gangue with hematite, chlorite, and pitchblende;

(3) fracturing and veining by comb quartz;

(4) calcite filling interstices and locally replacing the dark siliceous gangue.

Eke Lake Deposit—FF1-4

References: Christie (1953, p. 107); Lang (1952, p. 89); Dawson (1954).

This deposit occurs in red altered rocks in the foot-wall of the Black Bay fault. The fault, where exposed in the trenches, dips about 70 degrees southeast and is filled with gouge. The pitchblende deposits occur in bands of hematitized and albitized diabase and mafic sediments and lie between 6 and 25 feet in the foot-wall of the fault. This deposit is a type example of wall-rock alteration (*See* Dawson, 1954).

Metallic minerals recognized in this deposit are: hematite, pitchblende, chalcopyrite, and pyrite. Non-opaque minerals are quartz, calcite, and chlorite. Veinlets of comb quartz are the only distinct units of introduced minerals.

Pitchblende occurs interstitial to, and intersecting, crystals of comb quartz. It is also disseminated in the dense red-altered and carbonatized rock. Some colloform pitchblende appears to have been corroded by later calcite. Chalcopyrite is commonly disseminated through pitchblende and in the gangue enclosing pitchblende. Hematite is densely disseminated through the rock and calcite, giving both the characteristic red colour. In the quartz veins, most hematite is largely crystalline or massive.

This deposit is of interest because pitchblende occurs in the red-altered rock and in the comb quartz that intersects this rock.

Nesbitt (now Gatzke) Lake Deposit

References: Christie (1953, p. 108); Lang (1952, p. 104); Robinson (1950, p. 8).

These deposits occur in a zone parallel with the Nesbitt fault and extend sporadically over a distance of 3,000 feet. Some of the deposits are in or near minor fractures and others occur in massive gneiss. However, they are all in a linear zone. There is some variation from deposit to deposit, both in the mineralogy and in the wall-rock alteration. Usually wall-rock alteration is pronounced in deposits along the fractures and is virtually absent in deposits in massive gneiss. In general, the deposits appear to be transitional to the country rock and lack sharply defined walls.

They consist largely of sericitized oligoclase in crystals up to 2 inches long, and relatively fresh microcline and sutured quartz. In some massive deposits, rounded and fractured grains of grey-green almandite-type garnet constitute up to 5 per cent of the mineral content. Biotite is the principal femic mineral. It is largely altered to chlorite and is accompanied by clinozoisite. Metallic and accessory minerals are: hematite, pyrite, molybdenite, uraninite, monazite, thorite, apatite, zircon, pyrrhotite, chalcopyrite, sphalerite, and galena.

Distribution of minerals in the deposits is erratic. In two deposits, however, there is some evidence of orderly arrangement in that quartz, biotite, and sulphides are mainly in the core. This core grades transitionally outward with increasing microcline to an outer envelope that is dominantly oligoclase. Moreover, microcline locally fills fractures in the oligoclase. Quartz, biotite, chlorite, and clinozoisite occur in part as veinlets traversing the feldspars. The sulphides are largely confined to the quartz-biotite-clinozoisite facies. Uraninite, monazite, thorite, and apatite occur in the feldspars and in the quartz and biotite. Garnet is associated principally with the feldspars.

Uraninite is found only in subhedral to euhedral discrete grains. It has been recognized in both types of feldspar, in quartz, and in biotite. Monazite has a similar distribution. Crystals of uraninite attain maximum dimensions of 2 mm., those of monazite are up to 3 mm. across. Thorite has been recognized only in heavy mineral concentrates. It is noteworthy that neither pitchblende nor calcite has been recognized in these deposits.

Showings NN 70 and 75

References: Christie (1953, p. 107); Lang (1952, p. 96).

These deposits are in a shear zone that follows the nose of a pronounced fold and in crosscutting shears. The localization of the mineralization was controlled by lens-like swellings in the shears. Wall-rocks are red-altered amphibolite and mafic schist. Vein filling is made up largely of rock fragments, cemented by much quartz and chlorite and minor calcite.

Metallic minerals recognized are: pyrite, chalcopyrite, pitchblende, and traces of galena. The trenches expose highly weathered vein filling, little of which provides useful data. Gangue minerals are quartz, chlorite, calcite, and some anatase.

Most quartz exhibits comb texture and individual crystals show zonal growth marked by variation in the number of inclusions. Amethyst bands in the zoned quartz are common. Pitchblende is largely colloform in texture and is interstitial to the quartz grains and as rims on their terminal faces. It also occurs as wisps in bands of chlorite with pyrite and chalcopyrite. In many quartz veins chlorite forms the cement between terminal faces of quartz crystals growing out from each wall (*See* Figure 39). Chlorite, in stringers up to 2 inches wide, also cements fragments of broken wall-rock. Calcite appears to have been the last mineral to crystallize and has corroded the quartz and replaced chlorite in irregular patches.

Showing 50-TT-62

This deposit consists of an irregular granite pegmatite containing large segregations of foliated biotite and cutting radially across a fold in massive amphibolite and intercalated quartzite. Walls of the pegmatite are not sharply defined. It appears to be transitional to the host rocks through a migmatite zone up to 2 feet wide. Although no regular zoning is apparent in the pegmatite there are marked local segregations in which quartz or feldspar or biotite are almost free of other minerals and in which single crystals attain diameters of up to 1½ inches. The radioactivity is largely confined to the biotite facies.

The pegmatite is made up largely of highly sericitized plagioclase feldspar, near oligoclase in composition, sutured quartz, and much biotite. Quartz in veinlets intersects the oligoclase and biotite. Biotite crystals are bent and variably altered to chlorite. Accessory minerals are monazite, and apatite with traces of zircon. Autoradiographs show that radioactivity of this rock is due almost entirely to the monazite. Monazite occurs in euhedral zoned crystals up to 3 mm. in length (*See* Figure 40). It is developed principally in the biotite but is also found in the quartz and feldspar. A partial chemical analysis of the monazite is: Th, 11·47 per cent; U, 0·161 per cent; Pb, 0·919 per cent. Apatite is more sparsely and uniformly distributed. It has been noted as inclusions in single crystals of monazite. Mottled opaque areas in the chlorite are not radioactive and appear to be due to development of iron oxides.

GUNNAR MINES LIMITED

Ed-Bon Group—St. Mary's Channel

References: Hoiles (1953); Fraser and Robinson (1954).

This deposit is largely overlain by overburden and has been explored almost wholly by vertical diamond drill-holes. As a result, little is known of the structures responsible for the trough-shaped orebody.

The ore occurs in a mass of albite monzonite that overlies well-banded hybrid gneiss and amphibolite of the Tazin group, which strike north 60 degrees east and dip between 45 and 70 degrees southeast. Drillholes show that this monzonite passes into well-banded gneisses at depth. The albite monzonite is overlain locally by outcrops of "grey capping granite".

This deposit is unusual in that pitchblende and secondary uranium minerals are disseminated through the monzonite without any observed structural control. The monzonite varies widely in appearance and many adjacent bands are sharply defined. The texture varies from that of a coarse-grained igneous rock to that of a fine-grained sandstone. Locally, it is slightly foliated. In colour it varies from green to grey to deep red. The megascopic variation is further enhanced by bands in which the rock is vuggy and softened. Despite these variations the composition is generally quite uniform and consists essentially of albite with minor perthite and quartz. Locally, traces of biotite and muscovite occur. Calcite and some dolomite occur throughout the rock, distributed as irregular grains. Toward the base the carbonates comprise up to 25 per cent of the rock but in general comprise only about 5 per cent.

Three specimens of drill core representing this rock were combined, crushed, and leached in 10 per cent HCl to remove the carbonates. Partial analysis of the residue is: Na_2O, 10·66 per cent; K_2O, 0·94 per cent; CaO, not detected; MgO, 0·05 per cent. This analysis indicates that the plagioclase is albite and that the albite comprises a very high percentage of the rock.

Some of the potassium is present as muscovite but most of it is in the form of replacement perthite and as rims of potash feldspar on grains of albite and other minerals (*See* Figure 41). In one particular band large grains of replacement type microcline-microperthite occur, in which textural evidence suggests that potash feldspar partly replaced grains of albite.

The feldspars are remarkably fresh and free from sericite or epidote except near the base of the ore section. In many thin sections, however, the feldspar crystals are bent and, locally, broken. In a few zones brecciation and mylonitization have occurred. Occurrence of euhedral quartz cemented by calcite and of large grains of calcite in the rock suggest that the mylonite was porous and vuggy. Lack of euhedral development of feldspar in the vugs suggests that they are due to fracturing subsequent to crystallization of the feldspar.

Uranium is dispersed widely in the porous albite monzonite so that boundaries of the orebody can only be defined by assay. Most high-grade shoots are zones of brecciation, often marked by red hematite, and a few are in veins carrying massive hematite and pitchblende. The primary deposits have been affected by widespread secondary alteration. Chemical tests made at the Mines Branch and designed to show the approximate percentage of uranium occurring in secondary minerals indicated a definite trend, ranging from over 60 per cent secondary uranium in samples from near the surface to 30 per cent in samples from depths of 400 feet.

Pitchblende is the only primary uranium mineral that has been recognized. Other metallic minerals are: hematite and traces of pyrite, chalcopyrite, and galena. Non-metallic introduced minerals are: calcite, dolomite, chlorite, and quartz.

Pitchblende occurs principally as rims on grains of albite and commonly is associated very intimately with chlorite and iron oxides. It is remarkable that there does not appear to be any genetic or spatial relation between pitchblende and the carbonates. Cusps and tongues of pitchblende protruding into the albite, irregular swellings in the rims of pitchblende about albite, and widening of pitchblende stringers where they meet each other, all suggest that in some degree pitchblende has replaced albite (*See* Figure 42). Under high magnification it is apparent that calcite and chlorite have corroded early pitchblende, and that as a result late dispersions of almost sub-microscopic pitchblende in calcite and chlorite have been deposited, which in part vein the early massive pitchblende. Locally, the early pitchblende has developed botryoidal habit where it was deposited in open space. The sulphides are found as traces in the later calcite and chlorite gangue. Hematite is present both as red dusty disseminations and as ragged, or flamboyant segregations. Although red alteration of the rock is locally an indicator of high uranium content, several high-grade pitchblende specimens are entirely free from hematite and red stain.

In several specimens rims of potash feldspar have formed on grains of albite and pitchblende (*See* Figure 41). Grains have also been observed that have a core of albite, an inner rim of pitchblende, and an outer rim of potash feldspar. However, other grains having an inner rim of potash feldspar have an outer rim of pitchblende. Although the paragenetic sequence cannot be established it seems probable that deposition of pitchblende and of potash feldspar may well have been contemporaneous. Identity of this unusual occurrence of late potash feldspar was confirmed by X-ray diffraction.

Although there is a general diminution of supergene alteration with depth it is very variable; many shallow intersections are unaltered whereas some deep ones are highly altered. The principal supergene mineral is uranophane but some dusty pitchblende may also be a product of supergene processes. Barite is quite commonly associated with uranophane and locally is yellow to orange in colour.

The unusual depth of supergene alteration in this deposit is probably due in large measure to effects of circulating artesian water. Several diamond drill-holes encountered artesian flow and one in which flow was encountered at 500 feet was cased so that its waters are readily available. Partial analyses of this water and of water from Lake Athabasca at the mine are tabulated below in order to bring out the magnitude of the leaching being carried out by the circulating meteoric waters.

Water[1]	U_3O_8	Parts per million				
		pH	Ca	Mg	HCO_3	Alk. as $CaCO_3$
D.D. hole	0·0014 g/litre	8·2	73·1	21·2	224·2	183·8
L. Athabasca	Not detected	7·9	2·6	....	19·5	14·0

[1] Analyses, except for U_3O_8, made by Industrial Waters Section of Mines Branch, Department of Mines and Technical Surveys, Ottawa.

Although this water has been tapped by a diamond drill-hole, there is an appreciable pressure. The muskeg overlying the orebody extends down to the lake and it is probable that artesian flow enters this muskeg through natural fissures and solution channels. Artesian flow indicates that there is no direct channel from the orebody to the lake.

LORADO URANIUM MINES LIMITED

Viking Lake Deposit

This deposit is the only example of a complex, radioactive, pegmatite dyke known to the writer in the Goldfields region. It occurs at the contact of banded amphibolite and rather massive granitoid gneiss. The dyke strikes north 25 degrees east and dips 75 degrees southeast.

The outer envelope of the dyke has sharply defined walls against the host rocks. It is composed of milky quartz in which pods of coarse-grained microcline occur. Individual crystals of this red microcline attain lengths up to 8 inches.

The main interior part of the dyke is composed principally of much altered soda feldspar in shadowy crystals up to 1½ inches in diameter. This rock is much sheared with parallel orientation of the plentiful biotite that it contains. The soda feldspar weathers chalk-white and locally on fresh fracture resembles serpentine in that it is soft, greenish, and greasy to the touch. This sheared texture is due to differential sericitization of the feldspar, in part so complete that the original crystals are virtually obliterated. In most parts of this facies of the dyke individual grains and twinning in the feldspar are discernible but precise determination of the albite content is impossible. Biotite is largely altered to chlorite and chlorite is also present in distinct veinlets. Some magnetite is present and locally uranothorite and pyrochlore-microlite have been recognized.

The central radioactive core of this pegmatite is almost transitional from the soda feldspar facies. It consists of somewhat brecciated red feldspar with quartz, biotite, and chlorite. The feldspars are albite, in which the twinning lamellæ are bent and fractured, and microcline-microperthite, which is also fractured. Both feldspars are slightly sericitized. Quartz commonly shows suture texture and is clear. Biotite is distributed through the feldspars and quartz and is only slightly altered to chlorite. Chlorite cements fractures in the rock.

Principal accessory minerals are: pyrochlore-microlite, magnetite, titanite, uranothorite, uraninite, cyrtolite, meta-allanite, and pyrite.

Pyrochlore-microlite occurs in rounded masses up to 4 cm. in greatest dimension. In most samples iron oxides fill syneresis cracks. It varies in colour from grey-green to brownish black but has a consistent waxy lustre. It is metamict, but after heating yields an X-ray powder pattern that resembles those of minerals in the pyrochlore-microlite series. Partial X-ray fluorescence analysis of this material is: U, 13 per cent; Nb, 13·5 per cent; Ta, 3 to 4 per cent; Pb, 0·75 per cent.

Magnetite occurs in streaks up to 0·1 inch thick, parallel with the foliation, and constitutes possibly 1 per cent of the rock. Uraninite crystals are usually subhedral to anhedral and attain maximum diameters of 0·2 inch. Uranothorite is anhedral and occurs in elongated masses up to 1 cm. long. Titanite is found in subhedral crystals up to 1 inch in greatest dimension.

No systematic distribution of these accessory minerals was recognized. They do, however, appear to be most highly concentrated in the centre of the core. Individual grains are usually single crystals in so far as data are available. These rounded grains are rarely seen in contact with other accessory minerals; usually feldspar, quartz, or biotite intervenes.

NATIONAL EXPLORATIONS LIMITED

Pat Group—C Showing

This deposit occurs in a shear zone that transects hybrid gneisses of the Tazin group. These gneisses are sedimentary rocks that have been markedly altered to the extent that they resemble foliated leuco-granite. Lenses of unaltered and partly altered paragneiss and amphibolite occur in this rock. The foliation strikes north 55 degrees east and dips on the average 70 degrees southeast.

The shear zone has a low to flat dip and appears to be a rolling structure with an average strike of north 45 degrees west and a dip varying from 10 degrees northeast, through horizontal, to 45 degrees southwest. This shear zone is from 3 to 8 feet thick. It is marked by well-defined shearing over 6 inches at the hanging-wall with minor sub-parallel shears occurring locally through the zone. The principal mass of rock in the zone is made up of blocky, brecciated, and slightly red-altered gneiss, cemented by calcite, clay, chlorite, and locally by graphite. Subsidiary slip planes that vary in strike but dip more steeply than the main shear zone branch from the main shear zone.

The deposit is opened by an inclined shaft and several hundred feet of drifting on the 80-foot level. Rock exposed at this level in the shear zone is generally blocky with marked softening of sheared bands and development of gouge. Despite the consistent assay values, primary or secondary uranium minerals were recognized only rarely in the hand specimen.

Metallic minerals in these deposits are: pyrite, hematite, pitchblende, and traces of chalcopyrite and galena. Non-metallic minerals that have been introduced, at least in part, are: calcite, an unidentified clay, chlorite, and graphite.

Under the microscope it is apparent that the rock is largely brecciated. Interstices between broken fragments of plagioclase, perthite, and quartz are filled with chlorite, clay, pyrite, and graphite. Locally, the rock is completely mylonitized on such a fine scale that its constituent minerals cannot be resolved under the microscope. Commonly, at the hanging-wall, but locally throughout the zone, calcite has cemented the brecciated rock; fragments of breccia, cemented as described above, occur in bands and rounded masses in the calcite. All degrees of replacement of these fragments by calcite may be recognized.

Autoradiographs show that, apart from rare occurrences of pitchblende, most of the radioactivity emanates from streaks of brecciated rock partly replaced by calcite. It is usually impossible to identify a radioactive mineral in this rock. There are minute opaque grains disseminated locally through these areas but the uniformity of the radioactivity suggests that it is due to secondary dispersion of uranium in the altered rock. Radioactivity is highest in zones cemented by calcite, but throughout the breccia autoradiographs show that there are minor concentrations of small size in the chlorite and clay cement.

In the few places where pitchblende has been recognized it is in the calcite, flanking streaks of partly replaced rock. Pyrite is ubiquitous in the shear zone. Pyrite and traces of chalcopyrite and galena also occur with pitchblende in residual rock fragments but not with the pitchblende in the calcite.

The uranium content of this deposit is spatially associated with calcite but primary and secondary uranium minerals occur in partly replaced rock and are absent in calcite. It is probable, therefore, that pitchblende and sulphide deposition took place in open breccia zones that were later filled by calcite, which also partly replaced rock fragments and cement. On the 80-foot level most of the uranium content is due to highly dispersed secondary minerals that are too small to be identified.

NESBITT-LABINE URANIUM MINES LIMITED

ABC Group

References: Christie (1953, p. 111); Lang (1952, p. 75).

This property is crossed by a major normal fault striking north 37 degrees west and dipping 40 degrees southwest. Along this fault sandstones of the Athabasca series are in contact with chlorite-epidote rocks and granites of the Tazin group. The principal deposits in this group occur where a second fault, striking north 45 degrees east and dipping 68 degrees northwest, tails off against the main northwesterly fault (*See* plan by S. M. Roscoe, in Lang, 1952, p. 76). The ore occurs principally in the shattered zones along the northeasterly trending fault.

Metallic minerals recognized in these deposits are: hematite, pitchblende, chalcopyrite, pyrite, and traces of galena. Non-metallic minerals are: quartz, chlorite, and calcite.

Although these deposits are marked by slight red alteration of the wall-rock, there has been relatively meagre introduction of gangue minerals. The deposits are made up dominantly of hematite that appears to have been deposited in brecciated zones both by filling and by replacement.

It seems probable that hematite of at least three generations is represented. The hematite of the earliest and dominant generation is massive and wavy to flamboyant in texture (*See* Figure 43) and makes up about one-half of the deposit. With the introduction of pitchblende, and the chlorite, quartz, and calcite gangue, specular hematite developed in single crystals and felted masses, possibly by recrystallization. Finally, late in the sequence, dusty red hematite dispersed through gangue minerals was emplaced. The segregation of red hematite particles in gangue minerals is illustrated in Figure 44.

Pitchblende is distributed through the hematite-rich areas. There is some evidence that pitchblende occurs in areas of chlorite and specular hematite in preference to areas of quartz and flamboyant hematite. Pitchblende occurs: (1) in equidimensional grains (*See* Figure 45); (2) in a rough mosaic cemented by hematite; and (3) massive, cementing hematite and gangue (*See* Figure 46). Throughout the deposits the association of pitchblende and hematite is close, as illustrated by the above two figures. There is also an intimate association of pitchblende with chalcopyrite, the presence of chalcopyrite in these deposits being usually indicative of higher than average content of pitchblende.

Presence of small amounts of vanadium in the ore carrying flamboyant hematite is probably due to nolanite, for this mineral occurs in somewhat similar material at the Ace mine.

Much of the quartz in the flamboyant hematite particularly may be residual from the original rock. Other gangue is relatively sparse and only chlorite and calcite can be attributed definitely to introduction by hydrothermal agencies.

The paragenesis appears to have been:

(1) Brecciation followed by tensional dilation.

(2) Breccia filling and some replacement by hematite with development of chlorite.

(3) Introduction of pitchblende with chlorite and the recrystallization of hematite to specular hematite. Chalcopyrite and pyrite were probably deposited toward the end of this period, possibly contemporaneous with calcite.

(4) Introduction of late hematite in chlorite-rich gangue.

(5) Veining by late calcite stringers.

Maj and Jam Groups

References: Christie (1953, p. 109); Lang (1952, p. 92).

The principal deposits in these groups occur at the northwest corner of the property where two levels are opened from a vertical shaft. In this area, argillite, slate, and minor quartzite have been intricately dragfolded against a granitized mass that extends southeast to the Ace and Fay mines. These rocks are cut by two parallel faults 550 feet apart that strike north 50 degrees east, dip 50 degrees northwest, and flatten at depth. The more southerly of these faults marks the contact between the mafic rocks and the granitized rocks to the southeast. Cross fractures, most of which are normal in strike to that of the faults and vary in dip from 50 degrees northeast through vertical to steeply southwest, are occupied by veins that form a ladder-work in the folded rocks between the two faults.

Pitchblende deposits are restricted to the cross fractures within the slate. J. F. B. Silman, mine geologist, reports that with only one minor exception, veins are barren in the argillite even although they may be well mineralized in the slate.

Red alteration of the wall-rocks is not pronounced and is restricted to the slate and locally to the quartzite. Usually the red alteration does not extend more than 2 or 3 inches into the wall-rock from the vein, although stringers of hematite may extend 2 feet from the veins.

Metallic minerals that have been recognized in these deposits are: hematite, pitchblende, chalcopyrite, pyrite, bornite, magnetite, and traces of galena, covellite, and tin. Non-metallic, introduced minerals are: calcite, chlorite, and, locally, quartz.

On the basis of work done to date, two general conclusions are: (1) that introduced minerals are restricted to the veins proper, and (2) that pyrite and chalcopyrite diminish in quantity with depth, whereas the reverse is true of hematite.

The habit and associations of pitchblende in these deposits vary considerably. It occurs: (a) in masses of coalescing spheroids; (b) in botryoidal masses; (c) in crusts pseudomorphic after calcite; (d) in massive intergrowths with calcite, some of which are peppered with discrete grains of sulphides; and (e) as ragged flecks along the vein walls.

Autoradiographs show that there is no appreciable penetration of pitchblende into the vein walls. Ragged flecks of pitchblende are found locally at the rock-calcite contacts, but more commonly the wall-rock is coated by a thin crust of calcite that has been partly or wholly replaced, pseudomorphously, by pitchblende (*See* Figure 22). Fragments of wall-rock with these pitchblende pseudomorphs on one side only are found cemented in later vein calcite.

Colloform pitchblende is commonly in the form of masses of coalescing botryoids cemented in calcite. The whole mass is often nearly spherical in shape so that its boundaries transect single crystals of calcite. The masses may be made up of more than one generation of pitchblende. Commonly the older generation is relatively coarse grained and shows typical radial syneresis cracks filled by calcite and sulphides. The younger generation is made up of discrete equidimensional grains, some of which are round but many of them angular (*See* Figure 47). Pitchblende of this later generation rims the older colloform pitchblende and appears to be later than the cementing calcite and sulphides (*See* Figure 47). It is grains of this later pitchblende that make up the periphery of the spherical masses. Apparently this calcite, in which these grains occur, had no control over their distribution because their boundary transects single crystals of calcite. It is inferred that calcite either replaced an earlier gangue mineral or, more probably, has been recrystallized. In the 'Riley' fault zone colloform pitchblende occurs in massive hematite as well as in vein calcite.

Some pitchblende in the hand specimen is bronze in colour. This material consists of a massive intergrowth of pitchblende, calcite, and chlorite, through which euhedral to anhedral discrete grains of pyrite and chalcopyrite are dispersed. These intergrowths vein late calcite.

Hematite occurs largely in the vein walls where it is usually red and fine grained or in massive, grey, ragged patches. Locally, it is present in the veins both dispersed in, and veining, pitchblende and calcite. In the 'Riley' fault it veins and cements syneresis cracks in botryoidal pitchblende and is moulded around the pitchblende masses. Crystals of specular hematite are largely restricted to calcite of the veins. Magnetite and massive hematite occur together.

Copper and iron sulphides in masses that attain maximum diameters of 0·5 inch occur sporadically in the gangue, particularly where quartz is prevalent. They are also present locally in the wall-rock immediately adjacent to the veins. Within the calcite veins, pyrite and chalcopyrite occur most commonly in pitchblende-calcite intergrowths. The bulk of these minerals are dispersed as discrete grains in pitchblende intergrowths but pyrite, particularly, occurs also as rims of discrete grains around the periphery of pitchblende masses. In some veins dispersed sulphides occur in patches of isotropic and distinctly radioactive gangue, in some of which pitchblende could not be identified. This gangue is made up principally of calcite, chlorite, and iron oxides. Sulphides also occur as occasional grains sparsely distributed in the veins. White specks of this type are probably galena. Silman (1954) reports the occurrence of native tin in grains up to 1·5 mm. in diameter, which occur in a late generation of calcite.

Oldman River Showing

This deposit occurs on the north bank of Oldman River, between Forget and McKay Lakes. The radioactivity is sporadically distributed in a band of biotite gneiss that lies between granite-gneiss to the east and pegmatitic granite and granitized quartzite to the west. The massive, coarse-grained biotite gneiss is poorly exposed but appears to be a segregation within the pegmatitic granite.

The biotite gneiss is composed principally of biotite locally containing knots or phenocrysts of microcline and quartz. The specimens having the highest radioactivity are composed of approximately 80 per cent biotite and 20 per cent monazite. The biotite does not exhibit markedly parallel orientation; it occurs principally in a mosaic texture of flakes ranging from 2 to 5 mm. in size. Some local areas were noted in which the grain size is distinctly smaller. Biotite is very little altered to chlorite but contains mottled brown, almost opaque, patches of iron oxides.

Monazite is scattered as discrete single grains through the biotite. These grains are quite uniform in size and range from 0·2 to 1·0 mm. Most of them are rounded, anhedral, and somewhat elongate; a few show subhedral outlines. Most monazite grains show wavy extinction; some of them are altered in a network texture to a light green material that cannot be identified. Partial analysis of this monazite is: Th, 5·40 per cent; U, 0·263 per cent; Pb, 0·50 per cent.

Monazite occurs enclosed in single crystals of biotite, but a large percentage of grains cross intergranular boundaries of the biotite. Some monazite grains contain flecks of biotite that are in parallel orientation with the biotite enclosing the monazite. There is, however, no positive indication of the relative age of the two minerals.

Crystals of uraninite have been identified in heavy mineral concentrates of this rock. Massive pyrite occurs interstitial to the monazite and biotite.

ORBIT URANIUM DEVELOPMENTS LIMITED

Showings 2 and 3

Reference: **Lang (1952, p. 98).**

Two showings, Nos. 2 and 3, that occur within 1,000 feet of each other near the shore of Black Bay are of particular interest because one is pegmatitic and the other hydrothermal in character.

The No. 3 showing consists of narrow veins that appear to have filled a joint system in massive, pink, feldspathic quartzite. The principal jointing strikes south 50 degrees east and dips vertically. Metallic minerals recognized in this deposit are: hematite, chalcopyrite, pitchblende, and minor (?) galena. Non-opaque minerals are: calcite, quartz, and chlorite.

The feldspathic quartzite has been shattered and cemented by quartz. Subsequent shattering is restricted to the vein walls within 0·25 inch of the vein and is cemented by calcite, chlorite, and pitchblende. Films of pitchblende and calcite occur along cracks in the vein walls up to 2 inches from the shattered zones. The massive hematite is probably older than the pitchblende, because vein material that is rich in hematite and chalcopyrite contains relatively little pitchblende.

Most of the pitchblende occurs as colloform rims on fragments of rock cemented by chlorite. Both pitchblende and rock are corroded and cemented by clear calcite. Massive pitchblende forms sharply defined stringers in this calcite. Chalcopyrite and (?) galena in finely disseminated form occur with the colloform pitchblende. Their distribution suggests that their deposition overlapped that of the pitchblende and that in larger part they accompanied the calcite that corroded the pitchblende. Massive pitchblende in relatively small amount, which veins the younger calcite, appears to have been the last mineral to be deposited.

Hematite appears in masses in the rock. In dusty red form, it is disseminated in the older calcite but it exhibits no intimate association with pitchblende.

The No. 2 showing occurs in a highly contorted hybrid gneiss. There is no evidence of faulting or shearing in this deposit. The radioactive zone consists of: migmatite intercalated with the gneiss; segregated lenses and bands of quartz and biotite, of amphibolite with feldspar xenoliths, of biotite and chlorite with feldspar xenoliths, of quartz, and of pegmatite in bodies that have no defined walls or shape. Boundaries between all these facies are transitional. Although the whole zone is anomalously radioactive, the highest radioactivity occurs in the quartz-biotite segregations, and to a lesser extent in the pegmatite.

The pegmatite is composed of fresh perthitic microcline in grains up to 1 inch in diameter, and fresh albite with quartz, biotite, and traces of muscovite. Accessory minerals are almost wholly restricted to the biotite, and include: apatite, zircon (cyrtolite), thorite, uraninite, and iron oxides. The apatite and zircon are slightly radioactive. The more granitic facies of the zone contain a plagioclase feldspar intensely altered to sericite and lack fresh albite, apatite, and thorite. The quartz-biotite facies of the zone contain only traces of microcline and are free from other feldspars. All the accessory minerals found in the pegmatite also occur in the quartz-biotite rock, the uraninite and thorite in greater amount than in the pegmatite. Pyrite is also present in minor amount.

One mineral that occurs in the pegmatite and in the quartz-biotite facies of the zone is markedly radioactive, colourless, has high relief, contains disseminated black opaques, is euhedral (probably prismatic), and is isotropic and metamict. This may be thorite, but the thorite recognized in concentrates is yellow and cloudy.

Uraninite, zircon, and the unknown mineral all have bleached haloes in the biotite.

An X-ray fluorescence analysis of a recleaned heavy mineral fraction from the quartz-biotite facies is as follows: U_3O_8, 75 per cent; ThO_2, 8·4 per cent; PbO, 17 per cent. Zirconium was not detected; it is probable, therefore, that the fraction included only uraninite, with possibly traces of thorite.

PITCHE (URVAN OR TAMLYN) GROUP

References: Christie (1953, p. 114); Lang (1952, p. 97).

The principal deposit and several other deposits on this property occur in fractures intersecting gently folded quartzite and graphitic schist. The principal showing is in a vertical fracture that strikes north 15 degrees west. Ore minerals are concentrated in this fracture where it intersects the graphitic schist. The vein material is roughly banded with concentrations of pyrite on both walls. Bands rich in pyrite, in nolanite, and in pitchblende, together with 'horses' of soft, grey to black, coke-like material and other gangue, make up the centre of the vein. Texture and transitional contacts suggest that the vein is a replacement deposit.

Metallic minerals recognized in this deposit are: pyrite, nolanite, chalcopyrite, specular hematite, and pitchblende. Principal introduced non-metallic minerals are quartz and chlorite. No carbonate minerals have been recognized in this deposit. S. Kaiman has identified tyuyamunite as the common secondary mineral of uranium in the surface showing.

Pitchblende in particles of less than one micron in size is disseminated through the gangue. Concentrations of pitchblende coincide with concentrations of discrete grains of pyrite and chalcopyrite; in some such instances the pitchblende particles appear to coalesce to form a matrix for the sulphides. Pitchblende also is disseminated uniformly through the gangue that is interstitial to plates of nolanite. Many specimens rich in nolanite, however, contain little pitchblende, nevertheless, some preferential association of pitchblende with nolanite does seem to exist. Pitchblende has also been recognized as thin films filling fractures in quartz.

This deposit is particularly interesting because of its vanadium content, most of which occurs in nolanite (*See* Fahey, Robinson, and Schaller, 1955). In hand specimens, nolanite is grey with a bluish tarnish and appears massive. Commonly it cements coarse-grained fractured pyrite. Under the microscope its common habit is in hexagonal plates that locally coalesce to form masses of the mineral. Hexagonal plates of this mineral and laths of hematite are enveloped in chalcopyrite (*See* Figure 49). Fine-grained pyrite and chalcopyrite occur in the gangue that has corroded the nolanite. Chalcopyrite is also found enveloping, and disseminated through, areas of pitchblende.

PITCH-ORE URANIUM MINES LIMITED

References: Christie (1953, p. 114); Lang (1952, p. 98).

This property is located on the eastern limb of the Martin Lake syncline. Principal deposits occur in a branching, blocky, left-handed fault system that intersects intercalated arkose and basalt of the Athabasca series. An average attitude for the fault system is, strike north-south, dip 65 degrees west. Detailed mapping by Tremblay indicates that the horizontal component of the displacement is 700 feet (personal communication).

In these deposits, ore minerals are virtually restricted to the basalt, and usually occur within 15 feet of one of the component faults or joints of the system. With one or two minor exceptions, the arkose is barren even where adjoining basalt has been well mineralized. Faults that contain ore minerals in the basalt become barren where they pass into arkose and this change usually takes place within 2 or 3 inches of the contact. Where a fault plane marks the contact between arkose and basalt the preference for deposition of metallic minerals in the basalt is strikingly displayed. In general, however, the most favourable location for uranium deposition appears to be in the basalt, within 20 feet of its contact with arkose.

The deposits may be arbitrarily divided into three groups: (1) in veins and fault breccias cemented by calcite; (2) in red-altered basalt that shows no evidence of fracturing; and (3) in green schistose material along fault planes.

In the veins and fault breccia, wall-rock and rock fragments are replaced in varying degree by calcite and chlorite. Many of these fragments are coated by a thin crust of euhedral quartz. This quartz crust is corroded and replaced by calcite and chlorite. Some of the quartz is mantled by pitchblende or clausthalite. In deposits in red-altered basalt the rock contains (?) replacing calcite and chlorite but there is little evidence of fracturing or shattering. Red alteration of these areas is marked, and uranium is evenly distributed through the rock. The green schistose material that occurs in some faults is made up of montmorillonite-type clay and chlorite. Visible pitchblende is distributed through this schist.

Non-metallic minerals are calcite, chlorite, quartz, and traces of rutile. Metallic minerals recognized in the deposits, in order of abundance are: hematite, chalcopyrite, pitchblende, clausthalite, pyrite, bornite, and covellite.

Calcite is found in vesicles in the basalts remote from the ore deposits. Near the veins basalt is variably replaced by calcite. This replacement is usually accompanied by development of chlorite and red hematite. Calcite appears as the principal vein and breccia-filling mineral and also in stringers. Chlorite is largely restricted to the wall-rock, particularly near the veins and in the schistose material of the faults. With or without calcite, chlorite fills vesicles in the red-altered basalt in concentric rings of coarse and fine grain. Quartz appears only as crusts of euhedral crystals in veins and breccias.

Pitchblende occurs commonly as residual wisps at the vein walls, in the veins and in the rock. It is probable that markedly radioactive zones of red-altered basalt contain finely disseminated pitchblende but it has not yet been recognized. Colloform pitchblende mantles quartz and calcite, and massive pitchblende cements cleavage rhombs of calcite.

Red dusty hematite is disseminated through the altered basalt. Hematite is concentrated in massive form near the veins, but in the veins it is flamboyant or euhedral. Chalcopyrite and traces of pyrite occur with the wispy pitchblende and locally are distributed in this pitchblende. The even distribution of sulphides in wisps of pitchblende and in surrounding calcite and chlorite, when compared with other areas in which sulphides appear to be restricted to pitchblende, suggests that pitchblende has been selectively replaced, the sulphides being left in situ.

Clausthalite is quite a prominent constituent of these deposits locally. In some veins it is intimately associated with pitchblende and sulphides, in others it occurs alone in the gangue.

RIX ATHABASCA URANIUM MINES LIMITED

Leonard Series Deposits

References: Christie (1953, p. 115); Lang (1952, p. 82).

These deposits occur in a series of sub-parallel fractures extending westward from a marked northeasterly trending scarp that may mark a fault or shear zone. The host rocks are interbanded amphibolite and mafic sediments, injected by parallel bands of coarse granite or pegmatite. The pitchblende is concentrated in the fractures where they intersect amphibolite-granite contacts, but is more persistent in the amphibolite and mafic sediments than it is in the granite. On the surface, uranium stain appears in quartz-rich facies of the granite, remote from the fractures, but the main uranium-bearing fractures intersect and offset the granite bands. It is possible, therefore, that the pegmatitic granite contains sparse, syngenetic, uraniferous minerals.

Mineralogical examination of this property has been restricted to the fracture of No. 1 zone, on which an adit has been driven. This adit has exposed a number of radioactive zones, one of which contains megascopically botryoidal pitchblende. This ore shoot is a lens made up of chlorite, dolomite, calcite, and quartz of rather coarse texture that resembles a granitized gneiss. A band containing galena with some chalcopyrite flanks the pitchblende shoot in the foot-wall.

Metallic minerals recognized are: pitchblende, galena, chalcopyrite, dusty hematite, and traces of pyrite. Non-opaque minerals are: dolomite, chlorite, calcite, and quartz. Botryoidal pitchblende has developed as rims on the dolomite, chlorite, and quartz, and occurs also in the chlorite. It is cemented, veined, and locally replaced by calcite and chalcopyrite. Massive pitchblende, in which a significant percentage of fine-grained galena is disseminated, occurs in the syneresis cracks of the botryoidal pitchblende and around its margins. Galena in masses up to 2 mm. in size occurs largely in the calcite, with calcite veining the chlorite, and in the chlorite. Although the botryoidal pitchblende was deposited as rims on crystals of dolomite stained by dusty hematite, the dolomite has been largely replaced by calcite so that locally only skeletal crystals of dolomite remain.

In other radioactive zones the pitchblende occurs principally in ragged, isolated masses in calcite and chlorite. Hematite staining outlines the original botryoidal texture of this pitchblende, which has been largely replaced by calcite. In these deposits dolomite is rarely present and in them galena is restricted to very fine-grained disseminations around the pitchblende, but chalcopyrite and pyrite are present in relatively larger amount.

It would appear that pitchblende was deposited preferentially where earlier dolomite was present, particularly where dolomite and chlorite are intermixed. The pitchblende and dolomite were variably replaced by later calcite. Uranium and lead resulting from solution of pitchblende were partly redeposited as pitchblende and galena. This is borne out by a relatively high content of radiogenic lead in the galena.

Showing DD1-58

Reference: Lang (1952, p. 82).

This deposit consists of a mass of granitic rock irregular in outline that occurs in banded gneiss, paragneiss, and amphibolite whose general trend is north 30 degrees east. The radioactive granite extends 560 feet parallel with the strike of foliation and attains a maximum width of 150 feet. This mass is composed largely of parallel lenses that coalesce in the central part, are transitional to the country rocks laterally, and finger out into the country rock at both ends. This granite is quite uniformly radioactive and is marked by patches of yellow 'uranium stain' in joints and where shells of rock have been spalled off by frost.

The rock exhibits little foliation on outcrop but residual foliation is preserved by alinement of biotite and chlorite on fresh fracture. In part the rock is rather coarse grained; individual feldspar crystals attain diameters of 1 inch. It is composed largely of highly sericitized oligoclase, fresh perthitic microcline, and quartz, with subordinate biotite and garnet. Accessory minerals are: euhedral monazite, zircon (variety cyrtolite), pyrite, iron oxides, molybdenite, and crystalline uraninite.

The oligoclase is highly altered to sericite and epidote, biotite is partly altered to chlorite, and the almandite-type garnet is veined by a network of biotite and chlorite that resembles the texture of serpentine in olivine. In contrast, microcline and quartz are fresh and unaltered. These data, together with the field occurrence and markedly higher radioactivity, suggest that this granite has recrystallized from gneiss, with the addition of potassium feldspar, urania, and rare earth phosphates.

In one outcrop where the granite is much jointed the rock is considerably reddened by hematite. In some of the joints, pitchblende with traces of calcite occurs.

Rix Mine

References: Christie (1953, p. 116); Lang (1952, p. 82).

Principal deposits on this property occur in intensely red-altered zones that transect a series of hybrid gneisses. Foliation of these rocks is roughly parallel with their banding and strikes north 45 degrees east with a steep dip southeast, whereas the trend of the red-altered zones is north 55 degrees west and their dips vary from 30 to 45 degrees southwest. The rocks themselves are now dominantly granitized. Many bands are leucogranites, but minor well-defined bands of biotite schist, chlorite schist, and amphibolite are intercalated with them.

The red-altered zones appear to be transitional outward from their cores to the enclosing country rock. In the centre the alteration has obliterated original textures and foliation but both are partly preserved toward the edge of the zones. The red-altered rock is a breccia locally traversed by bands of mylonite. The breccia and mylonite are cemented by chlorite, by fine-grained mosaic quartz, and by calcite. Dusty red to metallic hematite permeates the cementing minerals but not the brecciated rock fragments. This cemented mylonite and breccia has suffered a second crushing resulting partly in veining but mainly in coarser brecciation. The apertures of this second breccia contain pitchblende and accompanying calcite and chlorite.

A branching fault having up to 4 inches of gouge along its various planes traverses the red-altered zones and the country rock. It is roughly parallel with the red-altered zones, but in detail, it intersects them, passing from hanging-wall to foot-wall and vice versa. Neither the intensity of the red alteration nor the uranium content shows any consistent relationship to this fault. In two places, however, higher than average uranium content does occur in 'horses' where the fault splits and recombines. It is probable that the faulting commenced during the second period of brecciation, although in the main it is post-ore.

Metallic minerals recognized in these deposits are hematite, pyrite, pitchblende, galena, and chalcopyrite. Minute grains of an anisotropic mineral have the characteristics of pyrrhotite. Non-metallic introduced minerals are quartz, and two generations of calcite and chlorite. In addition patches of 'leucoxene' (probably minute crystals of rutile) are common.

Hematite is so thickly disseminated through the chlorite, quartz, and calcite that cement the breccia that the rock as a whole is deep red in colour. Concentrations of metallic hematite almost invariably coat walls of openings in the later breccia. Much of the pitchblende occurs with the hematite of these concentrations and is usually disseminated through them. Where fragments of this material have been broken off and cemented in calcite, the chlorite, quartz, and feldspar of the vein wall have been largely replaced by calcite and the hematite is altered to pyrite. In rare instances pitchblende and hematite rim an older stained generation of calcite and are cemented by younger, clear calcite. Pitchblende is most commonly in discrete angular grains or in masses with ragged boundaries. Locally, it occurs as milky concentrations in the calcite. In a few instances disseminated pitchblende occurs in the centre of colloform patches of chlorite within the feldspars. It is common to find iron as hematite in the wall-rock and as pyrite in the calcite veins; with pitchblende marking the transition zone between the veins and the walls. Pyrite and galena in discrete grains commonly flank pitchblende where it occurs in calcite. Both sulphides occur locally, also as discrete grains, in the pitchblende.

Chlorite appears as a cement in the earlier breccia and as colloform replacements of the brecciated feldspar. It is also concentrated in the wall-rock of openings in the second breccia. It is intimately intermingled with pitchblende that flanks the wall-rocks.

Two generations of calcite are present. Calcite of the first generation is usually stained by iron oxides, shows well-developed cleavage planes, and marked twinning, some lamellæ of which are bent. Zoned crystals are also common. The second generation calcite is usually clear and shows twinning lamellæ but its cleavage is only slightly developed. The first generation calcite appears as ghost crystals in the other. Identity of both generations was confirmed by X-ray diffraction. Quartz appears in rather fine-grained mosaic form in patches and also in stringers with matching walls. Euhedral crystals of quartz are corroded by vein calcite.

TYPES OF DEPOSITS

Three distinct types of uranium deposits are recognized in the Goldfields region. They are: (1) epigenetic deposits, in which the uranium and associated minerals were deposited in apertures in pre-existing rocks; (2) syngenetic deposits, in which uranium minerals are thought to have crystallized at the same time as the associated rock-forming minerals; and (3) supergene deposits that formed as a result of weathering of hypogene deposits. All supergene deposits known to the writer are transitional into epigenetic deposits at depth. The distinction between epigenetic and syngenetic deposits is usually sharply defined. There are, however, a number of deposits in which characteristics of both types appear.

Epigenetic deposits of the region, in approximate order of abundance, comprise: veins, shear zones, breccia zones, and replacement deposits. In these deposits, pitchblende is virtually the only hypogene uranium mineral; in two or three deposits thucolite is also present. Principal minerals associated with pitchblende in these deposits are: calcite, chlorite, hematite, and chalcopyrite. Although a fairly wide range of metallic minerals occurs in these deposits, thorium and rare earth elements are conspicuously lacking. Red alteration of the wall-rocks and vein constituents of these deposits is commonly present, but a few such deposits in which red alteration is lacking do occur.

Syngenetic deposits are much less abundant than epigenetic deposits in the region studied. The study, however, was largely confined to the area in which epigenetic deposits predominate. This group includes one true pegmatite deposit, some monazite-rich biotite segregations, and one granite, but its most abundant constituents are migmatitic facies of the hybrid gneisses. Uranium-bearing minerals in this group include: uraninite, monazite, cyrtolite, and, less commonly, uranothorite, pyrochlore-microlite, and xenotime. All these minerals contain thorium and rare earth elements in addition to uranium. In some of these deposits thorium exceeds uranium in amount. Red alteration of the country rocks and of these radioactive rocks themselves is relatively rare. It is generally true, however, that red granites or red facies of granite are more radioactive than the normal grey to pink facies.

Deposits of supergene minerals in significant amount are rare, although nearly all hypogene deposits have a shallow capping in which supergene uranium minerals occur. Recent glacial action has removed most of the pre-existing supergene deposits and subsequent climate has not been favourable to their development. There is a large number of supergene uranium minerals represented in the deposits of the Goldfields region, of which uranophane and liebigite are the most common. Limonite is a common associate of the supergene uranium minerals.

WALL-ROCK ALTERATION

Detailed description of wall-rock alteration of three deposits appears in a report by Dawson (1951), who has subsequently described the alteration of a larger number of deposits (Dawson, 1954). Red alteration of vein walls and vein minerals is almost always present in epigenetic deposits but varies greatly in intensity and extent. The red colour is due to dusty red hematite that is either disseminated through various rock-forming and non-metallic vein minerals or is distributed along intergranular boundaries of these minerals. Commonly associated with this hematite is the development of calcite and chlorite in the wall-rocks. It is the writer's observation that where alteration results in development of all three minerals in the wall-rocks pitchblende is more commonly present than where only one or two of these minerals occur.

Although Dawson has shown that there is commonly little over-all addition of iron involved in the alteration process, the writer has noted that metallic and specular hematite with minor limonite are commonly concentrated on the vein wall and locally within the vein. These occurrences may be attributed in part to residual concentrations and recrystallization accompanying partial replacement of the rock by calcite and chlorite.

In a smaller, but substantial, number of deposits concentrations of titanium minerals, principally rutile and anatase, less commonly titanite, have been observed in the wall-rocks and in the vein material.

As Dawson (1951) and Christie (1953) have stated, there are numerous zones showing marked red coloration that are not radioactive. Many such zones are mylonites or breccias through which hematite is disseminated. In some of these zones the original constituents are partly or wholly altered to a plagioclase feldspar near albite in composition. In some deposits silicification has accompanied, or substituted for, feldspathization. Some of these feldspathized and silicified zones have been re-brecciated and have become hosts to important epigenetic deposits of uranium.

STRUCTURE OF EPIGENETIC DEPOSITS

Christie (1953) has observed that most of the epigenetic deposits of the region occur in minor fractures related to major faults. Hale (1953) and Smith (1952) have placed particular emphasis on the role of dilatancy in controlling localization of the ore and have described particularly the development of conduits where a fracture intersects two rocks of differing competence. These conclusions are generally corroborated by the writer's observations throughout the whole region, and also by the crustification, banding, rimming, development of euhedral crystals, and existence of vugs in the deposits. In a few deposits there is evidence of replacement, particularly where carbonate minerals are present in the host rocks. Evidence of replacement is also found in introduction of calcite and some chlorite, locally accompanied by pitchblende, into the wall-rocks of vein deposits.

Deposits are principally in tensional fractures, most of which are small; in cymoid veins; in shear zones; and in brecciated zones. The uranium mineralization has been dispersed through thousands of small fractures, and it is only where a number of these fractures occur *en échelon*, or otherwise in a zone, that they attain sufficient size collectively to be of economic interest. Shear zones and brecciated zones do attain sizes that permit development of large ore shoots in them. The comminution of wall-rocks in these latter channels has made possible some mineralization by replacement in them in addition to the dominant vein-filling process.

Replacement deposits in the region are clearly due to the presence of numerous fractures, closely spaced, in carbonate-rich rocks.

It is apparent, therefore, that because vein filling of open spaces has played the dominant role in the deposition of pitchblende in epigenetic deposits, structure is the principal factor localizing the deposition of the ores.

DISTRIBUTION OF EPIGENETIC DEPOSITS IN DIFFERENT ROCK TYPES

Host rocks of pitchblende deposits examined by the writer are shown in the following table. Lithologic terminology is that of the writer. The occurrences listed are all discrete deposits, except for five instances where more than one rock was traversed by the deposits. In these cases the deposit was listed under both rocks. Many of these deposits contain several veins and ore shoots. The results are given in Table I.

TABLE I

	Deposits
Granite, syenite, etc	8
Salic gneiss and migmatite	20
Mafic gneiss, chlorite schist, etc	25
Quartzite, feldspathic quartzite	5
Ferruginous quartzite	4
Dolomite, dolomitic quartzite	6
Amphibolite	12
Argillite	8
Diabase	11
Basalt	4
Altered mylonite and breccia	4
Graphitic schist	3
Conglomerate	3

If the abundance of these deposits in each rock type is correlated with the absolute abundances of the various rock types in the region (*See* Map 1015A), it is evident that Christie's conclusions are fully corroborated (*See* Christie, 1953, p. 83). These conclusions are briefly: that preferred host rocks include basic or mafic rocks; granites are favourable where they are crushed and contain carbonate and chlorite; arkose and conglomerate are less favourable; and pure quartzite is unfavourable. Where a fracture system intersects more than one rock type its intersection with the contact of the two rocks is usually favourable to ore deposition. At many localities this may be explained by dilatant zones developing near the contact. In many such occurrences, however, there is no evidence of greater dilatancy in one rock than in the other. Christie (1953, p. 83) describes eight properties in which deposits are confined to one rock type along fractures intersecting two or more contrasting rocks, such as basalt and arkose, amphibolite and quartzite, etc. It is notable that in these and several more deposits of the same kind pitchblende always occurs in the more basic type or in the one richer in carbonate. These observations indicate that under equivalent structural conditions, rocks rich in iron, magnesium, and in carbonate minerals are markedly more favourable to pitchblende deposition than acidic rocks, such as quartzite, arkose, and granite.

CHAPTER III

GENERAL MINERALOGY

Most of the specimens and samples studied in this investigation were collected by the writer in five successive annual visits to the Goldfields region. In some instances particular samples representative of a specific part of a deposit or of a specific mineral assemblage were collected and sent in by owners or officers of properties and companies. Because of the difficulty in obtaining equivalent specimens after the deposit has been opened up, the writer is particularly grateful for specimens that were collected during exploration.

Laboratory studies included: microscopic examination of thin and polished sections aided by matching autoradiographs made from both types of sections; identification of doubtful minerals by X-ray powder patterns, the material for most of which was mounted from sections under the microscope; ultra-violet radiation for detection of some transparent films of secondary uranium minerals; examination of heavy mineral fractions from all syngenetic and some epigenetic deposits; together with decrepitation, X-ray spectrographic, spectrographic, partial chemical, and other analyses as required. Several isotopic analyses of lead derived from various minerals and ores are acknowledged in the text.

Due to the difficulty encountered in making satisfactory polished sections from many of these ores considerable reliance has been placed on studies of thin sections mounted on autoradiographs made from them (*See* Robinson, 1952b). The writer has, however, had the advantage of examining a number of polished sections that were sent to the Geological Survey and Museum, London, England, on loan, and which were admirably repolished there.

A characteristic of both epigenetic and syngenetic deposits of the region is the small-grain size of the uranium minerals. Moreover, in most of the epigenetic deposits the radioactive grains are disseminated, in part at least, through an intimate and fine-grained mixture of other minerals. In many sections, under the high magnification necessary to resolve grains of less than a micron in diameter, it is extremely difficult to identify the different minerals. In some specimens under a magnification of 1,200 diameters, the contacts between some minerals could not be resolved. The contacts appeared to be 'milky' as though the transition zone was composed of particles too small to be resolved at that magnification. In some bands uniform mixtures of several minerals in discrete grains of very small size simulate the distribution of a single mineral in massive form and have well-defined contacts against other minerals. Except where they are intergrown with metallic minerals, quartz and calcite usually exhibit grain sizes of ½ to 10 mm. Chlorite, however, is almost always fine grained.

Supergene uranium minerals are commonly developed as little more than stains on fracture surfaces, although locally they develop in crusts, in rosettes of crystals, and in tumescent aggregates. Under the microscope, it is apparent that most of these crusts are heterogeneous. X-ray powder patterns of these minerals are in many cases diffuse and indicative of cryptocrystalline development. Professor C. Frondel was kind enough to lend spindles of many authenticated secondary uranium minerals. Identification of all such minerals in this investigation is based on comparison of X-ray powder patterns with those obtained from Dr. Frondel's spindles. In many specimens secondary minerals are so intimately intergrown that they cannot be segregated for identification. Concentric shells of secondary uranium minerals similar to those occurring around pitchblende under tropical weathering conditions are rare. In most cases secondary uranium minerals appear to have migrated into cracks and fissures away from the primary minerals.

MINERALS OF EPIGENETIC DEPOSITS

Minerals listed and described in this section of the report are those that are thought to have been introduced by hydrothermal solutions or to have been developed as a result of hydrothermal alteration; rock-forming minerals and minerals of metamorphic origin are not included.

The hydrothermal minerals are listed in Table II under their respective anions, following the general outlines of Dana's classification, except that in each group minerals are listed alphabetically. In order to give some indication of the prevalence of the various minerals, the number of deposits in which they were recognized is given in parentheses after the name. Minerals of sixty-nine deposits were checked in compiling these figures. Some minerals, although they occur in many deposits, are present only in very small quantity. For this reason, symbols to indicate whether a mineral is normally a major constituent (M), minor constituent (m), or trace (t), follow the figure of the number of occurrences.

TABLE II

Minerals in Epigenetic Deposits

Native elements	copper	(7)	t
	gold	(5)	t
	graphite	(3)	M
	silver	(2)	t
	tin	(1)	t
Sulphides, arsenides, antimonides, selenides, etc.	arsenopyrite	(3)	m
	berzelianite	(2)	t
	bornite	(10)	t
	chalcocite	(3)	t
	chalcopyrite	(51)	m
	clausthalite	(9)	m
	cobaltite	(1)	t
	copper-cobalt-nickel selenide	(2)	m
	covellite	(3)	m
	dyscrasite	(1)	t
	galena	(37)	t.m.
	klockmannite	(5)	m
	marcasite	(7)	t
	niccolite	(3)	m
	pararammelsbergite	(1)	m
	proustite	(1)	t
	pyrite	(50)	M

TABLE II—*con.*

Minerals in Epigenetic Deposits—con.

Sulphides, arsenides, antimonides, selenides, etc.—*con.*	pyrrhotite	(2)	t
	rammelsbergite	(3)	M
	siegenite	(1)	m
	sphalerite	(6)	t.m.
	tiemannite	(1)	m
	ullmannite	(1)	t
	umangite	(5)	M
Oxides	hematite	(59)	M
	ilmenite	(1)	m
	limonite	(3)	m
	magnetite	(5)	m
	octahedrite	(8)	m
	pitchblende	(67)	M
	quartz	(45)	M
	rutile	(5)	m
Oxygen salts	albite	(4)	M
	ankerite	(2)	m
	annabergite	(2)	m
	azurite	(1)	t
	barite	(1)	m
	calcite	(53)	M
	chalcomenite	(2)	m
	chlorite	(39)	M
	dolomite	(9)	M
	erythrite	(2)	m
	fluorite	(1)	M
	garnet	(2)	m
	gypsum	(2)	m
	hisingerite	(1)	M
	malachite	(4)	m
	nolanite	(4)	m
	orthoclase	(1)	m
	sericite	(3)	m
	serpentine	(2)	t
	siderite	(1)	m
	titanite	(2)	t
	tourmaline	(1)	m
Hydrocarbon	thucholite	(3)	m

MINERALS OF SYNGENETIC DEPOSITS

Although many small syngenetic, radioactive deposits are known in the region, little development has been done on any of them. In consequence, few such deposits were visited by the writer.

In the main these deposits consist of migmatitic facies in hybrid gneisses that locally contain radioactive areas of granitic or pegmatitic texture. Segregations of biotite in such pegmatitic facies are commonly radioactive. Only one pegmatite, with defined walls and zonal arrangement of minerals, is known to be radioactive.

Commonly these granitic rocks consist of a much-altered plagioclase feldspar, near albite in composition, with large grains of relatively fresh microcline microperthite and some quartz that commonly exhibits suture texture. In a few specimens a younger fresh generation of sodic-plagioclase feldspar is also present. Femic minerals are usually biotite and muscovite with biotite markedly predominant. The feldspars and femic minerals are variably altered to sericite, epidote, and chlorite. Autoradiographs have shown that radioactivity of these deposits is due to certain accessory minerals, nearly all of which show euhedral to subhedral outlines. In a total of ten syngenetic deposits the following accessory minerals have been recognized:

TABLE III

Accessory Minerals in Radioactive Deposits of Syngenetic Origin

apatite	(6)
fergusonite	(1)
meta-allanite	(1)
molybdenite	(3)
monazite	(7)
pyrite	(4)
pyrrhotite	(2)
pyrochlore-microlite	(1)
thorite	(2)
uraninite	(7)
uranothorite	(1)
xenotime	(1)
zircon (cyrtolite)	(6)

SUPERGENE URANIUM MINERALS

In most deposits, supergene uranium minerals extend only a few feet below the surface, but in two exceptional cases, one near a major structure and the other in the "sponge rock" of the Gunnar deposit, secondary minerals are known to extend to depths in excess of 400 feet. Under the writer's direction, Miss A. Muirhead examined secondary uranium minerals in specimens from thirteen deposits. In addition, a few secondary minerals have been identified from other deposits by the writer. Hogarth (1951) identified cuprosklodowskite, kasolite, metazeunerite and uranophane from Nicholson No. 1 extension zone and Kaiman (personal communication) identified tyuyamunite from the Pitche group. Approximately 20 per cent of the supergene uranium minerals studied are either metamict or so nearly so that their X-ray powder patterns were too diffuse for identification. Seven minerals gave X-ray powder patterns that have not yet been identified.

The following list includes all secondary uranium minerals that have been identified from the region, with the number of occurrences in parentheses.

TABLE IV

Secondary Uranium Minerals

becquerelite	(2)
cuprosklodowskite	(2)
fourmarierite	(1)
kasolite	(1)
liebigite	(15)
masuyite	(1)
metazeunerite	(1)
sklodowskite	(2)
studtite	(1)
tyuyamunite	(2)
uranophane	(8)
uranopilite	(2)
vandendriesscheite	(1)
zippeite	(3)

DESCRIPTION OF MINERALS IN EPIGENETIC DEPOSITS

NATIVE ELEMENTS

Copper occurs in nearly all deposits in which copper selenides are found, but it has been observed also in two deposits in which selenides are not known. In all occurrences it is found in calcite gangue and commonly replaces calcite along cleavage directions. It is always found in the relatively young generation of calcite in the centre of the vein and remote from other metallic minerals. It appears, therefore, to have been one of the latest minerals deposited.

Gold is found in pitchblende deposits and in deposits entirely free from pitchblende. In the latter type it is intimately associated with galena and sphalerite, and veins pyrite. The gangue is quartz. In all pitchblende deposits where gold occurs the gangue is carbonate, both calcite and dolomite being present in two deposits.

Qualitative spectrographic analyses on gold derived from two pitchblende deposits and from two non-radioactive deposits showed no consistent differences. Gold from the Nicholson No. 2 zone contains an exceptionally large amount of the platinum group metals (Hawley and Rimsaite, 1953, and Robinson, 1950).

In two deposits gold occurs both as inclusions in pitchblende and alone or with galena, tiemannite, and chalcopyrite in the carbonate gangue; in the other three pitchblende deposits gold is in the carbonate gangue and was not seen in contact with pitchblende. Gold in pitchblende is in rounded grains; in the carbonate it is irregular to arborescent in habit.

At the Box mine, veins of pitchblende and hematite clearly intersect, and are later than, the gold-bearing veins. The mineralogy of the Box and Athona mines differs markedly from that of auriferous pitchblende deposits. It seems probable, therefore, that the gold-sulphide veins are earlier than the pitchblende deposits.

Graphite is intimately associated with pitchblende in only three deposits. Graphite has been positively identified only at the Pitche showings and by analogy at the neighbouring Nyberg showings. Although carbon is reported with the black chloritic schist of the ABC group, the graphite structure has not been identified in X-ray powder patterns of material from that deposit.

Distribution of graphite in all three deposits suggests that structural control has been responsible, in part at least, for its deposition or for its redistribution.

Silver has been positively identified only in concentrates from Nicholson No. 2 zone by Kaiman (personal communication) and from Nicholson No. 1 extension by Hogarth (personal communication). The writer has been unable to identify silver in the Bolger property (*See* Conybeare in Christie, 1953).

Tin has been reported by Silman (1954) in grains and feathery aggregates occurring in late calcite of several veins from the Nesbitt-Labine mine. Identification by X-ray powder pattern was confirmed by spectrographic analysis, which, in addition to tin, shows traces of copper and silver.

SULPHIDES, ARSENIDES, SELENIDES, ETC.

Arsenopyrite (FeAsS) is known to occur in only three deposits, and then sparsely in discrete subhedral grains.

Berzelianite (Cu_2Se) is the least common of the copper selenides in this region. It has been identified with umangite and klockmannite in two properties. Commonly it occurs as rounded grains in umangite.

Bornite (Cu_5FeS_4) is rarely found in more than trace amounts. Quite commonly it occurs in deposits containing copper and lead selenides. However, chalcopyrite is its most common associate. In four instances exsolved laths of chalcopyrite were noted in bornite (*See* Figure 29). No close association of bornite with pitchblende has been observed.

Chalcocite (Cu_2S) has been recognized only in deposits containing bornite. Its occurrence suggests that, in part, it is supergene in origin.

Chalcopyrite ($CuFeS_2$) is the most common sulphide found in pitchblende deposits. However, it is rarely present in large amount and is visible megascopically in less than 50 per cent of the specimens in which it occurs. Most commonly it occurs as discrete grains, which are usually quite uniform in size throughout any one specimen.

Chalcopyrite is also more intimately associated with pitchblende than any other sulphide, and in many specimens it is so thickly peppered through areas of pitchblende that the whole appears to be bronze coloured. In five deposits, grains of chalcopyrite disseminated through pitchblende are largely euhedral and commonly exhibit triangular sections (*See* Figure 18). In more than 25 per cent of deposits chalcopyrite occurs preferentially in areas in which pitchblende is intimately intergrown with gangue minerals. In some deposits chalcopyrite is sharply restricted to such areas. This association is so common that the writer automatically looks for pitchblende, first, in areas where fine-grained chalcopyrite is thickly disseminated. Chalcopyrite is commonly present in shrinkage cracks in and occurs sparingly as inclusions in the outer layers of colloform pitchblende.

Distribution of chalcopyrite in the gangue is much less regular than in pitchblende. In the veins of a few deposits grains attain maximum dimensions of 3 cm. Minute grains of chalcopyrite are common in wallrocks of veins that transect basalt and diabase. Chalcopyrite locally is mantled by galena and by copper selenides. Its intimate spatial association with the outer layers of colloform pitchblende, and particularly with massive pitchblende-gangue intergrowths, is characteristic of its occurrence in these deposits.

Clausthalite (PbSe) is much more widespead than other selenides. It is present in all deposits of copper selenides and in four other deposits is the only selenide found. It is virtually indistinguishable in the hand specimen from galena. Quite possibly, therefore, it has been mistaken for galena in some deposits. However, checks were made by X-ray powder pattern wherever practicable. X-ray powder patterns of clausthalite from this region yield a calculated cell edge (a_0) of 6·05A as compared with that of 6·16A in Dana (1944). The common association of sulphides with clausthalite suggests that some sulphur may have substituted for selenium in the structure, thus reducing the cell edge. It should be noted that clausthalite and galena are isostructural, so that such substitution is to be expected.

Clausthalite rarely occurs in large masses. It is usually disseminated sparsely in discrete grains or occurs as thin films. In deposits free from other selenides most clausthalite occurs with bornite and chalcocite. Quite commonly it is in large enough grains to exhibit excellent cubic cleavage visible under a hand lens.

Isotope analyses of lead from various clausthalite concentrates are listed in Table VIII, page 85.

Cobaltite (CoAsS) has been found sparsely as euhedral grains in the Nicholson No. 4 zone only.

Copper-cobalt-nickel selenide ((Cu, Co, Ni) Se approx.) has been described (Robinson and Brooker, 1952) but not yet named. It is isotropic and resembles pentlandite megascopically. It occurs as rounded, locally rectangular, grains enveloped and veined by umangite. Few grains exceed 2 mm. in diameter.

Covellite (CuS) occurs with chalcocite as an alteration of bornite and, rarely, of chalcopyrite.

Dyscrasite (Ag_3Sb) was identified by Kaiman (personal communication) with antimonian silver, from Nicholson No. 2 zone.

Galena (PbS) occurs with pyrite, sphalerite, and a quartz gangue in non-radioactive auriferous deposits, and also with pitchblende and chalcopyrite in a carbonate gangue. In the former type of deposit galena is usually coarse grained and shows well-defined cleavage.

In radioactive deposits the occurrence of galena is very similar to that of chalcopyrite, except that galena is virtually restricted to the vein material and only rarely appears in the wall-rock. Grain size of galena is usually less than that of chalcopyrite. In more than half the known occurrences it is of the order of one micron or less and is visible only under oil immersion (*See* Figure 19). In such deposits galena has been identified positively only where its particles are disseminated thickly enough to provide lines in a composite X-ray powder pattern. In other similar deposits galena has been identified by analogous occurrence, colour, and isotropism. These criteria are not adequate to differentiate positively between galena and clausthalite.

Galena grains disseminated through pitchblende exhibit cubic outlines in approximately 25 per cent of the specimens examined. Euhedral grains are commonest in areas of massive pitchblende-gangue intergrowths.

Two concentrates of galena were submitted for isotope analysis by the writer to C. B. Collins of the University of Toronto who reported that galena from a pitchblende vein contains 30 per cent of radiogenic lead, whereas galena from the Box mine (quartz, sphalerite, pyrite ore) contains only 7 per cent radiogenic lead. Isotopic analyses of galena are given in Table VIII, page 85.

Klockmannite (CuSe) is present in minor amount wherever umangite is found. It is remarkable that klockmannite appears to flank or vein masses of umangite. In all deposits seen it is markedly subordinate to umangite in amount. With umangite, klockmannite locally envelopes and veins pitchblende.

Marcasite (FeS_2) has been positively identified by X-ray powder patterns in only two deposits; in the remainder it was identified only by meagre optical data and analogous occurrence. It is acicular to capillary in habit, locally occurring as radiating aggregates but more commonly as extremely minute discrete crystals visible only under oil immersion. In four occurrences these minute crystals are concentrated where chlorite, carbonate, etc., have replaced pitchblende.

Niccolite (NiAs) occurs only with other arsenides and sulpharsenides. Its textural relations with rammelsbergite suggest that the two minerals were deposited contemporaneously.

Pararammelsbergite ($NiAs_2$) was identified by X-ray powder pattern in ores from the Nicholson No. 4 property rich in pitchblende and relatively poor in other metallic arsenides. It is distinctly subordinate in amount to rammelsbergite.

Proustite (Ag_3AsS_3) was identified in specimens from the dump of Nicholson No. 4 zone by Hogarth (personal communication).

Pyrite (FeS_2) is the most abundant sulphide in the Goldfields region. It is found abundantly as a metamorphic, rock-forming mineral, as the principal metallic mineral in many non-radioactive mineral deposits, and in the pitchblende deposits themselves. Much of the pyrite in the first two types of occurrence is coarse grained and euhedral. Pyrite in pitchblende deposits, however, is usually fine grained and massive to subhedral.

In the wall-rocks of pitchblende veins pyrite is locally mantled or replaced by hematite, whereas in the veins some hematite is replaced by pyrite. In most deposits hematite is concentrated in the wall-rocks and pyrite appears mainly in the vein material. In many specimens the boundary between hematite and pyrite is a rim of pitchblende on the vein wall; hematite occurs in the wall-rocks and pyrite in the vein matter.

The association of pyrite with pitchblende is not as intimate as that of chalcopyrite but is nonetheless similar to that of chalcopyrite. Pyrite in extremely finely divided discrete grains is densely disseminated through pitchblende in some specimens (*See* Figure 17). However, it is notable that although both pyrite and chalcopyrite are disseminated through pitchblende, it is rare to find both in the same area of pitchblende. Pyrite is common also in syneresis cracks in, and disseminated through outer layers of, colloform pitchblende. Hematite is more common in the inner layers. Discontinuous rims around pitchblende masses of discrete grains of pyrite one grain deep are also characteristic of the occurrence of this mineral.

Pyrrhotite (FeS) occurs in traces only, as minute, scattered grains. Its absence is noteworthy in deposits in which hematite and pyrite are abundant.

Rammelsbergite ($NiAs_2$) is the principal massive arsenide in deposits of the Nicholson property and at Fish Hook Bay. It is intimately intergrown with niccolite. In some specimens it shows radiating texture with an almost colloform habit. Rammelsbergite clearly veins massive pitchblende, but dusty pitchblende has filled partings in rammelsbergite that are parallel with its outer, colloform surfaces.

Siegenite ($(Co, Ni)_3S_4$) occurs in a number of rosettes in which chalcopyrite forms the core and the outer rim. The siegenite always occurs as an intermediate rim and commonly makes up more than half of the complete rosette. In many of these rosettes autoradiographs indicate the presence of a narrow band of dusty pitchblende and thucholite between the siegenite and the outer chalcopyrite and also an outer envelope around the rosette. It is known only from the Nicholson No. 4 deposit.

Sphalerite (ZnS) occurs plentifully in the gold-quartz ores of the Box and Athona mines but is notably scarce in pitchblende deposits. In the few deposits where it does occur it is present in extremely small amount. This is the more remarkable in view of the widespread distribution of pyrite, chalcopyrite, and galena.

Tiemannite (HgSe) has been identified only in the high-grade gold-pitchblende lens of Nicholson No. 2 zone where it is intimately associated with gold and galena rather than with pitchblende.

Ullmannite (NiSbS) has been identified only from Nicholson No. 4 zone where it appears as minute discrete grains with pyrite and chalcopyrite in carbonate gangue.

Umangite (Cu_3Se_2) is much the most abundant selenide in deposits of the region, although it is not as widespread as clausthalite. In two deposits it comprises more than 50 per cent of the vein matter. It is associated principally with other selenides, specular hematite, pitchblende, and locally with pyrite and chalcopyrite. Two deposits of umangite are virtually free from introduced gangue minerals; umangite cements the shattered rock. Umangite appears to have veined, mantled, or replaced hematite, pitchblende, the copper-cobalt-nickel selenide, and berzelianite. Klockmannite appears as a probable alteration product around the edges of masses of umangite. Umangite alters to chalcomenite in a curiously ordered texture (*See* Figure 26) that does not bear any relation to grain boundaries or crystal directions in the umangite. This pattern is similar in direction to that of cleavage in calcite and suggests that umangite may have replaced earlier calcite.

OXIDES

Hematite (Fe_2O_3) is widespread in its regional occurrence and is the most common and intimate metallic associate of pitchblende. In addition to its occurrence as a vein mineral hematite is abundant as the principal mineral in the cherty iron formation. It is common as an accessory mineral in granites and gneisses; as specularite it is present in metamorphosed carbonate rocks; and in red earthy form it colours large mylonite zones.

In hydrothermal deposits hematite is distributed in the wall-rocks and in the veins. It displays platy, micaceous, radiating, flamboyant, and earthy habits. Away from the vein hematite is usually disseminated as red earthy material in part along intergranular boundaries and in part through individual mineral grains. Near the vein walls hematite is commonly concentrated in massive form, particularly in areas of chlorite. The walls of most veins are marked by a mixture of massive and earthy hematite.

Hematite shows a remarkable affinity for pitchblende and almost invariably forms a thin coating on all available surfaces of masses of pitchblende. Very commonly, too, earthy hematite fills syneresis cracks in colloform pitchblende and almost invariably is intimately intergrown with massive pitchblende, except where pyrite or chalcopyrite have developed. Specular hematite with umangite and calcite has been observed filling syneresis cracks in pitchblende (*See* Figure 37).

It is remarkable that euhedral specular hematite occurs more commonly in a carbonate gangue than elsewhere. In many specimens the hematite of the wall-rock is massive whereas in the adjacent vein specular hematite predominates in calcite or dolomite gangue. Where carbonate gangue has replaced hematite-pitchblende intergrowths hematite has commonly recrystallized to specularite. A similar occurrence is illustrated by Bowie (1953) where hisingerite has replaced pitchblende, leaving a rim of euhedral crystals of hematite.

In a few deposits massive hematite forms the bulk of the vein material. This hematite exhibits flamboyant habit (*See* Figure 43). Radiating sheaves of hematite occur at the Nicholson No. 4 deposit, some of which have altered pseudomorphously to magnetite (*See* Figure 7). In this deposit, too, botryoidal hematite is common. Unusually large single crystals of hematite are somewhat rounded by umangite in two deposits in the Eagle group.

Tests prove the presence of an appreciable content of titanium in massive and specular hematite. This is probably due in part to admixed ilmenite. The abnormally high magnetism of some of the hematite is due to minute inclusions of magnetite in the two cases that were investigated. Composite X-ray powder patterns prove that there is an appreciable content of limonite in some of the fine-grained chlorite-hematite and chlorite-hematite-pitchblende mixtures.

Ilmenite ($FeTiO_3$) has been identified from a vein on the sixth level of the Ace mine, where it occurs with nolanite, hematite, and colloform pitchblende in a gangue of residual feldspar, quartz, chlorite, and apatite. Later calcite fills the vein. Ilmenite exhibits flamboyant to platy texture very similar to that of hematite, with which it is intimately intermingled.

Limonite (hydrated iron oxide) occurs principally in the gossan capping of the deposits. However, the variety goethite is found replacing carbonates along cleavage directions, so that locally it simulates cuneiform texture (*See* Figure 8). As noted above, limonite is also present with fine-grained hematite intergrowths. Bowie (1953) reports that goethite is older than arsenides and sulphides in Nicholson ores, a conclusion that is not corroborated by this writer's observations.

Magnetite (Fe_3O_4) is present in concentrates from many deposits, but is here reported only where it has been identified in vein material. Most of the magnetite in concentrates comes from wall-rock or rock inclusions in the vein. Where magnetite has been identified in vein material it is invariably associated intimately with hematite. In the instance illustrated in Figure 7 it would appear that magnetite is pseudomorphous after hematite.

Octahedrite (TiO_2) is reported in the above table only where it has been identified by X-ray diffraction patterns. The octahedrite commonly occurs in the wall-rock close to the vein but is found less abundantly in the vein material itself. Probably it has wider distribution than is suggested because similar material to that identified is commonly too finely divided to permit identification.

Pitchblende (UO_2) is the term used in this report to refer to the varieties of uraninite that occur in hydrothermal deposits. It differs from uraninite principally in its negligible (less than 0·1 per cent) content of thorium and rare earths. As contrasted with the usual macrocrystalline and often euhedral habit of uraninite, pitchblende is usually cryptocrystalline and anhedral. However, in rare instances euhedral crystals of urania have been recognized in hydrothermal deposits of the region, and these are included under the term pitchblende for purposes of this report.

X-ray fluorescence analyses of over forty pitchblende concentrates have failed to detect a trace of either thoria or rare earth oxides. Of the many chemical analyses for uranium and thorium in hydrothermal ores of the region only one has detected a significant amount of rare earths (Ellsworth in Alcock, 1936) and none has detected thorium in amounts exceeding the equivalent of 0·1 per cent in the pure mineral. Five analyses of pitchblende concentrates from Goldfields region in Collins *et al.* (1954) show a maximum thorium content of 0·0097 per cent. Evidence to date, therefore, indicates that the pitchblende of the Goldfields region does not contain thoria or rare earth oxides in significant amount. This is in marked contrast with the urania of pegmatites, migmatites, and granites, which is discussed under the term uraninite (p. 70).

Pitchblende, like other cryptocrystalline material, is usually adulterated by inclusions of other minerals. In the Goldfields region the amount of adulteration varies greatly, but after careful examination of a comprehensive suite of ores the writer reached the conclusion that it would be impossible to segregate pitchblende with a purity better than about 95 per cent. Because of this lack of purity and because it is impossible to estimate amounts of impurities of nearly submicroscopic size, even where it is possible to be reasonably sure of their identities, no complete analysis of pitchblende from the region has been made, other than that by Rodden (*See* Kerr, 1950, p. 36) on a pitchblende concentrate from the Martin Lake mine.

Cohen (1953) has suggested that urania having a particle (crystallite) size of less than 10^{-3} cm. be called pitchblende. Using Cohen's criteria of uniformity and broadening of lines on an X-ray powder pattern made from a solid piece, pitchblende from the Goldfields region is uniformly cryptocrystalline with an estimated average particle size of the order of 10^{-5} centimetres. Brooker and Nuffield (1952), however, have shown that other factors affect breadth of line in X-ray powder patterns of pitchblende. Other evidence indicative of particle size of Goldfields pitchblende is less direct. Areas of gangue, free from metallic minerals when examined in polished section under magnification of the order of 1,200 diameters, are shown by autoradiograph to be radioactive. This material seen in thin section is slightly cloudy and brown but appears to be free from any supergene alteration. Neighbouring pitchblende areas are transitional to this apparently pitchblende-free material, through a zone in which there is a "milky" border phase. In two out of six X-ray powder patterns made from this pitchblende-free material faint broad lines of the UO_2 pattern were recognized. It seems probable, therefore, that the radioactivity of this gangue results from disseminated pitchblende in particles too small to be resolved at 1,200 diameters magnification. It has been estimated that pitchblende grains of one micron (10^{-4} cm.) can be recognized in polished calcite at that magnification. The crystallite size of this material is presumably considerably less than the maximum size of coalesced particles and might well be of the order of 10^{-5} cm.

Textures of pitchblende that are recognized in deposits of the Goldfields region are arbitrarily classified under four main headings: (1) colloform; (2) massive; (3) sooty or dusty; and (4) euhedral. Dusty or sooty urania powder is relatively rare and does not account for more than 5 per cent of the pitchblende. Euhedral grains are so rare that they are little more than a mineral curiosity. Colloform pitchblende is estimated to comprise about 40 per cent of the total and massive material the remainder. Two or more of these types may, and commonly do, occur in any one deposit, sometimes in contact with each other. Colloform pitchblende is usually the oldest generation. In many instances the colloform pitchblende has been brecciated and cemented by later minerals including massive pitchblende; it is rare to find similar brecciation of massive pitchblende. Brecciated colloform pitchblende cemented by calcite and younger massive pitchblende is illustrated in Figure 28. Kidd and Haycock (1935) recognized two forms of pitchblende at Great Bear Lake, which are analogous to the hard colloform, and softer massive, forms that are found in many Goldfields ores. Generally, the hard colloform material has higher reflectivity and relief than the massive pitchblende and also is normally much jointed in contrast with the smoother massive variety. Autoradiographs of the two forms do not reveal any appreciable difference in intensity of alpha emission, and X-ray powder patterns of the two types from the same specimen are identical. In some specimens there is transition from one type to the other.

Colloform pitchblende takes the form of peripherally banded and radially jointed spherulites or irregular rounded masses (*See* Figures 9, 14, 25, 28, 33, 34, 35, and 48) or forms wavy banded rims on earlier vein minerals or on fragments of wall-rock (*See* Figures 32, 47, and 50). In the latter case the outer surface of the pitchblende rim shows the multiple convex colloform habit, whereas the inner surface conforms to the surface on which deposition took place. Later minerals were deposited on the outer surface of these pitchblende rims, so that they have superficially the appearance of discontinuous veins. Joints are pronounced; usually they are radial but some follow peripheral bands. These joints form a pattern that Bastin (1950) and most other writers attribute to syneresis, or shrinkage that occurs due to loss of water on ageing of the original gel. Syneresis cracks commonly are filled by dusty red hematite, chlorite, calcite, various sulphides, and later pitchblende. Euhedral specular hematite also occurs in syneresis cracks (*See* Figure 37). Normally the colloform pitchblende contains a relatively low percentage of impurities other than those in the syneresis cracks. Where appreciable quantities of impurities do occur in colloform pitchblende their concentrations are always highest in the outer layers of the pitchblende rims. The inner layers of pitchblende coating the rock or other minerals are usually almost pure or may contain some hematite, whereas the outer layers contain sulphides, calcite, and even gold.

Spherulitic pitchblende occurs as individual botryoids, as irregular swarms of botryoids and as swarms of minute pellets partly coalescing in a roughly spherical framboidal texture. Some botryoids are enveloped by an inner rim of calcite and an outer rim of pitchblende (*See* Figure 35). In some specimens the main colloform surface and outlying botryoids have an outer rim of pitchblende separated from them by calcite. It is noteworthy that these rims occur where the botryoids or colloform surface are in, or bounded by, calcite but not by quartz (*See* Figure 14). Similar rings are illustrated by Smith (1952). Only rarely is more than one of these concentric rings developed. The core of the larger botryoids usually exhibits the typical syneresis cracks (*See* Figure 48).

It has been noted that framboidal aggregates of pellets may occur within only two or three crystals of calcite, so that many pellets occur within a single crystal. In general, the grouping of pellets is itself roughly spherical and the outer margin of these groups shows no relation to the crystal structure of the host calcite. Usually in these groupings the pellets merge at their centres and are dispersed at their perimeters. Adulteration of pitchblende botryoids by other minerals occurs largely in syneresis cracks, the pitchblende of the botryoids themselves being relatively pure as compared with that in colloform rims.

Some framboidal aggregates are composed of two generations of pitchblende. The older generation consists of spherical botryoids with radial fractures that have been partly replaced by calcite and sulphides. Some of these botryoids have coalesced into masses with colloform outlines. These composite botryoids are rimmed by younger pitchblende that is apparently identical with that comprising the pellets of the framboidal aggregates (*See* Figure 47).

Massive pitchblende occurs cementing fragments of earlier minerals, replacing earlier minerals, as intergrowths with other minerals, as flocculent segregations in carbonates, and as (?) residual wisps in chlorite, hisingerite, and other minerals.

In a few deposits, pitchblende occurs as the cement of brecciated quartz, calcite, and other vein material (*See* Figure 3). This pitchblende is usually intergrown with only minor amounts of other minerals. In at least four deposits brecciated colloform pitchblende is cemented by gangue in which later massive pitchblende occurs (*See* Figure 28).

The extent to which pitchblende actually replaces other minerals is difficult to assess. Massive pitchblende pseudomorphic after calcite is illustrated in Figures 22 and 23. Pitchblende has also been found replacing calcite along cleavage planes (*See* Figure 36). Pitchblende occurring along zonal boundaries in zoned crystals of calcite may be due to replacement or may possibly have been deposited during crystallization of the calcite. The principal problem involves possible replacement of the host by colloform pitchblende. In most specimens it is obvious that rims of colloform pitchblende were deposited on pre-existing material and that later minerals were deposited on the pitchblende (*See* Figure 50). However, where numerous pellets of pitchblende occur in a single crystal of calcite it is possible, although in the writer's opinion unlikely, that they developed by replacement.

A large proportion of all massive pitchblende occurs intimately intergrown with other minerals, notably calcite, chlorite, and iron oxides. Very commonly chalcopyrite, pyrite, and/or galena are thickly disseminated through these intergrowths as discrete, and in some instances euhedral, grains (*See* Figures 17, 18, and 19). Where chalcopyrite or pyrite are so disseminated in large amount the pitchblende acquires a distinct bronze sheen. The distribution of chalcopyrite particularly, and locally of pyrite, through massive pitchblende is characteristic of parts of at least fifteen deposits. In many specimens chalcopyrite is confined to areas of pitchblende intergrowths. Intergrowths of pitchblende with the gangue minerals are usually extremely fine-grained. In many of them it is impossible to resolve the contacts between pitchblende and the gangue at magnifications of 1,200 diameters. There is usually a transitional zone that appears to be "milky" in polished section and opaque in thin section. It is usually marked by iron oxide stain. This transitional appearance is interpreted as being due to dissemination of pitchblende as sub-microscopic particles in the gangue. In part at least it is equivalent to the "flocculent" pitchblende that is described and well illustrated by Bowie (1953) from the Nicholson No. 4 mine.

Pitchblende occurs as 'wisps' in chlorite and other gangue minerals in a high percentage of deposits. The wisps consist of elongated "shreds" of pitchblende that appear to have been drawn out with the host mineral, or of irregular to lens-shaped particles in the gangue. These particles are always sharply defined in their contacts with the gangue, unlike the intergrowth or flocculent type. In most instances these wisps of pitchblende appear to be residual in later gangue minerals that have invaded and partly replaced earlier material.

Urania occurring in dusty or sooty form has been described by Kerr (1951) and others. This type of material is relatively rare in the Goldfields region and occurs in important amount only in the Nicholson No. 4, Fish Hook Bay, and Gunnar properties. Similar material in trace amounts does occur in a few other deposits. The occurrence of this type of urania is restricted to deposits where softening and alteration of the minerals has occurred. It is likely that some alteration is still going on at the three major occurrences. X-ray powder patterns of this material are commonly but not invariably more diffuse than those of ordinary massive pitchblende. In the Nicholson property Bowie (1953) has shown that much of the disseminated pitchblende is rimmed and replaced by thucholite or by hisingerite. In the unconsolidated sooty black pitchblende from the Nicholson No. 4 zone the carbon content of acid-leached material indicates the probable presence of thucholite with pitchblende. Sooty pitchblende is always mixed with other minerals so intimately that attempts to segregate pure material have been unsuccessful. Its occurrence in vuggy deposits filled with meteoric water suggests that it may well be supergene in origin.

Finally, urania in euhedral crystals has been identified at the Ace and Eagle mines (*See* Figure 24). X-ray powder diffraction patterns of uncrushed crystals exhibit the "spotty" patterns typical of single crystals. No thorium or rare earths were detected in concentrates made from a sample from a surface trench of the Eagle mine, where the best of the euhedral urania occurs. In this occurrence urania crystals are largely restricted to the comb quartz gangue although some of them are in contact with calcite. Some of these crystals have been moulded on the terminal faces of comb quartz and exhibit their own euhedral faces only on the outer surfaces. Later quartz in turn has grown on the outer surfaces and the contact is marked by a distinct reaction rim where quartz has replaced euhedral urania. It should be noted that pitchblende pseudomorphous after calcite occurs in the same specimens as the euhedral pitchblende.

Uncrushed pitchblende pseudomorphous after calcite yields a cryptocrystalline X-ray powder pattern. Clusters of slightly rounded cubes of pitchblende are found also in the Ace mine (*See* Figure 16).

The genetic significance of the various types and habits of pitchblende is discussed in Chapter VI.

Quartz (SiO_2) is a silicate, but here is discussed with the oxides for convenience. Although quartz is fairly commonly present in hydrothermal uranium deposits it is rarely the dominant gangue mineral and is usually subordinate in amount to calcite and chlorite. In various non-radioactive deposits, notably the Box and Athona gold mines, quartz is the dominant gangue mineral.

In pitchblende deposits, much of the quartz exhibits comb texture. This comb quartz is usually zoned and exhibits marked variation in the amount of inclusions from one zone to another. Amethyst zones occur locally. Quartz is also quite commonly present as discrete euhedral crystals in calcite. In massive form it forms composite stringers with calcite. Usually quartz is intermediate in age between the early and late generations of calcite. In many instances calcite has partly replaced euhedral crystals of quartz and in the Ace mine there are examples of quartz selectively replacing calcite (*See* Figure 10).

The most intimate association of quartz with pitchblende occurs locally in the Ace mine and in DD-1-62 deposit, where discrete grains of pitchblende are disseminated through fine-grained cherty quartz (*See* Figure 15). Pitchblende also occurs mantling euhedral quartz, cementing brecciated quartz, and mantled and replaced by quartz. In general, however, there is not a close association of pitchblende with quartz; their association appears to be largely incidental because their deposition did overlap in time.

Rutile (TiO_2) occurs in almost exactly the same way as does octahedrite. Concentrations of the mineral are usually too fine grained to permit recognition by morphological criteria; usually occurrences have the appearance of leucoxene. Identification in all instances rests upon X-ray powder diffraction patterns. Rutile is usually in the wall-rock immediately adjacent to the vein and only rarely occurs in the vein itself.

OXYGEN SALTS

Albite ($NaAlSi_3O_8$) in this report is to be read as including plagioclase feldspar from An^{10} to An^{30}. The occurrence of this mineral as a product of metasomatism and wall-rock alteration is described by Dawson (1954). Alteration responsible for deposition of albite preceded deposition of pitchblende but in its last phase may have overlapped coagulation of pitchblende. In the Ace mine veinlets of untwinned oligoclase with interstitial pitchblende have been reported. At the Ace and Rix mines the high-grade pitchblende ore occurs in rock largely altered to oligoclase. In the Ace mine, particularly, rounded grains of pitchblende, usually with haloes of iron oxide or chlorite, occur in the oligoclasite (*See* Figure 16). Mention should also be made of the replacement of albite by pitchblende in the deposits of Gunnar Mines Limited (*See* Figure 42). Untwinned albite has also been recognized with comb quartz in the Donaldson property and in the Ace shaft.

Ankerite ($Ca(Mg, Fe)(CO_3)_2$) occurs locally in the Nicholson No. 4 mine where calcite, dolomite, and siderite have also been identified.

Annabergite ($(Ni, Co)_3(AsO_4)_2 \cdot 8H_2O$) is restricted to surface deposits of the Nicholson Nos. 1 and 4 zones and in one trench at Fish Hook Bay.

Azurite ($(Cu_3(OH)_2(CO_3)_2)$ has been identified with *malachite* ($Cu_2(OH)_2(CO_3)$) in only one deposit. Probably a more detailed examination of gossan zones would uncover other trace occurrences of these minerals.

Barite ($BaSO_4$) has been recognized in only two properties. At both it occurs as subhedral grains or aggregations, in vugs and open fractures.

Calcite ($CaCO_3$) is the dominant non-metallic mineral in pitchblende deposits of the region, and in these deposits it is with calcite that pitchblende is most intimately associated. Other carbonates—dolomite, ankerite, and siderite—have been recognized locally and only in small amounts in deposits of the region, but calcite is abundantly and ubiquitously present.

In most deposits calcite of more than one generation is present. In many deposits early calcite has accompanied processes of wall-rock alteration and late calcite occurs in veinlets cutting all other minerals; calcite deposition has, therefore, spanned almost the entire period of mineralization.

As Dawson (1951) and Smith (1952) have observed, calcite is commonly disseminated in the immediate wall-rocks of many veins. Quite commonly too it forms a selvage on the vein walls. This early calcite is commonly red due to disseminated hematite and in many instances exhibits wavy extinction and bent twinning lamellæ due to strain. Where it appears in the vein proper calcite is usually coarse grained; single grains span the width of narrow veins. In wider veins ribbon banding clearly indicates different generations of calcite (*See* Figure 50). In yet other instances, intergrowth textures in which irregular pieces of calcite all lying in parallel orientation occur in a single grain of a later generation of calcite suggest that partial solution and recrystallization of early calcite has taken place.

In some instances calcite has developed as rims of euhedral crystals and as single zoned crystals. The euhedral rims, in a few instances, have been pseudomorphously replaced by pitchblende (*See* Figures 22 and 23). Pitchblende also appears along zonal boundaries in zoned crystals of calcite.

Calcite was deposited before and after pitchblende in many deposits (*See* Figure 50). It must also have been deposited contemporaneously with pitchblende as indicated by the ring structures (*See* Figures 14 and 35) and the intimate intergrowths (*See* Figures 18, 19, and 21). Bowie (1953) has suggested that annular development of pitchblende, which is somewhat similar to these ring structures, is due to replacement because calcite inside and outside the pitchblende annulus is in parallel orientation. This is true of the ring structures only occasionally. It may well be due to parallel growth on a part of the calcite core that was not coated by pitchblende. The extraordinary continuity of parallel crystal growth in calcite is probably responsible for its relatively coarse grain and is well illustrated locally by the continuity shown where it veins pitchblende (*See* Figure 38).

Replacement of calcite by other minerals is not readily proved except where copper, hematite, and pitchblende replace calcite along cleavage directions (*See* Figure 30). In other examples, minerals are distributed through calcite grains with no relation to cleavage or other crystal direction. An example of pitchblende pellets is illustrated in Figure 47. In such instances there appears to be little evidence of replacement and it is difficult to visualize unsupported spherulites being cemented by the calcite. The facts might be explained by recrystallization of original calcite or selective replacement of an earlier mineral by calcite.

There does not appear to be any significant variation in the composition of calcite even although some of it effervesces readily in 10 per cent HCl and some does not. No differences were detected either in X-ray powder patterns or in comparative spectrograms. Variation in composition of calcite is tabulated on page 76.

Chalcomenite ($CuSeO_3.2H_2O$) occurs only as an alteration product on umangite and klockmannite. Locally, its occurrence as blades oriented in three directions (*See* Figure 26) does not appear to have any relation to the grains of umangite in which it occurs. The general pattern is similar to that of rhombohedral carbonate cleavage.

Chlorite (complex silicate) is a common gangue mineral in the veins and is widespread in the wall-rock and along the vein wall. The principal chlorite mineral is penninite with minor prochlorite. Dawson (private communication) has recognized clinochlore rarely. Marked darkening of the X-ray film of some chlorites when using copper X-radiation suggests an unusually high content of iron. Because chlorite commonly contains iron oxides this criterion has been used only on material mounted from thin sections where iron oxides are absent. Most of the specimens in which iron content is abnormally high were found to be prochlorite. In this report all varieties are discussed together as chlorite.

In the wall-rocks chlorite occurs as an alteration product of biotite, hornblende, etc., and in veins as an introduced or remobilized mineral. Much of the chlorite is cloudy and barely translucent, but where it appears in veins it is more commonly clear with discrete particles of opaque minerals in it. In both types of occurrence chlorite locally contains a mineral that somewhat resembles zoisite but both minerals are so finely divided and so intimately mixed that identification of the second mineral, even by X-ray, has not been possible.

Chlorite is almost as intimately associated with pitchblende as is calcite. In the Ace mine, particularly, pitchblende disseminated through the oligoclasite very commonly has an outer envelope of chlorite (*See* Figure 11). In many deposits pitchblende in the wall-rocks occurs preferentially as irregular inclusions in chlorite. Almost all massive pitchblende, moreover, is intimately intergrown with chlorite as well as with calcite and iron oxides. In a slight majority of these intergrowths chlorite exceeds calcite in amount. It also is usually present in the few intergrowths where calcite is absent. Chlorite is found less commonly than calcite filling syneresis cracks in pitchblende. It is, therefore, a preferred host mineral for pitchblende, particularly in wall-rocks.

In a few specimens the calcite of late veinlets also contains some chlorite. Composite stringers of calcite, chlorite, and quartz also occur. Stringers of chlorite alone are quite common and are usually intersected by calcite. Chlorite replacing calcite pseudomorphously has been recognized in the Ace mine (*See* Figure 12).

Dolomite ($CaMg(CO_3)_2$) has been recognized in nine deposits and in only two of these is it present in significant amount. Only in Nicholson No. 4 deposit does dolomite possibly exceed calcite in amount. In that deposit most of the dolomite present is in the host rocks. Dolomite in the Leonard adit is apparently hydrothermal in origin, however, as it is in at least two other deposits. Hydrothermal dolomite is always subordinate in amount to calcite.

Erythrite ($(Co,Ni)_3(AsO_4)_2.8H_2O$) occurs only in those deposits where annabergite is found. Usually erythrite is decidedly more abundant than annabergite.

Garnet (complex silicate) occurs plentifully in some of the rocks of the vein walls and in vein quartz at the Bar group. The crystals are equidimensional but vertices are rounded. Although garnetiferous gneiss is known, there seems to be some preferred association of the garnet with the quartz of the veins.

Gypsum ($CaSO_4.2H_2O$) has been identified with supergene uranium minerals in only two properties. Its occurrence suggests that it too is supergene.

Hisingerite. This rare hydrated iron silicate was identified by Bowie (1953) who has published comparative analytical and X-ray data for it. In the Goldfields region it is known only from the Nicholson No. 4 deposit, but Osborne and Archambault (1950) list two other Canadian localities for the mineral.

On the first level of the Nicholson No. 4 mine hisingerite occurs with massive blue hematite in masses up to 2 feet in diameter. This material is distinctly radioactive due to the presence of pitchblende, much of which is disseminated in minute grains in the hisingerite and rimming blades of specular hematite. Bowie shows that hisingerite is late and replaces pitchblende, hematite, goethite, and dolomite.

Hisingerite exhibits only traces of anisotropism, largely because it is virtually cryptocrystalline. Bowie notes that maximum anisotropism occurs in spherulitic material and that the range of refractive index is 1·584-1·621 on Nicholson material. On the same material Bowie gives the following analysis by E. C. Hurst: SiO_2, 32·34 per cent; TiO_2, 0·06 per cent; Al_2O_3, 1·35 per cent; Fe_2O_3, 36·88 per cent; FeO, 1·46 per cent; CaO, 0·96 per cent; MgO, 4·48 per cent; H_2O-110°C., 7·54 per cent; $H_2O+110°C.$, 14·32 per cent; total 99·39. He has found also that the Nicholson hisingerite yields five diffuse rings on an X-ray powder pattern whose interplanar spacings in angstroms, and estimated intensities are: 4·40 S; 3·55 S; 2·58 S; 1·70 W; and 1·53 S.

Malachite ($Cu_2(OH)_2(CO_3)$) has been recognized in the surface exposures of at least four pitchblende deposits, but no doubt occurs in trace amounts in a much larger number. It is usually present with chalcomenite in the selenide deposits.

Nolanite ($3FeO.V_2O_3.3V_2O_4$) is the name proposed for a new iron vanadate mineral that occurs in the Fish Hook Bay, Zone A deposit, in the Nicholson No. 2 mine, in the main showing on the Pitche group, and in the Ace mine. It is present as a major constituent in the shear zone on the Pitche group and as a minor constituent in the other three.

The mineral was recently described and named by Fahey, Robinson, and Schaller (in press); structural data were presented by Barnes and Qurashi (1952). It is an iron vanadate that occurs typically in hexagonal plates, in aggregates of divergent plates, in a boxwork structure (*See* Figure 27), and in massive aggregates. The hexagonal plates in part have coalesced to form massive material. The plates are often somewhat rounded but are well preserved locally where they are embedded in chalcopyrite (*See* Figure 49).

Nolanite appears to have been deposited before most of the pitchblende and before most of the sulphides. Hematite, euhedral pyrite, and possibly some pitchblende, were deposited before nolanite.

Nolanite occurs in sufficient amount locally to make it a possible source of vanadium.

Orthoclase ($KAlSi_3O_8$) occurs in the wall-rocks of many pitchblende deposits and in the ores of the Gunnar deposit. At Gunnar textural relations suggest that the orthoclase and pitchblende may be genetically related. In that deposit sharply defined rims of orthoclase occur on albite and similar rims appear on and between areas of pitchblende (*See* Figure 41). In some instances, however, pitchblende appears to rim orthoclase. It is possible, therefore, that deposition of orthoclase and pitchblende did overlap.

Sericite (KAl silicate) is not common even in the wall-rock alteration of pitchblende deposits. It has been identified, however, in the Gunnar deposit and in trace amounts in two others. It occurs as flecks in the feldspars and in veinlets.

Serpentine ($H_4Mg_3Si_2O_9$) has been identified positively in only two deposits. In both instances it was found in late veinlets.

Titanite ($CaTiSiO_5$) was identified in the wall-rocks of two deposits immediately adjacent to the veins. In its occurrence it closely resembles that of rutile and octahedrite and was identified only by X-ray powder patterns.

Tourmaline (BAl silicate) in minute acicular crystals is intimately associated with other vein matter in small gash veins containing pitchblende at the Box mine.

HYDROCARBON

Thucholite is a hydrocarbon of variable composition that was named by Ellsworth (1928) to indicate its principal constituents, thorium, uranium, carbon, and hydrogen. The radioactive hydrocarbon of the Goldfields region was originally identified as thucholite by Ellsworth (*See* Alcock, 1936) despite its lack of thorium. Very commonly thucholite from Nicholson No. 4 deposit contains minute grains of residual pitchblende, and according to Bowie (1953) the U_3O_8 equivalent of some specimens reaches 20 per cent.

E. J. Brooker of the Geological Survey of Canada made a diagnostic analysis of two grammes of the purest available Nicholson thucholite as follows:

	Per cent
Average loss on ignition	94·66
SiO_2	0·18
PbO	0·32
CaO	1·75
MgO	0·24
NiO	0·58
CoO	0·26
$Fe_2O + Al_2O_3$	0·11
CuO	0·26
U_3O_8	0·28
Rare earth group as oxides	0·05
Al group insolubles	0·02
Total	98·71

Note that S, Sb, As, B, F, Na, and K were not determined. It is probable that nickel and cobalt are present as arsenates.

Thucholite is fairly abundant in the surface exposures of Consolidated Nicholson No. 4 deposit and occurs in disseminated, sooty form underground. It has been reported also from the Box mine and Fish Hook Bay.

In the surface exposures at Nicholson thucholite occurs in nearly spherical masses much fractured radially as though from severe shrinkage. It is there associated with oxygen salts of uranium, nickel, cobalt, copper, and iron and occurs in weathered crumbly dolomite. In the upper adit similar masses in dolomite flank a veinlet of pitchblende. Much of the "sooty pitchblende" of the second level is, as Bowie (1953) has shown, composed of pitchblende grains, mantled, and apparently partly replaced, by thucholite. Kaiman, in an unpublished report, illustrates evidence pointing to development of thucholite by replacement of pitchblende through an intermediate phase. Bowie (1953) attributes deposition of thucholite to polymerization of mobile hydrocarbons by the radiations emitted by pre-existing pitchblende.

DESCRIPTION OF ACCESSORY MINERALS IN SYNGENETIC DEPOSITS

Apatite ($Ca_5(PO_4)_3(F, Cl, OH)$) is commonly present in trace amounts as an accessory mineral. It is almost invariably euhedral in tiny discrete crystals. Crystals of apatite, somewhat rounded, have been recognized as inclusions in crystals of monazite. Autoradiographs do not indicate that apatite is definitely radioactive; it is difficult to distinguish between random tracks and the one or two tracks to be expected from such tiny crystals of apatite.

Fergusonite ($(Y, Er, Ce) (Nb, Ta)O_4$) has been identified from one deposit, which has been described as a gossan capping. It is associated with uraninite, pyrrhotite, quartz, and plentiful iron oxides.

Meta-allanite (complex Ca Fe Al rare earth silicate) has been identified in small amount from the complex pegmatite north of Viking Lake. It is present only as euhedral platy material against books of biotite.

Molybdenite (MoS_2) has been identified in pegmatites, in one of which it is associated with monazite in a biotite segregation, and also in radioactive "granite".

Monazite ((Ce, La, Y, Th) (PO_4)) is the radioactive mineral most commonly present in the syngenetic deposits. Its most abundant development occurs in biotite segregations within migmatites and pegmatites. In one specimen of massive biotite subhedral crystals of monazite comprise 20 per cent of the whole by volume. Although there is a marked segregation of monazite in biotite, it is present also in the feldspar and quartz of the pegmatite. In the granite it is usually rather sparsely disseminated and almost invariably occurs as discrete euhedral crystals. Zonal growth lines are visible in some of these monazite crystals (*See* Figure 40).

All monazite has been found to be distinctly radioactive, as indicated both by the Geiger counter and by autoradiographs. Monazite from two deposits was segregated as fairly pure mono-mineralic concentrates. Partial chemical analyses of these concentrates by S. Abbey, Geological Survey of Canada, are given on pages 32 and 40.

In the biotite segregations monazite is associated with apatite and zircon; traces only of uraninite were identified in one specimen. Monazite, however, does occur with uraninite in ordinary pegmatites and in radioactive granite.

Pyrite (FeS_2) is quite common in syngenetic deposits, and where found it is usually massive and interstitial to other minerals.

Pyrrhotite (FeS) occurs sparsely in only two of these deposits, associated with chalcopyrite and sphalerite in one deposit and with molybdenite in the other.

Pyrochlore-microlite (complex niobate-tantalite) is the principal radioactive mineral of the Viking Lake pegmatite. It occurs in massive habit, some masses attaining lengths of 2 inches. It contains iron oxides in what appear to be syneresis cracks. No other radioactive minerals have been seen in contact with the pyrochlore-microlite. A rough diagnostic analysis by the X-ray spectrograph indicates that the mineral is near the pyrochlore end of the series and that uranium is the principal radioactive component.

Thorite ($ThSiO_4$) has been identified in two deposits, in both of which uraninite and cyrtolite are also present. The thorite is sparsely disseminated as discrete grains, which are commonly subhedral. Because thorite is usually metamict, single grains in thin section cannot be identified in some instances (*See* p. 41). Positive identification was made in grains segregated from heavy mineral fractions.

Uraninite (UO_2) is readily detected by its high radioactivity and is easily identified because it is not metamict. For purposes of this report, single grains that yield a spotty UO_2 pattern by X-ray diffraction (*See* Cohen, 1953) are classified as uraninite as distinguished from pitchblende. Where it was possible to segregate sufficient uraninite concentrate diagnostic analyses by X-ray spectrograph were made. These all show significant amounts of thoria, which is indicative of uraninite. The following analyses are diagnostic only.

Deposit	U_3O_8	ThO_2	PbO
	%	%	%
That Lake (p. 9)	75	5·6	13
Orbit No. 3 (p. 40)	75	8·4	17
Lorado (Viking Lake) (p. 35)	51	4·5	16·4

In a biotite concentrate from the Hacker vein, Brooker determined chemically: U, 6·47 per cent; Pb, 1·63 per cent; thorium and rare earth oxides, 0·19 per cent.

Uraninite occurs in discrete equidimensional grains that are usually subhedral to euhedral. It varies considerably, however, in its mineral associations and distribution. Most commonly it is found in isolated grains that occur in feldspar, quartz, and biotite. In some instances grains of uraninite occur enclosed in single grains of other minerals. Only in the pegmatite of the Lorado property have large crystals been found, some of which attain diameters of nearly 1 centimetre. In the "Hacker Zone" the uraninite occurs as swarms of minute grains, all less than 0·001 mm. in diameter. These grains are virtually restricted to bands of disseminated biotite, and the uraninite is in the biotite only.

In all instances where grains of uraninite are big enough to examine it has been noted that they are coated with a very thin layer of red hematite. In some instances they are marked by a bleached halo in the surrounding rock whose width is usually slightly greater than the diameter of the uraninite grain.

Uranothorite ($(U, Th) SiO_4$) has been identified only from the Viking Lake pegmatite. It is anhedral and occurs principally in small platy masses along joint planes. It is subordinate in amount to both pyrochlore and uraninite.

Xenotime ($Y PO_4$) has been identified only from heavy mineral fractions of the "That" Lake pegmatite.

*Zircon (*var. *Cyrtolite)* ($ZrSiO_4$) is very commonly present as a minor accessory mineral in the syngenetic deposits. It is usually euhedral with the edges and vertices somewhat rounded. Some crystals are partly isotropic and their X-ray powder patterns are slightly diffuse. All zircons of which autoradiographs were made proved to be slightly radioactive.

DESCRIPTION OF SECONDARY URANIUM MINERALS

The following descriptions are necessarily brief because identification was made by X-ray powder patterns only.

Becquerelite ($2UO_3.3H_2O$) occurs as bright orange-coloured crusts surrounding areas of yellow-green uranopilite on surfaces of massive hematite-pitchblende intergrowths.

Cuprosklodowskite ($Cu(UO_2)_2Si_2O_7.6H_2O$) has been identified from Nicholson No. 1 extension and Nicholson No. 4. It occurs as fine yellow needles (Hogarth, 1951) and as greenish yellow, somewhat botryoidal crusts. In one instance it appears to be closely associated with malachite and uranophane.

Foumarierite ($PbU_4O_{13}.7H_2O$) occurs in thin brownish orange crusts with a notably high waxy lustre. These crusts envelop shiny black botryoidal pitchblende. Uranophane coats the foumarierite.

Kasolite ($Pb(UO_2)SiO_4.H_2O$) is described by Hogarth (1951) as occurring in orange-yellow colloform crusts; but he notes also that microscopic fragments have a prismatic outline.

Liebigite ($Ca_2U(CO_3)_4.10H_2O$) occurs very commonly as a colourless to greenish white film that is usually thin and of small extent. These films occur in otherwise fresh pitchblende ore and are readily seen only under ultra-violet light, which induces a bright bluish fluorescence.

Masuyite (hydrated lead uranium oxide) occurs as crusts of orange-brown material of high, waxy lustre that coat dull greenish black pitchblende.

Metazeunerite ($Cu(UO_2)_2(AsO_4)_2.8H_2O$) is described by Hogarth (1951) as small green plates in vugs close to sulphides, silver, and altered pitchblende.

Sklodowskite ($Mg(UO_2)_2Si_2O_7.7H_2O$) occurs as loosely bound crusts of yellowish white to brown rather earthy material. In one specimen acicular crystals of the mineral occur. It is not fluorescent.

Studtite (hydrated lead uranium carbonate) is with masuyite. It occurs as slightly nodular, light brown aggregates. It is not fluorescent.

Tyuyamunite ($Ca(UO_2)_2(VO_4)_2.nH_2O$) occurs in two of the deposits in which nolanite is found. In these deposits a number of other unidentified secondary uranium minerals also occur.

Uranophane ($Ca(UO_2)_2Si_2O_7.6H_2O$) is certainly the most common of the readily visible secondary uranium minerals. Probably it could be identified from half the deposits of the region. Its colour varies greatly from pale yellow through yellow to orange and locally is yellow-green to bright grass green and dark green.

Uranopilite ($(UO_2)_6(SO_4)(OH)_{10}.12H_2O$) is clear yellow and occurs both in minute acicular crystals and in irregular aggregates of earthy material. It shows bright yellowish green fluorescence.

Vandendriesscheite (hydrous lead uranium oxide) occurs as orange-yellow earthy coatings on uranophane.

Zippeite ((UO_2) $(SO_4)OH_2.nH_2O$) is found in rosettes of yellow acicular crystals. These rosettes are found in fractures that are slightly open. The crystals exhibit brilliant, greenish fluorescence.

CHAPTER IV

DISTRIBUTION AND PARAGENESIS OF MINERALS AND ELEMENTS

GENERAL STATEMENT

In Chapter II, a general subdivision of uranium deposits into epigenetic, syngenetic, and supergene classes is presented, and in Chapter III lists of minerals found in each of these types of deposit are given. This chapter presents a synopsis of the distribution of the deposits and the elements they contain.

The broad picture of the occurrence of uranium in the whole region bordering on Lake Athabasca has been described previously (Robinson, 1952a). Uranium deposits occur sporadically in a belt within the Canadian Shield along the north shore of Lake Athabasca extending eastward for 240 miles from the Palæozoic contact in the west to the Charlebois Lake region in the east. Within this belt the largest and most important concentration of uranium deposits is in the Goldfields region, and although early prospecting and most of the development work has been confined to the part of this region within 20 miles of the north shore of Beaverlodge Lake prospecting and development in the past year have greatly extended the territory in which uranium deposits are known.

SPATIAL DISTRIBUTION OF EPIGENETIC AND SYNGENETIC DEPOSITS

Epigenetic uranium deposits occur along the north shore of Lake Athabasca from St. Joseph's Point to the mouth of Oldman River. They extend southward throughout the Crackingstone Peninsula and northward in an area centred on and roughly within 7 miles of the shoreline of Beaverlodge Lake. Another zone containing epigenetic deposits includes Laird Island and some of the country between the south shore of Tazin Lake and Camsell Portage. A few epigenetic deposits occur also west of Camsell Portage, in the vicinity of Fiddler's Point, Alberta.

Although syngenetic uranium deposits are not known in the centres of any of these main areas, there is a broad transition zone about their peripheries in which epigenetic and syngenetic deposits are intermingled. In this transition zone deposits also occur that have epigenetic and syngenetic characteristics. A few epigenetic deposits occur well outside the areas outlined above. However, most uranium deposits outside these areas are syngenetic.

In an earlier paper (Robinson, 1952a) the writer indicated that the belt, of which the Goldfields region is a part, lies in an area in which the surface of Archæan rocks dips southward under rocks of the Athabasca series. In the Goldfields region itself the principal zone of epigenetic deposits is centred on the residual area of Athabasca rocks of the Martin Lake syncline (*See* Figure 1). Recent work by Hale (private communication) indicates that Athabasca series rocks occur in the Laird Island-Camsell Portage area. They occur also farther west at Fiddler's Point.

In that part of the epigenetic zone centred on Beaverlodge Lake and lying between the Black Bay fault and the St. Louis fault, R. B. Allen (private communication) concluded that epigenetic deposits are concentrated near the Athabasca-Tazin contact.

The writer knows of no syngenetic uranium deposit that occurs in rocks of the Athabasca series. On the other hand, epigenetic deposits of the Martin Lake syncline intersect rocks that appear to be at least 2,500 feet stratigraphically above the base of the Athabasca series. In areas of Archæan rocks immediately underlying strata of the Athabasca series epigenetic deposits are concentrated and syngenetic deposits are lacking. An example of such an area is the Crackingstone Peninsula, which extends from Beaverlodge Lake southwestward into Lake Athabasca. This area is flanked by flat-dipping Athabasca rocks on three sides (*See* Figure 1) and within the area only epigenetic deposits of uranium are known. In other areas of Archæan rocks, which flank areas underlain by remnants of Athabasca series, epigenetic deposits are also dominant, but the ratio of syngenetic to epigenetic deposits increases with increasing distance from the pre-existing Athabasca contacts. Thus, except where Archæan rocks appear as what is in effect a window, zones of epigenetic uranium deposits in them are flanked by zones of intermingled epigenetic and syngenetic deposits, beyond which syngenetic deposits are dominant.

The general distribution of epigenetic deposits is modified by the Black Bay and St. Louis faults, for extensions of epigenetic deposits are present in the hanging-walls of both these normal faults. These extensions are parallel with the occurrence of remnants of Athabasca series rocks and of Tazin group rocks immediately underlying them in the hanging-walls of the faults. As indicated above, this is evidence that uranium deposits occur preferentially near the Athabasca-Tazin contact. Alternatively, it is possible that the faults have served as conduits that extended the zone of mineralization.

Despite the occurrence of uranium in granite pegmatites and migmatites, which do seem to be spatially related to hydrothermal pitchblende deposits, there is no evidence of zonal or peripheral distribution of uranium deposits about any bodies of intrusive or extrusive igneous rocks.

DISTRIBUTION OF MINERAL SUITES

Summarizing the data of Chapter III, the principal minerals associated with pitchblende in epigenetic deposits are: hematite, chalcopyrite, pyrite, and galena in gangue composed of calcite, chlorite, and quartz. As shown in Table II, these minerals are found in most of such deposits. In two separate areas distinctive suites of minerals are added to this basic association.

A group of copper selenides, comprising umangite, with minor klockmannite and berzelianite, together with clausthalite and native copper, occur in a narrow belt extending northward from the Gil group through Martin Lake mine to the west end of the Eagle mine property. The same suite is known from only one property outside this belt. That property occurs in rocks of the Athabasca series lying on the isthmus between Cinch and Martin Lakes. In some deposits at the northern end of this belt a Cu-Co-Ni selenide is also present. At the northern end, too, some of the selenide deposits contain very little pitchblende and are made up largely of umangite with only small amounts of gangue minerals, sulphides, and hematite. Of the selenides composing this suite, only clausthalite is widespread in deposits outside the north-south belt. There is no known structure that could account for this geographic localization. Moreover, the deposits containing this suite occur in rocks of the Tazin group and of the Athabasca series. Textural associations indicate that the minerals making up the suite were among the last to have been deposited.

The second distinctive suite of minerals consists of various arsenides and sulpharsenides of nickel, cobalt, and iron. These minerals occur in the area between Cornwall Bay and Fish Hook Bay and in deposits 0·5 mile north of the 'hook' in the latter bay. A fairly complete suite of these minerals has been identified from the Nicholson No. 4 zone, but rammelsbergite, niccolite, and arsenopyrite occur in three other deposits in the area described. It may be significant that the deposits in which the arsenides are found all strike in the northwest quadrant, whereas northeast to east is the usual strike of most pitchblende deposits in the region.

Gold is present with pitchblende in five deposits, of which four are in the Cornwall Bay-Fish Hook Bay area. Although gold in traces was found over a considerable area during the boom of 1935-38, its principal concentration, including the two mines that went into production, lies in the Lodge Bay-Fish Hook Bay area. In that area gold is associated principally with pyrite, galena, and sphalerite in a quartz gangue. This mineral assemblage appears to constitute a distinct group and the occurrence of gold with pitchblende may well be fortuitous. The writer concurs with Christie's observation that in the eastern end of the Box orebody, stringers containing hematite and pitchblende intersect and slightly offset those containing gold. Most of the gold prospects are non-radioactive.

Two copper prospects, one on the Consolidated Nicholson Mines property and one at the southwest end of Fredette Lake contain traces of pitchblende. In view of the lack of chalcopyrite associated with gold and its almost ubiquitous association with pitchblende, it seems probable that most copper in the district was deposited at the time of pitchblende mineralization.

The one nickel sulphide deposit in the region, at Dinty Lake (*See* Cooke, 1937, and Blake, 1952), contains pyrrhotite, pyrite, and chalcopyrite but is not radioactive.

ELEMENTS OCCURRING IN EPIGENETIC DEPOSITS

A suite of thirty-three samples of high-grade ore from various deposits and parts of deposits throughout the Goldfields region was submitted for comparative spectrographic analysis. Some of these samples were subsequently submitted for partial chemical analysis to assist in evaluating spectrographic results. The elements determined were reported in five groups that conform approximately to the following ranges, expressed as approximate percentages of the total weight as follows: (1) greater than 10; (2) 10-1·0; (3) 1·0-0·1; (4) 0·1-0·01; and (5) less than 0·01. Table V summarizes the number of occurrences of each element in the various ranges with the equivalent percentage in parentheses.

TABLE V

Occurrence of Elements and their Equivalent Percentage

Element	Range (per cent)					Not detected
	>10	10·0-1·0	1·0-0·1	0·1-0·01	<0·01	
Silicon	33 (100)					
Aluminium	19 (58)	11 (33)	3 (9)			
Iron		31 (94)	2 (6)			
Uranium		23 (70)	9 (27)	1 (3)		
Calcium		28 (85)	2 (6)	3 (9)		
Sodium		10 (30)	8 (24)	4 (12)		11 (34)
Barium		3 (9)	13 (39)	15 (46)	2 (6)	
Magnesium		4 (12)	15 (46)	14 (42)		
Strontium				10 (30)	19 (58)	4 (12)
Copper			6 (18)	18 (55)	9 (27)	
Lead			14 (42)	14 (42)	5 (16)	
Manganese			25 (76)	7 (21)	1 (3)	
Vanadium	1 (3)	1 (3)	9 (28)	12 (36)	10 (30)	
Yttrium				6 (18)	20 (61)	7 (21)
Ytterbium				4 (12)	20 (61)	9 (27)
Lanthanum					14 (42)	19 (58)
Scandium					20 (61)	13 (39)
Titanium			9 (27)	20 (61)	4 (12)	
Zirconium				9 (28)	12 (36)	12 (36)
Beryllium				2 (6)	28 (88)	2 (6)
Boron					32 (97)	1 (3)

Thirty samples of calcite and dolomite were picked out by hand from samples of pitchblende ores and submitted for comparative spectrographic analysis. Due to the fine-grained and disseminated nature of the minerals of the epigenetic deposits in the district these carbonate samples were variously adulterated by impurities. Moreover, it was found to be impossible in most instances to select samples composed wholly of carbonate of a single generation. Even where this was done it was not possible to correlate the carbonate of one generation from one deposit to another. For those elements that are probably present, wholly or in part, as constituents of the carbonate minerals, Table VI summarizes the number of occurrences of each element in the various ranges, together with the equivalent percentage in parentheses.

TABLE VI

Occurrence, Elements of Carbonate Minerals and Equivalent Percentage

Element	Range (per cent)					Not detected
	10·0	10·0–1·0	1·0–0·1	0·1–0·01	0·01	
Calcium	30 (100)					
Magnesium	4 (13)	7 (24)	4 (13)	15 (50)		
Iron		6 (20)	21 (7)	3 (10)		
Manganese			24 (79)	6 (21)		
Strontium			16 (54)	3 (10)	10 (33)	1 (3)
Barium				2 (7)	27 (90)	1 (3)
Vanadium					20 (67)	10 (33)

Despite the paucity of samples the results given in Table V are sufficiently consistent to be indicative of the general tenor of epigenetic uranium ores in the Goldfields region. The dominance of silicon and aluminium is due principally to minerals derived from wall-rocks, wall-rock inclusions in the veins, and from chlorite, quartz, and feldspar of the ore zones.

Iron, in large measure, is present as hematite but in minor amount is due to chlorite, limonite, pyrite, and locally to siderite and various sulphides and arsenides.

Uranium is almost wholly due to pitchblende, but, as was noted in Chapter II, in some radioactive areas of various deposits pitchblende could not be identified under the microscope. In such areas it is possible that some uranium has been adsorbed on other minerals.

Calcium is almost wholly present as the carbonate, and consideration of Table VI suggests that most of the magnesium, strontium, and manganese may also be attributed to the carbonates, together with some of the barium, iron, and vanadium. Sodium is almost wholly attributed to albite.

Copper occurs principally as chalcopyrite but native copper, umangite, bornite, and chalcocite all contribute to the copper content of deposits in various amounts. Lead is largely attributed to radiogenic residues in pitchblende, but unusually high contents of lead occur where visible galena and/or clausthalite are found.

Scandium, yttrium, ytterbium, and lanthanum cannot be definitely attributed to any specific mineral or elemental association. Where one occurs the others are usually present, but their presence is not parallel to the amount of uranium in the ores. Yttrium and ytterbium are known in the carbonates and Boyle (private communication) has found that rare earths are concentrated in late carbonates at Yellowknife, N.W.T. A similar distribution is noted in the results of these carbonate analyses, in which the rare earths are present in the coarse, clear, late calcite but are absent in the earlier iron-stained calcite.

Titanium is present largely in the wall-rocks but also in the veins, as rutile, anatase, ilmenite, and titanite. Its presence in analyses of the carbonates suggests that some titanium is present in the hematite. Zirconium is probably derived from zircon in the wall-rocks. Beryllium and boron are almost certainly derived from silicates of the wall-rocks.

Results of the carbonate analyses are disappointing in that no correlation of the various constituents is possible. The principal variant is the calcium/magnesium ratio. There is some evidence that strontium and vanadium are more abundant in carbonates low in magnesium, but iron, manganese, and barium show no preference. Yttrium and ytterbium occur as traces in nine of the thirty samples, of which eight are clear, white, coarse-grained calcite, typical of the later generations that fill the centre of the veins.

Elements that are considered to be due to impurities contained in the carbonates are not included in Table VI. Sodium, aluminium, and silicon are the principal contaminants, with much iron, and minor copper, lead, nickel, and cobalt.

These analyses are too few to demonstrate any exceptional distribution of elements geographically, or with depth, except in the one instance of the Ace mine. In that deposit there is an increase in the vanadium content in veins in the foot-wall remote from the St. Louis fault and an increase of vanadium with depth. Due to the large number of variables and to the great difficulty in making clean concentrates of single minerals, it seems unlikely that a study of element distribution will lead to positive conclusions until the number of mine openings permits selective sampling on a scale that will satisfy the requirements of statistical analysis.

ELEMENTS OCCURRING IN SYNGENETIC DEPOSITS

No data equivalent to those for epigenetic deposits are available for syngenetic deposits. However, certain elements are commonly found in those accessory minerals that contain uranium or are associated with uranium minerals, notable among them being thorium, cerium, yttrium, zirconium, and phosphorus. Less commonly molybdenum, niobium, and tantalum are found.

If a bulk sample representing all syngenetic radioactive deposits of the region were taken the amount of thorium present would probably be found to exceed that of uranium. This conclusion is based on several partial analyses of minerals and ores and on the relative abundance of the various minerals.

Syngenetic deposits examined by the writer, together with those visited by other officers of the Geological Survey, present no evidence to suggest that there is any local concentration of deposits rich in specific elements. Rather, the different types of syngenetic deposits appear to be intermingled, and remarkably similar deposits occur sporadically over distances of many miles. For example, monazite-biotite deposits are known sporadically from Foster Lakes, Saskatchewan, to Taltson River, Northwest Territories, a distance of 350 miles.

SUMMARY

(1) Only epigenetic uranium deposits are known in rocks of both the Tazin group and the Athabasca series; syngenetic deposits are restricted to the Tazin group rocks and to granite and granite-gneiss.

(2) There is an apparent spatial distribution of epigenetic uranium deposits in rocks near the Athabasca-Tazin contact, both above and below it.

(3) There is no evidence of a zonal or peripheral arrangement of uranium deposits about any igneous rock in the region.

(4) Epigenetic deposits of uranium contain iron, calcium, copper, and lead as their principal metallic elements, with local additional associations of vanadium or selenium or cobalt-nickel-arsenic. Carbonates, chlorite, and locally quartz are the principal non-metallic compounds of these vein deposits. Thorium is absent and rare earths are present as traces only.

(5) Syngenetic deposits contain more thorium than uranium in most instances, and rare earths are common, principally as phosphates.

(6) Although it is possible that metasomatic processes were responsible for concentrations of radioactive and other minerals that are characteristic of the syngenetic deposits, the relatively great quantities of uranium, and particularly of carbonate radicle, in the epigenetic deposits were certainly not derived from adjacent rocks and must have been transported thousands of feet at least.

PARAGENESIS

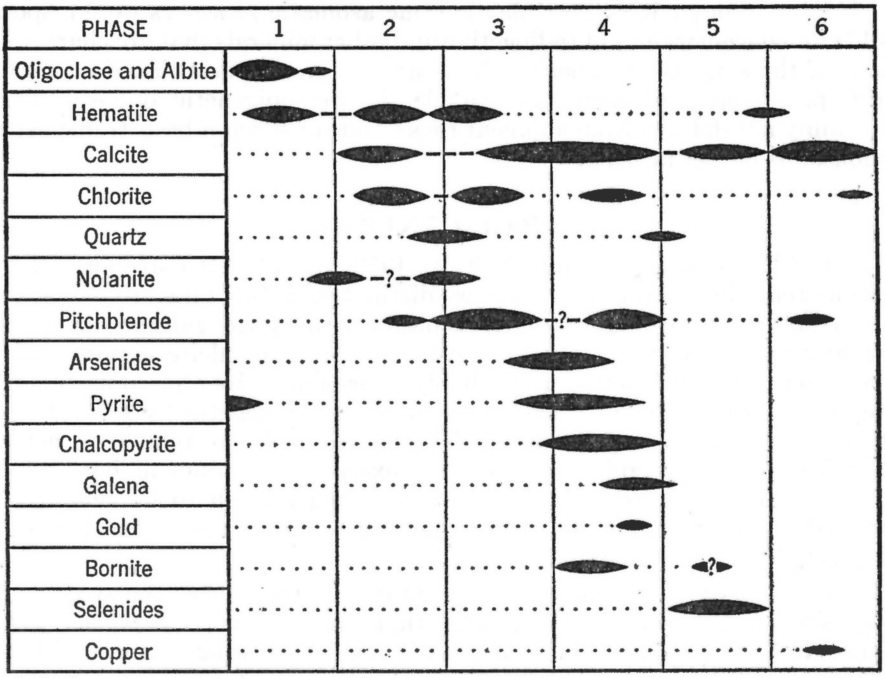
Field evidence cited by Christie (1953, p. 93) and corroborated by the writer indicates that there are two distinct periods of mineralization: the older one resulting in gold-quartz deposits with pyrite, galena, and sphalerite; and the younger one in which the uranium-calcite deposits were emplaced. A third period is probably represented by the copper-nickel deposit at Dinty Lake, which is considered to be genetically related to a body of norite. The gold-quartz deposits are probably related to neighbouring bodies of granite, but with the exception of minor diabase dykes there are no exposures of igneous rocks young enough to be genetically related to the uranium deposits. Only the paragenesis of the uranium deposits has been investigated.

In Chapter V evidence is presented that suggests that the syngenetic deposits are generally slightly older than the epigenetic deposits. The areal distribution and the existence of deposits showing features of both epigenetic and syngenetic mineralization suggest that syngenetic mineralization may have been transitional to epigenetic mineralization. In the transitional deposits at Nesbitt Lake and Orbit Uranium No. 2, evidence points to the epigenetic mineralization being later than the syngenetic mineralization.

Sequence of deposition in the syngenetic deposits is difficult to assess. In the one complex pegmatite the radioactive minerals occur in the centre associated with sheared albite and biotite. At Nesbitt Lake and Orbit No. 2 the uraninite and thorite occur in the quartz biotite facies whose spatial position suggests that they are relatively late. In part, this association is borne out by Christie's observation that pegmatite dykes pass transitionally into quartz veins (Christie, 1952, p. 37). Finally, in some monazite crystals inclusions of biotite are in parallel orientation with that of biotite outside the monazite, suggesting late emplacement of monazite.

In the epigenetic uranium deposits the sequence of deposition is complex and involves several generations of hematite, calcite, chlorite, pitchblende, and pyrite. Two generations of quartz, chalcopyrite, nolanite, and possibly galena are also present. The general paragenesis is presented (*See* Figure 2) but there are numerous exceptions to, and local reversals of, this idealized sequence.

The six phases of mineralization (*See* Figure 2) are not all represented in any one deposit. Moreover, evidence used as a basis for correlation within these different phases is tenuous. Finally, the phases themselves are probably transitional and overlapping.



G. S. C.

Figure 2. Paragenesis of more common minerals.

The composite sequence of events in deposition of the epigenetic uranium deposits appears to have been as follows:

(1) Faulting or brecciation was followed locally by intense feldspathization with concurrent hematitization. In a number of localities the resulting feldspar rock was subsequently mylonitized and elsewhere wall-rocks were further broken and brecciated.

(2) Into these broken and mylonitized rocks, nolanite, pitchblende, calcite, and chlorite were introduced with concurrent dissolution of hematite, part of which was redeposited as specularite about pitchblende grains (*See* Figure 16) and part of which went to form chlorite. During this phase it is thought that the chlorite aureoles around pitchblende (*See* Figure 11) were developed. As fissures developed toward the end of this phase hematite and calcite coated their walls. In some deposits euhedral quartz, and in others subhedral nolanite (*See* Figure 9), were deposited on the walls at the end of this phase.

(3) This phase is characterized by the development of colloform pitchblende as rims on the walls, on fragments of wall-rocks, and on earlier vein minerals. The early part of the phase is marked by contemporaneous deposition of chlorite and hematite and locally nolanite or quartz. This oxide environment gives place to a sulphide environment late in this phase with development of pyrite and chalcopyrite and locally arsenides or gold. The arsenide deposition, where present, overlapped and slightly preceded sulphide deposition. The sulphides commonly are contemporaneous with calcite. They appear also in the outer layers of the colloform

pitchblende rims and particularly as a filling of syneresis cracks. Sulphides also occur disseminated in the calcite outside the pitchblende. In many deposits, botryoids of pitchblende grew in the calcite late in this phase.

(4) Massive pitchblende, usually intergrown intimately with calcite and one or more of chalcopyrite, pyrite, and galena, is typical of this phase. Evidence as to whether only massive pitchblende should be included in this phase is conflicting. Certainly it is possible that some botryoidal pitchblende is contemporaneous with massive pitchblende. It is probable, for example, that pitchblende replacing calcite (*See* Figures 22 and 23), which locally has a colloform outline (*See* Figure 14), is contemporaneous with massive pitchblende. Massive pitchblende and pitchblende-calcite-sulphide intergrowths do occur in gangue cementing brecciated colloform pitchblende and have been found cementing matching fractures (*See* Figure 21). Quite likely some of this later pitchblende was derived from dissolution and replacement of earlier colloform pitchblende (*See* Figure 31).

(5) This phase is essentially marked by the presence of selenides and may well be transitional from phase 4. Where copper selenides occur with sulphides the grains of sulphides are rounded, replaced, and veined. Sequence among the selenides is Cu-Co-Ni-selenide first followed by berzelianite, umangite, and klockmannite. It is not possible to determine the paragenesis of clausthalite and tiemannite but evidence of distribution suggests that clausthalite may be relatively early in phase 5. In two or three deposits it occurs with galena. Meagre evidence indicates that umangite replaced calcite, in part at least. With calcite, the selenides mantle and vein pitchblende but do not occur intergrown with pitchblende.

(6) This phase is characterized by the occurrence of late hematite, late pitchblende, and native copper, deposited along cleavage planes of late calcite. Evidence of minor replacement of calcite is seen in rounding of calcite edges where two cleavages meet. Figure 36 illustrates pitchblende occurring along calcite cleavage. This same calcite cements brecciated colloform pitchblende similar to that in Figure 28. Similar late pitchblende intersects massive pitchblende of phase 4 (*See* Figure 22).

Late stringers of calcite that locally contain some chlorite are the latest evidence of hypogene mineralization.

There is no conclusive evidence to indicate that there was a major break in the process of mineralization. However, the wide range in ages of pitchblende in ores from deposits of the Goldfields region (presented in Tables IX and X) indicates that mineralization has continued or recurred over a time interval in excess of a thousand million years. This evidence is corroborated by the anomalously high content of radiogenic lead in galena and clausthalite from these deposits (*See* Table XI). Certainly it seems probable that the radiogenic lead in these minerals was released by dissolution of earlier pitchblende because galena from the non-radioactive deposits (e.g., Box mine) contains relatively little radiogenic lead.

All supergene minerals appear to have been formed by weathering processes that are recent in age and still continuing. It is probable that most pre-Glacial supergene deposits were removed by glacial erosion.

CHAPTER V

AGE OF RADIOACTIVE DEPOSITS

INTRODUCTION

The recent expansion of facilities for determination of geological age based on radioactive decay rates of uranium, potassium, and thorium coincided in time with exploration of uranium deposits in the Goldfields region. As a result, a relatively large number of age determinations have been made on vein material from the region. These determinations, which are reviewed below, yielded apparent ages ranging from 190 million to 1,850 million years. Moreover, no single explanation can account for these extraordinary differences in 'apparent ages'.

In an attempt to resolve the meaning of these widely divergent ages and thus to provide some understanding of the history of uranium mineralization in the region, the writer collected a suite of thirty pitchblende ores and six ores from which galena or clausthalite concentrates could be made. He also collected material suitable for age determination from three syngenetic deposits. The samples chosen are representative of different types of deposits and of different parts of the region. These collections include numerous samples from the Ace mine to be used in relating ages of different parts of the deposit to depth and to fractures of varying strike. The samples were concentrated by gravity methods. In addition, concentrates of the lead minerals, galena and clausthalite, were made to provide data used in correcting for ore-lead in the various pitchblende concentrates.

Because it was recognized that such a suite would be suitable for correlating results obtained by different laboratories and by different methods, each concentrate was carefully mixed and cut into four equivalent fractions. Fractions of each of the thirty-six concentrates were forwarded to: R. M. Farquhar, Geophysics Laboratory, University of Toronto; J. L. Kulp, Lamont Geological Observatory, Columbia University; and Lorin Stieff, United States Geological Survey, Washington, D.C. This program is not yet complete but grateful acknowledgment is made for permission to use analyses made to date in all three laboratories. It is anticipated that full data and discussion will be published by those participating when all analyses are complete.

EARLIER AGE DETERMINATIONS OF GOLDFIELDS DEPOSITS

First age determinations were based on the uncorrected lead/uranium ratios as determined by chemical analyses. Results of two analyses of his own and two by Kroupa were published by Ellsworth (1950). In the same year a complete chemical analysis of pitchblende from the Martin Lake mine was published by Kerr (1950) and subsequently a lead isotope analysis and calculation of age by Kerr and Kulp (1952). Twenty-five age determinations, based solely on isotopic analysis using the Pb^{207}/Pb^{206} ratio, were published by Collins, Lang, Robinson, and Farquhar (1952). Subsequently, some of these, together with several new analyses and some chemical analyses, were published by Collins, Farquhar, and Russell (1954).

Table VII lists ages determined by chemical analyses and by a combination of chemical and isotopic analysis extracted from previous publications. In addition the range of ages determined by isotopic analyses only are given.

TABLE VII

Ages of Pitchblende Concentrates from Goldfields Region Extracted from Previous Publications

Property	Analyst	Age in millions of years[1]			
		Pb^{206}/U^{238}	Pb^{207}/U^{235}	Pb^{207}/Pb^{206}	Pb/U
ABC group	Collins	—	—	920	—
Ace mine	Collins	—	—	1,820	—
Beth (Gully) zone	Collins	—	—	970	—
Bolger group	Collins *et al.*	444	437	400	—
Cinch Lake	Collins	—	—	1,010-1,120	—
Donaldson group	Collins	—	—	850	—
Eagle mine	Collins *et al.*	—	—	1,430-1,700	—
Fish Hook Bay (Hacker zone)	Collins *et al.*	1,485	1,648	1,850	—
Gil group	Ellsworth	—	—	—	764
Gil group	Collins *et al.*	822	850	930	—
Martin Lake mine	Kerr and Kulp	860	980	900[2]	870
Martin Lake mine	Collins *et al.*	400	630	1,580	—
Martin Lake mine	Collins *et al.*	—	—	1,110-1,670	—
Mic zone	Collins	—	—	1,160	—
Nicholson No. 1	Kroupa	—	—	—	590
Nicholson No. 2	Collins	—	—	1,160	—
Nicholson No. 4	Collins *et al.*	—	—	1,050-1,800	—
Nicholson No. 4	Kroupa	—	—	—	1,414
Pitche group	Collins *et al.*	—	—	490	—
Rix	Collins *et al.*	—	—	1,210-1,590	—
Strike group	Collins *et al.*	—	—	1,780	—
Tam Lake	Collins *et al.*	—	—	945	—
YY concession	Collins *et al.*	190	260	940	—
50-AA-14	Collins *et al.*	592	664	920	—
49-CC-11	Collins *et al.*	—	—	1,140	—
50-CC-61	Collins *et al.*	—	—	680	—
50-DD-22	Collins *et al.*	—	—	1,630	—

[1] For a time scale, relating ages in millions of years to geological periods, reference should be made to Marble (1950, p. 18).

[2] Presumably this age represents values corrected for radon diffusion. Using the same analyses and correcting for lead using the isotope analysis of clausthalite from the neighbouring Pitch-Ore mine, the writer obtains the following age: Pb^{207}/Pb^{206}, 1,060.

There is a marked difference of opinion regarding the relative validity of ages derived from the different ratios. Collins *et al.* (1954) express the opinion that ages calculated from the Pb^{207}/Pb^{206} are most likely to be correct because they will be least affected by differential loss of lead or uranium. Similar conclusions are reached by Nier, Thompson, and Murphy (1941). On the other hand, Kulp (1953) has shown experimentally that loss of radon that has a half-life of 3·8 days may be a significant factor increasing the Pb^{207}/Pb^{206} ages very markedly and decreasing the Pb^{206}/U^{238} ages to a much smaller extent. Because the half-life of the equivalent gaseous isotope actinon (Rn^{219}) is only 3·9 seconds its loss by diffusion is less likely and the Pb^{207}/U^{235} ratio should, therefore, be more reliable.

Before these methods of age determination were available the age of the Athabasca series was thought to be late Proterozoic due to its open folding and almost complete freedom from metamorphism. Some observers even suggested that it might be early Palæozoic. Unfortunately, there is no other useful criterion by which these continental sediments and intercalated volcanics can be dated. There is even less hope of dating rocks of the Tazin group.

ISOTOPIC ANALYSES OF LEAD FROM GALENA AND CLAUSTHALITE

Isotopic ratios (with $Pb^{204} = 1 \cdot 0$) for lead from ten concentrates of lead minerals are presented in Table VIII. Pitchblende content of most of these concentrates was negligible but concentrates R-3 and R-313 had radioactivities equivalent to 1 per cent and $1\frac{1}{2}$ per cent pitchblende respectively. Lead from this pitchblende constitutes a negligible percentage of the total lead in each concentrate and no correction has been made for it.

The isotopic ratios of lead from some of these concentrates differ markedly from average isotopic ratios of normal Precambrian ore leads in that they are variably enriched in Pb^{206} and Pb^{207}, the end products of radioactive decay of U^{238} and U^{235} respectively. In order to bring out the amount of these radiogenic isotopes, the ratio of isotopes of the average *ore* lead of Precambrian age (Kulp, 1953, p. 29) was subtracted from the isotope ratio of each concentrate in amounts proportional to the Pb^{208} content of each concentrate. Where a significant amount of radiogenic Pb^{206} and Pb^{207} is present the ratio of these two isotopes is given.

Isotope ratios listed in Table VIII for lead in galena and clausthalite from pitchblende veins contain abnormally high quantities of Pb^{206} and Pb^{207}, whereas those from non-radioactive veins conform more closely to the average isotopic composition of Precambrian ore leads. Variations in Pb^{204}/Pb^{208} are not significantly greater than might be attributed to error in analysis of Pb^{204}, and the constancy of this ratio indicates that there has been no significant addition of Pb^{208}, the end product of radioactive decay of thorium.

The abnormally high content of Pb^{206} and Pb^{207} in galena and clausthalite of pitchblende veins is attributed to dissolution of early pitchblende and chemical separation of the accumulated radiogenic lead in it from the uranium. This lead was probably precipitated with ordinary ore lead as galena or clausthalite. The amount of radiogenic lead is probably some indication of the amount of early pitchblende redissolved by the lead-bearing solutions. These conclusions are corroborated by the fact that isotopic composition of lead from galena of non-radiogenic veins is in relatively close agreement with that of normal Precambrian ore leads.

The ratio of Pb^{207}/Pb^{206} in these minerals cannot be used to estimate their age because, of course, the ratio is fixed when the minerals crystallize. The ratio is indicative only of the time interval between consolidation and dissolution of the uranium mineral whose radioactive decay gave rise to these radiogenic lead isotopes. Because the ratio of U^{235}/U^{238} at the time of this decay is not known, the ratio of Pb^{207}/Pb^{206} cannot be converted to a time interval in years.

TABLE VIII

Isotopic Ratios of Leads from Galena and Clausthalite

Sample No.	Mineral	Deposit	Isotopic ratios[1]			Radiogenic		Ratio[2]	Analyst
			Pb^{206}	Pb^{207}	Pb^{208}	Pb^{206}	Pb^{207}	Pb^{207}/Pb^{206}	
R-3	galena	Ace Creek—pitchblende vein.....	43·5	18·71	35·72	27·6	3·35	0·1214	Collins
R-100	galena	Nesbitt Lake—in radioactive pegmatite........................	15·44	15·44	35·70	-0·5	0·10	—	Farquhar
R-214	galena	Box mine—gold-quartz, little pitchblende....................	21·88	15·74	35·40	6·1	0·52	0·0853	Collins
R-313	galena	Leonard adit—foot-wall of pitchblende vein....................	58·1	21·90	37·72	41·3	5·67	0·1372	Farquhar
R-457	clausthalite	Ace mine, 6th level—with colloform pitchblende..............	39·32	19·04	37·05	22·8	3·11	0·1365	Farquhar
R-457	"	" " " " "	39·80	18·93	36·55	23·5	3·21	0·1366	Oak Ridge
R-530	clausthalite	Pitch-Ore, trench 8—pitchblende vein..........................	20·6	16·2	38·5	3·5	-0·36	—	Farquhar
R-530	"	" " " " "	19·74	15·81	37·55	3·0	-0·34	—	Oak Ridge
R-642	clausthalite	Bar group, zone 1A—pitchblende vein..........................	26·55	17·26	36·48	10·3	1·57	0·1523	Farquhar
R-653	galena	Ace mine, non-radioactive vein...	14·4	15·1	34·4	-0·9	0·3	—	Oak Ridge

[1] Ratios with $Pb^{204}=1\cdot 00$.
[2] Ratio of radiogenic Pb^{207}/Pb^{206}.

TABLE IX

Age Determinations on Epigenetic Deposits

Sample No.	Location	Type of ore	Isotope corrn. by sample No.	Ages in millions of years			
				$\frac{Pb^{206}}{U^{238}}$	$\frac{Pb^{207}}{U^{235}}$	$\frac{Pb}{U}$	$\frac{Pb^{207}}{Pb^{206}}$
R-352	Nicholson No. 2 deposit, 1st level	Colloform pitchblende, nolanite, sulphide	R-530	860	930	865	1,135
R-753	Gunnar, Ed-Bon, 4-foot trench	Massive pitchblende, trace sulphides	Nil	730	755	745	865
R-547	Leonard adit	Colloform pitchblende, galena sulphides	R-313	765	895	750	1,280
R-532	Pitch-Ore, trench No. 10	Massive pitchblende, clausthalite	R-530	975	1,060	985	1,280
R-535	Martin Lake mine, bottom of No. 2 flow.	Colloform pitchblende, clausthalite, selenides	R-530	780	905	790	1,260
R-536	Martin Lake mine, top of No. 2 flow	Colloform and massive pitchblende, clausthalite	R-530	1,120	1,280	1,160	1,585
R-537	Martin Lake mine, No. 1 flow	Colloform pitchblende, sulphides	R-530	825	910	830	1,150
R-150	Eagle mine, 2nd level, central	Colloform and replacing pitchblende, sulphides	R-530	1,280	1,385	1,335	1,590
R-420	Eagle mine, 1st level, west end	Massive pitchblende, sulphides	Nil	895	960	890	1,155
R-646	ABC adit, at the fault	Massive hematite-pitchblende, minor sulphides	R-530	263	325	285	660
R-608	Nesbitt-Labine mine, 2nd level	Massive pitchblende, minor sulphides	R-457	215	247	215	660
R-609	Nesbitt-Labine mine, 1st level	Massive pitchblende, minor sulphides	R-457	317	365	320	730
R-611	Athabasca U., GG No. 2 trench	'Residual' pitchblende, minor sulphides.	R-642	215	272	242	945
R-508	Bar group, No. 5 zone, trench	Massive pitchblende, minor sulphides	R-642	320	350	325	557
R-622	Ace mine, 1st level, W., 126′ from fault	Ragged massive pitchblende, trace sulphides	R-457	1,435	1,530	1,440	1,700
R-623	Ace mine. 1st level W., 109′ from fault	Massive pitchblende, trace sulphides	R-457	1,445	1,585	1,480	1,790
R-624	Ace mine, 1st level W., 80′ from fault	'Residual' pitchblende pyrite, clausthalite	R-457	560	825	580	1,665
R-626	Ace mine, 1st level W., 22′ from fault	Annular to massive pitchblende in quartz	R-457	1,270	1,440	1,310	1,785
R-627	Ace mine, 1st level W., at fault	Granular pitchblende, minor sulphides	R-457	1,100	1,325	1,125	1,755
R-628	Ace mine, 1st level E., 45′ from fault	Massive pitchblende, minor chalcopyrite	R-457	210	235	210	535

R-629	Ace mine, 1st level E., 7′ from fault	Massive pitchblende, some pyrite	R-457	....	....	(240)*	....
R-632	Ace mine, 2nd level E., north-south fracture	Pitchblende-chalcopyrite intergrowth	R-457	850	930	870	1,160
R-633	Ace mine, 2nd level E., east-west fracture 60′ from fault	Pitchblende-chalcopyrite, some galena	R-457	575	665	590	1,035
R-636	Ace mine, 2nd level W., 90′ from fault	Massive pitchblende, trace clausthalite	R-457	....	....	(1,600)*	....
R-639	Ace mine, 2nd level W., 5′ from fault	Partly colloform pitchblende, two generations	R-457	....	....	(1,160)*	....
R-620	Ace mine, 3rd level W., 100′ from fault	Pitchblende-calcite intergrowth	R-457	720	820	725	1,090
R-630	Ace mine, 3rd level W., 90′ from fault	Ragged pitchblende, trace clausthalite	R-457	....	....	(850)*	....
R-631	Ace mine, 3rd level W., 30′ from fault	Massive pitchblende	R-457	....	....	(1,550)*	....
R-618	Ace mine, between 5th and 6th levels 60′ from fault	Massive pitchblende, sulphides	R-457	....	....	(320)*	....
R-747	Ace mine, 6th level E., 15′ from fault	Massive pitchblende, chalcopyrite	R-457	....	....	(345)*	....

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*Ages in parentheses are calculated directly from the uncorrected Pb/U ratio obtained by X-ray fluorescence analysis. These are probably in error where the lead content is high (i.e., where ages are great), because visible clausthalite is known in the areas from which samples R-636, 630, and 631 were taken.

DETERMINATION OF AGE OF EPIGENETIC DEPOSITS

The ages of pitchblende concentrates made from samples collected by the writer are presented in Table IX. These data are new and are not recalculations of earlier work. Quantitative chemical analyses for total uranium and lead were made for samples R-150, 352, 532, 536, 547, and 626 only. Lead and uranium were determined for all other samples by X-ray fluorescence analysis. Results of this method checked reasonably well with chemical analyses except that values for lead were consistently high. Lead values were, therefore, corrected by a factor to bring them into line with chemical analyses. However, the ages will have to be corrected by varying amounts when chemical analyses are available for all samples.

Isotopic analyses by all three laboratories are available for one sample and by two laboratories for six others. These analyses generally are in close agreement and an average value is reflected in the calculated ages. For all other samples isotopic analyses are those made by R. M. Farquhar.

In calculating ages, the lead isotope ratios were first corrected for lead contained in normal lead minerals. The isotopic analyses of these lead minerals as shown in Table VIII vary widely. It was necessary, therefore, to consider geological and mineralogical evidence in deciding which analysis to apply in correcting lead isotope ratios of the various pitchblende concentrates. In some instances calculations were made for each of two corrections and average values are shown in Table IX. Because thorium is absent in the epigenetic deposits, the corrections were based on proportions of the Pb^{208} contents rather than on those of the less accurately known Pb^{204} contents. In all instances the sample number of the lead mineral used for correction of the isotopic analyses is listed.

Ages were determined by each of the ratios Pb^{206}/U^{238}, Pb^{207}/U^{235}, Pb^{207}/Pb^{206}, and total radiogenic lead/total uranium. For the first three ratios resulting figures were converted into millions of years using the nomographs published by Kulp *et al.* (1953) and the fourth ratio was converted to age by means of the graph published by Wickman (1944). The calculated ages and other data are presented in Table IX.

As shown in Table IX there is reasonably good agreement in ages based on the Pb^{206}/U^{238} and radiogenic lead/total uranium ratios. For this reason, and because in other specimens the correction for total non-radiogenic lead was small, values for ages based on total lead/total uranium are given in parentheses for those samples for which isotopic analyses are not available. However, because most of these ages are based on X-ray fluorescence analyses of total lead and total uranium, it is possible that when precise chemical analyses are available, changes in age of the order of tens of millions of years will result.

Ages based on Pb^{207}/U^{235} ratios are all higher by an average of 87 million years than those obtained as a mean of the Pb^{206}/U^{238} and radiogenic lead/total uranium results, and ages based on the Pb^{207}/Pb^{206} ratio are all higher by an average of 400 million years. These discrepancies are qualitatively, those that would be expected if diffusion of radon (Rn^{222}) had occurred in significant amount.

The high ratio of radiogenic Pb^{207} to radiogenic Pb^{206} in galena and clausthalite of the pitchblende veins may be attributed in part to deficiency of Pb^{206} in the vein system due to loss of Rn^{222} by diffusion. However, the fact that the above ratio is higher than that of lead from pitchblende in the same veins indicates that the ratio of Pb^{207}/Pb^{206} in the pitchblende from which the radiogenic lead in the galena and clausthalite was derived by dissolution was higher than it is in the same pitchblende today. This is to be expected because the greater the Pb^{207}/Pb^{206} ratio in a uranium mineral the greater is its age; in other words the rate of accumulation of Pb^{206} relative to that of Pb^{207} increases with time. The ratio of Pb^{207}/Pb^{206} in pitchblende at the time of its dissolution hundreds of millions of years ago is preserved in the galena and clausthalite deposited at that time.

In epigenetic deposits of the Goldfields region the following factors would facilitate gaseous diffusion of Rn^{222}: (1) pitchblende, the only important mineral of uranium, is composed of extremely small crystallites, so that escape of gas from the crystal lattice to intergranular spaces would be easy; (2) colloform pitchblende is traversed by innumerable syneresis cracks that, despite some filling by other minerals, would serve as conduits for escape of the gas; and (3) there is much evidence of fracturing subsequent to early mineralization, and the fractures have been followed by later mineralization, which would facilitate not only removal of gas but of Pb^{206} that had been deposited in cracks and fissures as a result of radioactive decay of the gas.

Because disparities in ages computed from the different ratios appear to be due largely to diffusion of Rn^{222}, ages determined from the Pb^{207}/U^{235} ratio are used as the standard in subsequent discussion.

Such standard ages vary from 235 million to 1,585 million years. From the ages in Table IX and from the Pb^{207}/U^{235} ages in Table VII, supplemented by uncorrected Pb/U ages from Table IX, it is apparent that there are at least two groups of ages that may well represent distinct periods of mineralization. These two groups are shown in Table X.

TABLE X

Groups of Ages of Epigenetic Deposits

Age in million years	Sample No.	Location
Group I 895	R-547	Leonard adit
905	R-535	Martin L. mine—No. 2 flow
910	R-537	Martin L. mine—No. 1 flow
850	—	Gil group
(850)*	R-630	Ace mine—3rd level west
930	R-352	Nicholson No. 2 deposit
930	R-632	Ace mine—2nd level east; north-south fracture
Group II 235	R-628	Ace mine—1st level east
247	R-608	Nesbitt-Labine mine—2nd level
(240)*	R-629	Ace mine—1st level east
260	—	YY concession (Con group)
272	R-611	Athabasca Uranium Mines Ltd.-GG2
325	R-646	ABC adit
350	R-508	Bar group—Beaverlodge Uranium
(320)*	R-618	Ace mine—between 5th and 6th levels
365	R-609	Nesbitt-Labine mine—1st level
(345)*	R-747	Ace mine—6th level east

*Ages, based on uncorrected Pb/U ratios, would probably be lower by 1 to 4 per cent if corrected for non-radiogenic lead.

The choice of limits of age of these groups is arbitrary. A group of four ages ranging from 590 to 665 million years and another including the period of primary mineralization from 1,385-1,585 million years might also be listed. Other groupings are less distinct and many individual determinations transitional to these groups exist. Studies of the mineralogy of the deposits indicate that at least two, and in some instances three, generations of pitchblende are present. It is doubtful if any of the samples used for age determination were composed of only one generation of pitchblende. It is probable that even in samples of pitchblende from the same part of a deposit there will be a slight difference in 'apparent age' due to different proportions of two generations of pitchblende.

Of the deposits in group I, all but the R-352 and R-632 occur in approximately east-west fractures. In group II about half the deposits are in east-west fractures and the other half in fractures striking slightly west of north. With the single exception of the sample from the YY concession, all deposits represented in group II lie in the angle between the foot-walls of the ABC and St. Louis faults and within an area of about 7 square miles.

It is apparent that in the deposits of the Ace mine, the whole range of ages of epigenetic mineralization is represented. There does not appear to be any relation of age to depth, to distance from the St. Louis fault, or to type or direction of fracture. In general, however, it seems certain that the chalcopyrite-rich pitchblende deposits of the ore zone east of the shaft are distinctly younger than those of the zone west of the shaft. There are also distinctly different ages reflected in the ores of the Martin Lake and Eagle mines.

In group I, five out of the seven deposits are marked by a dominance of colloform pitchblende; in group II, none of the deposits is known to contain colloform pitchblende, but in many of them pitchblende is pseudomorphous after other minerals. In group I, all the deposits with the exception of the Ace mine, 3rd level west, contain more than one generation of pitchblende. Evidence as to presence of significant amounts of more than one generation in deposits of the younger group is either lacking or indefinite.

Although it is expected that some corrections to the ages reported in Tables IX and X will have to be made when chemical analyses are available, it seems probable that these ages do represent a true picture of the time interval over which pitchblende deposition occurred in the Goldfields region. If further evidence proves that the Pb^{207}/Pb^{206} ages are more reliable for these deposits, the general effect would be to increase the absolute ages by about 350 to 900 million years, but the interval of nearly 1,300 million years over which deposition has taken place would remain approximately the same. Corroboration for this long interval is to be found in the textural evidence of shattering and recementing of vein minerals, in the prevalence of at least two generations of pitchblende, and in the abnormal content of Pb^{206} and Pb^{207} in galena and clausthalite of the pitchblende veins.

DETERMINATION OF AGE OF SYNGENETIC DEPOSITS

Despite the large number of syngenetic deposits of thorium and uranium in the region, the radioactive minerals in most of them are so sparsely disseminated that sufficient material for chemical analysis could be segregated from only three of them. Of these the necessary data are available for two samples of monazite and one sample of uraninite and microcline. The monazite samples are from the Oldman River deposit (*See* p. 40) and the 50-TT-62 deposit (*See* p. 32). In both cases textural evidence indicates that the monazite is syngenetic and, therefore, can be used to date the biotite-pegmatite segregations in which it occurs. Monazite from a similar deposit in the Foster Lakes region of Saskatchewan was also analysed, with results reported below. Segregation of monazite from all three deposits was relatively easy to concentrates containing at least 95 per cent monazite.

Chemical analyses for uranium, thorium, and lead were made by S. Abbey of the Geological Survey of Canada and isotopic analyses of the lead were made by R. M. Farquhar at the University of Toronto. Because of some variation in the results of analyses for lead by different methods, check analyses for lead were made by X-ray fluorescence analysis. Values of lead that were used were those mostly approaching a linear function when plotted against intensities of the corresponding Pb L∝ emissions. In the isotopic ratios, correction was made for ordinary lead using the ratio for galena of R-100 (Table VIII) in proportion to the amount of Pb^{204} present. Resulting ages are listed in Table XI.

TABLE XI

Ages of Monazite Concentrates

Sample	Locality	Ages in millions of years			
		Pb^{206}/U^{238}	Pb^{207}/U^{235}	Pb^{207}/Pb^{206}	Pb^{208}/Th^{232}
R-395	Desjarlais Lake	1,705	1,775	1,950	1,615
R-573	Oldman River	1,450	1,780	2,220	1,705
—	Foster Lakes	1,585	1,725	1,920	1,515

It is apparent that in these results as in those from epigenetic deposits ages based on Pb^{206}/U^{238} ratios are lower than those based on Pb^{207}/U^{235}, whereas ages based on the Pb^{207}/Pb^{206} ratio are distinctly higher. As in most similar analyses, the Pb^{208}/Th^{232} ages are somewhat lower than most of those based on lead/uranium ratios. However, approximately 85 per cent of the lead is Pb^{208} and thorium greatly exceeds uranium in amount, therefore, analytical precision is likely to be much greater in the Pb^{208}/Th^{232} ratio than in the others. It is probable that the true ages of the two monazites from the Goldfields region are between 1,700 and 1,800 million years.

Ages determined by G. J. Wasserburg of the University of Chicago on uraninite from the Viking Lake pegmatite are: Pb^{206}/U^{238} 1,850 million years and Pb^{207}/U^{235} 1,880 million years. Ages determined independently by Wasserburg and by H. Shillibeer of the University of Toronto on microcline from the same pegmatite are within 5 per cent of the lead/uranium ages.

SUMMARY

(1) The earliest introduction of uranium in epigenetic deposits probably occurred between 1,500 and 1,600 million years ago and followed, possibly transitionally, earlier deposition of uranium and thorium in syngenetic deposits.

(2) The abnormal amount of radiogenic Pb^{206} and Pb^{207} in galena and clausthalite of the pitchblende veins, together with the great range of apparent ages in individual pitchblende deposits and textural evidence, indicate that most epigenetic deposits have been reopened and reworked over a long period.

(3) Marked grouping of ages suggests that there may have been well-defined periods of mineralization in the periods 1,400-1,600, 850-950, and 230-350 millions of years ago. The variation in age within the groups and ages falling between groups are probably due to varying proportions of pitchblende of two or more different ages in the various samples.

(4) Latest reworking of epigenetic deposits appears to have occurred in Palæozoic time. With one exception, deposits of this age lie within a small area in the angle between the foot-walls of the St. Louis fault and the ABC fault.

(5) Pitchblende occurring in the deposits whose ages fall in the 850-950 million year group is predominantly colloform, whereas only massive pitchblende occurs in deposits of the 230-350 million year group.

(6) It seems probable that the oldest generation of pitchblende in the Goldfields region is the same age as that of the Eldorado mine, Great Bear Lake. It may also be significant that monazite of the region appears to be the same age as one from Foster Lake, and by comparison with Pb^{207}/Pb^{206} ages, with a deposit in a pegmatite of Charlebois Lake area.

CHAPTER VI

GENESIS AND CLASSIFICATION OF EPIGENETIC URANIUM DEPOSITS

SUMMARY AND CONCLUSIONS

In this chapter, evidence indicative of conditions under which epigenetic uranium deposits of the region were formed is summarized and interpreted. Results of additional work on temperatures of deposition and on the probable nature of the mineralizing solutions are also presented.

The following conclusions are reached:

(1) Some epigenetic deposits were formed only slightly later than syngenetic deposits.

(2) The epigenetic deposits were reworked at intervals over a very long interval of time. Most recent reworking may have been late in the Palæozoic Era.

(3) Epigenetic deposits have been formed chiefly by cavity filling of fissures, breccias, fracture zones, and similar dilatant systems, suggestive of relatively shallow depths. Replacement deposits occur in carbonate host rocks and in part in the early phases of mineralization of feldspathic mylonites. Replacement of early vein minerals is common. Supergene alteration is an important factor in only two major deposits.

(4) That early pitchblende was deposited largely from colloidal sols is indicated by its texture; later pitchblende was probably deposited from true solutions. Mineral evidence, corroborated by some preliminary experimental evidence, suggests that most of the deposition may have been from aqueous solutions containing high concentrations of CO_2, and if so uranium was probably transported as a complex carbonate.

(5) Maximum and minimum indicated temperatures of deposition are 475 degrees and 120 degrees Centigrade. It is probable that much of the mineral deposition took place between 250 and 350 degrees Centigrade.

(6) Persistence of uranium values to depths already known, together with widespread lateral occurrence of the element and lack of change in mineralogy with depth, indicate that pitchblende ores will be found over a vertical range in excess of 2,500 feet.

(7) Deposits of the region are classed with the complex type of Everhart and Wright (1953) and specifically they are grouped with those of the Eldorado mine and Shinkolobwe. It is probable that in these deposits conditions of temperature and pressure varied widely over a long period of spasmodic deposition. Their general characteristics, however, approximate those of the leptothermal class of Graton.

(8) Although some components of epigenetic and syngenetic deposits are foreign to the enclosing rocks and must, therefore, have been introduced, there is no decisive evidence of the origin of the solutions from which these components were deposited.

RELATION OF EPIGENETIC TO SYNGENETIC DEPOSITS

The monazite of two samples from syngenetic deposits is slightly older than all minerals whose age is known except the pitchblende of a few concentrates from epigenetic deposits. It is possible, therefore, that syngenetic deposition changed transitionally into epigenetic mineralization without a pronounced break in time.

The following criteria support the hypothesis of a syngenetic-epigenetic transition: (1) the two types of deposit overlap in spatial distribution; (2) rock textures and mineral distribution suggest that the radioactive migmatites and granites developed by metasomatic processes rather than by *lit par lit* injection; (3) in two deposits, criteria of both syngenetic and epigenetic mineralization are present without structural or textural evidence indicative of a time interval between the two; (4) in syngenetic deposits, thorium and rare earth minerals occur with early feldspar, whereas much of the uranium is concentrated as uraninite in late quartz and biotite; (5) in some epigenetic deposits crystals of urania occur in early quartz and oligoclase; (6) rutile, octahedrite, and apatite occur in syngenetic and epigenetic deposits. There is evidence in some epigenetic deposits that the effects of early transitional mineralization have been obscured during a later period of hydrothermal solution and deposition.

Thorium and rare earth elements are present in important amounts in most syngenetic deposits, but in epigenetic deposits no analyses of pitchblende exceed 0·1 per cent combined thorium and rare earth oxides. This suggests some discontinuity in deposition. As indicated above, however, thorium and rare earths predominate in older facies of syngenetic deposits whereas uranium is more abundant in the younger facies. In epigenetic deposits it is possible that, with resurgence of uranium deposition in relatively great amount as pitchblende, residual thorium and rare earths are so dispersed that they form only a trace of the whole. The presence of thorium and rare earths in trace amounts in epigenetic deposits, together with the presence of titanium and phosphorus (in apatite) in both types of deposit supports other evidence pointing to possible transition between epigenetic and syngenetic deposition of uranium.

DURATION OF MINERALIZATION

It is apparent from the ages of pitchblende concentrates given in Chapter V that pitchblende mineralization must have taken place intermittently over a very long period. Textural evidence shows that there are at least two, and probably three, generations of pitchblende in some deposits (*See* Figures 4, 21, 22, 30, 31, and 47). The presence in the vein of shattered and recemented pitchblende (*See* Figure 28) and of rock fragments coated with pitchblende on one side only indicates that movement occurred during the period of mineralization.

Less direct evidence of changing conditions of deposition is the occurrence of chalcopyrite exsolved from bornite (*See* Figure 29), which occurs in gangue cementing shattered pitchblende. This suggests a resurgence of mineralization at a temperature above 475°C., followed by relatively rapid cooling (*See* Edwards, 1947).

There is much additional evidence of changes in conditions of deposition. Dissolution of colloform pitchblende and deposition of later massive pitchblende is illustrated in Figure 31. Two generations of pitchblende, the earlier one colloform, and the later massive, are illustrated in Figures 21 and 31. Early colloform pitchblende is seamed by hematite, but later colloform pitchblende and most of the massive pitchblende are intergrown with sulphides and the latest massive pitchblende is usually free from other metallic minerals. Replacement of one mineral by another, indicating solution changes, is common; in many cases there are reversals, where the replaced mineral of one occurrence is the replacing mineral of another. Finally, the abnormal but varying proportion of radiogenic lead found in galena and clausthalite indicates re-solution after long periods of radioactive decay.

Evidence given above indicates that uranium was deposited, dissolved, and redeposited at intervals over a very long period of geological time rather than during a single metallogenic epoch.

MINERALIZATION OF EPIGENETIC DEPOSITS

The principal process of mineralization of the epigenetic deposits was deposition in open space. Deposits themselves are fissure veins, cymoid veins, and breccia-filled openings. Smith (1952) and Hale (1953) have illustrated evidence indicating that ore deposition took place largely in dilatant zones.

Ore textures also are dominantly those due to deposition in open space. Quartz and calcite exhibit comb texture in many deposits and pitchblende commonly occurs as rims on rock fragments and earlier minerals (*See* Figures 9, 32, 33, 47, and 50). These rims have rotund outer surfaces indicative of growth in open space. Finally, there are residual, crystal-lined vugs (as distinguished from solution cavities) in two deposits.

Many deposits formed subsequent to consolidation of rocks of the Athabasca series. Christie and Kesten (1949, p. 30) and Smith (1952, p. 111) believe that there was only a shallow rock cover above existing uranium deposits in the post-Athabasca period.

Replacement was the principal process only at the Nicholson No. 4 deposit, but has played some part in other deposits in dolomitic quartzite and dolomite. The occurrence of pitchblende in wall-rocks at the Ace, Rix, and Gunnar mines is also due in part to replacement (*See* Figures 11 and 42). Replacement of early vein minerals by later ones is widespread but on a relatively minor scale. Pitchblende replacing calcite is illustrated in Figures 30 and 36, and it has also been observed corroding euhedral terminations of comb quartz. Calcite replacing pitchblende is illustrated in Figure 31. Quartz replacing calcite is illustrated in Figure 10, and in other occurrences euhedral crystals of quartz are corroded and rounded by calcite. Chlorite replacing calcite is shown in Figure 12.

Supergene alteration of uranium deposits in the Goldfields region is not important because earlier supergene products have been removed by glaciation and the rate of post-glacial alteration has been retarded by the cold climate. In comparison with quartz-sulphide deposits of the region, however, the pitchblende-calcite deposits are exceptionally vulnerable to alteration by meteoric solutions.

Supergene alteration has played an important role in the deposits of the Ed-Bon group of Gunnar Gold Mines Limited, the Bolger group, and those of zone A in Fish Hook Bay. At Bolger, surface waters have leached primary pitchblende and deposited secondary uranium minerals in the overlying talus on the hill slope. At the Ed-Bon and Fish Hook Bay deposits, however, supergene minerals extend to depths of more than 200 feet below the present level of Lake Athabasca. At the Ed-Bon group this is probably due to circulating artesian waters (*See* p. 34).

NATURE OF MINERALIZING SOLUTIONS

The nature of the solutions from which the epigenetic deposits were derived may be inferred in part from the resulting mineral assemblage. Corroborative evidence is available as a result of preliminary laboratory experiments.

Although the paragenetic sequence indicates that there must have been wide variations in the concentrations of various ions in solution, the presence of calcite at almost all stages of mineral deposition is significant because in most deposits both calcium and the carbonate radical must have been introduced. It seems probable, therefore, that most of the vein-forming elements were transported as carbonates. The solubility of most cations in carbonate solutions increases with increasing pressure of CO_2 and, conversely, precipitation is most likely to occur where the pressure is decreased. It is in precisely such low pressure or dilatant zones that mineralization has occurred in large measure.

In an autoclave at 200°C. and under CO_2 pressure of 180 pounds per square inch calcite and pitchblende are taken into aqueous solution in significant amount. Moreover, addition of small amounts of sodium as the bicarbonate markedly increased solubility of pitchblende. It is possible that, as Gruner (1952) reported from his studies of sulphate solutions, ferrous iron might also act as a catalyst in precipitation of UO_2 from carbonate solutions. Lacking evidence to the contrary, therefore, it is concluded that epigenetic deposits were formed largely from carbonate solutions.

Bastin (1950, pp. 26, 27) lists five textural features that suggest colloidal deposition. Text-book examples of four out of the five are illustrated by the following figures in this report: (1) rotund or spheroidal forms (*See* Figures 14, 25, 28, 32, 33, 34, 35, and 48); (2) syneresis or shrinkage cracks (*See* Figures 4, 9, 37, 48); (3) pellet texture (*See* Figure 47); (5) interference surfaces (*See* Figure 34). His fourth criterion, framboidal texture, is represented by the way in which the 'pellets' of Figure 47 are concentrated in spherical groupings with sharply defined perimeters that are independent of the coarsely crystallized calcite in which they occur. In terms of Bastin's criteria, therefore, it seems probable that much of the pitchblende in the Goldfields region was formed by coagulation of colloidal sols.

It is thought, however, that the massive pitchblende crystallized from true solutions. This massive material lacks all textural features of colloidal deposits except that it is fine grained. It occurs as rims on earlier colloform pitchblende (*See* Figure 47), replacing calcite along cleavage planes (*See* Figure 36), and intergrown with sulphides and gangue (*See* Figures 17, 18, 19, and 21). Obviously, the dispersion medium of a sol must be a concentrated solution of the disperse phase. Therefore, concentrated normal solutions are likely to persist after coagulation of a sol and from them massive pitchblende would be precipitated under suitable conditions. It is probable, however, that much of the massive pitchblende was deposited long after the colloform variety and some of it may have been precipitated from solutions whose uranium content was derived from solution of earlier colloform pitchblende. It is probable that these later solutions also deposited sulphides or selenides. The fact that lead sulphides and selenides contain abnormal amounts of radiogenic-lead isotopes Pb^{206} and Pb^{207} suggests that this lead was derived by solution of pitchblende that had been consolidated over the very long periods necessary for accumulation of the radiogenic lead. These solutions, hundreds of millions of years later than the original ones, may have differed considerably in composition, but like all the others they deposited calcite.

TEMPERATURES OF DEPOSITION OF HYDROTHERMAL DEPOSITS

Because pitchblende, the principal ore mineral, is thought to have been deposited from colloidal solutions (*See* p. 96), and because temperature is a relatively minor factor in coagulation of such solutions, it is necessary to turn to other minerals and mineral components for evidence as to temperatures at which these deposits were formed. For this purpose the following indicators are considered briefly: associated minerals, ex-solution textures, decrepitation temperatures, and oxygen-isotope ratios of calcite.

Associated Minerals

A general sequence from an essentially oxide suite (hematite and pitchblende with minor magnetite, anatase, and rutile) to a sulphide environment, followed locally by selenides and native copper, suggests that temperatures initially may have been high, *circa* 500°C., and that they decreased to about 150°C. or lower. Evidence adduced in Chapter V indicates that mineralization took place intermittently over a very long period. It is quite probable, therefore, that there were reversals in the thermal gradient.

Specular hematite occurs later in the paragenetic sequence than massive hematite and is largely confined to vein material. Although Christie (1953) cites its presence as being indicative of high temperatures, Rastall (1923) and Kato (1923) show that it may also occur in shallow deposits at relatively low temperatures.

Bowie (1953) has pointed out that the presence of goethite in Nicholson ores indicates a temperature of deposition of less than 130°C. and records that some hisingerite, arsenides, and sulphides formed after goethite, and, therefore, at or below 130°C. The writer's observations suggest that most sulphides, arsenides, and pitchblende are earlier than goethite. This is illustrated by Figure 8, showing goethite replacing calcite along cleavage planes, and by Figure 5 from the same slide showing pitchblende being replaced by the same generation of calcite in which some sulphides and sulpharsenides occur.

Evidence of Ex-solution Textures

High temperature of deposition is suggested by ex-solution textures of chalcopyrite in bornite (*See* Figure 29), which, according to Edwards (1947, p. 84), indicates that the deposit was formed above 475°C. and that it cooled rapidly. Bowie (1953) cites the occurrence of blades of specular hematite with ex-solution bodies of magnetite as evidence of very high temperature of initial deposition. The writer, however, has observed in the same deposit evidence of pseudomorphous replacement of hematite by magnetite (*See* Figure 7), which according to Gruner (1926) could take place at temperatures as low as 150°Centigrade.

DECREPITATION TEMPERATURES

Dr. M. H. Haycock tested a suite of ten samples of calcite and nine samples of quartz by the decrepitation method described by Scott (1948). Temperatures of formation as determined by these tests together with other relevant data are listed in Table XII.

TABLE XII

Palæotemperatures of Quartz and Calcite

Sample No.	Description	No. of runs	Ave. temp. Degs. C.
R 10	Coarse-grained calcite from centre of vein; Martin Lake mine	5	304
R 149	Coarse-grained calcite cementing pitchblende; Ace mine	4	345
R 150	Late calcite cementing pitchblende that replaced earlier calcite; Eagle mine	4	309
R 163	Calcite cementing pitchblende-encrusted rock; Ace mine	4	342
R 218	Coarse-grained calcite with selenides; Martin Lake mine	4	291
R 313	Mixed calcite and dolomite cementing colloform pitchblende; Leonard adit	4	351
R 353	Post-pitchblende calcite; Nicholson No. 2 deposit	4	299
R 461	Calcite containing massive pitchblende; Nesbitt-Labine mine	3	289
R 631	Calcite cementing massive pitchblende; Ace mine, 3rd level	2	348
R 635	Calcite from barren zone; Ace mine	2	335
R 26	Comb quartz in which urania crystals occur; Eagle group at surface	3	390
R 148	Massive quartz with pitchblende; Ace mine, 1st level	2	400
R 214	Quartz associated with gold; Box mine	4	352
R 314	Quartz with pitchblende and calcite; Leonard adit	4	364
R 340	Quartz associated with arsenopyrite; Allgold Bay	3	234
R 396	Comb quartz, amethyst in part, from pitchblende vein; Fold Lake	4	356
R 396	Greasy quartz with sulphides, from the same pitchblende vein as R 396; Fold Lake	4	361
R 635	Cherty quartz from barren zone; Ace mine, 2nd level	5	256
R 638	Quartz with pitchblende from ore zone; Ace mine, 2nd level	4	371

The calcite specimens were taken from the centre of the veins because it is impossible to obtain pure calcite from the vein walls and wall-rocks. Most of this calcite belongs to phases 5 and 6 (*See* Figure 2) and represents material late in deposition and, therefore, presumably of relatively low temperature.

It will be noted that samples from the Ace mine together with those from the Leonard series adit fall in the range 335°-351°C. and for those associated with pitchblende the range is 342°-351°C. The remaining samples representing Martin Lake, Eagle, and Nesbitt-Labine mines fall in a lower temperature range, from 289°-309°C. In the Ace mine, calcite from the ore zones is all higher in temperature than the one sample from a barren vein.

Quartz samples represent a more scattered group of deposits. Two of them, R 214 and R 340, represent non-radioactive gold veins at 352° and 234°C., one, R 635, is from a barren zone in a pitchblende deposit at 256°C., and the remainder are associated with pitchblende at temperatures ranging from 356°-400°C. Again temperatures of gangue from pitchblende ores are all higher than the one sample from a barren zone. The relatively higher temperatures of the quartz compared with those of calcite corroborate the paragenetic sequence as determined by textural relations.

OXYGEN ISOTOPE RATIOS

By arrangement with the New York office of the Raw Materials Division of the United States Atomic Energy Commission, samples of pitchblende and calcite were supplied by the writer to be used in experimental palæotemperature work being done at the Argonne National Laboratory. Research has shown that palæotemperatures of some oxygen compounds can be related to the oxygen isotope ratio $0^{18}/0^{16}$. Although data are insufficient as yet to permit interpretation of palæotemperatures of pitchblende by this method, Dr. H. R. Hoekstra (private communication, January 1954) reports as follows on the three calcite samples:

"Interpretation of the results on the calcite samples give the following temperatures:

R 535—150°C.
R 547—190°C.
R 631—120°C.

These values are subject to some uncertainty due to lack of information as to the isotopic content of the precipitating solution. In calculating the above temperatures, I have assumed the $0^{18}/0^{16}$ ratio of the solution to be equal to that of sea water. Several workers have made estimates of juvenile water composition which are somewhat higher in 0^{18}, but I feel the maximum deviation to be expected would be three parts per thousand. The calculated temperatures at this 0^{18} composition would be 190°, 250°, and 150° respectively ...."

It may be noted that calcite of R 535 is taken from the same vein as that of R 218 (reported by Haycock), and that calcite of R 547 is from the same lens as R 313.

SUMMARY

The evidence of uranium mineralization in pegmatites of approximately the same age as the hydrothermal uranium deposits, together with the presence of deposits having characteristics of both pegmatites and hydrothermal veins, suggests that initial temperatures of deposition in the hydrothermal veins were probably high, possibly of the order of 500°Centigrade.

The data recorded above do not provide conclusive evidence as to temperatures prevailing during uranium mineralization. It seems probable, however, that deposition started at high temperatures and ended at low temperatures and that some reversals of thermal gradient did occur. The bulk of the pitchblende was deposited relatively early in the paragenetic sequence, but because a weighted average of indicated temperatures favours the lower range, it seems probable that most pitchblende was deposited between 250° and 350°C., that of phase 5 being deposited below 200°Centigrade.

VERTICAL EXTENT OF DEPOSITS

The greatest known vertical extent of a single ore zone in the region is slightly more than 800 feet. Within this vertical distance there is no discernible systematic variation in the mineralogy. The only systematic geochemical change is an apparent increase of vanadium with depth. It is interesting to note, for instance, that an uncommon and presumably low temperature mineral such as clausthalite occurs with pitchblende in outlying veins of the Ace mine both at the surface and below the 800-foot horizon. When neighbouring surface deposits whose elevation is 250 feet above the surface of this deposit are considered there is no change in mineralogy over a vertical range of 1,100 feet. It seems reasonable to infer, therefore, that any changes with depth in conditions governing precipitation of pitchblende have been so slight that they cannot be discerned over a vertical range of 1,100 feet.

Three other factors that indicate probable extension of pitchblende deposits to considerable depths are: (1) the great length and great apparent displacement of the three major faults, St. Louis, ABC, and Black Bay, in whose complementary fractures some of the ore deposits occur; (2) the occurrence in the region of nearly contemporaneous syngenetic and epigenetic uranium deposits; and (3) the lack of exposures of any large mass of igneous rocks in the region that might be contemporary with, or later than, the uranium deposits. If Everhart and Wright's (1953) classification of Goldfields deposits with those of Great Bear Lake is valid, then reports of projected development of five levels below the present 1,300-foot depth at the Eldorado mine augur well for the Beaverlodge deposits. It seems probable that pitchblende in the Goldfields region will be found to persist to depths of 2,500 feet or more.

CLASSIFICATION OF EPIGENETIC DEPOSITS

Under the description "Deposits of the Lake Athabaska District", deposits of the Goldfields region are included in a survey by Everhart and Wright (1953) of pitchblende deposits in thirteen areas throughout the world. They conclude that most pitchblende deposits belong to one of two types: (1) complex carbonate-nickel-cobalt-native silver ores containing a wide variety of metals in meta-sediments; and (2) simple siliceous-pyrite-galena type containing a few metals and some fluorite in felsic igneous rocks. Although nickel-cobalt minerals are restricted to a small part of the region and although silver has been positively identified from only one deposit, the Goldfields deposits otherwise conform to type (1). They occur principally in other than felsic igneous rocks, the dominant gangue mineral is calcite, and a fairly wide list of metallic elements is represented. In Figure 3 of the above paper, based on age, host rocks, and metallic content, deposits of the Goldfields region are grouped with those of Great Bear Lake and Shinkolobwe. Probably the most distinctive feature of the Goldfields deposits, however, is the relative abundance of oxides and oxygen salts and the widespread but very sparse dissemination of sulphides, selenides, and native metals. The presence of selenium and vanadium with uranium at Goldfields is an association that is also common in carnotite-type deposits of the Colorado Plateau. Selenides with pitchblende are known from the Montreal River district, Ontario, and from the Harz Mountains of Germany.

Dominant minerals in these deposits are not among the indicator minerals that may be used to classify the deposits according to temperature and depth of formation. The differing temperatures of formation indicated suggest that there has been telescoping of two or more hydrothermal classes. In view of the long time interval during which intermittent deposition has taken place, it is likely that no one set of conditions did prevail. However, the criteria of vein filling with replacement in carbonate rocks; coarse banding of veins with some vugs and angular fragments of wallrocks; presence of carbonate rich in manganese, and of plentiful specularite in the veins; and absence of exposures of genetically associated igneous rocks are all indicators of the leptothermal class of Graton (1933).

GENETIC ASSOCIATION OF URANIUM DEPOSITS

Evidence adduced in this and earlier chapters indicates that syngenetic deposits are probably the products of metasomatism and epigenetic deposits are the products of hydrothermal solutions. Because there is evidence of transition from metasomatic to hydrothermal deposits, it is probable that solutions giving rise to both emanated from the same source. There is little evidence in the Goldfields region, however, to link the mineralizing solutions to any igneous rock or to any particular period of orogeny. Certainly the evidence appears to rule out genetic relationship to any igneous rocks exposed in the region and the time interval during which intermittent mineralization took place may well include more than one period of orogeny.

There is general agreement in age of the oldest deposits in the Goldfields region with those of the Charlebois Lake area and Eldorado mine. Genetic association of the Goldfields uranium deposits might be analogous to that of deposits in these areas. The syngenetic deposits of the Charlebois Lake area occur mainly in metamorphic rocks but are consistently parallel with the margins of masses of granite. Mawdsley (1950, p. 19) states "The pegmatite granite is mineralogically similar to and most of it occurs along the margins of the granite masses. It very evidently is an end phase of the emplacement of these large masses of granite and granite gneiss. Some of the pegmatite granite is pronouncedly radioactive and these facies show evidence of the concentration along with uraninite, of more than the average quartz and molybdenite, and possibly other substances, which have to a large extent replaced the more usual pegmatite granite. This migration of material and replacement probably took quite an appreciable time of the very long interval required to consolidate the pegmatite granite at depth within the earth's crust, close to a large, hot, consanguine granite mass...". These syngenetic deposits lie at the eastern end of the belt of radioactive deposits of which the Goldfields region forms a part.

Kidd and Haycock (1935) found the evidence bearing on the origin of the mineralizing solutions at Great Bear Lake was not conclusive, but suggest that the solutions from which pitchblende was deposited were co-magmatic with the Dowdell Point granite. It is interesting to note that the age of these deposits falls in the range 1250-1368 m.y. by Pb^{206}/U^{238} ratio and 1330-1430 m.y. by Pb^{207}/Pb^{206} ratio, and that other nearby deposits at Hottah Lake gave ages ranging from 333-350 m.y. and 460-580 m.y. respectively. Moreover, there is a single determination for the Eldorado mine of 650 m.y. It seems probable, therefore, that at Great Bear Lake as in the Goldfields region, mineralization took place intermittently over a long time interval.

The uranium deposits of these two districts, both of which have something in common with the Goldfields region, are tentatively related to granites of magmatic origin. No similar rock has yet been recognized in the Goldfields region to which the uranium deposits might be genetically related.

CHAPTER VII

REFERENCES

No attempt has been made to provide an exhaustive bibliography. The following list includes only those papers to which reference is made in the text. Additional references on geology of the region may be found in Alcock (1936a) and Christie (1953).

Alcock, F. J. (1936a): Geology of the Lake Athabaska Region, Saskatchewan; Geol. Surv., Canada, Mem. 196.

———(1936b): The Gold Deposits of Lake Athabaska; Trans. Can. Inst. Min. and Met., vol. 39, pp. 531-546.

Allan J. A., and Cameron, A. E. (1922): An Occurrence of Iron on Lake Athabaska; Fourth Ann. Rept., Mineral Resources of Alberta, pt. 2.

Allen, R. B. (1950): Fracture Systems in the Pitchblende Deposits of the Beaverlodge Lake Area, Saskatchewan; Trans. Can. Inst. Min. and Met., vol. LIII, pp. 299-300.

Barnes, W. H., and Qurashi, M. M. (1952): Unit Cell and Space Group Data for Certain Vanadium Minerals; Am. Min., vol. 37, pp. 407-422.

Bastin, E. S. (1950): Interpretation of Ore Textures; Geol. Soc. Amer., Mem. 45.

Blake, D. A. W. (1951): Forget Lake Map-area, Saskatchewan; Geol. Surv., Canada, Paper 51-7.

———(1952): Nevins Lake Map-area, Saskatchewan; Geol. Surv., Canada, Paper 52-1.

Bowie, S. H. U. (1953): Thucholite and Hisingerite-Pitchblende Complexes from Nicholson Mine, Saskatchewan, Canada; United Kingdom Geol. Surv. and Mus., Atomic Energy Division, Report No. 141, July 1953.

Brooker, E. J., and Nuffield, E. W. (1952): Studies of Radioactive Compounds: IV. Pitchblende from Lake Athabaska, Canada; Am. Min., vol. 37, pp. 363-385.

Christie, A. M. (1953): Goldfields-Martin Lake Map-area, Saskatchewan; Geol. Surv., Canada, Mem. 269.

Christie, A. M., and Kesten, S. N. (1949): Goldfields and Martin Lake Map-areas, Saskatchewan (Preliminary Account); Geol. Surv., Canada, Paper 49-17.

Cohen, W. (1953): A Note on Pitchblende and Uraninite; U. S. Atomic Energy Comm., Tech. Inf. Service, RME-3046, pp. 58-61.

Collins, C. B., Lang, A. H., Robinson, S. C., and Farquhar, R. M. (1952): Age Determinations for Some Uranium Deposits in the Canadian Shield; Proc. Geol. Assoc. Can., 1952, pp. 15-41.

Collins, C. B., Farquhar, R. M., and Russell, R. D. (1954): Isotopic Constitution of Radiogenic Leads and the Measurement of Geological Time; Bull. Geol. Surv., Amer., vol. 65, pp. 1-22.

Cooke, H. C. (1937): Preliminary Report, Goldfields Area, Saskatchewan; Geol. Surv., Canada, Paper 37-3.

Dawson, K. R. (1951): A Petrographic Description of Wall-rocks and Alteration Products Associated with Pitchblende-bearing Veins in the Goldfields Region, Saskatchewan; Geol. Surv., Canada, Paper 51-24.

Edwards, A. B. (1947): Textures of the Ore Minerals and their Significance; Australia Inst. Min. Met., Melbourne, 185 pages.

Ellsworth, H. V. (1928): Thucholite, a Remarkable Primary Carbon Mineral from the Vicinity of Parry Sound, Ontario; Am. Min., vol. 13, pp. 409-411.

———(1950): Lead-uranium Ratios of Two Saskatchewan Pitchblendes; Rept. Comm. on Measurement of Geologic Time, 1949-50, Washington, D.C.

Everhart, D. L., and Wright, R. (1953): The Geologic Character of Typical Pitchblende Veins; Ec. Geol., vol. 48, pp. 77-96.

Fahey, J. J., Robinson, S. C., and Schaller, W. T. (1954): Description of Nolanite (in preparation for 1955 publication).

Fraser, J. A., and Robinson, S. C. (1954): Preliminary Description of the Geology and Mineralogy of the Gunnar Deposit, Saskatchewan; Can. Min. Jour., vol. 75, pp. 59-62.

Graton, L. C. (1933): The Depth-zones in Ore Deposition; Ec. Geol., vol. 28, pp. 513-555.

Gruner, J. W. (1926): Magnetite-Martite-Hematite; Econ. Geol., vol. 21, pp. 375-393.

———(1952): New Data of Syntheses of Uranium Minerals; U.S. Atomic Energy Commission, Technical Information Service, RMO-983.

Hale, W. E. (1953): Geology of the Black Bay Map-area, Northern Saskatchewan, with reference to the Pitchblende Occurrences; Queen's University, unpublished Ph.D. thesis.

———(1954): Black Bay Map-area, Saskatchewan (Preliminary Account); Geol. Surv., Canada, Paper 53-14.

Hawley, J. E., and Rimsaite, Y. (1953): Platinum Metals in some Canadian Uranium and Sulphide Ores; Trans. Can. Inst. Min. and Met., vol. 56, pp. 19-26.

Hogarth, D. D. (1951): Studies of Radioactive Compounds: II: Metazeunerite, Uranophane, Kasolite, and Cuprosklodowskite in Canada; Am. Min., vol. 36, pp. 411-414.

Hoiles, R. G. (1953): New Trends in Prospecting for Uranium Ore, St. Mary's Channel, Saskatchewan; Can. Min. Jour., vol. 74, pp. 83-86.

Kato, T. (1923): Editorial; Econ. Geol., vol. 18, pp. 695-696.

Kerr, P. F. (1950): Mineralogical Studies of Uraninite and Uraninite-bearing Deposits; Int. Tech. Rept. Raw Materials Operations, U.S. Atomic Energy Commission.

———(1951): Natural Black Uranium Powder; Science, vol. 114, pp. 91-92.

Kerr, P. F., and Kulp, J. L. (1952): Precambrian Uraninite, Sunshine Mine, Idaho; Science, vol. 115, pp. 86-88.

Kidd, D. F., and Haycock, M. H. (1935): Mineragraphy of the Ores of Great Bear Lake; Bull. Geol. Soc. Am., vol. 46, pp. 879-960.

Kulp, J. L., Bate, G. L., and Braecher, W. S. (1953): Present Status of the Lead Method of Age Determination; U.S. Atomic Energy Comm., Technical Information Service, NYO-6200.

Lang, A. H. (1952): Canadian Deposits of Uranium and Thorium; Geol. Surv., Canada, Econ. Geol. Series No. 16.

Marble, J. P. (1950): Summary Report of the Committee on the Measurement of Geologic Time for 1949-1950; U.S. Nat. Research Council.

Mawdsley, J. B. (1950): The Geology of the Charlebois Lake Area; Saskatchewan Geol. Surv., Precambrian Geology Series, Report No. 5.

Nier, A. O., Thompson, R. W., and Murphy, B. F. (1941): The Isotopic Constitution of Lead and the Measurement of Geological Time; Phys. Rev., vol. 60, pp. 112-116.

Osborne, F. F., and Archambault, M. (1950): Hisingerite from Montauban-les-Mines; Naturaliste Canadien, vol. 77, pp. 283-290.

Rastall, R. H. (1923): Metallogenetic Zones; Econ. Geol., vol. 18, pp. 105-121.

Robinson, S. C. (1950): Mineralogy of the Goldfields District, Saskatchewan (Interim Account); Geol. Surv., Canada, Paper 50-16.

———(1952a): The Occurrence of Uranium in the Lake Athabasca Region; Can. Inst. Min. and Met. Bull., vol. LV, pp. 150-153.

———(1952b): Autoradiographs as a Means of Studying Distribution of Radioactive Minerals in Thin Section; Am. Min., vol. 37, pp. 544-547.

Robinson, S. C., and Brooker, E. J. (1952): A Cobalt-Nickel-Copper Selenide from the Goldfields District, Saskatchewan; Am. Min., vol. 37, pp. 542-544.

Scott, H. S. (1948): The Decrepitation Method Applied to Minerals with Fluid Inclusions; Econ. Geol., vol. 43, pp. 637-654.

Silman, J. F. B. (1954): Native Tin Associated with Pitchblende at Nesbitt Labine Uranium Mines; Am. Min., vol. 39, pp. 529-531.

Smith, E. E. N. (1952): Structure, Wall-rock Alteration and Ore Deposits at Martin Lake, Saskatchewan; unpublished Ph.D. thesis, Harvard University.

Smith, F. G., and Kidd, D. J. (1949): Hematite-Goethite Relations in Neutral and Alkaline Solutions under Pressure; Am. Min., vol. 34, pp. 403-412.

Tyrrell, J. B. (1896): Report on the Country Between Athabasca Lake and Churchill River; Geol. Surv., Canada, Ann. Rept., 1894, vol. VIII, pt. D.

Wickman, F. E. (1944): Some Graphs on the Calculation of Geological Age; Sveriges Geol. Undersökning, Arsbok 33, pp. 1-8.

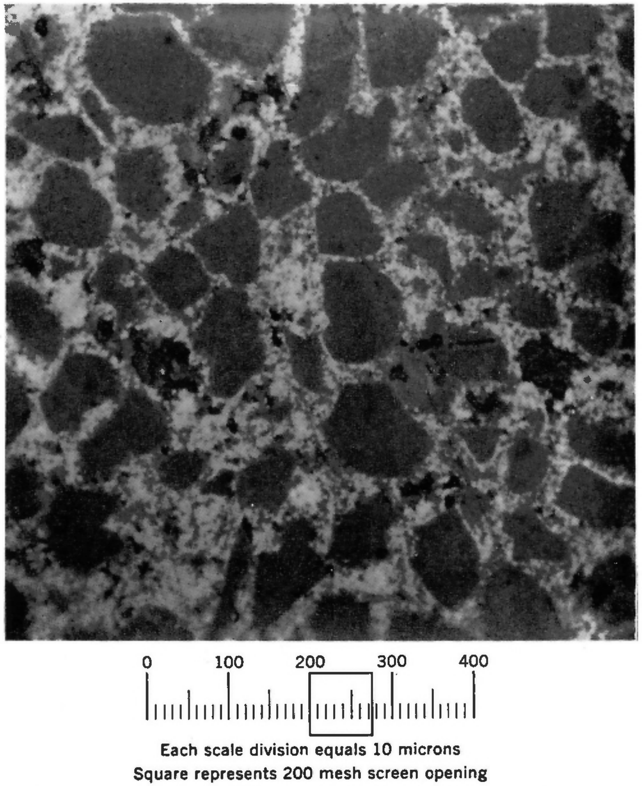

Figure 3. Reflected light. Pitchblende (light grey) and calcite (medium grey) cementing brecciated quartz (dark grey). (106635)

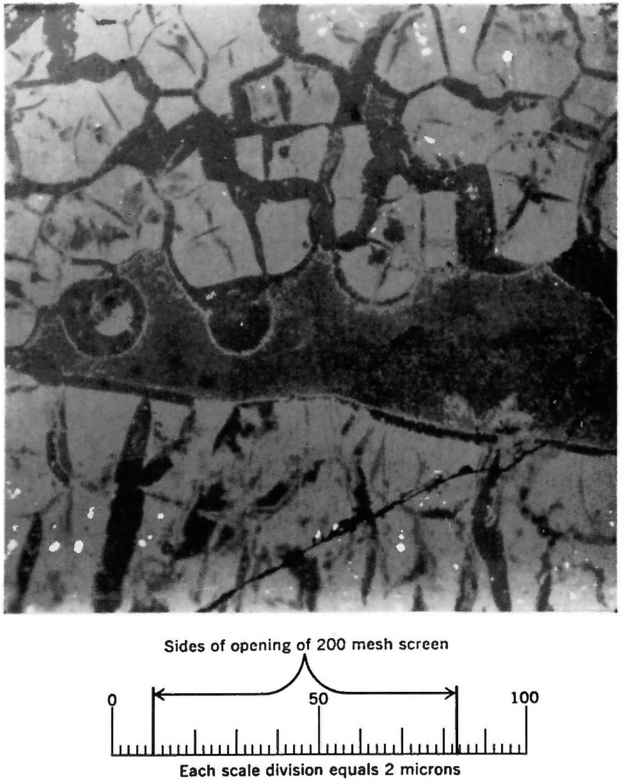

Figure 4. Reflected light. Syneresis cracks in colloform pitchblende (grey) filled by calcite (black) containing disseminated younger pitchblende. (106636)

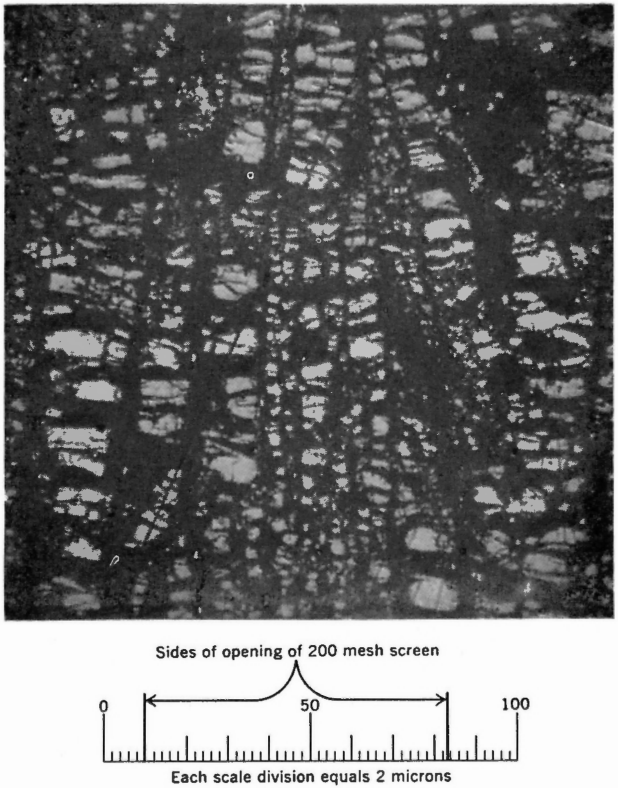

Figure 5. Reflected light. Residual pitchblende (grey) replaced by calcite (dark grey). (106637)

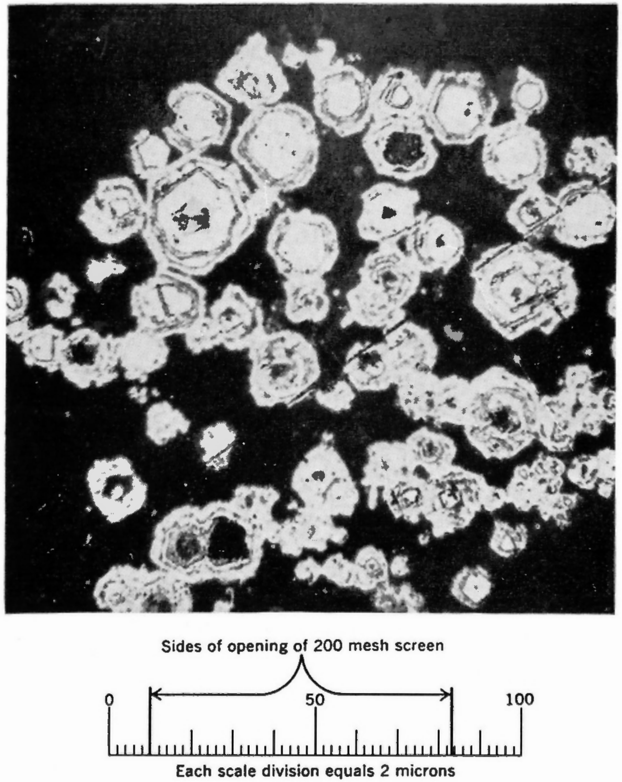

Figure 6. Reflected light. Composite subhedral grains of pyrite and ullmannite (light grey) in calcite (black). (106638)

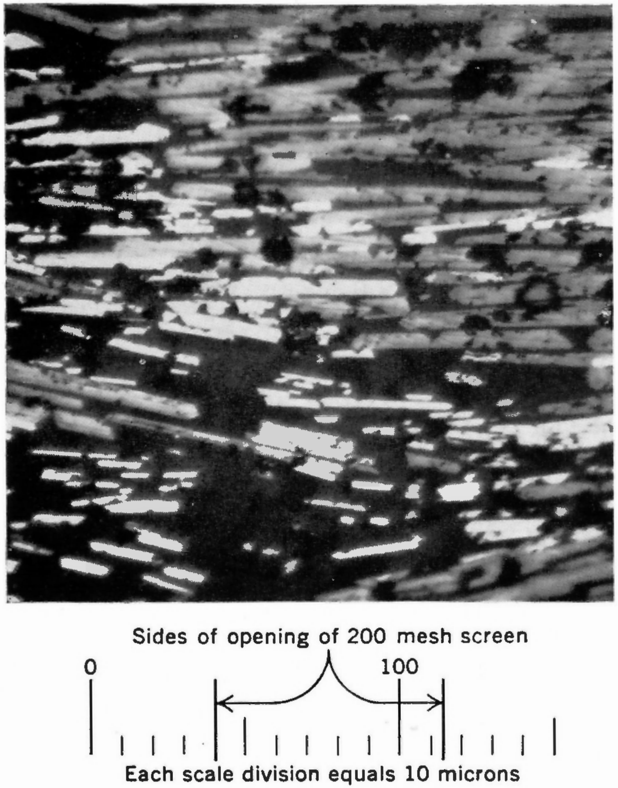

Figure 7. Reflected light. Blades of hematite (white) and pseudomorphous magnetite (grey) in dolomite (dark grey). (105440)

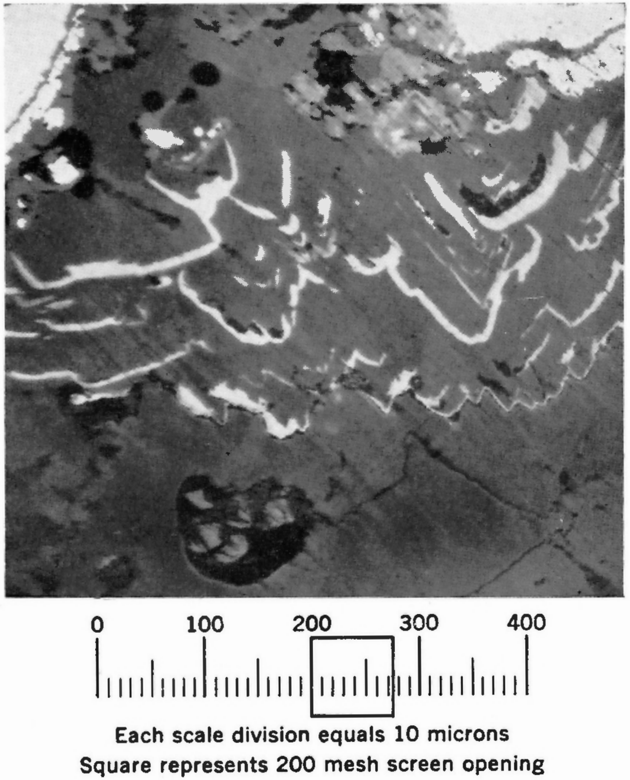

Figure 8. Reflected light. Geothite (light grey) following cleavage in calcite (dark grey). (105426)

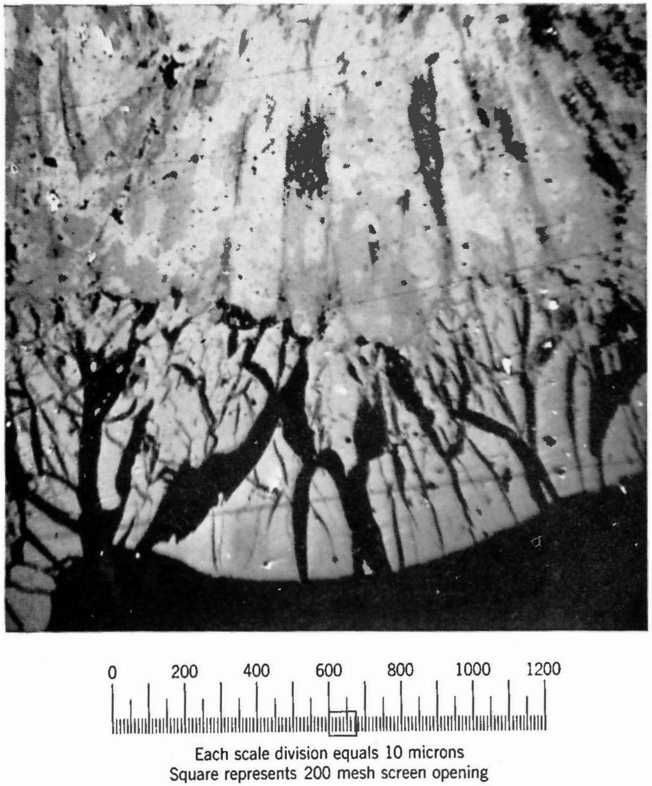

Figure 9. Reflected light, partly crossed nicols. Anistropic nolanite (parti-coloured grey) rimmed by fractured, colloform pitchblende (smooth grey), which is cemented by calcite (black). (106639)

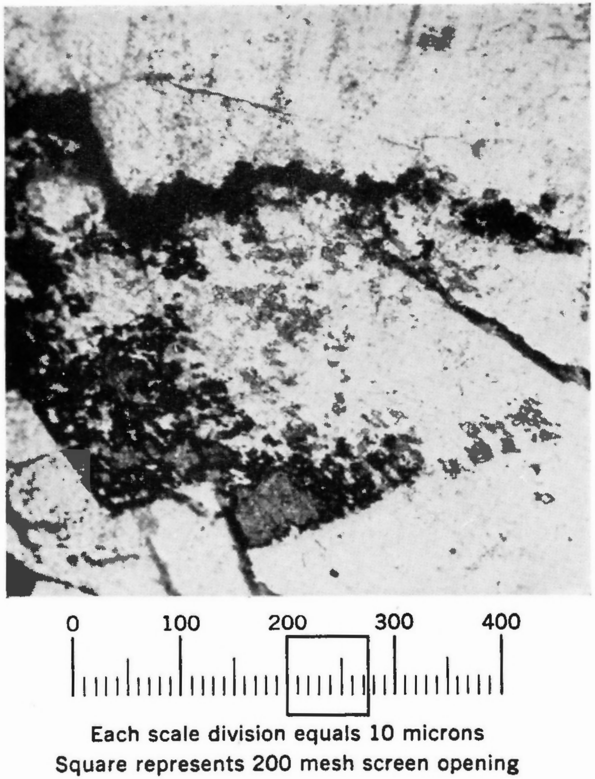

Figure 10. Transmitted light. Iron-stained calcite (dark grey to black) replaced by quartz (light grey). All calcite is in parallel orientation. Pitchblende rim is black. (106640)

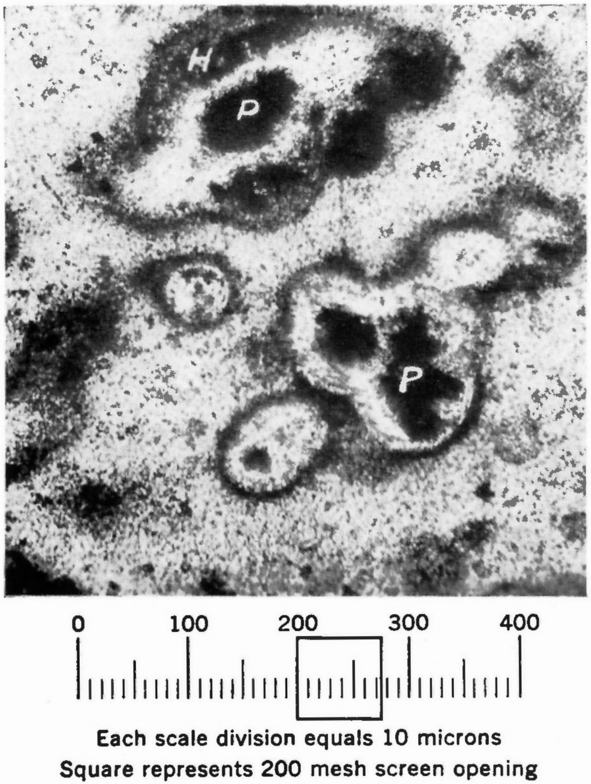

Figure 11. Transmitted light. Pitchblende (P) with an inner rim of chlorite (light grey) and an outer rim of disseminated hematite (H) in oligoclasite. (104751)

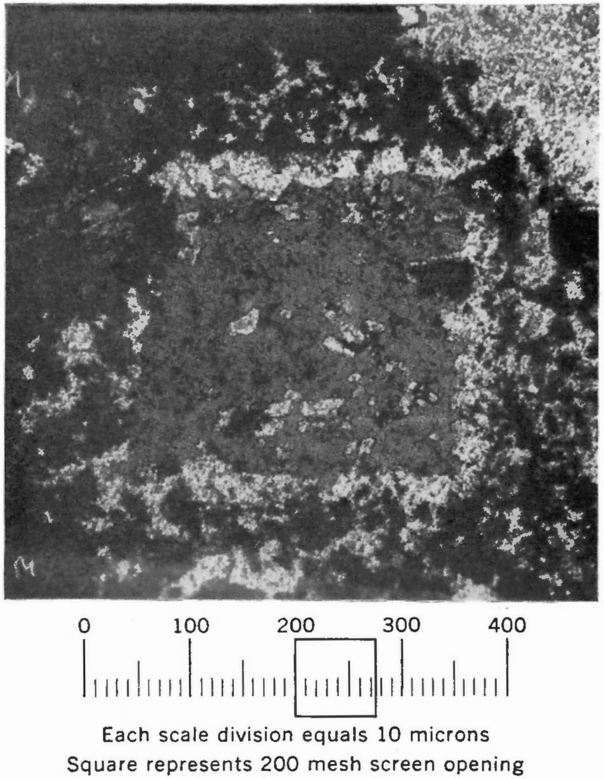

Figure 12. Transmitted light. Part of single crystal-grain of calcite (white) replaced by chlorite (medium grey). Black matrix is hematite-stained oligoclasite. (106641)

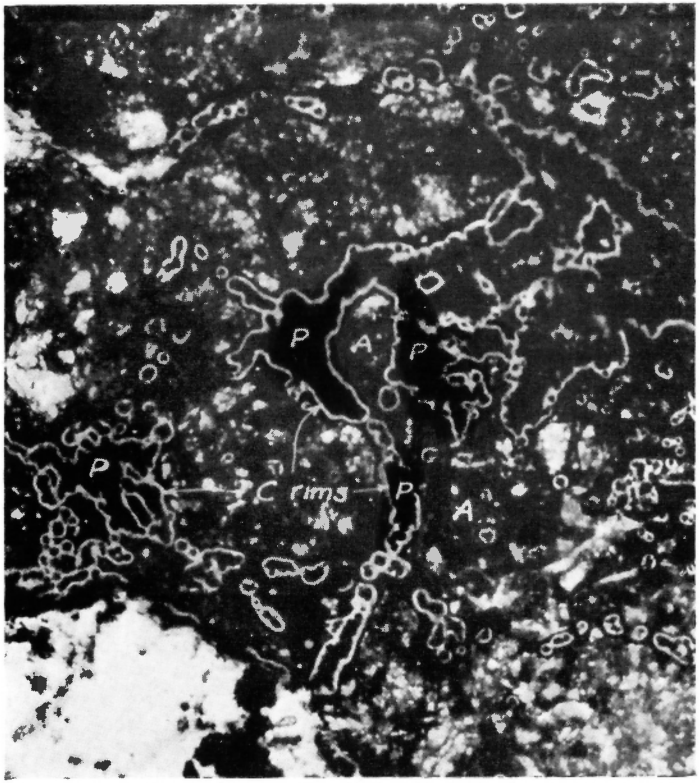

Figure 13. Transmitted light. Rims of calcite (white) on pitchblende (black) in oligoclasite (parti-coloured dark grey). Magnification 8 diameters. (104760)

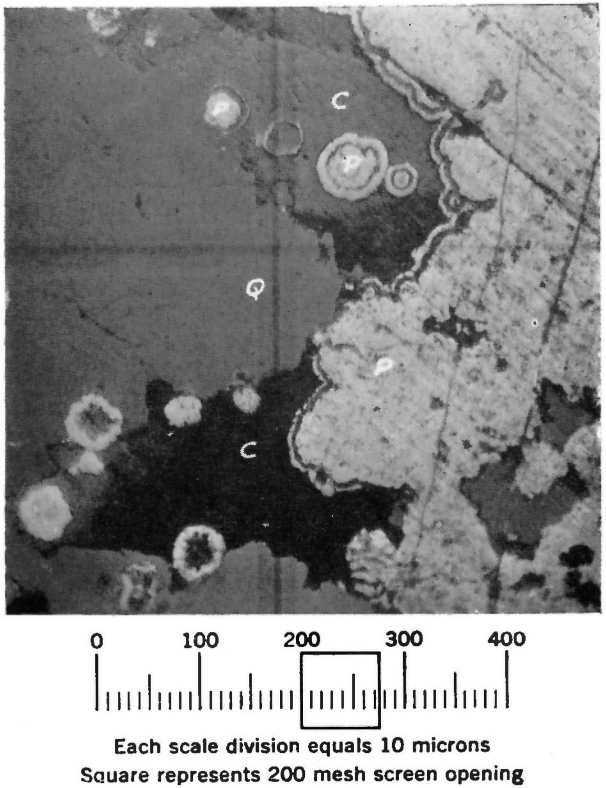

Figure 14. Reflected light. Pitchblende (P) bordered by quartz (Q) and partly etched calcite (C). Note outer rims of pitchblende in calcite but not in quartz. (104759)

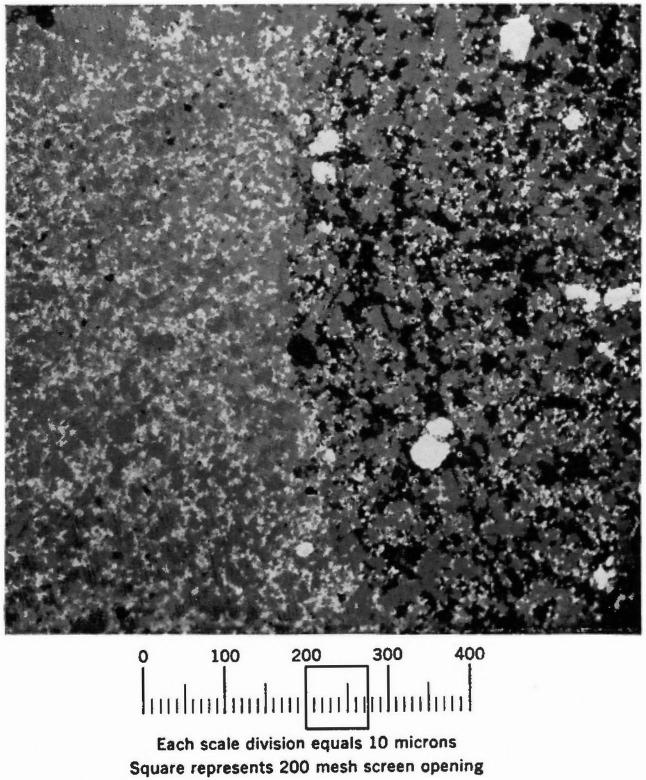

Figure 15. Reflected light. Pitchblende (light grey) and pyrite (white) disseminated in a matrix composed of cherty quartz (dark grey) and calcite (medium grey, black where etched by HCl). (106642)

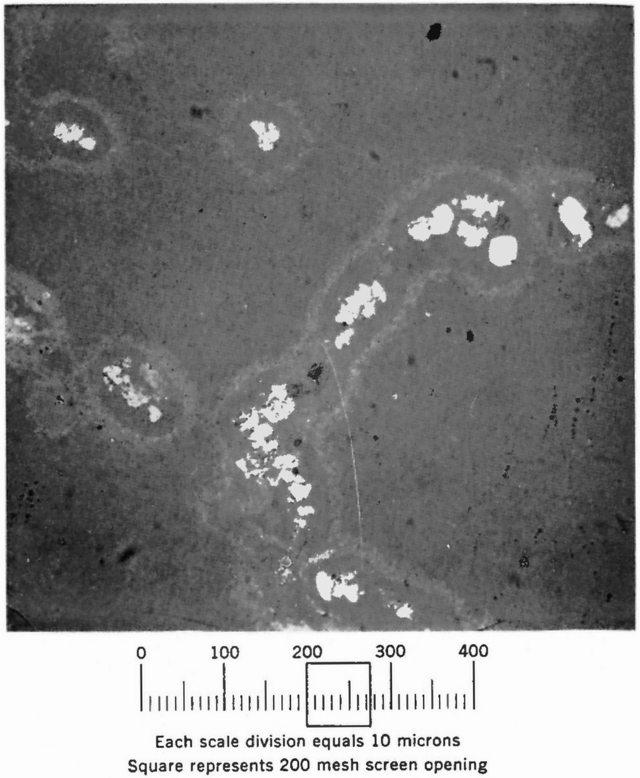

Figure 16. Reflected light. Pitchblende (white) as subhedral crystals in isotropic chlorite and calcite (medium grey) replacing oligoclasite groundmass (dark grey) with a peripheral band of disseminated, very diminutive crystals of specular hematite (light grey). (106643)

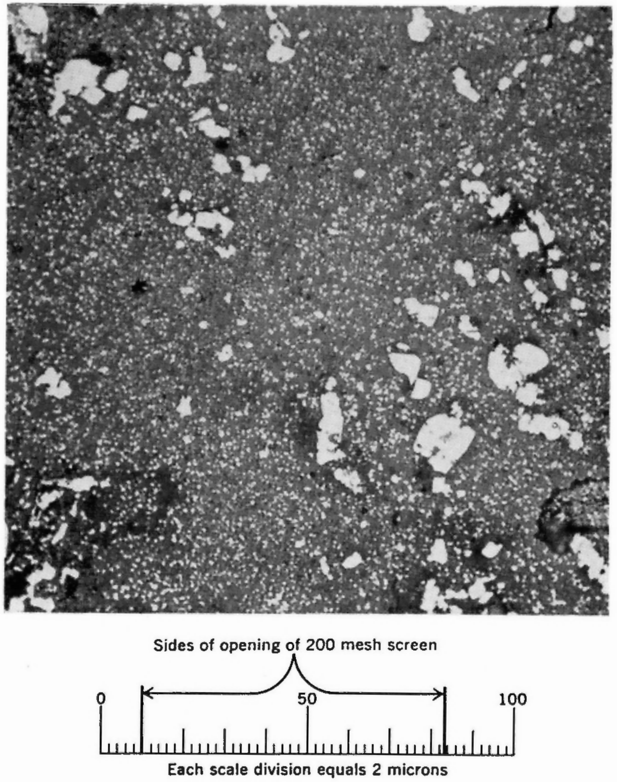

Figure 17. Reflected light. Grains of pyrite (white) in a matrix of pitchblende (medium grey). (106644)

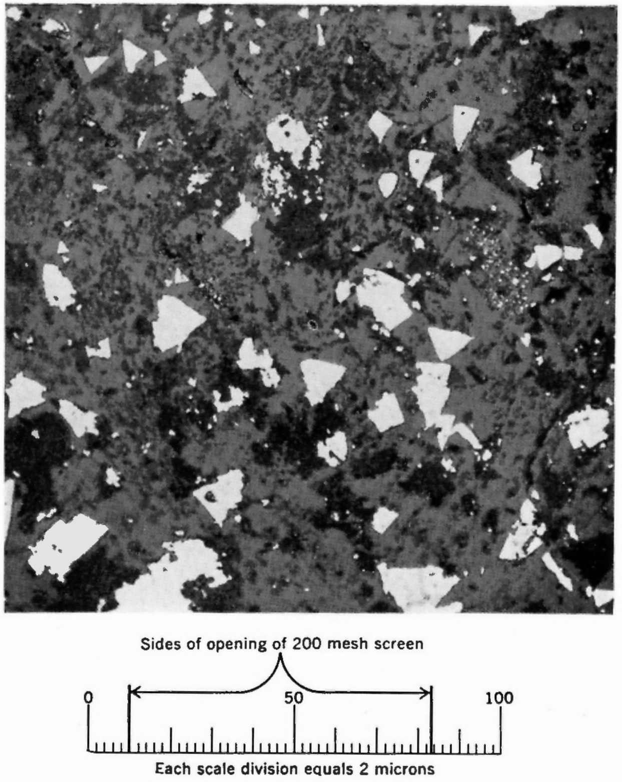

Figure 18. Reflected light. Subhedral grains of chalcopyrite (white) in a groundmass of pitchblende (medium grey) and gangue (dark grey). Patch of light grey particles is hematite. (106645)

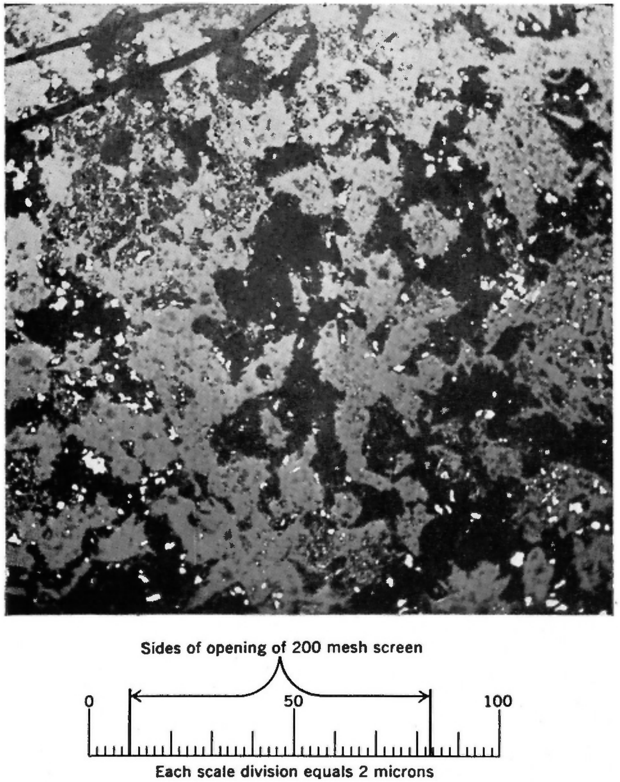

Figure 19. Reflected light. Intergrowth of pitchblende (medium grey) and gangue, largely calcite (dark grey to black), with disseminated grains of galena (white). (106646)

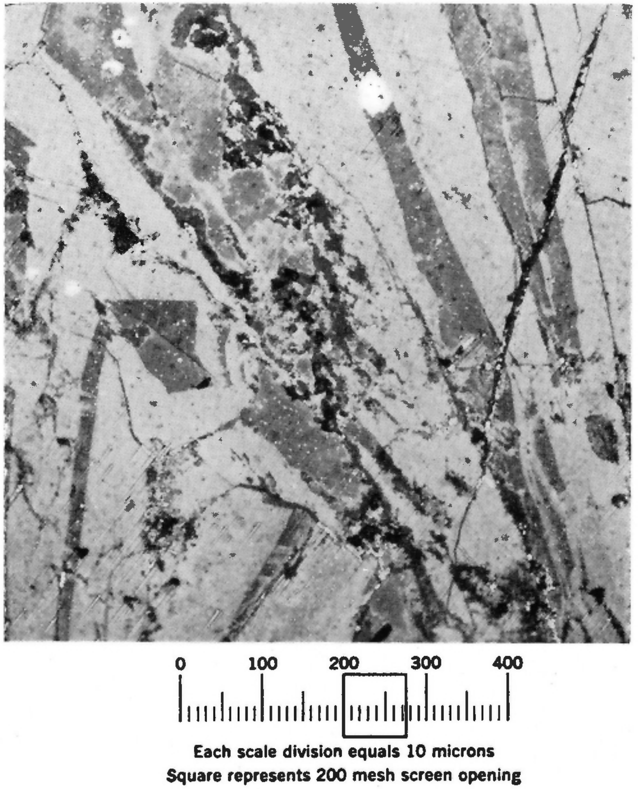

Figure 20. Reflected light. Bladed pitchblende (light grey) and calcite (dark grey) with traces of pyrite, chalcopyrite, and bornite (white). (106647)

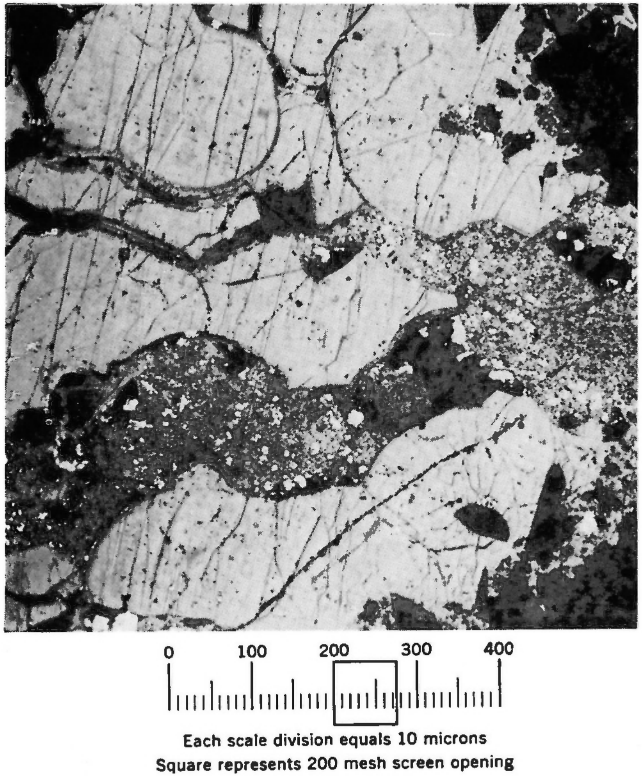

Figure 21. Reflected light. Mixtures of calcite (dark grey), pitchblende (medium grey), and sulphides (white) filling fractures with matching walls in colloform pitchblende (medium grey). (106648)

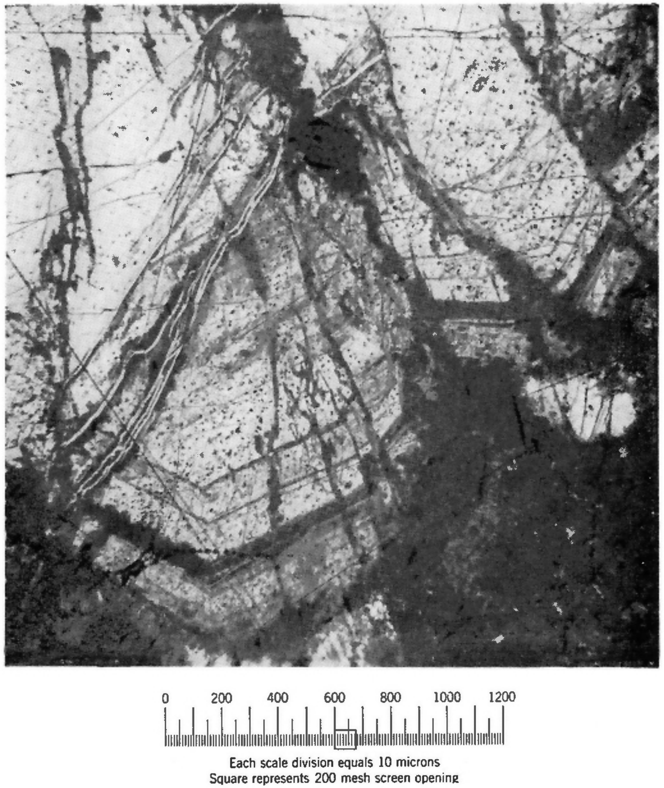

Figure 22. Reflected light. Pitchblende (light grey) replacing zones of calcite (dark grey) selectively. Note veinlets of later hard fresh pitchblende transecting the earlier pitchblende. (106649)

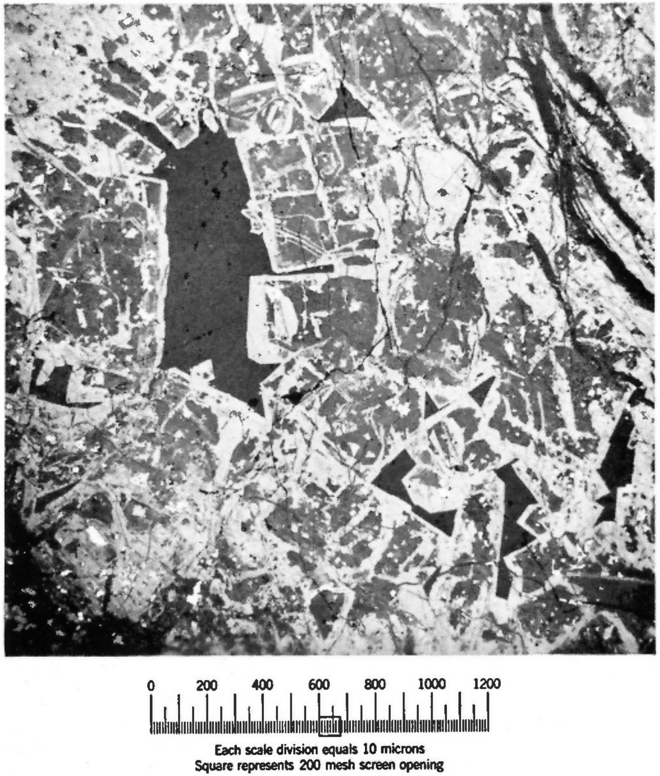

Figure 23. Reflected light. Partial replacement of older calcite crystals (medium grey) by pitchblende (very light grey), the whole cemented by younger calcite (dark grey). White specks are sulphides. (106650)

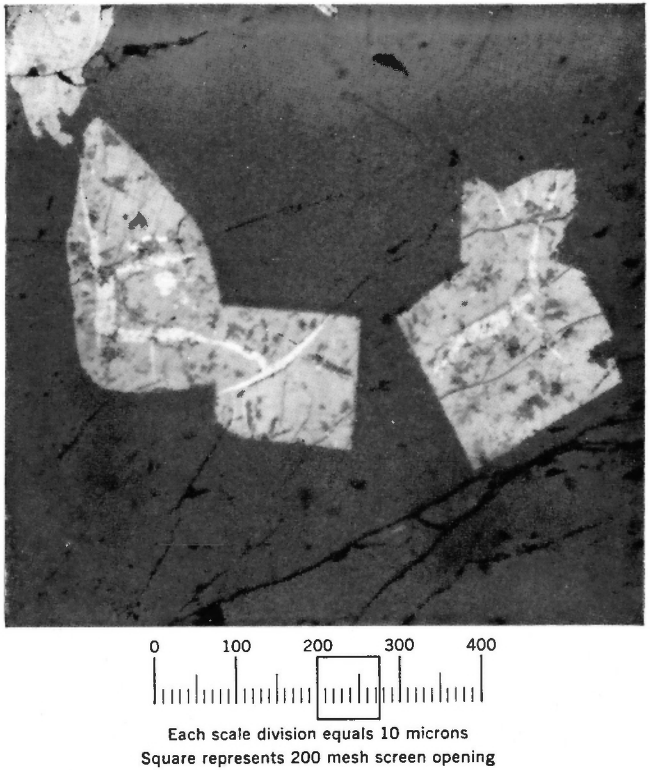

Figure 24. Reflected light. Crystals of urania (medium grey) fractured and cemented by hematite (light grey) in quartz (dark grey). (106651)

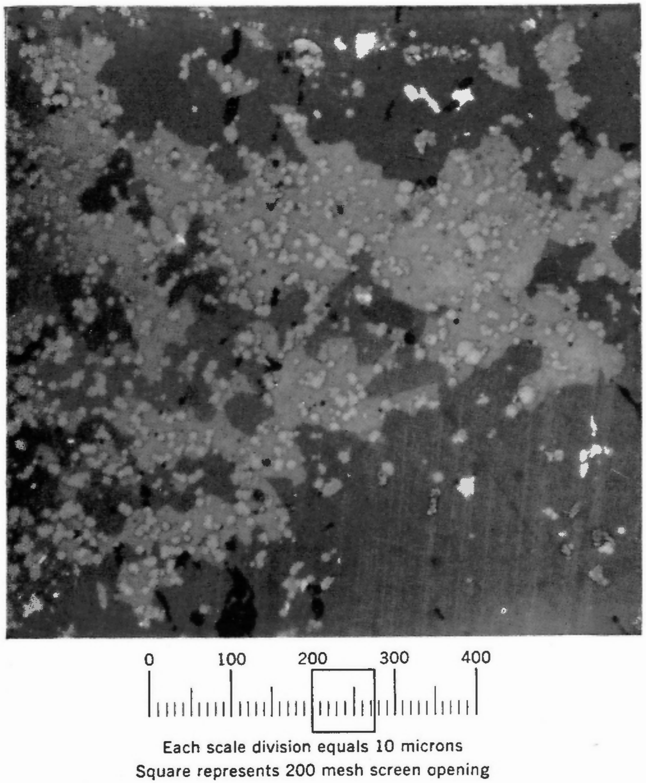

Figure 25. Reflected light. Spherulites of pitchblende (light grey) in umangite (medium grey) and calcite (dark grey). White grains are clausthalite. (106652)

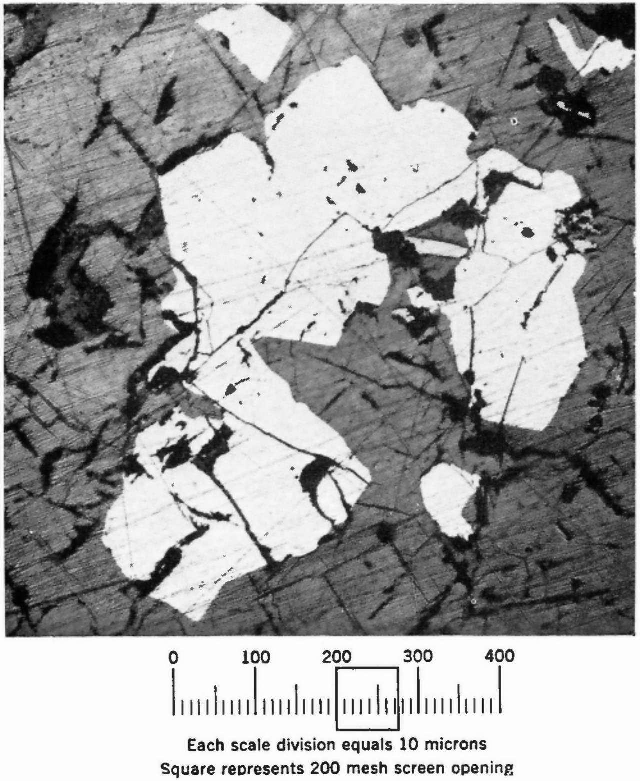

Figure 26. Reflected light. Cu-Co-Ni-selenide (white) in umangite (grey) that is cut by blades (black) of klockmannite and chalcomenite. (106653)

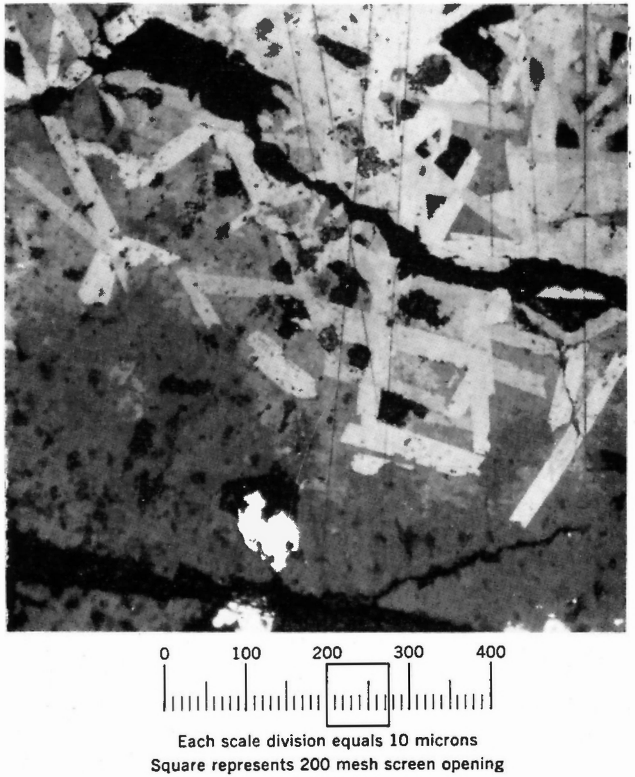

Figure 27. Reflected light. Crystals of nolanite (varicoloured medium grey) in weathered dolomite (dark grey). White is chalcopyrite. (106654)

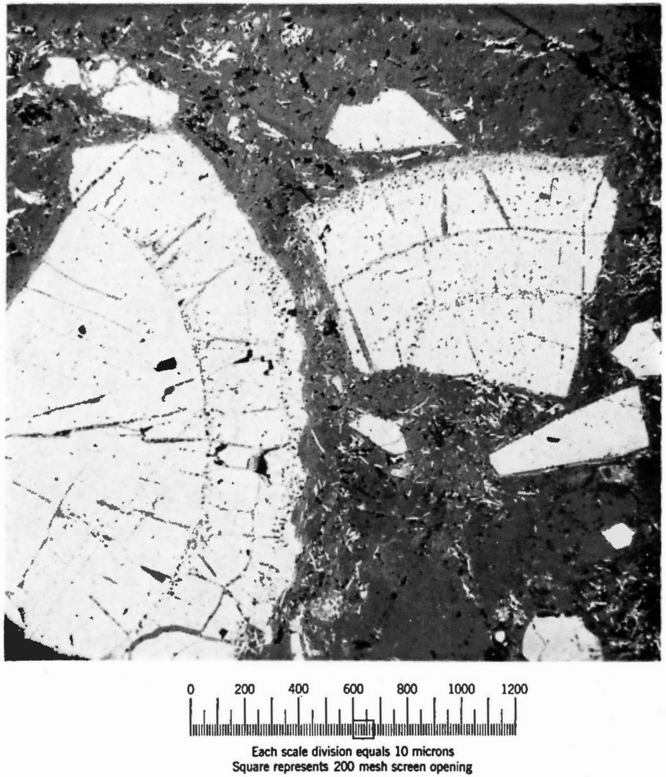

Figure 28. Reflected light. Brecciated fragments of colloform pitchblende (light grey) cemented in a matrix of calcite (dark grey) containing blades of specular hematite (light grey). (106655)

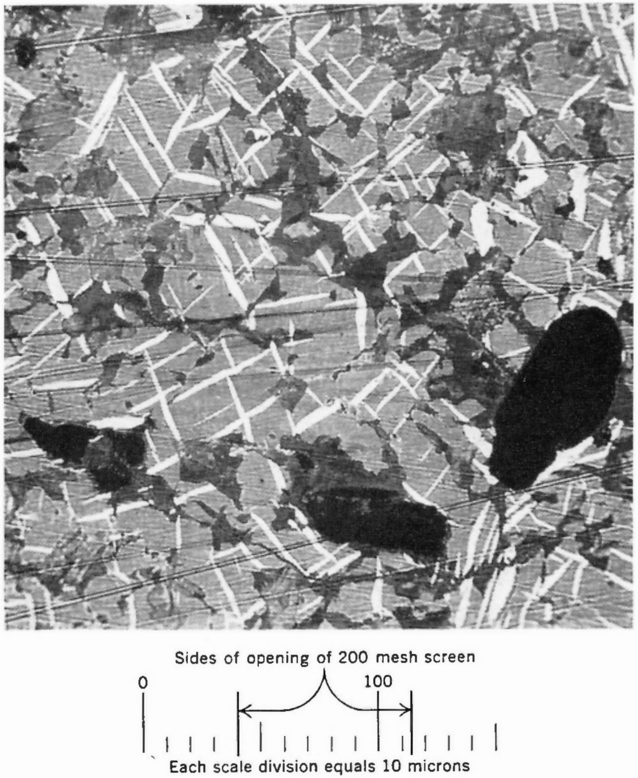

Figure 29. Reflected light. Ex-solution blades of chalcopyrite (white) in a matrix of bornite (medium grey). Both have been replaced by covellite (mottled dark grey). Pits are black. (106656)

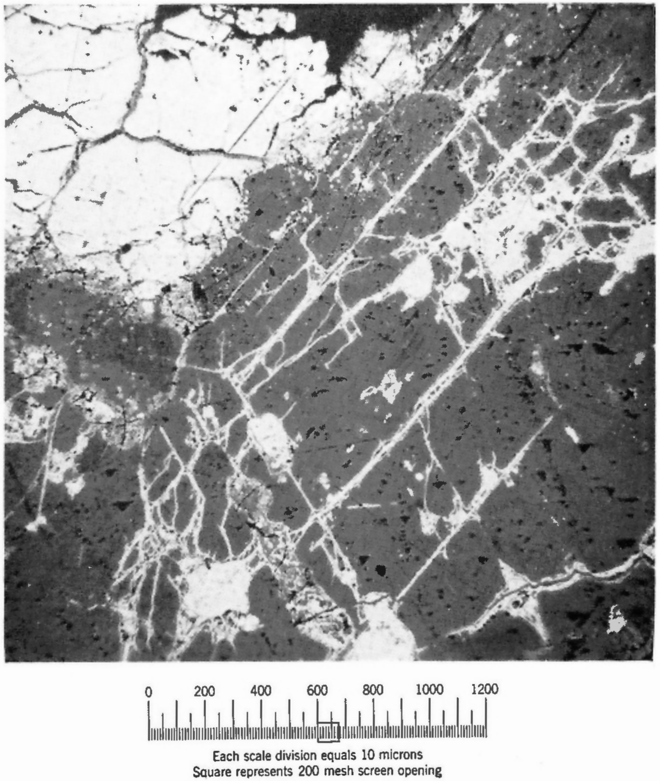

Figure 30. Reflected light. Pitchblende (light grey) in calcite (dark grey). Note that one large area of pitchblende has been corroded by calcite (*See also* Figure 31) and a later generation of pitchblende replaces calcite along cleavage planes. (106657)

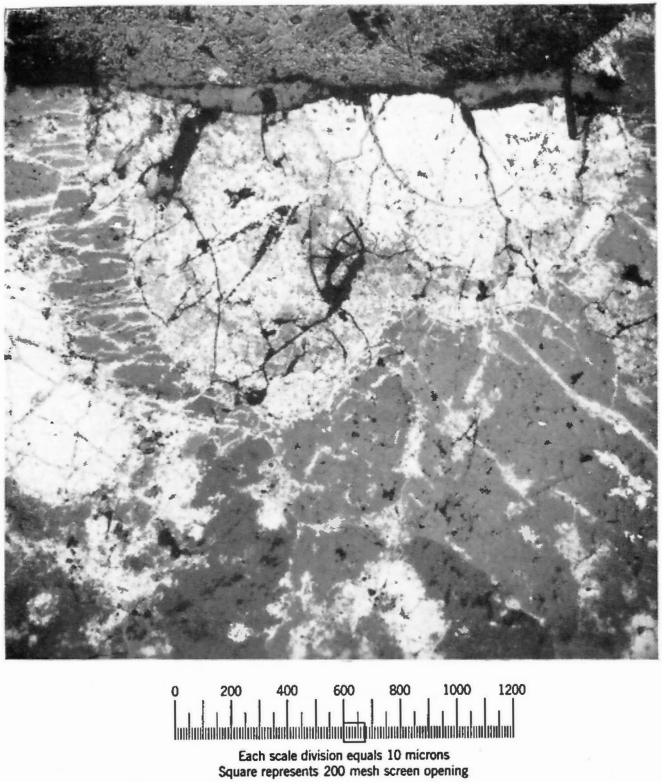

Figure 31. Reflected light. Colloform pitchblende (light grey) partly replaced by calcite (dark grey). Note stringers of later pitchblende transecting calcite. (106658)

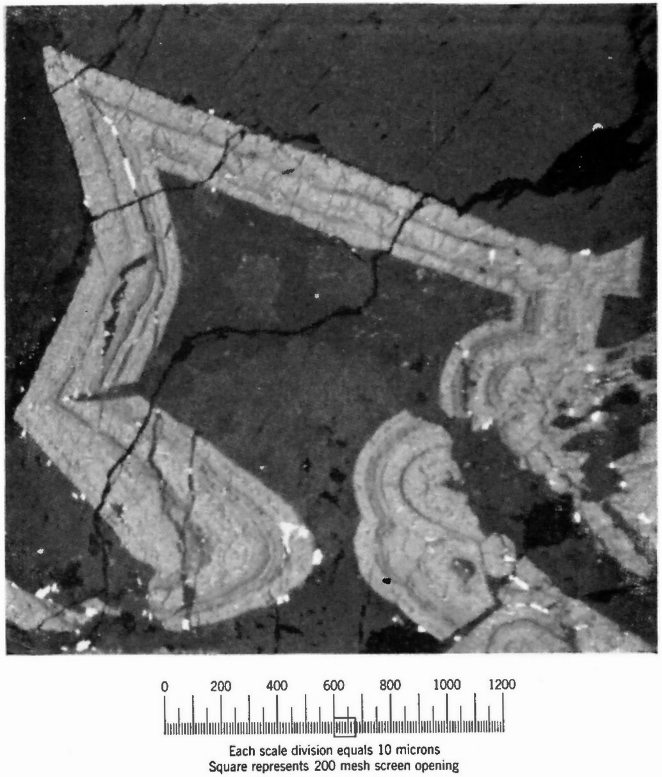

Figure 32. Reflected light. Banded colloform pitchblende rims (light grey) on calcite (varicoloured dark grey). White spots are sulphides. Note break in colloform pitchblende cemented by younger calcite, whereas pitchblende was deposited in an angular opening in older calcite. (106659)

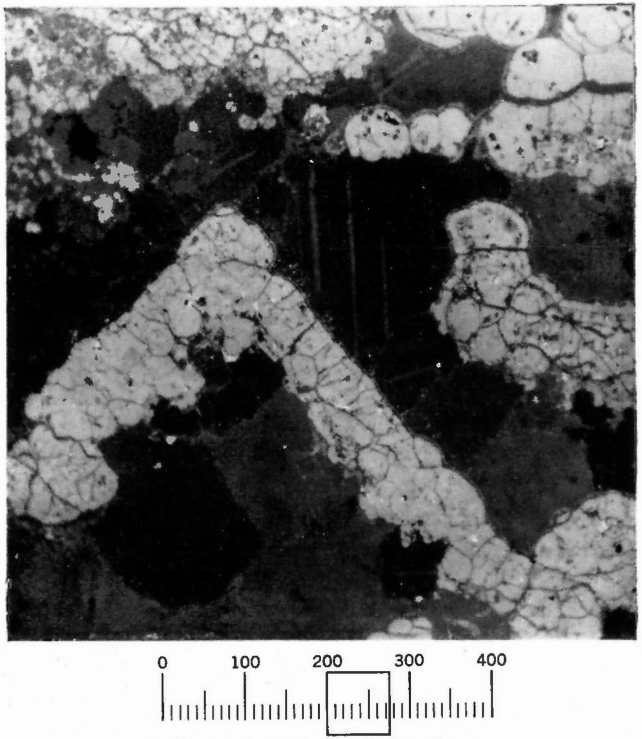

Figure 33. Reflected light, partly crossed nicols. Colloform pitchblende rims (light grey) cemented in recrystallized calcite (varicoloured dark grey). (106660)

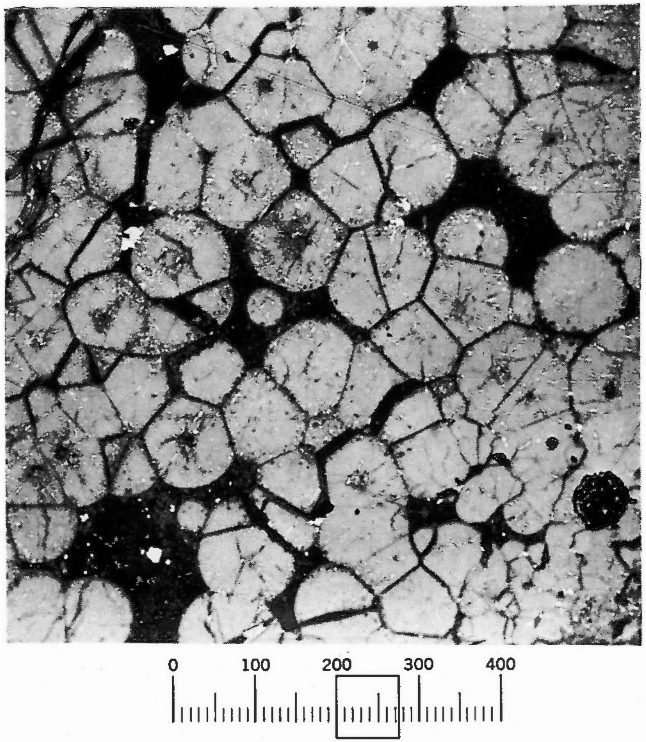

Figure 34. Reflected light. Coalescing pellets of pitchblende (light grey) in calcite (dark grey) with sulphides and selenides (very light grey to white). Note straight interference surfaces and rotund free surfaces of the pitchblende. (106661)

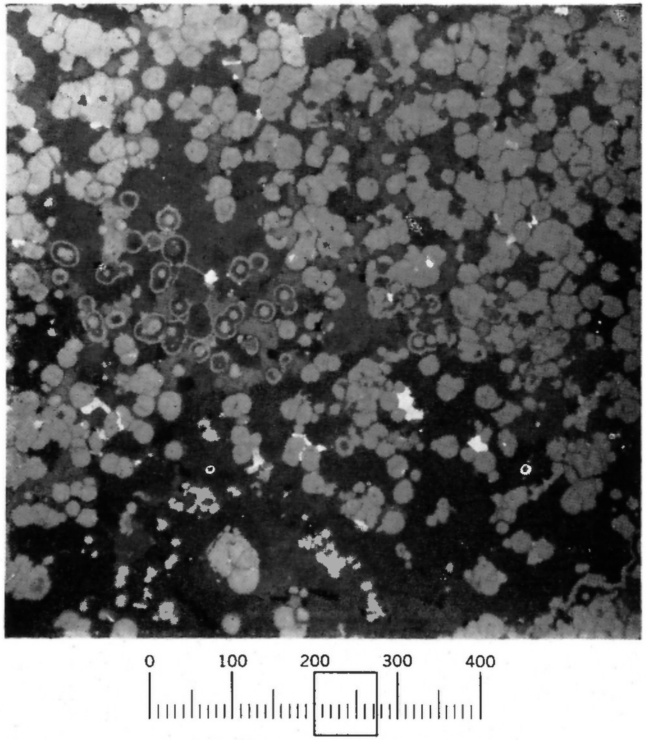

Figure 35. Reflected light. Botryoidal grains of pitchblende (light grey) in calcite (varicoloured dark grey) with clausthalite (white). Note rings of pitchblende about cores of calcite and of calcite and pitchblende. Note, too, that some of these rings are broken or replaced by calcite. (106662)

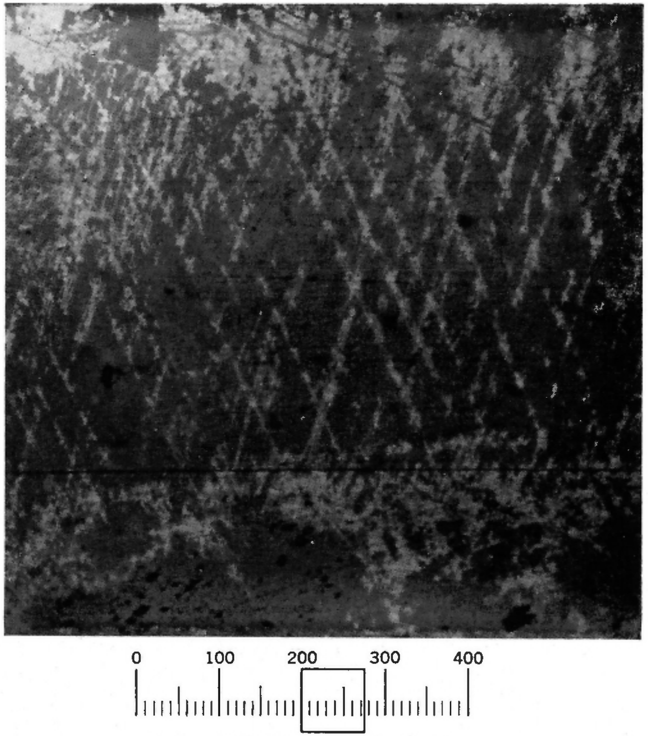

Figure 36. Reflected light. Pitchblende (light grey) replacing calcite (dark grey) along cleavage planes. (106663)

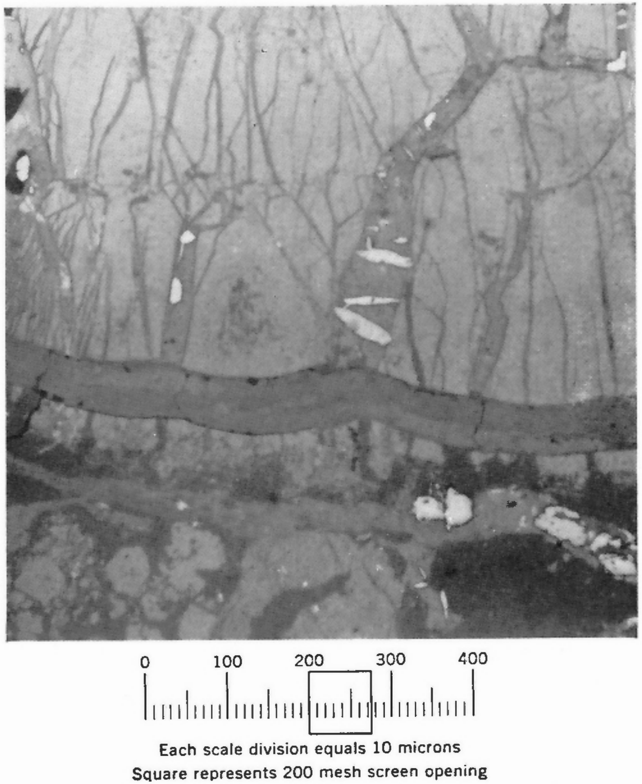

Figure 37. Reflected light. Syneresis cracks in pitchblende (light grey) filled by umangite (medium grey) and euhedral crystals of specular hematite (white). Dark grey is calcite and secondary alteration products. (106664)

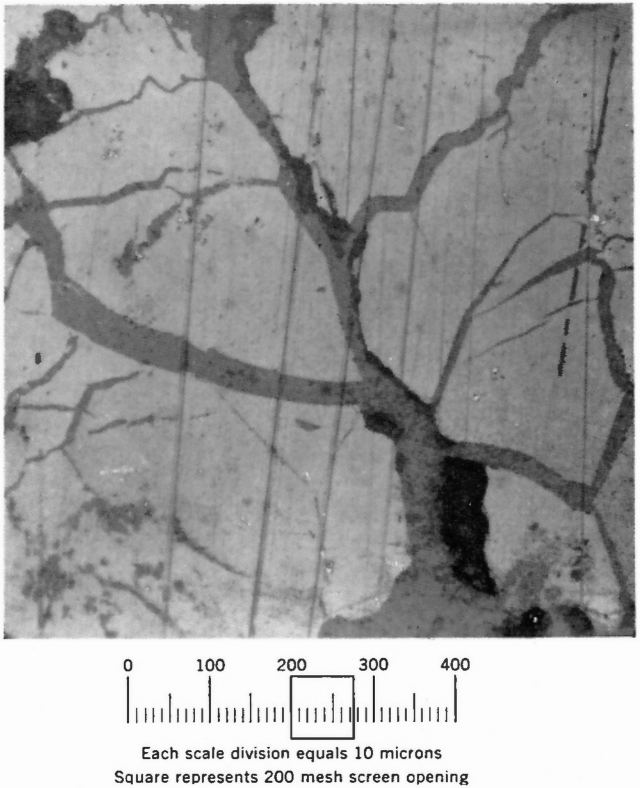

Figure 38. Reflected light. Matching fractures in pitchblende (light grey) filled by calcite (dark grey) that is all in parallel orientation. (106665)

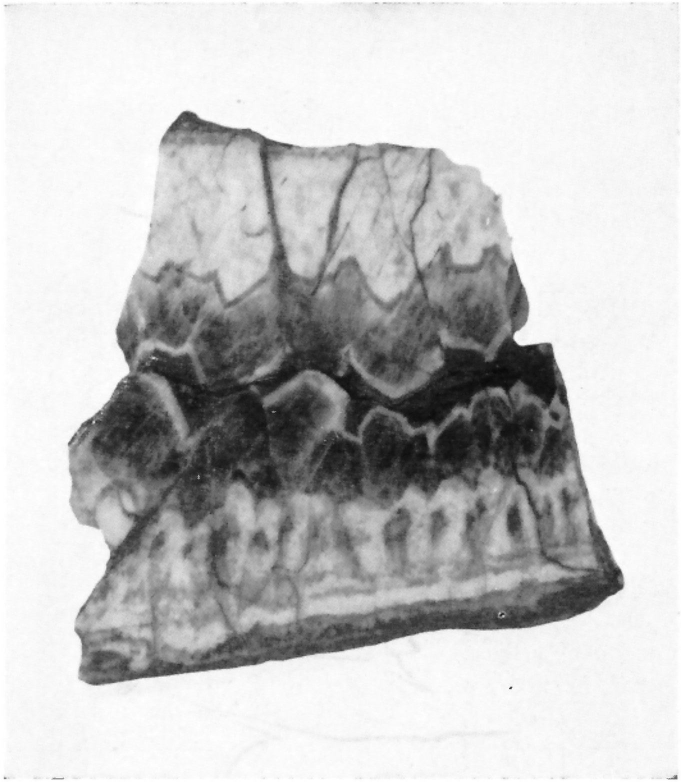

Figure 39. Full scale. Section through vein of comb quartz, amethyst in part, showing chlorite (black) filling centre of vein. (106456)

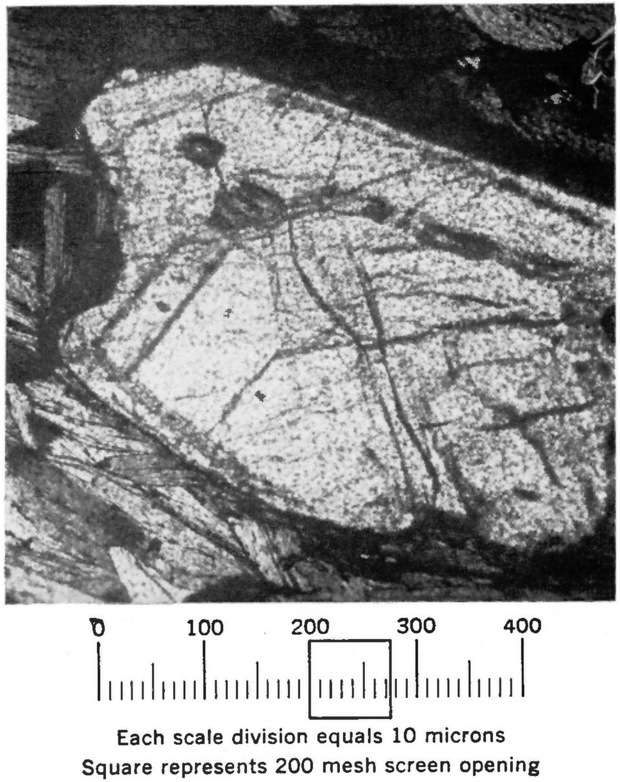

Figure 40. Transmitted light. Zoned crystal of monazite in biotite and showing inclusions of biotite. (106666)

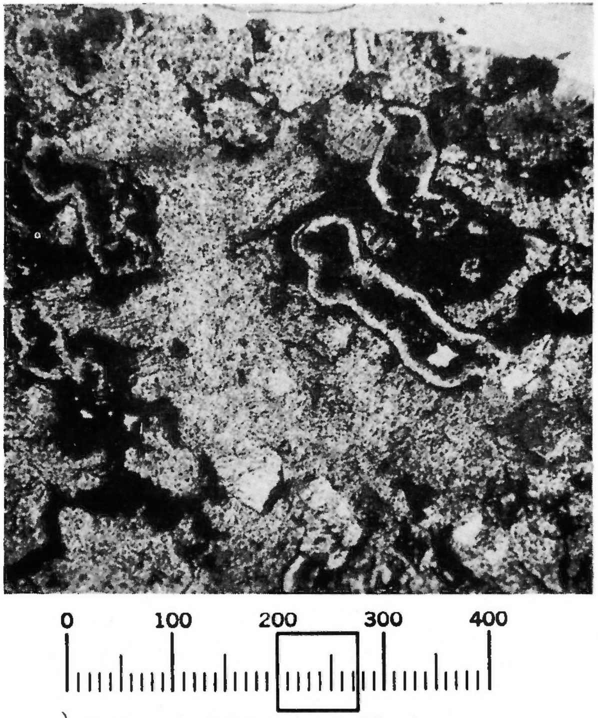

Figure 41. Transmitted light. Rims of potash feldspar (white) on and in pitchblende (black). Matrix is plagioclase feldspar. (106667)

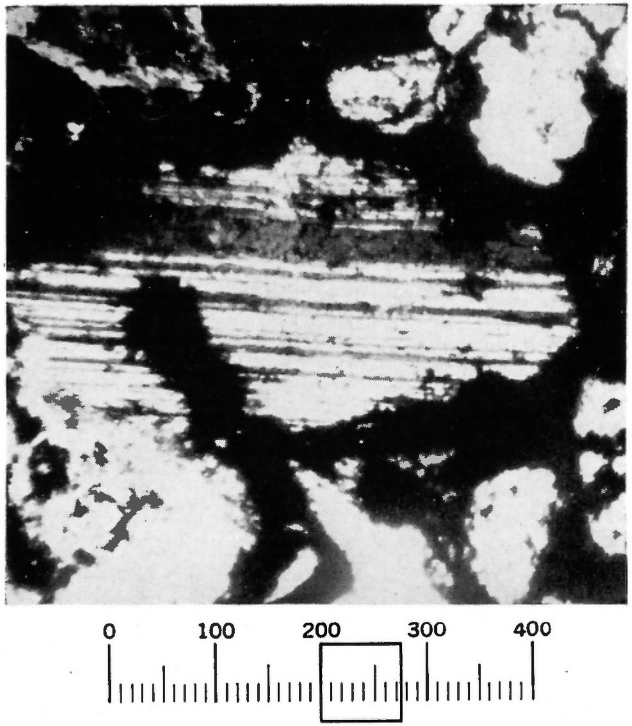

Figure 42. Crossed nicols. Albite crystal rimmed and replaced by pitchblende (black). (106668)

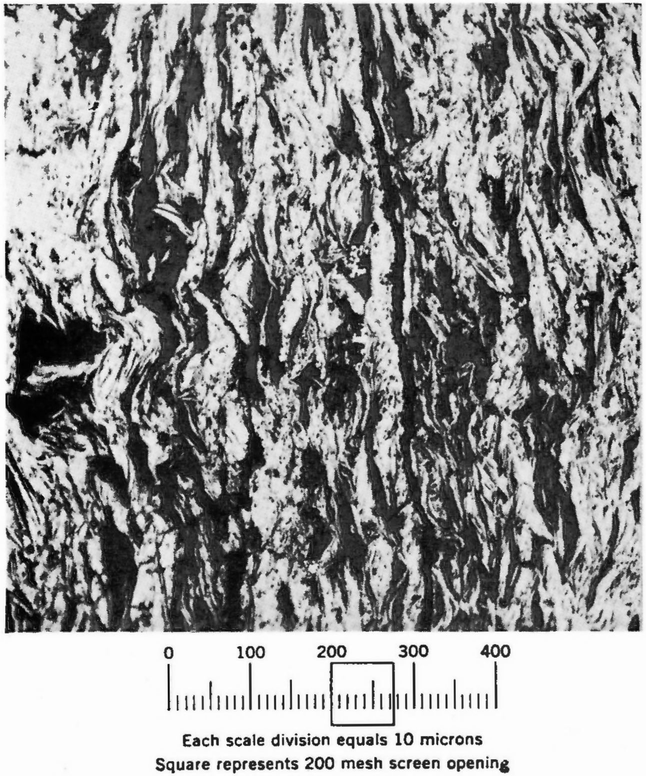

Figure 43. Reflected light. Flamboyant hematite (white) in mixed quartz and calcite gangue (dark grey). (106669)

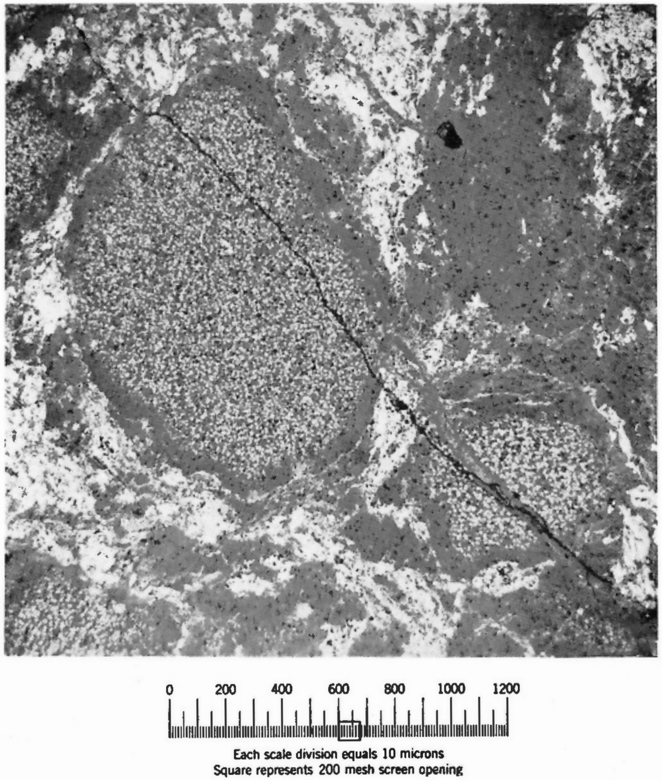

Figure 44. Reflected light. Areas of disseminated hematite (grey) and flamboyant hematite (light grey) in quartz-chlorite gangue (dark grey). (106670)

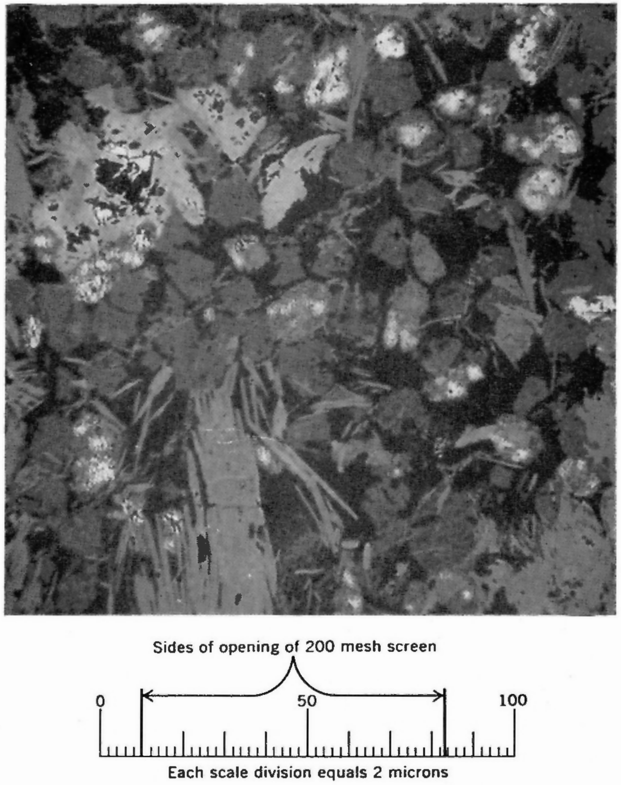

Figure 45. Reflected light. Angular grains of pitchblende (dark grey) with specular hematite (grey) and chalcopyrite (light grey) in calcite-quartz gangue (black). Halation obscures outlines of chalcopyrite. (106671)

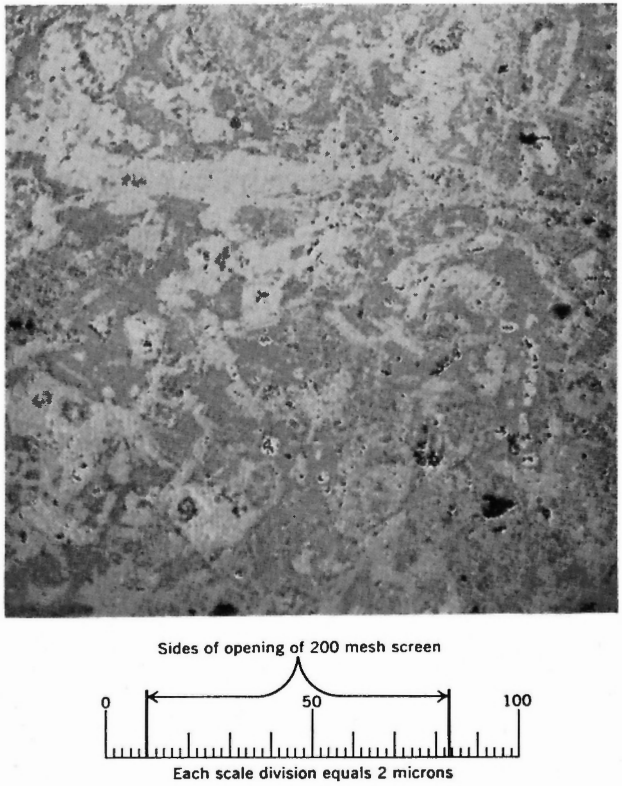

Figure 46. Reflected light. Hematite (light grey), disseminated through a matrix of pitchblende (grey). Pits are black. (106672)

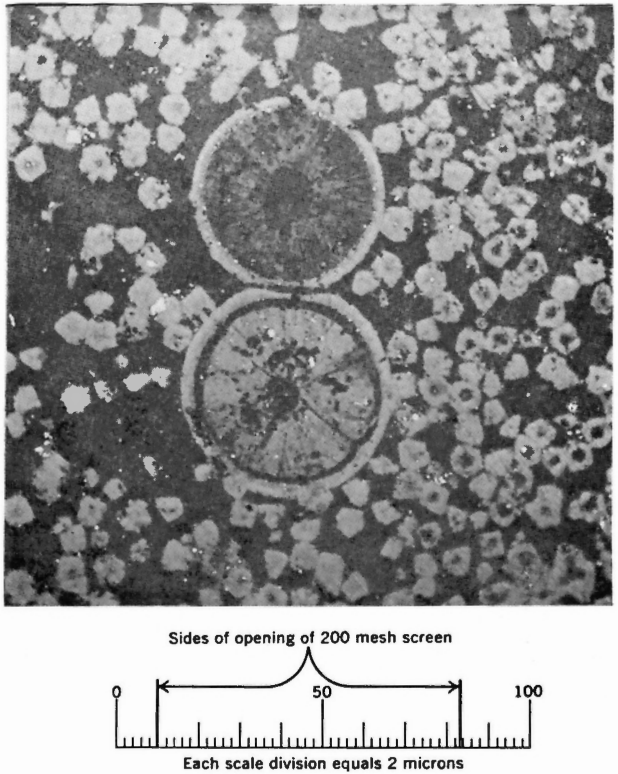

Figure 47. Reflected light. Old pitchblende (grey) partly replaced by calcite (dark grey) and chalcopyrite (white), rimmed by younger pitchblende of the same age as the angular grains or pellets of pitchblende. (106673)

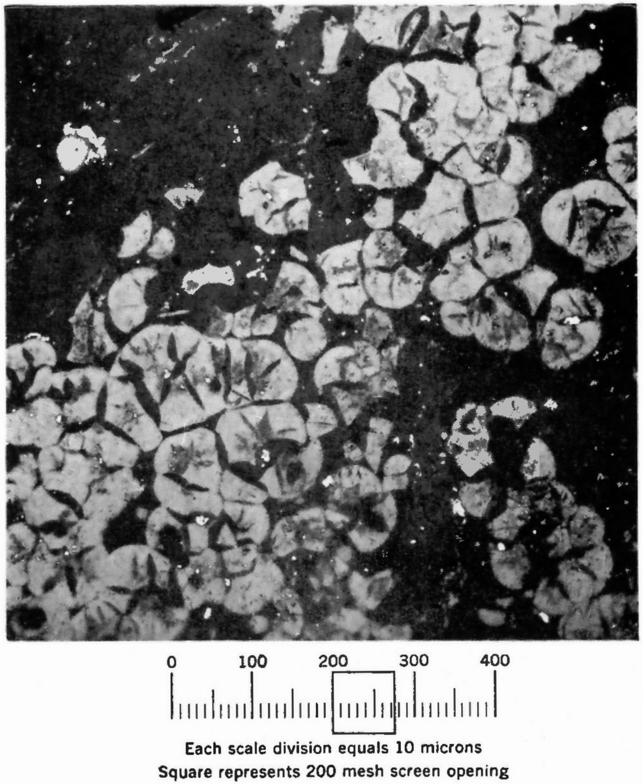

Figure 48. Reflected light. Coalescing pitchblende pellets (grey) showing characteristic shrinkage cracks filled by calcite (black). Chalcopyrite particles are white. (106674)

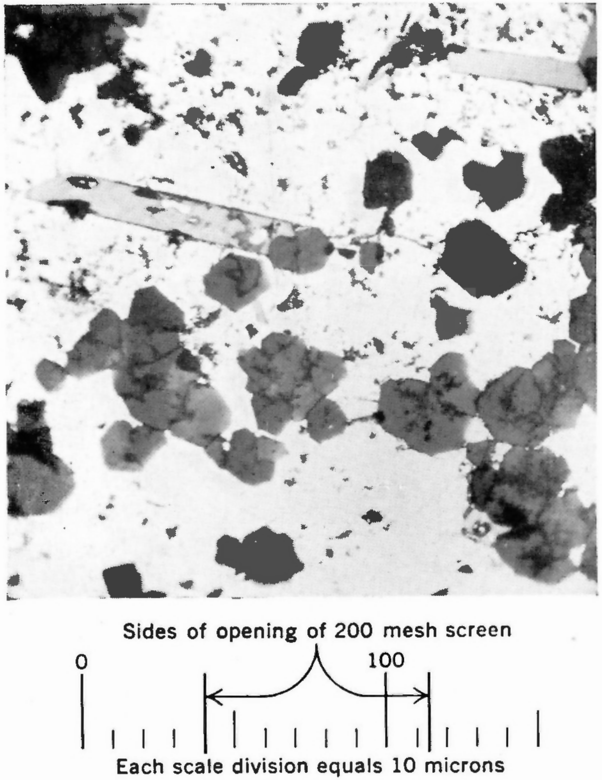

Figure 49. Reflected light. Hexagonal plates of nolanite (grey) and laths of hematite (light grey) in chalcopyrite (white). (106675)

Figure 50. Transmitted light. Rim of pitchblende (black) on older iron-stained calcite (grey) cemented by outer layers of fresh younger calcite (light grey). (104231)