

SYMPOSIUM ON THE GEOLOGY OF CORONATION MINE, SASKATCHEWAN

**Edited by
A.R. BYERS**

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SYMPOSIUM ON THE GEOLOGY
OF CORONATION MINE,
SASKATCHEWAN

A collection of papers on various aspects of the geology, geophysics and geochemistry of the Coronation Mine, published by the Geological Survey of Canada under the sponsorship of the National Advisory Committee on Research in the Geological Sciences.

Edited by A.R. Byers

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No. 1 THE CORONATION MINE PROJECT

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This symposium on the Coronation mine marks the first attempt to make a detailed and comprehensive study of a Canadian base metal ore deposit. The project was initiated and sponsored in 1957 by the National Advisory Committee for Research in the Geological Sciences upon the recommendation of the Subcommittee on Mineral Deposits. Its aim was "to obtain complete geological and other related scientific information on at least one Canadian metallic mineral deposit". A special committee was set up with H. G. Gunning as chairman to make recommendations regarding the selection of an ore deposit and the organization and personnel for the project. J. M. Harrison, then Director of the Geological Survey of Canada, agreed to have the Survey supervise the project and in due course D. R. E. Whitmore was appointed to coordinate the study and to participate actively in the field and laboratory investigations. It was not until January, 1960, however, that the Coronation mine was selected for the study with the cooperation of Hudson Bay Mining and Smelting Company, Limited. Field studies were started in May, 1960, shortly after the mine went into production, and continued until the ore bodies were mined out in 1964. In 1967, the writer was appointed by the National Advisory Committee for Research in the Geological Sciences to supervise the assembly and publication of the final report.

Personnel from the following institutions have participated in the project: Universities of Manitoba, Saskatchewan and Western Ontario; Saskatchewan Research Council; Geological Survey of Canada; Hudson Bay Mining and Smelting Company, Limited, and Canadian Aero Service Limited. Papers were invited from all the principal participants and eleven were submitted. These together with five papers previously published by the Canadian Institute of Mining and Metallurgy constitute the sixteen papers that form this symposium. Regrettably, a chemical investigation of the wallrock alteration, a study of the sulphur isotope composition of the ore, and a detailed gravity survey in the immediate vicinity of the deposit were never completed. It is also unfortunate that no isotopic studies were made to determine the absolute age of the intrusive rocks, the metamorphism of the wallrocks and the mineralization.

Several of the papers were submitted two years ago, and the authors have been unable to bring them up to date with respect to subsequent investigations by other workers particularly in the field of sulphide phase relationships.

The following account summarizes the geologic data and principal ideas regarding the origin of the Coronation deposit as presented in this volume.

In the Flin Flon region, irregularly shaped masses of volcanic rocks, belonging to a basalt-andesite-rhyolite, geosynclinal, pre-orogenic suite, occur as remnants between large bodies of gabbroic to granitic

composition. Sedimentary rocks, interlayered with the volcanic rocks, increase in amount to the west and north and so does, in general, the grade of metamorphism. Thus, the volcanic complex changes to the west and north into a series of metasedimentary gneisses. However, locally within the complex, e. g. in the Coronation mine area, the metamorphic grade rises to that of the staurolite-almandine subfacies of the almandine-amphibolite facies.

Large igneous masses were emplaced and regional metamorphism took place during the Hudsonian orogeny. The ultrabasic to basic rocks of the Boundary intrusions and Phantom Lake granite, in the vicinity of Flin Flon, are younger and probably represent a late post-tectonic phase of the orogeny.

After the rocks of the area had consolidated a north-northwest trending system of faults, known as the Ross Lake Fault system, fractured the cratonic block.

Burke's preliminary interpretation of the regional seismic data suggests a two-layered crust having a total thickness of 40 km. The upper layer with a thickness of 10 km is characterized by a velocity of 6.0 km/sec. and the lower layer by a velocity of 6.4 km/sec. Gendzwill, on the basis of gravity data and using densities of surface rocks, postulates that the volcanic complex and granitic intrusions extend to a depth of 3.0 to 4.7 km. Below this depth they either rest on lighter rocks or have had substantial quantities of granitic material added to them.

The Coronation deposit is one of 12 known economic copper-zinc deposits that lie within a radius of 15 miles of Flin Flon. These deposits occur within zones of shearing in the metamorphosed rocks of the volcanic complex. More specifically the ore bodies are disseminated to massive, pyrite-pyrrhotite deposits with economic quantities of chalcopyrite and sphalerite. Besides these ore deposits there are a large number of deposits that consist essentially of massive to disseminated pyrite and pyrrhotite with a combined copper-zinc content that rarely exceeds 0.5 percent. These deposits occur not only in the volcanic rocks but also in the metasediments and high grade gneisses to the north and west of Flin Flon. For a more detailed description of the sulphide deposits the reader is referred to Byers and Dahlstrom (1954) and Byers, et al. (1965).

The Coronation ore bodies lie in a zone of shearing that transects the bedding of the enclosing metamorphosed, volcanic rocks at angles of up to 20 degrees. This zone has been traced, on the basis of geophysical data and diamond drilling, for a length of four miles. Over most of its length the zone lies 500 to 1,000 feet west of large bodies of granodiorite and gabbro. In the vicinity of the mine the volcanic rocks are intruded by dykes of andesite porphyry and rhyolite porphyry related to the volcanic rocks, dykes and small irregular bodies of diorite and gabbro, dykes of quartz-feldspar porphyry related to the granodiorite, and several small dykes which, on the basis of their composition and alteration, may belong to the Boundary intrusions.

The deposit consists of three ore shoots within a zone of lower-grade mineralized rock which is 900 feet long, up to 120 feet wide, and extends to a vertical depth of 1,000 feet. In the northern section of the mineralized zone the sulphides are concentrated into a larger footwall ore shoot and a smaller hanging wall ore shoot. The footwall ore shoot is mainly a vein of chalcopyrite-rich sulphides commonly in sharp contact with the

enclosing wallrock and containing angular to subrounded inclusions of the wallrock. The hanging wall ore shoot is composed of patches of cordierite-anthophyllite rock with intergrown sulphides generally with a gneissic or layered structure. Some disseminated sulphide mineralization occurs between the two ore shoots. The third ore shoot occupies a large part of the southern half of the mineralized zone. The mineralization is highly dispersed and the ore consists of a complex breccia or stockwork of sulphides and silicates and a skarn-like intergrowth of disseminated sulphides and silicates.

The three ore shoots and the mineralized zone plunge steeply south, corresponding the plunge of linear structures in the adjacent volcanic rocks.

Two ages of mineralization are recognized: an older pyrite-sphalerite-pyrrhotite-chalcopyrite and a younger tetrahedrite-chalcopyrite-calcite type. The latter is restricted to relatively minor veins which constitute less than 10 percent of the ore.

Pyrite, pyrrhotite, chalcopyrite, altered plagioclase, hornblende, tremolite-actinolite, cordierite, anthophyllite, chlorite and quartz are the principal minerals in most of the ore and occur in widely differing proportions. The ore contains minor amounts of magnetite, sphalerite, garnet, zoisite, clinozoisite, and gahnite. Some of the pyrite is brecciated and cut and replaced by pyrrhotite and chalcopyrite. In some of the gneissic ore the c-axes of pyrrhotite grains tend to be orientated perpendicular to the foliation.

Arnold and Ferris point out that most of the pyrrhotite is monoclinic with a uniform composition characteristic of all natural pyrrhotite irrespective of geological environment or conditions of formation. In contrast to the constant bulk composition of the pyrrhotite, the FeS content of sphalerite ranges widely throughout the deposit. They consider the data are inconsistent with the observation that pyrrhotite and pyrite co-exist with sphalerite in the ore bodies, but are consistent with a pyrite-sphalerite assemblage associated with a non-uniform fugacity of sulphur throughout the deposit.

The study by Faulkner on the content of cobalt and nickel shows that the pyrrhotite generally contains less than 400 ppm nickel (average 270 ppm) and up to 4,000 ppm cobalt (average 1,025 ppm), with Co/Ni ratios greater than 0.5 (average 4.60).

According to Gilliland the concentration of ore minerals decreases towards the margins of the ore bodies. In narrow sections of ore chalcopyrite is concentrated near the centre of the ore body, but in the wider sections of the south ore body the concentration has a double peak with respect to the centerline of the ore body. The concentrations of pyrite, pyrrhotite, and to a lesser extent magnetite tend to occur some distance away and on either side of the concentration of chalcopyrite.

Wallrock alteration is somewhat variable and not extensive. Locally the alteration is characterized by anthophyllite and cordierite, in other places by an iron-rich, dark-green chlorite. Original plagioclase of the volcanic rocks is altered to a mixture of epidote, zoisite and carbonate; and hornblende has been transformed to chlorite and magnetite.

The results of partial and whole rock silicate analyses by Faulkner (1964) of samples from the footwall of the ore zone show no easily interpreted trends. The chemical data indicate a slight decrease in CaO and FeO and an overall increase in total iron as the ore is approached.

The temperatures and pressures of mineral formation, as determined by Arnold (1964) on the basis of pyrrhotite-pyrite and sphalerite geothermometry, are no longer valid in the light of subsequent research. Kanehira using magnetite-ilmenite and arsenopyrite-pyrite mineral assemblages estimates a temperature of about 500° C. From their work on liquid inclusions the temperature and pressure of formation of late quartz veins which cut the sulphides is estimated by Arnold and Rutherford to have a maximum range of 260-375° C and 1,640 to 2,440 bars.

It was hoped that this study would lead to a deciphering of the geologic history of the Coronation deposit and so contribute to a better understanding of the origin of similar sulphide deposits in general. Unfortunately, the factual data, as presented in this volume, may and have been interpreted in a variety of ways. Thus Whitmore considers the deposit to have been formed during volcanism in a near-surface lithologic-stratigraphic trap and subsequently to have undergone metamorphism during the Hudsonian orogeny. Faulkner, on the other hand, finds the field and geochemical evidence to be consistent with a late age and the ore to have a genetic connection with the Ross Lake fault system and the Boundary intrusions. Smith considers the syntectonic granitic intrusions as the source of solutions that caused the enrichment of copper in the country rocks and perhaps deposited the ore bodies.

The geologic evidence indicates that the deposit is not the product of a single event but has had a long and complex history. The lack of radiometric age dating and sulphur isotope data make the problem of the genesis and subsequent history of the ore deposit much more difficult and open to greater speculation.

The ultimate origin of the ore cannot be proved because of post-depositional changes. The idea that the ore originated during volcanism as a "strata-bound" deposit is questionable. As with the other ore deposits in the Flin Flon area, the location of the Coronation ore bodies within a zone of shearing and the parallelism between the plunge of the orebodies and linear structures in the enclosing rocks suggest that the ore-bearing solutions penetrated the rock along these structural and textural lineaments formed during the deformation of the volcanic rocks. It is suggested that the solutions may be products of geosynclinal magmatism that took place during an early stage of the Hudsonian orogeny and may be related to the basic intrusions that accompanied the deformation of the geosyncline.

At a later stage in the orogeny, when the rocks underwent regional metamorphism, the ore and wallrock were recrystallized under the prevailing metamorphic conditions. At the same time the sulphides were partly remobilized and injected into adjacent, local areas of dilation within the zone of shearing.

Post-metamorphic movements, perhaps related to the Ross Lake fault system, together with solutions at relatively low temperatures, caused some dispersion and lateral secretion of sulphides with the formation of the late sulphide and quartz veins and produced local chloritization of the wall-rocks. These solutions may have been related to the post-tectonic Boundary intrusions.

In conclusion, it is to be hoped that the facts and views expressed in this symposium will stimulate further studies of sulphide deposits and so promote a better insight into the factors controlling the distribution and localization of sulphide ores, in particular those of Precambrian age.

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No. 2 GENERAL GEOLOGY OF THE CORONATION
MINE AREA

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ABSTRACT

The Precambrian rocks of the Flin Flon region are divided into three units. Predominantly volcanic rocks of the Amisk Group and clastic sedimentary rocks of the Missi Group form a sequence of rocks, which, in the northern part of the region, have been metamorphosed to gneisses constituting the Kisseynew Complex. Numerous basic intrusions are associated with the Amisk volcanic rocks. During a period of orogeny, all these rocks were subjected to deformation and regional metamorphism accompanied by granodioritic intrusions. The masses of granodiorite, as well as all earlier rocks, are cut by late wrench faults and shear joints. The Coronation mine area is a very small part of the Flin Flon region, south of the boundary with the Kisseynew gneisses. This area is underlain by rocks of the Amisk Group, basic intrusions, and granodioritic masses. The volcanic rocks contain some sulphide mineralization, including the orebodies of the Coronation, Birch Lake, and Flexar mines.

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INTRODUCTION

The Coronation orebody is one of several massive sulphide deposits in the Flin Flon region. As part of the Coronation Mine Project, an area 4 by 8 1/2 miles, surrounding the Coronation mine and extending north to the Birch Lake mine and Flexar mine, has been mapped on a scale of 1 inch = 1,000 feet. This area will be referred to as the Coronation mine area. The purpose of this report is to give an account of the geology of the Coronation mine area, in order to provide some background for detailed studies of the Coronation mine.

GEOLOGICAL SETTING

Figure 1 shows the general geology of the Flin Flon region and the location of the Coronation mine area. The geology of the region in Manitoba has been taken from a compilation by Davies et al. (1962) and the geology of the Saskatchewan part of the region is based on reports by Byers et al. (1954a and 1965). All of the region has been mapped on a scale of 1 inch = 1 mile or 1 inch = 1/2 mile. Figure 2 provides a key to these maps. For many areas, the maps are accompanied by comprehensive geological reports. Two smaller areas, around Flin Flon (Stockwell, 1960) and around Ledge Lake (Heywood, 1966), have been mapped on a scale of 1 inch = 1,000 feet. Accounts of the regional geology are included in the following publications: Byers et al., 1954a, 1954b, 1965; Davies et al., 1962; Harrison, 1951a and 1951b; Kalliokoski, 1952 and 1953; McGlynn, 1959; and Robertson, 1951.

The Flin Flon region is part of the Churchill structural province, which is characterized by K-Ar dates of $1,735 \pm 95$ million years (Stockwell, 1964). The oldest rocks, known as the Amisk Group, consist of volcanic flows and pyroclastic rocks together with subordinate amounts of clastic sedimentary rocks. Conglomerate, greywacke, and arkose, belonging to the Missi Group, were deposited on the eroded Amisk rocks. Rocks of the Missi Group occur as small detached masses within the Amisk rocks. In various areas east of Flin Flon, pre-Missi granitic intrusions are believed to occur, indicating a pre-Missi orogeny. However, in the area west of Flin Flon, the only pre-Missi intrusive rocks are small porphyry bodies presumably related to the volcanic rocks (Byers, 1953; Byers et al., 1954a). According to this evidence, the Amisk-Missi unconformity represents a rather short time interval and does not mark an intervening orogeny.

The Amisk and Missi rocks form an easterly trending belt, about 20 miles wide. North of this belt, a large area is underlain by gneisses belonging to the Kiseynew Complex. The contact is commonly marked by a topographic lineament, known as the Kiseynew front. The age relationship between the Amisk-Missi rocks and the Kiseynew gneisses is uncertain. In some areas east of Flin Flon, the Kiseynew front is marked by faulting and it has been interpreted by Harrison (1951b) and Kalliokoski (1953) as a major fault zone along which the Kiseynew gneisses have been thrust over Amisk-Missi rocks. On the other hand, Robertson (1951) and McGlynn (1959) have suggested that the Kiseynew front essentially marks the contact between dissimilar rocks. In some places, an erosional unconformity is present, whereas in many exposures the contact is conformable. Locally this

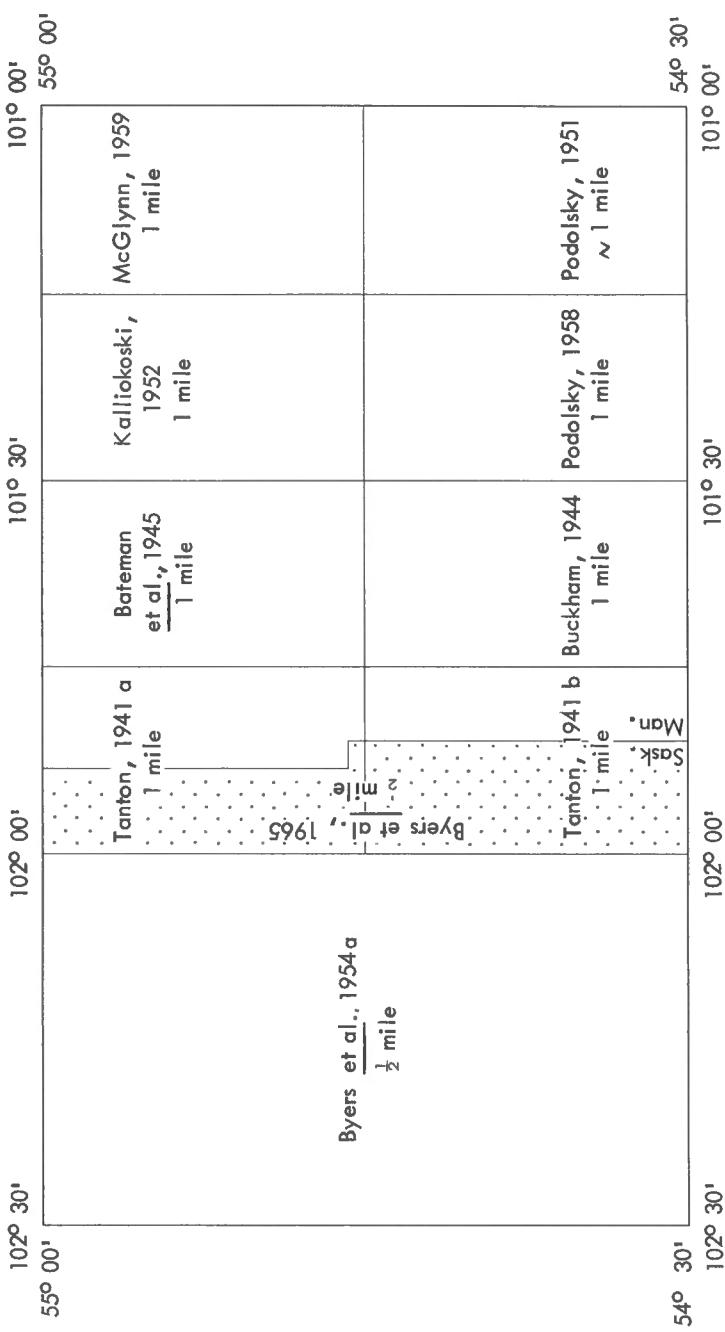


Figure 2. Key to published geological maps of the Flin Flon region.

relationship is complicated by faulting. They also emphasize that the change of metamorphic grade from Amisk rocks to Kiseynew gneisses is gradational. In the Amisk-Wildnest Lakes area, the Kiseynew gneisses are considered to be metamorphosed Amisk and Missi rocks (Byers et al., 1954a, 1965). In this area at least, the Kiseynew front essentially represents a metamorphic boundary across which the grade of metamorphism increases to the north over a relatively short distance. The metamorphic grade of the Kiseynew gneisses corresponds to the amphibolite facies, whereas that of the Amisk-Missi rocks corresponds to the greenschist and lower amphibolite facies. Most of the Kiseynew gneisses are derived from sedimentary rocks. Therefore, the Kiseynew front also represents the boundary between predominantly volcanic Amisk rocks and predominantly meta-sedimentary Kiseynew gneisses.

A variety of porphyritic intrusive rocks, varying in composition from andesite to rhyolite, form dikes, sills, and small irregular bodies in Amisk volcanic rocks. These porphyritic intrusions are thought to be closely related to the Amisk volcanic rocks and are included in the Amisk Group (Byers et al., 1954a). In addition to these small intrusions, basic intrusions of larger dimensions, together with some associated ultrabasic rocks, are very common in the volcanic rocks of the Amisk Group and most of these intrusions are probably related to the same period of igneous activity. However, some of the basic intrusions occurring along margins of granodiorite masses appear to be related to the period of granodiorite intrusions (Byers et al., 1954a). Some basic intrusions are considered to be even younger than the granodiorite. The Boundary Intrusions in the vicinity of Flin Flon (Stockwell, 1960) belong to this group of post-tectonic rocks. All rocks of the Amisk and Missi Groups, the Kiseynew gneisses, and the basic intrusions related to the Amisk volcanism have been intruded by large masses of granodiorite and subjected to regional metamorphism and deformation. Along the margins of the granodiorite masses, some basic rocks form part of the intrusive complex.

In the southern part of the Flin Flon region, the Precambrian rocks are unconformably overlain by Ordovician sandstone and dolomite.

LITHOLOGY

The Coronation mine area is included in the region mapped by Byers et al. (1954a and 1965) on a scale of 1 inch = 1/2 mile. These maps form part of detailed geological reports. In connection with the Coronation Mine Project, the area was mapped on a scale of 1 inch = 400 feet by E. Froese, D. R. E. Whitmore, and M. J. Rutherford. The gabbro intrusion to the east of Ruth and Table Lakes has been studied by Wohlberg (1964), and some intrusive rocks in the Mystic Lake area have been described by Eckstrand (1962).

An unpublished map on a scale of 1 inch = 1000 feet was included in a thesis by Froese (1963). For the present publication, this map has been somewhat modified and reduced to 1 inch = 1/2 mile and is shown as Figure 3. A small area around the Coronation mine is shown as Figure 4.

The subdivision of rock units in the Coronation mine area is given in Table 1.

Table 1

Table of Formations for the Coronation Mine Area

Age	Rock Units	Rock Types
Ordovician	Red River Fm. Winnipeg Fm.	Dolomite Sandstone
Precambrian	Synorogenic intrusive rocks	"Quartz-eye" diorite Granodiorite Gabbro and diorite
	Intrusive rocks related to Amisk volcanism	Basic feldspar porphyry Acidic feldspar porphyry Ultrabasic rocks Amphibolite Gabbro and diorite
	Amisk Group: Metamorphosed volcanic and sedimentary rocks	Cordierite-anthophyllite rocks and sulphide ores Biotite gneisses Brecciated quartz-feldspar porphyry Basic volcanic breccia Acidic pyroclastic rocks Basic pyroclastic rocks Basic volcanic flow rocks

Amisk Group

The basic volcanic flow rocks are dark greenish grey and weather light greenish grey. Primary structures are preserved in many places. The grain size is fine to very fine, more rarely medium. The rocks consist essentially of hornblende, plagioclase of composition An_{30-40} , and epidote.

The basic pyroclastic rocks consist of tuffs and agglomerates. The tuffs are similar in color, grain size, and composition to the basic flow rocks. Their distinguishing feature is a thinly layered structure. Agglomerate is also common and generally consists of acidic fragments, up to six inches across, set in a more basic groundmass. At the east end of Mystic Lake, basic tuff is interlayered with "augen" gneiss, occurring as discontinuous and lenticular layers a few feet to several tens of feet thick. The rock consists of quartz, plagioclase, biotite, and muscovite. Remnants of plagioclase form medium-grained "augen" in a very fine-grained groundmass.

Acidic pyroclastic rocks are very fine-grained, light grey, and buff-weathering. A thin compositional layering is characteristic. Agglomerate is present in some outcrops. The main minerals are quartz, plagioclase, biotite, and either muscovite or hornblende. Garnet is present in a few rocks.

A rather peculiar rock type is here called basic volcanic breccia. This rock lacks compositional layering. Plagioclase and hornblende crystals up to 1/4 inch occur in a fine-grained groundmass. In some exposures, the rocks look like intrusive hornblende-feldspar porphyries. However, on closer inspection, a patchy distribution of plagioclase and hornblende crystals becomes apparent suggesting a fragmental structure. The absence of pillows and amygdules is taken as an indication that these rocks are of pyroclastic origin, in spite of the lack of compositional layering.

Within the unit of basic volcanic breccia, irregular masses of brecciated quartz-feldspar porphyry occur. This rock is light grey and buff-weathering. Quartz and feldspar crystals occur in a very fine-grained groundmass consisting of quartz, feldspar, and a very small amount of mica. The rock commonly is coarsely fragmental, rather angular fragments being embedded in a more basic groundmass. This rock unit, together with the basic volcanic breccia, probably represents a deposit of massive pyroclastic rocks in contrast to the layered tuffs and agglomerates.

Biotite gneisses are present in the Mystic Lake area where they are interlayered with basic pyroclastic rocks. The rocks are grey and weather light grey. Gneissic layers a few millimeters thick are typical. Besides this structure, there also is a coarser compositional layering, several inches thick. The rock is medium-grained; feldspar is somewhat porphyroblastic. The main minerals are quartz, plagioclase of composition An_{28-40} , microcline, biotite, and muscovite. Garnet, anthophyllite, and staurolite occur locally in layers devoid of microcline and muscovite. The biotite gneisses are metamorphosed equivalents of either pyroclastic or sedimentary rocks. The absence of agglomerate layers and a more pelitic composition than that of acidic pyroclastic rocks suggest a sedimentary origin.

Mineral Deposits

Three known commercial sulphide deposits occur within the volcanic rocks of the area; these are the Coronation, Birch Lake, and Flexar orebodies. The Birch Lake mine has been described by Macdougall (1952) and Byers *et al.* (1954a). The Flexar mine is being developed at the present time and no information on the geology is available. The geology of Coronation mine has been described by Byers *et al.* (1965) and is presented in more detail by Whitmore (1969). Some of the silicate gangue minerals have been described by McGinn (1956) and Rutherford (1961). A more detailed account is given by Froese (1969). The ore minerals have been studied by Ferris (1961), and Kanehira (1969). Gilliland (1965) has reported some zoning of the Coronation orebody.

The sulphide minerals are pyrite, pyrrhotite, chalcopyrite, and sphalerite. Magnetite is commonly associated with the sulphides. The ore consists of massive sulphides and disseminations and stringers in the host rocks. Near the Coronation orebody, an irregular mass of cordierite-anthophyllite rocks occurs in the basic volcanic rocks. Small masses of acidic pyroclastic rocks are also present. The ore is developed in all three of these rock types. Although the cordierite-anthophyllite rocks are spatially related to the ore in a general way, their exact distribution is very irregular. They do not form any zonal arrangement about the orebody. At the Birch Lake mine, cordierite-anthophyllite rocks do not occur and so far they have

Table 2

Composition of Basic Volcanic Flow Rocks and of Gabbro

Location	Basic volcanic flow rocks.																				Gabbro	
	F60-219	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20		
	F60-296	F60-236	F60-302	F60-292	F60-297	F60-291	F60-295	F60-286	F60-91	F60-167	F60-298	F60-276	F60-177	F60-299	F60-300	F60-294	F60-174	F60-95	F60-145			
SiO ₂	47.6	50.4	50.7	50.8	51.5	51.6	52.0	52.2	52.7	54.4	54.6	55.7	56.4	56.6	57.2	58.3	59.7	60.5	61.3	48.6		
Al ₂ O ₃	15.5	15.7	11.0	13.9	14.5	16.6	14.1	18.1	17.1	15.8	16.4	15.8	16.1	15.9	15.3	15.9	14.5	14.5	15.4	21.9		
Fe ₂ O ₃	1.7	2.7	1.6	4.3	4.5	4.3	3.6	1.1	2.5	2.3	2.2	2.8	2.6	0.9	4.4	2.5	1.4	1.7	2.0	1.1		
FeO	9.3	7.47	8.4	11.81	5.91	7.81	10.01	8.38	8.8	9.6	8.0	9.06	6.9	7.85	7.50	8.38	7.88	8.1	5.6	4.01		
MgO	11.8	6.5	12.9	3.9	7.2	5.4	5.7	6.5	5.0	4.6	5.7	3.4	4.7	6.3	3.8	3.8	4.1	4.8	2.9	6.2		
CaO	8.2	10.8	11.0	10.4	7.5	5.6	8.1	5.9	8.0	8.0	8.3	7.0	7.8	5.4	5.5	3.6	5.7	4.9	8.0	12.4		
Na ₂ O	2.4	2.5	1.2	0.54	3.2	4.1	2.6	3.7	3.8	3.1	3.1	3.9	3.7	4.3	4.1	3.6	4.8	2.4	3.5	1.7		
K ₂ O	0.22	0.38	0.36	0.28	0.62	0.66	0.42	0.46	0.38	0.20	0.12	0.30	0.38	0.16	0.64	0.20	0.18	0.12	0.12	0.34		
TiO ₂	0.28	1.0	0.31	1.5	0.88	1.1	1.3	0.33	0.38	0.44	0.43	1.1	0.27	0.31	0.34	0.30	0.77	0.44	0.40	0.37		
MnO	0.19	0.21	0.17	0.22	0.19	0.25	0.19	0.17	0.17	0.28	0.17	0.20	0.17	0.18	0.15	0.19	0.18	0.16	0.10	0.26		
P ₂ O ₅	0.03	0.14	0.03	0.21	0.15	0.19	0.16	0.07	0.04	0.06	0.06	0.18	0.05	0.07	0.08	0.07	0.15	0.06	0.07	0.07		
H ₂ O	2.6	1.8	2.2	1.8	2.8	2.1	2.0	2.6	1.7	1.5	1.7	1.4	1.5	1.7	2.1	1.7	1.2	2.3	1.0	2.4		
CO ₂	n.d.	0.08	n.d.	0.30	0.08	0.07	0.01	0.02	n.d.	n.d.	n.d.	0.06	n.d.	n.d.	0.04	0.08	0.24	0.03	n.d.	n.d.		
S	—	0.03	—	0.11	0.03	0.03	0.00	0.01	—	—	—	0.02	—	—	0.20	0.15	0.03	—	—	—		
Less S = O	99.8	99.9	99.9	99.9	99.5	99.8	100.4	99.7	100.6	100.3	100.8	101.0	100.6	99.7	101.3	101.4	100.8	100.0	100.4	99.6		

Analysts: Nos. 1, 3, 9, 11, 13, 18, 19 Hounslow, Queen's University																				
Nos. 2, 4-8, 12, 14-17, 20 Rapid Methods Group, Analytical Chemistry Section, Geological Survey of Canada																				
Trace elements in silicate fraction (spectrographic analysis; p.p.m.)																				
Zr	55	78	26	190	76	94	120	19	37	33	33	78	35	27	36	29	52	40	31	22
Cr	600	310	>600	36	26	<10	29	40	22	<10	<10	45	38	60	24	46	<10	38	<10	160
V	490	200	200	480	540	590	560	300	382	275	300	430	290	320	540	420	520	250	274	190
Co	55	52	60	54	39	24	55	29	34	42	42	41	37	36	36	28	43	41	19	46
Ni	180	96	260	34	94	11	37	43	18	18	24	55	30	36	29	18	21	16	110	16
U	24	130	10	170	22	61	110	125	>150	90	90	140	32	100	180	200	16	<3	<3	130

Trace elements in silicate fraction (spectrographic analysis; p.p.m.)

	55	78	26	190	76	94	120	19	37	33	78	35	27	36	29	52	40	31	22
Zr																			
Cr	600	310	>600	36	26	<10	29	40	22	<10	45	38	60	24	46	<10	38	<10	160
V	215	490	200	480	540	590	560	300	382	275	300	290	320	540	420	520	250	274	190
Co	55	52	60	54	39	24	55	29	34	42	41	37	36	36	28	43	41	19	46
Ni	180	96	260	34	94	11	37	43	18	18	24	55	30	36	29	41	18	16	110
Cu	24	130	10	170	22	54	61	110	125	>150	90	140	32	100	180	200	<3	<3	130

Analysts: Nos. 1, 3, 9, 10, 11, 13, 18, 19 G. MacDonald, Queen's University; Nos. 2, 4-8, 12, 14-17, 20 E. Froese, Queen's University

not been found in the Flexar mine. A cordierite-cummingtonite rock was found in only one locality on the surface; namely 600 feet east from the shore of Birch Lake and 200 feet south from its north end. This rock is exposed in a trench cut through overburden. All the surrounding rocks are basic volcanic flow rocks.

Intrusive Rocks Related to Amisk Volcanism

The Amisk Group is intruded by large bodies of basic rocks. Of these, gabbro is more common than diorite but, because of their altered condition, the two are not readily distinguishable. A large body of gabbro occupies the Table-Birch Lakes area. The rock is medium-grained. It consists of green hornblende and white aggregates of feldspar alteration products. Wohlberg (1964) studied a part of this intrusion and found that the white aggregate consisted entirely of zoisite. The gabbro mass is foliated and pegmatitic segregations parallel to the foliation are common. Locally the rock grades into quartz diorite, characterized by a streaky layering of quartz-rich and quartz-poor layers. A similar mass of gabbro occurs between Barney Lake and Mystic Lake, but here foliation is very poorly developed or absent. In some specimens, remnant grains of labradorite and clinopyroxene are present.

Among the eastern margin of the Barney-Mystic Lakes gabbro, a poorly-foliated mass of amphibolite is present. This is also a medium-grained rock. In contrast to the gabbro, it contains more hornblende (up to 70 per cent). The hornblende crystals are somewhat porphyroblastic and protrude as little knobs on the weathered surface.

The gabbro in the Table-Birch Lakes area contains tabular bodies of ultrabasic rocks, having sharp contacts. The rocks are dark green to black and weather to various shades of brown. Fine-grained peridotite and medium-grained pyroxenite commonly form lenticular layers a few inches thick. The rocks are extensively serpentinized. Other alteration products are talc and magnesite.

Acidic feldspar porphyry forms dikes and irregular masses in rocks of the Amisk Group and in gabbro. It is light yellowish grey and typically buff-weathering. Plagioclase phenocrysts occur in a very fine-grained groundmass of quartz, plagioclase, and hornblende. Sills and dikes of quartz-feldspar porphyry, too small to be shown on the map, are common in Amisk rocks. Phenocrysts of quartz and albite are set in a very fine-grained groundmass of quartz, plagioclase, and biotite.

Basic feldspar porphyry forms small irregularly-shaped intrusions and dikes in Amisk rocks and gabbros. Plagioclase phenocrysts occur in a fine-grained groundmass of plagioclase and hornblende. The phenocrysts increase in number and size for a distance of about six inches away from the walls, where the rock becomes uniform. The gabbro masses and Amisk rocks are also intruded by small diabase dikes in which subhedral plagioclase laths give rise to a diabasic texture. In some dikes, brownish phenocrysts are present, consisting of hornblende, chlorite, and a few remnants of pyroxene.

Synorogenic Intrusive Rocks

The Amisk rocks and gabbro masses are intruded by large bodies of granodiorite. Along the margins of these bodies, gabbros and diorites are present in many places. They are structurally conformable to the granodiorite masses and very likely represent contaminated border zones or older gabbro dragged along by the granodiorite intrusions.

Granodiorite forms a large homogeneous mass, largely covered by overburden, in the southeastern corner of the map-area. Some of the marginal gabbroic rocks are very basic, containing in some places only 20 per cent feldspar. A complex of granodiorite, with inclusions of gabbro and complicated contact relationships to the adjacent gabbro, occupies the northeast corner of the map-area. A variety of rock types are intermixed and intrusive breccias are common. Homogeneous granodiorite forms two elliptical bodies northeast of Barney Lake.

The granodiorite is light pink and medium-grained. The main minerals are quartz, plagioclase (An_{25-30}), microcline, biotite, and hornblende.

"Quartz-eye" diorite, consisting almost totally of quartz and plagioclase, occurs on some of the islands in Table Lake. It is characterized by rounded and angular quartz phenocrysts. Plagioclase phenocrysts are also common.

Paleozoic Rocks

Flat-lying Ordovician dolomite forms prominent escarpments flanked by coarse talus slopes. It is fine-grained, light grey in color, and weathers light-grey to buff. Sandstone underlies the dolomite, but is not exposed in the Coronation mine area.

CHEMICAL COMPOSITION OF THE BASIC VOLCANIC ROCKS

In order to show the chemical characteristics of the basic volcanic rocks from the Coronation mine area, some analyses are given in Table 2. The samples come from a unit of basic volcanic flow rocks extending from the Coronation mine north to Stitt Lake (Figure 3). The location of the samples is given in Table 2 by the distance in miles north or south and east or west from the intersection of the 2nd Meridian and the 17th Baseline. Some of the rock samples contained disseminated pyrite. For these, the analyses given refer to the silicate fraction. The trace element content of the pyrite separated from these samples is given as well. Some of the analyses were carried out by A. W. Hounslow while at Queen's University, Kingston, according to methods of rapid silicate analysis described by Hounslow and Moore (1966). The other samples were analyzed by similar methods in the Analytical Chemistry Section, Geological Survey of Canada. Trace elements were determined by G. MacDonald and E. Froese at Queen's University according to the method described by Hawley et al. (1956) for silicate rocks and Hawley et al. (1961) for sulphides.

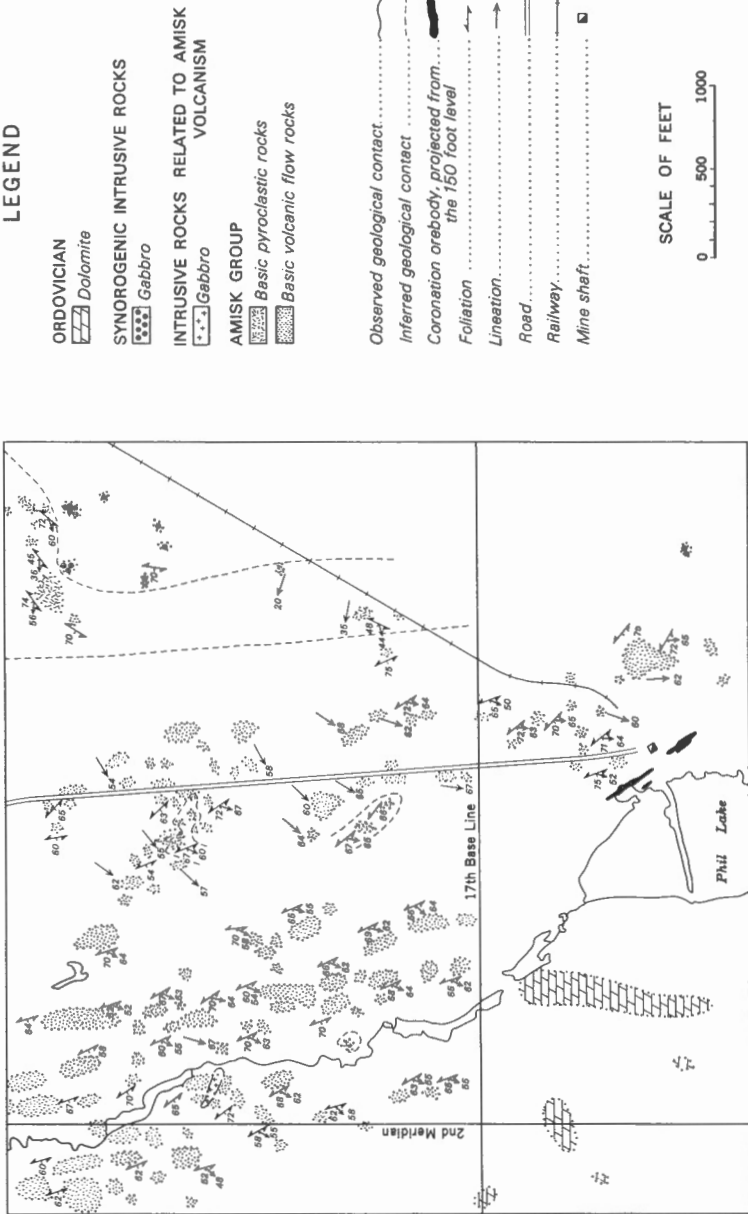


Figure 4. Geology of the immediate vicinity of the Coronation mine.

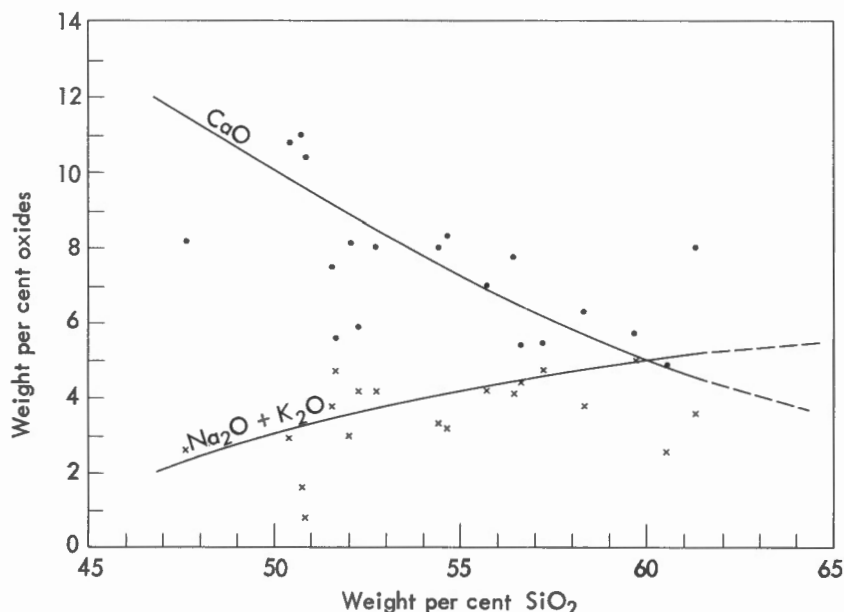


Figure 5. Variation diagram of $(\text{Na}_2\text{O} + \text{K}_2\text{O})$ and of CaO showing the alkali-lime index, i.e. the percentage of SiO_2 at which the two curves cross.

The quartz-bearing acidic pyroclastic rocks probably belong to the same sequence of volcanic rocks as the basic volcanic flow rocks. In such case, the basic volcanic flow rocks belong to the basalt-andesite-rhyolite association (Turner and Verhoogen, 1960, p. 272-288). This feature is also indicated by the variation in composition of the basic volcanic flow rocks. Figure 5 is a variation diagram of $(\text{Na}_2\text{O} + \text{K}_2\text{O})$ and CaO plotted against SiO_2 , all oxides expressed as weight per cent. The percentage SiO_2 at which the percentages of $(\text{Na}_2\text{O} + \text{K}_2\text{O})$ and of CaO are equal is known as the alkali-lime index (Peacock, 1931). For the rocks from the Coronation mine area, this index is about 60 which is typical of the basalt-andesite-rhyolite association. In this respect and in their low content of K_2O , the rocks are chemically very similar to Archean volcanic rocks from the Superior Province of the Canadian Shield (Wilson *et al.* 1965).

Although the basic volcanic rocks are mineralogically very similar, their chemical composition varies appreciably. This is particularly evident from the norms also given in Table 2. This is taken as an indication that

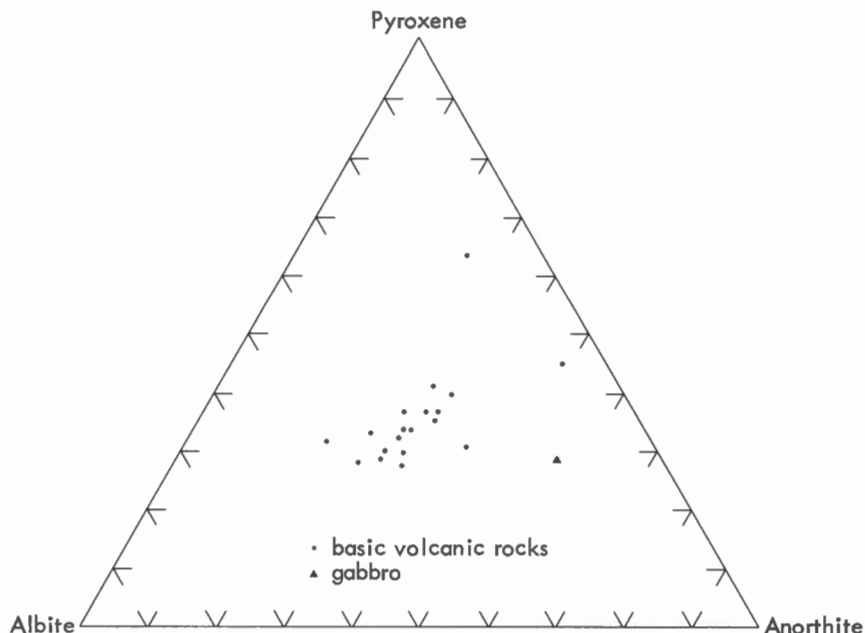


Figure 6. The composition (weight per cent) of basic volcanic rocks and of gabbro in terms of normative albite, anorthite, and pyroxene (diopside + hedenbergite + enstatite + ferrosilite).

differentiation has been effective. The rocks are composed essentially of normative albite, anorthite, and pyroxenes. These constituents are accompanied by minor amounts of magnetite, ilmenite, orthoclase, and quartz or olivine. In Figure 6, the rock compositions are plotted on the triangular diagram albite-anorthite-pyroxene (sum of diopside, hedenbergite, enstatite, and ferrosilite), all constituents expressed in weight per cent. The proportion of plagioclase to pyroxene is rather constant for most volcanic rocks. This feature suggests simultaneous crystallization. In contrast, the basic intrusions which probably are accumulated differentiation products appear to have a different ratio of plagioclase to pyroxene. In Table 2, an analysis of

a typical sample from the gabbro mass between Barney Lake and Mystic Lake is given. This composition is also plotted in Figure 6. The gabbro is characterized by very basic plagioclase and a higher proportion of plagioclase to pyroxene. On the other hand, the ultrabasic rocks would, of course, plot at the pyroxene corner.

The basalt-andesite-rhyolite association is typically developed during the later stages of orogeny. However, this association does also occur in geosynclinal, pre-orogenic rock sequences (Turner and Verhoogen, 1960, p. 258). In such cases, the tectonic setting would be that commonly ascribed to spilites which are considered to be typical products of geosynclinal magmatism. The geological setting of the Flin Flon region suggests very strongly that the volcanic rocks of the Amisk Group and the associated basic and ultrabasic intrusions are products of geosynclinal magmatism, although the volcanic rocks very definitely do not have a spilitic composition. This is one important feature of the volcanic rocks. And another important point is the operation of differentiation as indicated by the chemical variability of the basic volcanic rocks themselves and by the presence of acidic pyroclastic rocks and basic and ultrabasic intrusions.

STRUCTURAL GEOLOGY

The structural geology of the Flin Flon region is dealt with in various geological reports previously referred to. Special attention is paid to the structural geology of the Saskatchewan part of the Flin Flon region in reports by Byers *et al.* (1954a, 1954b, 1965), which include structural maps on a scale of 1 inch = 2 miles. Because the Coronation mine area is part of the area covered by these reports, they are of particular relevance in providing a setting of the regional structural geology.

The Amisk rocks in the Coronation mine area, as in most areas of the Flin Flon region, have undergone penetrative movement. This has caused a deformation of primary structures and has produced a foliation and lineation in most rocks. These structural features are related to one major orogenic movement which gave rise to deformation, regional metamorphism, and intrusion of granodiorite bodies (Byers *et al.*, 1954a, 1954b, 1965). Most of the basic intrusions are probably related to the period of Amisk volcanism and as such are pre-tectonic. Their response to deformation differed from that of the volcanic and sedimentary rocks. Rather than being penetrative, deformation appears to have been localized, giving rise to gneissic zones separated by areas of massive rocks. Some gabbro masses are only very poorly foliated.

Two generations of foliation are observed in the area. The older foliation trends northerly with only gentle changes in strike. In the north-east and southeast corners of the area, large intrusions of granodiorite have developed a foliation near their margins and in adjacent rocks, which truncates the northerly foliation. Thus two stages of deformation can be recognized but there need not be a great time interval between them; very likely they formed during the same orogeny.

Cross joints subperpendicular to the lineation are very common. Later shear joints, which belong to a regional post-orogenic fault system cut all rocks, including the granodiorite bodies (Byers, 1962).

Primary Structures

In volcanic flow rocks, some primary structures, such as amygdules, pillows, and flow breccia are preserved. Rocks in which these occur form irregular, lenticular areas, the long axes of which possibly indicate the strike of the formations. In many places, these trends are nearly parallel to the foliation; however, a divergence in strike is not rare. No flow contacts were observed and tuffaceous horizon markers extending over an appreciable distance are lacking. A small layer of agglomerate in basic flow rocks, 2000 feet north of the Coronation mine, provides the best available information on the relationship between bedding and foliation (Fig. 4). The southern part of the layer is nearly parallel to the northerly foliation. To the north, the layer swings to strike east. Here the foliation, as indicated by flattened fragments, cuts across the layer and along it the layer is deformed into a zig-zag shape.

Primary structures preserved in pyroclastic rocks are thin compositional layering and layers of interbedded agglomerate. In the Coronation mine area, the layering is practically parallel to the flattening of the fragments. This is due to an extreme transposition of bedding (Turner and Weiss, 1963, p. 92-93). However, in some exposures outside the Coronation mine area (e. g. at the north tip of Phantom Lake), such rocks provide the best demonstration of non-parallelism of bedding and foliation. The plane of flattening of fragments (foliation) may be at an appreciable angle to the layering (bedding). The layering very likely reflects an original stratification, but the present thickness is the result of deformation.

Compositional layering in biotite gneisses very likely is also a reflection of inherited stratification. These rocks probably are of sedimentary origin.

Foliation and Lineation

The most prominent structural features of the rocks are foliation and lineation. In volcanic flow rocks, the foliation is defined by flattened amygdules, pillows, and flow breccia fragments and occasionally a very streaky layering. In pyroclastic rocks, the foliation is defined by flattened agglomerate fragments. Compositional layering is parallel or subparallel to the plane of flattening. In both rock groups, biotite, where present, is oriented parallel to the foliation defined by flattened elements. In biotite gneisses, the foliation is formed by the parallel orientation of biotite and by a segregation into thin biotite-rich and felsic-rich units. Compositional layering on a larger scale, up to several inches thick, is subparallel to the foliation. Compositional layering is also present in parts of the cordierite-anthophyllite rocks and in some of the ore from the Coronation mine.

Lineation in volcanic rocks is defined by elongated amygdules, pillows, and fragments. The long dimensions of hornblende crystals and the axes of gentle warps in the foliation planes are parallel to the direction of elongation. Minor folds are not developed, except near the contacts with the granodiorite intrusion north of Mystic Lake. The axes of these minor folds are parallel to the elongation of agglomerate fragments. In the biotite gneisses the lineation consists of spindle-shaped mineral aggregates. These are particularly noticeable as small streaks on foliation planes.

Two generations of foliation and lineation are recognized in the area. An older northerly foliation is truncated by a later foliation developed parallel to the contacts of granodiorite intrusions. The later foliation is particularly well developed around the mass underlying the northeast corner of the map-area. Some foliation is developed in marginal parts of the granodiorite but it is more prominent in the gabbros and volcanic rocks flanking the intrusion. The foliation in the intrusive rocks consists of a gneissic structure, that is an alternation of thin mafic-rich and felsic-rich layers. Truncation of the older foliation is particularly obvious in the Mystic Lake area. Also in this area, irregular folds, several tens of feet in amplitude, are developed in volcanic rocks along the contact, and agglomerate fragments are greatly deformed. The fold axes and the long axes of fragments both plunge steeply north. Following the contact to the west through Carson Lake and Birch Lake, the younger foliation truncates the older one at a progressively smaller angle, and to distinguish the two stages of deformation is more difficult. The granodiorite in the southeast corner of the map-area has somewhat different contact relationships. On the south shore of Mystic Lake, the granodiorite has bent the northerly-striking foliation to the east in the form of a smooth arc, instead of forming a narrow zone of minor folds like that along the north shore. Southwest along the contact, the granodiorite is flanked by a zone in which rocks, instead of being sharply truncated, are deformed into lineated rocks. Only locally, particularly towards the south boundary of the map-area, has this deformation been sufficiently intense to develop a northeasterly-striking foliation.

In some of the intrusions, conformable with the northerly-striking foliation in adjacent volcanic rocks, a foliation is developed which differs from the ones so far described. This foliation is very well developed in the Table Lake area. On the other hand, the intrusive body between Barney Lake and Mystic Lake is foliated only slightly. The foliation does not penetrate the whole rock mass; rather it consists of gneissic zones, a few feet to several tens of feet wide, separated by unsheared rock. Furthermore, the strike of the foliation is variable, the dip remaining steeply to the west. The average attitude is nearly conformable to the foliation in the adjacent volcanic rocks but individual attitudes, even from the same outcrop, deviate considerably from the average. In order to represent this foliation, pole diagrams from suitable areal subdivisions were constructed. For each of these areas, the average attitude of the foliation is shown by a large symbol and the extent of the fluctuation, arbitrarily chosen as the spread of the 8 per cent contour on the pole diagram, is indicated by small symbols. In areas with few structural observations, only the average attitude is shown.

Origin of Foliation and Lineation

In the Coronation mine area, numerous primary structures with approximately spherical shape can be recognized in their deformed state. Therefore, the strain ellipsoid for finite homogeneous strain (Turner and Weiss, 1963, p. 268) is a useful reference system for structural elements in the present study. The long, intermediate, and short axes of the strain ellipsoid, known as the principal axes of strain, will be designated as A, B, and C. According to this definition and the previous description, the foliation of the volcanic rocks is parallel to AB and the lineation is parallel to A.

The actual ratio of the strain axes could not be measured. Pillows and fragments are too irregular and could not be observed in three dimensions. The deformation of amygdulites could be estimated in some places. It is usually not very intense. Rarely are amygdulites deformed any more than to give a ratio of 10:5:1. Southwest of the Coronation mine, the approximate ratio is 3:1:1. Here the rocks are only poorly foliated. In the contact zone of the granodiorite, north of Mystic Lake, the deformation is more intense as indicated by greatly elongated agglomerate fragments. On the whole, it seems that the degree of deformation differs considerably in various localities.

The deformation of a spherical element into a strain ellipsoid gives complete information about the strain in a body. The orientation of other deformed features, e. g. bedding planes, with respect to the strain ellipsoid is variable. However, with continued deformation the orientation of any inhomogeneity will approach the AB plane of the strain ellipsoid. This limiting position is in many places very nearly reached, as indicated by parallelism of flattened agglomerate fragments and compositional layering in tuff.

The preferred orientation of biotite and hornblende is easily seen in outcrop and in hand specimens. This orientation bears a consistent relationship to the strain ellipsoid, wherever the relationship can be observed. The preferred orientation of biotite is parallel to the AB plane and that of hornblende is parallel to the A axis.

The attitude of foliation and lineation in volcanic rocks records the orientation of the strain axes. This attitude fluctuates very little in any one locality and shows gradual changes in space. This suggests that the deformation within an area of constant attitude of foliation and lineation had common elements. The individual strain ellipsoid gives no indication of the mechanism of deformation. However, a tendency towards parallelism suggests that flowage parallel to some flow channel was effective and the AB plane of all strain ellipsoids in some restricted area approached parallelism with the flow channel. If the width of the flow channel remains constant, the result is plane strain in the deformation plane, i. e. the plane parallel to the flow direction and perpendicular to the flow channel. If the flow channel varies in width, an extension or compression perpendicular to the deformation plane will take place. In such a case, the A axis of the strain ellipsoid may be either parallel or perpendicular to the deformation plane.

In the development of the northerly foliation, the contacts between the gabbro masses and the volcanic rocks probably controlled the orientation of the flow channel for the volcanic rocks. The gabbro masses responded to deformation in a manner different from that of the volcanic rocks. Whereas the foliation in the volcanic rocks reflects a penetrative movement, the deformation in the gabbros is localized in the form of gneissic zones separated by massive rocks. The attitude of this foliation fluctuates considerably and different orientations can be observed in the same outcrop. The orientation of gneissic zones corresponds to that of shear fractures in a rock failing by fracturing rather than flow. Probably the same act of deformation produced the flow structures in the volcanic rocks and the gneissic zones in the gabbros. The development of structural differences presumably reflects different rock properties.

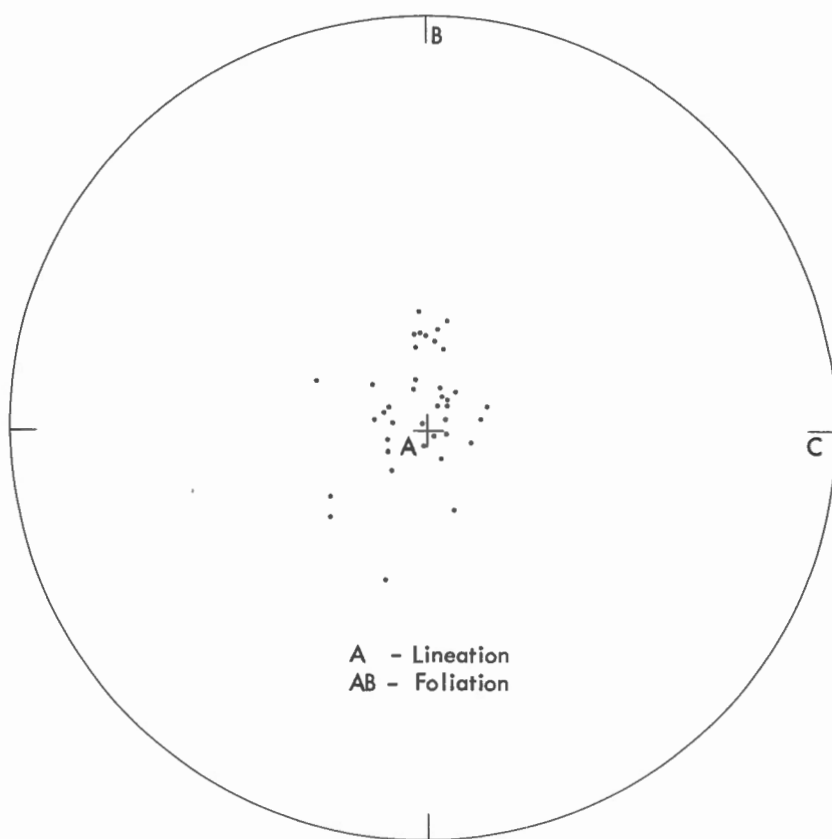


Figure 7. Orientation of poles to cross joints with respect to the lineation A and foliation AB (area between Stitt Lake and Echo Lake).

Joints Perpendicular and Parallel to the Lineation

Joints perpendicular to the lineation (cross joints) are very prominent in all lineated rocks of the area. They are typically spaced a few inches apart and rather uniformly developed throughout the rock. They are very tight and remarkably plane. No displacement was observed on any of these joints. In volcanic rocks, they may have a thin coating of epidote. Joints

parallel to the lineation (perpendicular to the B axis) are not nearly as common or well developed. They have been observed only in the Stitt Lake area.

Joints of this nature are commonly considered as tension fractures developed perpendicular to the least compressive stress. The relationship of these joints to the strain ellipsoid suggests at first a coincidence of strain and stress axes. However, this is true only for the special case of pure strain lacking a rotational component (Turner and Weiss, 1963, p. 271). Such a situation in deformed rocks is rare. It was considered of interest, therefore, to look into the possibility of small consistent deviations in the orientation of cross joints with respect to the strain ellipsoid.

In order to show the angular relationship between cross joints and the strain ellipsoid, the attitudes of cross joints were measured and for each cross joint the foliation and lineation at the same point of observation was recorded. From a restricted area, the pole of each cross joint was plotted on a stereonet together with the attitudes of the associated foliation and lineation. Then the diagram was rotated through the smallest angles possible to make the lineation vertical and bring the foliation into the north-south position. Diagrams were constructed for several areas; an example is shown in Figure 7. Some diagrams show an elongation of the scatter of poles parallel to AB. In some diagrams the maximum is slightly off-center. However, it was concluded that the cross joints are statistically perpendicular to the A axis of the strain ellipsoid. Because the stress axes and strain axes of deformation probably were not parallel, it is concluded that the cross joints are not related to the stress system of deformation. The cross joints obviously reflect the anisotropy of the rocks and could possibly be related to stresses set up when an anisotropic medium expands or is subjected to slight bending.

Shear Joints and Wrench Faults

Throughout the map-area, steeply-dipping joints are very common in all rock types. They are easily distinguished from cross joints by a number of features. These joints are not as tight as cross joints and their surface is more irregular. Branching joints are very common, whereas they are absent in the case of cross joints. The shear joints are not nearly as regularly distributed throughout the rock and not at such small intervals as the cross joints. And, above all, many shear joints show evidence of displacement.

The development of these joints apparently was the last structural event in the area and took place after all rocks had become sufficiently rigid to fail by brittle fracture. The joint patterns from various rock units of the area are very similar. In a general way, there is a northeasterly-striking set with right-hand displacement and a northwesterly-striking set with left-hand displacement. A wrench fault in the Mystic Lake area belongs to the first set. The two sets very likely belong to one joint system. In that case, because of their steep dip, movement on them would be nearly horizontal and any observed displacement would indicate the sense of movement. No clear-cut set of tension joints, striking easterly, was identified; rather the maxima of the two shear sets overlap in this region.

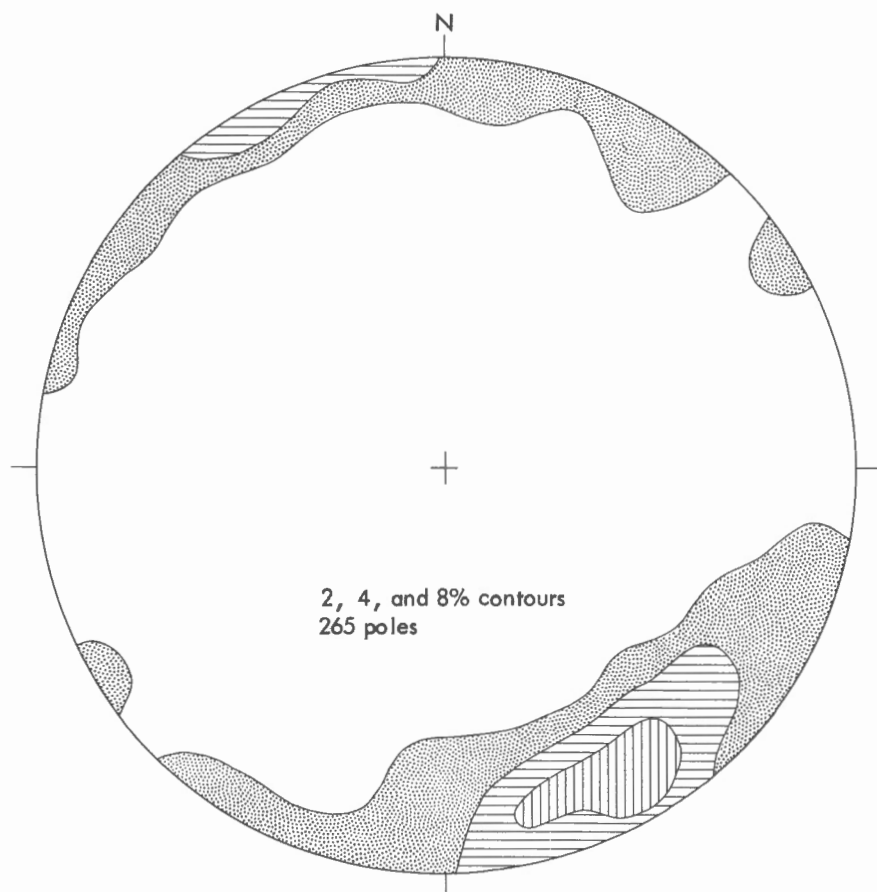


Figure 8. Poles of shear joints in volcanic rocks and biotite gneisses underlying the Mystic Lake area.

Shear joints are particularly well developed in the Mystic Lake area. Exposures are very good and the sense of movement could be observed on many joints. Figures 8, 9, and 10 give stereograms of all joints from the Mystic Lake area and of joints with determined sense of movement. The sense of movement is indicated by displaced markers, by associated tension joints and by second-order shear joints. Zones of closely-spaced joints are very common. Instead of a shear joint, a zone of en échelon tension joints may be developed. These tension joints are typically gaping. They are

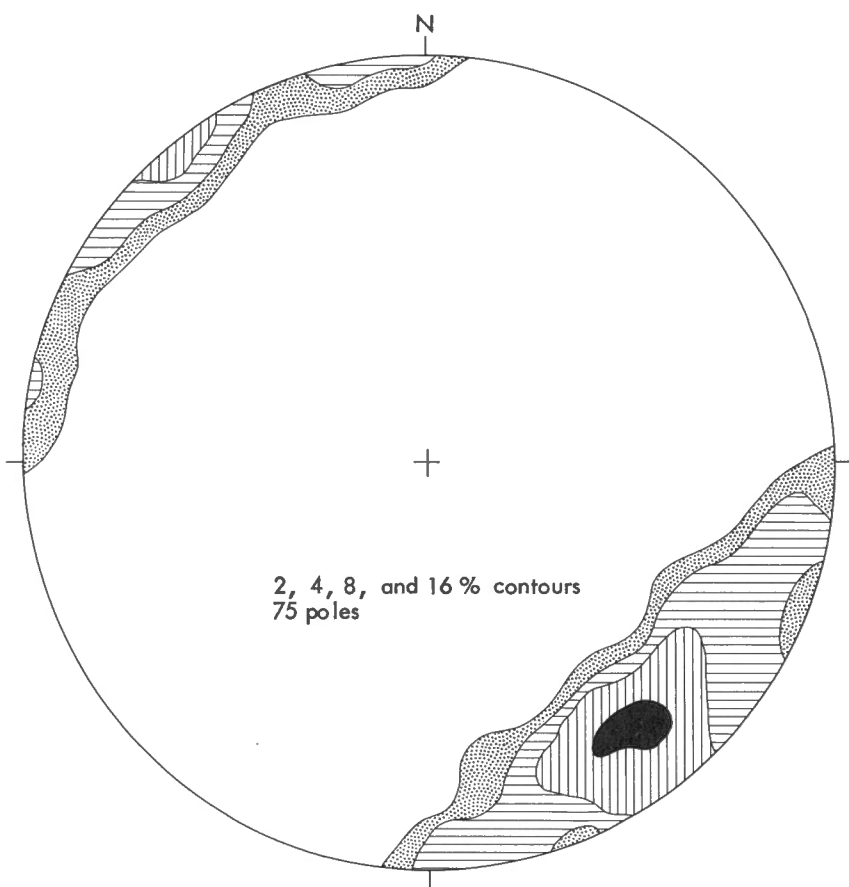


Figure 9. Poles of shear joints with right-hand movement in the Mystic Lake area.

curved in the sense of a possible drag fold associated with the joint. Displacement along shear joints is only a few inches to several feet.

In the Mystic Lake area, the wrench fault, which belongs to the set of shear joints with right-hand movement, is exposed in one place and marked by mylonite and breccia. The observed dip is 60 degrees northwest. However, the average dip of joints belonging to the right-hand set is 72 degrees northwest; this is probably a better value for the dip of the fault. The fault is a right-hand wrench fault, possibly with a small normal dip-slip

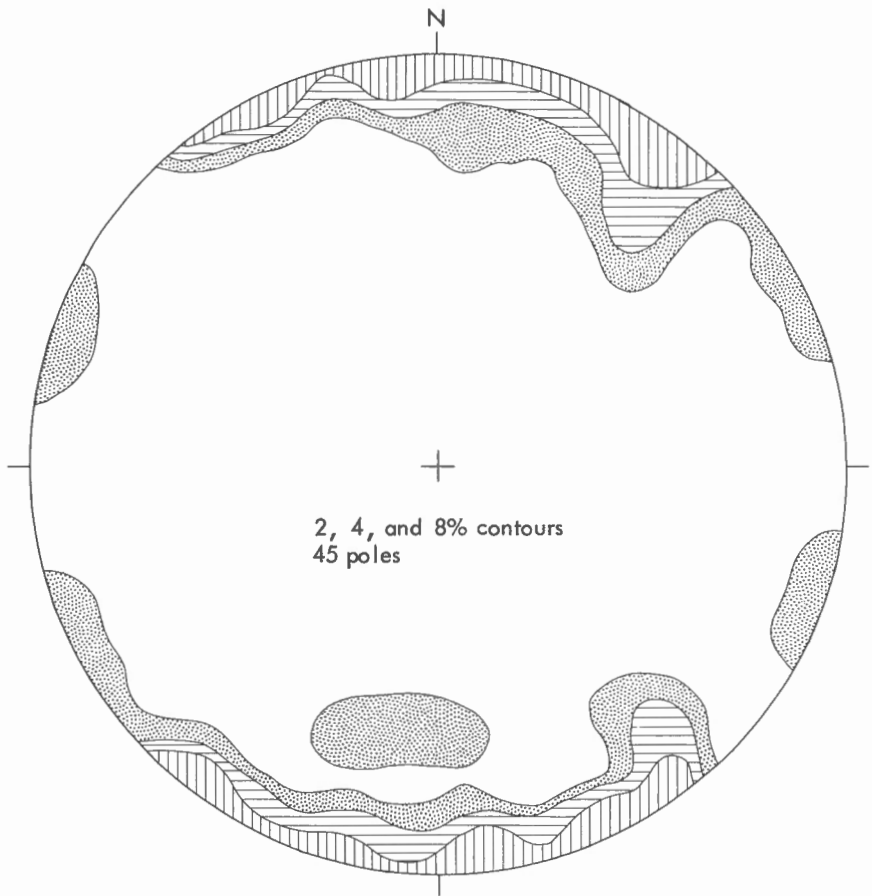


Figure 10. Poles of shear joints with left-hand movement in the Mystic Lake area.

component. The strike separation, practically equal to the strike-slip, is 1,000 to 1,400 feet, as determined by numerous displaced markers.

The shear joints are fractures due to brittle failure. The Mohr-Coulomb theory of brittle failure (Hubert, 1951) may have some relevance in an analysis of joint orientations. According to this theory, failure by shear occurs on two sets of conjugate planes intersecting in the intermediate stress axis σ_2 and making an angle $\theta = 45 - \frac{\phi}{2}$ with the greatest stress axis σ_1 , where ϕ is the angle of internal friction. In most rocks ϕ happens to be about

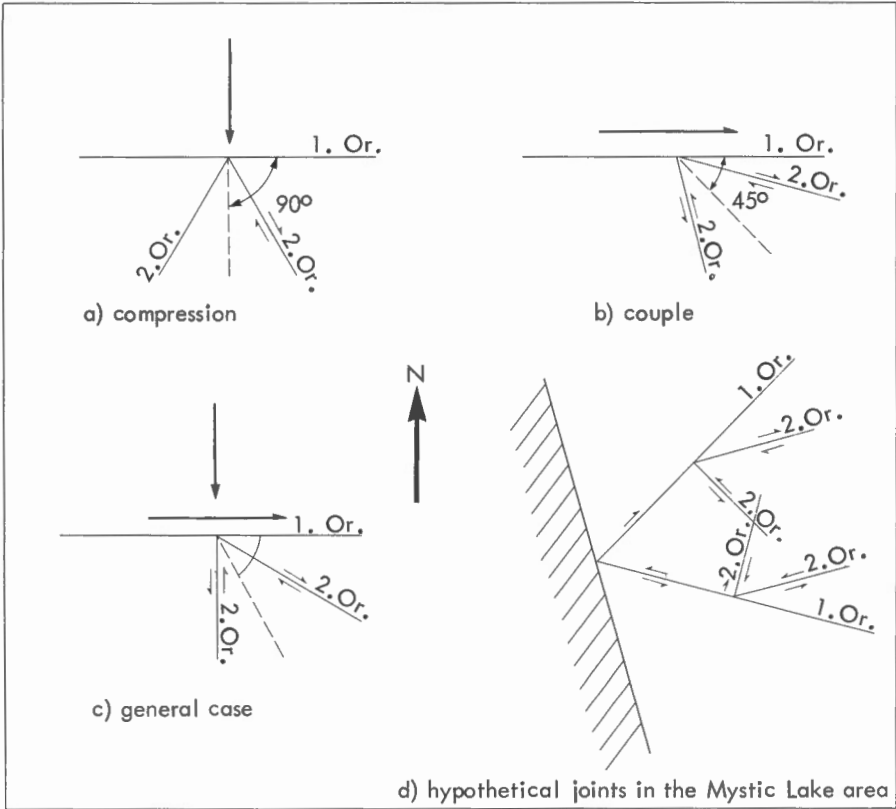


Figure 11. The development of second-order shear joints.

30 degrees; thus $\theta = 30$ degrees. The direction of movement on both sets of planes is perpendicular to the σ_2 axis and the sense of movement on the two sets is opposite. A difficulty in this analysis arises when deformation movement continues beyond the point of failure causing sets of initial conjugate shear fractures. This results in a rearrangement of stresses in a mechanically heterogeneous body of rock, and further failure occurs in numerous different stress systems. Any pattern in the joint distribution may be quickly

lost in such circumstances. However, the initial fractures may be such influential planes of discontinuity that the stress distribution proceeds with some regularity, giving rise to second-order shears (McKinstry, 1953). Then a common stress system for all the joints obviously cannot be defined but, if some regularity of the development of second-order shears can be observed, it may be possible to speculate on the nature of the external forces (with respect to the area under consideration) which produced the joints.

In the Mystic Lake area, the two joints show rather broad maxima, about 0 degrees to 90 degrees for the joints with right-hand movement, and 60 degrees to 150 degrees for the joints with left-hand movement. This feature and the observed development of second-order shears along some joints indicates that stress distribution across joints has taken place. The orientations of second-order shears with respect to the main shear are not predictable. Two limiting values of the angle between the bisectrix of the two sets of second-order shears and the main shear can be recognized (Fig. 11). If the force transmitted across the main shear acts normal to it (compression), the angle is 90 degrees. If the force transmitted acts tangentially (couple), the angle is 45 degrees. In general, the force can be expected to have a normal and tangential component, and the angle will lie somewhere between 45 degrees and 90 degrees. The joint pattern in the Mystic Lake area, can be interpreted as a result of compression in a direction of north 75 degrees east. This resulted in a system of first-order shears and two systems of second-order shears, as shown diagrammatically in Figure 11. This also explains the overlap of joints with right-hand and left-hand movement, striking in a direction of about north 75 degrees east.

The orientations of the two sets of shear joints fit well into Byers' (1962) regional pattern of fault systems in the western Canadian Shield. However, in the much larger area considered, the northwesterly-striking fault set, in the Flin Flon region chiefly represented by the Ross Lake fault zone, is better developed than the northeasterly-striking fault set. For this reason, Byers (1962) suggests that the external force with respect to the western Canadian Shield, responsible for the development of the fault systems, was applied as an approximate north-south counterclockwise couple.

SUMMARY OF GEOLOGICAL HISTORY

Supracrustal rocks of the Flin Flon region consist of the Amisk Group of predominantly volcanic rocks overlain unconformably by the Missi Group of clastic sediments. Some workers have suggested that the Amisk-Missi unconformity represents an intervening orogeny. However, Byers *et al.* (1954a, 1954b, 1965) came to the conclusion that the Missi rocks were deposited shortly after the period of Amisk volcanism. The presently observed geological features can be referred to one tectonic cycle. In case earlier orogenies took place, their effects have been obliterated by the last one.

During the geosynclinal stage, the rocks of the Amisk and Missi Groups were deposited. Basic and some ultrabasic intrusions, probably related to the igneous activity responsible for the Amisk volcanic rocks, were intruded into the volcanic pile.

During the orogenic stage, the rocks of the Amisk and Missi Groups and the basic intrusions were deformed and metamorphosed. North of the

Kisseynew front, the grade of metamorphism is relatively high (amphibolite facies) and the deformation was intense, obliterating most primary structures. This process gave rise to the Kisseynew gneisses. They are metamorphosed equivalents of Amisk and Missi rocks. The predominance of metasedimentary rocks in the Kisseynew gneisses suggests a lateral variation from volcanic rocks in the southern part of the Flin Flon region to sedimentary rocks in the northern part. South of the Kisseynew front, the grade of metamorphism varies from greenschist facies to lower amphibolite facies. Concomitant with deformation and regional metamorphism, large masses of granodiorite were intruded. In some localities, the intrusions and a marginally developed foliation cut across an earlier foliation. It is very likely that only a small time interval separates the development of the two foliations. They are thought to be phases of the same period of deformation.

During the cratonic stage, cross joints developed. They are related to the anisotropic structure of foliated and lineated rocks. Shear joints, independent of rock type or structure, developed in response to horizontal forces.

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No. 3 GEOLOGY OF THE CORONATION
COPPER DEPOSIT

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ABSTRACT

The Coronation mine is developed on a pyritic copper deposit in Precambrian, basic volcanic rocks, one of a group of similar deposits typical of this type of terrain throughout the world and of which the Flin Flon deposit is the outstanding local example. In comparison with most such deposits, including Flin Flon, the Coronation has suffered greater metamorphism and deformation. Three quarters of the deposit consists of an intergrowth of chalcopyrite, pyrite and pyrrhotite with a cordierite-anthophyllite rock considered to be a metamorphosed chloritic wall rock alteration equivalent to that still characteristic of the footwall of the Flin Flon deposit. About 15 per cent of the deposit consists of massive sulphide veins which in part extend as dike-like apophyses into altered volcanic rocks. The remaining 10 per cent consists of sulphides redistributed post metamorphically along late chloritic shear zones and in partly open cavities in some of which stalactitic structures have developed and in others arsenic has been added to the mineralization.

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INTRODUCTION

The Coronation ore deposit did not outcrop. It was discovered in 1953, Coronation year, by diamond drilling of a second choice anomaly revealed by a ground electromagnetic survey. As mined the deposit was 600 feet long, up to 65 feet wide and extended from the bedrock surface beneath 12 feet of overburden to a depth of 1050 feet. Mining began in 1960 and ended in 1965. A total of 1, 412, 861 tons was produced with a grade of 4.25 per cent Cu (Cairns, 1967).

Various aspects of the Coronation deposit have been investigated by several research workers as contributions to the Coronation Mine Project. This account of the geology of the deposit and its immediate surroundings is based on geological mapping by the staff of the Geological Department, Hudson Bay Mining and Smelting Company, Ltd., and the writer, as well as examination of the drill core by the writer who alone must bear responsibility for the conclusions expressed.

Brief accounts of the geology of the deposit have been presented by Byers (1960) and Whitmore (1962, 1964). A more extended description of the mine is included in a geological report on the Flin Flon area by Byers et al. (1965).

GENERAL GEOLOGICAL SETTING

The geology of the area surrounding the Coronation mine together with the regional geological setting is described in this volume by Froese (1969a).

The rocks of the Flin Flon region form part of a volcanic belt within the Churchill Province of the Canadian Shield. In addition to the Coronation they contain a number of copper-bearing sulphide deposits which are similar in composition and general setting and presumably similar also in origin. By far the largest of these is the Flin Flon deposit, lying 13 miles to the northeast in rocks of somewhat lower metamorphic grade than those at the Coronation. It is at least forty times the size of the Coronation. The other deposits are more similar in size (Table I).

Table I

Some Pyritic Copper Deposits of the Flin Flon Area
Relative Size & Grade

	Size	Grade	
	(millions of tons)	Cu	Zn
Flin Flon	64.0	2.2	4.6
Coronation	1.4	4.2	-
Schist L.	.81	3.8	7.8
Cuprus	.51	3.2	6.4
Birch L.	.28	6.2	-
North Star	.26	6.1	-
Mandy	.14	7.5	9.4
Don Jon	.09	3.1	-

The volcanic rocks of the Flin Flon region together with associated basic intrusions as well as small amounts of sediments have been deformed, metamorphosed, and intruded by large masses of granodiorite. In the Coronation mine area the rocks fall into two groups. The first group constitutes a complex of volcanic and sedimentary rocks together with a group of basic intrusions which are probably related to the same magmatism that produced the volcanic rocks. The second group consists of large granodiorite intrusions with some basic rocks along the margins. Emplacement of these intrusions was accompanied by regional metamorphism and deformation.

IMMEDIATE GEOLOGICAL SETTING

The rocks in the immediate vicinity of the mine belong in three categories. They are

1. Volcanic rocks and related intrusions
 - (a) flows
 - (b) tuff
 - (c) minor intrusions
2. Metasomatically altered volcanic rocks
 - (a) cordierite-anthophyllite rock
 - (b) chloritic rock
3. Veins and similar foreign bodies
 - (a) quartz-chalcopyrite veins
 - (b) sulphide bodies
 - (c) minor intrusions

Although some of the units within these categories are too small to be represented, the relationships among the various units may most readily be grasped by study of the accompanying level plans (Figs. A-C).

Volcanic Rocks

The basic category is of course the volcanic rocks. The others are either derived from them, or lie within them as foreign masses.

Flows

As exposed underground or intersected by drill holes near the mine, the most abundant rock is a basic lava containing widely scattered amygdules. A fragmental structure is not uncommon. Fragments are indistinctly bounded, similar to one another and set in a similar matrix in the manner of a flow breccia. Local concentrations of amygdules and flow breccia occur which may be assumed to mark flow contacts. The lava on either side of such contacts is similar, however, and with the exception of the 450 level (Fig. C), where several hundred feet of contact are indicated, the

contacts cannot be traced far. Probably they separate flow units rather than distinct flows and the mine may thus in large part be developed in a single complex flow.

The lava is metamorphosed, and the most common mineral assemblage is oligoclase-andesine, hornblende, and epidote commonly accompanied by a small amount of quartz.

Tuff

A rock somewhat more acidic than the lava, not obviously clastic, lacking amygdules and with a gross layered structure, occurs at the south end of the mine on the 900 level. A few exposures underground show a fine layered structure discordant with the general trend (Fig. D). Similar layered but less acidic rock is present at the south end on levels above the 900 known chiefly from drill hole intersections. It is not exposed at the surface and has not been traced far from the ore zone.

Characteristically this rock is a biotite schist. Some layers contain garnets. In composition it resembles coarse fragmental rocks found northwest of the mine and like them it is considered to be a tuff.

Attitude of the Volcanic Rocks

North and east of the shaft a zone of pillowed flows in contact with the mine flows is intersected by a number of drill holes. The contact thus defined strikes N60° W and dips 70° SW. Unfortunately the pillows do not indicate tops, and evidence of attitude elsewhere, principally a narrow agglomerate zone at the 750 level station in the mine, in which graded bedding suggests tops to the southwest, is not altogether convincing.

The tuffaceous zone at the south end of the mine and also the flow contact on the 450 level suggest a similar strike. If this is considered to be a stratigraphic horizon it is evident that the foliation of the rocks as well as the mineral deposit itself transects the bedding at an angle of 20 degrees.

Volcanic Intrusive Rocks

With the flows occur acidic and basic intrusions. In some underground openings (Fig. C) these are abundantly exposed although in all they make up only a small proportion of the total volume of rock in the vicinity of the mine. Quartz-feldspar porphyry and feldspar porphyry form complex anastomosing dikes highly irregular in outline but with a general easterly strike. Similar rocks occur in drill holes but striking as they do cannot be correlated from hole to hole. These intrusions appear related to the volcanics and are interrupted or replaced by the orebodies.

Gabbro resembling that exposed at the surface near Table Lake occurs sparingly on the 1350 level below the ore zone. It has been observed also in two stopes where narrow dikes cut part of the ore zone.

Metasomatically Altered Volcanic Rocks

Cordierite-Anthophyllite Rocks

Rocks derived through chemical alteration of the lavas occupy a considerable part of the mine area. The presence of amygdules, and to a lesser degree fragments, within them afford evidence of their original nature. In composition (Table II) they differ from the basic lava in that they are notably richer in Fe and Mg and poorer in Ca and Na. Mineralogically they are characterized by the presence of cordierite and anthophyllite.

Table II

Composition of Rocks from the Coronation and Flin Flon Mines

	1/727.1	2/727.5	3/D424
SiO ₂	55.9	53.1	65.8
Al ₂ O ₃	15.8	14.9	9.0
Fe ₂ O ₃	3.9	3.4	0.1
FeO	6.00	15.48	8.1
MgO	5.1	7.3	12.7
CaO	5.3	0.35	0.0
Na ₂ O	3.1	0.44	<0.1
K ₂ O	0.28	0.40	<0.1
TiO ₂	0.35	0.31	0.2
MnO	0.18	0.14	0.1
P ₂ O ₅	0.04	0.06	0.2
H ₂ O	3.8	4.6	5.0
CO ₂	0.36	0.11	<0.1

1. Amygdular basic lava footwall of Coronation ore zone
Section 66 + 00 S.
Collected by D.R.E. Whitmore.
Analyst: R.M. Staff, Geol. Surv. Canada 1962.
2. Cordierite-anthophyllite rock with disseminated sulfides
from ore zone Section 66 + 00 S.
Collected by D.R.E. Whitmore.
Analyst: R.M. Staff, Geol. Surv. Canada 1962.
3. Chloritic alteration rock without sulfides. Composite
from footwall Flin Flon ore.
Collected by R. Cairns.
Analyst: S. Courville, Geol. Surv. Canada 1963.

Outlines of the cordierite anthophyllite masses are sharp, the gradation from basic lava to cordierite anthophyllite rock taking place within a few inches. Along the contacts some rocks are characterized by the development of anthophyllite without cordierite and by the assemblages

anthophyllite-cummingtonite and cummingtonite-hornblende (without epidote). A more detailed description of these rocks is given in this volume by Froese (1969b).

Rocks poor in Ca and Na consisting dominantly of chlorite are commonly found as alteration products of lavas in the vicinity of sulphide bodies, as for example at Flin Flon (Table II) where they are abundantly developed in the foot-wall. Relationship between such metasomatically altered rocks and sulphide mineralization appears close although probably not as close as the commonly used term "wall-rock alteration" would imply.

Similarly the cordierite-anthophyllite rock may be considered a wall-rock alteration. Although it may have formed directly as such, it may also represent a metamorphosed chloritic alteration rock which would imply that the Coronation orebody itself was metamorphosed. Gneissic textures in the ore support this as well as the fact that the grade of regional metamorphic seen in the Coronation area is compatible with a cordierite anthophyllite assemblage and higher than that at the Flin Flon mine.

Distribution of the cordierite-anthophyllite rock although irregular shows a relationship to the sulphide mineralization as may be seen by reference to the three level plans.

At the south end cordierite-anthophyllite rock distribution corresponds fairly closely to the ore outlines. Almost all the ore is cordierite-anthophyllite bearing and in over 50 per cent of the ore these are the dominant silicates at least in the upper levels (Fig. B).

To the north in the central portion of the ore zone the cordierite-anthophyllite rock tends to swing to the west away from the main ore axis and to contain little ore (Fig. A).

At the north end the ore is chiefly in sulphide veins with one or both walls showing little or no alteration. Such veins are sharply bounded and have a dike-like or intrusive appearance (Fig. E). Some silicate sulphide intergrowths are present here too, on the west side particularly, and here again the distribution of cordierite anthophyllite corresponds with mineralization. The proportion of the ore in which it is the dominant silicate is much less (Fig. B).

Chloritic Alteration Rocks

Chlorite is a constituent of nearly all parts of the mineralized zone and in a few parts it predominates. It is less closely related to the mineralization than the cordierite anthophyllite rock, occurring in small amounts in the country rock relatively far from the mineralization. It is not possible to say definitely that it is more abundant in the mineralized zone though this appears likely. In the mineralized zone it shows a marked relationship to a late fault and subsidiary slips particularly on the east side of the south orebody. Whether rocks alongside similar slips away from the orebodies are similarly chloritized is not known. The systematic search necessary to determine this could not feasibly be undertaken.

Generally chlorite replaces the cordierite-anthophyllite assemblage where the two occur together. The chloritic alteration is therefore later. The slips and fractures which have controlled its distribution can still be seen, whereas slips and fractures which may have controlled the earlier cordierite-anthophyllite alteration can no longer be distinguished.

Veins and Similar Foreign Bodies

Veins of sulphide and quartz with sulphide cut both volcanic and metasomatically altered rocks. Most of the sulphide veins contain chalcopyrite but some are barren. Most of the quartz veins contain grossularite and are considered the metamorphosed equivalent of original quartz-calcite veins which accompanied the chloritic wall-rock alteration that has now been transformed to cordierite-anthophyllite rock. Quartz-calcite veins are less numerous. Some of these are related to the late chloritic slips.

At least 15 per cent of the Coronation ore was in the form of mappable sulphide veins. The percentage of sulphide veins is considerably higher if the veins below mappable size and breccia matrix are also considered. Relations of these are discussed below under mineralization.

A few acidic intrusions cut across the ore zone. They are fine grained, granodioritic in composition, and form several sharp walled dikes 2 to 8 feet thick striking N50°E and dipping 30°N. At the north end of the mine on the 300 level one of these transects gneissic foliation in the ore.

MINERALOGY

The mineralogy of the ore is relatively simple. Detailed studies have been made by Ferris (1961) Gilliland (1965) and Kanehira (1969). Magnetite, some grains with exsolved ilmenite laths, is associated with most of the sulphide ore. The main sulphide minerals are pyrite, pyrrhotite and chalcopyrite. Sphalerite is rare. Commonly pyrite is brecciated. Pyrrhotite and chalcopyrite fill interstices between pyrite and silicate grains. Chalcopyrite veins, in places, cut all other minerals both silicate and sulphide, a relationship which would place chalcopyrite "late" in the traditional paragenetic sequence; but there is no real evidence of any appreciable difference in age among the three principal sulphides, if by age we mean the time of the original accumulation of the sulphides. The "late" appearance of chalcopyrite is a common feature of many sulphide deposits, and an explanation for it is better sought in the peculiarities of the physical and chemical behaviour of chalcopyrite in contrast to other sulphides considering any deformation the sulphide mass may have undergone subsequent to its initial accumulation.

Chalcopyrite occurs also intergrown with other sulphides and as isolated blebs disseminated both in the unaltered and metasomatically altered volcanic rocks either alone or with other sulphides. The shape of some of the blebs suggests replacement of individual grains of biotite and hornblende.

OREBODIES

Although sphalerite and gold make minor contributions to the value of the ore chalcopyrite is the only significant ore mineral. It occurs in commercial quantities in parts of the several rock units described and these together make up the Coronation orebodies. The manner of distribution of the chalcopyrite differs from one unit to another and the boundaries between those parts of the units that are ore, and those parts that are not, are also

different. In short the orebodies are economic units rather than geological ones and they do not correspond.

The average composition of the ore is derived (Table III) from a composite of 40 samples selected from 17 holes cutting the orebody on the 300, 600 and 900 foot levels. Based on the same holes the average pyrite/pyrrhotite ratio is 2:1. The sulphides make up 39.75 per cent of the ore by weight of which 16.17 per cent is chalcopyrite.

Table III

Representative Composite Sample Coronation Ore
WHC 101 (76-64)
(Selected proportionately from drill holes intersecting
ore zone on 300', 600' and 900' levels)

SiO ₂	28.39		
Al ₂ O ₃	7.82	S	17.13
Fe ₂ O ₃ (incl. FeO)	37.86	Cu	5.67
CaO	2.65	Zn	0.36
MgO	5.41	Sr	0.0034
Na ₂ O	0.28	Ba	0.0042
K ₂ O	0.10	Cr	0.0037
H ₂ O +	3.36	Zr	0.0064
H ₂ O -	0.14	V	0.013
TiO ₂	0.24	Ni	0.0054
P ₂ O ₅	0.02	Co	0.042
MnO	0.12	Sc	< 0.004
CO ₂	0.85	Ag	0.005

not found: Pb, Sn, B, Be, Y, Yb, Mo

Collected by D. R. E. Whitmore.

Analyst: J. A. Maxwell, Geol. Surv. Canada.

The orebodies are most suitably indicated by assay contours (Fig. B). For emphasis the contours show chalcopyrite content rather than copper values. The choice of contours is to some extent arbitrary. Actual stopping outlines lay between the 1 per cent and 5 per cent chalcopyrite contours shown and depended on the overall as well as the local requirements of mining. The 18 per cent chalcopyrite contour is used also to show the high grade portions of the ore.

As thus indicated, there are three orebodies: the southern, north-eastern and northwestern. As a group the three orebodies may be termed the ore zone and they together with the lower grade mineralized material lying among and beyond them may be referred to as the mineralized zone. Relationships among orebodies, and mineralized zone on the one hand and the geological units on the other are complex and may most readily be appreciated by reference to the accompanying plans (Fig. A and Fig. C).

Within the mineralized zone chalcopyrite is the most widespread of the sulphides. It occurs in all of some 247 sections studied against 180 for pyrite and 157 for pyrrhotite. Outside the mineralized zone on the other hand chalcopyrite occurs in only 4 of 50 sections examined, pyrite in all, and pyrrhotite in none.

Northeastern Orebody

The northeastern orebody is the most distinct of the three Coronation orebodies. It is a tabular mass, or vein, of massive sulphide in most places with knife sharp boundaries although locally there are complications. Similar distinctly bounded veins are present within both the north-western and southern orebodies but are relatively short and impersistent and make up only a small part of these bodies.

The vein consists dominantly of pyrite with abundant chalcopyrite, up to 50 per cent over considerable areas and 100 per cent in short sections. Pyrrhotite is also present in the wider more massive parts of the vein and is a major constituent of some narrow (4"-6") foliated portions of the vein.

The vein is interrupted and in part modified by the chloritic slip that lies towards the footwall of the mineralized zone (Figs. A and D). The slip divides the vein into three parts (Fig. D): (1) an upper portion (150, 300 levels) striking more easterly than the slip and dipping 70 degrees westerly towards it; (2) a central portion corresponding in position with the slip and (3) a lower portion again striking more easterly than the slip.

The part within the slip is dominantly pyritic, much of it shows crushing, mylonitization of the pyrite and irregular strings of pyrite porphyroblasts. Pyrrhotite is absent and relatively this part is poorer in copper.

Assuming the parts east and west of the slip were once continuous and in line, the pre-slip orebody had a horizontal dimension of 440 feet and a vertical dimension of 450 feet. On the 450 foot level the extended central section is 380 feet in length suggesting a strike slip of this amount. The upper and lower portions are offset less than 150 feet vertically suggesting a dip slip component of this order, west side down.

The vein lies in contact with basic lava and cordierite-anthophyllite rock. Basic lava occurs chiefly on the footwall side though it is found on both sides particularly in the central portion. Boundary of the vein against the lava is almost dike-like in its sharpness. Against the cordierite-anthophyllite rock it is commonly less sharp and in some places is layered gradationally. Wall rocks along the central portion contain considerable chlorite and locally are chlorite schist with narrow films and leaves of chalcopyrite. This chlorite appears related to the slip rather than the mineralization. The chalcopyrite appears secondary and is commonly the only sulphide present.

Assay contours correspond closely to the vein boundaries (Figs. A and B).

Southern Orebody

Over three-quarters of the ore zone consists of sulphide silicate stockworks and intergrowths rather than massive sulphides and much of this

type of ore is in the southern orebody. The persistence of amygdules in the northern part and of rude layering across the southern part indicates the silicate portion derives from the volcanic rocks. Residual silicates (plagioclase, hornblende, epidote) are commonly present as are the high temperature metamorphic silicates (cordierite, anthophyllite) and low temperature metamorphic minerals (chlorite, sericite). Proportions of these three vary widely and erratically from point to point through the orebody so that it is difficult in a purely objective way to define discrete parts of it consisting dominantly of one or the other mineral assemblage. However there is a tendency for the original silicates to persist in the zones across the southern part of the orebody interpreted as tuffaceous layers, and for chlorite to be concentrated along the east side of the orebody near the footwall slip. On the accompanying plans rocks containing over 25 per cent cordierite-anthophyllite have been defined as cordierite-anthophyllite rock.

Textural relationships between ore and gangue minerals are variable. Much of the ore, particularly where cordierite and anthophyllite are present, is a skarn-like intergrowth with varying proportion of sulphides from low grade dissemination up to nearly massive sulphides. The low grade material particularly in a zone along the west side of the ore shows a streaky gneissic layering. In such ore a preferred orientation of pyrrhotite has been observed by Kanehira (1969).

Much of the ore is a complex breccia consisting of silicate fragments in a matrix of sulphides. Partial internal and marginal replacement of the fragments by sulphides obscures the picture so that one cannot tell how much of the brecciated character is inherited from an original volcanic fragmental and how much has been developed through repeated fracturing and veining by sulphide. The latter undoubtedly accounts for much of the breccia but in an area on the 600 level near 65 + 00S an assortment of amygdular, massive and finely layered fragments are in close juxtaposition within a minimal sulphide matrix, and may represent an agglomerate.

Northwestern Orebody

The northwestern orebody consisted of patchy areas of cordierite-anthophyllite rock with intergrown sulphides. Most of the gneissic ore observed underground was in this orebody.

DISCUSSION

In a discussion of the geological features of an ore deposit it is essential to distinguish two aspects viz. (1) the initial accumulation of the ore minerals and (2) any subsequent modification of the deposit. In comparison with Flin Flon and other similar deposits the Coronation ore zone has undergone a history of metamorphism and deformation. The features now observable provide more information on this history than on the ultimate origin of the ore.

A large proportion of the ore typified by the south orebody consists of an intergrowth of sulphides and silicates. Many features indicate that the total mineral assemblage constitutes one metamorphic rock. The textural relationships between silicates and sulphides are consistent with those which

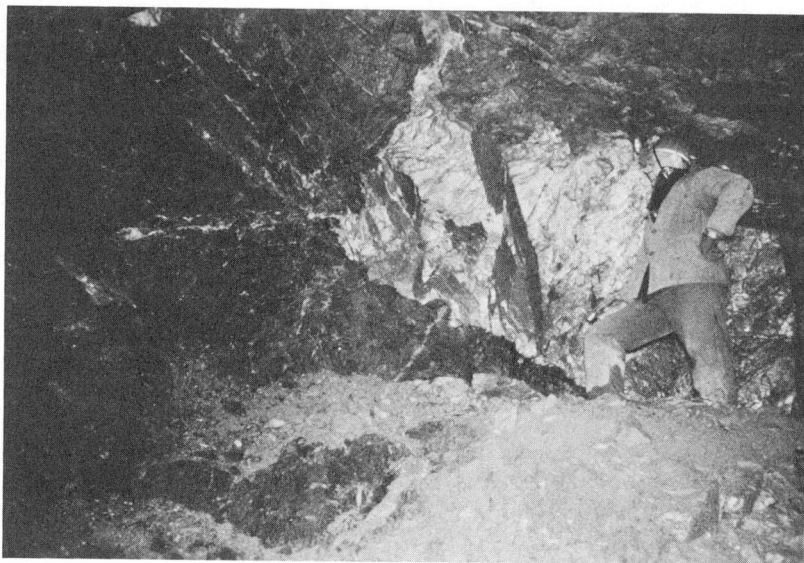


Figure E. Massive sulfide body in unaltered basic lava 300 level
Section 58 + 00 S.

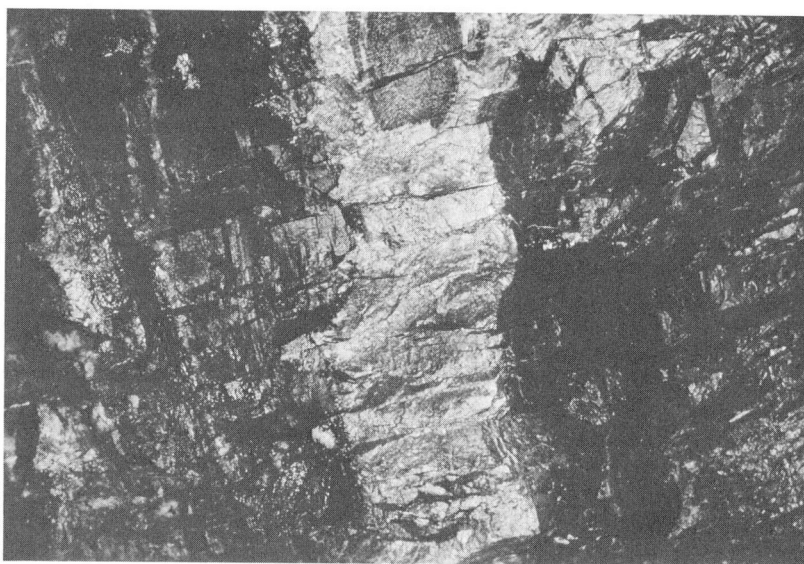


Figure F. Massive sulfide vein in gneissic ore. Northwest orebody
450 level Section 60 + 00 S.

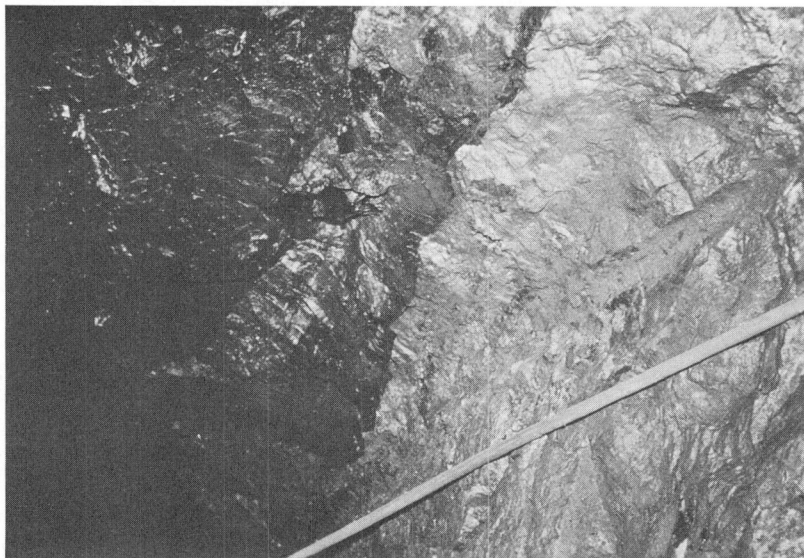


Figure G. Massive sulfide ore cutting breccia ore 450 level south end.



Figure H. Stalactitic ore in cavity within breccia ore near hanging-wall 600 level Section 64 + 00 S.

may be expected to be produced by deforming an aggregate of minerals of diverse physical properties. In the gneissic ore some of the pyrrhotite shows a preferred orientation similar to other metamorphic minerals. In some parts repeated brecciation and flowage of sulphides around fragments and into fractures has given rise to a very irregular fabric. Such relationships result essentially from a reworking of the ore in place. The dike-like massive sulphide portion of the ore (Fig. G) which in places cuts foliated metamorphic silicate intergrowths (Fig. F) and in others basic flow rock (Fig. E) appears to be an extension of such remobilized sulphides.

Except for chloritized rocks along later shear zones, the silicate mineral assemblages of the wall rocks and within the ore are compatible in grade of metamorphism with the rocks of the surrounding area i.e. staurolite almandine subfacies of the almandine amphibolite facies (Winkler, 1967). There is also some evidence of a relationship between silicate assemblages and the type of iron sulphide present in the ore. In the basic volcanic rocks pyrite is the dominant iron sulphide. In cordierite-anthophyllite rocks pyrrhotite is more common. Gahnite in the ore probably also indicates a reaction under metamorphic conditions between sulphides and silicates. In summary a large part of the ore constitutes a metamorphic rock which has suffered the same deformation and metamorphism as the rocks which enclose it. The cordierite-anthophyllite rock is itself a regionally metamorphosed chloritic wall-rock alteration associated with the original mineralization. Already alluded to earlier in this paper this view has been briefly stated by Whitmore (1962, 1964) and Froese and Whitmore (1964). It is further developed in this volume by Froese (1969b).

Metamorphic silicate-sulphide intergrowths (75 per cent) and their related sulphide veins (15 per cent) together comprise 90 per cent of the deposit. The remaining 10 per cent represent post metamorphic developments. Of these the greatest part (7 per cent) consists of chlorite-chalcopryrite, chlorite-quartz-chalcopryrite-pyrite intergrowths, commonly schistose, developed for the most part in and near the foot-wall slip and subsidiary fractures. The derivative nature of the chalcopryrite and other sulphides and their dependence on the presence nearby of metamorphic silicate or massive sulphide ore mineralization is apparent.

About 2 per cent of the ore occurs in what is termed stalactitic ore, columnar and nodular masses of sulphide in open cavities or in cavities partly filled with calcite. Axes of columns (stalactites) are vertical (Fig. H). Steeply dipping and flat cavities occurred principally near the hanging wall of the north part of the south orebody. Pyrite is the dominant sulphide present and again the lateral secretion type of relationship to the earlier mineralization is apparent.

A very small part of the ore, less than 1 per cent, consists of flat veins of calcite, colloform chalcopryrite, tennantite and marcasite (Fig. I). Three of these were recognized in various parts of the mine. The most prominent of them intersected the ore zone at the 300 level near the north end where it comprised a sheeted zone 10 feet thick dipping southeasterly at 7 degrees. No continuous vein is present, but rather lenticular vuggy pods of mineralization on one or other of the several fractures comprised in the sheeted zone. The same sheeted zone can be identified in the shaft near the 450 level, where it contains calcite lenses without sulphides although a few crystals of arsenopyrite appear in the wall rock.



Figure I. Flat tennantite-chalcopyrite veins 300 level Section 60 + 00 S.

The present features of the Coronation deposit are thus either metamorphic or post metamorphic and the ultimate origin of the mineralization must on evidence from the Coronation alone remain obscure. That this should be so is not surprising, the approach to an understanding of the origin of this type of deposit, or any type of deposit for that matter, must be made through a study of them as a group or groups. This involves detailed study of individual deposits but only as part of a larger study not as an end in itself.

The common occurrence of deposits like the Coronation in volcanic rocks suggests that they are related to the volcanism, or at least in the case of the Coronation to the magmatic event which produced the complex of volcanics and basic intrusions. Relationship to the granodiorite is less obvious and indeed as discussed in this volume by Faulkner (1969) basic rocks are geochemically a more likely source than are acidic rocks. It appears probable then that the original mineralization was effected by hydrothermal solutions related to the basic magmatism of which the enclosing volcanics and the nearby basic intrusions are both an expression. It appears probable also that this original mineralization would have accumulated in the volcanics near the surface and that the tuffaceous zone towards the south of the Coronation may represent that surface or a plane parallel to and not far from it. This would indeed suggest that the original mineralization developed in a fracture zone below this surface and if so the study by Gilliland (1965) indicates some of the original zoning may still be discerned in spite of the metamorphism. His work and also that of Faulkner (1969) both suggest transport of the metals to the site of deposition as halides. Sulphides were precipitated presumably by a reaction of the metal chlorides with hydrogen sulfide.

ACKNOWLEDGMENTS

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No. 4 METAMORPHIC ROCKS FROM THE
CORONATION MINE AND
SURROUNDING AREA

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Geological Survey of Canada

ABSTRACT

The Coronation sulphide deposit and a spatially associated mass of cordierite-anthophyllite rocks occur in basic volcanic rocks of the Amisk Group. Sulphide ores are developed in cordierite-anthophyllite rocks as well as in basic volcanic rocks. Assemblages of gangue minerals in both rock types are compatible with the metamorphic grade of the surrounding area, corresponding to the staurolite-almandine subfacies of the almandine-amphibolite facies. A preferential development of pyrrhotite in cordierite-anthophyllite rocks and pyrite in basic volcanic rocks is considered as evidence of reaction between silicates and sulphides at metamorphic conditions. The presence of gahnite probably also indicates metamorphic reactions between sphalerite and aluminous silicates. The cordierite-anthophyllite rocks are thought to represent original zones of chloritization developed at the time of mineralization, rather than products of high-temperature metasomatism. The chloritic alteration zones and the sulphide mineralization, as well as the enclosing volcanic host rocks, have been subjected to regional metamorphism.

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Introduction

The Coronation orebody occurs in a terrain of regional metamorphism and the gangue of the mineralization consists of metamorphic minerals. It is of interest to compare the grade of metamorphism of the surrounding area with that indicated by the wall rocks of the mine and the assemblages of gangue minerals. A large part of the orebody occurs in cordierite-anthophyllite rocks. This raises the question whether these rocks are products of regional metamorphism or of contact metamorphism subsequent to regional metamorphism. The geological setting suggests the possibility that the orebody like the surrounding rocks has been subjected to regional metamorphism. If this is true, some relationship between coexisting sulphide, oxide, and silicate minerals would be expected because the total assemblage constitutes one metamorphic rock. The geology of an area surrounding the Coronation mine is described by Froese (1969) and the geology of the mine is presented by Whitmore (1969). Both accounts are included in this volume.

Some Comments on Grade of Metamorphism

Temperature and total pressure are conditions imposed on rocks by the environment of metamorphism. A strictly genetic classification of metamorphic rocks would be achieved by grouping rocks which recrystallized within a specified range of P_{total} and T . However, a P_{total} - T diagram is not easily subdivided according to mineralogical criteria because few reactions are dependent on P_{total} and T only. Prominent examples of such reactions in metamorphic rocks are the polymorphic transitions of the aluminum silicates. The stability fields of andalusite, kyanite, and sillimanite, are shown in Figure 1 according to experimental work by Richardson *et al.* (1968), Gilbert *et al.* (1968), and Holdaway (1968). The phase diagram of this system now appears reasonably well established and, although the application of this diagram is complicated by metastable crystallization, the aluminum silicates provide the best indicators of the limits of total pressure in pelitic rocks.

For a given metamorphic belt, total pressure is less variable than temperature. Furthermore, many metamorphic reactions are rather insensitive to variations in total pressure. Therefore, it may be expedient to group rocks crystallized at some constant total pressure according to other variables. Keeping temperature as one property of metamorphic environment, it is convenient to choose one of the composition variables in mineral reactions, that is, $P_{\text{H}_2\text{O}}$, and attempt to classify rocks according to fields in a $P_{\text{H}_2\text{O}}$ - T diagram. This diagram can be subdivided on the basis of reactions which, at constant P_{total} , can be shown as functions of $P_{\text{H}_2\text{O}}$ and T . If a reaction is a function of one additional composition variable, it can be represented by a series of curves, each valid for a specific value of the chosen composition variable. It is generally considered that reaction curves on a $P_{\text{H}_2\text{O}}$ - T diagram separate 'high-grade' mineral assemblages (to the right) from 'low-grade' assemblages (to the left). Thus, in this simple case, metamorphic grade describes the combined effect of two variables; furthermore, $P_{\text{H}_2\text{O}}$ may not be a property of the metamorphic environment but may vary from rock to rock. The multitude of metamorphic reactions makes it difficult to single out a few reactions for subdividing the $P_{\text{H}_2\text{O}}$ - T diagram into a convenient number of fields in order to achieve a measure of metamorphic grade. It has been the practice to use a group of reactions which plot close

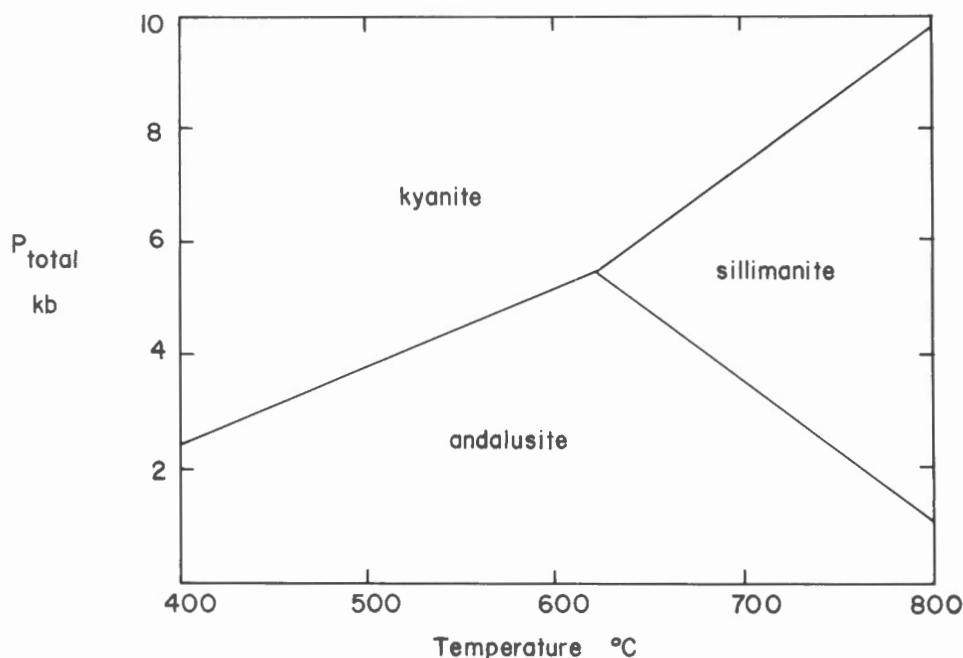


Figure 1. Stability fields of the aluminum silicates (from Richardson *et al.*, 1968; Gilbert *et al.*, 1968; and Holdaway, 1968).

together on a PH_2O - T diagram as the boundary between rocks of different metamorphic grade, that is between different metamorphic facies. This is essentially done, for various total pressures, in the recent extensive tabulation of facies by Winkler (1967). Although such boundaries cannot be sharp and, like most classification boundaries, are arbitrary, a subdivision of the PH_2O - T diagram provides a useful classification of metamorphic rocks.

Metamorphic Grade of the Coronation Mine Area

Rocks of the Amisk and Missi Groups of the Flin Flon region range in metamorphic grade from the greenschist facies to the lower amphibolite facies (Ambrose, 1936; Byers *et al.*, 1954, 1965; Heywood, 1966). Mineral assemblages in the Coronation mine area correspond closely with those given as typical of the staurolite-almandine subfacies of the almandine-amphibolite facies (Winkler, 1967). However, cordierite also occurs and the aluminum silicate present is andalusite rather than kyanite. The occurrence of andalusite provides an upper limit of total pressure in the order of 4 kb.

Three reactions have been used to provide limits of the PH_2O - T conditions for rocks from the Coronation mine. These are:

- (1) Fe chloritoid + Al silicate \rightleftharpoons Fe staurolite + quartz + water
- (2) Fe staurolite + quartz \rightleftharpoons Fe cordierite + Al silicate + water
- (3) Muscovite + quartz \rightleftharpoons K feldspar + andalusite + water

The equilibrium conditions of the first two reactions are taken from Richardson (1968) and those of the third one from Evans (1965). The experimental

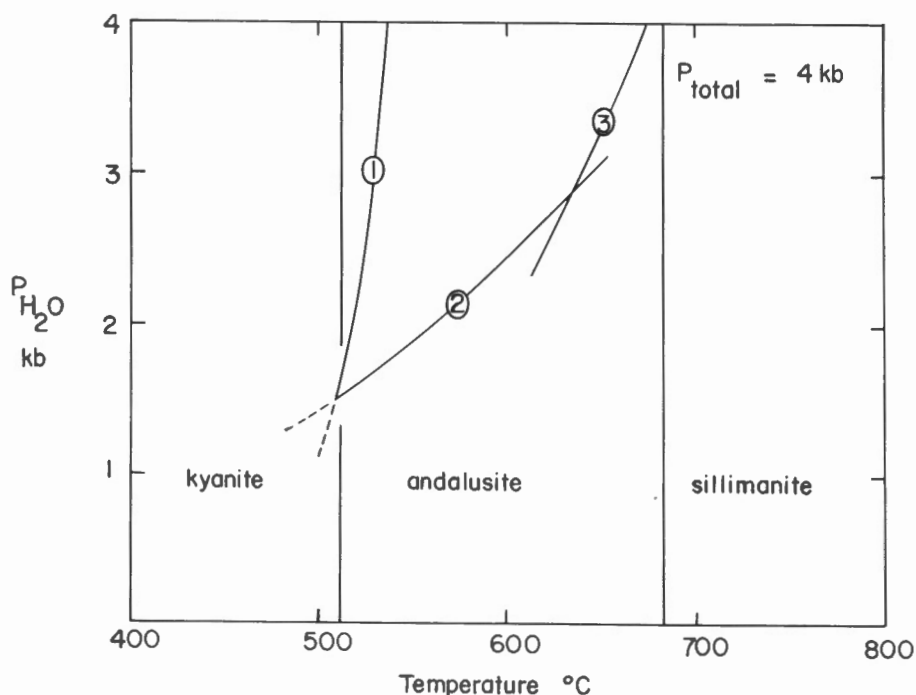


Figure 2. Limits of P_{H_2O} - T conditions for rocks from the Coronation mine area, provided by the following reactions:

- | low temperature | high temperature |
|---|------------------|
| (1) Fe chloritoid + Al silicate \rightleftharpoons Fe staurolite + quartz + water (Richardson, 1968). | |
| (2) Fe staurolite + quartz \rightleftharpoons Fe cordierite + Al silicate + water (Richardson, 1968) | |
| (3) Muscovite + quartz \rightleftharpoons K feldspar + andalusite + water (Evans, 1965). | |

determinations were made under the condition of $P_{H_2O} = P_{total}$. However, the position of the equilibrium curves on a P_{H_2O} - T diagram at $P_{total} = 4$ kb will be practically the same. Substitution of Mg for Fe in the first two reactions and of Na for K in the second reaction will shift their position on a P_{H_2O} - T diagram. However, in the first reaction, a small substitution of Mg for Fe apparently does not have an appreciable effect. This reaction has also been investigated by Hoschek (1967) using as starting materials chloritoid and staurolite with a ratio of Fe/(Fe + Mg) equal to 0.84 and 0.83, respectively. His results agree well with those obtained by Richardson (1968) for the pure iron end members. Substitution of Mg for Fe will shift the boundary of the second reaction to higher pressures; thus, the shown curve is a lower limit. According to Richardson (1968), the following reaction, not yet experimentally investigated, takes place at a somewhat higher temperature than reaction (1):

- (4) Fe chloritoid + quartz \rightleftharpoons almandine + Fe staurolite + water

Rocks from the Coronation mine area are marked by the association of almandine and staurolite and by the stability of muscovite. Thus, on the basis of the discussed reactions, the estimated ranges of the P_{H_2O} - T conditions are 2-4 kb and 550-600°C.

Petrographic Descriptions

Volcanic Rocks from the Surface

Both flow and pyroclastic rocks are fine-grained and have a crystall-oblastic texture. The rocks are completely recrystallized; the constituent minerals form a mosaic of anhedral to subhedral grains. By far the dominant mineral assemblage characteristic of the basic rocks is quartz, plagioclase, green hornblende, and epidote. A small amount of biotite is present in some basic rocks. Remnant grains of clinopyroxene, extensively replaced by hornblende, were found in one specimen of basic volcanic breccia. Tourmaline and apatite are rare accessories. Colorless cummingtonite occurs in some rocks. Cummingtonite is not compatible with epidote. If the two minerals occur in the same thin section, they are separated by a layer of hornblende several millimeters thick. Acidic rocks consist of quartz, plagioclase, and biotite with accessory amounts of either epidote and muscovite, or garnet. In some rocks plagioclase is fresh and untwinned or poorly twinned, in others it is altered to saussurite and sericite. Where the composition can be determined optically it is An_{30-40} . As part of a regional study, Pyke (1961) determined 14 plagioclases from volcanic rocks of the Coronation mine area by X-ray diffraction; their composition ranges from An_{15} to An_{39} . In one locality, a cordierite-cummingtonite-garnet rock occurs in an area of basic volcanic rocks.

Biotite Gneisses from the Surface

These rocks have a crystalloblastic texture. The minerals form a mosaic varying in grain size from fine to medium. The common minerals are quartz, plagioclase of composition An_{30-40} , biotite, and in some rocks muscovite and microcline. Plagioclase is extremely sericitized and, more rarely, also contains patches of brown saussurite. Some of the biotite is altered to chlorite. Microcline occurs interstitially and as large metacrysts. Almandine is a common constituent in rocks containing neither muscovite nor microcline. In addition, either staurolite or anthophyllite may be present. Almandine and staurolite occur as irregular, skeletal grains. Colorless to pale green anthophyllite is subhedral and tends to form radial growths. The composition of one biotite and one garnet is given in Table 1.

Rocks from the Coronation Mine

Unmineralized rocks as well as assemblages of gangue minerals are included in this description. Sulphides in sufficient amounts to make ore occur in all mineral assemblages are described below. The orebody as well as an irregular mass of cordierite-anthophyllite rock occurs in a sequence of basic volcanic rocks containing a small portion of acidic pyroclastic rocks. Some ore is found in relatively unaltered volcanic rocks. In some places, however, a coarsening of the grain size of the silicates is very pronounced;

this medium-grained rock may also contain some grossularite-andradite. Cummingtonite together with green hornblende is present in a few rocks. The volcanic rocks are cut by numerous quartz-epidote veins, which may also contain calcite and grossularite. Some calcite veins are also present. Frequently a reaction rim of grossularite and epidote is formed along the contact of these veins with the wall rock. A green spinel is a common accessory mineral in biotite-bearing acidic pyroclastic rocks. In several rocks, it has been identified as gahnite (see Kanehira, 1969).

Part of the orebody is developed within medium-grained cordierite-anthophyllite rocks. These rocks also occur without appreciable mineralization. Cordierite forms large metacrysts which typically are veined by a pale green chlorite. In some rocks it is extensively chloritized and sericitized. Only rarely can some irregular polysynthetic twinning be seen. The anthophyllite is colorless to pale green and tends to form radiating clusters of subhedral blades. Most of the cordierite-anthophyllite rocks are quartz-bearing. Plagioclase is generally absent but, if present, is compatible with cordierite and anthophyllite. Garnet often occurs as subhedral and corroded grains. Andalusite is present in some rocks not containing anthophyllite or is separated from anthophyllite by a short distance (about one to two mm). An exceptional association of andalusite, anthophyllite, staurolite, and biotite, all apparently compatible, was observed in one specimen. Along contacts of andalusite and cordierite, an alteration of these minerals to a mixture of spinel and white mica (pyrophyllite?) is commonly observed. Staurolite occurs in some cordierite-anthophyllite rocks as corroded grains surrounded by cordierite or, more rarely, by garnet. These grains are interpreted as armored relics, implying that staurolite is not compatible with anthophyllite. An exception to this is the previously mentioned association of andalusite, anthophyllite, and staurolite in one rock. Green spinel is a common accessory mineral.

The change from basic volcanic rocks to cordierite-anthophyllite rocks takes place over a short distance of a few inches to a few feet. Transitional rocks are characterized by the development of cummingtonite. In the volcanic rocks, cummingtonite occurs together with hornblende. Hornblende is absent near cordierite-anthophyllite rocks. The common occurrence of cummingtonite is in basic volcanic rocks associated with hornblende. Near cordierite-anthophyllite rocks, cummingtonite occurs in rocks containing neither hornblende nor anthophyllite. More rarely, cummingtonite occurs in association with anthophyllite or cordierite-anthophyllite. Anthophyllite and hornblende have not been observed in the same thin section and seem definitely incompatible.

The composition of one garnet and one anthophyllite is given in Table 1. Approximate analyses by optical spectrography of other garnets and anthophyllites from garnet-anthophyllite-cordierite rocks indicated that the composition of these minerals varies from rock to rock. The atomic ratio $\text{Fe}/(\text{Fe} + \text{Mg})$ of garnets ranges from 0.74 to 0.83. For anthophyllites the range is 0.54 to 0.70.

Opaque Minerals

The mineralogy of the opaque minerals from the Coronation mine has been studied by Ferris (1961) and Kanehira (1969); Kanehira's account is given in this volume. In the present study, attention has also been paid to

Table 1

Chemical Composition of Some Minerals

Location	Mystic Lake		Coronation mine	
	Garnet F61-112	Biotite F61-76	Garnet 66-410	Anthophyllite M12-5
SiO ₂	36.82	35.43	36.44	45.90
Al ₂ O ₃	23.87	18.41	24.18	13.43
Fe ₂ O ₃	2.42	3.08	4.44	1.58
FeO	31.92	18.33	28.29	25.59
MgO	1.81	9.19	3.70	8.86
CaO	1.60	0.43	1.84	0.38
TiO ₂	0.54	2.07	0.13	0.37
MnO	0.27	0.13	0.67	0.21
K ₂ O		7.56		0.03
Na ₂ O		0.32		0.86
H ₂ O		4.62		2.37
	99.25	99.57	99.69	99.58
a ^o	11.57 Å	—	11.57 Å	—
N	1.815	—	1.805	—
d	4.22	3.05	4.07	3.25
N α	—	—	—	1.676
N β	—	—	—	1.684
N γ	—	1.634	—	1.696
quartz	35	25	20	10
plagioclase	20	40	--	--
biotite	15	20	5	--
almandine	20	15	20	10
anthophyllite	5	--	30	30
cordierite	--	--	25	35
magnetite	tr	tr	tr	5
chlorite	5	--	--	--
pyrrhotite	--	--	--	5

Chemical analysis by S. Courville, Geological Survey of Canada.

Unit cell edges by R. N. Delabio, Geological Survey of Canada.

disseminations of opaque minerals in the silicate rocks. In the ore and in silicate rocks, pyrite forms euhedral to anhedral grains. In the ore, pyrite is commonly brecciated and the fractures may be filled with pyrrhotite and chalcopyrite. Pyrrhotite and chalcopyrite may also occupy small fractures in the rocks and cleavage cracks in amphiboles. Chalcopyrite appears to have been particularly mobile forming some very thin veinlets in the silicate rocks. Sphalerite is rare and found only as small grains, commonly within chalcopyrite, occasionally also in pyrrhotite and between gangue minerals. Pyrrhotite, chalcopyrite, and sphalerite occur as anhedral grains. In some samples of the ore and in metamorphic rocks with disseminated sulphides, a preferred orientation of the pyrrhotite has been observed. This feature has been studied in detail by Kanehira (1969). Magnetite is common in the ore and in many metamorphic rocks. It is particularly abundant in cordierite-anthophyllite rocks; the crystals are relatively large and subhedral to anhedral, whereas in basic volcanic rocks smaller grains with irregular shapes predominate. Ilmenite occurs as laths along octahedral planes of magnetite and also as irregular grains within magnetite and in gangue. Some of the lath-shaped ilmenite grains contain minute exsolution rods of hematite, seen only under oil immersion. Some of the irregular magnetite grains contain small specks of hematite possibly also of exsolution origin. Hematite is not present as separate grains.

The occurrence of magnetite, pyrite, and pyrrhotite in the ore and as accessory minerals in rocks bears some relationship to the particular assemblage of silicate minerals in the ore and rocks. In basic volcanic rocks, pyrite and magnetite are the dominant opaque minerals; pyrrhotite is less common. This applies to disseminated sulphides as well as portions of the ore developed in basic volcanic rocks. In acidic pyroclastic rocks, pyrrhotite is the main iron sulphide. Pyrite is much rarer. Magnetite is commonly absent, particularly if graphite is present. In cordierite-anthophyllite rocks, magnetite and pyrrhotite are the dominant opaque minerals. Pyrite is present in some rocks but usually not in contact with magnetite. A very common textural feature of magnetite in cordierite-anthophyllite rocks is an extensive replacement by a dense, brownish green aggregate of secondary minerals, probably mainly chlorite, and by pyrrhotite. This produces skeletal magnetite grains. The texture suggests that pyrite and magnetite are not compatible in these rocks and some pyrrhotite was formed at the expense of magnetite. But it is not clear why such reactions would produce the peculiar skeletal magnetite grains.

Representation of Mineral Assemblages

Compatible mineral assemblages of metamorphic rocks from the Coronation mine area are listed in Table 2. Mineral reactions and stabilities can be shown, at constant total pressure, as depending on PH_2O and T and on the relative amounts of components other than water. The chemical system required to express the composition of all minerals of interest consists of too many components to allow a graphical representation of all possible mineral assemblages. Therefore, it is necessary to consider different subsystems representing a restricted assemblage of minerals.

Several interesting mineral reactions can be shown in the relatively simple system $\text{SiO}_2 - \text{Al}_2\text{O}_3 - \text{FeO} - \text{MgO}$ because many minerals in pelitic rocks can be approximately expressed in terms of these components.

Table 2

Compatible Mineral Assemblages of Metamorphic Rocks from the Coronation Mine Area

Rocks from the Surface

Volcanic Rocks

± quartz, plagioclase, hornblende, ± epidote, ± biotite
quartz, plagioclase, hornblende, cummingtonite, ± biotite
quartz, plagioclase, biotite, ± muscovite, ± epidote
quartz, plagioclase, biotite, ± almandine, ± cummingtonite
quartz, cordierite, cummingtonite, ± almandine (rare)

Biotite Gneisses

quartz, plagioclase, biotite, \pm muscovite, \pm microcline
quartz, plagioclase, biotite, almandine, \pm anthophyllite
quartz, plagioclase, biotite, almandine, \pm staurolite

Rocks from the Coronation Mine

Volcanic Rocks

± quartz, plagioclase, hornblende, ± epidote, ± biotite
quartz, plagioclase, hornblende, epidote, grossularite-andradite,
± biotite
quartz, epidote, ± grossularite, ± calcite
quartz, plagioclase, hornblende, cummingtonite
quartz, plagioclase, biotite, ± almandine, ± anthophyllite
quartz, plagioclase, biotite, ± muscovite, ± epidote
quartz, plagioclase, biotite, muscovite, staurolite (rare)

Cordierite-anthophyllite Rocks

quartz, plagioclase, anthophyllite, \pm cummingtonite, \pm biotite
 \pm quartz, \pm plagioclase, cordierite, anthophyllite, \pm almandine,
 \pm biotite
 \pm quartz, \pm plagioclase, cordierite, anthophyllite, \pm cummingtonite
(rare)
 \pm quartz, \pm plagioclase, almandine, anthophyllite, \pm cordierite,
 \pm biotite
 \pm quartz, \pm plagioclase, almandine, anthophyllite, \pm cummingtonite
(rare)
 \pm quartz, \pm plagioclase, cordierite, \pm almandine \pm staurolite,
 \pm biotite
 \pm quartz, \pm plagioclase, cordierite, andalusite, \pm staurolite, \pm biotite
quartz, cordierite, anthophyllite, andalusite, staurolite (rare)

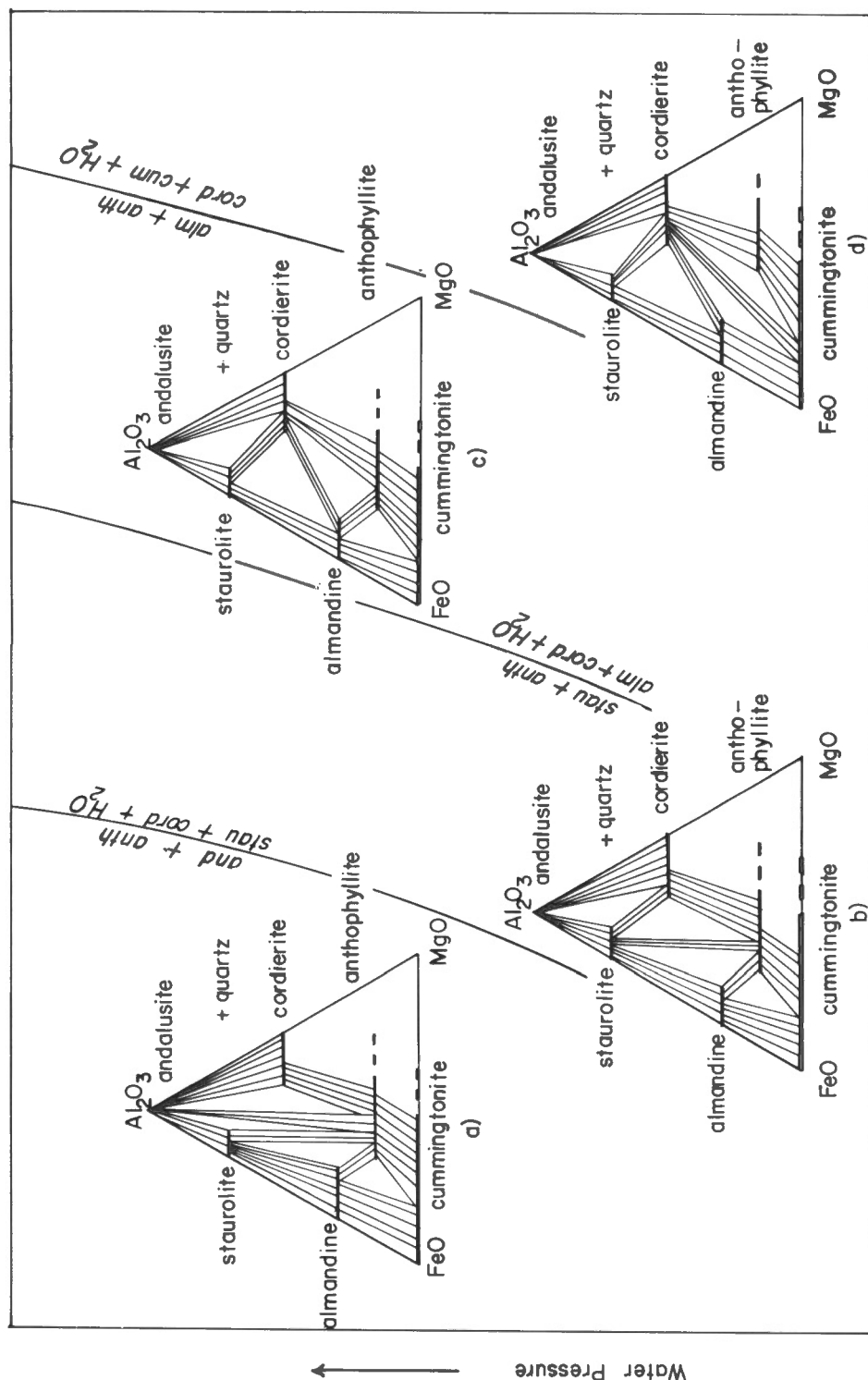
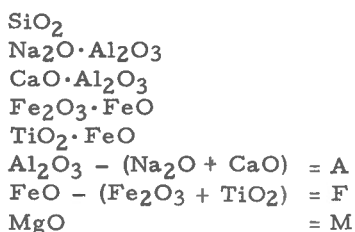


Figure 3. Reactions in the system SiO_2 - Al_2O_3 - FeO - MgO deduced from compatible mineral assemblages.

Restricting the consideration to mineral assemblages containing quartz, mineral relationships can be shown in a triangular phase diagram Al_2O_3 - FeO - MgO , valid for specified values of P_{total} , PH_2O , and T . Reactions involving four minerals (in addition to quartz) are marked by a cross-over of tie-lines on the phase diagram and by a curve on a PH_2O - T diagram at constant P_{total} . Reactions involving three minerals (in addition to quartz) are marked by a compatibility triangle which shifts in response to variations of P_{total} , PH_2O , and T . At constant P_{total} , such reaction can be shown by a series of curves on a PH_2O - T diagram, each curve valid for a specific composition of one of the minerals. Textural observations, together with chemical analyses of some minerals and a general knowledge of compositional restrictions of minerals, suggest certain reactions, which are shown in Figure 3. These reactions have not been experimentally investigated but their PH_2O - T conditions must be somewhere between the limits previously discussed. With only a few exceptions, the mineral assemblages of rocks from the mine and from the surrounding area are consistent with the topology of the phase diagram shown in Figure 3c. On the basis of mineral compatibilities in this system, no differences in metamorphic grade between rocks from the mine and those from the surface could be detected. Differences in composition of coexisting garnet, anthophyllite, and cordierite indicate that PH_2O and/or T conditions varied somewhat from rock to rock.

As a next step, mineral relationships in the following system will be considered: SiO_2 - Na_2O - CaO - Fe_2O_3 - TiO_2 - Al_2O_3 - FeO - MgO . Phase relations at specified values of P_{total} , PH_2O , and T can be shown in terms of relative amounts of three components (triangular phase diagram), if the activities of the other components are kept constant. It is convenient to write the components in the following way:



In this rearrangement, it is possible to recognize restricted mineral assemblages in which certain components have a constant activity. Thus, mineral assemblages containing quartz, plagioclase of fixed composition, magnetite, and ilmenite are characterized by constant activities of the following components: SiO_2 , $\text{Na}_2\text{O} \cdot \text{Al}_2\text{O}_3$, $\text{CaO} \cdot \text{Al}_2\text{O}_3$, $\text{Fe}_2\text{O}_3 \cdot \text{FeO}$, $\text{TiO}_2 \cdot \text{FeO}$. Phase relations can then be shown by the relative amounts of components designated as A, F, and M. Figure 4 is an A - F - M diagram for rocks from the Coronation mine and surrounding area, based on observed mineral assemblages as listed in Table 2, disregarding some of the assemblages marked rare. This diagram shows correctly mineral compatibilities but the exact configuration of compatibility triangles and tie lines is not known. The top part of this diagram is practically the same as shown in Figure 3c. The position of garnet will shift slightly if CaO is subtracted from Al_2O_3 . Many pelitic rocks do not contain magnetite, but the Fe_2O_3 content of the minerals in question is so low that the subtraction of this amount from FeO is insignificant. The TiO_2 content of these minerals is only a trace. The restrictions

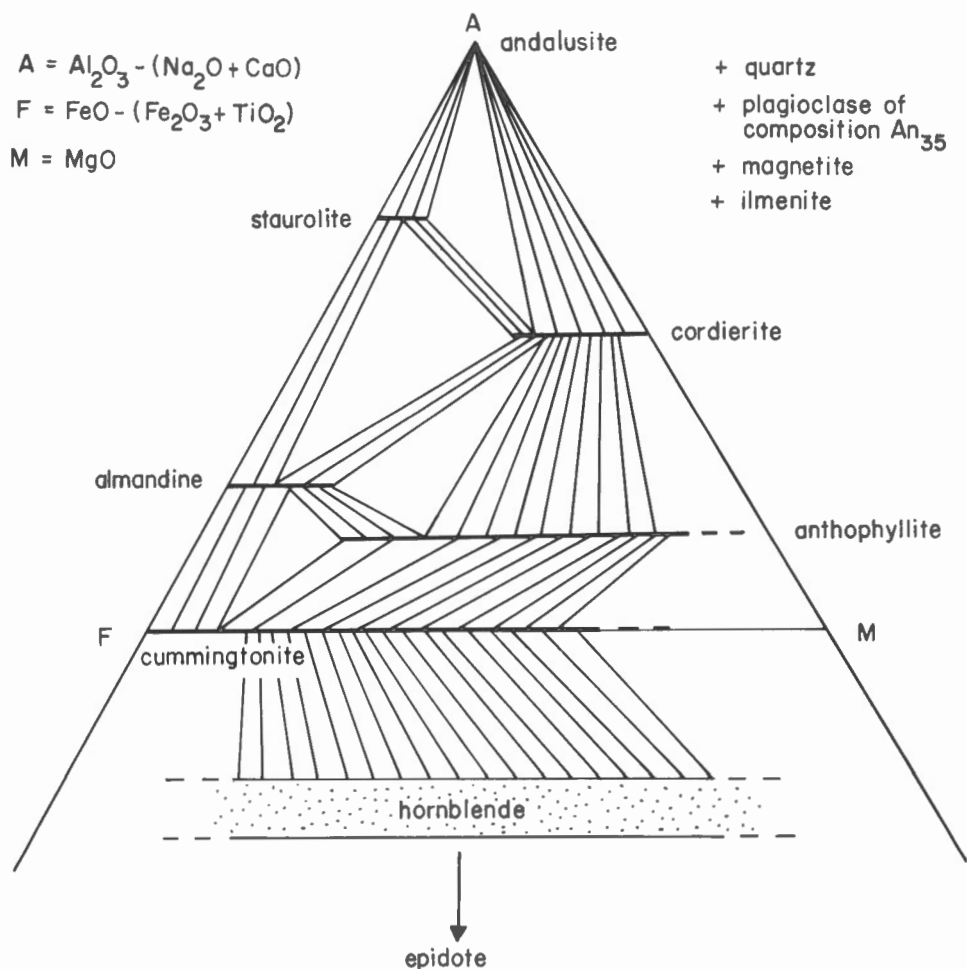


Figure 4. Compatible mineral assemblages in the system $\text{SiO}_2 - \text{Na}_2\text{O} - \text{CaO} - \text{Fe}_2\text{O}_3 - \text{TiO}_2 - \text{Al}_2\text{O}_3 - \text{FeO} - \text{MgO}$ in the presence of quartz, plagioclase of composition An_{35} , magnetite, and ilmenite.

of the representation are more severe as applied to the calcium-rich part of the diagram. The contents of CaO , Fe_2O_3 , and TiO_2 in hornblende are appreciable. Yet not all rocks contain magnetite and ilmenite and the composition of plagioclase varies somewhat from rock to rock. Nevertheless the chosen graphical representation is a useful approximation. The procedure is similar to Korzhinskii's (1959) grouping of determining and excess components, except that $\text{Na}_2\text{O} \cdot \text{Al}_2\text{O}_3$ and $\text{CaO} \cdot \text{Al}_2\text{O}_3$ are not excess components; their activities are kept constant by specifying a plagioclase of fixed composition. This method of representation has been found useful in previous studies by Froese (1963a) and Reinhardt (1968).

The system shown in Figure 4 may be expanded to include $\text{K}_2\text{O} \cdot \text{Al}_2\text{O}_3 = \text{K}$ as a component. This necessitates the modification of component A to read

$A = Al_2O_3 - (Na_2O + CaO + K_2O)$. Phase relations between minerals, in the presence of quartz, plagioclase of fixed composition, magnetite and ilmenite, can be shown in a tetrahedron $A - K - F - M$ (Fig. 5a). Mineral assemblages containing either muscovite or K feldspar as a common phase could be shown on a plane by projecting points within the tetrahedron onto the $A - F - M$ plane either through muscovite (Thompson, 1957) or through K feldspar. However, this method cannot be applied in rocks from the Coronation mine area because neither muscovite nor K feldspar is a phase common to the mineral assemblages of interest. As can be seen in Table 2, biotite is a phase compatible with many mineral assemblages. Its absence in many basic rocks and in some cordierite-anthophyllite rocks is due to a lack of K_2O in the rocks rather than to incompatibility with the mineral assemblages. In the $A - K - F - M$ tetrahedron, four-phase biotite-bearing assemblages will be represented by subtetrahedra, all of which have one corner on the biotite composition surface. Volumes representing three-phase assemblages subtend a line on the biotite composition surface, and volumes representing two-phase assemblages subtend a surface. In order to show an approximate subdivision of the $A - K - F - M$ tetrahedron, a planar section for an $M/(F + M)$ ratio of 0.5 is given in Figure 5b. However, mineral compatibilities in biotite-bearing assemblages may be shown more conveniently by a subdivision of the biotite composition surface. Compatibilities are more readily visualized by means of this representation than by an attempt to draw tie lines in the tetrahedron. Figure 6 shows mineral compatibilities in rocks from the Coronation mine and surrounding area by means of a subdivided biotite composition surface. Due to lack of biotite analyses, this diagram is schematic. Again, no difference in metamorphic grade between rocks from the Coronation mine and those from the surface could be detected on the basis of mineral compatibilities in this system.

Metamorphism of Sulphides

If the ore has been metamorphosed, coexisting sulphide and silicate minerals constitute one metamorphic rock. In order to detect any systematic relationship between minerals, equilibria have to be considered in some common system. Mineral assemblages in the system $SiO_2 - Na_2O - CaO - Fe_2O_3 - TiO_2 - Al_2O_3 - FeO - MgO$, at constant P_{total} , PH_2O , and T and in the presence of quartz, plagioclase of fixed composition, magnetite, and ilmenite, can be represented by three components A , F , and M (Fig. 4). If sulphur is added to this system as an additional component, phase relations can be shown in a tetrahedron $A - F - M - S$ (Fig. 7). Pyrite and pyrrhotite will be two corners common to various subtetrahedra. The other two corners of each of these subtetrahedra will lie on the $A - F - M$ face connected by a tie line between two silicate minerals. Tie lines between various pairs of silicate minerals, along which pyrite and pyrrhotite are stable, constitute a broken line which divides the $A - F - M$ face into relatively iron-rich mineral assemblages coexisting with pyrrhotite and relatively iron-poor ones coexisting with pyrite. The position of the pyrite-pyrrhotite line, like the total configuration of the phase diagram, is valid for some specified P_{total} , PH_2O , and T . The position of this line shown in Figure 7b is approximately correct for rocks from the Coronation mine. There is some evidence that PH_2O - T conditions varied somewhat from rock to rock. Also, the composition of plagioclase is variable and some rocks do not contain magnetite and/or

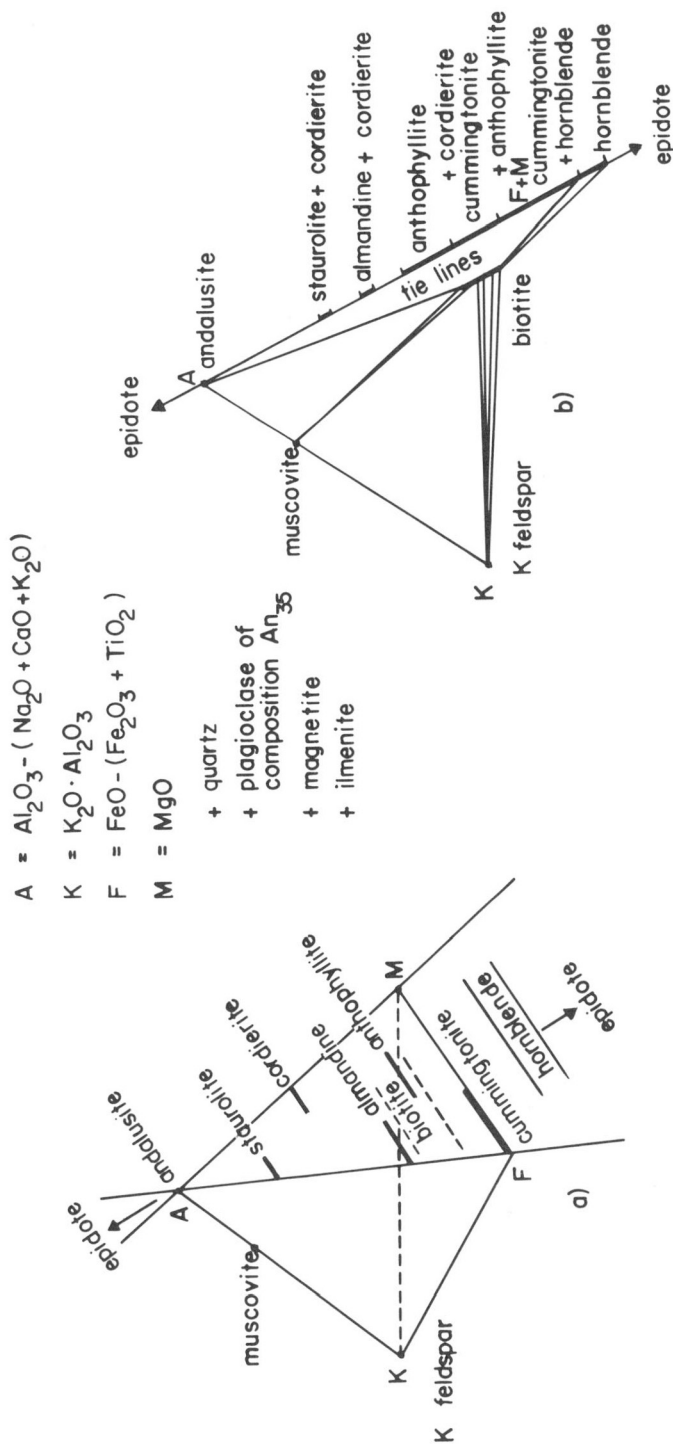


Figure 5. Minerals in the system $SiO_2 - Na_2O - CaO - Fe_2O_3 - TiO_2 - Al_2O_3 - K_2O - FeO - MgO$ shown in the tetrahedron A - K - F - M (a) and along a section through the tetrahedron for a $M/(F+M)$ ratio of 0.5 (b).

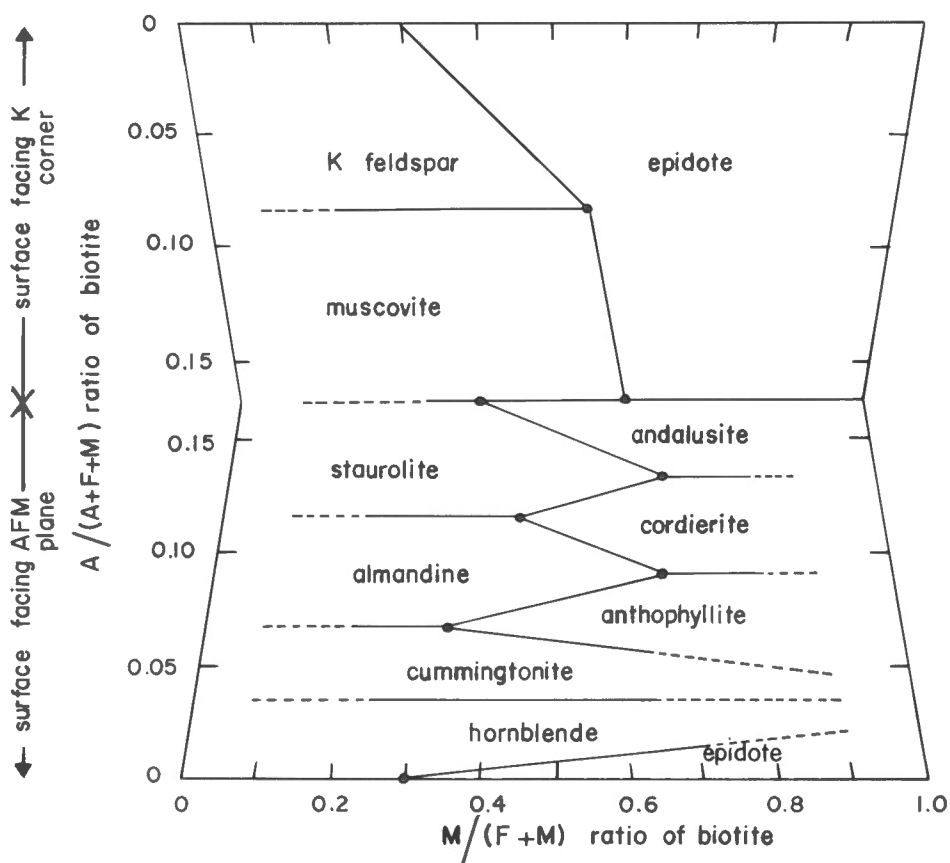


Figure 6. Compatible mineral assemblages in the system SiO_2 - Na_2O - CaO - Fe_2O_3 - TiO_2 - Al_2O_3 - K_2O - FeO - MgO in the presence of quartz, plagioclase of composition An_{35} , magnetite, ilmenite, and biotite, shown by a subdivision of the biotite composition surface within the tetrahedron A - K - F - M.

ilmenite. Therefore, a particular silicate mineral assemblage is not consistently accompanied by either pyrite or pyrrhotite. But in general, it has been observed that pyrrhotite is the common iron sulphide in ore developed in cordierite-anthophyllite rocks, and pyrite is the common iron sulphide where the gangue minerals are hornblende-epidote. This relationship suggests equilibration between sulphide and silicate minerals at metamorphic conditions.

The occurrence of gahnite probably is an indication that the ore has been subjected to metamorphism. Gahnite typically is found in ore deposits enclosed by metamorphic rocks. Very likely gahnite can be a metamorphic mineral formed by reactions between sphalerite and aluminous minerals.

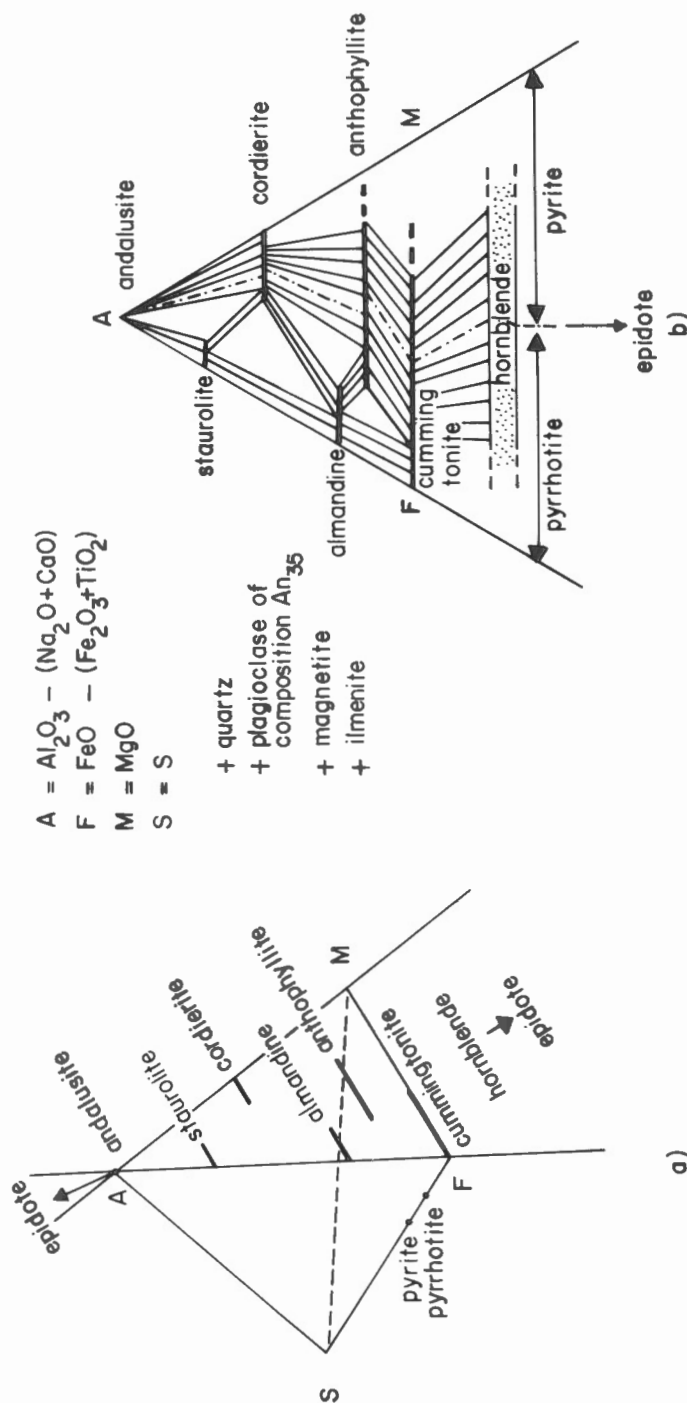
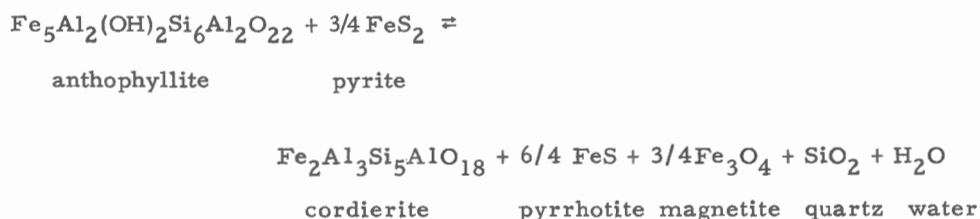


Figure 7. Minerals in the system $\text{SiO}_2 - \text{Na}_2\text{O} - \text{CaO} - \text{Fe}_2\text{O}_3 - \text{TiO}_2 - \text{Al}_2\text{O}_3 - \text{MgO} - \text{S}$ shown in the tetrahedron A - F - M - S (a). Compatible mineral assemblages can be shown on the A - F - M face, pyrrhotite occurring in relatively iron-rich mineral assemblages and pyrite in relatively iron-poor ones (b).

So far the relationship between sulphides and assemblages of gangue minerals from the Coronation mine has been discussed. Now the relationship between disseminated sulphides and silicate minerals in metamorphic rocks will be considered. It was noted that pyrite is the common iron sulphide in basic volcanic rocks, whereas pyrrhotite is the common iron sulphide in pelitic rocks (acidic pyroclastic rocks and biotite gneisses). The same observation has been made by others, for instance by Banno and Kanehira (1961). However, in many pelitic rocks magnetite is absent. In some cases, this is due to the presence of graphite which keeps the oxygen pressure very low (Miyashiro, 1964). In the absence of magnetite, the phase diagram of Figure 7 does not apply because the activity of component $\text{FeO} \cdot \text{Fe}_2\text{O}_3$ is smaller than unity. It is of interest to see in what direction the pyrite-pyrrhotite line would be shifted by lowering the activity of $\text{FeO} \cdot \text{Fe}_2\text{O}_3$. This is apparent from the following reaction equation:



A lowering of the activity of $\text{FeO} \cdot \text{Fe}_2\text{O}_3$ will drive this reaction to the right resulting in anthophyllite with a higher Mg/Fe ratio. The coexisting cordierite will also have a higher Mg/Fe ratio. Therefore, the pyrite-pyrrhotite line will be shifted to the A-M side in Figure 7b. A lowering of the oxygen pressure may also appreciably increase the amounts of H_2S and CH_4 in the fluid phase, thereby reducing the water pressure. This again will shift the pyrite-pyrrhotite line towards the A-M side. Thus pyrrhotite has a large stability field in pelitic rocks as shown on the A-F-M diagram in the presence of magnetite and even a larger one in its absence.

The Origin of Cordierite-Anthophyllite Rocks

Cordierite-anthophyllite rocks have a peculiar composition, which is characterized by the absence of alkalis and calcium. Their origin is of considerable interest because in some localities an association of cordierite-anthophyllite rocks and sulphide ore has been observed. The classic study of these rocks is the investigation of the Orijärvi area by Eskola (1914). He pointed out that their composition does not correspond to that of any sedimentary or igneous rock. For this reason their origin was attributed to contact metasomatism involving a relative enrichment in iron and magnesium and depletion in calcium and alkalis. Later on, Wegmann and Kranck (1931) suggested that regional metamorphism and granitization could also give rise to local concentrations of basic material as counterparts to the concentration of acidic material in granitized rocks. Again, the origin of cordierite-anthophyllite rocks was ascribed to metasomatism but, in this case, metasomatism was thought to be related to regional metamorphism. Both proposed explanations assume that the production of the peculiar rock composition is due to metasomatism in connection with metamorphism.

In contrast to these explanations based on metasomatic processes, Tuominen and Mikkola (1950) suggested that in the Orijärvi area, cordierite-anthophyllite rocks represent isochemically metamorphosed quartz-chlorite rocks. Thus the present mineralogy of the rocks is due to metamorphism, but the composition of the rock was determined by an earlier process unrelated to metamorphism. They point out that cordierite-anthophyllite rocks in the Orijärvi area are regionally distributed and bear no obvious relationship to granite bodies. According to their view, the cordierite-anthophyllite rocks are recrystallized chloritic zones produced by intense deformation prior to metamorphism.

Cordierite-anthophyllite rocks are associated with a variety of rock types in different geological settings. Thus all three proposed processes may be valid in appropriate environments. In the case of the Coronation orebody, the available evidence points to an origin by isochemical recrystallization during regional metamorphism. The cordierite-anthophyllite rocks are clearly not a product of contact metasomatism. They bear no relationship to any intrusive contact and the grade of metamorphism, as far as can be determined, is the same as that of the surrounding rocks. Metasomatism related to regional metamorphism can be ruled out because there has been very little, if any, granitization in the Coronation mine area. The chemical composition of the rocks requires that the pre-metamorphic rock was rich in quartz and chlorite. It has been shown by Akella and Winkler (1966) that quartz and Al-rich chlorite with an intermediate $\text{Fe}/(\text{Fe} + \text{Mg})$ ratio react to form cordierite and anthophyllite at temperatures exceeding 560°C at $\text{PH}_2\text{O} = 2000$ bars and 530°C at $\text{PH}_2\text{O} = 500$ bars. Although an isochemical metamorphism of chloritic rocks, as proposed by Tuominen and Mikkola (1950), appears to be a satisfactory explanation for the cordierite-anthophyllite rocks of the Coronation mine, their proposed mechanism of producing the chloritic rocks probably is not valid in this case. Rather than being regionally distributed the cordierite-anthophyllite rocks are related spatially to the orebody. Therefore, it appears more likely that these rocks represent original zones of chloritic alteration, the process of chloritization presumably being related to mineralization (Whitmore, 1962, 1964, 1969; Froese and Whitmore, 1964). The process of chloritization involves essentially a removal of Na_2O and CaO . On the other hand, CaO appears to be concentrated in some hornblende-epidote-grossularite rocks of the mine and also in numerous calcite and quartz-calcite veins. Possibly some of this CaO is derived from a chloritization of other rocks. If the calcite veins may be considered as the counterpart of chloritization, the process of redistribution of CaO took place before metamorphism because the calcite veins have been metamorphosed, as indicated by epidote-grossularite reaction rims along their contacts.

Conclusions

As far as can be determined on the basis of compatible mineral assemblages, the grade of metamorphism of rocks from the Coronation mine, including the cordierite-anthophyllite rocks, is the same as that of the surrounding area. A relationship between assemblages of sulphide minerals and silicate gangue minerals indicates that all minerals were subjected to regional metamorphism. The presence of gahnite is attributed to reaction between sphalerite and aluminous silicates at metamorphic conditions. The

cordierite-anthophyllite rocks are considered to be regionally metamorphosed zones of chloritization, presumably produced at the time of mineralization prior to metamorphism.

Acknowledgments

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No. 5 SULPHIDE ORES FROM THE CORONATION MINE,
SASKATCHEWAN

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ABSTRACT

The Coronation mine deposit lies concordantly in Precambrian metamorphic rocks of the amphibolite facies. Anthophyllite-cordierite rocks are found in a zone immediately adjacent to the deposits.

Pyrite, pyrrhotite, chalcopyrite, sphalerite, and magnetite are the main metallic minerals of the ores. Ilmenite is not uncommon, though always scarce in amount. Native gold and arsenopyrite are rarely found. Cubanite occurs occasionally as exsolution lamellae in chalcopyrite. Marcasite is found in minute veinlets of a later mineralization.

Chemical compositions of coexisting magnetite and ilmenite were roughly estimated at Fe_3O_4 97%· Fe_2TiO_4 3% and FeTiO_3 91%· Fe_2O_3 9%. 131 spacing of arsenopyrite associated with pyrite is $1.6320 \pm 0.0005 \text{ \AA}$. These mineral assemblages appear to be consistent with the formation temperatures of pyrrhotite-pyrite pairs, about 500°C , estimated by Ferris (1961) and Arnold (1964).

Pyrrhotite grains of some ores having foliated structure show a preferred orientation, i.e., the c-axes of pyrrhotite grains tend to be oriented perpendicularly to the foliation.

The mineral assemblages and structures of ores jointly suggest that the present state of the ore deposits was mostly formed during a period of regional metamorphism.

Minor veins composed of chalcopyrite, tetrahedrite, pyrite, and calcite are found in the mine. The veins formed by a later mineralization.

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I Introduction

The Coronation mine is located in the eastern part of Saskatchewan, about 12 miles southwest of Flin Flon. Production commenced in 1960 and ceased in 1964 due to exhaustion of the copper-bearing orebodies.

Froese (1963) studied the structure and metamorphism of the area in detail. According to him the metamorphic grade of the area corresponds to the amphibolite facies.

Ferris (1961) estimated formation temperatures of pyrrhotite and sphalerite based on the equilibrium relations of the mineral pairs, pyrrhotite-pyrite and pyrrhotite-sphalerite. The formation temperatures of 41 pyrrhotites range from 479° to 519° C, and the estimated temperatures of 2 sphalerites are 436° and 470° C.

Arnold (1964) refined the geothermometric study of the Coronation ores and estimated temperatures and pressures of crystallization of pyrrhotite, pyrite, sphalerite, and vein quartz. The estimated temperatures and pressures are $497^{\circ} \pm 5^{\circ}$ C and 1760 ± 680 atm for the mineral pairs of pyrite-pyrrhotite and pyrrhotite-sphalerite. In vein quartz of later mineralization the estimated temperatures of trapping of liquid inclusions are somewhat lower than 300° C.

Gilliland (1964) explored mineral distribution within the orebody. He considered that a temperature gradient may have existed in the orebody and the orebody may have been formed from hydrothermal solutions.

Whitmore (1964) suggested that the initial accumulation of sulphides of the Coronation orebody may have taken place contemporaneously with the development of the volcanic pile prevailing in the area, and that both the volcanics and orebody may have been involved in deformation and metamorphism.

The investigation described in the present paper is mostly confined to ore-microscopic studies of the Coronation ores, and forms part of the comprehensive study of the Coronation mine area. The outline of the geology and ore deposits, petrological descriptions of rocks, and assemblages of gangue minerals of ores are largely based on the unpublished thesis by Froese (1963) and personal communications from D.R.E. Whitmore.

Acknowledgments

The specimens of rocks and ores described in this paper were offered by D.R.E. Whitmore and E. Froese. Well-formed crystals of pyrrhotite from Elizabethtown, Ontario, were supplied from Systematic Reference Series of the National Mineral Collection. The X-ray powder photographs of several minerals and the chemical analysis of a zinc-spinel were made by the staff of the X-ray laboratory and analytical chemistry laboratory of the Geological Survey of Canada, respectively. The writer expresses deep gratitude for their kind help.

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II Outline of geology

Froese (1963, 1969b) has outlined the geology of the Coronation area. The Coronation mine area lies within the Churchill structural province of the Canadian Shield. The area is occupied by metamorphic rocks of Amisk Group and intrusive rocks of gabbroic to granitic composition. The metamorphic and intrusive rocks are unconformably overlain by Ordovician sandstone and dolomite in the southern part of this area. Potassium-argon ages of biotites of the metamorphic and intrusive rocks are about 1700 m.y. (Stockwell, 1963). This suggests that the area suffered Hudsonian orogeny and that most of the intrusives are related to that orogeny.

The Amisk Group of this area is composed mainly of metamorphic equivalents of basic to intermediate volcanics and associated pyrrhoclastics. Biotite gneisses, which are of clastic origin, are exposed in limited areas and are interlayered with schists of basic and intermediate composition. Cordierite-anthophyllite rocks are found around the Coronation orebody. These rocks may be considered as metamorphic rocks derived from metasomatically altered volcanic rocks.

In the basic and intermediate rocks, the chief constituent minerals are common hornblende, epidote, plagioclase, quartz, and magnetite. Cummingtonite, biotite, muscovite, and almandine are found in some specimens. Tourmaline, calcite, ilmenite, and pyrite are often present as accessory minerals.

The major constituent minerals of the biotite gneisses are quartz, plagioclase, biotite, and almandine. Muscovite and microcline are not uncommon. Staurolite and andalusite are found in a few specimens.

Cordierite-anthophyllite rocks are composed of cordierite, anthophyllite, quartz, plagioclase, and magnetite. Biotite, cummingtonite and gahnite are not uncommon. Andalusite, staurolite, and almandine are found in some specimens. Ilmenite is not rare, although scarce in amount.

Mineral assemblages indicate that the metamorphic grade of this area corresponds to the amphibolite facies.

Granitic and basic intrusive complexes are present. The granitic intrusive complex comprises granodiorite and quartz diorite, while the basic intrusive complex includes quartz-diorite, diorite, gabbro, and peridotite. These complexes form larger intrusive bodies crudely concordant with the structure of the surrounding metamorphic rocks. Diabase and porphyritic dykes of acidic to basic composition occur on a smaller scale.

III Mode of occurrence of the ore deposit

The Coronation orebody forms a concordant lens occurring within metamorphosed volcanic rocks. The foliation of the metamorphic rocks dips southwestward at about 65° and the lineation plunges southward at about 60°. The elongation of the orebody coincides with the linear structure of the surrounding metamorphic rocks.

In detail, the shape of the orebody is not regular, but it pinches and swells rather irregularly both along the strike and down the dip.

IV Mineral composition and fabrics of the ores

In the Coronation mine two types of mineralization are distinguished. A pyrite-pyrrhotite-chalcopyrite-sphalerite phase of mineralization and tetrahedrite-chalcopyrite veins. The former resulted in formation of the main part of the Coronation orezone, while the latter is restricted to relatively minor veins of a later stage. The veins will be described in a separate chapter.

The ores of the orezone are classified into two major types, massive and those consisting of a mixture of sulphides and silicates. In massive ores, the amount of sulphide minerals ranges from 60 to 90 per cent by volume. These massive ores may be further subdivided into massive pyrite and massive pyrrhotite-chalcopyrite. The mineral composition of some selected specimens of massive ores is shown in Table 1.

Table 1. Mineral composition of some selected specimens of ores in volume per cent

Type of ore	Massive pyrite ore			Massive pyrrhotite-chalcopyrite ore				
Mineral No.	1	2	3	4	5	6	7	8
Pyrite	66	67	61	--	4	--	--	tr
Pyrrhotite	--	--	tr	46	31	38	59	26
Chalcopyrite	8	0.5	7	42	41	49	29	39
Sphalerite	3	0.5	tr	2	4	3	--	tr
Magnetite	5	2	1	--	7	2	--	--
Silicates	18	30	31	10	13	8	12	35

Table 2. Analysis of gahnite (Specimen No. WH-84-525)

	Wt. %	
Al ₂ O ₃	49.52	
Fe ₂ O ₃ *	17.31	
MgO	2.67	
ZnO	23.49	
SiO ₂	4.2	
S	1.08	
CaO +	0.2	* Total Fe expressed as Fe ₂ O ₃
Na ₂ O +	0.2	+ Approximate values
K ₂ O +	0.05	. Spectrographic results
TiO ₂ .	0.02	
Cr ₂ O ₃ .	0.03	Analysts: S.A., J.G.S.G., and W.F.W.
V ₂ O ₅ .	0.02	of the Geological Survey of Canada.
Mn .	0.04	
CuO .	0.03	

Plate IA. Layered structure of massive pyrrhotite-chalcopyrite ore. Two polished surfaces normal to the layered structure in the same specimen. Light grey: chalcopyrite-rich layer; dark grey: pyrrhotite-rich layer; black: silicates. Natural size.

Plate IB. Layered structure of massive pyrite ore. A lenticular body of massive pyrite ore is seen in the central part of the figure. A polished surface normal to the layered structure. Grey: pyrite; black: silicates. Natural size.

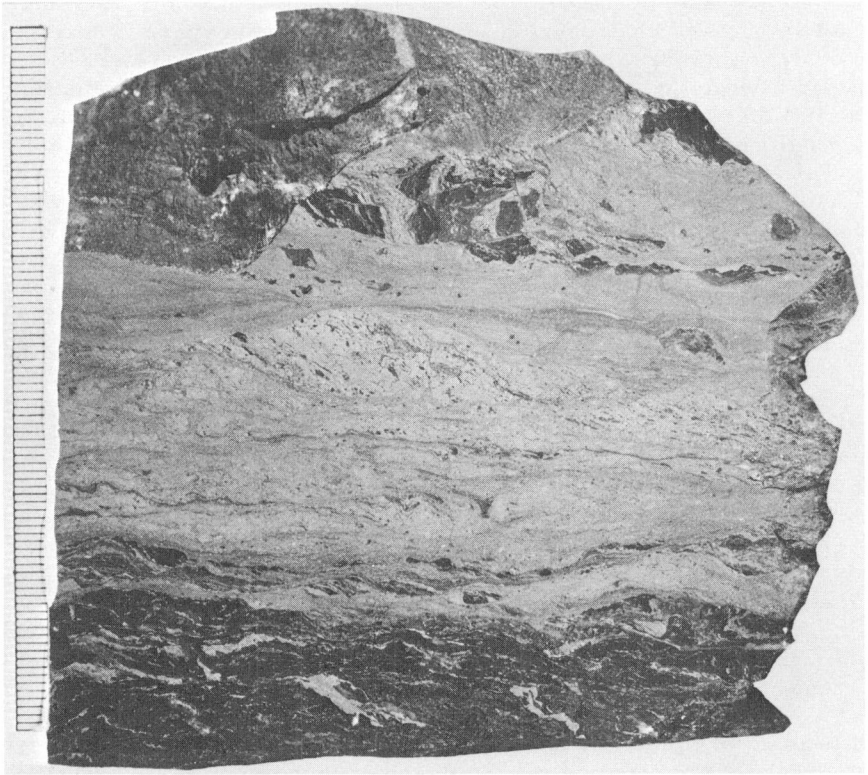


Plate IA

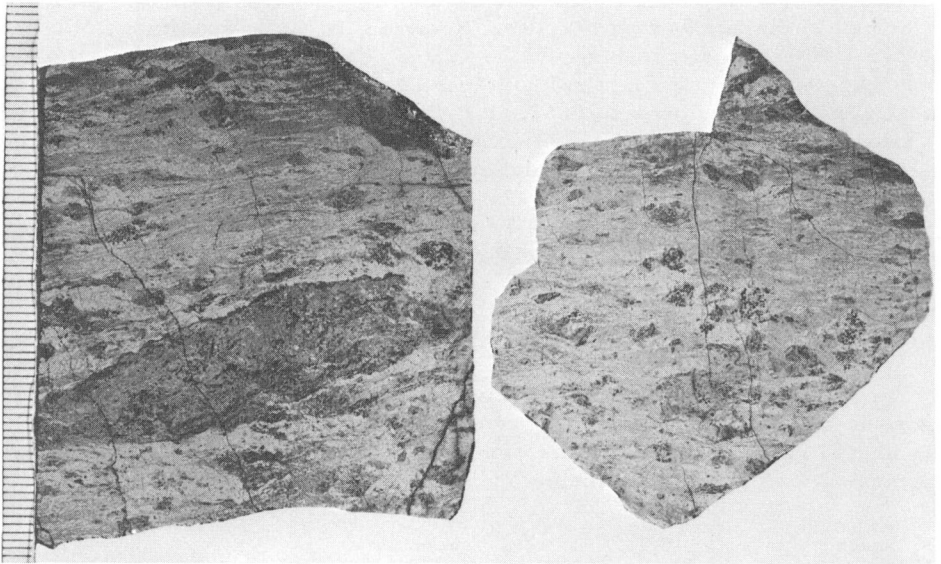


Plate IB.

Massive pyrite ore consists of pyrite, gangue minerals and subordinate amounts of chalcopyrite, sphalerite, and magnetite. Some specimens contain a minor amount of pyrrhotite. In massive pyrrhotite-chalcopyrite ore, the amount of chalcopyrite is comparable with that of pyrrhotite; together these minerals comprise from 65 to 90 per cent of the ore. Sphalerite, magnetite, and gangue minerals occur in subordinate amounts. In many specimens a minor amount of pyrite is present. Massive sphalerite ore consists of sphalerite with subordinate amounts of pyrite, chalcopyrite, pyrrhotite, and gangue minerals. The first two types of ores constitute the main part of the massive sulphide orebody, and the last is very rare.

In the ores consisting of mixtures of sulphides and silicates, sulphides occur as stockworks of fine stringers admixed with silicates. The amount of sulphide minerals in the ores is variable and ranges from about 10 to 20 per cent by volume in general. There is a gradual change from this type of ore to rocks containing sulphides below ore grade. This type of ore is composed of chalcopyrite, pyrrhotite, magnetite, and gangue minerals. Subordinate amounts of pyrite, sphalerite, and ilmenite are also present. In places pyrite predominates and the ore may be termed a pyrite-silicate type.

Quartz and chlorite are the abundant gangue minerals of the massive sulphide ores. Small amounts of calcite and muscovite are also present. In some specimens calcite predominates. Anthophyllite, cordierite, biotite, quartz, and chlorite are common gangue minerals in most of sulphide-silicate ores. Andalusite, cummingtonite, and gahnite are found in some specimens.

A prominent feature in sulphide-silicate ore is a streaky layering, which is parallel to the foliation of the country rocks. (Froese, 1963, frontispiece). Most of the massive pyrrhotite-chalcopyrite ore examined shows a remarkable layered structure, i.e., pyrrhotite-rich and chalcopyrite-rich layers alternate with one another in a minor scale as shown in Figure A of Plate I. In such ores preferred orientation of pyrrhotite grains is distinct as described in the succeeding chapter. However, in some specimens of massive pyrrhotite-silicate ore, structure varies from massive to brecciated, with rock fragments included in a sulphide base. (Froese, 1963, Plate 24). Locally massive pyrite-ore also exhibits a layered structure, parallel to the foliation of the country rocks. In some specimens small lenticular bodies of massive pyrite ore are included and conformably arranged in a layered pyritic base as shown in Figure B of Plate I. Internal structures of the ore bodies, in addition to the ore zone as a whole, exhibit a high degree of congruency with the structures of the country rocks.

V Preferred orientation of pyrrhotite

Froese (1963) reported simultaneous extinction of pyrrhotite grains in one specimen from the Coronation mine. In the present study it was found that simultaneous extinction of pyrrhotite grains due to preferred orientation is common in sulphide ores, especially foliated ores.

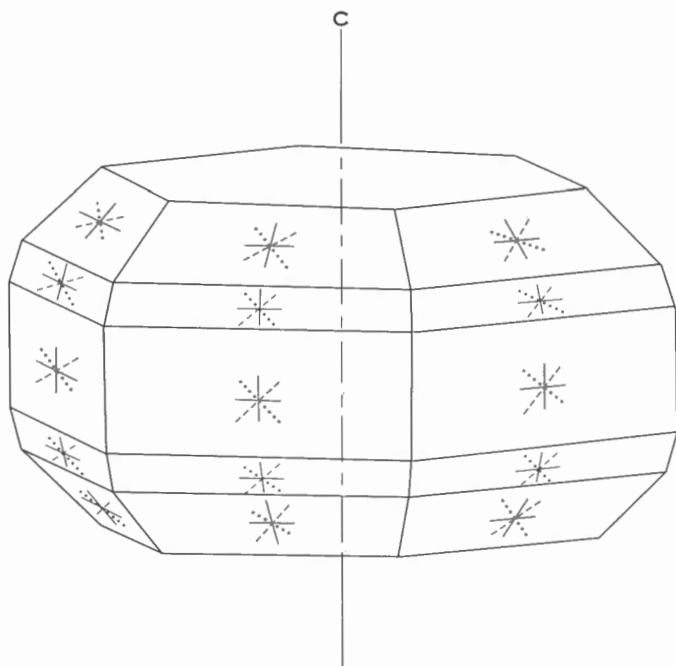


Figure 1. A schematic diagram showing the relationships between the crystallographic orientation and optical properties of pyrrhotite.

Solid line — extinction position

Broken line — maximum illumination position with bluish grey polarization colour

Dotted line — maximum illumination position with yellowish grey polarization colour

Section normal to the c-axis is always dark.

Optical properties of pyrrhotite

Pyrrhotite is strongly anisotropic. Generally a single grain of pyrrhotite exhibits two extinction positions 90° apart alternating with maximum illumination positions at about 45° to the extinction positions. Distinct polarization colours, yellowish grey and bluish grey are observed alternately in the maximum illumination positions.

Single euhedral crystals of pyrrhotite were examined to correlate the optical and crystallographic orientations. A crystal from Elizabethtown, Ontario, was used for this examination. A Leitz Pan Photo microscope with a xenon lamp illuminating source was used.

Sections parallel to the \underline{c} -axis show strong anisotropism and are extinguished at positions either parallel or perpendicular to the \underline{c} -axis. At the diagonal positions the sections are most strongly illuminated, and in the clockwise and counterclockwise rotation of the stage from the extinction position parallel to the \underline{c} -axis, they show distinct polarization colours of yellowish grey and bluish grey, respectively. Sections perpendicular to the \underline{c} -axis are isotropic. Sections oblique to the \underline{c} -axis show anisotropism, and they are extinguished at positions either parallel or perpendicular to the vertical projection of the \underline{c} -axis on the polished surface. The respective polarization colours appear in the same manner as in the sections parallel to the \underline{c} -axis, though weaker. The intensity of anisotropism depends on the angle between the section and the \underline{c} -axis. The anisotropism is strongest in the section parallel to the \underline{c} -axis. The relationships between the crystallographic orientations and the optical ones are shown schematically in Figure 1. The characteristic polarization colours were observed on pyrrhotite grains examined under the microscope used in this study, and may show some variations with other instruments and also possibly with other material.

On the basis of these optical properties, one may determine the orientation of the \underline{c} -axis or the vertical projection of the \underline{c} -axis in the individual grains of pyrrhotite under the microscope. When the polarization colour changes from bluish grey to yellowish grey in the 90° clockwise rotation, the extinction position between the two maximum illumination positions is parallel to the vertical projection of the \underline{c} -axis of the pyrrhotite grain. The angle between the section and the \underline{c} -axis may be roughly estimated from the intensity of anisotropism.

Reflectivity is also related to the crystallographic orientation. It may be possible to determine the crystallographic orientation of pyrrhotite grains by the reflectivity measurements. The method of the observation of extinction and anisotropism is more practical and thus has been utilized in this study.

Preferred orientation of pyrrhotite

Some sulphide specimens show a distinct layering consisting of an alternation of pyrrhotite-rich and chalcopyrite-rich layers millimeters in width. Linear structures are not found in the hand specimens of ores. A typical specimen was cut and polished in sections parallel and perpendicular to the layering. In each polished surface the extinction positions of pyrrhotite grains, which appear subsequently to bluish grey polarization colour in

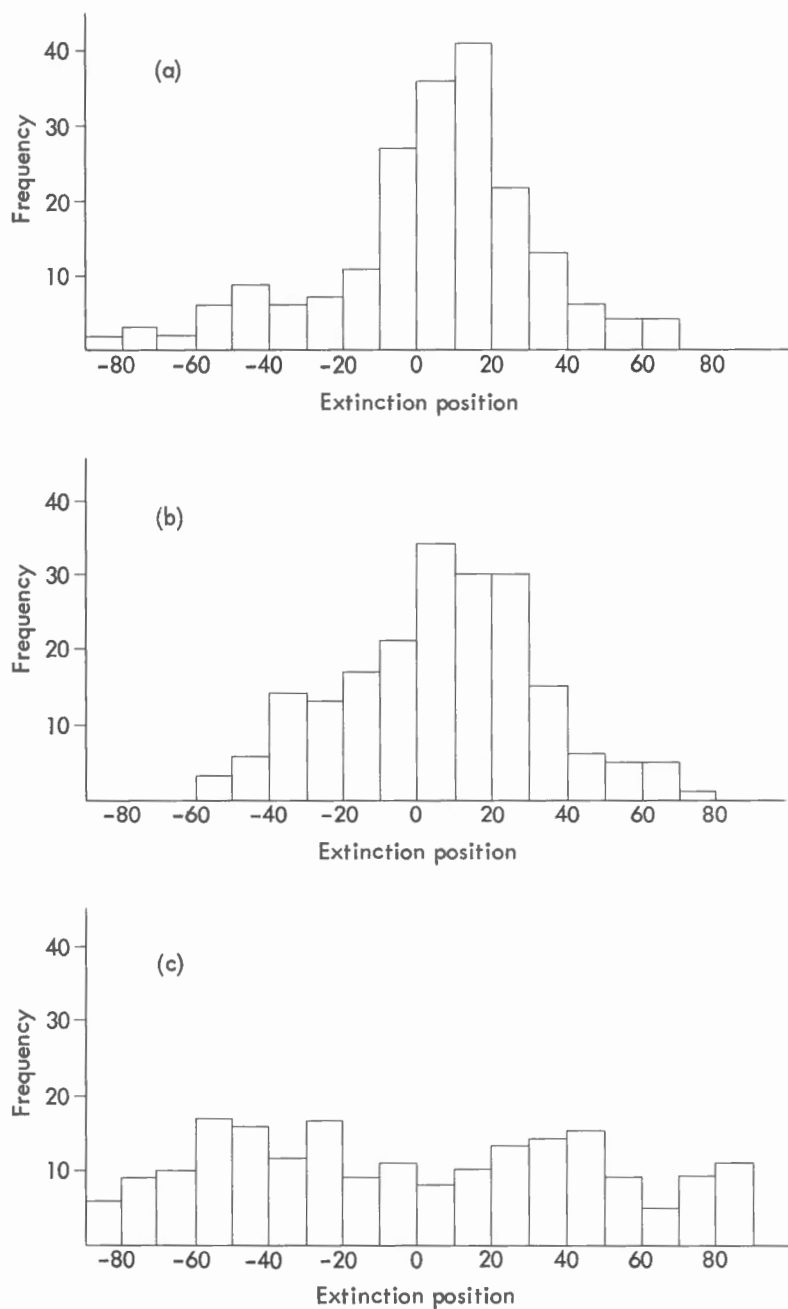


Figure 2. Orientation frequency diagrams of extinction positions of pyrrhotite grains in massive pyrrhotite-chalcopyrite ore. (Specimen No. P9-7).
(a) 200 measurements on a polished surface normal to the foliation.
(b) 200 measurements on another polished surface normal to the foliation.
(c) 200 measurements on a polished surface parallel to the foliation.

Plate IIA. Pyrrhotite of foliated ore. Section parallel to the foliation. Some grains are extinguished, others are illuminated to various degrees. Crossed nicols. 60x.

Plate IIB. Pyrrhotite (white to grey) and chalcopyrite (black) of foliated ore. Section normal to the foliation. Most of pyrrhotite grains are illuminated in a similar way. Crossed nicols. 60x.

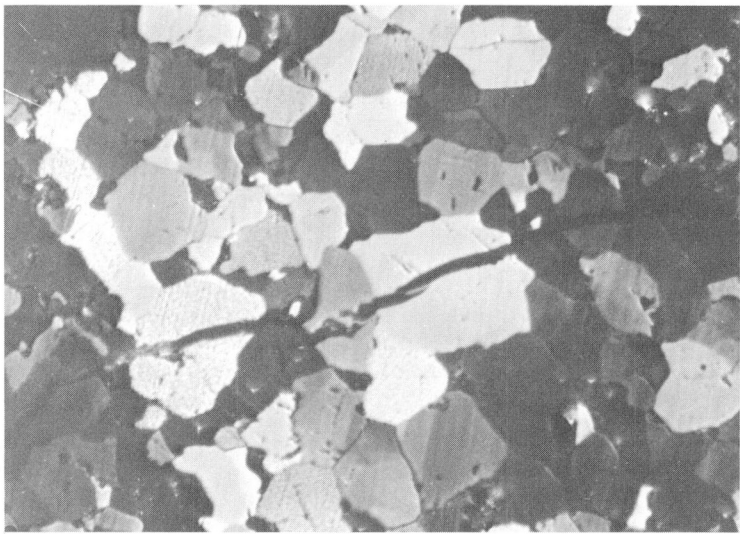


Plate IIA.

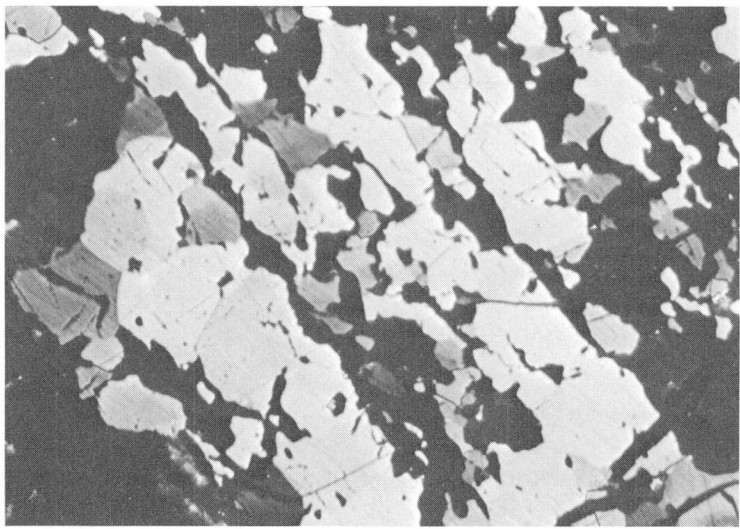


Plate IIB.

Plate IIIA. Pyrrhotite (white to grey) and chalcopyrite (black) of foliated ore. Section normal to both of two polished surfaces shown in Figures A and B of Plate II. Most of pyrrhotite grains are illuminated in a similar way. Crossed nicols. 60x.

Plate IIIB. Massive pyrite ore, showing euhedral to subhedral grains of pyrite (white) and interstitial chalcopyrite (grey) and silicates (black). 140x.

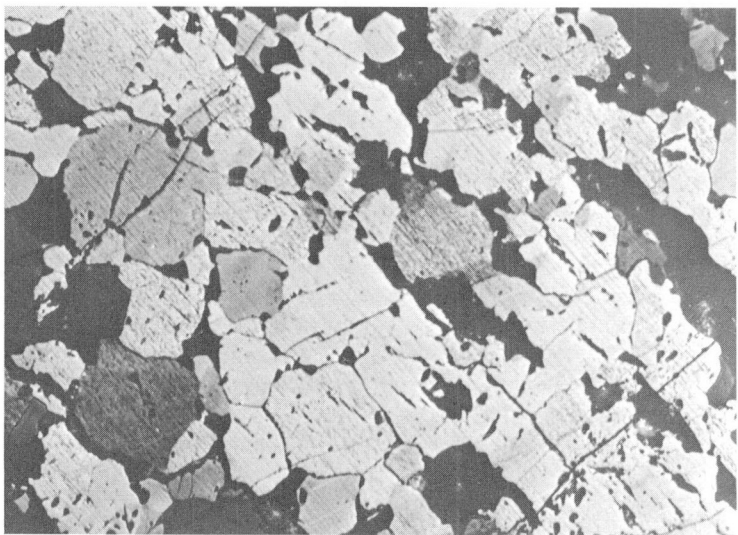


Plate IIIA.

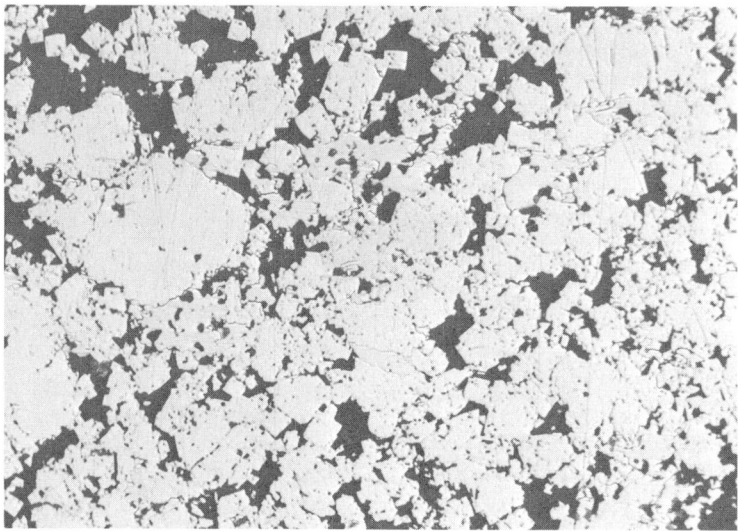


Plate IIIB.

the clockwise rotation, were statistically measured, and the orientations of the vertical projection of the \underline{c} -axis were determined.

The results are shown in frequency diagrams (Figs. 2a and 2b) from polished sections cut perpendicular to the layering. In each diagram the position perpendicular to the layering in the polished section is fixed as the origin of the abscissa. Distinct maxima are found in both diagrams, indicating that the vertical projections of the \underline{c} -axis are preferentially oriented perpendicular to the layering. On the other hand, no maxima occur in Figure 2c, which is from the polished section cut parallel to the layering. In this diagram any position may be arbitrarily fixed as the origin of the abscissa.

Most pyrrhotite grains are strongly anisotropic on the polished surface perpendicular to the layering, while on the polished surface parallel to the layering many pyrrhotite grains are not strongly anisotropic and some appear practically isotropic. In the former the \underline{c} -axis of most pyrrhotite grains may be considered oriented nearly parallel to the polished surface, whereas in the latter, decreasing and disappearance of anisotropism may be ascribed to the orientation of the \underline{c} -axis nearly or fully perpendicular to the polished surface. The orientation of the \underline{c} -axis may, however, deviate in every direction from an exactly perpendicular position, in which case the orientation of the vertical projection of the \underline{c} -axis may be distributed without any systematic concentration as shown in Figure 2c.

Photomicrographs of the polished surfaces are shown in Figures A and B of Plate II and Figure A of Plate III. One can see a simultaneous extinction of pyrrhotite grains in the figures of the polished surfaces perpendicular to the layering, but can not in that of the polished surface parallel to the layering.

Thus it may be concluded that the \underline{c} -axis of pyrrhotite grains of the foliated ore tend to be preferentially oriented perpendicularly to the foliation. The same conclusions are reached from perusal of Figures 3 and 4.

Figure 4 is an orientation frequency diagram of pyrrhotite grains in graphite-pyrrhotite-biotite-quartz schist from the Coronation area. The \underline{c} -axis of pyrrhotite is oriented perpendicularly to the schistosity. The preferred orientation of pyrrhotite is in harmony with that of biotite, the basal planes of which lie parallel to the schistosity.

VI Minerals of ores

The following metallic minerals were identified in specimens of the orebodies.

<u>Element</u>	<u>Sulphides</u>		<u>Oxides</u>
Native gold	Pyrite	Arsenopyrite	Magnetite
	Pyrrhotite	Cubanite	Ilmenite
	Chalcopyrite	Marcasite	Hematite
	Sphalerite		

Cubanite and hematite occur only as exsolution lamellae in chalcopyrite and ilmenite, respectively. Marcasite evidently belongs to a later mineralization.

Silicates and other transparent minerals of the ores have been studied and described by Froese (1963 and 1969b). Of these gangue constituents, only the zinc spinel, gahnite, will be described in some detail.

Pyrite

Pyrite was found in most of the specimens examined, and is the chief constituent of massive pyrite ore. In massive pyrite ore pyrite forms a compact aggregate with the interstices filled with chalcopyrite, sphalerite, quartz and other gangue minerals (Fig. B of Plate III). Many grains of pyrite contain tiny grains of chalcopyrite, sphalerite, and rarely pyrrhotite. Some massive pyrite ores, having a distinct layered structure, are composed of pyrite of two contrasted grain-sizes (Fig. A of Plate IV).

Pyrite is commonly closely associated with pyrrhotite and the textures suggest contemporaneous formation; it may be considered that pyrite and pyrrhotite are in equilibrium in these ores.

In some specimens, however, pyrite grains are replaced by chalcopyrite along parting planes, and in others, rounded grains of pyrite are rimmed by pyrrhotite. These facts suggest that pyrite is of earlier formation than the other sulphide minerals in these instances. Massive pyrrhotite-chalcopyrite ore is often penetrated by veinlets consisting of pyrite, marcasite, and calcite. Pyrite thus appears to have been formed in various stages of mineralization.

Zoned structure is conspicuous in euhedral pyrite grains of some specimens, particularly in pyrite related to a later period of formation (Fig. B of Plate IV).

Marcasite

Marcasite occurs locally in veinlets, millimeters in width, cutting the massive sulphide ore. It is accompanied by pyrite, calcite and/or chlorite. The pyrite shows euhedral cubic outlines and its grain-size ranges from 0.03 to 0.2 mm, while marcasite is euhedral to subhedral averaging 0.03 mm in diameter. Most of the grains of marcasite show simple or repeated twinning. (Fig. A of Plate V).

In a few specimens, pyrrhotite in contact with the veinlets is partly replaced by marcasite. In one specimen of massive pyrite ore, fine-grained marcasite occurs along the grain-boundaries of the coarse-grained pyrite aggregate.

Pyrrhotite

Pyrrhotite is one of the chief constituents of massive pyrrhotite-chalcopyrite ore. Here, pyrrhotite forms equigranular and allotriomorphic aggregates with chalcopyrite. Pyrrhotite grains are usually equidimensional (Fig. B of Plate V), but in some specimens they show an elongate form, which coalesce to form ribbons within a pyrrhotite-rich band.

In massive sphalerite ore minute grains of pyrrhotite are found within sphalerite grains and also along grain boundaries of sphalerite (Fig. A of Plate VIII). In ores consisting of mixture of sulphides and silicates, pyrrhotite usually occurs in a streaky layering.

As described in the preceding section, pyrrhotite grains in some ores, particularly in massive pyrrhotite-chalcopyrite ore exhibiting a foliated structure, have a distinct preferred orientation.

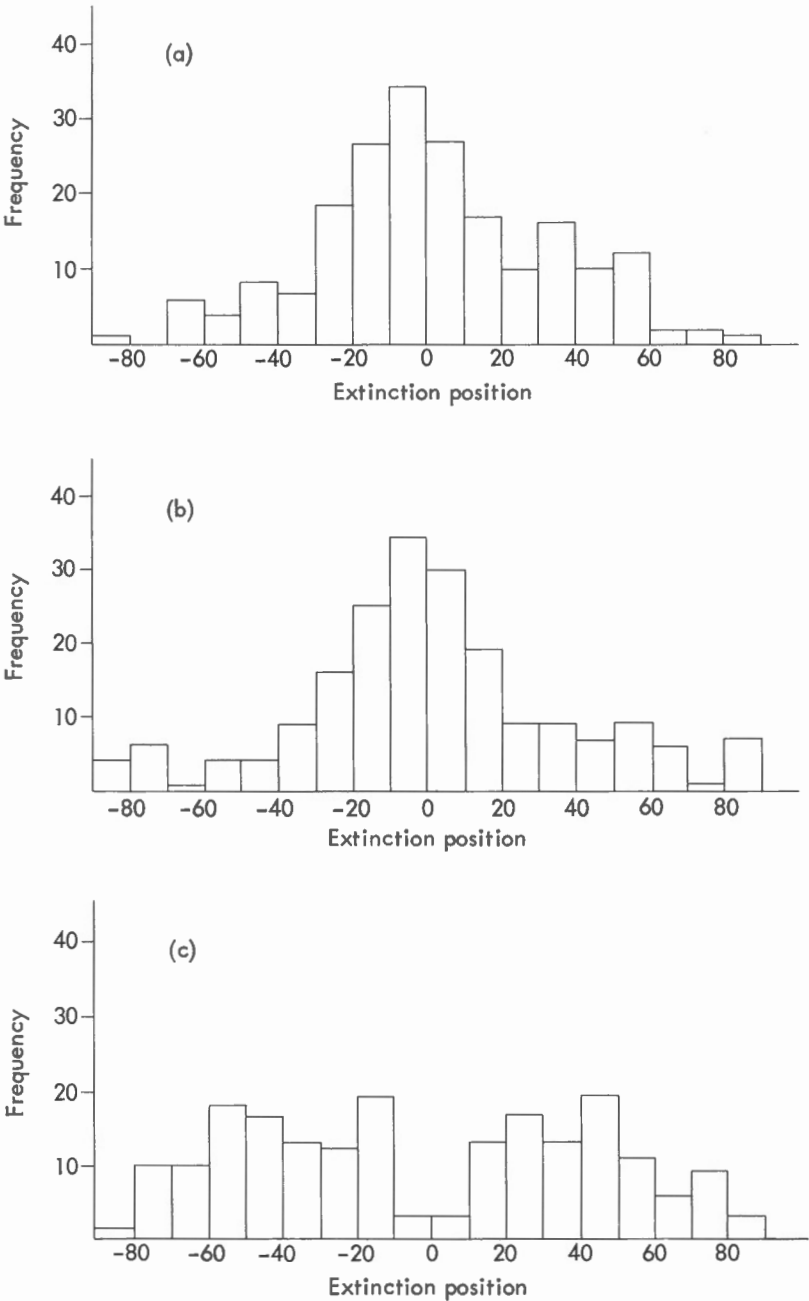


Figure 3. Orientation frequency diagrams of extinction positions of pyrrhotite grains in massive pyrrhotite-chalcopyrite ore. (Specimen No. P9-10).
(a) 200 measurements on a polished surface normal to the foliation.
(b) 200 measurements on another polished surface normal to the foliation.
(c) 200 measurements on a polished surface parallel to the foliation.

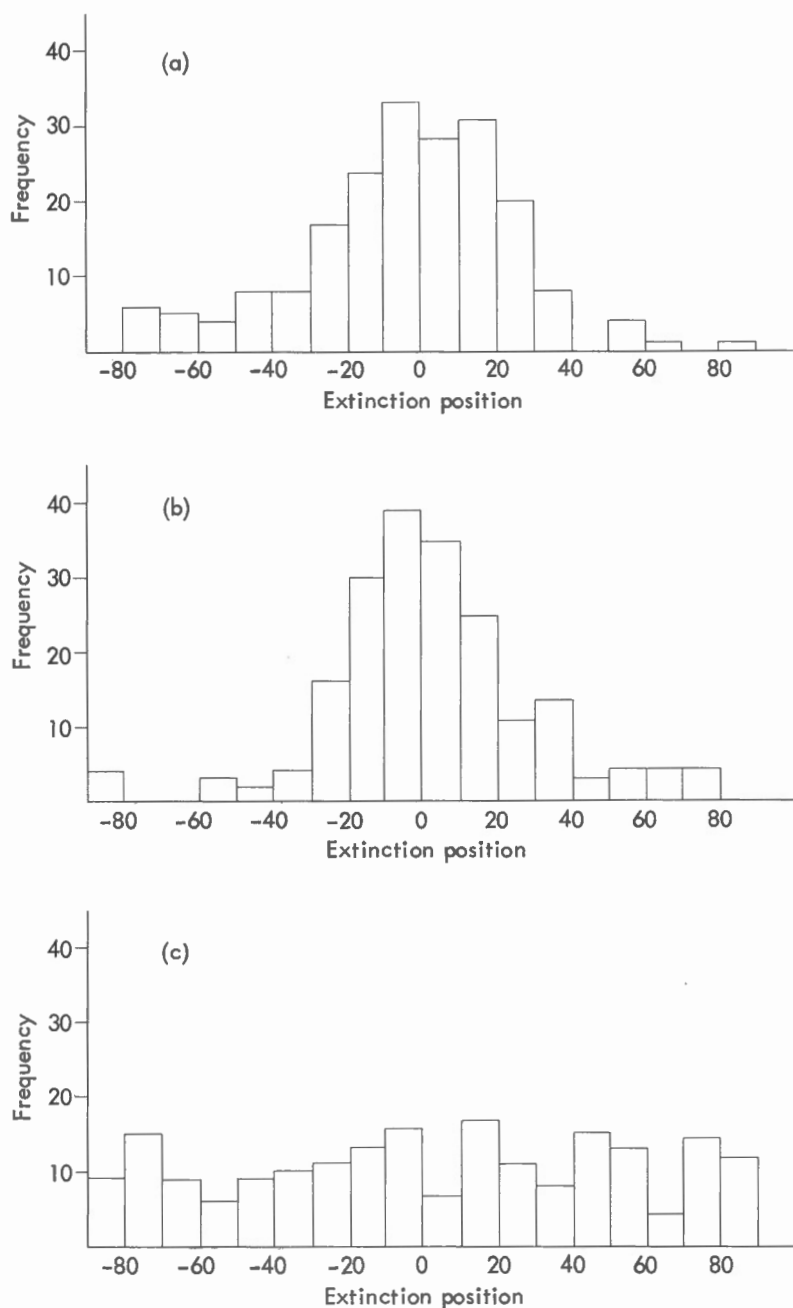


Figure 4. Orientation frequency diagrams of extinction positions of pyrrhotite grains in massive pyrrhotite-chalcopyrite ore. (Specimen No. P10-37).
(a) 200 measurements on a polished surface normal to the foliation.
(b) 200 measurements on another polished surface normal to the foliation.
(c) 200 measurements on a polished surface parallel to the foliation.

Plate IVA. Massive pyrite ore, showing two contrasted grain-sizes of pyrite. The same specimen as in Figure B of Plate I. 140x.

Plate IVB. Euhedral crystals of zoned pyrite. Etched by 1:1 HNO_3 . 140x.

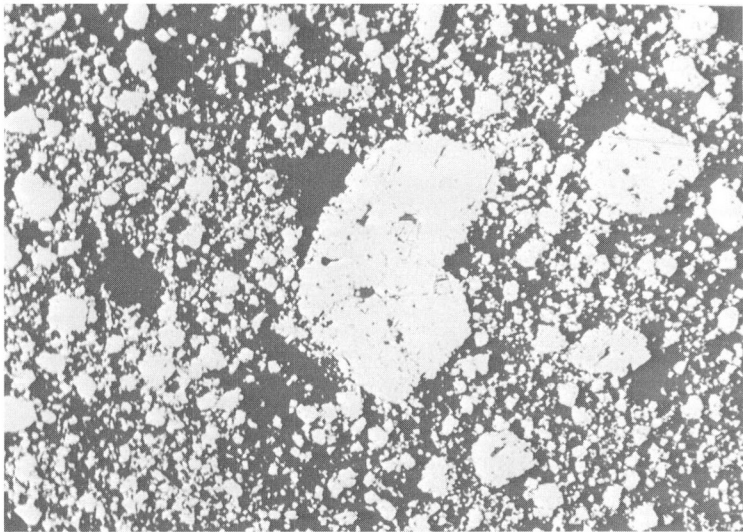


Plate IVA.

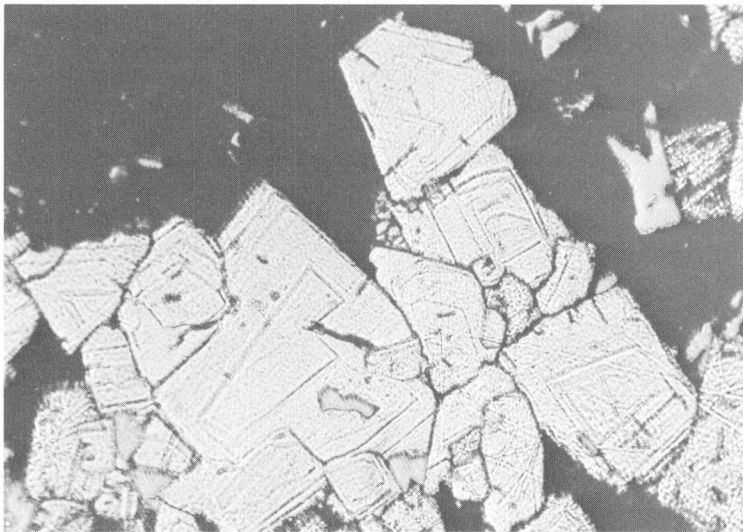


Plate IVB.

Plate VA. Pyrite-marcasite association. Marcasite shows characteristic repeated twins. Crossed nicols. 140x.

Plate VB. Pyrrhotite, showing the mosaic of fine-grained crystals. Crossed nicols. 60x.

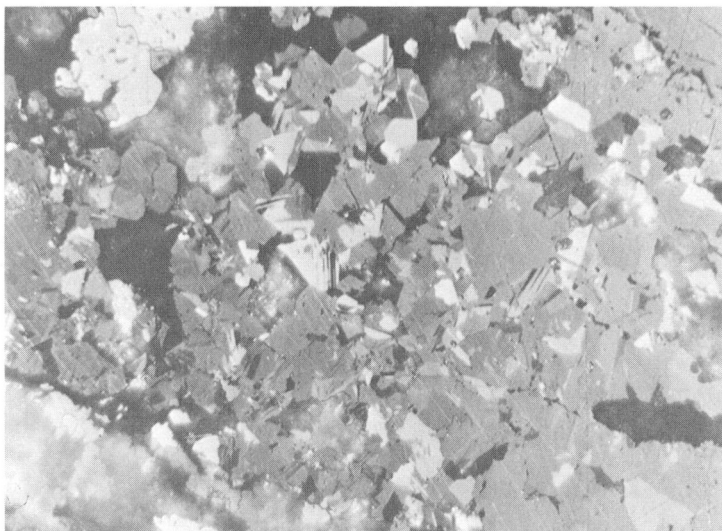


Plate VA.

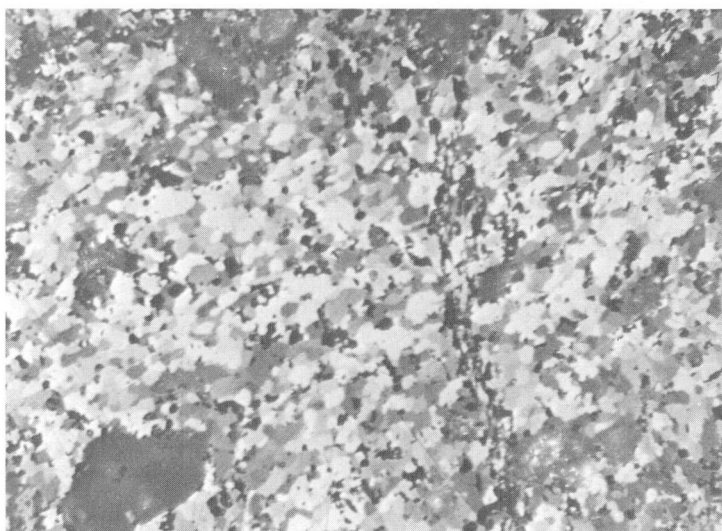


Plate VB.

Plate VIA. Lamellar twinning of pyrrhotite. Crossed nicols. 140x.

Plate VIB. Pyrite replaced by chalcopyrite along the partings. Oil immersion. 330x.

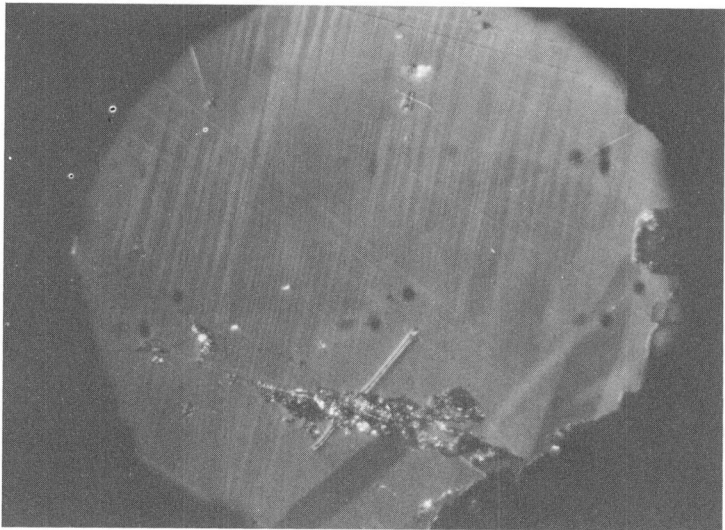


Plate VIA.

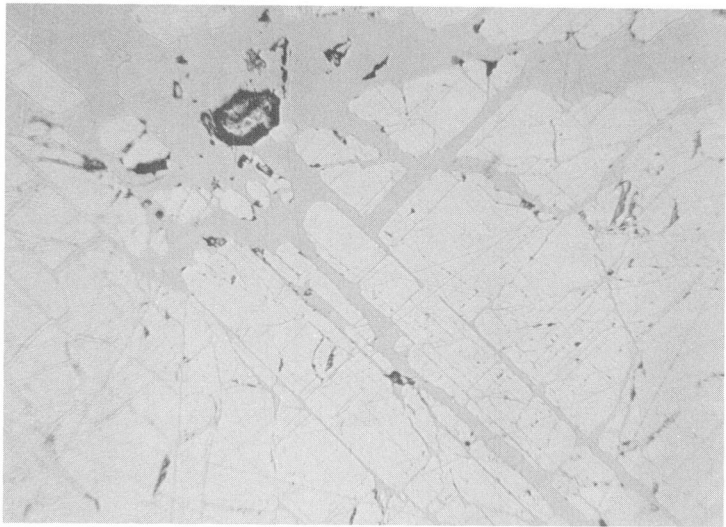


Plate VIB.

Pyrrhotite grains in two specimens show lamellar twinning as shown in Figure A of Plate VI. In these specimens, pyrrhotite is rather coarse-grained, and the grain-size ranges from 0.5 to 1.5 mm. The width of the lamellae is 0.01 mm in average. The extinction positions of adjoining lamellae are several degrees out of alignment. In the diagonal position nearly parallel to the twin bands, the pyrrhotite grains, as a whole, show bluish grey polarization colours and in the other diagonal position, they show yellowish grey. From the relation between the crystallographic orientation and optical properties in pyrrhotite, it may be concluded that the extinction position perpendicular to the twin bands is parallel to the vertical projection of the c - axis of the pyrrhotite crystal.

Chalcopyrite

Chalcopyrite was found in all the specimens examined. In massive pyrrhotite-chalcopyrite ores, chalcopyrite forms equigranular and allotriomorphic aggregates with pyrrhotite. In massive pyrite ores, chalcopyrite fills the interstices of the pyrite aggregate. In some specimens chalcopyrite replaces pyrite along parting planes (Fig. B of Plate VI).

Chalcopyrite is weakly anisotropic in some specimens, but it is practically isotropic in others. Many grains of chalcopyrite show lamellar twinning. The lamellae have apparently no preferred orientation (Fig. A of Plate VII).

In a few specimens, chalcopyrite contains a small amount of exsolution lamellae of cubanite.

Cubanite

The mineral was identified in a few specimens both under the ore-microscope and by X-ray powder diffraction.

Cubanite-bearing ore is composed of chalcopyrite, pyrrhotite, and subordinate amounts of pyrite, sphalerite, cubanite, magnetite, and gangue minerals. Pyrrhotite and chalcopyrite form equigranular and allotriomorphic aggregates. Cubanite occurs in thin lamellae within chalcopyrite (Fig. B of Plate VII). In the polished surface of the ore, the width of the lamellae ranges from 0.01 to 0.05 mm, and the amount of cubanite does not exceed 1 per cent of chalcopyrite.

Sphalerite

Sphalerite is not uncommon but scarce in amount in most sulphide ores. The mineral is commonly associated with chalcopyrite. In massive pyrrhotite-chalcopyrite ore having a foliated structure, sphalerite aggregates form small lenses or disc-like bodies, which lie nearly parallel to the foliated structure. Sphalerite is the chief constituent mineral of massive sphalerite ore, a rare type of mineralization in the Coronation mine. In this type of ore sphalerite forms equigranular and allotriomorphic aggregates. Some rock fragments included in sulphide ore are irregularly penetrated by veinlets of sphalerite and/or chalcopyrite.

Grain-boundaries of sphalerite are occasionally rimmed by chalcopryite, or rarely by pyrrhotite. Many sphalerite grains contain oriented or random tiny grains of chalcopryite or rarely of pyrrhotite. (Figs. A and B of Plate VIII and Fig. A of Plate IX). These textures may indicate exsolution between sphalerite and chalcopryite and between sphalerite and pyrrhotite.

Sphalerite grains invariably show repeated twinning, revealed by etching.

Arsenopyrite

Arsenopyrite was identified in one specimen of drill core. The mineral occurs in narrow bands ranging from 1 to 2 mm in width. The mineral is associated with pyrite, chalcopryite, sphalerite, and chlorite (Fig. B of Plate IX). Arsenopyrite and pyrite seem to have been formed in equilibrium. The d_{131} spacing of the arsenopyrite is $1.6320 \pm 0.0005 \text{ \AA}$. Plotting this value on a diagram of d_{131} against sulphur and arsenic content of arsenopyrite constructed by Morimoto and Clark (1961), the atomic content of sulphur and arsenic of the arsenopyrite corresponds to 35 and 32 per cent, respectively.

Native gold

Native gold 10μ or less in maximum length was found in one specimen of massive sulphide ore. The ore consists of chalcopryite, sphalerite, pyrite, pyrrhotite, and small amounts of gangue minerals and marcasite. Sphalerite contains small grains of pyrrhotite and chalcopryite. Native gold is associated with chalcopryite grains included in sphalerite (Fig. A of Plate X). Discrete grains of native gold are also found in sphalerite. The mineral is quite yellowish, suggesting a low content of silver.

Magnetite

Magnetite is common in massive sulphide ores, though always scarce in amount. It occurs sporadically as large grains in sulphide aggregates.

Magnetite is one of the chief constituents of the cordierite-anthophyllite rocks and the sulphide-silicate type ores. In these, magnetite forms large euhedral grains containing ilmenite lamellae (Fig. B of Plate X). The magnetite-ilmenite intergrowths coexist with discrete grains of ilmenite in some specimens. The equilibrium relation between magnetite and ilmenite will be described in a succeeding chapter.

Many grains of the magnetite-ilmenite intergrowth are replaced by chlorite, pyrrhotite, and chalcopryite, and rarely by pyrite (Fig. A of Plate XI). Usually magnetite is preferentially replaced, leaving relict ilmenite lamellae in a groundmass of chlorite and sulphides.

Plate VIIA. Massive pyrrhotite-chalcopyrite ore, showing spindle-shaped twin lamellae in chalcopyrite. Crossed nicols. 60x.

Plate VIIB. Exsolution lamellae of cubanite in chalcopyrite. Pyrrhotite occurs in thin layers along the grain-boundaries of chalcopyrite. 140x.

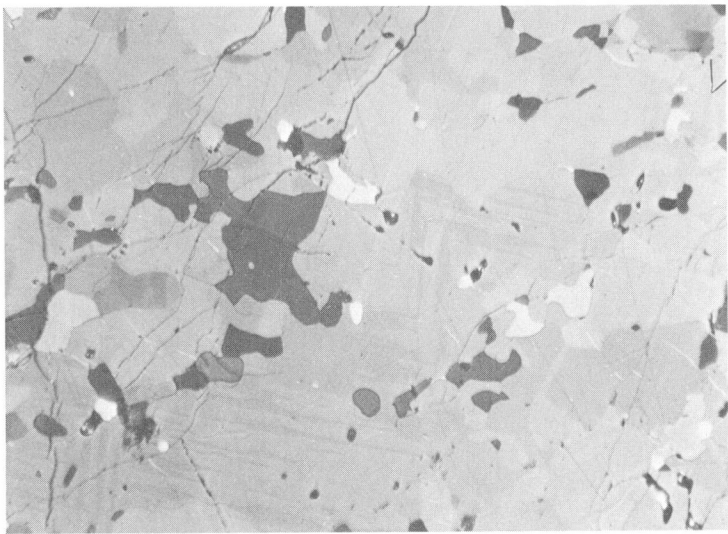


Plate VIIA.

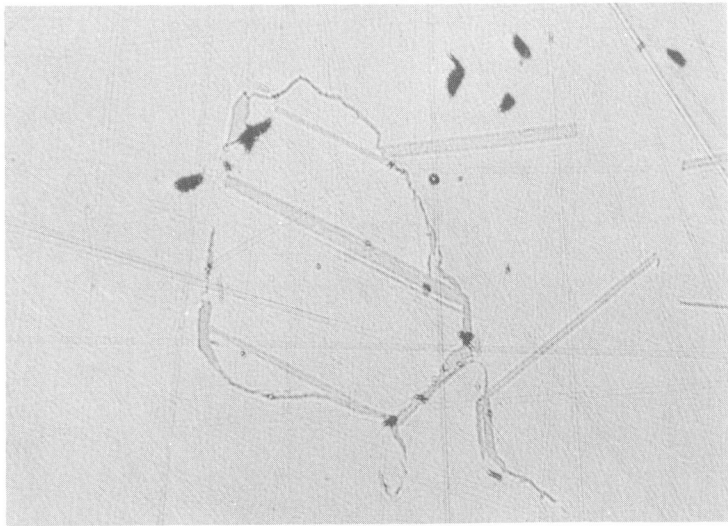


Plate VIIB.

Plate VIIIA. Massive sphalerite ore with small amounts of pyrite (white), pyrrhotite (light grey), and chalcopyrite (tiny dots). Pyrrhotite occurs mainly along the grain-boundaries of sphalerite. 140x.

Plate VIIIB. Sphalerite-chalcopyrite intergrowth. Chalcopyrite (white) occurs along the grain-boundaries of sphalerite (grey) and also within sphalerite as minute lenses. See next figure. 60x.

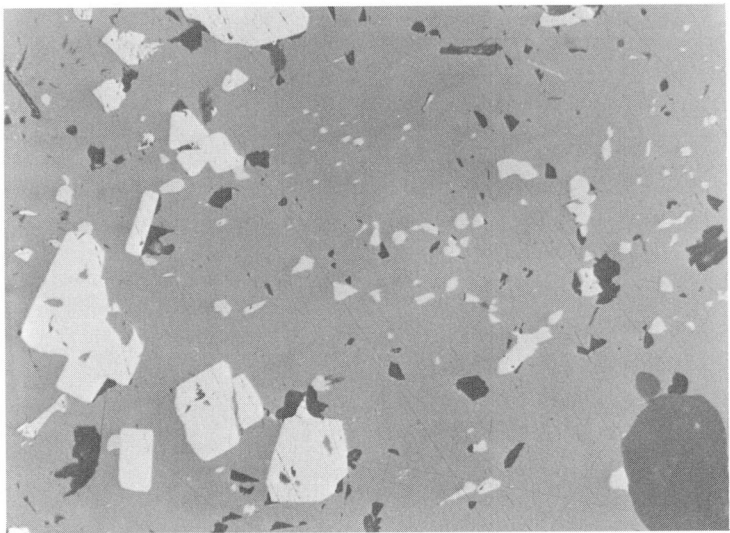


Plate VIIIA.

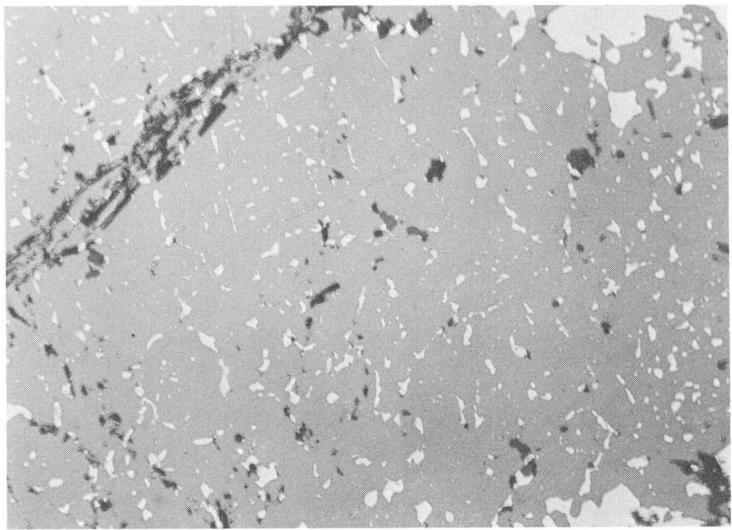


Plate VIIIB.

Plate IXA. Seriate arrangement of lenses of chalcopyrite (white) in sphalerite (grey). Oil immersion. 375x.

Plate IXB. Arsenopyrite (white) and pyrite, showing euhedral outline against chalcopyrite (grey) and silicates (black). 140x.

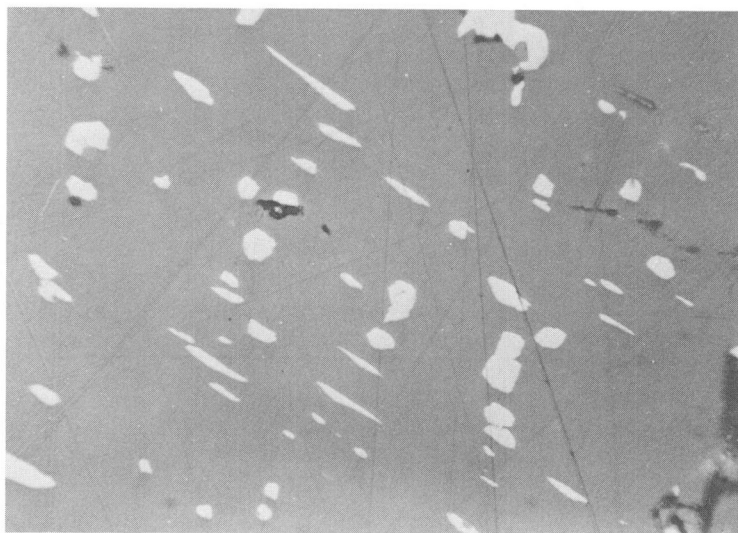


Plate IXA.

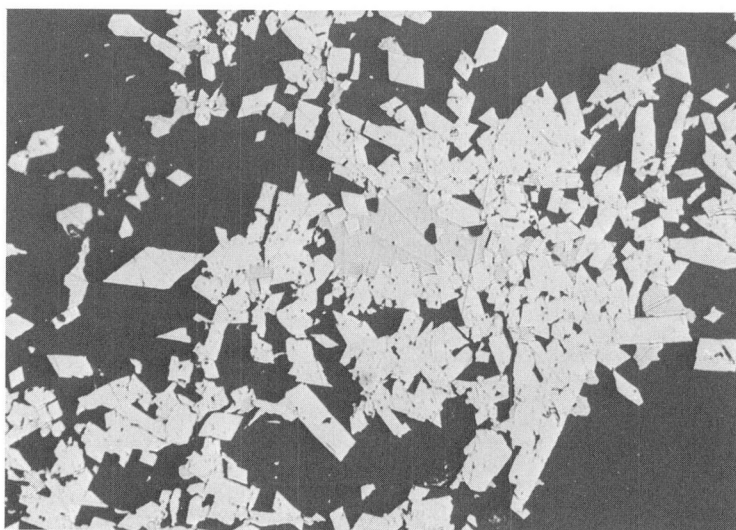


Plate IXB.

Plate XA. Native gold (white), pyrrhotite (grey), and chalcopyrite (light grey) in sphalerite (black). Oil immersion. 850x.

Plate XB. Magnetite-ilmenite intergrowth, showing ilmenite lamellae in the octahedral planes of magnetite crystal. 140x.

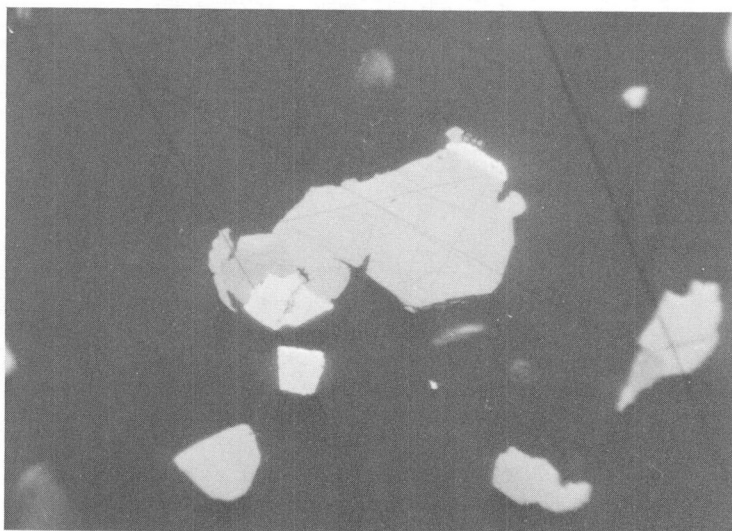


Plate XA.

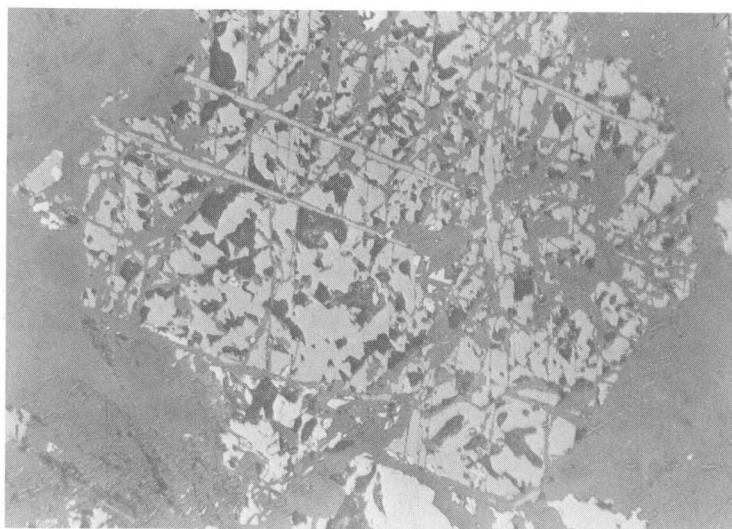


Plate XB.

Ilmenite

Ilmenite is commonly found in the sulphide-silicate ores and cordierite-anthophyllite rocks. The mineral usually occurs as small grains, containing hematite lamellae in some specimens (Fig. B of Plate XI). Aside from discrete grains, ilmenite occurs as lamellae in magnetite. The mineral is rare in massive sulphide ore.

Many grains of ilmenite show lamellar twinning, probably on (10 $\bar{1}$ 1). In schistose ores and rocks ilmenite grains are deformed or fractured, exhibiting complicated lamellar twinning and wavy extinction (Figs. A and B of Plate XII).

Gahnite

Froese (1963) reported that a green spinel, gahnite, is a common accessory in siliceous metamorphics of the Coronation area. The mineral was studied in some detail in the present work.

The green spinel has the following properties: refractive index, $n=1.800 \pm 0.005$; specific gravity, $G=4.5 \pm 0.1$; cell edge, $a_0=8.114 \pm 0.005 \text{ \AA}$.

The spinel was separated from a small piece of drill core by means of the isodynamic separator and heavy solution (methylene iodide). The separated specimen was 0.3 gr in weight, and it contained a few per cent of pyrite, quartz, and silicates as impurities.

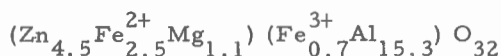
The chemical composition is given in Table 2. The analysis indicates that the content of the chromite series molecule is negligibly small. Since ferric iron and ferrous iron were not differentiated by the analysis, the content of the magnetite series molecule is not strictly evaluated. The approximate molecular composition of the spinel was estimated by the following procedure. Silica, most of which should originate from impurities, and minor constituents was neglected. Iron corresponding to 1.08 per cent S, which forms pyrite, was deducted from Fe_2O_3^* content of the analysis. Then, Fe_2O_3^* content was divided into FeO and Fe_2O_3 in such a manner as that metal atoms of $\text{Al} + \text{Fe}^{3+}$ calculated on the basis of 0=32 come to 16.

The estimated chemical composition with corresponding metal atoms are given in Table 3.

Table 3. Estimated composition of gahnite

	Wt. %	Metal atoms on the basis of 0 = 32	
Al_2O_3	54.8	15.3)	16.0
Fe_2O_3	3.6	0.7)	
FeO	12.6	2.5)	8.1
ZnO	26.0	4.5)	
MgO	3.0	1.1)	
Total	100.0		

The approximate chemical formula is expressed as follows:



The approximate molecular composition is given below.

Spinel series Gahnite ----- 53)
 Hercynite ---- 30) ----- 96
 Spinel----- 13)

Magnetite series ----- 4

The host rock of the analysed gahnite consists of cordierite, anthophyllite, biotite, magnetite, and quartz. Subordinate amounts of gahnite, pyrrhotite, pyrite, chalcopyrite, sphalerite, chlorite, and epidote are present. Gahnite was found in about twenty thin sections. The mineral assemblages of gahnite-bearing rocks are as follows:

Cordierite-anthophyllite-biotite-magnetite-quartz-gahnite
 Cordierite-anthophyllite-biotite-andalusite-quartz-gahnite
 Hornblende-biotite-plagioclase-magnetite-quartz-gahnite

Subordinate amounts of pyrrhotite, pyrite, chalcopyrite, and sphalerite are occasionally present. Chlorite and muscovite are common alteration products of these rocks.

Gahnite occurs chiefly in granite pegmatite, but also it is relatively common in ores of Franklin, New Jersey, and Falun, Sweden (Deer, Howie, and Zussman, 1962). Eskola (1914) reported the occurrence of gahnite in a granitic pegmatite, cordierite-anthophyllite rocks, and sulphide ore from the Orijärvi region, Finland. Recently Vokes (1962) described a gahnite from the Bleikvassli sulphide ore, Norway, and Schreyer, Kullerud, and Ramdohr (1964) reported the occurrence of gahnite in the country rocks and that of Zn-rich spinel, kreittonite, in the sulphide ores from the Bodenmais, Bavaria. Gahnite seems to be not as rare in sulphide deposits associated with metamorphic rocks of the amphibolite facies as was formerly believed.

At Bleikvassli and Bodenmais gahnite is considered to have formed in equilibrium with the associated minerals during metamorphism of the rocks and sulphide ores. Froese (1963) considered this was the case in the Coronation area as well.

VII Chalcopyrite-tetrahedrite-calcite veins

Aside from the sulphide orebodies, narrow veins composed of chalcopyrite, tetrahedrite, calcite, and a small amount of pyrite are found in the Coronation mine.

Colloform banding is a prominent feature of the veins. Layers of chalcopyrite alternate with thin layers consisting of intricate aggregates of chalcopyrite, tetrahedrite, and pyrite. In the outer zone of the banding, columnar crystals of chalcopyrite are radially arranged, and their long axes are oriented perpendicularly to the outer surface of the colloform layers. The cores are occupied by allotriomorphic aggregates of chalcopyrite and tetrahedrite (Fig. A of Plate XIII). In some instances the outer surface is rimmed by tetrahedrite.

Plate XIA. Magnetite-ilmenite intergrowth. Magnetite is partly replaced by chalcopyrite (white) and chlorite (dark grey). 60x.

Plate XIB. Ilmenite-hematite exsolution intergrowth, showing seriate arrangement of hematite exsolution bodies (light grey) in ilmenite base (grey). Oil immersion. 550x.

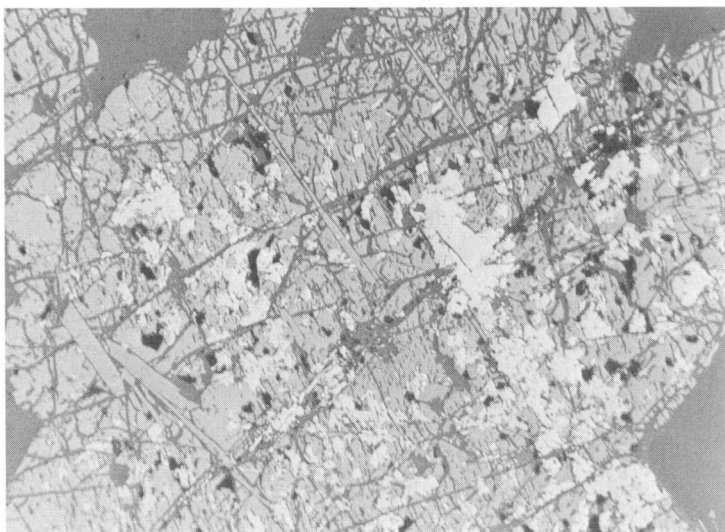


Plate XIA.

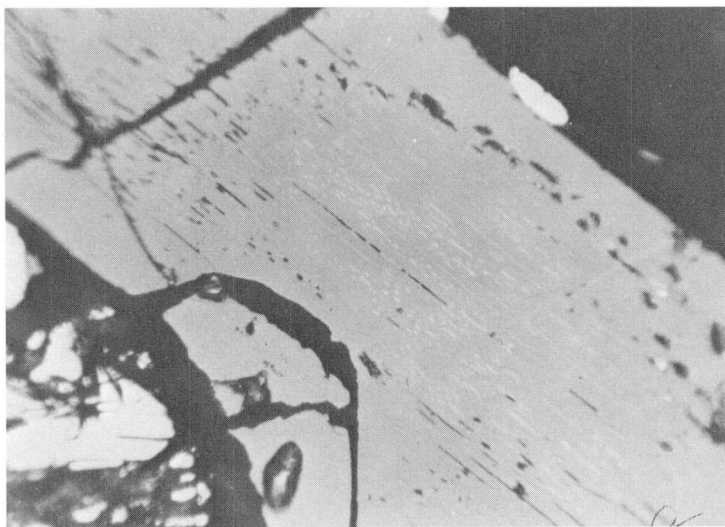


Plate XIB.

Plate XIIA. Twinning of ilmenite. Twin lamellae are displaced along basal plane of host crystal of ilmenite. The ilmenite contains a small amount of probable unmixed phase (white), which was not identified. Crossed nicols, oil immersion. 550x.

Plate XIIB. Twinning of ilmenite, showing two sets of twinning lamellae. Crossed nicols, oil immersion. 550x.

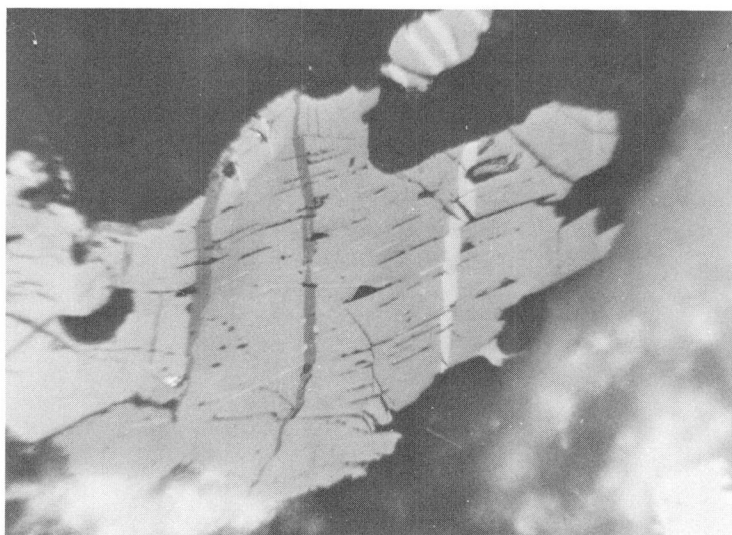


Plate XIII A.



Plate XIII B.

Plate XIII A. Colloform texture in chalcopyrite, showing radially arranged columnar crystals of chalcopyrite. Etched by $\text{KMnO}_4 + \text{KOH}$. 60x.

Plate XIII B. Chalcopyrite (white) partly replaced by bornite (grey) and covellite (dark grey). The mineral surrounding chalcopyrite is tetrahedrite (light grey). Oil immersion. 550x.

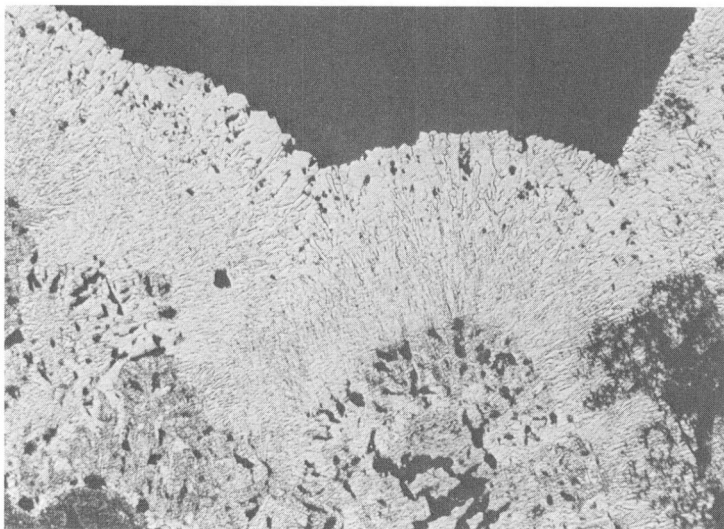


Plate XIII A.

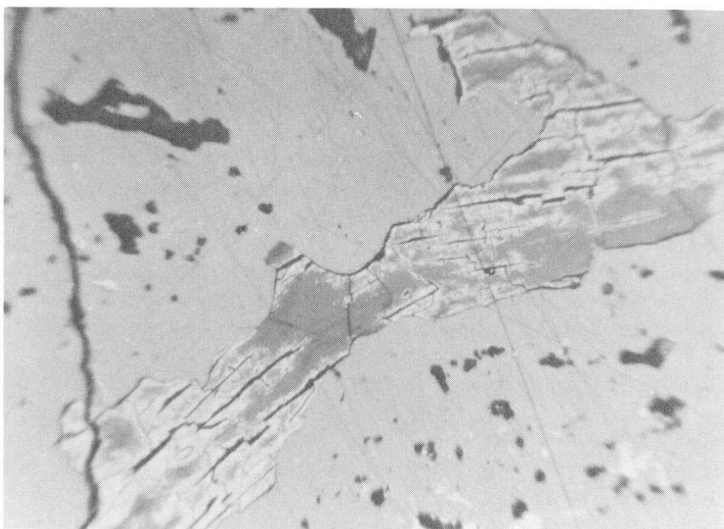


Plate XIII B.

Chalcopyrite is partly replaced by covellite and bornite. The minerals show, in some specimens, a zoning in which covellite forms the core and bornite the margin (Fig. B of Plate XIII). Covellite and bornite are probably supergene.

VIII Formation temperatures of minerals

Ferris (1961) estimated the formation temperatures of the pyrrhotite-pyrite pairs of the Coronation ores by an X-ray method. The estimated temperatures of 41 pyrrhotite-pyrite pairs range from 479° to 519°C. Arnold (1964) refined the geothermometric study of the Coronation ores and he gave $497^{\circ} \pm 5^{\circ}\text{C}$ for the mean minimum temperature of crystallization of coexisting pyrrhotite-pyrite pairs. He estimated also the crystallization temperatures of quartz veins cutting sulphides from primary liquid inclusions in quartz. The estimated temperature is somewhat lower than 300°C.

In the present study a rough estimation of the formation temperatures of coexisting pairs of Fe-Ti oxides and arsenopyrite-pyrite was done. Marcasite may be considered to have formed at lower temperatures.

Coexisting pairs of Fe-Ti oxides

The ores and cordierite-anthophyllite rocks from the Coronation mine usually contain magnetite or ilmenite, or both. Magnetite is idiomorphic and larger in grain-size than the other constituent minerals.

As described in a preceding section magnetite contains ilmenite lamellae arranged along the crystallographic orientation of magnetite. Ilmenite occurs not only as lamellae in magnetite, but as discrete grains. The discrete grains of ilmenite contain usually hematite exsolution lamellae showing a seriate arrangement (Fig. B of Plate XI), while the ilmenite lamellae in magnetite are free from exsolution bodies of hematite.

The solubility of ilmenite in magnetite is considered to be extremely limited even in higher temperatures. Verhoogen (1962) showed from a theoretical point of view that magnetite-ilmenite intergrowths may be derived from magnetite-ulvöspinel solid solution by oxidation, and Lindsley (1962) showed that magnetite-ilmenite intergrowths similar to those of the natural occurrence were experimentally formed from magnetite-ulvöspinel solid solution by oxidation. Thus it may be considered that the titaniferous magnetite of the Coronation ores and rocks originally crystallized as a magnetite-ulvöspinel solid solution and it was oxidized and separated into magnetite and ilmenite during prolonged cooling.

Some specimens contain both magnetite-ilmenite and ilmenite-hematite intergrowths. They suggest that magnetite-ulvöspinel and ilmenite-hematite solid solutions were originally in equilibrium, and later the former was oxidized and separated into magnetite and ilmenite, and the latter was separated into ilmenite and hematite.

The chemical composition of magnetite and ilmenite was estimated by X-ray powder diffraction. The X-ray powder photographs were taken by Mr. R.N. Delabio of the Geological Survey of Canada. The edge dimension (a_0) of magnetite was plotted on the diagram of the cell edge dimension against the composition of $\text{Fe}_3\text{O}_4 - \text{Fe}_2\text{TiO}_4$ solid solution series

constructed by Lindsley (1962). The rhombohedral unit cell volume (V_{rh}) of ilmenite was calculated from the diffraction by $(02\bar{2}4)$ and $(11\bar{2}6)$ planes in hexagonal index, and the value was plotted on the diagram of the unit cell volume against the composition of $Fe_2O_3 - FeTiO_3$ solid solution series constructed by Nagata and Akimoto (1956).

Five specimens containing magnetite-ilmenite and ilmenite-hematite intergrowths were examined. The cell edge of five magnetites ranges from 8.394 ± 0.005 to 8.396 ± 0.005 Å. This indicates that the magnetites are nearly pure Fe_3O_4 . The cell volume of three ilmenites forming lamellae and two occurring as discrete grains was obtained. The value was nearly identical in all the ilmenites; $V_{rh} = 105.1$ Å³ ($a_{rh} = 5.534 \pm 0.005$ Å, $\alpha = 54^\circ 44' \pm 3'$). The value corresponds to the composition $Fe_2O_3^{5\%} \cdot FeTiO_3^{95\%}$.

The volume of ilmenite lamellae in the magnetite-ilmenite intergrowths is estimated at about 2 per cent, and the volume of hematite lamellae in the ilmenite-hematite intergrowths amounts to about 5 per cent. Thus the chemical composition of the original magnetite-ulvöspinel and ilmenite-hematite solid solutions corresponds to $Fe_3O_4^{97\%} \cdot Fe_2TiO_4^{3\%}$ and $Fe_2O_3^{9\%} \cdot FeTiO_3^{91\%}$, respectively.

Buddington and Lindsley (1964) studied the equilibrium relationships between magnetite-ulvöspinel and ilmenite-hematite solid solutions, and presented a diagram showing the compositional changes of coexisting pairs of Fe-Ti oxides as functions of temperatures and oxygen fugacities. The diagram is not applicable for magnetite-ulvöspinel solid solutions containing low Fe_2TiO_4 molecule, and the coexisting pair of Fe-Ti oxides from the Coronation mine can not be plotted on the diagram. However, a rough extrapolation may be permissible. According to the diagram the temperature and oxygen fugacity for the pair, magnetite 90 per cent ulvöspinel 10 per cent-hematite 9 per cent ilmenite 91 per cent, are $600^\circ C$ and 10^{19} atm, respectively. It is evident that the coexisting pair from the Coronation mine, magnetite 97 per cent ulvöspinel 3 per cent-hematite 9 per cent ilmenite 91 per cent, have been formed under the conditions of temperature and oxygen fugacity considerably lower than the above. It seems to the present writer that $500^\circ C$ and 10^{25} atm are a reasonable estimation for the pair of Fe-Ti oxides from the Coronation mine.

Arsenopyrite-pyrite association

Arsenopyrite coexists with pyrite, though arsenopyrite is very rare in the Coronation ores. The 131 spacing of the arsenopyrite is 1.6320 ± 0.0005 Å. On the basis of Clark's experimental study (Clark, 1960), the formation temperatures of the arsenopyrite-pyrite association may be estimated at about 500° and $450^\circ C$ assuming confining pressures of 1500 and 1000 atm.

Marcasite

In the Coronation ores the textural relations suggest that the marcasite was formed in a later stage.

Table 4. Metallic minerals of the Coronation ores.

	Minerals of higher temperature formation			Minerals of lower temperature formation	Minerals of supergene alteration
	Mineral	Equilibrium composition	Separation on cooling		
Conformable orebody	Pyrite			Pyrite	
	Pyrrhotite	$\sim \text{Fe}_{0.934}\text{S}^*$ in Po-Py Ass.		Marcasite	
	Chalcopyrite		Cub lamellae	Pyrrhotite	
	Sphalerite	$\sim \text{FeS } 14\%^*$ in Sph-Po Ass.	Po, Cp dots	Chalcopyrite	
	Arsenopyrite	$\text{Fe}_{33}\text{As}_{32}\text{S}_{35}$ in Asp-Py Ass.		Sphalerite	
	Magnetite	$\sim \text{Mt}_{97}\text{Us}_3$ in Mt-II Ass.	Il lamellae		
	Ilmenite	$\sim \text{Il}_{91}\text{Hm}_9$ in Mt-II Ass.	Hm lamellae		
Veins	Native gold				
				Chalcopyrite Tetrahedrite Pyrite	Bornite Covellite

* After Ferris (1961) and Arnold (1964).

Abbreviations: Mt: magnetite, Us: ulvöspinel, Il: ilmenite, Hm: hematite,
Cub: cubanite, Po: pyrrhotite, Py: pyrite, Sph: sphalerite,
Asp: arsenopyrite, Cp: chalcopyrite.

Table 5. Non-metallic minerals associated with metallic minerals listed in Table 4.

	Minerals of higher temperature formation				Minerals of lower temperature formation	Minerals of supergene alteration
Conformable orebody	Quartz	Anthophyllite	Biotite	Gahnite	Quartz	
	Plagioclase	Cordierite	Muscovite	Carbonate	Chlorite	
	Hornblende	Andalusite	Almandine	Graphite	Epidote	
	Cummingtonite	Staurolite	Tourmaline		Muscovite	
					Prehnite	
Veins					Carbonate	
					Quartz	
					Calcite	
					Chlorite	

Most of the minerals were identified by Froese (1963).

Marcasite is considered a low-temperature polymorph of pyrite, but its stability field is not clear. Anderson and Chesley (1933) heated synthetic marcasite in glass tubes for 5 hours, and they found that marcasite was completely converted to pyrite at 425°C, but it was not converted at 405°C. Schubert (1959) heated marcasite in glass tubes, and he detected pyrite converted from marcasite at 365°C. He concluded that marcasite is stable instead of pyrite below 350°C.

Though the exact stability field of marcasite is not clear, it may be concluded that the marcasite of the Coronation ores has not experienced temperatures as high as 365°C.

IX Mineral assemblages of ores

Two distinct mineralizations

In the Coronation mine two periods of mineralization are distinguished. One resulted in the main formation of the orebodies and the other formed the minor veins consisting of chalcopyrite, tetrahedrite, and calcite. Marcasite-bearing veinlets cutting the orebodies are of a later stage of formation. The direct age relation between the marcasite-bearing veinlets and chalcopyrite-tetrahedrite-calcite veins is not clear. Bornite and covellite replacing chalcopyrite of the veins may be products of supergene alteration.

The mineral assemblages of the country rocks and gangue minerals of the ores were studied by Froese (1963, 1969b) in detail. According to him the assemblages of the gangue minerals of the conformable orebody are compatible with those of the country rocks which belong to the amphibolite facies.

The country rocks have been subjected in general to weak retrograde alteration. The ores and cordierite-anthophyllite rocks are locally chloritized to a great extent. Prehnite, epidote, and calcite are also found as alteration products in the ores and country rocks. The localization of the intensely chloritized rocks are not related immediately to the sulphide mineralization of the orebodies as shown in Figure 1. Basic schists in contact with chalcopyrite-tetrahedrite-calcite veins are also chloritized. The mutual relationships among the retrograde alteration of the country rocks, chloritization of cordierite-anthophyllite rocks, formation of the chalcopyrite-tetrahedrite-calcite veins, and marcasite-bearing veinlets are not clear. However, all these mineralizations are supposed to have taken place at temperatures lower than the major formation of the orebodies.

As described in a preceding section magnetite is occasionally replaced by sulphides and chlorite. This sulphide mineralization may be related to the chloritization.

Metallic minerals and corresponding non-metallic minerals are summarized as shown in Tables 4 and 5.

Assemblages of pyrite, pyrrhotite, and magnetite

Two hundred polished sections were made from the drill cores of the Coronation mine. The sections include sulphide-silicate type ores, cordierite-anthophyllite rocks, and subordinate amounts of massive ores and

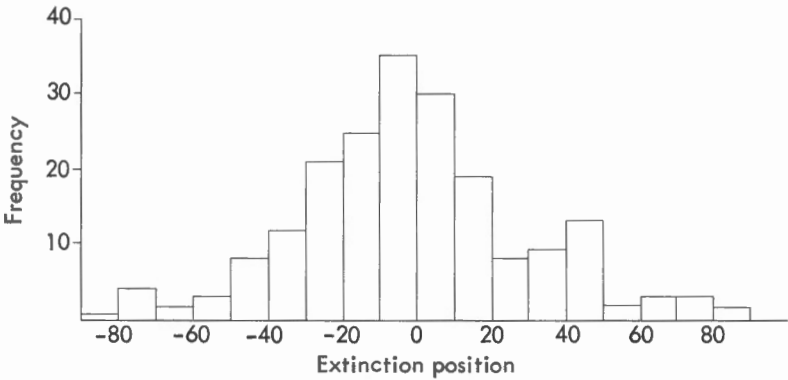


Figure 5. Orientation frequency diagram of extinction positions of pyrrhotite grains in graphite-pyrrhotite-biotite-quartz schist. (Specimen No. WH60C78-6). 200 measurements on a polished surface normal to the schistosity.

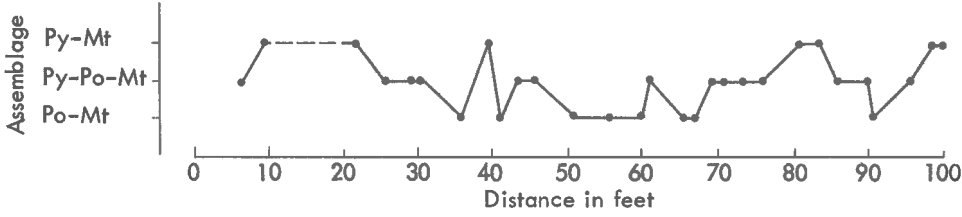


Figure 6. Variation of mineral assemblages from drill hole No. 81. Abbreviations: Py, pyrite; Po, pyrrhotite; Mt, magnetite.

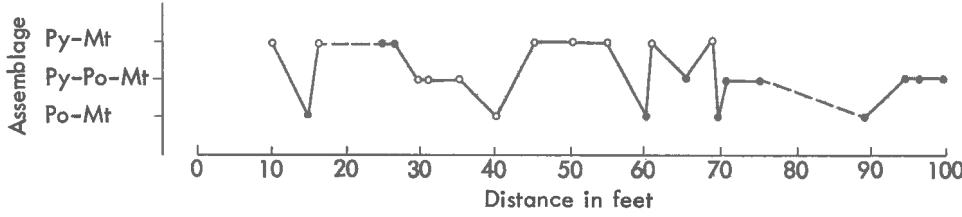


Figure 7. Variation of mineral assemblages from drill hole No. 85. Abbreviations: Py, pyrite; Po, pyrrhotite; Mt, magnetite. Solid circle, magnetite-bearing assemblage; open circle, magnetite-free assemblage.

basic schists. The assemblages of metallic minerals were examined under the ore microscope, and the results are shown in Table 6.

Table 6. Assemblages of pyrite, pyrrhotite, and magnetite.

Assemblage	Number of specimens
Pyrite alone	49
Pyrite-magnetite	29
Pyrite-pyrrhotite	31
Pyrite-pyrrhotite-magnetite	62
Pyrrhotite alone	3
Pyrrhotite-magnetite	26

Chalcopyrite is contained in all the specimens, and sphalerite is found in about a half of the specimens examined. Ilmenite is commonly associated with magnetite.

Figures 6 and 7 show variations of the assemblages of pyrite, pyrrhotite, and magnetite in the core specimens from two drill holes.

Assuming that the minerals formed in equilibrium at a temperature, say 500°C, as indicated by the mineral pairs of pyrite-pyrrhotite, pyrite-arsenopyrite, and magnetite-ilmenite, and that all the minerals are stoichiometric in composition, we can calculate oxygen and sulphur fugacities, under which the individual assemblages are stable. The calculated values are given in Table 7.

Table 7. Oxygen and sulphur fugacities corresponding to the various assemblages of pyrite, pyrrhotite, and magnetite at 500°C.

Assemblage	$f_{O_2}(\text{atm})$	$f_{S_2}(\text{atm})$
Pyrite-magnetite	10^{-22} -- 10^{-19}	10^{-5} -- 10^{-3}
Pyrite-pyrrhotite-magnetite	10^{-22}	10^{-5}
Pyrrhotite-magnetite	10^{-29} -- 10^{-22}	10^{-15} -- 10^{-5}

Magnetite-free assemblages give only sulphur fugacities. Actually since pyrrhotite and magnetite are not stoichiometric, the fugacities for the natural assemblages may be somewhat different from the calculated ones.

However, the variations of the mineral assemblages correspond roughly to the variations of oxygen and sulphur fugacities, and the Figures 6 and 7 suggest that the oxygen and sulphur fugacities were not homogeneous even within a limited zone at the time of mineralization.

X Deformation and metamorphism of the ore deposit

The most prominent structures of the Coronation ores are layering of sulphides and preferred orientation of pyrrhotite. The layered structure of sulphide ores were reported from other deposits, such as the Mandy and Flin Flon, in the area adjacent to the Coronation mine, and their origin was explained in various ways.

Bruce (1920) considered that the layered structure of chalcopyrite-sphalerite ores of the Mandy deposit resulted from selective replacement of foliated rocks, while Hanson (1920) described mineral paragenesis and structures of the Mandy deposits as well as some other sulphide deposits in metamorphic rocks of the Canadian Shield, and concluded that the layered structure of the Mandy deposit resulted from slight shearing during ore deposition. On the other hand, Spurr (1923) claimed in his unique book on the ore magma hypothesis that the layering of the Mandy deposit is a kind of 'flow-structure' which was formed in the course of intrusion of sulphide "ore magma" in his terms. Later Newhouse and Flaherty (1930) reviewed and discussed the nature and origin of layered or schistose sulphide ores. They could not find any deformation textures in ores of the Mandy and Flin Flon deposits, and then they approved the view of selective replacement origin of the layered structure of the ores presented by Bruce (1920). Brownell and Kinkel (1935) described the structure of the Flin Flon deposit and the mineral paragenesis of the ores in detail. Their interpretation on the structure and mineral paragenesis of the ores are based on a hypothesis of replacement origin. They found sphalerite bands in solid sulphide ore. The bands were parallel to the schistosity of the wall rocks, and they considered the structure to be a feature inherited from the replaced rocks.

In the Coronation deposit, internal structure of the orebodies, like the ore zone as a whole, is conformable with the structure of the country rocks. In addition, we can find a distinct preferred orientation of pyrrhotite grains in foliated sulphide ores; the c -axes of pyrrhotite grains tend to be oriented perpendicularly to the foliation.

Ramdohr (1953) found a preferred orientation of pyrrhotite grains in the Rammelsberg sulphide ores in which many plate-shaped crystals of pyrrhotite show parallel arrangement and they are extinguished simultaneously. He considered that the preferred orientation resulted from differential movement during metamorphism of the ores.

The preferred orientation of pyrrhotite of the Coronation ores may be ascribed to differential movement during crystallization or recrystallization of the ores, and the layered structure was formed essentially under the influence of differential movement during crystallization or recrystallization of the ores.

Froese (1963) found that assemblages of gangue minerals are compatible with the regional grade of metamorphism, and he considered that cordierite-anthophyllite rocks closely associated with the Coronation orebody are metamorphosed equivalents of volcanic rocks which have been metasomatically altered at the time of initial accumulation of sulphides, and the orebody and associated altered rocks were subjected to the same metamorphism as the country rocks. Whitmore (1964) discussed origin and development of pyrite-copper-zinc deposits of the Coronation type, and he suggested that the initial accumulation of sulphides may have taken place contemporaneously with the development of the volcanic pile. In addition the Coronation orebody

has been involved in subsequent deformation and metamorphism, as well as post-metamorphic changes of a retrograde nature which have modified the features of the orebodies. The results of the present study seem to be well-matched with their observations and views.

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No. 6 NICKEL, COPPER AND ZINC IN
BEDROCK OF THE CORONATION MINE
AREA, SASKATCHEWAN

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ABSTRACT

Concentrations of Ni, Cu, and Zn were determined in some 1,500 specimens of bedrock from an area of about 32 square miles including the Coronation, Birch Lake and Flexar mines, all of which are pyritic copper replacement deposits in meta-volcanic rocks of the Amisk Group.

Concentrations of Ni, Cu, and Zn in thick bodies of meta-gabbro are distinctly different from those in basic meta-volcanic rocks, and are consistent with genetic relationships between ultrabasic rocks and the meta-gabbros, which were probably emplaced after folding and foliation of the volcanic rocks.

Distribution of Cu in basic meta-volcanic rocks and meta-gabbros suggests epigenetic enrichment of permeable zones near their intersections with transcurrent, northeasterly faults which may be related to aeromagnetic maxima within large granodioritic complexes.

The granodioritic complexes are postulated as the source of hydrothermal solutions which caused the enrichment of Cu in country-rock, deposited numerous, nearly barren sulphide bodies, and perhaps deposited the mineable orebodies.

INTRODUCTION

The writer began field work for a geochemical study of bedrock in a region including the Coronation mine area in 1960, at the same time as the Coronation Mine Project was initiated. Results of the regional study have been published elsewhere (Smith, 1964). Partly to co-operate in the Coronation Mine Project and partly to check the results of the regional study, bedrock in the vicinities of the Coronation and Birch Lake mines was sampled in much greater detail in 1961. This paper presents the results of analyses of Ni, Cu, and Zn in the areas of detailed sampling, together with the results of less detailed and systematic sampling over the whole of the Coronation mine area.

The area referred to here as the 'Coronation mine area' covers about 32 square miles in east central Saskatchewan. The centre of the area is about 10 miles southwest of Flin Flon at north latitude $54^{\circ}38'$ and west longitude $102^{\circ}00'$. In the National Topographic System, the area straddles the boundary between 63L9 and 63K12. Saskatchewan Highway No. 167 from Flin Flon passes through the northwest corner of the area, and a gravel road to the Coronation mine provides access from the highway to the southern part of the area (see Plates 1 to 3).

GEOLOGICAL SUMMARY

The general geology of the area is described by Froese (1969a), with references to earlier geological studies by others in the region which includes the area. The geological base for Plates 1 to 3 is taken from Froese's map with some modifications from other sources cited on the plates.

Briefly, the area is underlain by meta-volcanic rocks of the Amisk group, which are predominantly meta-basaltic and meta-andesitic lavas and pyroclastic rocks (1)* in the western part of the area, but which include acidic meta-volcanic rocks (2), notably on the islands of Mystic Lake. The volcanic rocks are intruded by thick bodies of layered meta-gabbroic rocks (3) and related ultrabasic rocks (4), small bodies and dikes of 'quartz-eye' diorite (5), and large granodioritic complexes (7) with associated hybrid mafic rocks (6). Numerous late dikes of acidic and basic porphyries and meta-basalt cut the volcanic rocks and the meta-gabbros. Outliers of Ordovician rocks (8) occur in the southern part of the area and north of Spectral Lake.

All rocks older than the late dikes, including the granodioritic complexes, are foliated in varying degrees of intensity. Many of the late dikes are unfoliated and truncate foliation in the rocks which they intrude. Formational contacts, layering and foliation all trend northerly and dip vertically to steeply west except near the contacts of the granodioritic complexes (Froese, 1963). Byers *et al.* (1954, 1965) interpret this to be the result of isoclinal folding with steep to vertical axial planes. Numerous zones of shearing, most of which are not shown in Plates 1 to 3, strike northerly and dip steeply, sub-parallel to layering and foliation in the volcanic rocks. One northeasterly fault with proven displacement and widespread northeasterly shear joints is described by Froese (1969a).

* Numbers in brackets refer to map-units in Plates 1 to 3.

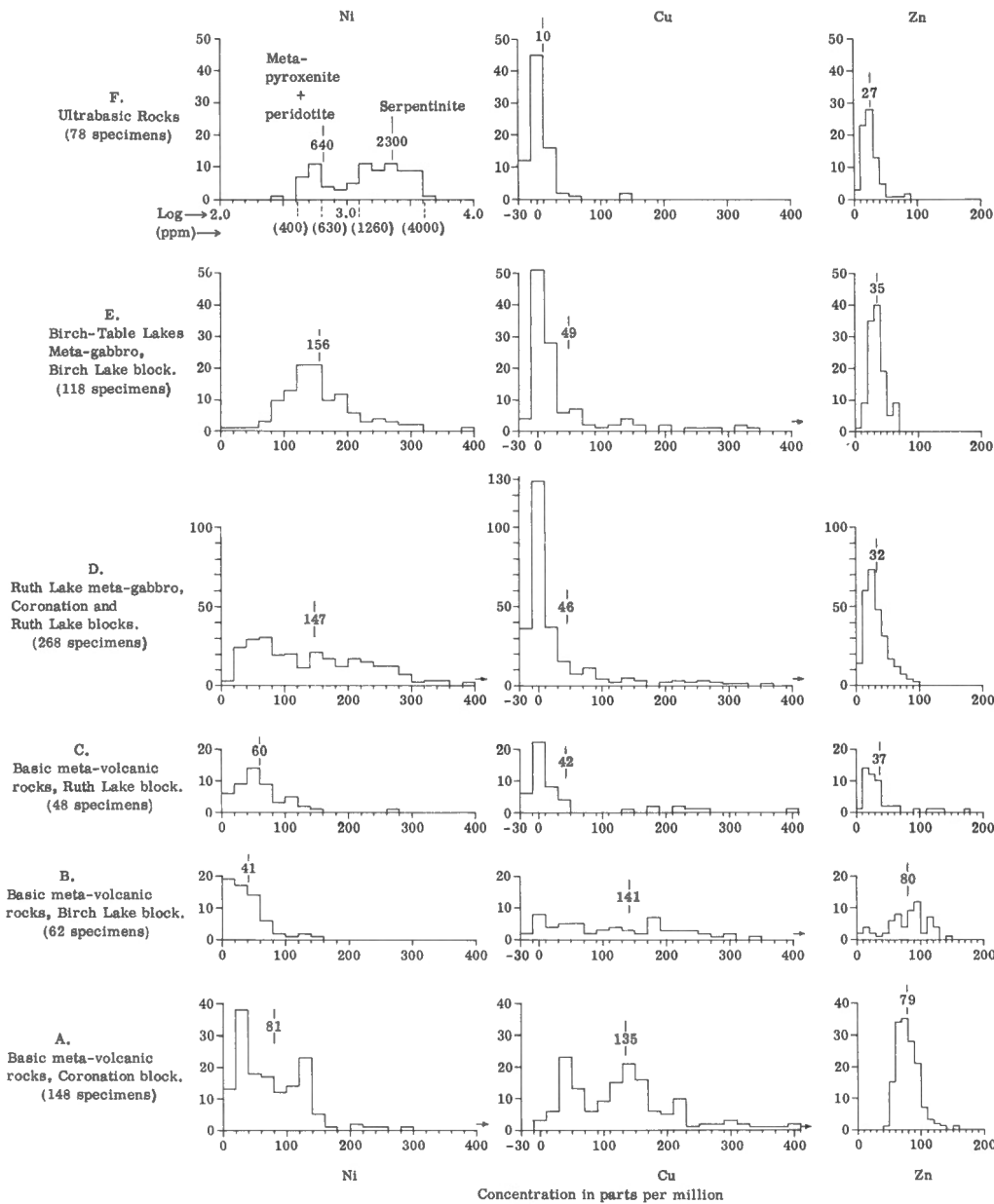


Figure 1. Frequency distribution histograms of concentrations of Ni, Cu, and Zn in selected rock units. Concentration intervals are denoted by smallest divisions on abscissae, and are either 10 ppm (thin bars), 20 ppm (thick bars), or logarithmic (Ni in ultrabasic rocks, F). Note that several different ordinate scales have been used. Numbers above histograms are arithmetic means. Small arrows indicate the number of concentrations of Ni and Cu exceeding 400 ppm. Negative concentrations of Cu result from combined random and systematic errors of analysis, and should be interpreted as "not detectable".

Numerous bodies of iron sulphides, many of which contain low concentrations of copper and/or zinc, have been discovered by electromagnetic surveys in the volcanic rocks and in the meta-gabbros (see Plates 1 to 3). Three pyritic copper replacement deposits of mineable grade and size, the Coronation, Birch Lake, and Flexar Mines, are in shear zones in basic meta-volcanic rocks (Byers *et al.*, 1954, 1965; MacDougall, 1952; Faulkner, 1969; Whitmore, 1969).

GEOCHEMISTRY

Analytical Method

All analyses were done by an X-ray fluorescence method previously described by the writer (Smith, 1964). The method was designed for rapid analyses of trace metals in rock samples ground under standard conditions to fine powders, but otherwise untreated. The intensity of WL α radiation, which originates from the tungsten target of the X-ray tube and is partly absorbed by the sample, is used to correct for variable absorption effects and also to predict background intensities. Calibration curves are based on natural samples which represent the full range of absorption characteristics and which were spiked with known amounts of the metals to be determined. With proper instrumental and monitoring precautions, reproducibility (standard deviation) of determinations of Ni, Cu, and Zn is better than ± 10 ppm in the range from zero to 100 ppm, and better than ± 10 per cent of the amount present in higher concentration ranges. Random errors combined with probably small systematic errors result in some impossible negative concentrations of Cu. To avoid statistical distortion of the data, these negative concentrations were simply treated as such in calculating averages and in the frequency distribution plots of Figure 1.

Absolute accuracy has not been quantitatively tested because of the difficulty of making synthetic standards with the same matrix characteristics as natural metamorphic and igneous rocks. A comparison of analyses of ten geochemical standard samples by the methods of the present study with analyses by other methods is given in Table 1. The results demonstrate acceptable consistency except for Ni in standard rocks PCC-1 (peridotite) and DTS-1 (dunite), where determinations by the present method are more than one and one-half times higher than the arithmetic means of spectrochemical determinations by the United States Geological Survey. These two rocks are very rich in Mg and poor in Ca and K relative to Fe (see Flanagan, 1967, Tables 8 and 10). Quantitative analyses of such 'anomalous' matrices require refinements of the analytical method which were not applied in the present study. Analyses of high concentrations of Ni in serpentinites may therefore be subject to large positive systematic errors. Analyses of other rock-types are subject to smaller systematic errors which are estimated from the scatter of points around the calibration curves to be in the order of ± 10 per cent of the amount present.

Sampling

Three different categories of samples are represented in Plates 1, 2, and 3. The first category is represented by small "x"'s in three blocks - one

Table 1
Comparative Analyses of Geochemical Standard Rock Samples

Sample Number	Ref.	Reported Concentrations in parts per million						
		Ni		Cu			Zn	
		SRC*	Others Mean Range	SRC*	Others Mean Range	SRC*	Others Mean Range	
G-1	(1)	11	<10	19	13	35	40	26-55
W-1	(1)	93	30-140	138	110	65	82	78-90
G-2	(2)	2	2-4	6	11	79	N.D.	
GSP-1	(2)	9	4-12	35	41	96	N.D.	
AGV-1	(2)	17	7-20	72	69	78	N.D.	
BCR-1	(2)	10	6-29	20	27	108	N.D.	
PCC-1	(2)	3,700	1,500-2,800	7	10	37	N.D.	
DTS-1	(2)	3,600	1,500-2,600	1	6	39	N.D.	
Sy. Rk. -1	(3)	55	—	14	24	209	200	
Sulph. Ore-1	(3)	11,900	—	9,400	8,500	250	294	

* Single analyses by X-ray fluorescence method of present study.

(1) 'Others' from Stevens et al. (1960, pp. 90, 95, 103).

(2) 'Others' from Flanagan (1967, Tables 3, 5, 7, 9, 11, 13).

(3) 'Others' from Michaelis (1963, Table 78).

N. D. Not determined.

north and west of the Coronation mine, one east of Ruth Lake, and one surrounding the Birch Lake mine. This sampling was done by the writer and E. G. Wohlberg in 1961, with the object of investigating the distribution of elements in country-rock in chosen parts of the area. Each 'x' represents the location of a single fresh specimen of bedrock judged to be representative of the principal rock-type in a given outcrop. Specimens of dikes, veins, shear-zones and those with abundant iron sulphides or visible ore sulphides are purposely excluded from the plots, although many such specimens were collected and analysed. Insofar as distribution of outcrops permitted, specimens were collected at chained intervals of 200 feet along picket lines perpendicular to strike and 400 to 600 feet apart. For the sake of brevity, this sampling will be referred to as 'systematic sampling', which does not imply that it is free of the obvious biases of outcrop distribution and geological judgment.

Samples of the second category are some of those collected in 1960 for the writer's regional study (Smith, 1964) at linear intervals of about 1/4 of a mile. Locations of these samples are represented by some of the circles in Plates 1 to 3. Single specimens were collected on the same basis as those in the areas of detailed systematic sampling.

Samples of the third category were collected by E. Froese and M. J. Rutherford under the supervision of D. R. E. Whitmore in 1960, 1961, and 1962, in conjunction with geological mapping. These samples, also represented by some of the circles in Plates 1 to 3, are very irregularly distributed over the area. Most of the samples consisted of several chips from different parts of single outcrops, and the analyses in some cases, therefore, represent averages of different rock-types. Furthermore, some chips in some samples contained visible sulphides, and no attempt was made to remove these chips before preparing the samples for analysis. Analyses of these samples are plotted in Plates 1 to 3 primarily to present the results of 'spot assays' of Ni, Cu, and Zn. Except in a general way, they cannot be used to assess the distribution of Ni, Cu, and Zn in the various rock-units underlying the area.

Results of Analyses

Ni, Cu, and Zn were determined in some 1,800 specimens, of which about 1,500 are represented in Plates 1 to 3; only the data from the three blocks of systematic sampling are contoured in these plates. Data for selected rock-units are also presented graphically in Figures 1 and 2. Individual analyses are not tabulated because the list would be voluminous and of little practical use. Some of the data are on IBM cards, and when time permits all of the data will be so filed and made accessible at the Saskatchewan Research Council.

Geochemistry and Geology of Selected Rock-types

The following discussion is concerned mainly with rock-types which were systematically sampled, namely basic meta-volcanic rocks (1), meta-gabbroic rocks (3, 6) and ultrabasic rocks (4). For the sake of brevity, systematic sampling in the area north and west of the Coronation mine will be referred to as 'the Coronation block', that east of Ruth Lake as 'the Ruth Lake block', and that surrounding the Birch Lake mine as 'the Birch Lake block'.

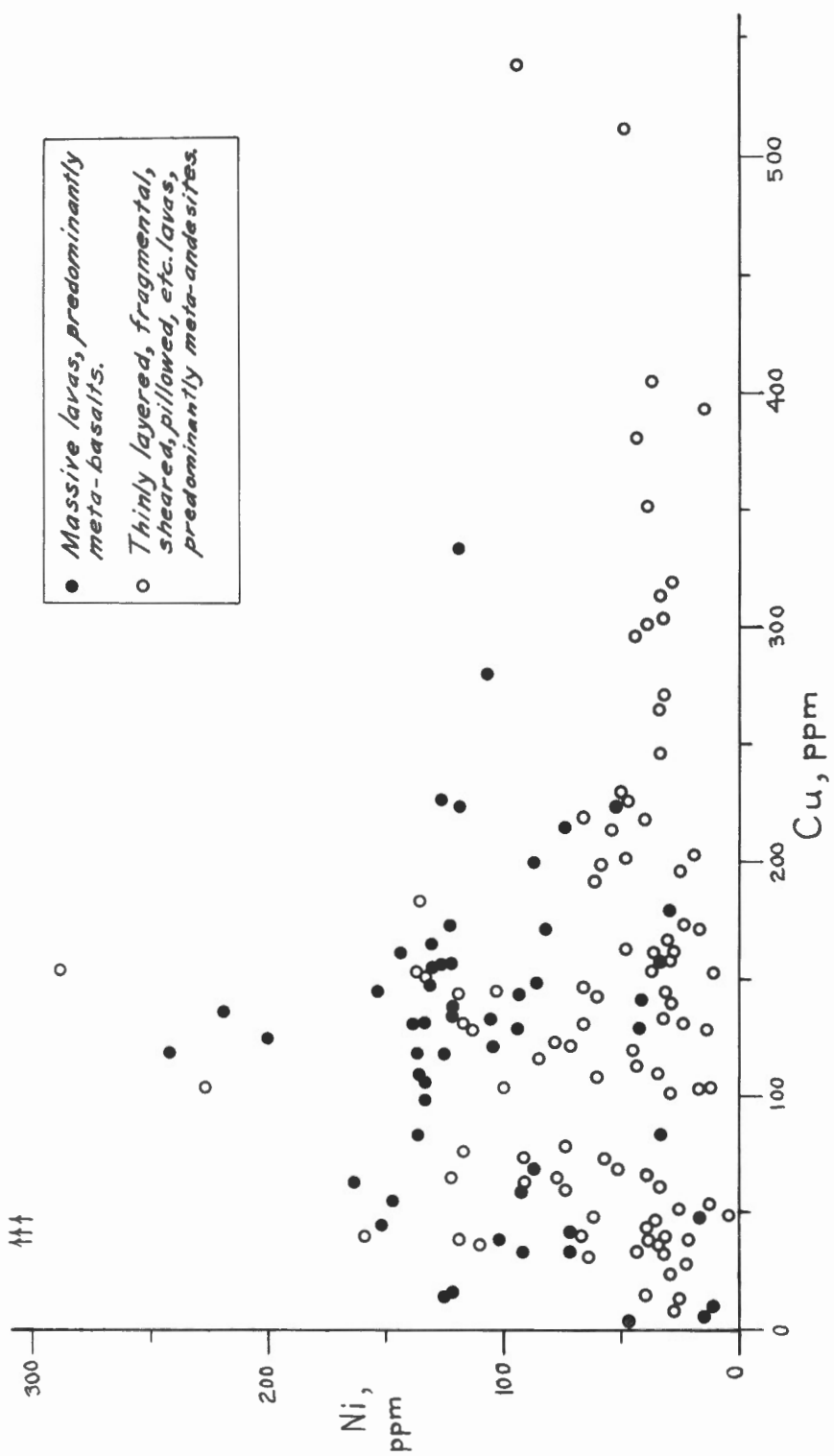


Figure 2.

Basic Meta-Volcanic Rocks (1), Coronation Block

Contours of nickel concentrations in basic meta-volcanic rocks in the Coronation block (Plate 1) have an irregular north-northwesterly trend defined mostly by relatively high concentration (>100 ppm) in a belt near the road between the Coronation mine and Tanyss Lake. The rocks containing the relatively high nickel concentrations are predominantly massive, fine- to medium-grained epidote amphibolites which in many places have a gabbroid appearance. Amygdules and flow-contact structures in some horizons suggest that the rocks are thick, massive flows. Chemical analyses reported by Froese (1963, Tables 2, 3, and map) are variable but suggest that these rocks are generally of basaltic composition, and they will therefore be referred to as 'meta-basalts'. The nickel-poor meta-volcanic rocks west of the belt of meta-basalts are distinctly different. They are generally thinly-layered mixtures of many different types of strongly foliated epidote amphibolites, including fragmental lavas, flow breccias with dacitic fragments, pillowed lavas, amygdaloidal lavas, pyroclastic rocks, and many horizons of sheared, chloritized, and carbonatized rocks. The rocks are predominantly of meta-andesitic appearance, and Froese's chemical analyses (*idem*) demonstrate that they are generally less basic than the meta-basalts. They will therefore be referred to as 'meta-andesites'. The trend of nickel contours in basic meta-volcanic rocks in the Coronation block can therefore be explained by a north-northwesterly striking contact between nickel-rich meta-basalts on the east and nickel-poor andesites on the west. Irregularities in the contours are probably caused by a certain amount of interlayering of the two rock-types, unmapped folds and faults, and the limitations of the sampling. The bimodal frequency distribution of nickel in specimens of basic meta-volcanic rocks from the Coronation block (Fig. 1A) suggests that there may be a discrete rather than a gradational difference between meta-andesites and meta-basalts. Finally, it may be worth noting that the rocks poorest in nickel (<50 ppm) are directly on strike with the Coronation orebody (Plate 1).

The distribution of copper in basic meta-volcanic rocks in the Coronation block (Plate 2) does not reflect the north-northwesterly formational trend nor the difference between meta-andesites and meta-basalts. Although the contours suggest transcurrent trends, the extent of sampling in the Coronation block itself is too restricted to establish their reality and directions. The frequency distribution of copper in these rocks shows distinct modes at 40 and 140 ppm (Fig. 1A). These cannot be explained by differences between meta-andesites and meta-basalts, because as mentioned previously, there is no spatial correlation between copper concentrations and rock-types, and furthermore there is no correlation between copper and nickel in specimens with less than 200 ppm of copper (Fig. 2). The evidence suggests that copper was redistributed in the volcanic rocks by epigenetic processes, a conclusion which was also reached by Froese (1963, p. 89). Figure 2 demonstrates that most of the concentrations of copper exceeding 200 ppm are in nickel-poor specimens. This would be consistent with preferential enrichment of meta-andesites, probably because they were more permeable than the massive meta-basalts. However, the enrichment must have been partly controlled by other factors, because not all meta-andesites are rich in copper (Fig. 2 and Plate 2).

Distribution of zinc in basic meta-volcanic rocks in the Coronation block shows no well-defined trends (Plate 3), no doubt partly because the total

range of concentrations is small (Fig. 1A) and the contour interval of 25 ppm approaches the standard deviation of ± 10 ppm for the analyses. An ill-defined, apparently discontinuous belt of relatively zinc-rich rocks (>100 ppm) just west of the road trends north-northwesterly. Only 14 out of 148 specimens contain as much or more than 100 ppm of zinc, and of the 14, ten contain less than 50 ppm of nickel. A plot of Zn versus Ni (not illustrated) reveals a low negative correlation in meta-andesites, which would be consistent with a primary origin of the observed distribution of zinc. A complete lack of correlation between Zn and Cu is consistent with the proposed epigenetic redistribution of Cu.

Basic Meta-Volcanic Rocks (1), Ruth Lake Block

A thin zone of basic meta-volcanic rocks near the east margin of the Ruth Lake meta-gabbro east of Ruth Lake was systematically sampled (Plate 1). Although the extent of the sampling is not great enough to define significant contour trends, Plates 2 and 3 and Figure 1C demonstrate that these rocks are distinctly poorer in copper and zinc than any of the meta-volcanic rocks in the Coronation block, in which respect they closely resemble the Ruth Lake meta-gabbro with which they are in contact (see Fig. 1D). Most of these rocks are intensely foliated, fine-grained epidote amphibolites which in some localities are so intimately interlayered with unfoliated gabbroid rock that the contact with the Ruth Lake meta-gabbro cannot be accurately defined. Many of the massive gabbroid layers are as thin as one to six inches, and they commonly have indistinct contacts with intervening layers of intensely foliated meta-volcanic rocks. This is strong evidence that the Ruth Lake meta-gabbro was emplaced after the volcanic rocks had been foliated, presumably during folding, notwithstanding the fact that the main body of meta-gabbro is itself foliated in some localities (Froese, 1969a). The indistinct contacts suggest some reaction between the meta-volcanic rocks and the meta-gabbro, probably including leaching of copper and zinc from the meta-volcanic rocks.

Basic Meta-Volcanic Rocks (1), Birch Lake Block

The unit of basic meta-volcanic rocks underlying Birch Lake and extending south to Ruth Lake was systematically sampled insofar as exposures of the unit on the lake shores and islands permitted. Plates 1 and 3 and Figure 1B show that most specimens are relatively poor in Ni and richer in Zn, similar to meta-andesitic rocks of the Coronation block, which they also resemble in outcrops. Concentrations of Cu exceeding 100 and 200 ppm are more frequent in the south part of Birch Lake and near the north end of Ruth Lake, which gives rise to transcurrent trends in the 100 ppm copper contours (Plate 2). A small proportion of specimens are very poor in Cu and Zn. In Plate 3, many zinc-poor specimens are seen to be close to the contact with the Birch-Table Lakes meta-gabbro to the west, which again suggests that emplacement of zinc-poor meta-gabbro (see Fig. 1E) might have caused leaching of Zn from neighbouring volcanic rocks. Leaching of Cu, if it occurred, is not well-defined by the sampling.

Ruth Lake Meta-gabbro (3)

The Ruth Lake meta-gabbro has been described in some detail by Wohlberg (1964). Briefly, it consists of layered, locally foliated, medium-grained amphibole-zoisite rocks, and includes a zone of discontinuous pegmatitic bodies of similar composition. Two chemically analysed specimens of meta-gabbro provided by Froese to Wohlberg (*ibid.*, Table 1) from the southern part of the body are normatively pyroxene-anorthite (An 91 and 89) rocks. Because the meta-gabbro is mineralogically similar throughout, the writer concludes that the body as a whole is distinctly ultrabasic compared to the basic volcanic rocks of the area. Evidence that the meta-gabbro was emplaced after the volcanic rocks had been foliated and presumably folded has already been presented. The writer therefore believes that the Ruth Lake meta-gabbro, spatially associated ultrabasic rocks, and other similar bodies of meta-gabbro are genetically related and were emplaced toward the end of the main period of folding of the volcanic rocks, probably along the axis of a major down-buckle of the volcanic rocks (see Gendzwill, 1969).

Contours of nickel concentrations in the Ruth Lake meta-gabbro demonstrate a distinct zonal arrangement (Plate 1), with nickel-rich rocks on the west grading irregularly into nickel-poor rocks on the east. The concentration of nickel bears no relation to the proportion of mafic minerals (amphibole and some chlorite); in fact, the nickel-rich rocks are poorer in mafic minerals and total Fe, on the average, than the nickel-poor rocks (Wohlberg, unpublished information and 1964, Plate 4). This suggests that nickel, probably as sulphide, was added to the meta-gabbro from the nickel-rich ultrabasic rocks (4), either during emplacement of the ultrabasic rocks or at the time of their serpentinization and the concomitant(?) metamorphism and hydration of the meta-gabbro. The frequency distribution plot of Ni (Fig. 1D) shows no distinct modes, which is consistent with a somewhat irregular 'diffusion gradient' in the meta-gabbro.

Concentrations of Cu and Zn in most specimens of the Ruth Lake meta-gabbro are very low compared to those in the meta-volcanic rocks in the Coronation and Birch Lake blocks (Fig. 1, cf. A, B and D). The frequency distributions are nearly identical to those in the Birch-Table Lakes meta-gabbro (Fig. 1E) and very similar to those in the ultrabasic rocks (Fig. 1F), which is consistent with the genetic relationship postulated for these rocks.

The small proportion of specimens of the Ruth Lake meta-gabbro containing more than 100 ppm of Cu are grouped in ill-defined, transcurrent trends (Plate 2). The simplest interpretation of this feature is that the meta-gabbro was locally enriched in Cu by the same epigenetic processes that are postulated to have caused Cu enrichment in the meta-volcanic rocks.

The distribution of Zn in the Ruth Lake meta-gabbro bears a roughly inverse relationship to the distribution of Ni, with relatively Zn-poor, Ni-rich rocks on the west and Zn-rich, Ni-poor rocks on the east (cf. Plates 1 and 3). Zn probably substitutes for Fe in mafic minerals, and its distribution would therefore reflect the greater proportion of iron-bearing minerals in the eastern part of the meta-gabbro (cf. Wohlberg, 1964, Plate 4).

Birch-Table Lakes Meta-gabbro (3)

The part of the Birch-Table Lakes meta-gabbro west of Birch Lake is lithologically similar to the Ruth Lake meta-gabbro. Distribution of Ni is roughly symmetrical, with the highest concentrations in the central zone and the lowest near the east and west contacts with Ni-poor meta-volcanic rocks (Plate 1). This suggests that the reaction between meta-gabbros and meta-volcanic rocks postulated under the description of 'Basic Meta-Volcanic Rocks (1), Ruth Lake Block' might have involved impoverishment of the meta-gabbros in Ni; however, there is no evidence that the meta-volcanic rocks were correspondingly enriched in Ni. Compared with the Ruth Lake meta-gabbro, the frequency distribution of Ni in the Birch-Table Lakes meta-gabbro shows lower proportions of both low (< 100 ppm) and high (> 200 ppm) concentrations (Fig. 1, cf. E and D). The lower proportion of low concentrations might be accounted for by less reaction between meta-gabbro and wall-rocks or by an original chemical difference between the two meta-gabbros. The lower proportion of high concentrations is consistent with lack of enrichment in Ni by ultrabasic rocks. Absence of ultrabasic rocks in contact with the meta-gabbro is confirmed by an aeromagnetic low centred on the Birch-Table Lakes meta-gabbro west of Birch Lake (Geol. Surv. Can., Map 1028G).

All but one of the small number of Cu concentrations exceeding 200 ppm are grouped along an apparent northeasterly trend, just south of and parallel to the west bay of Birch Lake. This suggests that enrichment in Cu was localized by transcurrent structures.

Mystic Lake Meta-gabbro (3)

The western part of the Mystic Lake meta-gabbro is lithologically similar to the amphibole-zoisite rocks of the Ruth Lake meta-gabbro, whereas the eastern part is plagioclase-bearing amphibolite (Froese, 1969a). Three chemically analysed specimens supplied by Froese to Wohlberg (1964, Table 1) are normatively pyroxene-bytownite (An 76) rocks. Judging by the 'spot samples' plotted in Plates 1 and 3, concentrations of nickel and zinc are similar to those in the meta-gabbros described above. However, concentrations of copper exceeding 100 ppm appear to be relatively more abundant (Plate 2). Whether these are regularly distributed or concentrated along transcurrent trends cannot be judged by the widely-spaced samples. On the basis of his regional study (Smith, 1964), the writer believes that the frequency of occurrence of anomalously high copper concentrations is related to proximity to the granodioritic complexes, which are postulated as the source of the copper-bearing solutions that accomplished the enrichment. This would be consistent with the proximity of granodioritic complexes to the north and south of the Mystic Lake meta-gabbro.

Ultrabasic Rocks (4)

The ultrabasic rocks are predominantly serpentinites with discontinuous interlayers of less abundant meta-pyroxenite and meta-peridotite. The aeromagnetic map of the area (Geol. Surv. Can., Map 1028G) suggests that the relatively thin body of ultrabasic rocks exposed along the east shores of

Table and Ruth Lakes is continuous over a strike length of more than 10 miles. The north-south continuity of the ultrabasic rocks and the meta-gabbro bodies supports the contention that these rocks were not involved in the complex folding of the volcanic rocks, but were emplaced along north-south structures subsequent to the folding.

High concentrations of nickel in the ultrabasic rocks (Fig. 1F) are not contoured in Plate 1 to avoid obscuring contour trends in adjacent rocks. The very low concentrations of copper and zinc are included in the contours in Plates 2 and 3; they contribute little information about trends except insofar as they conform with similarly low concentrations in adjacent meta-gabbros.

Meta-diorite and Meta-gabbro (6), Birch Lake Block

Rocks included in map-unit 6 east of Birch Lake are a heterogeneous mixture of meta-gabbros similar to the Ruth Lake meta-gabbro, foliated amphibolites, thinly layered meta-volcanic rocks, and granodioritic gneisses. The distributions of nickel, copper, and zinc in Plates 1, 2 and 3 reflect this heterogeneity, but otherwise contribute little information of petrogenetic value.

Granodioritic Complexes (7)

Distributions of nickel, copper and zinc in the granodioritic complexes have been described by the writer (1964). Although the metal distributions are principally related to the distribution of different rock-types, some transcurrent trends are evident in the distribution of copper (*ibid.*, overlay 2). The aeromagnetic map (*op. cit.*) shows distinct northeasterly maxima in the granodioritic complexes and associated mafic rocks; those within the area are indicated in Plates 1 to 3. These observations suggest that northeasterly faults might have been active at the time of the late stages of crystallization of the granodiorites, providing channelways along which iron was concentrated, partly in mafic minerals and partly in magnetite and perhaps sulphides. The same channelways might have provided access of sulphur-, iron-, and basemetal-bearing solutions to surrounding country rock. In this connection, Byers *et al.* (1965, p. 76) noted the proximity of iron sulphide bodies to contacts with granodioritic plutons, and the writer (1964), demonstrated an average increase in copper concentrations in basic volcanic rocks with increasing proximity to the granodiorites.

Byers *et al.* (1954, 1965) have demonstrated that the granodioritic complexes were emplaced during the isoclinal folding, predominantly in major anticlinal structures. The writer believes that the granodiorites were still partly mobile and hydrothermally active very late in or after the cycle of isoclinal folding, mainly for the following reasons:

1. At many localities in the marginal zones of the complexes, dikes and stockworks of unfoliated granodiorite cut various foliated rocks, including more mafic granodiorite. One dike of massive granodiorite cuts volcanic rocks near the Coronation mine road west of the south end of Tanyss Lake (Plates 1 to 3).

2. Other late dikes demonstrate the continuation of igneous intrusion after folding and foliation of country-rock. Although none of these dikes may be related to the granodiorites, there is no evidence that some of them are not.
3. Sulphide bodies which are spatially associated with the granodiorites (Byers *et al.*, 1954 and 1965) appear to be more abundant near known northeast faults and their possible extensions, and also near a northeast topographic lineament extending from the central part of Brutus Lake to Meridian Creek east of Tanyss Lake (see locations of electromagnetic conductors, Plate 1). The parallelism of the faults and lineament with aeromagnetic maxima in the granodioritic complexes suggests that they may be related structures, and that the hydrothermal solutions which formed the sulphide bodies were channeled by northeast faults both within and near the granodioritic complexes. If the granodiorites are the parent rocks of the hydrothermal solutions, it follows that late-stage activity in the granodiorites post-dated at least early movements on northeast faults.

Geochemistry and Economic Geology

Interpretation of the economic significance of relatively high concentrations of trace metals is limited by the lack of analyses of individual minerals. It is not known, for instance, whether the metals occur wholly in solid solution in silicate and oxide minerals or whether they are partly in sulphides.

In the case of nickel, the highest concentrations are found in serpentinites (Fig. 1F). Examination of three polished sections revealed minute, highly reflective specks near the margins of zoned magnetite grains. These were tentatively identified as iron-nickel alloy in the metallic state, but their abundance in the rock specimens could not be estimated by microscopic methods. Specimens from a sulphide-molybdenite showing in meta-gabbro north of the road in the northwest corner of the area (Froese, personal communication) contain as much as 0.4 per cent Ni and 0.8 per cent Cu (Plates 1, 2). South of the showing, other showings and sulphide bodies located by electromagnetic surveys (Plates 1, 2, 3), and aeromagnetic maxima not apparently associated with ultrabasic rocks (Geol. Surv. Can., Map 1028G) suggest that at least part of the Ni, Cu, and Zn is in sulphides at this locality. By analogy, other high concentrations of Ni in meta-gabbros may also be in sulphides, especially in a zone west and northwest of Echo Lake where some high concentrations of Cu are also found; north of Stitt Lake; along the east shores of Table and Ruth Lakes; in the northeast corner of Mystic Lake; and in the Mystic Lake meta-gabbro north of Meridian Creek. No nickel assays higher than 0.06 per cent were found in any of the electromagnetic conductors (A.A. Koffman, personal communication); this presumably means that there are no massive copper-nickel orebodies close to the surface in the area, because the electromagnetic survey covered the whole of the Coronation mine area, with the exception of the granodiorites proper. However, it does not rule out the possibility of finding disseminated nickel ore of mineable grade.

The large range of concentrations of Cu compared with Zn in many rock-units (Fig. 1) suggests that part or all of the copper is in erratically distributed chalcopyrite, which has been found by careful re-examination of

some hand-specimens. This interpretation is consistent with transcurrent trends of copper contours in Plate 2, especially in the normally copper-poor meta-gabbros (3). It would therefore seem advisable to devote careful prospecting to localities where high concentrations of Cu are near northeasterly-trending contacts, topographic lineaments, faults, and possibly extensions of aeromagnetic maxima in the granodioritic complexes into adjacent country rock. Intersections of these trends with northerly-trending shear zones and other permeable horizons might be particularly favourable sites. Examples of such localities in Plate 2 are near the west bay of Birch Lake, where the Flexar orebody is already known; the north shore of Ruth Lake and south bays of Konuto Lake; Meridian Creek west and east of Tanyss Lake; and the headlands near the west shore of Mystic Lake.

Anomalously high concentrations of Zn are absent in the systematic samples contoured in Plate 3, with the possible exceptions of transcurrent zones in Ruth Lake meta-gabbro. Among the spot samples, the highest concentration is about 0.3 per cent in a specimen from a trench in the north-west corner of the area, where disseminated sulphides in meta-gabbro were observed, but sphalerite was not specifically identified (Froese, personal communication). The same specimen contains about 0.03 per cent Ni and 0.1 per cent Cu. A specimen from a headland on the southeast shore of Mystic Lake contains 940 ppm (ca. 0.1 per cent) of Zn and 320 ppm of Cu, and in this case no observable sulphides were reported by Froese (personal communication). Apart from these isolated observations, the distribution of Zn in bed-rock provides little information of possible economic significance.

There is no direct evidence that the distribution of Ni, Cu, or Zn in country-rock is related to the formation of the known mineable orebodies in the area. All three orebodies occur in relatively nickel-poor, thinly layered, and sheared basic meta-volcanic rocks (Plate 1). Transcurrent trends of relatively high concentrations of Cu in these rocks (Plate 2) have been here interpreted as the result of epigenetic enrichment localized in permeable zones; the copper orebodies might conceivably be extreme examples of such enrichment. This interpretation could be compatible with most of the evidence presented by others in this volume and elsewhere, depending on when and how the enrichment of country-rock in Cu and the formation of the orebodies took place. The writer has suggested that iron-, sulphur-, and copper-bearing solutions were associated with the latest stages of igneous activity in the granodioritic complexes, that the solutions were channeled along northeasterly structures, and that they gave rise to the numerous iron sulphide bodies in the area, many of which contain copper and zinc sulphides in concentrations that have not yet been found by diamond drilling to be of mineable grade. If these interpretations are true, Faulkner's conclusions (this volume) would seem to indicate that the same solutions could not have deposited the mineable orebodies, because the variations of cobalt and nickel contents of pyrrhotite in 'barren' and economic deposits are discretely different. Furthermore, in a concise summary of the relationships and nature of the barren and economic sulphide deposits, Byers *et al.* (1965, pp. 76-83) conclude that the economic deposits were localized by late (post-granodiorite) faults of the Ross Lake system and that they are genetically related to similarly late, basic intrusive rocks. On the other hand, Froese (1963 and 1969b) concludes that the Coronation orebody and its altered wall rocks were formed before regional metamorphism (and therefore certainly before the end of igneous activity in the granodioritic complexes, according to the

writer's interpretation). It therefore seems possible that in the long and no doubt complex history of intrusion, crystallization, deformation, and re-intrusion of the granodioritic complexes, a series of hydrothermal solutions of different kinds might have encountered different structural, metamorphic, and chemical conditions in the surrounding country-rock. For instance, some earlier solutions might have mixed with nickel-rich solutions from the ultrabasic rocks and related gabbros, thereby accounting for nickel-rich pyrrhotite in some of the 'barren' sulphide deposits (Faulkner, 1969). Other solutions from the granodiorites might have been of different compositions and times of origin, and might have deposited the economic sulphide bodies in a variety of permeable zones, including shear-zones older than the latest movements along the Ross Lake fault system.

The number of variables which are undefined in the present state of knowledge leaves geochemical interpretations open to wide speculation. The writer prefers to rest the case on the observed proximity of both barren and economic sulphide deposits in this area to the granodioritic complexes and to admittedly ill-defined transcurrent trends of copper distributions and structural features.

SUMMARY OF CONCLUSIONS

Basic meta-volcanic rocks (1) are nickel-poor meta-andesites and relatively nickel-rich meta-basalts.

Compared to the meta-volcanic rocks, meta-gabbroic rocks (3) are distinctly ultrabasic, richer in nickel, and markedly poorer in copper and zinc. They were emplaced, together with slightly younger but related ultrabasic rocks proper (4), after isoclinal folding and foliation of the volcanic rocks, and their emplacement was accompanied by leaching of copper and zinc from adjacent volcanic rocks. The meta-gabbroic rocks themselves were enriched in nickel near the ultrabasic rocks, either when the ultrabasic rocks were emplaced or when they were serpentinized. Small occurrences of copper-nickel mineralization are probably genetically related to the meta-gabbros.

Granodioritic complexes (7 and parts of 6) were emplaced during folding but intrusion and hydrothermal activity continued after cessation of folding and beginning of transcurrent faulting. The formation of relatively iron-rich, magnetite-bearing rocks within the granodioritic complexes might have been a late-stage igneous process localized by northeasterly faults.

Meta-volcanic rocks and meta-gabbros were epigenetically enriched in copper near transcurrent structures, particularly where the structures intersect permeable zones. The enrichment might have been caused by solutions migrating at various times from the granodioritic complexes. Nearly barren and economic sulphide deposits are preferentially close to the granodioritic complexes, and both may be spatially related to transcurrent structures and to copper enrichment in country-rock.

All of these conclusions are hypothetical. Confirmation would require more extensive, systematic and detailed mapping and sampling of bedrock, including parts of the granodioritic complexes; petrological, mineralogical, and petrochemical studies; and detailed studies of other barren and economic sulphide deposits in the area.

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No. 7 GENETIC IMPLICATIONS OF COBALT AND
NICKEL DISTRIBUTION IN SULPHIDE DEPOSITS
OF THE CORONATION MINE

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ABSTRACT

Many sulphide deposits of the Coronation mine-Flin Flon area occur in essentially conformable shear zones, generally in metamorphosed volcanic and pyroclastic rocks.

The deposits may be divided on the basis of quantitative mineralogy into a larger 'barren' group consisting of pyrite and/or pyrrhotite with nominal amounts of other base-metal sulphides, and a smaller 'economic' group consisting of pyrite and/or pyrrhotite with relatively large amounts of other base-metal sulphides, notably chalcopyrite and sphalerite.

Results of analyses of pyrrhotite samples from these deposits for cobalt and nickel are summarized as follows:

		Co ppm		Ni ppm		Mean
Deposits	No.	Range	Mean	Range	Mean	Co/Ni
Coronation mine	60	68-4150	890	25-1050	315	2.82
Other 'economic' deposits	16	85-3450	1550	45- 275	116	13.4
'Barren' deposits	76	10- 525	165	125-2720	925	0.178

The contrasting Co/Ni ratios of the two groups strongly suggest that they are not genetically related.

The 'barren' deposits were probably formed by reaction of a sulphur-bearing hydrothermal phase from adjacent syntectonic granodiorites with ferromagnesian minerals in permeable and structurally unstable wallrock zones.

The metals of the 'economic' deposits were probably concentrated as chloro-complexes, either directly during mafic magmatic differentiation, or by selective leaching of rocks by deep-seated chloride-rich brines. The field evidence is consistent with either possibility.

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Introduction

The Coronation mine-Flin Flon general area has been the subject of much detailed geological study, and descriptions of the general geology and sulphide mineralization have been capably presented by Byers and Dahlstrom (1954), and especially by Byers, Kirkland and Pearson (1965). Only such details as may be new or pertinent to the present paper will therefore be given here, and the reader is referred to the above publications for more general information.

Coronation mine is but one example of a number of essentially conformable sulphide deposits in the Flin Flon area. Most of these deposits have been located by diamond drilling of geophysical anomalies. They fall into two relatively distinct groups on the basis of quantitative mineralogy: a larger or 'barren' group consisting of pyrite and/or pyrrhotite with nominal amounts of other base-metal sulphides, and a smaller or 'economic' group (which may or may not be of commercial value) consisting of pyrite and/or pyrrhotite with relatively large amounts of other base metal sulphides, notably chalcopyrite and sphalerite. The 'economic' group includes the Coronation deposit, the main Flin Flon orebody, and other commercial deposits.

Despite the contrast in quantitative mineralogy, both groups show many similarities in physical form and geological settings. Although some other differences between the two groups have been suspected or confirmed since this study was made, it must be emphasized that quantitative mineralogy was the sole criterion used in classifying the deposits studied. No account was taken of location, setting or structure in this initial grouping.

The location of the majority of deposits studied is given in Figure 1. Samples included from deposits outside this area will be mentioned later.

A study of the distribution of cobalt and nickel in these two groups of sulphide deposits was undertaken to provide further clues on the genesis of the sulphides. The geochemistry of cobalt and nickel has been reasonably well documented, and the following generalizations will serve as a basis for interpretations to follow:

1. The content of cobalt and nickel is highest in ultramafic rocks and decreases as the mafic content of a rock decreases.
2. The Co/Ni ratio is less than one in most igneous, metamorphic and sedimentary rocks; it increases from mafic to silicic rocks, especially during magmatic differentiation.
3. Some silicic rocks have Co/Ni ratios greater than one, but the absolute amounts of cobalt and nickel in such rocks are usually low.
4. In massive vein-type sulphide deposits where pyrite (Py), pyrrhotite (Po) and chalcopyrite (Cp) are the major sulphides, the Co/Ni ratio is usually greater than one for the deposit as a whole, and for pyrite and pyrrhotite individually.
5. The distribution of cobalt and nickel among the three major sulphides is usually as follows:

Cobalt: $Py > Po > Cp$

Nickel: $Py < Po > Cp$.

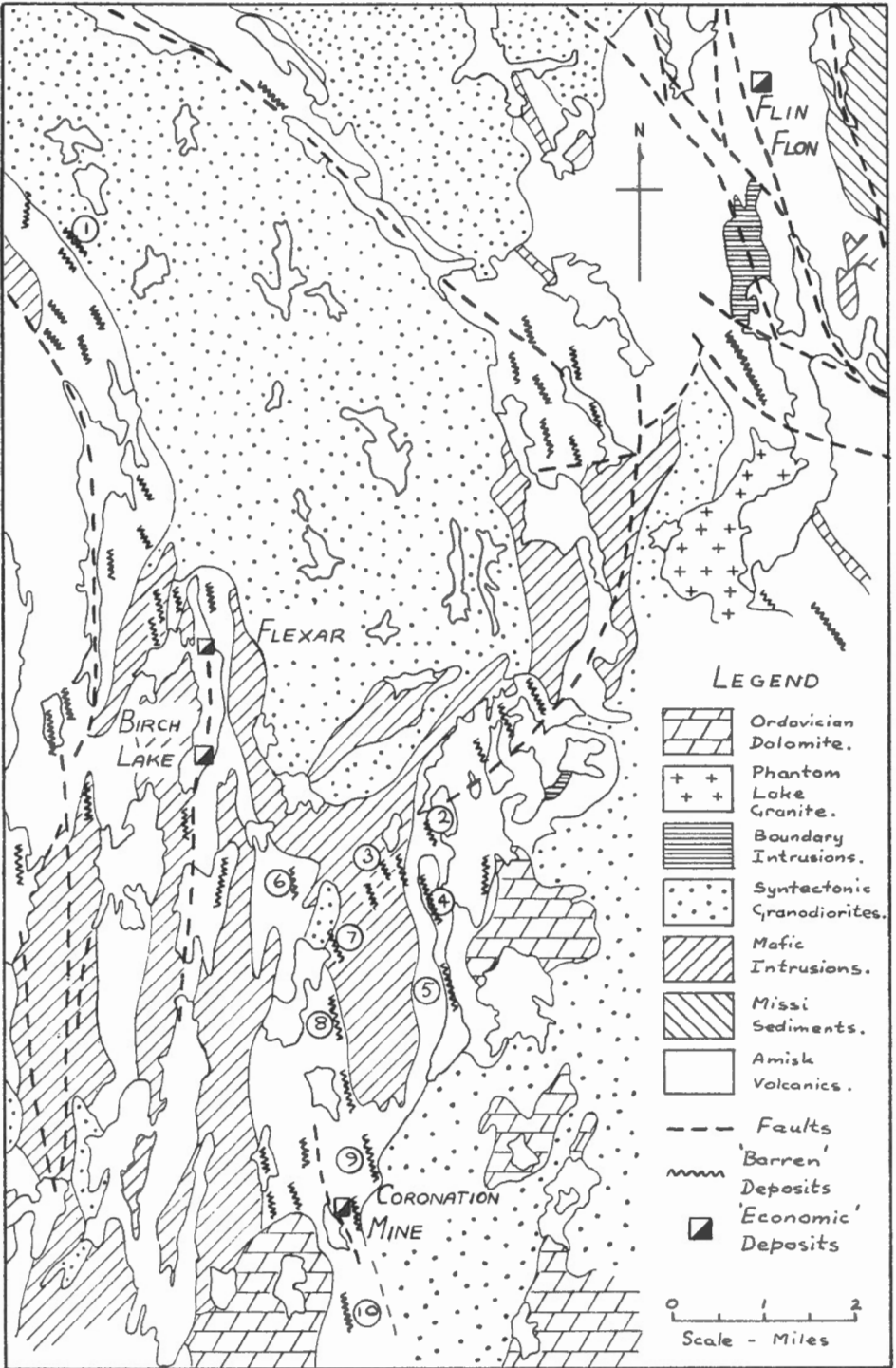


Figure 1. Location of sulphide deposits and general geology, Coronation mine-Flin Flon area.

As a result of statement 5 above, pyrrhotite is the most likely mineral to reflect changes in the general distribution of cobalt and nickel in a particular deposit, and thus was picked for detailed study. Preliminary work verified that the above distribution relations were present in the 'economic' deposits considered.

Large areal departures from the pattern described in statement 2 are rare, and the Co/Ni ratios in rocks from such areas are seldom much greater than one (Markhinin and Sapozhnikova, 1962). Smith (1964), studied the copper, zinc and nickel trace content of bedrocks in the East Amisk area in which a number of the analysed sulphide deposits are located. He found that the nickel content of some mafic rocks is about half the expected concentration, while some syntectonic granodiorites contain about twice the expected concentration. More interesting variations were found for the copper and zinc content than for the nickel content however, and there are no published data on the areal cobalt distribution. The only available data are those of Froese (1963), who gives some spectrographic analyses for trace elements in 20 volcanic flow rocks from the Coronation mine area.

The results for ten of these samples cannot be assessed in the present context, in that they were selected mineralized samples, and sulphide and silicate fractions were analysed separately. The average cobalt and nickel content of the other ten samples is 40 ppm and 64 ppm respectively, for a Co/Ni ratio of 0.62. It is interesting that within the likely error for such analyses four of the samples have individual Co/Ni ratios greater than one, and seem to support Smith's finding noted above, in that they appear to be nickel deficient, rather than cobalt enriched.

The average results for ten samples are not enough to characterize an area of several hundred square miles as 'normal' and the individual results of four of these samples are certainly not enough to characterize the area as 'anomalous'. There is clearly a need in this regard for reliable cobalt data of the scope of Smith's data for nickel. Until such data is forthcoming however, it must be assumed that the cobalt and nickel content of the bedrocks in the area under study is not anomalous.

'Barren' Deposits

The 'barren' deposits have been described in some detail by Byers and Dahlstrom (1954), Byers, Kirkland and Pearson (1965) and by Beck (1959). Briefly the deposits are rather variable veinlike replacement bodies, differing considerably in degree of replacement. All variations from thin zones a few tens of feet in length to large zones several thousand feet long and several hundred feet thick and from massive to scattered disseminated sulphides may be found. The sulphides are mostly pyrite and/or pyrrhotite, generally both sulphides being present. Traces of chalcopyrite and sphalerite can usually be found in most of the deposits, and rarely may amount to as much as a percent of the total sulphides.

The gangue usually consists of quartz and variously altered and replaced remnants of the original country rocks. Most of the samples analysed were recovered from drill core from the locations shown in Figure 1, but in order to improve the areal distribution, a few samples from deposits outside this area, e.g., from the La Ronge, Saskatchewan and Snow Lake, Manitoba areas were included (see Faulkner, 1964). Of particular interest

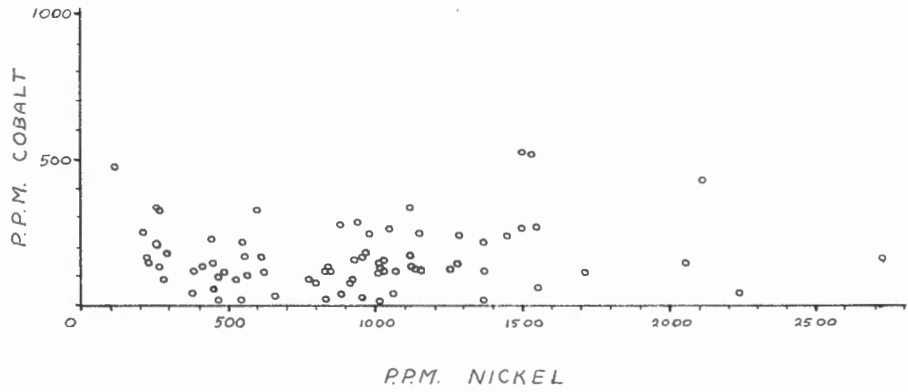


Figure 2. Cobalt and nickel content of pyrrhotites from the 'barren' deposits.

were six samples from five deposits that are distinctly stratigraphic in character, and have been traced laterally for considerable distances, frequently into metamorphosed iron-formations (Byers and Dahlstrom, 1954; Byers, 1960). In all, 76 samples from 20 different deposits were analysed.

'Economic' Deposits

Apart from differences in the proportions of chalcopyrite and sphalerite, there is surprisingly little difference in the broad geological setting of the 'barren' and 'economic' deposits. The 'economic' deposits are represented by a number of mines, past and present, including the Flin Flon mine, the Mandy and Schist Lake mines, the Birch Lake mine and Flexar deposit and Coronation mine. The latter was chosen as the representative 'economic' deposit, and approximately 400 hours were spent underground in sampling and mapping between 1959 and 1962, as mining operations progressed. Sixty samples, distributed as evenly as underground workings and the occurrence of pyrrhotite allowed, were analysed from Coronation mine, and 16 more from other 'economic' deposits.

There are also a number of narrow zones in the Flin Flon area which are 'economic' by definition, although not of commercial value. Unfortunately no samples could be recovered from these zones, but to offset this as far as possible, samples were included from parts of Coronation mine which were definitely not of commercial value.

Coronation Mine

A general description of Coronation mine has been given by Byers, Kirkland and Pearson (1965), and particular aspects are considered elsewhere in this volume. A description of the underground structure and its relation to the mineralization will be given here, as it has special relevance to the interpretation of the results to follow.

The orebody consists of varying amounts of massive to disseminated pyrite, pyrrhotite and chalcopyrite with minor amounts of sphalerite and some magnetite in a series of ore shoots plunging 80° south within a shear zone approximately 900 feet long, 1,000 feet deep and up to 200 feet wide, which dips steeply west. As far as can be ascertained, the shear zone is concordant, and follows a zone of altered tuffs and dacitic flows between a relatively massive andesitic footwall and amygdaloidal to massive mafic flows in the hangingwall.

The relation of the mineralization and the wallrock alteration to the shearing is very pronounced. Movement on the shear zone is left-hand, with slickensides plunging an average of 10° south-southwest. The total displacement appears small, and is estimated at no more than fifty feet. Most of this displacement has been localized in a hangingwall and a footwall shear zone separated by 100 to 150 feet of varying disturbed and altered country rocks.

For descriptive convenience, the orebody can be divided into three general sections (see Fig. 4).

1. The northern section, in which almost all the displacement is confined to the hangingwall and footwall shear zones, with relatively little cross fracturing and alteration of the intervening ground. The sulphides are

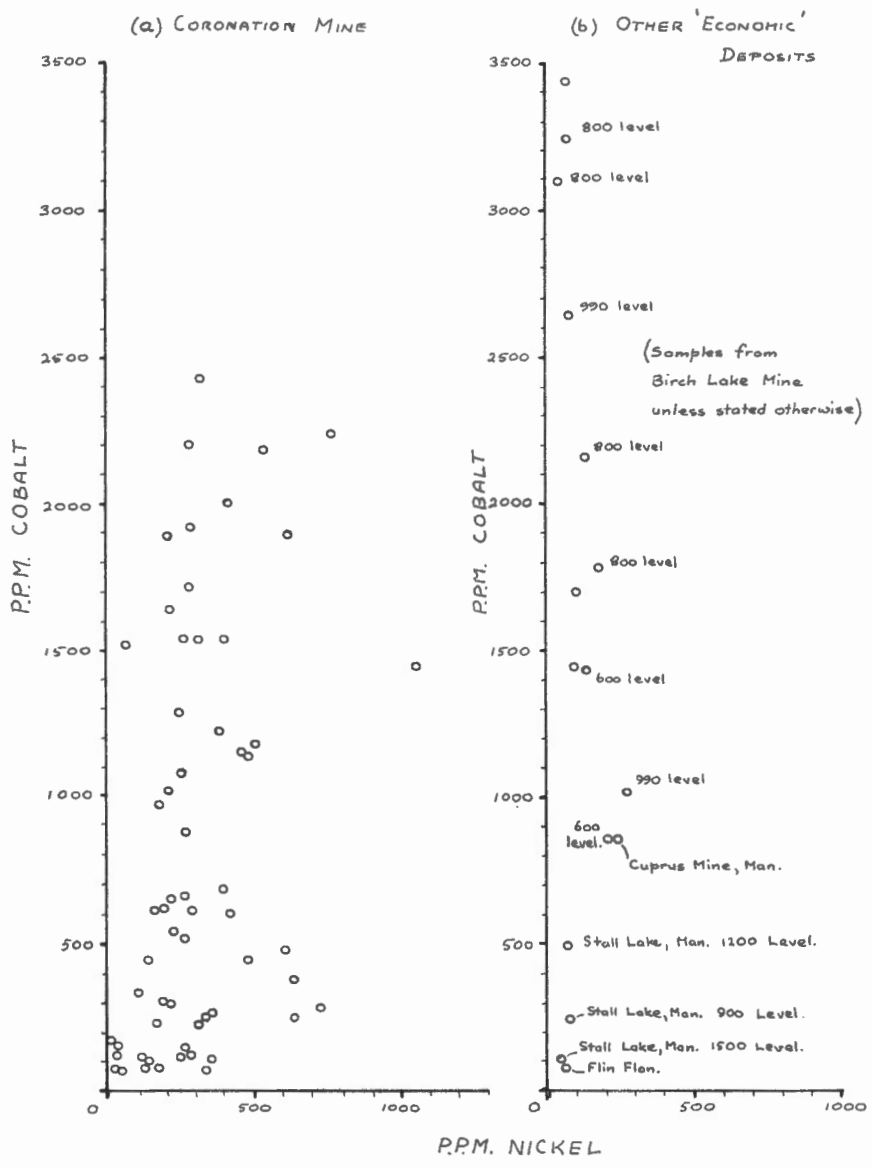


Figure 3. Cobalt and nickel content of pyrrhotites from the 'economic' deposits.

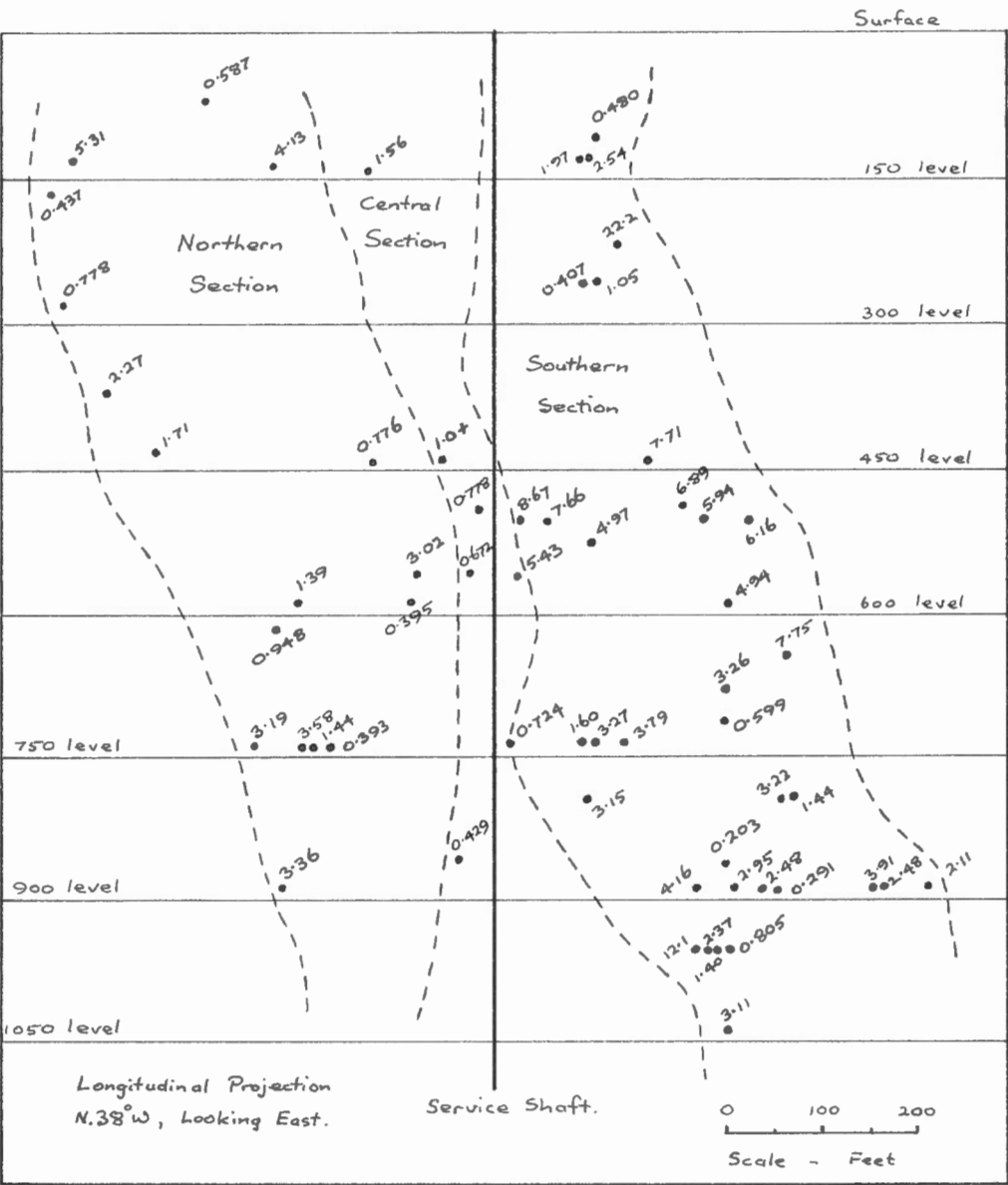


Figure 4. Locations and Co/Ni ratios of pyrrhotites from Coronation mine.

concentrated into a larger footwall oreshoot and a smaller hangingwall oreshoot, both containing large proportions of massive sulphides. Some disseminated sulphide mineralization occurs between the two oreshoots.

2. The central section, which is more sparingly but more evenly mineralized, with some low-grade concentrations on the main hangingwall and footwall shear zones.

3. The southern section, in which the shearing and wallrock alteration are extensively dispersed throughout the full width of the ore zone, and into the country rocks on either side. The mineralization is likewise highly dispersed, varying from coarse pyritic 'core-like' masses on the projected continuations of the northern hangingwall and footwall shear zones to the more typical stringers, irregular masses and disseminated sulphides. Wallrock alteration is more extensive, more complex and generally coarser in this section.

It is readily apparent from underground examination that most of the movement on the shear zone took place in two major stages. The bulk of the sulphides is associated with an earlier stage of movement. Pyrrhotite and chalcopyrite in particular frequently are conformably layered, and lineations in the sulphides parallel the general plunge of the orebodies, individual oreshoots, and linear features in the adjacent metamorphosed country rocks. These features indicate that the bulk of the sulphides has at least some metamorphic history, but the significance of this fact should not be overrated.

The later stage of movement has broken up the earlier massive sulphides to some extent, and given rise to a host of vein openings ranging in length from fractions of an inch to tens of feet, which are filled with near massive sulphides, particularly rich in chalcopyrite, and particularly free of gangue. Layering and especially linear features are notably absent from these later veins.

In traditional terms this would be explained as an 'earlier' mineralization, followed by a later 'reopening' and copper-rich mineralization. Such an explanation is neither desirable nor justified by the evidence; it being more likely that sulphides were selectively remobilized into these later vein openings, losing their linear and banded features in the process.

The location of sulphide samples from the three sections described above, is given in Figure 4. No attempt has been made to indicate their locations across the ore zone for reasons which will appear later.

Pyrrhotite Separation

Following the choice of pyrrhotite for detailed study, a simple hand-held A. C. electromagnetic separator was used to isolate pyrrhotite from the crushed and screened samples, spread evenly on clean paper. By varying the current to the electromagnet, and the height of the magnet above the sample, it was possible to make preliminary removal of occasional magnetite grains and to leave composite sulphide particles with the residues, thus making a clean separation of pyrrhotite from pyrite, chalcopyrite and silicates. The conditions for a clean separation were found by trial, with constant checking of the quality of the separation with the aid of a binocular microscope. Pyrrhotite was separated from the -200 mesh (U. S. S.) fraction following difficulties with composite particles in coarser fractions from some samples. Adhering fines and dust were removed from the separates by

agitation in acetone, followed by a magnetic separation under acetone, and final drying. Further details of the separation procedures followed for the pyrite and chalcopyrite samples analysed are given by Faulkner (1964).

Analytical Procedure

Chemical-spectrophotometric methods of analysis for cobalt and nickel were chosen. The relatively low productivity of such methods is more than offset by potentially good precision and freedom from matrix or other physical interferences.

In outline, the analytical procedure was as follows: The sulphide was dissolved in a mixture of bromine and hydrochloric acid, followed by oxidation of any ferrous iron with hydrogen peroxide, and then a routine ether extraction of the ferric iron. Aliquots of the final solution were analysed using a Nitroso-R method for cobalt and an alkaline dimethylglyoxime method for nickel, followed by spectrophotometric measurements of the metal complexes. The full experimental details of these and other procedures used are given by Faulkner (1964).

Reliability of Results

Replicate analyses of Standard Sulphide No. 1 using a method closely comparable to that developed for the pure sulphides indicated that a relative deviation (percent standard deviation) for the determination of cobalt and nickel of less than four was possible.

Duplicate analyses (including duplicate separations) of two samples from 'barren' deposits and three samples from Coronation mine gave relative deviations less than ten in all but one case (range 2.2 to 15.3, corresponding to a 'probable error of the mean' of 1.2 to 7.3 percent). In contrast, duplicate analyses made of different pieces from one large 'economic' specimen, or of different specimens collected within two feet of three particular underground locations, gave relative deviations considerably greater than ten in all but one case (range 8.3 to 65, corresponding to a 'probable error of the mean' of 4.0 to 30.6 percent).

Clearly these latter deviations are greater than would be expected from the method itself, and must reflect real differences in cobalt and nickel distribution within single large specimens, and particularly between specimens from the same location.

Such variations in trace element content over small distances were not unexpected from the underground examinations that were made. The chances of equilibrium being achieved over even small distances in an environment as structurally and mineralogically complex as the Coronation mine shear zone must be considered remote. Even within comparatively uniform and unaltered surface outcrops in the Coronation mine-Flin Flon area, Smith (1964) has found significant trace-element variations.

Thus emphasis in the interpretation of the results to follow will be placed on the differences between deposits as a whole, rather than on differences between individual samples in any one deposit.

Effects of Partition

The expected partition relationships of cobalt and nickel between coexisting pyrite, pyrrhotite and chalcopyrite were found. The average partition ratios for 5 widely separated samples were found to be 2.78:1.0:0.129 for cobalt and 0.347:1.0:0.157 for nickel.

Arnold (oral communication as reported by Faulkner, 1964), using an X-ray method, found higher partition ratios for cobalt between coexisting pyrite and pyrrhotite in two of the four samples he analysed, giving an average ratio of 15.1:1.0. The average partition ratio for nickel in these four samples was 0.47:1.0.

Discussion of Results

The results of the analyses of pyrrhotites from the 'barren' deposits are shown in Figure 2 plotted as ppm cobalt against ppm nickel. Table 1 gives some data for the individual deposits studied.

Similar plots of the results for the pyrrhotites from Coronation mine are given in Figure 3a, and for pyrrhotites from the other 'economic' deposits in Figure 3b. The locations of the Coronation mine samples analysed, with Co/Ni ratios, Co ppm and Ni ppm are shown on longitudinal projections of the mine in Figures 4, 5 and 6 respectively.

Table 1

Results for the 'Barren' Deposits given in Figure 1

Barren Deposit	Mineralized D. D. H. Sections or Widths	No. of Samples	Mean Co ppm	Mean Ni ppm	Mean Co/Ni
No. 1	25'-50' and 418'	2	43	1650	0.026
No. 2	Not known	4	92	1134	0.081
No. 3	378'-427'	6	164	864	0.190
No. 4	about 50' in three D. D. H. holes	12	90	1142	0.079
No. 5	234'	2	127	1715	0.074
No. 6	143'-310'	11	145	603	0.240
No. 7	323'-343'	4	292	1185	0.246
No. 8	444'-530'	4	395	1520	0.260
No. 9	unknown widths from two holes	8	94	814	0.115
No. 10	113'-127'	4	205	998	0.205

Histograms of results for the 'barren' and 'economic' deposits are shown in Figure 7a and 7b respectively.

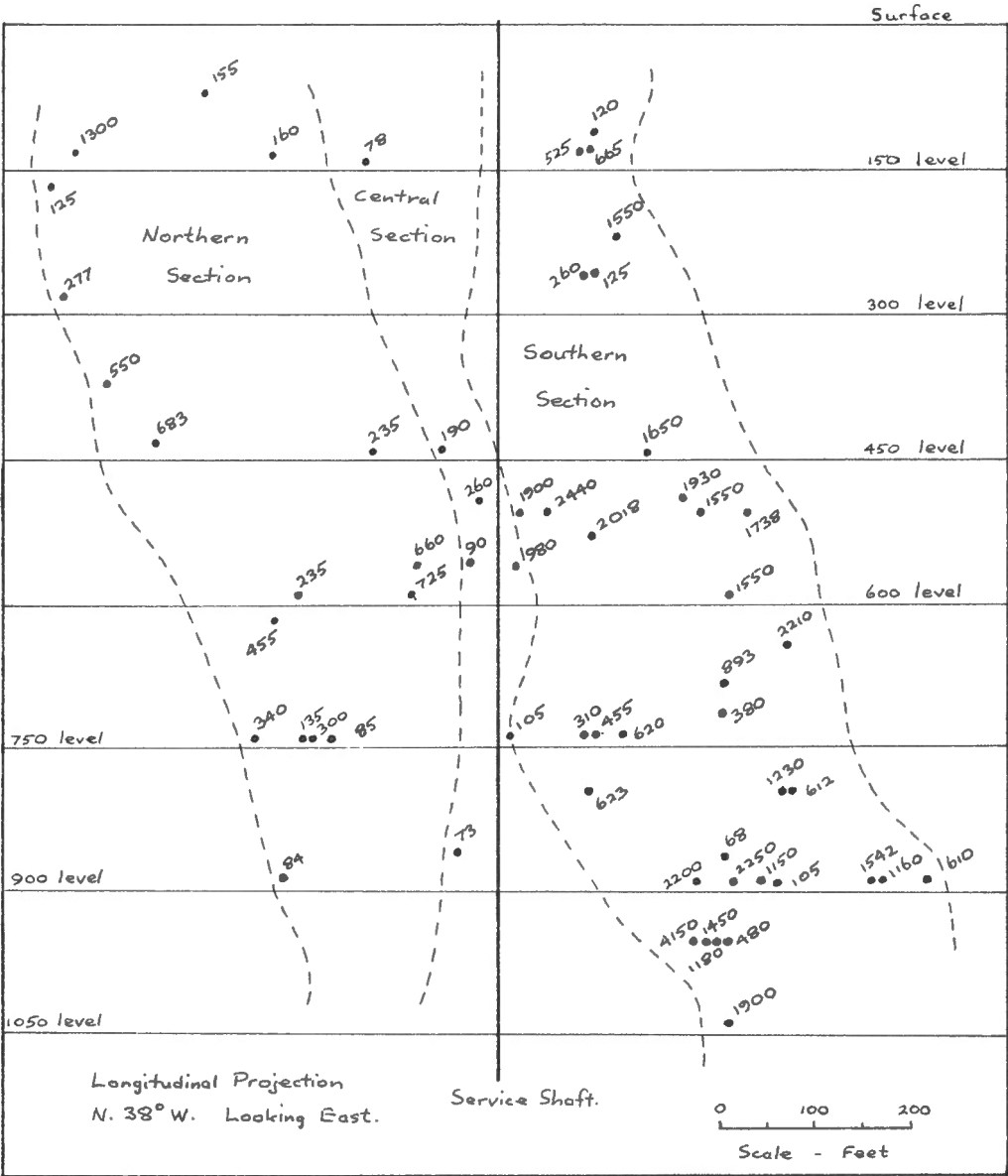


Figure 5. Locations and cobalt content of pyrrhotites from Coronation mine.

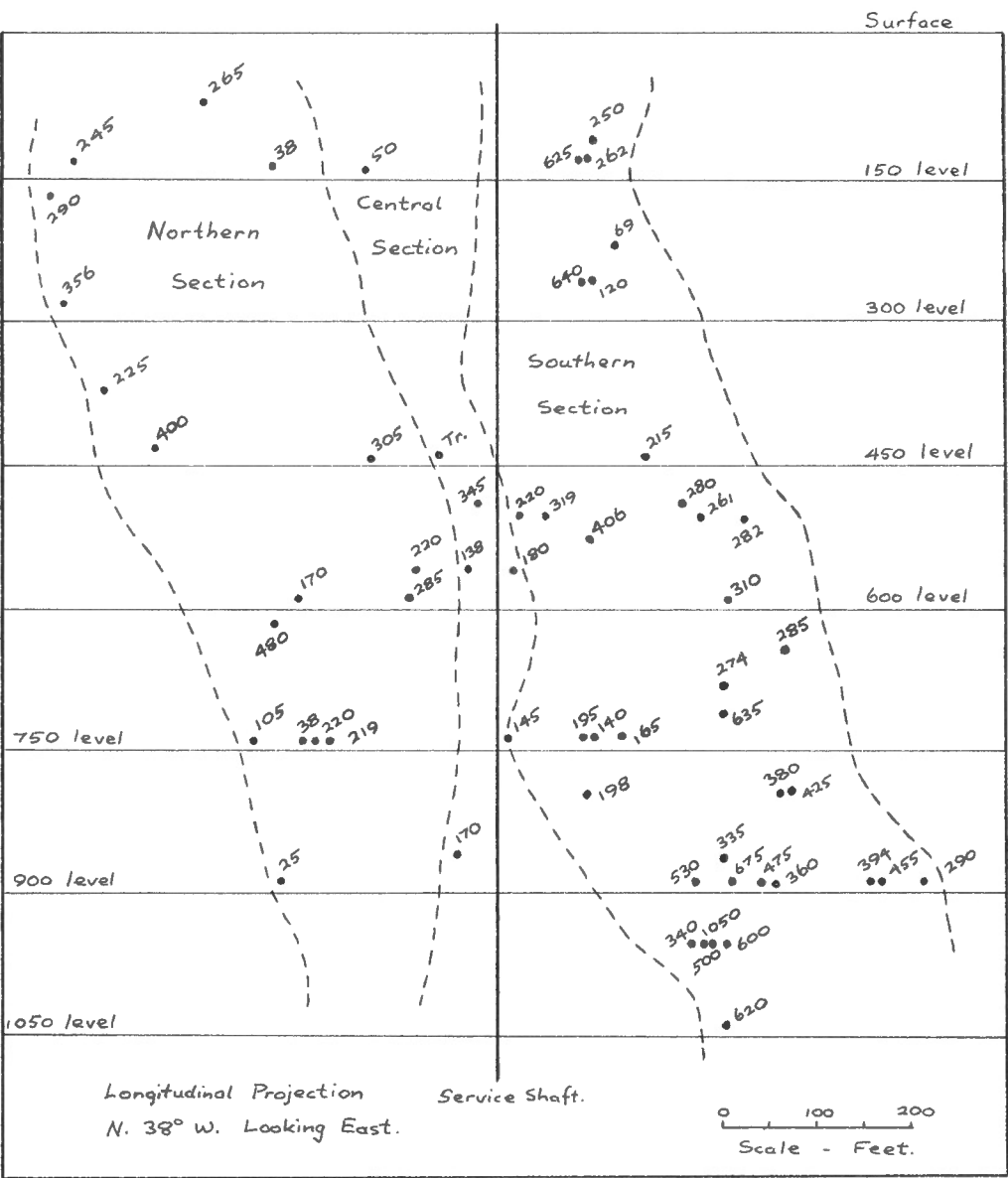


Figure 6. Locations and nickel content of pyrrhotites from Coronation mine.

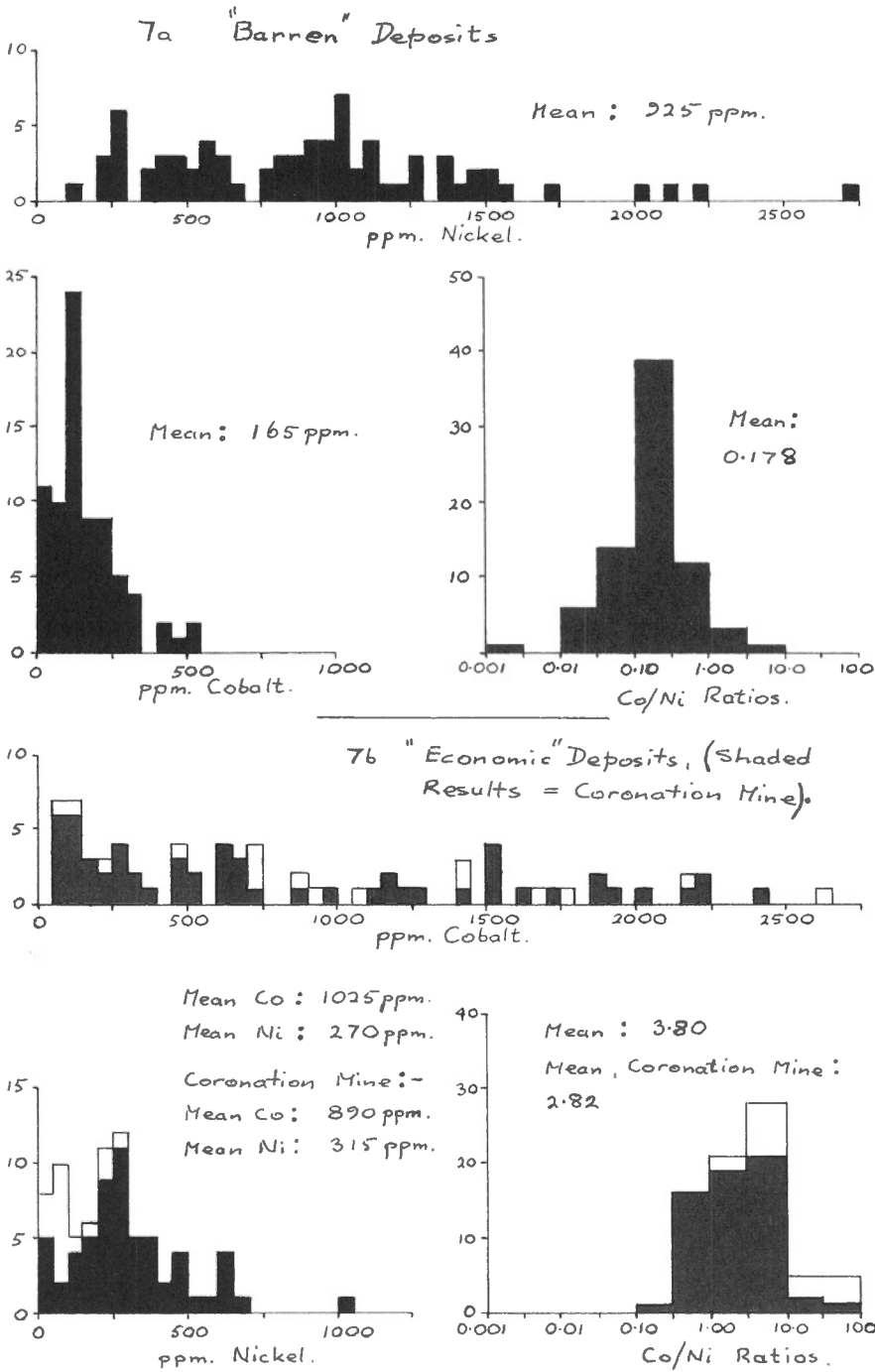


Figure 7. Histograms of results.

There are clearly some significant differences between the results from the two groups of sulphide deposits, deposits which it might be pertinent to recall were originally classified on the basis of differences in quantitative mineralogy.

The 'economic' samples with four exceptions, contain less than 700 ppm nickel, while the cobalt content varies through almost two orders of magnitude. The Co/Ni ratios are greater than 1.0 for a large majority of the samples, and except for a few samples with both low cobalt and nickel content, are greater than 0.5.

In complete contrast, samples from the 'barren' deposits show a relatively constant low cobalt content, but a widely varying nickel content. A large majority of the samples have Co/Ni ratios less than 0.5 and only four samples have Co/Ni ratios greater than 1.0.

The effects of partition between coexisting sulphides enhances the contrast between the two groups of sulphide deposits, since as previously stated, the nickel tends to concentrate in the pyrrhotite, while cobalt tends to concentrate in the pyrite. Thus, for the 'economic' deposits as a whole, there is a most marked enrichment in cobalt over nickel, despite wide variations in absolute amounts from sample to sample from any one deposit and some differences between deposits (cf. higher Co/Ni ratios for Birch Lake samples).

The 'barren' deposits show noticeable variations from deposit to deposit, although with some exceptions the analyses are within ± 25 percent of the mean value for any individual deposit.

The fact that the general pattern of the results is preserved despite variations from deposit to deposit, and in the case of 'economic' deposits especially, within any one deposit, suggests that there was a distinctive geochemical control responsible for the formation of each group of deposits.

Thus there is the very definite possibility that these two groups of sulphide deposits are in no way genetically related to each other. This possibility is further strengthened by the following considerations: If the two groups of deposits were the results of different phases of some larger process of mineralization, it would be reasonable to expect to find some transitional deposits, whose quantitative mineralogy and cobalt and nickel distribution were a compromise between those of the 'barren' and 'economic' groups (Fig. 8). Also, even if the two groups were unrelated genetically we might expect that an 'economic' deposit for example represented a replacement of earlier iron sulphides of the 'barren' kind. If this were the case we ought to find some pyrrhotite samples high in both cobalt and nickel (Fig. 8). Neither of these alternatives is supported by the data.

Origin of the 'Barren' Deposits

Geochemical Considerations

An interesting perspective of the 'barren' deposits is gained from Table 2. Here the data of Vinogradov (1962), on the major rock types have been recalculated to ratios of Fe/Co/Ni/Cu/Zn, and the ratios for an average 'barren' deposit, based on the results presented here and data reported by Faulkner (1964), are given for comparison.

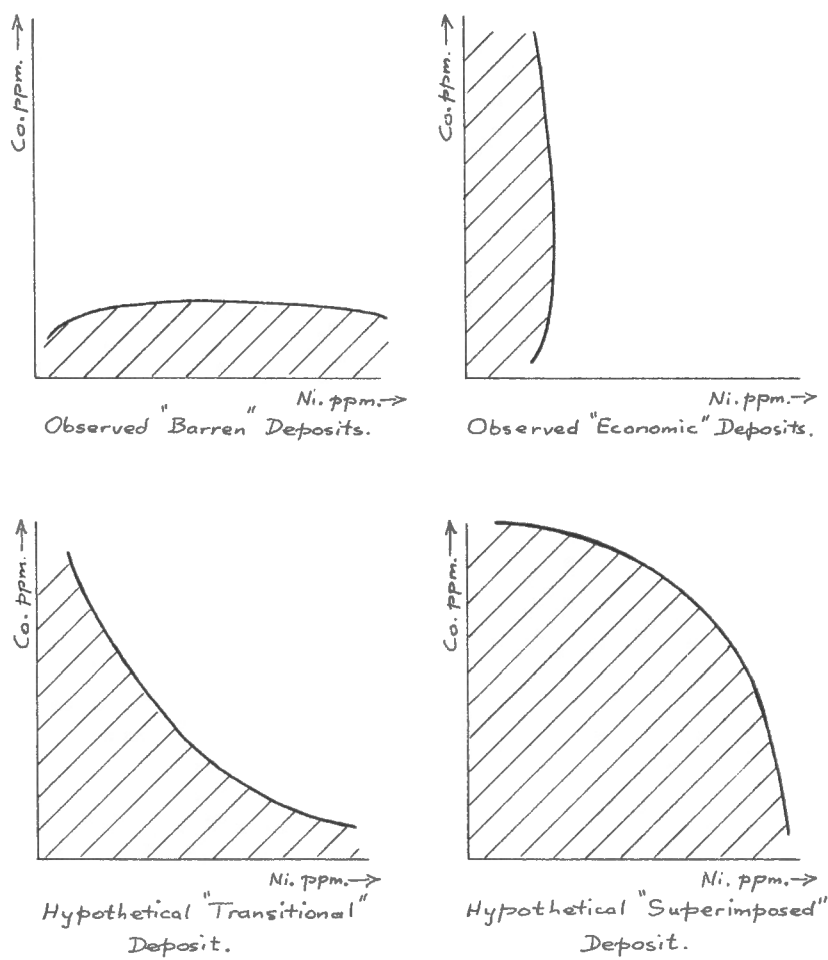


Figure 8. Schematic cobalt and nickel distributions (majority of pyrrhotite analyses expected to fall in shaded areas).

Table 2

Ratios of Elements in Average Rock Groups and
Representative Sulphide Deposits to the
Common Major Element - Iron

Rock Group or Sulphides	Fe	: 1000 Co	: 1000 Ni	: 1000 Cu	: 1000 Zn
Ultramafic Rocks	1.0	2.03	20.3	0.203	0.305
Mafic Rocks	1.0	0.526	1.87	2.34	1.52
Intermediate Rocks	1.0	0.171	0.940	0.598	1.21
Silicic Rocks	1.0	0.185	0.296	0.740	2.22
Sedimentary Rocks	1.0	0.600	2.85	1.71	2.40
Average Crust	1.0	0.387	1.25	1.72	1.78
'Barren' Deposit	1.0	0.269	1.51	3.26	3.26
Av. 'Stratigraphic Barren'	1.0	0.250	0.784	- No	Data -
'Economic' Deposit	1.0	4.88	0.332	108	21.7

There is no close parallel between the ratios for the average 'barren' deposit and for any one rock type, neither, except for the ultramafic rocks, are there any marked disparities. This is quite remarkable since the 'barren' deposits are scattered over several hundred square miles, and occur in a variety of settings and host rocks. About the same variations in Co/Ni ratios in fact, are to be found between individual deposits as occur between major rock groups. Thus it is unlikely that the Fe/Co/Ni ratios of individual deposits differ markedly from the Fe/Co/Ni ratios of the rocks in which they occur.

An important geochemical consequence of this argument is that in order to achieve any degree of areal uniformity of ratios, the iron, cobalt, nickel, copper and zinc must have been present throughout the sulphide-forming process in the chemical form in which these elements exhibit their greatest similarities, i.e. the bivalent cation. Any departure of one or more elements from this form at any stage of the sulphide-forming process would have greatly increased the chances for some relative enrichment or depletion, which would not lead to the observed ratios. Since these elements are known or believed to occur in ferromagnesian silicates and sulphide minerals as the bivalent cation, the simplest explanation of the origin of the 'barren' sulphides is that they were generated in situ.

The concentration of sulphur in the 'barren' deposits is definitely anomalous for any rock type, and must have been introduced. It is therefore proposed that the iron, cobalt, nickel, and traces of copper and zinc in the

'barren' sulphide deposits were liberated from certain permeable or structurally unstable volcanic rocks in which the deposits occur, by the action of some hydrothermal sulphur-bearing phase (using 'hydrothermal' in the broadest sense), in essentially the proportions in which they were present in the parent ferromagnesian minerals.

Genetic Implications

Having separated the 'barren' deposits from the 'economic' deposits on geochemical grounds, it is noticeable that the 'barren' deposits are closely related spatially to syntectonic granodioritic masses, and which therefore are the obvious choice for the origin of the sulphur-bearing phase. The fact that some of the mineralized shear zones are in or near the contaminated border zones of the granodiorites suggests a progressive build-up and some remobilization of sulphides as the granodiorites developed, and as more and more sulphur-bearing volatiles escaped into the host volcanic rocks. A considerable metamorphic history is therefore implicit in this process, and might well be a contributing factor to the relative uniformity of Co/Ni ratios within some deposits.

Smith (1964), has suggested on the basis of bedrock analyses, that some iron-rich rocks including 'barren' sulphide deposits in the vicinity of the granodiorites might have been enriched by copper and zinc originating from the granodiorites. It will be noted from Table 2 that the average 'barren' deposit is enriched slightly in copper and zinc compared to all the major rock groups. Although this enrichment is slight, it certainly does not detract from Smith's suggestion.

The field evidence itself, as pointed out by Byers (1960) suggested 'sulphur metasomatism' as the process responsible for the formation of the 'barren' deposits. The results for the six samples from the stratigraphic 'barren' deposits mentioned earlier, for which such a process is especially indicated, are also given in Table 2, and are fully comparable to results from other 'barren' deposits.

Experimental evidence in support of the mechanism proposed above has since been obtained in anhydrous and some hydrous systems by Kullerud and Yoder (1964).

Origin of the 'Economic' Deposits

Geochemical Considerations

The obvious feature of the results for the 'economic' deposits is the considerable enrichment of cobalt over nickel, compared to the 'barren' deposits.

For comparison purposes, the Fe/Co/Ni/Cu/Zn ratios for a typical 'economic' deposit, are given in Table 2. The ratios are based on available data for Coronation mine, and assume the sulphide phases to contain five per cent copper as chalcopyrite, one percent zinc as sphalerite, and the balance of the sulphides to consist of pyrite and pyrrhotite in the proportions of 4:1. The conservative value of 4:1 was used for the partition of cobalt between pyrite and pyrrhotite. Considerable variation in abundances of sulphides and

partition ratios would be possible to suit other 'economic' deposits, without altering the significance of the calculations.

Relative to nickel and iron, the 'economic' deposits are obviously enriched in cobalt, copper and zinc, compared to the 'barren' deposits and the averages for the major rock groups.

If it is assumed that the 'economic' deposits are related genetically in some as yet unspecified way to any of the rock types exposed in the Coronation mine-Flin Flon area, then whatever the actual mechanism of formation, cobalt, copper and zinc must have participated in some different and highly preferred form, in order to account for the extent of their enrichment.

We must now look for a major contrast in the chemistry of cobalt and nickel, rather than a similarity, as was the case for the 'barren' deposits. It is well known that cobalt and nickel show their greatest differences in the formation of complex ions. Since only a very few inorganic ligands are geologically tenable this virtually restricts consideration to the formation of anionic complexes, and dictates an aqueous environment. In geological terms this means a hydrothermal environment.

The possible role of complex ions in the formation of hydrothermal ore deposits has been the subject of much recent literature, which it is not pertinent to review in detail here.

The available data has been capably and critically reviewed by Helgeson (1964). He concludes that the evidence strongly favours anionic chloro-complexes, and shows by extrapolations of available data to likely temperatures and pressures of ore deposition, that such complexes and in quantities sufficient for the purposes of metal transport and deposition.

For the 'economic' deposits the important point is that cobalt is known to form stable anionic chloro-complexes in a wide variety of chloride-bearing media (Bjerrum, Schwarzenbach and Sillén, 1958; Kraus and Nelson, 1956), while the existence of corresponding nickel complexes is questionable. Copper and zinc are also known to form stable anionic chloro-complexes, and at least at room temperatures, the chloro-complexes of ferrous iron are stable only at very high chloride concentrations (Kraus and Nelson, 1956; Kraus and Moore, 1953). Thus a possible chemical environment for the selective enrichment of cobalt, copper and zinc over nickel and iron, starting from material with normal distributions of these elements, can be established.

The sulphur in the 'economic' deposits, as in the 'barren' deposits, represents an anomalous enrichment, and it must likewise have been introduced with the heavy metals, or come from another source. It is a curious fact that while considerable support for the existence of metal chloro-complexes in natural hydrothermal solutions has been forthcoming (for example see White, Anderson and Grubbs, 1963, and Czamanske, Roedder and Burns, 1963) very little evidence for the presence of sulphur in any form in these natural solutions has been found. The general lack of sulphur compounds in the chloride-rich solutions found in fluid inclusions in gangue minerals associated with sulphide deposits for example is a well-known fact. Experimental work has as yet to establish the conditions, if any, under which the large quantities of sulphur represented by the average base-metal sulphide deposit could also be transported stably with metal chloro-complexes. This has led many workers recently to support ideas that the sulphur may have originated from another source, and that sulphides may result from the mixing

of hydrothermal solutions or groundwaters circulating at depth (Lovering, 1961, and oral communications). This problem will be considered in relation to the field evidence in due course.

Variations of Results within Coronation mine

Variations of trace element content in a deposit undoubtedly reflect the effects of temperature or concentration gradients and other variables, and may be of value in genetic speculations. The data for Coronation mine given in Figures 4, 5 and 6 suggest that there may be significant variations within the deposit. However, if such factors as partition, the mineral assemblages of individual samples, the sample locations in relation to the width of the orebody, and the already demonstrated variability of cobalt and nickel ppm over even small distances are considered, then delineation or interpretation of possible trends is much less certain. For example, the highest and lowest cobalt analyses were given by two samples from the same stope, not 100 feet apart.

A careful consideration of the data in the light of the above factors has been made, and the only trend that is considered definite and significant is the generally higher trace element content of samples from the southern section.

Nearly half of the southern section samples have cobalt concentrations exceeding 1000 ppm, contrasted with only one from the northern section for example. A similar but much less obvious trend is shown by the nickel data, and the Co/Ni ratios therefore show less variation than might otherwise be the case. The samples with high cobalt content mostly come from areas where the sulphides are disseminated, and where the wallrock alteration is particularly coarse and skarn-like.

A qualitative and necessarily somewhat subjective conclusion is that the more massive sulphides, especially those sulphides which have been 'remobilized' into the later vein openings, and the non-commercial portions of the deposit, tend to have lower cobalt and lower Co/Ni ratios.

No variations with width of the ore zone, or between hangingwall and footwall, or with depth can be substantiated. The preponderance of high cobalt results in the lower levels of the southern section, reflects only a relative ease of access, and consequently a large number of samples were taken from this area.

It might seem that despite the statistically haphazard distribution of samples, imposed by limitations of access, that trend-surface analysis of the data would be worthwhile. The objection to this is that the width of the orebody is relatively large compared to the depth and length. Thus the location of the sample across the ore zone represents a third variable which cannot properly be ignored nor compensated for, without prejudicing the validity of any results obtained.

Genetic Implications

An environment which leads to the concentration of base metals as chloro-complexes could arise in several ways. The two thought more likely are:

1. Differentiation of a magma to yield a chloride-rich hydrothermal residue into which cobalt, copper and zinc would partition preferentially as chloro-complexes.

2. Selective leaching of rocks by a chloride-rich hydrothermal solution, or deep-seated groundwater.

In either case, iron or nickel would partition as the normal cation, and would not therefore be enriched. In the first case sulphur, being a normal volatile residue, would initially be present with the chloro-complexes in some compatible form. In the second case, the sulphur is introduced from some other igneous source, and the mixing process results in the precipitation of sulphides.

Both possibilities can be supported on the basis of the field evidence.

For the first case, a mafic parental material is the logical choice, if only for the fact that it would naturally contain a greater concentration of the desired elements, and would therefore place the least demands on the formational environment, for a given quantity of base metals.

Further the mineralization which can be definitely linked with the silicic intrusions of the area (the syntectonic granodiorites) is the 'barren' kind, and there is no evidence for any genetic relationship between the 'barren' and 'economic' mineralizations.

Coronation mine exemplifies this position in that a syntectonic granodiorite outcrops within a quarter of a mile of the mine, and the mine shear zone presumably intersects the granodiorite at depth. Until quite recently, this would have been sufficient of itself to explain the genesis of the sulphides. However, the mine shear zone does not appear related to the marginal shearing characteristic of the emplacement of the granodiorites. There is no known connecting or intervening mineralization, nor minor intrusions, nor progressive changes in metamorphism for example, which suggest any possible connection. There is nothing underground in fact which would suggest the presence of this intrusion so near, were it not known from surface outcrops.

Similar arguments can be made for the other 'economic' deposits.

This is not the case for mafic intrusions however. At Coronation mine, in addition to several minor mafic intrusions actually in the ore zone, there is an extensive dioritic mass exposed on the 1,350-foot level, and a possible dioritic stock is exposed within about 450 feet of the service shaft. Several sill-like bodies of diorite have been intersected by the extensive hangingwall diamond-drill holes (Whitmore, oral communication), and there are a few post-ore diabase dykes. The service shaft intrusion mentioned above contains accessory chalcopyrite.

A much closer structural, spatial and potentially genetic relationship to mafic intrusions is shown by the 'economic' deposits of the Flin Flon area proper.

Byers (1963), has clearly demonstrated the very close association of these deposits to the late-age, Ross Lake fault system. Also closely related to this fault system, are the Boundary Intrusions. These rather variable and altered, but generally mafic intrusions both cut and are cut by, faults of the Ross Lake system.

This relationship clearly places a late age upon the sulphide deposition, if faults, intrusions and sulphides are all genetically and structurally related. If not, one must assume that the sulphides were of an earlier age

and were extensively remobilized at the time of the faulting, and that the intimate proximity with the Boundary Intrusions is coincidental.

It is interesting that two conditions which many geologists consider necessary for the formation of a major vein-sulphide deposit, are also requirements for current groundwater-mixing theories of sulphide formation.

The first is the proximity of a large regional fault structure. The second is the presence of intrusive igneous activity. From the point of view of groundwater mixing, the large regional structure has the depth and persistence to tap deep-seated chloride-rich groundwaters, which drilling has indicated can carry heavy metals. It also allows their movement along the structure to an area where igneous intrusive activity provides a groundwater or hydrothermal source of sulphur to precipitate the metals as sulphides. The two conditions are satisfied for the Flin Flon 'economic' deposits proper in that the Ross Lake fault system is itself part of an extensive regional fault system, and the late-age Boundary Intrusions are the potential source of the sulphur.

To fit such a relationship to the deposits of the Coronation mine-Birch Lake area is more difficult.

The key problem with the Coronation mine deposit at least, rests with the age of the mineralization. The possible structural connection to the Ross Lake fault system is good; the mine shear zone persists for a distance of at least two miles, and if not directly connected to the main Ross Lake fault system, it has the sense and direction of movement characteristic of such faults. A possible igneous connection with the Boundary Intrusions is tenuous; the nearest known outcrop is five miles from the mine. But Coronation mine and the Birch Lake deposits are small compared to the deposits in the Flin Flon area, which one might expect if they were removed from the main scene of structural and igneous activity. However the majority of workers would consider the mafic intrusions present in the vicinity of Coronation mine as pre-dating the Ross Lake fault system.

A minority view has been expressed by Byers, who had earlier regarded the age of the mafic and ultramafic intrusions of this area as older than the syntectonic granodiorites (Byers and Dahlstrom, 1954). He now feels (Byers, Kirkland and Pearson, 1965) that certain of these mafic intrusions, especially some post-ore dykes, might be related to the Boundary Intrusions.

The geochemical data and reasoning presented earlier for the economic deposits are consistent with two current theories of sulphide genesis, but give no direct information as to the age of any mineralization so formed. This must be ascertained from other evidence, which in the Flin Flon area is consistent with a late age of deposition, but for the Coronation mine deposit, is in dispute, with the likely mafic intrusive sources predating the likely structural age.

As stated earlier, the evidence indicates that the Coronation mine sulphides have had a metamorphic history. However, any sulphide deposit of Precambrian age, formed in the orogenic environment indicated by the present surface exposures would have. The question is how much?

The 'remobilized' massive sulphides in the Coronation mine deposit are free of the lineations and foliations which characterize much of the earlier sulphides. Much of the massive sulphides seen at the Schist Lake deposit was also free of such structural and presumably metamorphic features. The 'remobilization' at Coronation mine could therefore have taken place at the

same time as the deposition in the Flin Flon area proper, and at the time of movement on the Ross Lake fault system. The original deposition at Coronation mine could then have occurred during an earlier period of movement on the Ross Lake fault system if, as Byers believes, there are some Boundary type intrusions present in the vicinity. Otherwise, the deposition would have to be related to an earlier period of mafic intrusion and an earlier structure. Then the later shearing would have to have followed exactly the original shear zone, to account for the period of remobilization.

The former argument involves fewer assumptions, and is therefore to be preferred. Personally, I feel that it is significant enough that there is evidence of late-age mafic intrusions in the Coronation mine area, at least in the form of post-ore dykes. Whether or not they are Boundary Intrusions is immaterial to the geochemical reasoning.

Conclusions

1. A sharp contrast exists between the cobalt and nickel distributions in pyrrhotites from the 'barren' and 'economic' deposits which strongly suggests that the two groups of sulphide deposits are in no way genetically related to each other. Any theory of genesis of these deposits must recognize and explain this contrast.

2. The 'barren' sulphide deposits originated by 'sulphurization' or sulphur metasomatism of ferromagnesian minerals in certain permeable and structurally unstable wallrock zones. The sulphur probably originated from the syntectonic granodiorites of the area, and the trace contents of copper and zinc in these deposits originated from the parent ferromagnesian minerals.

3. The pattern of cobalt and base-metal enrichment in the 'economic' deposits suggests the metals were concentrated as chloro-complexes in a hydrothermal chloride-bearing medium.

4. Two current theories of sulphide genesis which involve the agency of chloro-complexes are considered in detail, i-(mafic) magmatic differentiation, ii-selective leaching by chloride-rich groundwaters followed by precipitation of sulphides due to groundwater mixing.

5. The field evidence is consistent with a late age and a genetic connection with the Ross Lake fault system and the Boundary Intrusions, on either theory, for the 'economic' deposits of the Flin Flon area proper.

6. A similar late origin is preferred for the Coronation mine deposit, despite the difficulties in establishing the age of the mineralization and likely mafic sources of metals and/or sulphur.

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No. 8 A PROPOSED ORE CONTROL AT THE
CORONATION MINE, SASKATCHEWAN

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ABSTRACT

Mineralogical cross sections of orebodies on the 300-, 600- and 900-foot levels of the Coronation mine have been interpreted in terms of centers of mineralization. The maximum concentration of chalcopyrite occurs closest to these centers, with pyrite and pyrrhotite concentrated some distance away. The magnetite concentrations are farthest removed from the centers.

A hydrous halide fluid model is established. Attempts to explain the observed mineralogy by the action of temperature gradients on the fluid model were unsuccessful. Likewise, the action of diffusion alone on the fluid model cannot explain the observed mineral distribution. The concept of attenuation is introduced - i.e., the rate of diffusion of a particle species is related to the product $r^2\sqrt{M}$, the attenuation coefficient, where r is the particle radius and M its molecular weight. Attenuation, acting on the fluid model alone, will not produce the observed mineral distribution, but, when considered together with the action of temperature gradients, the observed mineralogy can be well explained by the combined effects of these two processes on the assumed fluid model.

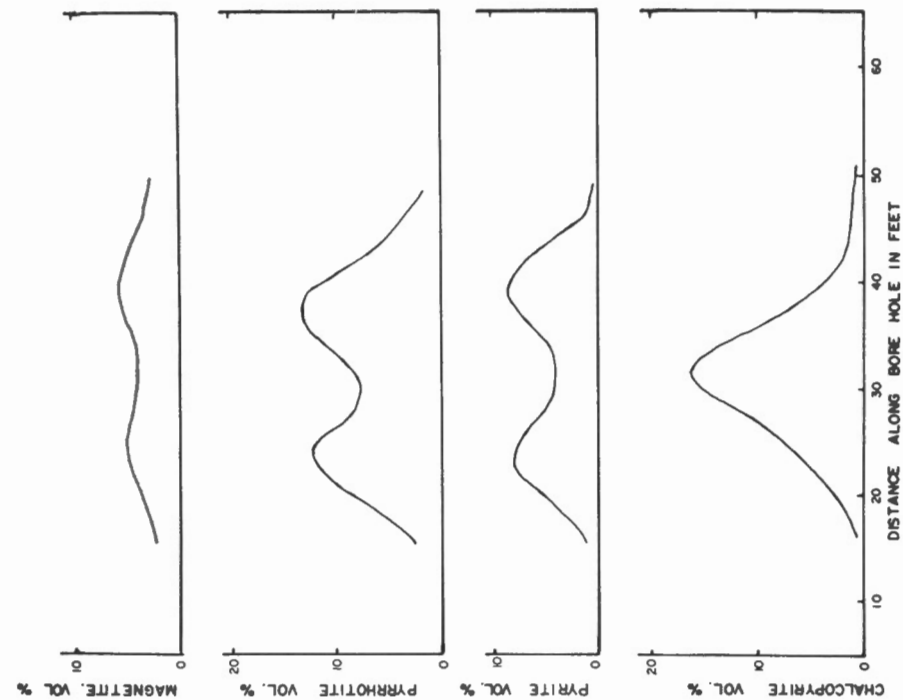


Figure 1. Typical Mineralogical Cross Section Through Narrow Orebodies.

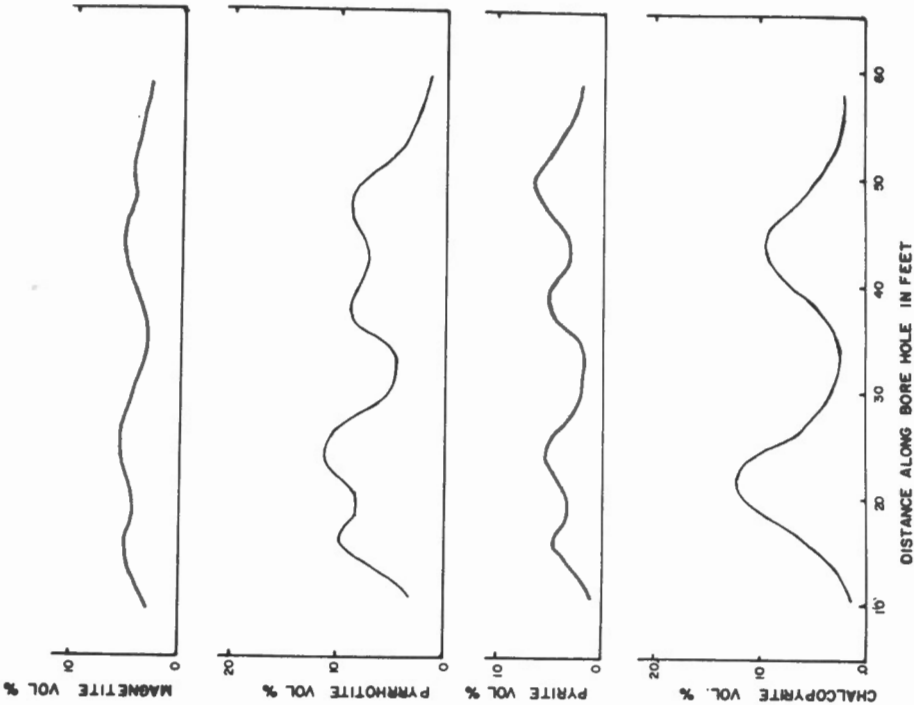


Figure 2. Typical Mineralogical Cross Section Through Wide Orebodies.

Introduction

This study is part of a comprehensive investigation, being carried out under the auspices of the Geological Survey of Canada, into the general geology, geophysics and origin of the Coronation mine orebody, located some 14 miles southwest of Flin Flon, Manitoba. A total of 194 specimens from twenty-two diamond drill holes on the 300-, 600- and 900-foot levels were examined using a Swift automatic point counter and reflecting microscope. This paper proposes a possible ore control based on an examination of the quantitative mineralogy.

Qualitative Mineralogy

Ferris (1961) has described the qualitative mineralogy and paragenesis of the Coronation mine; only a short account is given here. The ore minerals present are chalcopyrite, pyrite, pyrrhotite, magnetite and a very small amount of sphalerite. (The term "ore mineral" is used here as defined by Bateman, 1959; i.e. "... one that may be used to obtain one or more metals.").

The amount of sphalerite is very small and could not be determined quantitatively from the number of grains counted. Trace amounts of opaque oxides other than magnetite were not counted separately, but were included in the magnetite total. Some specimens were stained with hematite before crushing. Hematite was not observed in the sections, confirming the view that it is very minor. The non-opaque minerals have not been differentiated and are simply classified as "silicates."

The original textures may have been modified by later metamorphism (Froese and Whitmore, 1964), and therefore the present textures are unreliable guides to the initial mineralization.

Quantitative Mineralogy

Because of lack of space, all the mineralogical cross sections cannot be shown. Figures 1 and 2 show idealized sections across typical orebodies. The abscissa of each graph represents the location of each sample in the drill hole, and the ordinate represents the concentration of each ore mineral in volume percentage. The curves are derived from the individual point counts by a moving average method. There are, of course, considerable variations from these ideal cross sections, but the general trends are present in all the boreholes.

The concentration of ore minerals in all boreholes decreases toward the margins of the orebodies. Significant patterns of mineral distribution occur. The occurrence of each mineral will now be considered in turn.

Chalcopyrite

In boreholes cutting narrow orebodies, the chalcopyrite concentration curve has a single peak near the center of the orebody (see Figure 1). For holes cutting wider orebodies (Figure 2), the chalcopyrite concentration

has a double peak. For many boreholes with double chalcopyrite peaks, the orebody at that place is, or may be inferred to be, a composite body, made up of two intersecting orebodies. Because of this, each chalcopyrite peak is interpreted as representing a focus of mineralization.

The regular variation in the concentrations of the other minerals is not as obvious as that of chalcopyrite. However, when referred to the foci of mineralization inferred from the chalcopyrite distribution, the distributions of the other minerals appear to conform to regular patterns.

Pyrite

The concentration of pyrite tends to form a double peak around each mineralization focus. The peaks are not necessarily symmetrical, and the central low concentration does not, in general, coincide with the chalcopyrite peak.

Pyrrhotite

The concentration of pyrrhotite tends to vary in much the same way as that of pyrite. The mineral concentration peaks of pyrite and pyrrhotite occur so close together that it is impossible to determine whether one occurs farther away from the mineralization foci than the other.

Magnetite

The concentration of magnetite fluctuates erratically. The concentration is sufficiently high (up to 10 per cent) to eliminate a pre-mineralization origin for the magnetite distribution. In several boreholes, magnetite tends to form double peaks similar to those of pyrite and pyrrhotite, although the peaks are much less pronounced. The origin of the magnetite is doubtless similar to that of the other minerals. The highest magnetite concentration seems to be a little farther away from the mineralization foci than the highest concentrations of pyrite and pyrrhotite, but this may be only apparent.

The concentration peaks of the minerals are, in order, from left to right, of increasing distance from the mineralization foci as follows:

Chalcopyrite

Pyrite
Pyrrhotite

Magnetite

Temperatures of Mineral Formation

Arnold (1964) determined the temperature and pressure conditions during the crystallization of the ore minerals, and found only small temperature variations. His values, based on the pyrrhotite-pyrite and sphalerite geothermometers, are $497 \pm 5^\circ\text{C}$ and $1,760 \pm 680$ atm.

However, Froese and Whitmore (1964) showed that the orebodies have been metamorphosed subsequent to their emplacement, and therefore

Arnold's results will refer to later recrystallization rather than to the initial period of mineralization.

The foci of mineralization, as inferred from the mineral distribution, suggests the existence of temperature gradients at the time the orebodies formed, with the highest temperatures at the mineralization foci (i.e., the chalcopyrite peaks).

It is likely that the temperatures and pressures during this initial mineralization were at least as high as those measured by Arnold.

Genesis of the Orebodies

The shapes of the cross-sectional plots show that the intensity of mineralization generally decreases away from centers where shearing has occurred. Therefore, a discussion of the genesis may be confined to magmatic and metamorphic processes. The observed mineral distribution and general geology are strongly opposed to the formation of the deposits by early magmatic differentiation. However, subsequent injection of a previously segregated sulphide liquid is possible.

It appears that the processes most likely to have produced the orebodies are hydrothermal activity, injection of a sulphide melt, or metamorphic differentiation. Independent evidence is inconclusive. The close association of the ore with shear zones strongly suggests that these zones have acted as channels supplying heat, or material, or both. A granodiorite batholith lying about 1/2 mile east of the mine (E.L. Faulkner, 1964, personal communication) may have been the source of heat and/or fluids. Wall-rock alteration of the "skarn" type occurs in the southern ore zones, but is not extensive in the northern deposits (E.L. Faulkner, 1964, op. cit.).

Although by no means conclusive, this evidence does suggest a hydrothermal origin for the deposits.

The following discussion will be based on the assumption that the orebodies were formed from fluids flowing along feeder channels and penetrating the country rock. The fluid from which the orebodies crystallized could have had any composition from that of an essentially anhydrous melt to a hydrothermal fluid, where water is the dominant constituent. The nearby granodiorite batholith could have exuded hydrothermal fluids, but sulphide melts are more likely to be associated with more basic intrusions which have not been observed near the Coronation mine. Wall-rock alteration, usually considered as evidence of hydrothermal activity (Bateman, 1959, p. 103), does occur (E.L. Faulkner, 1964, op. cit.), but is not so great as to eliminate the possibility of a sulphide melt. The temperatures indicated, ca. 500°C, are more typical of hydrothermal conditions than of sulphide liquids, as the temperatures of the latter are considered to be higher [c.f., Lindgren's (1933) classification of mineral deposits].

The possible controls of mineral deposition in a deposit of this type are (1) the chemical composition of the fluid, (2) the temperature gradients across the orebodies and (3) the method of penetration of the country rock.

The approach used here has been to create a model representing the composition of the fluid, based on general geochemical principles, and then to determine whether the observed mineralogical distribution can be derived through the action of various physico-chemical mechanisms on the fluid

model. If a mechanism can be found that will produce a mineralogical distribution similar to that in the Coronation mine, such a process may well have been the ore-control mechanism, if the assumed model was reasonably correct.

Fluid Model

The following discussion considers only aqueous fluids, although, in general, the same principles apply to sulphide melts.

Data on the character of the ore-forming fluid have been gathered from (a) observations on ore deposits, (b) the sampling of emissions from fumaroles and volcanic vents, and (c) theoretical studies. The acid or alkaline nature of the mineralizing fluid is controversial (Graton, 1940, and Discussion), but direct observations have demonstrated the existence of such molecules as HCl, HF, H₂S and other volatiles, together with metals such as Fe, Sn, Pb, Cu and Zn, in the emissions from fumaroles (c.f., Bateman, 1959).

Assuming a hydrothermal origin, the properties of the fluid model may be proposed.

- (1) It is tentatively assumed that the fluid which produced the orebodies consisted largely of water, H₂S and HCl, and comparatively minor quantities of iron, copper and zinc in ionic form, the ionic balance being maintained largely by halide ions, of which the greater part was chloride.*
- (2) The amount of sphalerite in the mine is not large enough to treat, even on a semi-quantitative basis; hence, it will not be considered here.
- (3) Small amounts of Cl₂, H₂, O₂, etc., must also be present, as required by the Law of Mass Action. For example, for HCl,



In this case, the equilibrium constant K is given by

$$\log_{10} K = 22.9792 \text{ at } 25^\circ \text{C}$$

where

$$K = \frac{(\text{HCl})}{(\text{H}_2)^{1/2} (\text{Cl}_2)^{1/2}}, \quad \text{represents the degree of dissociation of HCl}$$

Thus, the concentrations of H₂ and Cl₂ will be extremely small, but nevertheless finite.

- (4) It is assumed that by the time the fluid reached the position of the orebodies it was already saturated with respect to all the ore minerals.
- (5) It is assumed that only mineral deposition has taken place. The occurrence of the orebodies in shear zones indicates that openings in the rock acting as channelways, and therefore presumably filled with fluid, were operative in the formation of the orebody, and therefore substantial non-replacive mineral deposition may have occurred. Dilation of the rock

* It is relevant to note that, on independent evidence, E.L. Faulkner (1963) suggested a halide hydrothermal origin for the Coronation orebodies.

could have occurred, but evidence is lacking. It is relevant to note that Butler (1932) and Schwartz (1959) consider that, during wall-rock alteration, the later-formed minerals depend essentially on the fluid composition. It seems probable, therefore, that relatively small errors will result from considering the process as pure deposition.

It is appropriate at this point to consider the physical condition of the "fluid." There is much discussion in the literature as to whether the fluids leaving a nearly crystallized pluton are liquid or gaseous. Here, the term "fluid" is used without prejudice as to the actual physical condition of the fluid, and it will be assumed that chemical reactions will follow their normal courses, subject to modification by temperature and pressure in either liquid or gas, and that physical processes such as diffusion will not be modified by the state of the fluid. Thus, the fluid model proposed is -

A hydrous halide hydrothermal solution containing copper and iron, existing at temperatures of approximately 500°C, and moderate pressures, moving through channels in shear zones, and depositing ore minerals in the cavities in these shear zones.

Temperature as a Control of Ore Deposition

Based on the assumptions made in the previous section, the formation of minerals from the fluid may be represented by the following set of equations:

For pyrrhotite:



For pyrite:



For magnetite:



For chalcopyrite:



The reaction for magnetite and pyrite could have been written in other ways, bringing in H_2 or O_2 instead of Cl_2 . The choice of Cl_2 is not arbitrary, but is made because the concentration of chlorine is likely to be higher than the concentration of either hydrogen or oxygen, as HCl at high temperatures dissociates to a greater extent than does water. Hence, Cl_2 will exert the limiting condition on the solubilities of these minerals. To determine the solubilities of the minerals, the equilibrium constants, K_1 to K_4 , for equations 1-4 above are required.

* Equation 4 should be written

$\text{CuCl}_2 + \text{FeCl}_2 + 2\text{H}_2\text{S} \rightleftharpoons \text{CuS} + \text{FeS} + 4\text{HCl} + \Delta\text{H}_5$ but data are not available for the heat of formation of chalcopyrite. However, the heat of reaction of $\text{CuS} + \text{FeS} \rightarrow \text{CuFeS}_2$ is probably negligible compared with ΔH_4 in this equation, and values of K and ΔH for chalcopyrite will be only slightly affected.

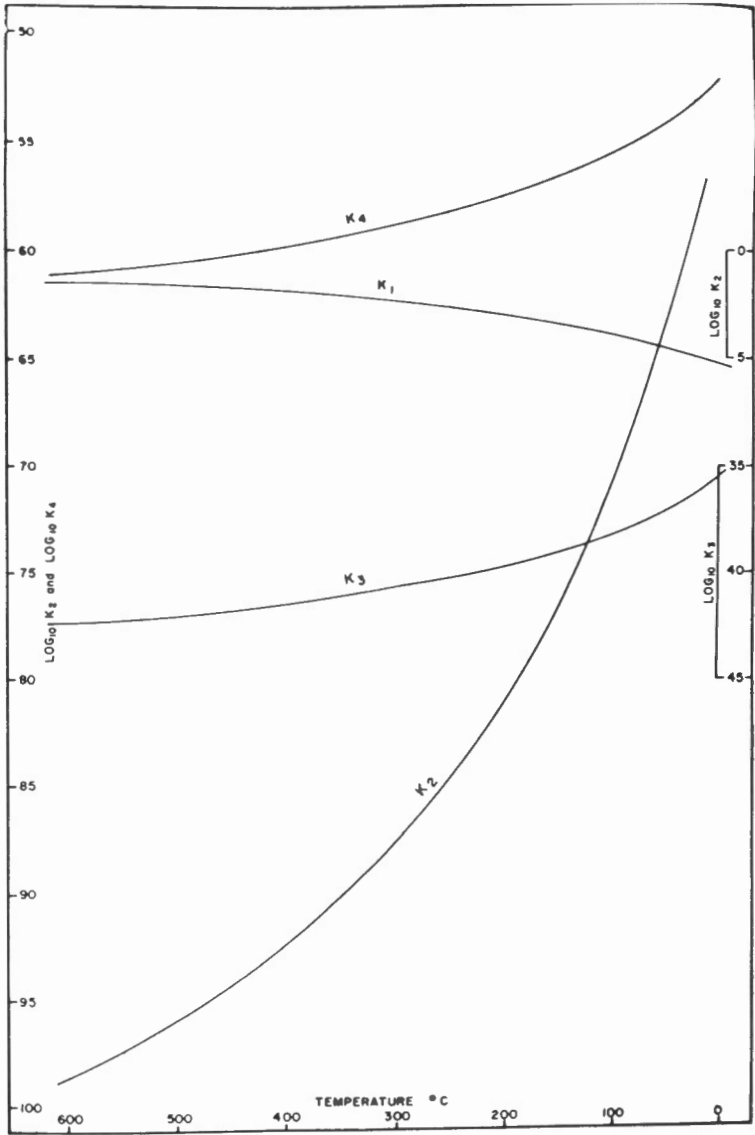


Figure 3. Variations of Equilibrium Constants, K₁-K₄, with Temperature.

The equilibrium constants for the reactions may be written:

$$K_1 = \frac{(\text{FeS}) (\text{HCl})^2}{(\text{FeCl}_2) (\text{H}_2\text{S})} \dots\dots\dots (5)$$

$$K_2 = \frac{(\text{FeS}_2) (\text{HCl})^4}{(\text{H}_2\text{S})^2 (\text{Cl}_2) (\text{FeCl}_2)} \dots\dots\dots (6)$$

$$K_3 = \frac{(\text{Fe}_3\text{O}_4) (\text{HCl})^8}{(\text{H}_2\text{O})^4 (\text{Cl}_2) (\text{FeCl}_2)^3} \dots\dots\dots (7)$$

$$K_4 = \frac{(\text{CuFeS}_2) (\text{HCl})^4}{(\text{CuCl}_2) (\text{FeCl}_2) (\text{H}_2\text{S})^2} \dots\dots\dots (8)$$

where (FeCl_2) , etc., are the concentrations (strictly, the activities) of the components.

From known heats of formation and equilibrium constants for various substances, and by applying the van't Hoff isochore, it is possible to derive the equilibrium constants for the various reactions at any temperature, assuming that the heat of formation does not vary significantly with temperature.

The variations in equilibrium constants with temperature are shown in Figure 3. It is immediately apparent from the figure that large changes of K result from comparatively small changes of temperature, particularly in the case of pyrite. For all minerals except pyrrhotite, K rises with decreasing temperature; i. e., more mineralization occurs at lower temperatures.

The problem now becomes one of interpreting the mineralogical distribution in the orebodies in terms of this temperature solubility data. It was postulated earlier that temperature gradients may have existed across the orebodies, with the highest temperatures having occurred at or near the chalcopyrite peaks. Let us examine the mineral distribution which would result from the action of such a temperature gradient on the fluid model. The temperature will be highest at the channel center. Farther from the channel the temperature decreases. Figure 3 shows that for chalcopyrite, pyrite and magnetite, K rises with decreasing temperature; i. e., more mineral should deposit as the temperature decreases. Therefore, the rock concentrations of these three minerals should rise farther away from the channel. For pyrrhotite, the opposite condition occurs, and its concentration should decrease away from the channel. The concentrations of pyrite, magnetite and chalcopyrite would not continue to rise indefinitely, as it is likely that the fluids did not extend beyond the present orebody limits, and, in any event, the available material in solution will quickly become exhausted. There should, therefore, be two optimum points for maximum deposition of pyrite, magnetite and chalcopyrite removed from the channel center, and a single maximum concentration for pyrrhotite at the channel center.

When this expected distribution is compared with the observed mineralogy it is evident that they do not agree. Whereas the concentration curves of pyrite and magnetite do show a double peak away from the channel center, that of chalcopyrite has only a single, central peak, and the concentration curve of pyrrhotite, instead of having a single, central peak, has a double peak similar to pyrite. It is apparent that the observed mineralogy cannot be explained on the basis of temperature changes alone acting on the model, although temperature may have played an important role.

Mode of Penetration of Country Rock as a Control of Ore Deposition

Material may penetrate a rock mass in two essentially different ways - flow and diffusion.

Pure flow of fluid involves the transfer of fluid in bulk, the composition of the fluid remaining uniform. The rock mass would be saturated with the fluid, and the dominant direction of flow would be parallel to that in the main channel. This situation would occur where a broad shear zone existed - more permeable at the center and less permeable away from the center, but still sufficiently permeable to allow bulk flow of fluid. Fluid in the outer parts of the orebody would continually exchange with fluid on the inside. As the shear zone is more permeable along the main channel, fresh hot fluid would reach the central zone more readily than it would reach the more remote parts of the orebody. The wall rocks will then act as a heat-sink, and therefore there will be a temperature gradient outward from the feeder channel. It is this variation in temperature to which any mineralogical variations will refer. The effects of temperature variations have been discussed in the previous section, and will not be considered further.

The other method of transfer of material is diffusion, where ions and molecules migrate through an immobile fluid, or rock mass, under the influence of temperature or compositional gradients.

Although the two processes are fundamentally different, bulk transfer of material grades into transfer by diffusion. Holser (1947) considers that metasomatic processes may be classified on the basis of the size of openings in the rock - (1) supercapillary (2) capillary (3) grain boundary and (4) intralattice. He considers that flow through supercapillary openings is probably the mechanism by which large quantities of replacing material may reach the replacing front. This corresponds to the massive flow described above. Capillary openings will still permit the movement of fluids, although the pattern of flow will be modified by capillary action.

Diffusion experiments by Duffell (1937) showed that the metallic ions of the solute lagged behind the solvent. Duffell postulated four causes for the lagging of the solute; a difference in rate of migration of acidic and basic portions of the solution, chemical reaction with the walls, absorption on the walls, and filtration by the rock. Results obtained by Mackay (1946) and Ovchinnikov (1960) indicate that filtration by the rock may play a considerable part in affecting the rates of migration of ions and other particles. Both Mackay and Ovchinnikov consider the dominant control of penetrability to be the size of the hydrated ion. The size of opening envisaged by Ovchinnikov and Mackay is more comparable with the "grain boundary" and "intralattice" types of opening of Holser. However, a capillary or sub-capillary opening could produce a similar effect, although the degree of ionic separation would be expected to be less perfect, as fluid flow, although restricted, is still possible through this type of opening.

Diffusion as a Mineralization Control

The observed mineral distribution will now be compared with the distribution to be expected if diffusion, as described above, had been the main

Table I—Hydrated Ionic Radii

[From Ovchinnikov (1960) and Szadecky-Kardoss (1958)]

Hydrated Ion	Ionic Radius (Angstroms)	
	Ovchinnikov	Szadecky-Kardoss
S=	—	2.8
O=	—	3.1
Zn ²⁺	3.4	3.5
Cu ²⁺	3.35	3.5
Fe ²⁺	3.5	3.5
Fe ³⁺	3.9	4.3

control of mineralization at the Coronation mine. The controlling factor should be the size of the ionic species forming the minerals.

Temperature gradients will also occur in this type of fluid transfer; in this section, however, the effect of temperature is not considered.

If the fluid which deposited the ore minerals was predominantly aqueous, it is possible that some, if not all, of the ions were hydrated. Values for the hydrated ionic radii of various elements are taken from Ovchinnikov (1960) and Szadecky-Kardoss (1958), quoted in Ovchinnikov, and are given in Table I.

Although differences in size are small, Cu²⁺ is definitely smaller than Fe³⁺, and S⁼ is smaller than O⁼. If the size of the hydrated ion is the factor controlling the penetrability of a given metal, as considered by Ovchinnikov and Mackay, then chalcopyrite should occur at least as far away from the channel as magnetite. In fact, however, it does not.

If the metals occurred as simple ions, the distribution should depend on the sizes of the nonhydrated metal ions.

Values of ionic radii, as taken from Mason (1958), are given below:

Cu ¹⁺	0.96 Å
Cu ²⁺	0.72 Å
Fe ²⁺	0.74 Å
Fe ³⁺	0.64 Å

Thus, ferric iron should travel the greatest distance, and copper the least distance, especially if copper occurs as the monovalent ion. At first sight, this agrees very well with the observed mineral distribution; i.e., with, from left to right, increasing distance from the channel center:

Chalcopyrite Iron sulphides Magnetite

On further consideration, however, it appears that, theoretically, the concentration of all the minerals should decrease with increasing distance from the channel. The ferric iron should travel farthest and, therefore, the slope of the magnetite concentration should be the least steep. The copper ion should travel the least distance and, therefore, its concentration gradient should be the steepest. However, the concentrations of iron sulphides and magnetite rise to a peak at some distance from the channel center, and then decrease. This should not occur if the mechanism is as proposed in this latter hypothesis.

It appears, therefore, that the size of the ions, hydrated or otherwise, cannot be the only, or even the dominant, control of deposition. It remains possible, however, that the minerals have been transported as ions, hydrated or otherwise, if a process other than that considered above has been responsible for the deposition.

Attenuation and its Effect on Ore Deposition

In this section, the concept of diffusion as presented by Mackay (1946) and Ovchinnikov (1960) is re-examined. Although filtration undoubtedly can give rise to fluid inhomogeneity, other factors are probably operative as well.

(1) - Graham's Law states that the rate of gaseous diffusion through an orifice is a function of the inverse square root of the molecular weight of the gas; this effect is expressed by a separation of ionic species of different molecular weights during diffusion, without regard to any filtrating mechanism. It is this effect which is utilized in the large-scale separation of uranium isotopes by gaseous diffusion.

(2) - Mackay and Ovchinnikov (ibid) have considered only the filtrating action of rock masses. Under sufficiently high pressures in rock openings containing fluid, the molecules of solvent will be very close together. Such closeness could very well obstruct the passage of solute particles, and give rise to a filtrating effect without the presence of a rock mass containing "ultrapores." During filtration, it is likely that the control of penetrability will be the cross-sectional area of the particle rather than its radius; that is, the penetrability will depend inversely on the product r^2/M , where r is the particle radius and M the weight of the particle.

The expression r^2/M is here termed the "attenuation coefficient," A . It is a measure of the effects due to both filtration and Graham's Law. A very approximate chemical derivation, given in the Appendix, supports the validity of the function r^2/M as a control of penetrability and gives the expression for the partial pressures or concentrations of the various particle species as

$$\log (a_x) = \log (a_0) - C.A.x. \dots\dots\dots (9)$$

where C is a constant common to all species (a_0) and (a_x) are the activities of the particle species concerned at the feeder channel, and at a distance x from the channel, and $A (= r^2/M)$ is the attenuation coefficient of the particle with molecular weight M and radius r . The equation states that the concentration of a given species decreases exponentially with increasing distance from the feeder channel at a rate that depends on its attenuation coefficient.

Values for r , M and r^2/M for the various particles can be calculated. If arbitrary values for (a_0) (the effective concentration at the channel center) and x (a distance from the channel center) are assigned, the relative slopes of the graphs of $\log(a_x)$ against x of the various species are given by $-A (= -r^2/M)$.

By inserting values of r^2/M for the various particles in equations 5 to 8, the relative changes in concentration of the ore minerals with distance can be deduced. (It has been assumed in the calculations up to this point that the equilibrium constant 'K' does not change with distance or temperature).

A convenient method of determining whether the concentration of a given ore mineral increases or decreases away from the channel is to sum algebraically the values of A_m , where A_m is the attenuation coefficient of a particle species m .

If ΣA_m is positive, then $\log(OM)$ decreases with the increase of x , where (OM) is the concentration of the ore mineral. If ΣA_m is negative, then $\log(OM)$ increases with the increase of x , where A is the sum of the attenuation coefficients of the chemical species from which the mineral forms, and (OM) is the concentration of the ore mineral.

Values of ΣA for the various minerals are tabulated in Table II.

These values show that the rock concentrations of pyrrhotite and chalcopyrite should increase with distance from the centers of mineralization, and that pyrite and magnetite concentrations should decrease. This does not correspond with the observed mineralogy. In constructing Table II, however, it was assumed that the metal ions were not hydrated.

A similar table, Table III, has been constructed assuming the metal ions to have been hydrated. The actual number of water molecules attached to each ion does not greatly affect the result; the values of M (molecular weight) used are those for the monohydrates. For the hydrated case, the concentration of all minerals should decrease with increasing distance from a center, which is also inconsistent with the observed mineralogy. It appears, in sum, that the action of diffusion or attenuation alone cannot produce the observed mineralogy.

Attenuation and Temperature as Controls of Ore Deposition

In this section, attenuation and changes in equilibrium constant with temperature are considered jointly and a more satisfactory result is obtained.

Unfortunately, at this stage, K , the equilibrium constant, cannot be plotted on the same scale as x , the distance, or A , the attenuation coefficient, to obtain meaningful results. Aside from all the unknowns in the constant C in Equation 9, the absolute values of (a_0) and the range of x are also unknown.

Changes in T will also change the attenuation coefficient, but the proportional change for each particle species will be the same. Therefore, the change in A occasioned by a change in temperature can be compensated for graphically by changing the shape of the curve of K .

A hypothetical case is considered, with the reaction concerned being



Table II—Values of ΣA for the Ore Minerals for Unhydrated Metal Ions

Mineral	ΣA
Pyrrhotite.....	-16.52
Pyrite.....	+68.14
Chalcopyrite.....	-32.07
Magnetite.....	-11.02

Table III—Values of ΣA for the Ore Minerals for Hydrated Ions

Mineral	ΣA
Pyrrhotite.....	+83.14
Pyrite.....	+193.04
Chalcopyrite.....	+171.78
Magnetite.....	+287.88

where A and B represent two ore-forming components and C and D represent an ore mineral and a co-existing dissolved component. Therefore

$$K = \frac{(C)}{(A)} \frac{(D)}{(B)}$$

If (C) is the unknown concentration; then:

$$\log (C) = \log K + \log (A) + \log (B) - \log (D)$$

$$\therefore \log \frac{(C)}{(C_0)} = k \log K + r_A^2 \sqrt{M_A} + r_B^2 \sqrt{M_B} - r_D^2 \sqrt{M_D} \dots (11)$$

Figure 4 shows the changes in concentration of components A, B and D from the channel outward, due to attenuation. The ordinate represents the concentrations of the various components, the abscissa, x , the distance from the channel. The slopes of the lines $\log (A)$, $\log (B)$ and $\log (D)$ correspond to the attenuation coefficients of:

for A, Fe^{2+} (hydrated) : for B, H_2S ; for D, 2HCl

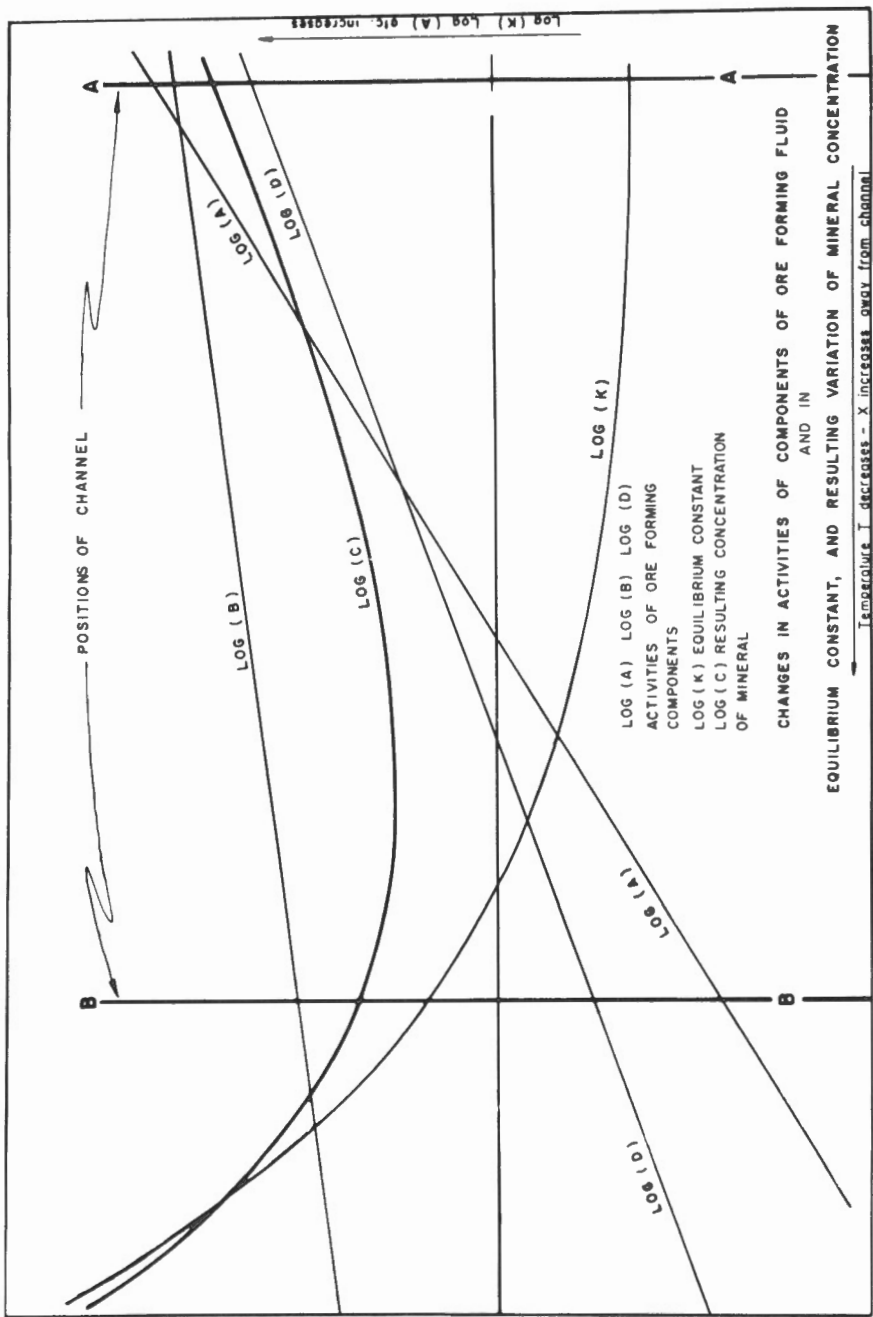


Figure 4

The equilibrium constant, K , is also shown. The resulting concentration of C is obtained by summing the values of the other variables algebraically according to Equation 11. This diagram thus shows the change in concentration of C (an ore mineral) resulting from the action of attenuation and temperature gradients on the fluid model.

It is apparent that the concentration of C decreases from the channel to a minimum, and then increases. The initial concentrations of A , B and D , and the value of K , determine where the position of the channel lies on Figure 4. If the channel lies to the right of the minimum concentration of C , e.g. at $A-A$, then the mineral will decrease in concentration from the channel outward. If the channel lies to the left of the minimum, e.g. at $B-B$, then the mineral will increase in concentration from the channel outward. (The rapid rise farther from the channel will not continue indefinitely, as, upon deposition, a point will be reached where the amount of metal ion becomes too low to produce mineralization).

Thus, we have a mechanism which explains the main features of the orebodies; i.e. (1) the occurrence of chalcopyrite in single concentration peaks, and the simultaneous occurrence of pyrrhotite and pyrite as double concentration peaks, and (2) the separation of the minerals into copper-rich and iron-rich assemblages.

Such deviations as occur from this ideal mineralogical distribution are to be expected as a result of later metamorphism and inhomogeneities in the temperature gradient, permeability, etc.

Conclusions

Independent evidence suggests that the Coronation mine orebodies are magmatic hydrothermal, although recrystallization may have occurred due to later metamorphism. The observed mineral distribution can be well explained by the action of temperature gradients and attenuation on a halide hydrothermal fluid. Although other fluids may also have produced the deposits, thermodynamic data are lacking for such fluids.

Although the evidence is not conclusive, it is considered that these mechanisms warrant consideration as an ore control.

The writer believes that these results justify further investigations into this type of mineralization control. Experimental and theoretical approaches, together with more data on the chemical and physical properties of systems at high temperatures and pressures, could well shed much light on the problems associated with base-metal deposits of this type.

Acknowledgments

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APPENDIX

Derivation of the Attenuation Coefficient

The derivation that follows is based on equations describing the rigid sphere model of the kinetic theory of gases. For the sake of simplicity, a fluid containing only one species of particle is selected. In nature, the various particle species will interfere with each other, but the results should still apply in a qualitative manner. Hirschfelder *et al.* (1954, p. 14) state that the coefficient of self-diffusion, D , is numerically equal to:

$$D = 2.6280 \times 10^{-3} \frac{\sqrt{T^3/M}}{pr^2} \text{ cm}^2/\text{sec.}$$

where T = absolute temperature, p = pressure in atmospheres, r = molecular diameter in Angstroms and M = molecular weight. This coefficient is a measure of the flux across some arbitrary interface in the fluid.

Now the flux ψ , i.e., the number of molecules passing through a given area in unit time, is defined by:

$$\psi = -D \frac{dn}{dz},$$

where n = number of molecules and z = distance.

$$\text{This may be written } \frac{dn}{dz} = \frac{-\psi}{D}$$

For steady conditions, for any one molecular or ionic species, and in the case of a linear source channel feeding the rock around it with no deposition, the amount of flux passing a given point will be constant, regardless of its distance from the feeder channel.

$$\therefore \frac{dn}{dz} = \frac{-k}{D}$$

$$\text{Now } D = k' \frac{\sqrt{T^3/M}}{pr^2}$$

At constant volume and temperature, n , the number of molecules = $k'' p$, where p is the pressure.

$$\therefore \frac{dp}{dz} = \frac{-Kpr^2}{\sqrt{T^3/M}}$$

$$\therefore \frac{dp}{p} = \frac{-Kr^2}{\sqrt{T^3/M}} dz$$

Integrating

$$\int_{p_0}^{p_x} \frac{dp}{p} = (\ln p) \quad \begin{matrix} p = p_x \\ p = p_0 \end{matrix} = \frac{-Kr^2}{\sqrt{T^3/M}} (z) \quad \begin{matrix} z = x \\ z = 0 \end{matrix}$$

$$\ln \frac{p_x}{p_0} = \frac{-Kr^2 x}{\sqrt{T^3/M}}$$

$$\therefore P_x = P_0 \exp. \frac{-Kr^2}{\sqrt{T^3/M}} \cdot x \dots\dots\dots (12)$$

This formula states that the pressure decreases exponentially from its value at the feeder channel. It applies to the case where only one molecular species is present, and takes no account of filtration by the rock, or of the porosity and permeability. No allowance has been made for loss of pressure due to hydraulic flow, or for non-steady-state conditions.

Apart from these assumptions, those made below are that no loss occurs due to deposition, and that the temperature is constant. (Although the temperature may vary, we are here concerned with the diffusion effect alone, taking no account of temperature changes). However, the time taken for deposition is probably long enough so that the amount deposited was negligible compared with the amount transported and in solution at any one place. If these assumptions be granted, then several deductions can be made. The varying factors between the different chemical species present are r and M . Thus, we may write equation 12:

$$p_x = p_0 \exp. - Cr^2 \sqrt{M} \cdot x, \text{ where } C \text{ is a constant common to all particle species.}$$

$$\text{i.e., } \log p_x = \log p_0 - Cr^2 \sqrt{M} \cdot x. \dots\dots\dots (13)$$

Substituting activities for pressures:

$$\log (a_x) = \log (a_0) - Cr^2 \sqrt{M} \cdot x. \dots\dots\dots (14)$$

This formula gives the activity of a particle species of weight M and particle radius r at a distance x from a source channel where the activity of the particle is (a_0) . The activity decreases exponentially, the rate of decrease at constant temperature depending on the product $r^2 \sqrt{M}$. This product is here termed the Attenuation Coefficient, A .

$$A = r^2 \sqrt{M}.$$

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No. 9 COMPOSITIONS OF PYRRHOTITE
 AND SPHALERITE FROM THE
 CORONATION MINE

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ABSTRACT

Random collections of pyrrhotite and sphalerite from all levels of the mine were made with the intention of using them to provide information on the thermal listing of the ores. Recent work has shown that both minerals are not suitable for geothermometry. However, the data accumulated has been interpreted and provides useful basic information on geological environment of formation of natural pyrrhotite.

Introduction

The original intention of studying pyrrhotites and sphalerites from the Coronation mine was to obtain information about the thermal history of the ores using the pyrrhotite-pyrite and sphalerite-pyrrhotite-pyrite geothermometers. Since this study was initiated in 1960, new data on natural and synthetic pyrrhotites indicate that all pyrrhotites suffer low temperature reactions which makes the application of pyrrhotite as a geothermometer rather hazardous. In addition, Barton and Toulmin (1966) and Boorman, 1967, have shown that sphalerite cannot be effectively used as a geothermometer. Although the original intention of the study was not achieved, the data accumulated for both pyrrhotite and sphalerite and the problems of their interpretation are of basic interest. These data are summarized in this report. For a detailed account of the regional geology and the geology and mineralogy of the mine, the reader is referred to papers by Froese, Whitmore and Kanehira, respectively, in this symposium.

The present study is based on an examination of 63 hand specimens collected at random from all the mine workings as they existed in 1959. The samples were taken from seven mine levels between the 150 and 1050 foot levels. Polished sections were made from each hand specimen and were examined in both etched and unetched condition. To simplify the reporting of the data, the pyrrhotite and sphalerite data are reported under separate headings.

Pyrrhotite Data

The majority of Coronation pyrrhotites are monoclinic. X-ray diffractometer chart records of bulk samples of pyrrhotite separated from many hand specimens from the mine showed two reflections in the 102 reflection position of hexagonal Fe_{1-x}S subcell.* In a majority of cases the two reflections ($20\bar{2}$ and $20\bar{2}$) are of equal intensity, however, in several cases the intensity of $20\bar{2} > 202$ (Fig. 1). According to Byström (1945), the two reflections are of equal intensity for monoclinic Fe_{1-x}S and of unequal intensity ($202 > 20\bar{2}$) for mixtures of hexagonal Fe_{1-x}S and monoclinic Fe_{1-x}S . The reason for the intensity of $20\bar{2} > 202$ is not known. No hexagonal Fe_{1-x}S was detected on diffractometer chart records as hexagonal Fe_{1-x}S is scarce and its concentration was below the limit of detectability of the X-ray method (≈ 10 weight %).

Examination of polished sections after etching with a saturated solution of chromic acid in water showed that the majority of pyrrhotite grains etched strongly. The identities of several strongly etched grains were confirmed as being monoclinic Fe_{1-x}S by taking X-ray powder photographs of material removed from the grains. A small quantity of relatively unetched lammellar pyrrhotite situated in a relatively strongly etched pyrrhotite matrix was observed in several polished sections. These are interpreted to be hexagonal Fe_{1-x}S (see Arnold, 1966, 1967). Small euhedral to anhedral grains of pyrite were commonly in contact with monoclinic Fe_{1-x}S .

* Indices for hexagonal Fe_{1-x}S and monoclinic Fe_{1-x}S subcells are used throughout this paper.

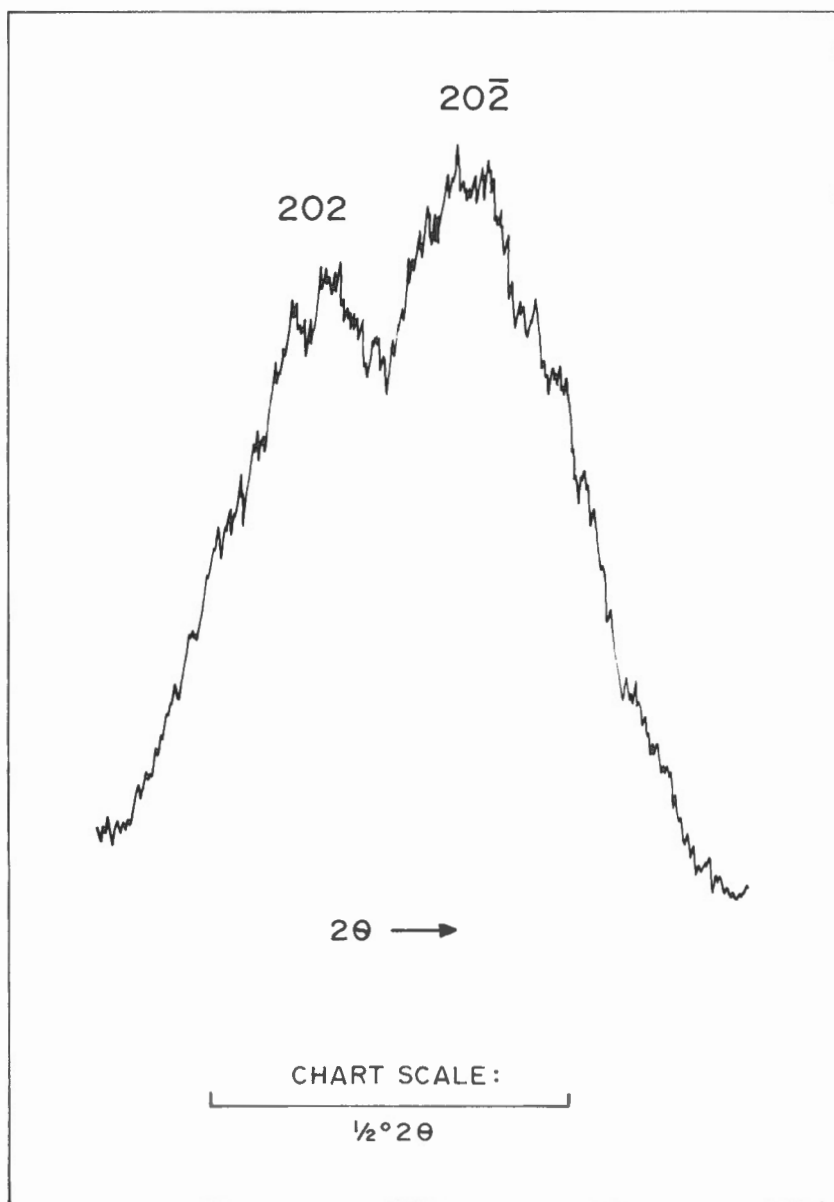


Figure 1. X-ray reflections for monoclinic Fe_{1-x}S with the intensity of $20\bar{2} > 202$. $\text{CuK}\alpha$ radiation. Scanning speed - $1/8^\circ 2\theta$ /min.

The total metal content (atomic % metals*) of pyrrhotite from 41 hand specimens was determined by the X-ray spacing method using a Norelco

*

$$\frac{\text{Fe} + \text{Ni} + \text{Co} + \text{Mn}}{\text{Fe} + \text{Ni} + \text{Co} + \text{Mn} + \text{S}} \times 100$$

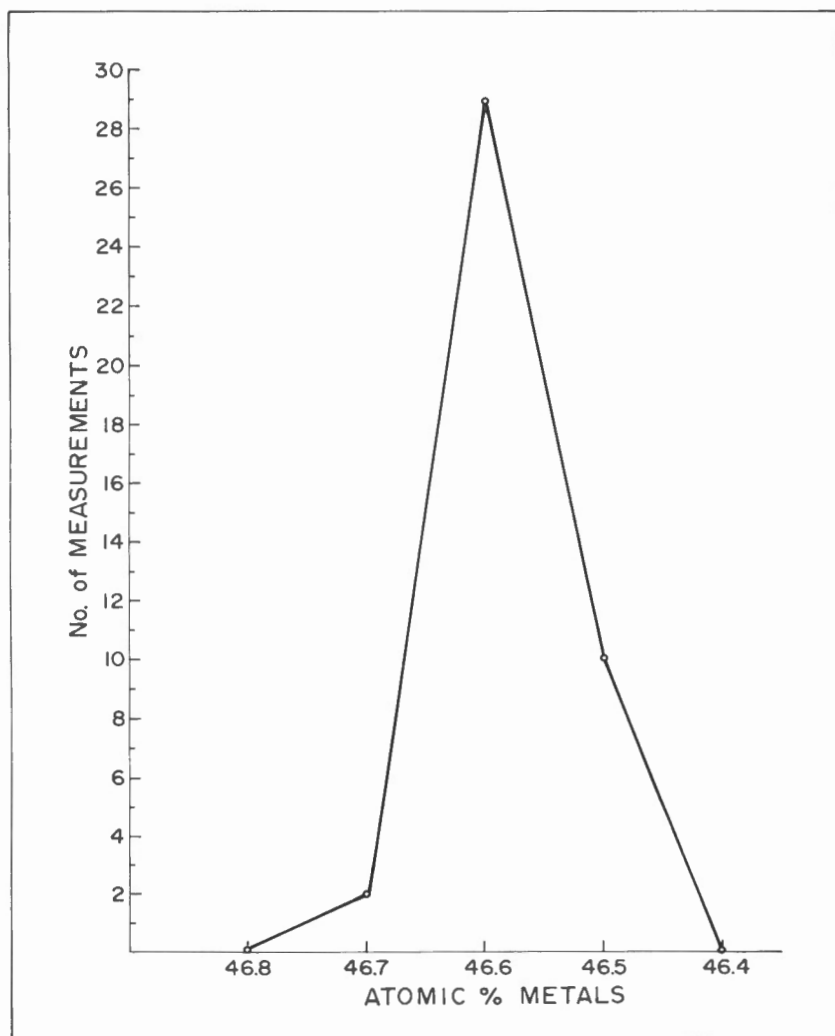


Figure 2. Frequency distribution of 41 bulk compositions of pyrrhotite from all mine levels.

wide angle focussing diffractometer and Lake Toxaway quartz as internal standard (Arnold and Reichen, 1962). The compositions ranged between 46.5 and 46.7 atomic % metals. A frequency distribution plot of these data is shown in Figure 2. The compositions were measured by Ferris (1961) on unhomogenized material with a Norelco diffractometer using a rapid scanning speed ($1^\circ 2\theta/\text{min.}$). Subsequent remeasurement of a number of these pyrrhotites after converting to hexagonal Fe_{1-x}S by heating at 350°C for 20 minutes in sealed, evacuated silica-glass tubes indicates that the original determinations are valid within the limit of error of measurement ($< \pm 0.2$ atomic % metals). The mean value for the 41 compositions is 46.58 atomic % metals with a standard error of the mean of $\pm .08$. All individual compositions are well within the limit of error of measurement of this mean value. It is

therefore evident that the compositions of pyrrhotite throughout this deposit are very uniform. The mean pyrrhotite composition conforms closely to the compositions of 46.5 to 46.7 atomic % Fe estimated for natural monoclinic Fe_{1-x}S by others (see compilation in Arnold, 1967).

The concentrations of Ni, Co and Mn in two pyrrhotites were measured by X-ray fluorescence analysis in bulk samples using synthetic pyrrhotites of known composition as standards. The data are summarized in Table 1.

TABLE 1
Trace Elements in Pyrrhotite

Mine Level (feet)	Ni	Co	Mn
150	.032	nd*	.010
900	.007	.130	nd*
* nd - not detected			

These data indicate an erratic distribution of these elements in pyrrhotite in different portions of the mine, in direct contrast to the uniformity of the metal/sulfur ratios of these pyrrhotites.

X-ray powder photographs of two pyrrhotites using a Debye-Scherrer type powder camera (114.59 mm diameter) showed a number of weak supercell reflections among which were reflections indicating d-values of 5.7, 5.3, and 4.7 Å. These values agree well with published supercell data for monoclinic Fe_{1-x}S (Desborough and Carpenter, 1965).

Sphalerite Data

In contrast to the abundance of pyrrhotite, sphalerite is relatively scarce in the Coronation ore and appears to decrease in concentration with depth so that it is practically absent in the 1050 foot level. Because of the scarcity of sphalerite, only two were quantitatively separated from the hand specimens for cell dimension determinations, chemical and trace element analyses. These data are supplemented by iron determinations in 49 small sphalerite grains by electron probe.

A summary of the data for the two separated sphalerites is given in Table 2.

Table 2
Data for Sphalerite

Mine Level (feet)	a_o (Å)	From cell dimensions	Chemical Analysis	Composition (mole % FeS)	
				Trace Elements (Wt. %)	
				Cd	Mn
150	5.41534 ±.00062	13.3 ± 1.4	13.4	.11	.10
450	5.41596 ±.00059	14.7 ± 1.3	-	.12	.15

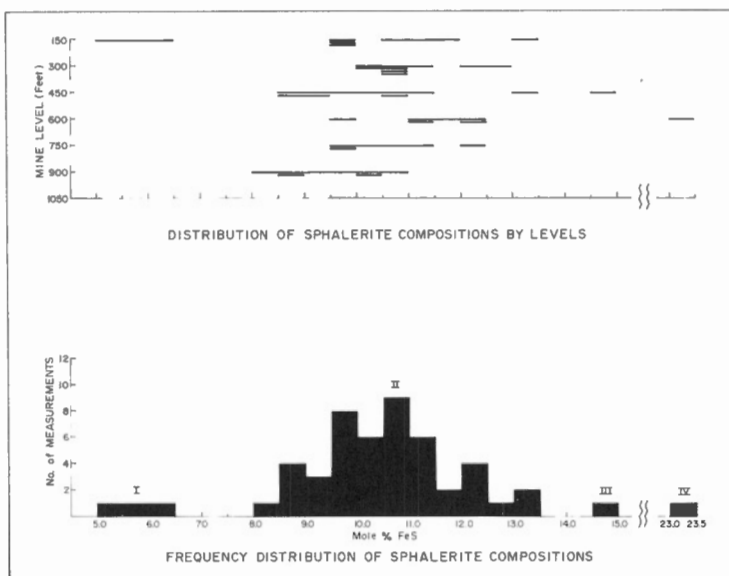


Figure 3. Lower: Frequency distribution of FeS contents of 49 sphalerite grains.

Upper: Distribution of the FeS contents of the same 49 sphalerites by mine level.

The iron content of one sphalerite was determined by both cell dimensions and chemical analysis as indicated. The two estimates agree very closely. Cadmium and manganese were measured by X-ray fluorescence analysis using analysed natural sphalerites as standards. The concentration of these elements in the two sphalerites is well below the concentration that can affect the cell dimensions (Kullerud, 1953).

The sphalerite cell dimensions were measured by a method described by Goldak (1960). In this method the angular position of an X-ray reflection is determined as a function of the angular interval between two X-ray reflections (α and β reflections are recommended) whose Miller indices and X-ray wave lengths are known. The method is independent of goniometer zero alignment and requires no internal or external standards but assumes negligible chart slippage. The accuracy of the position of the reflections depends on the accuracy of the measurement of the angular interval between reflections and the accuracy of the wave length values of the diffracted X-rays. Goldak presents an equation from which a_0 can be calculated directly for isometric substances. The sphalerite cell dimensions were translated into equivalent FeS contents by using the cell dimensions versus mole % FeS equation presented by Skinner *et al.* (1959).

Figure 3 summarizes the FeS content of 49 sphalerite grains from 23 polished sections determined by electron probe. Chemically analysed and relatively homogeneous, natural sphalerites were used as standards. The lower portion of Figure 3 shows a frequency distribution of the mole % FeS values. For convenience, the results have been divided into four groups. Group 1 includes three sphalerites containing 5.3 to 6.0 mole % FeS. Group

II sphalerites range in composition from 8.4 to 13.4 mole % FeS. Group III and IV contain only one sphalerite each with 14.7 and 23.2 mole % FeS, respectively. The overall range in FeS content of the sphalerites is therefore almost 18 mole %. In two cases sphalerites with high and low FeS contents are located only a few millimeters apart in the same polished section. For example, one section contained sphalerites with 11.4 and 23.2 mole % FeS and another contained sphalerites with 5.3 and 11.9 mole % FeS. The upper portion of Figure 3 shows the FeS contents arranged according to mine levels. There is no significant vertical zoning of these values.

Discussion of Results

Monoclinic Fe_{1-x}S is a low temperature phase which is estimated to develop below $\approx 300^\circ\text{C}$ (Hall and Yund, 1966), $308 \pm 5^\circ\text{C}$ (Clark, 1966) and $304 \pm 6^\circ\text{C}$ (Arnold, 1968). Experimental evidence now suggests that monoclinic Fe_{1-x}S is a metastable phase and that the assemblage hexagonal Fe_{1-x}S + monoclinic Fe_{1-x}S and monoclinic Fe_{1-x}S + pyrite are thermodynamically unstable with respect to hexagonal Fe_{1-x}S + pyrite (Hall and Yund, 1966; Arnold, 1968). However, it is apparent from natural assemblages that monoclinic Fe_{1-x}S can co-exist in metastable equilibrium with hexagonal Fe_{1-x}S and/or pyrite indefinitely. The development of natural monoclinic Fe_{1-x}S + pyrite directly at temperatures below $304 \pm 6^\circ\text{C}$ would not be predicted from the behavior of these phases in the synthetic system because of their apparent incompatibility. For example, charges of iron-deficient hexagonal Fe_{1-x}S plus sulfur with a bulk composition lying between that of monoclinic Fe_{1-x}S and pyrite, heated below $304 \pm 6^\circ\text{C}$, develop the assemblage hexagonal Fe_{1-x}S + pyrite with a trace of monoclinic Fe_{1-x}S . However, there is a possibility that hexagonal Fe_{1-x}S of appropriate composition plus pyrite, cooled from above $304 \pm 6^\circ\text{C}$ can result in the assemblage monoclinic Fe_{1-x}S + pyrite or hexagonal Fe_{1-x}S + hexagonal Fe_{1-x}S + pyrite (showing a range of ratios of the two pyrrhotites) by isochemical conversion of hexagonal Fe_{1-x}S during cooling, with pyrite remaining unreactive during the process. The inertness of pyrite after crystallization is well known to experimenters. The association of monoclinic Fe_{1-x}S with pyrite may therefore be evidence of initial heating of the mineral deposit above $304 \pm 6^\circ\text{C}$.

The development of monoclinic Fe_{1-x}S in the Coronation ores is consistent with the conclusions arrived at by studies of other ores; namely, that probably all natural pyrrhotites show the low temperature phase relations irrespective of geological environment or conditions of formation. This conclusion is consistent with the rates of reaction observed for synthetic pyrrhotites, which are sufficiently rapid that low temperature reactions are largely completed in less than a year. The rapid reaction rates therefore ensure that natural iron-deficient, hexagonal pyrrhotite cooled into the low temperature region below $304 \pm 6^\circ\text{C}$ will assume low temperature phase relations.

In contrast to the relatively constant bulk composition of pyrrhotite in the Coronation ores, the FeS content of sphalerite ranges rather widely throughout the deposit. In Figure 4, the FeS contents of sphalerite are plotted on a phase diagram summarizing the compositions of synthetic sphalerites as a function of temperature when sphalerite co-exists with various

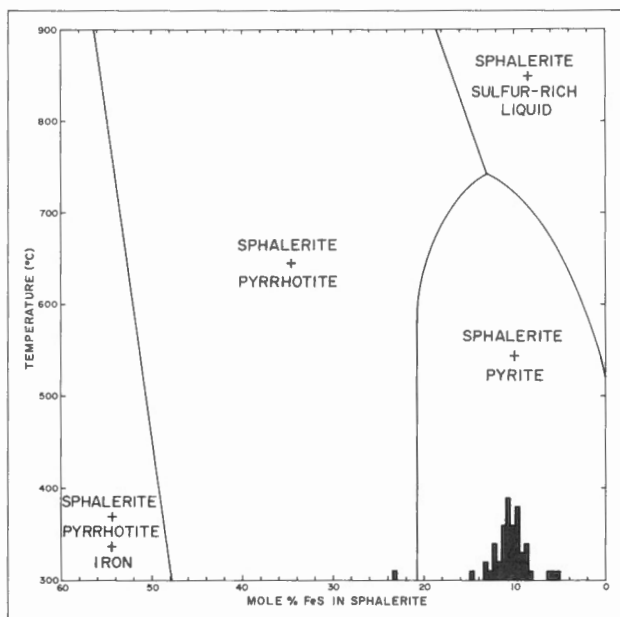


Figure 4. Phase diagram modified after Barton and Toulmin (1966) and Boorman (1967) showing composition of Coronation sphalerites (black areas) relative to the compositions of synthetic sphalerites co-existing with various phases.

phases. (See Barton and Toulmin, 1966; Boorman, 1967). It is evident that all but one of the natural sphalerite compositions fit within the field of sphalerite plus pyrite. This is a divariant region, so that at constant temperature of heating, the FeS content of sphalerite co-existing with pyrite will vary as the fugacity of sulfur varies, assuming equilibrium in the system. If sphalerite co-exists in equilibrium with pyrrhotite and pyrite at less than 600°C, according to the equilibrium relations it should contain approximately 20.8 mole % FeS (see Figure 4). Assuming a close approach to equilibrium in ores, the FeS contents of the Coronation sphalerites are inconsistent with the observation that pyrrhotite and pyrite co-exist with sphalerite in the ore body, but are consistent with a sphalerite-pyrite assemblage associated with a non-uniform fugacity of sulfur through the ore body. However, there is no unequivocal evidence that pyrite and sphalerite crystallized together in the absence of pyrrhotite. Also, the existence of sphalerites only a few millimeters apart in the ore, but differing significantly in composition is difficult to explain satisfactorily. A brief survey of sphalerite compositions from other Precambrian sulfide deposits of similar mineralogy and geological setting indicates that similar problems exist. Further studies will therefore be required to reconcile the compositions of natural sphalerites co-existing with pyrrhotite and pyrite with those indicated experimentally.

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No. 10. DATA FOR BRINE AND
CARBON DIOXIDE FILLED LIQUID
INCLUSIONS IN QUARTZ VEINS
FROM THE CORONATION MINE

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ABSTRACT

Liquid inclusions occur in quartz veins cutting the ore bodies in Coronation mine. Hand specimens collected from seven levels were examined and the contained liquid inclusions were found to be of three general types - brine-gas, brine-CO₂ fluid-gas and CO₂ fluid-gas. Interpretation of the observations permitted approximate estimates of the composition of the inclusion fluids and the conditions of trapping of the fluids, assuming the inclusions to be primary. Sphalerites and silicate gangue in the ore body were also examined for liquid inclusions, but without significant results.

Introduction

The present paper is primarily a report of observations on liquid inclusions in quartz veins cutting ore in the Coronation mine. Sphalerites and silicate gangue in the ore body were also examined for liquid inclusions but none suitable for study were identified. For an account of the mineralogy and geology of the Coronation mine ores and surrounding country rocks, the reader is referred to other papers in this symposium.

The quartz veins cutting ore in the Coronation mine are in the order of one foot wide, are continuous for hundreds of feet and may be related to a syntectonic granodiorite exposed on surface about one-quarter mile to the east of the mine. Stringers and patches of chalcopyrite, and pyrrhotite, apparently remobilized from the ores are incorporated in the veins near the contacts between veins and ore. The identification of an undistorted longitudinal-section of a zoned quartz prism about 3 inches long and 1 inch wide in one hand specimen, suggests that quartz crystallized from a solution and suffered little dynamic metamorphism after crystallization.

Thirty-five hand specimens of vein quartz were collected from seven levels ranging from 150 to 1050 feet below the surface. Liquid inclusions in six of these samples were studied in considerable detail. Due to incomplete mapping of the underground workings at the time of sample collection, it was not possible to positively trace a particular quartz vein from one level to another; therefore, the relationship between the samples collected from the various levels is not clear. In all probability a number of different veins were sampled but the samples are all genetically related.

Three general types of liquid inclusions were identified as listed in Table 1 together with their approximate frequency of occurrence.

Table 1
Types of Liquid Inclusions and Their Approximate
Frequency of Occurrence

Type of Inclusion	Frequency in per cent
1. Brine-gas, with or without contained crystals*	80
2. Brine-CO ₂ fluid-gas, with or without crystals* in brine	15
3. CO ₂ fluid-gas, with or without crystals* in fluid	5

* Soluble and/or insoluble (inert) crystals.

The three types of inclusions generally occur together separated from each other by a few inclusion diameters and are not obviously related to lineage structures but are randomly scattered about in quartz. The size of the inclusions studied range up to approximately 50 microns across, but the majority studied were in the 4 to 10 micron range. The shapes of the

inclusions vary from irregular to elongated to almost circular in outline. Point counts on a number of quartz plates indicate that the concentration of inclusions ranges between 10^6 to 10^9 per cubic centimeter, which probably accounts for the milky appearance of quartz in hand specimens.

Polished thin sections of quartz were prepared for microscopic examination on both heating and cooling stages. The heating stage employed was a home-made device similar to that described by Richter and Abell (1953). Temperatures of heating were measured by two chromel-alumel thermocouples resting on the quartz plate adjacent to the area being observed. The uncertainties in recorded temperatures of heating are within $\pm 3^\circ\text{C}$. A Thomas-McCrone Micro Cold Storage was used for cooling inclusions below room temperature and measuring freezing temperatures of brine. In this device the sample is cooled by passing cold dry air over it in a closed chamber. The brines in inclusions were frozen by immersing the quartz plates in a dry ice-acetone mixture (-78.5°C) before placing plates in the cold stage for observation. To ensure equilibrium melting of brine, the inclusions were heated and cooled a few degrees just below the true freezing temperature to observe the growth and melting of the remaining crystal as suggested by Roedder (1962). The uncertainty in the measured freezing temperatures are within $\pm 4^\circ\text{C}$. A Leitz 25X ocular and UMK 32/0.06 microscope objective were used which permitted observations on inclusions as small as 4 microns across to be made.

The results of chemical analyses of the fluids in the inclusions, the observations of the behaviour of the fluids during heating and cooling and the interpretation of these data are summarized under separate headings below.

Estimated Composition of Fluids in Inclusions

Two crushed, acid and electrolytically cleaned quartz samples were analyzed for CO_2 and H_2O by heating them in a combustion chamber at 1200°C and collecting the CO_2 and H_2O selectively in caroxite and $\text{Mg}(\text{ClO}_4)_2$ tubes, respectively. The concentrations of gases indicated by weight increase of the tubes are given in Table 2.

Table 2
Results of Combustion Analysis
Analyst: E. L. Faulkner

Sample	(gm/Kg of Quartz)	
	H_2O	CO_2
M 16	$3.20 \pm .02^*$	$0.87 \pm .04$
M 17	$1.50 \pm .02$	$0.76 \pm .03$

* Errors indicated are due to weighing errors.

The combustion temperature of 1200°C was considered adequate to break open most inclusions as the majority of inclusions explode at 400°C when heated on a heating stage. The results indicate that quartz contains a minimum of 0.15 to 0.32 weight per cent of H₂O with 2 to 4 times as much H₂O as CO₂.

The concentrations of potassium, calcium, sodium and magnesium contained in inclusions in quartz were determined by flame photometer. Extraction of inclusion fluids from 20 gram samples of crushed and cleaned quartz, and the measurement of concentration of the cations by electrodialysis were performed as described by Roedder (1958). The results of the analyses are given in Table 3.

Table 3
Cation Analyses of Inclusion Fluids
Analyst: E. L. Faulkner

Sample	mg/Kg of Quartz				Ratio			
	Mg ⁺⁺	K ⁺	Ca ⁺⁺	Na ⁺	Mg ⁺⁺	: K ⁺	: Ca ⁺⁺	: Na ⁺
M 16	4 ± 1	8 ± 1	77 ± 9	116 ± 15	1	:	2	: 19 : 29
M 17	3.5 ± 2	10 ± 1	79 ± 9	109 ± 10	1	:	3	: 22 : 31

The results in Table 3 show that sodium is the most abundant ion in the inclusion fluids and that there is about two-thirds as much calcium as sodium. Potassium and magnesium are present in minor amounts. The errors involved in the analyses are difficult to assess, but they are in all probability rather low. Contamination of the samples with the cations measured was negligible, as the samples were cleaned before analysis by electrodialysis and were subsequently ground in a metal ball mill. Impurities in quartz do not affect the results provided they are not soluble in water. Potentially the most serious error in the results arises from inclusions not opened during ball-milling. However, the cation ratios are probably not greatly affected by this possibility.

A meaningful comparison of the ratios in Table 3 with those reported in the literature for inclusions in quartz and various other minerals in ores and gangue is frustrated by the great variability of the ratios reported in the literature both for different kinds of occurrences and in some instances for the same mineral occurrence. The principal similarity between the literature data and that reported here for bulk samples of quartz is that Na > Ca > K. Roedder *et al.* (1963) report Na > Ca > K for 71 per cent of their analyses of inclusion fluids in minerals from various occurrences, and Hall and Friedman (1963) report the same relative concentrations for 90 per cent of their analyses of inclusion fluids from the Mississippi Valley lead-zinc deposits and the Cave-in-Rock fluorite district.

Whereas the chemical analyses of bulk samples of quartz give an estimate of the total salt content of the inclusions, freezing point depression measurements are related only to the salt content of the fluid. Table 4 summarizes the true freezing points of brine in brine-gas, brine-gas-NaCl

crystal inclusions, and in two cases of brine in inclusions containing CO_2 fluid and gas. It is apparent from the results that the freezing points of brine in inclusions containing CO_2 fluid are similar to those for inclusions containing no detectible CO_2 . True freezing points were taken as the temperature of disappearance of the last crystal in brine (ice or $\text{NaCl} \cdot 2\text{H}_2\text{O}$ depending upon bulk composition of inclusion) as the temperature of a completely frozen inclusion was slowly raised. As indicated in Table 4 some of the lowest freezing temperatures were obtained for inclusions containing NaCl crystals indicating a very high concentration of salt in these inclusions. The freezing temperatures of brines obtained are among the lowest reported in the literature for liquid inclusions and indicate the presence of salts in addition to NaCl , which by itself can only depress the freezing points to -21.1°C (Int. Crit. Tables IV). For example, all the freezing temperatures reported by Roedder (1963) but one, are above -34°C , whereas the exception is a value of -54°C obtained from a halite crystal.

The estimation of the salt content of the fluids from freezing point depression measurements requires some assumptions about the identity of the salts in solution. Chemical analyses (Table 3) indicate that Na^+ and Ca^{++} are the two most abundant cations, and the existence of NaCl crystals in many inclusions indicates that the bulk of Na^+ is present as the chloride. It is assumed here that CaCl_2 exists in the fluids because Ca^{++} was found to be relatively abundant in the fluids (see Table 3) and the fact that CaCl_2 is the only common salt capable of depressing the freezing points to the low values obtained. If this assumption is correct, the compositions of the brines can be largely represented by the ternary system $\text{H}_2\text{O}-\text{NaCl}-\text{CaCl}_2$ (see Yanatieva (1946)). CO_2 in solution in brine probably affects the results very little as the solubility of CO_2 in NaCl and CaCl_2 brines at low temperatures and pressures is probably quite low (see Takenouchi and Kennedy, 1965).

Liquidus contours in 10°C intervals between -20 and -40°C are shown in Figure 1 to demonstrate the change in $\text{NaCl}/\text{CaCl}_2$ ratio and total salt content of brine with temperature. Each contour is the locus of brine compositions having identical freezing temperatures as designated. The brines represented by the contours can coexist with one or more of ice, NaCl and $\text{NaCl} \cdot 2\text{H}_2\text{O}$ depending upon the total salt content of the inclusion and the temperature. $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$ which is a stable phase in the system did not form at any temperature as the calcium content in the inclusions was not sufficiently high. In general, as the freezing temperature of brine decreases, the $\text{NaCl}/\text{CaCl}_2$ ratio decreases and the liquid field decreases in area, narrowing the range of possible salt contents of brine. By applying the freezing temperatures of brines listed in Table 4 to the ternary system in Figure 1 it is apparent that the total salt content of the majority of brines in inclusions lies between approximately 24 and 34 weight per cent. It is also apparent that the $\text{NaCl}/\text{CaCl}_2$ ratio is <1 for brines in the majority of inclusions in direct contrast to a $\text{Na}^+/\text{Ca}^{++}$ ratio of >1 established by chemical analyses of bulk quartz samples (Table 3). This apparent inconsistency is explained by the abundance of NaCl crystals which are included in the analyses of bulk quartz samples but are not accounted for in the estimation of salt content of brines by freezing point depression measurements. The total salt content of some inclusions containing NaCl crystals has been estimated to approach 40 weight per cent. Sawkins (1966) has reported similarly high salt contents in inclusions in quartz from southwest England and from the Providencial mine in

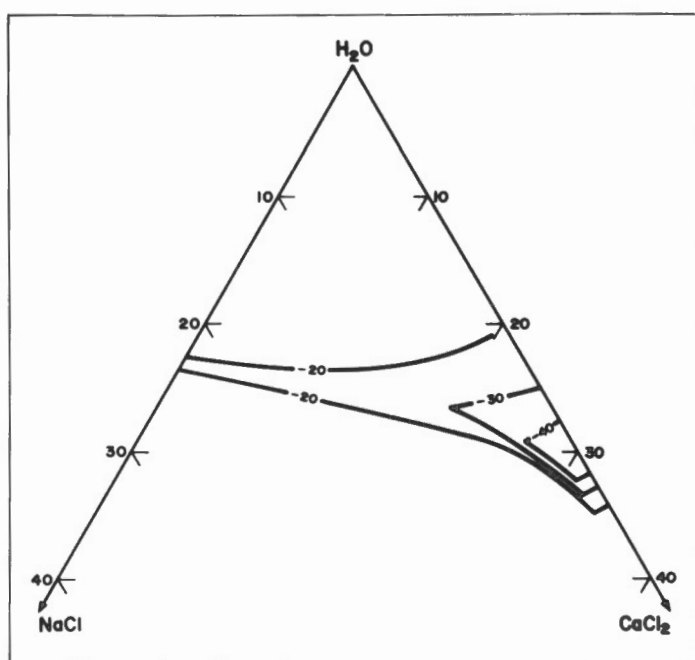


Figure 1. Partial NaCl-CaCl₂-H₂O system showing liquidus contours at three temperatures as indicated.

Mexico (Sawkins, 1964). Roedder and Coombs (1967) report that brines trapped in quartz and feldspar in Ascension Island granite contained 50 to 70 weight per cent NaCl.

Heating Experiments on Liquid Inclusions

In the interest of clarity, the data for inclusions containing no detectible CO₂ and for those containing CO₂ fluid are reported separately below.

A. Inclusions containing brine and no detectible CO₂

Four general varieties of inclusions containing brine and gas were identified: brine-gas; brine-gas-NaCl crystal; brine-gas-inert crystal; brine-gas-NaCl crystal-inert crystal(s).

On heating these types of inclusions on a microscope heating stage, the volume of liquid invariably increases and that of the gas decreases until it eventually disappears. On cooling the inclusions the gas bubbles reappear. As the gas phase invariably disappears below approximately 250°C the specific volume of the inclusions is less than approximately 1.15 cc/g, assuming 30 weight per cent NaCl brine (Smith, 1963, p. 220).

Soluble crystals in inclusions invariably show sharp cubic outlines such as are shown by NaCl and KCl crystals. The solubility behaviour of

B. Inclusions containing CO₂

Two general types of inclusions containing CO₂ fluid are recognized. Those containing CO₂ fluid and gas and those containing CO₂ fluid, brine and a gas phase situated in CO₂ fluid. Inclusions containing brine and CO₂ can show a wide ratio of the two fluids (Fig. 3). Crystals in these two types of inclusions are rare, and in only two cases were soluble crystals with cubic outlines (probably NaCl) observed in brine in CO₂ fluid-brine-gas inclusions (Fig. 3). The identification of CO₂ fluid in these two general types of inclusions was made by cooling the inclusions to about -20°C and then gently warming them. If an inclusion contains CO₂ fluid, the gas bubble decreases in diameter during warming of the inclusion and invariably disappears below 31°C (critical temperature of CO₂), at a temperature depending upon the degree of filling or bulk specific volume of the inclusion.

Inclusions containing detectible quantities of both CO₂ fluid and brine can be generally recognized by observing the relative movement of one fluid relative to the other. CO₂ fluid has a significantly lower refractive index (1.19) than saturated brine (1.33) and thus stands out in strong relief. Roedder (1963) suggests that as much as 10 per cent CO₂ fluid can exist in a brine-gas inclusion without detection, as CO₂ fluid becomes distributed about the brine-gas interface and is not detectible due to total reflection. Whether or not any undetected CO₂ fluid exists in any of the brine-gas inclusions examined in this study is not known.

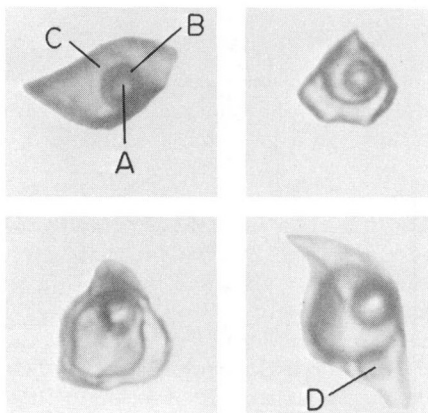
On heating inclusions containing CO₂ fluid and gas, the gas bubble decreases in size and disappears at temperatures ranging from -16 to 15°C (Table 6). As all gas bubbles disappear below 15°C the specific volumes of the inclusions are less than approximately 1.25 cc/g (Smith, 1963, p. 81).

On heating inclusions containing brine, CO₂ fluid and gas, the gas bubbles decrease in diameter and disappear between 2 and 29°C (Table 6). On continued heating either CO₂ fluid decreases in volume and eventually disappears or brine decreases in volume and eventually disappears. Which of these occurs, depends upon the initial ratio of the two liquids. The temperature at which only one fluid exists in the inclusions is the homogenization temperature (Table 6). The minimum homogenization temperatures range between 250 and 285°C and the maximum homogenization temperatures are not always measurable as many inclusions explode before homogenization due to the development of a high fluid pressure.

Discussion and Application of Results

The occurrence together of inclusions in quartz containing brine, CO₂ fluid and mixtures of the two fluids suggests that the solution from which quartz crystallized was rich in these components, assuming of course that the inclusions are primary. Takenouchi and Kennedy's (1965) experimental work in the system NaCl brine-CO₂ indicates that the addition of salt to this system sharply raises the critical temperature of the system with the result that the two-phase region of immiscible brine and CO₂-rich fluid extends up to approximately 600°C at 950 bars pressure for a 20 weight per cent NaCl brine. Considering the relatively low estimated temperatures of trapping of the inclusion fluids (260 to 375°C, see later discussion) and the relatively high salt content of the brines, there is a strong possibility that immiscible

Figure 3. Photomicrographs showing CO_2 fluid-brine-gas inclusions with different CO_2 fluid/brine ratios. Inclusions at lower right contains a NaCl crystal in brine (1600X).
 A - gas;
 B - CO_2 fluid;
 C - brine;
 D - NaCl crystal



brine and CO_2 -rich fluid existed in the solution from which quartz crystallized.

The variety of inclusion liquids now observed is then explained by trapping of the two components individually and together in varying proportions (Fig. 3). If the trapping of the two components is random, the relatively low frequency of occurrence of inclusions containing CO_2 (approximately 20 per cent of total, Table 1) reflects a low CO_2 /brine ratio in the quartz forming solution. The combustion analyses in Table 2 support the low CO_2 /brine ratio as they indicate H_2O to be 2 to 4 times as abundant as CO_2 .

The range of $\text{NaCl}/\text{CaCl}_2$ ratios and total salt content of brine in the inclusions can be accounted for by assuming the concentration of salt to be unevenly distributed in brine at any instant and/or changing with time as quartz progressively crystallizes from the solution. Whether or not NaCl crystals were originally trapped with brine or precipitated from brine after trapping is uncertain. If trapped, the NaCl crystals were of necessity rather small at time of trapping and grew at the expense of brine as quartz was cooled to earth surface temperatures.

If coexisting brine and CO_2 -rich fluid were trapped individually in inclusions as assumed, unmixing of the second fluid during cooling (CO_2 fluid from brine and vice versa) might be expected if the mutual solubilities at elevated temperatures are appreciable and the slopes of the flanks of the two-phase region below the temperature of trapping are favourable. The fact that brine-gas and CO_2 fluid-gas inclusions are found with no detectible second liquid can be explained in several ways, namely: (1) the second liquid exists in the inclusions but is not detectible as previously pointed out; (2) assuming a significant mutual solubility between the two components, the flanks of the two-phase region are too steep for appreciable unmixing to occur during cooling; (3) the mutual solubilities of the two components at the temperature of trapping are low, so that appreciable unmixing during cooling cannot occur. Takenouchi and Kennedy's (1964, 1965) work indicates that the addition of salt to the system $\text{H}_2\text{O}-\text{CO}_2$ sharply decreases the solubility of CO_2 in the aqueous phase and sharply raises the critical temperature of the system. This tends to increase the slope of the field boundary representing brine and together with the decreased solubility of CO_2 fluid in brine, minimize the unmixing of CO_2 fluid from brine. What the effect of increased salt content is on the solubility of brine in CO_2 fluid was not determined. More complete temperature-composition-pressure data for the system brine- CO_2 will be required to predict whether or not mutual unmixing can be expected in these coexisting fluids when cooled from the 260 to 375°C range.

Table 4
Freezing Point Depression Measurements

Sample No.	Mine Level (feet)	Inclusion Types		
		Brine-gas Range (°C)	Brine-NaCl crystal-gas Range (°C)	Brine-CO ₂ fluid-gas Range (°C)
MS	450	-30 to -40 (18)	-45 to -48 (3)	
M16	600	-37 to -45 (6)	-42 to -50 (6)	-19 to -40 (5)
M22	750	-32 to -42 (16)		
M24	750	-23 to -35 (25)		
M32	1050	-23 to -33 (15)		

(numbers in brackets refer to number of inclusions studied)

Table 5
Temperatures of disappearance of gas
and NaCl crystals in brine-gas
and brine-gas-NaCl crystal inclusions

Sample No.	Mine Level (feet)	Temperature of Disappearance of Gas		Temperature of Disappearance of NaCl crystal
		Range (°C)	Mean (°C)*	Range (°C)
M1	150	120 to 178	143 ± 1 (66)	170 to 260 (5)
MS	450	105 to 145	130 ± 1 (98)	140 to 260 (23)
M16	600	125 to 185	169 ± 2 (37)	160 to 300 (12)
M22	750	130 to 180	151 ± 2 (63)	200 to 270 (7)
M24	750	130 to 162	143 ± 1 (54)	160 to 280 (7)
M32	1050	140 to 204	169 ± 2 (72)	220 to 260 (3)

(numbers in brackets give the number of inclusions observed)

* Uncertainty in mean is the "standard error of the mean".

Table 6
Homogenization and Gas Disappearance Temperatures
in Inclusions Containing Carbon Dioxide

Sample No.	Mine Level (feet)	CO ₂ fluid-inclusions		CO ₂ fluid-brine inclusions	
		Temperature of Disappearance of Gas		Temperature of Disappearance of Gas	
		Range (°C)	Mean (°C)	Range (°C)	Homogenization Temperatures Range (°C)
M1	150	1 to 5 (3)	3 ± 2	12 to 18 (3)	
MS	450	7 to 12 (7)	9 ± 1	8 to 29 (28)	250 to 400 (8)
M16	600	2 to 15 (16)	7 ± 3	3 to 18 (15)	285 to 390 (10)
M22	750	-16 to 12 (23)	0 ± 5	5 to 10 (7)	270 to 370+ (8)
M24	750	3 (1)	3	2 to 12 (4)	275 to 405+ (7)

(numbers in brackets are the number of inclusions studied)

Table 7
Estimated Mean Temperature and
Pressure of Trapping of Fluids

Sample No.	Mine Level (feet)	Brine-gas (P=2000 bars assumed)	CO ₂ fluid-gas (P=2000 bars assumed)	Intersection of Isovolum Curves	
		Temp (°C)	Temp (°C)	Temp (°C)	Press (bars)
M1	150	290	280	335	2400
MS	450	270	315	260	1640
M16	600	335	300	370	2440
M22	750	305	265	375	2830
M24	750	290	280	335	2400

Estimating the temperature and pressure of trapping of fluids in inclusions from the temperatures of filling is theoretically possible but is hazardous in practice because of the many assumptions required and a lack of accurate pressure-volume-temperature data for the specific fluids involved. In spite of the recognized hazards, some tentative estimated temperatures of trapping were obtained using several methods to determine the extent of agreement or disagreement between the various estimates. One method also gave estimated pressures of trapping. In making these estimates the mean temperatures of filling for brine-gas and CO_2 fluid-gas inclusions (Tables 5 and 6) were used so the estimates are mean values for the respective quartz samples.

The assumptions that were made in estimating the temperatures of trapping of the fluids are as follows:

1. CO_2 -rich fluid and brine were trapped separately in inclusions at the same temperature and pressure.
2. No gas phase was trapped with the fluids.
3. The inclusions have neither gained nor lost material after formation.
4. The volume of each inclusion has remained constant since time of formation.
5. The pressure-volume-temperature data for NaCl brines are approximately the same as for CaCl_2 brines for the concentration of salts found in the brines.
6. The mutual solubilities of brine and CO_2 -rich fluid are sufficiently low so as not to obviate the application of pressure-volume-temperature data for pure CO_2 and 30 weight per cent NaCl brine to the fluids in the inclusions.

As the temperature and pressure of trapping of the fluids are both unknown, a pressure is assumed in order to obtain an estimate of the temperature of trapping. Lemmlein (1956) presents pressure corrections for the temperatures of filling of inclusions containing 30 weight per cent NaCl brine. These data are approximately applicable to the inclusion fluids studied here as freezing point depression measurements indicate between 24 and 34 weight per cent total salt in the majority of brines. For inclusions containing a NaCl crystal in addition to brine, the salt content of brine may approach 40 weight per cent due to partial dissolution of the crystal at the temperature of disappearance of the gas phase. But temperatures of filling from inclusions containing a NaCl crystal are relatively few (15 per cent, see numbers of samples in brackets, Table 5). Table 7 summarizes the estimated temperatures of trapping of inclusions containing brine with no observable CO_2 fluid, using Lemmlein's data and assuming 2000 bars pressure at time of trapping. The estimates range between 270 and 335°C for the five quartz samples studied. As salt in solution lowers the slope of isovolume curves, the temperature estimates for inclusions containing greater than 30 weight per cent salts are somewhat low and for those inclusions containing less than 30 weight per cent salts are somewhat high. However, as the temperature estimate for each sample is based on inclusions containing both more and less than 30

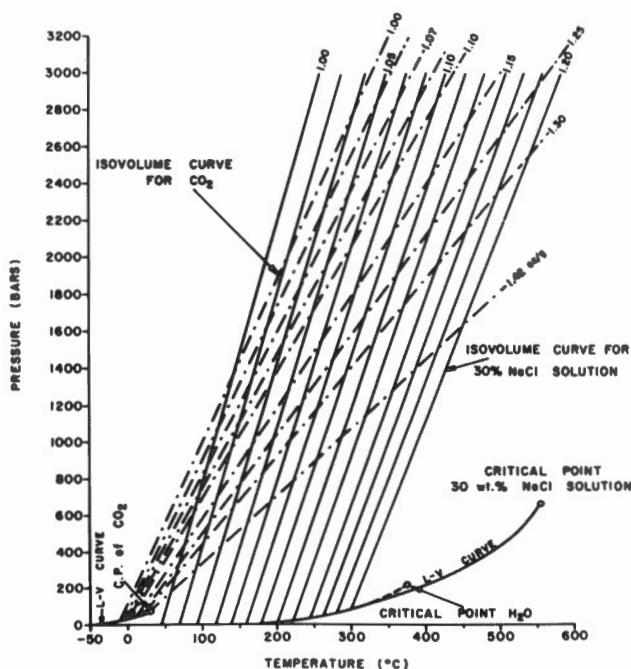


Figure 4. Pressure-temperature diagram showing selected P-V-T data for the systems CO_2 and 30 weight per cent NaCl brine.

weight per cent total salt, these errors are partially compensating. Lemmlein's (1956) pressure corrections for a 30 weight per cent NaCl brine are expressed by isovolume curves shown schematically in Figure 4 (see Smith, 1963, p. 220).

The temperature of trapping of CO_2 fluid-gas inclusions containing no observable brine can be obtained in the same manner as for inclusions containing brine, assuming that the data for pure CO_2 are applicable. Assuming again 2000 bars pressure at time of trapping, the estimated temperature of trapping obtained from the appropriate isovolume curves (Fig. 4) range between 265 and 315°C (Table 7).

If brine and CO_2 fluid were trapped in quartz at the same temperature and pressure, it is theoretically possible to combine the pressure-volume-temperature data for the two appropriate systems to obtain both the temperature and pressure of trapping. Figure 4 shows the appropriate portions of the systems CO_2 (Smith, 1963, p. 81) and 30 weight per cent NaCl brine (Lemmlein, 1956, in Smith, 1963, p. 220). The liquid-vapour curve gives the temperature-pressure relationship for inclusions up to the temperature of filling. Above this temperature, the temperature-pressure relationship is given by an isovolume curve originating on the liquid-vapour curve at the temperature of filling. If brine filled and CO_2 filled inclusions are trapped at the same conditions, the temperature and pressure of trapping are given by the point of intersection of the two appropriate specific volume curves, one for each system. These estimates based on the mean temperatures of filling for five quartz samples listed in Tables 5 and 6 range

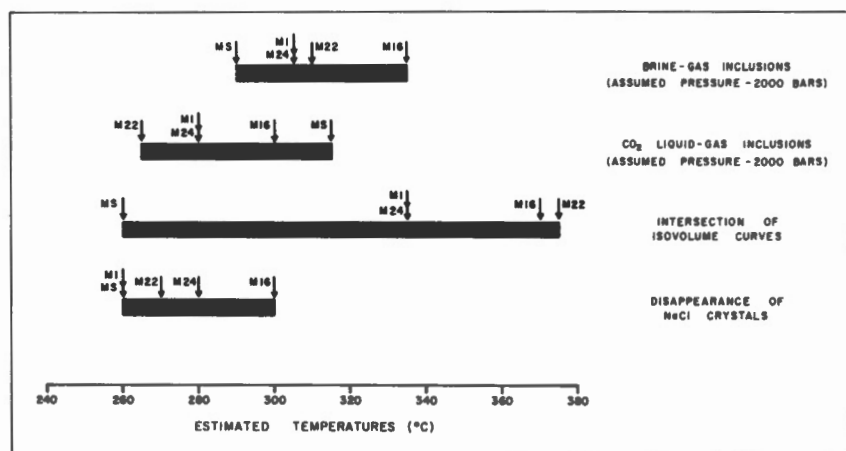


Figure 5. Diagrammatic summary of estimated temperatures of trapping of inclusion fluids using brine-gas and CO₂ fluid-gas inclusions as discussed in text. Maximum temperatures of disappearance of NaCl crystals in each quartz sample are also shown. Position of arrows indicate temperature estimates obtained from various samples as designated.

between 260 and 375°C and 1640 and 2440 bars pressure (Table 7). The pressure estimates are uncorrected for vapour pressure of the fluids.

A summary of the estimated temperatures of trapping is shown graphically in Figure 5 together with the temperatures of disappearance of NaCl crystals in some brine-gas inclusions. The range of temperature estimates obtained from the various samples by each method show a substantial overlap which is encouraging and perhaps suggests that the many assumptions made are approximately valid. It is not possible to judge from a comparison of the estimated temperatures of trapping of inclusion fluids and the disappearance temperatures of NaCl crystals whether these crystals were trapped or crystallized after trapping because of the uncertainty in the temperatures of trapping of inclusion fluids. All the estimated temperatures of trapping of inclusion fluids are considerably below the 500°C level estimated as the temperature of metamorphism of ores and country rocks by Froese (1969). As the quartz veins containing the inclusions cut the ore body and are apparently unmetamorphosed, the relatively low temperatures of trapping of inclusion fluids suggests the development of the quartz veins after partial cooling of ores and country rocks.

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No. 11 HEAT FLOW AND UNDERGROUND
 WATER FLOW IN THE
 CORONATION MINE AREA

A. E. Beck and J. P. Neophytou

ABSTRACT

Measurements of underground temperatures and thermal conductivities have been made in the Coronation mine area. The heat flow value corrected for structural effects is $0.7 \pm 0.2 \mu$ cal/sq cm/sec; no topographic correction is necessary but a correction for Pleistocene deglaciation would add 0.4μ cal/sq cm/sec to this value. The determination of tritium values of surface and underground water samples indicates that the effect of water-flows can be neglected.

TABLE 1

<u>Rock Type</u>	<u>Drift Level</u>	<u>Mineralization</u>	<u>Conductivity and Standard Deviation</u>
Andesite	Surface	Yes	7.8 ± 1.1
Tremolite Gneiss	Surface	Yes	8.0 ± 1.3
Tremolite Gneiss	300 feet	Yes	9.7 ± 0.1
Tremolite Gneiss	450 feet	No	5.7 ± 0.8
Andesite	450 feet	No	4.7 ± 0.4
Tremolite Gneiss	600 feet	No	5.3 ± 1.3
Tuff	1350 feet	No	6.8 ± 0.7

INTRODUCTION

In the summer of 1960 temperature measurements were made in numerous drill holes drilled throughout the Coronation mine near Flin Flon, Manitoba. The mine is a small one being about 300 feet wide, 1000 feet long and 1050 feet deep. The drift depths are in increments of 150 feet from the surface down to 1050 feet with an exploratory drift at 1350 feet.

Coronation is a copper sulphide ore body in basic volcanic rocks and consists of two lenses about 300 feet long which plunge steeply southwards. The two lenses are separated by about 200 feet of low grade disseminated ore and extend to about 1000 feet below the surface.

Temperature Measurements

Only those holes that were horizontal and open to at least 40 feet from the drift wall were used for the temperature measurements. Since the mine was less than five years old at the time the temperature measurements were made, a distance of 40 feet is well beyond the region of temperature disturbance due to ventilation (Misener, 1949; Jaeger, 1956); in some places it was possible to make temperature measurements up to 180 feet from the wall. Water was issuing from some of the holes but in most of these it was possible to push the tip of the probe beyond the point of entry of the water so that undisturbed rock temperatures were obtained. Between 10 and 15 readings of temperature were obtained at each level and an attempt was made to outline the ore body geothermally. Although there was some indication of a slight difference in temperatures between the north and south ends of the mine, the temperature measurements were neither accurate enough nor dense enough to give much weight to this trend. For this reason the average of all readings taken in the particular drift was taken as the temperature for that level. The results are shown in Figure 1.

From Figure 1 it can be seen that the temperatures at 150 and 300 feet are the same, indicating that the minimum temperature probably occurs at about 200 feet; inversion temperatures as deep and deeper than this have been noticed in many areas throughout the world and may reflect a fairly recent climatic increase in temperature. It can also be seen that there is a change of gradient between 550 and 600 feet. The least squares straight lines through these two sections gives $T = 2.6 + 15.3 (\pm 0.8) \times 10^{-5} \times D$ and $T = 3.2 + 11.6 (\pm 1.2) \times 10^{-5} \times D$ where T is the temperature in $^{\circ}\text{C}$, D is the depth in centimeter and the limits on the gradient are the 95% confidence limits.

Conductivity Measurements

Hand samples of typical rocks were collected from a few drift levels. Four discs were prepared from each sample and thermal conductivities determined on a guard-ring type divided bar apparatus (Beck, 1957). The results of the measurements are shown in Table 1, the units being $\text{mcal}/^{\circ}\text{C sec. centimeter}$ in the table and throughout the paper.

From Table 1 the weighted arithmetic means are 9.5 for the mineralized rock and 5.5 for the unmineralized rock, the errors being such that even quoting conductivities to the nearest 0.5 may be somewhat optimistic.

Heat Flow Values

Combining the conductivity data with the temperature gradients it can be seen that the heat flow from 300 to 600 feet lies between 0.8 and 1.4 μ cal/sq cm/sec., whereas between 600 and 1350 feet it lies between 0.6 and 1.1 μ cal/sq cm/sec.

The equilibrium heat flow values can be affected by a number of factors (Beck, 1965). Those that have been considered are underground waterflows, structure and climatic changes (particularly Pleistocene glaciation); the terrain is such that a correction for topographic effect is unnecessary. Details of the investigation into possible underground waterflows will be given later in the paper.

Structural Correction

Because of the complexity of the structure and the distribution of temperature measurement sites, a structural correction is difficult to apply and can be approached only in a rather crude manner. In the upper levels of the mine the distance penetrated by the probe was such that the temperatures were probably being measured just within or beyond the mineralized zone, whereas in the lower levels of the mine the distances penetrated were greater and temperatures were measured well beyond the mineralized zone. Thus the upper limit of heat flow, 1.4 μ cal/sq cm/sec., probably represents the true vertical component of heat flow in the mineralized zone whereas the lower limit of 0.6 is probably closer to the vertical component of the 'normal' heat flow value. Since the ore body is dipping steeply it is reasonable to assume that the mineralized aureole also dips at the same angle. If it is therefore assumed that the vertical component of heat flow in the host rock is 0.6 and that the ore body and its mineralized aureole dips at an angle of 75° then using the mean conductivity values given above and applying a correction for structure (Roy, 1963) we find that the heat flow in the mineralized zone should be 1.6, in reasonable agreement with that observed; if the heat flow in the host rock is assumed to be 0.7 the corresponding value is 1.3, which is again in reasonable agreement with that observed. Because even those temperature measurements made in the lower portions of the mine are still fairly close to the mineralized zone, even though outside it, it is unlikely that the heat flow vector is vertical so that 0.6 represents a lower limit for the heat flow value; for this reason we select 0.7 as a more likely value but because of all the other errors that are difficult to assess statistically, we assign rather large limits. Thus the value of heat flow is given as $0.7 \pm 0.2 \mu$ cal/sq cm/sec. before correction for glaciation effects.

Pleistocene Correction

The area around Flin Flon has undergone Pleistocene glaciation and deglaciation. This correction is also difficult to apply since neither the temperature rise nor the time of retreat is accurately known. However, if the retreat is assumed to have occurred suddenly 10,000 years ago causing the temperature to rise from -2 to +3° C (the present mean annual surface temperature) then assuming that the onset of the glaciation occurred long

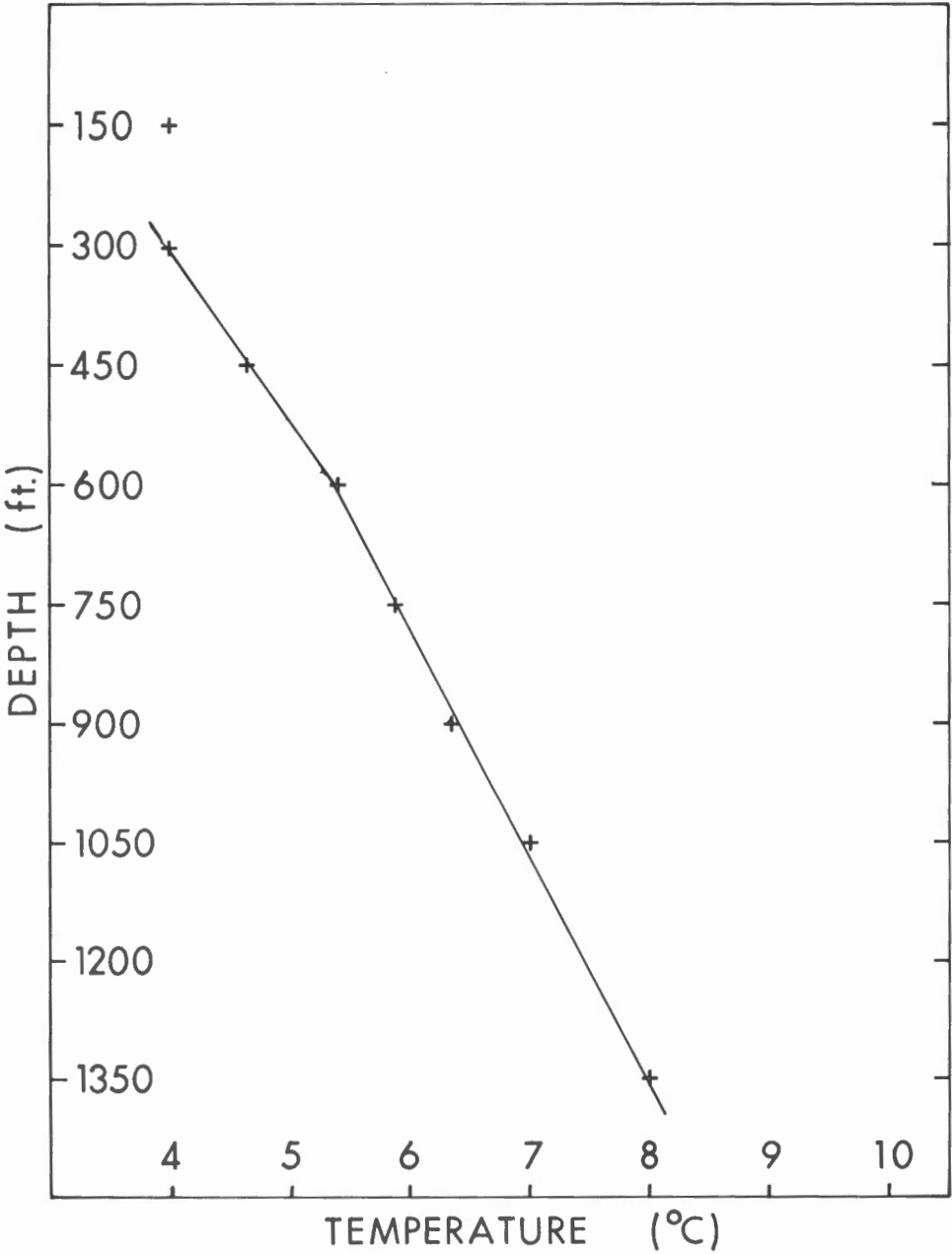


Figure 1. Mean temperature at each level versus depth of level.

enough ago for its effect to be ignored a correction (Jaeger, 1965) for the retreat of the Pleistocene ice sheets would add 0.4μ cal/sq cm/sec. to the observed value.

Tritium in Surface and Underground Water Samples

Water was issuing from a number of boreholes and minor joints on all levels, the flow rates varying from several gal./hr. to very slow drips. It was not known whether such water flows were present originally or had been induced by the introduction of the mine. For this reason two water samples were collected in August of 1961, one surface sample being taken from nearby Phil Lake and another sample being taken from water dripping from a borehole on the 1050 foot level. The analyses yielded the figures of 395 and 75 T.U. respectively where 1 T.U. (tritium unit) = $10^{18} \times {}^3\text{H}/{}^1\text{H}$; since pre-bomb waters contained less than 10 T.U. it was clear that rapid mixing had occurred down to the 1050 foot level although it was not clear whether this was general mixing in the region of the mine or simply local contamination and seepage along joint planes. Between the time the samples were collected and the time they were analysed, hydrogen bomb tests were carried out by the U. S. A. and the U. S. S. R.; it was estimated that these would introduce several tens of kgs of tritium into the upper atmosphere which could be expected to appear as fallout in rain in subsequent years. For this reason plans were made to use the expected tritium peak by collecting and analysing samples from a number of locations in the mine.

This collection was carried out in late July 1962; unfortunately, a critical sample from 1050 feet was lost in transit. Another detailed collection was made in August of 1964. Since that time samples have been collected each year from Phil Lake in order to record the annual decay of the tritium content. The sample location and results of the tritium analyses are given in Table 2. In some cases there was a delay between the time a sample was collected and the time it was analysed; where this occurred the tritium value has been corrected to the value it would have had on the sampling date. This correction amounts to less than 2% and is less than the error of measurement.

In order to analyse the data satisfactorily a comprehensive investigation of tritium production and the influence of meteorological factors on the fall-out pattern was undertaken, and the results compared with those of other workers (particularly Rutherford, 1961, 1964) and with the more comprehensive records kept for the fallout of strontium 90. Details of this work are given elsewhere (Neophytou, 1965) and we shall give here only a broad outline of the procedure and the results.

Most theories use a steady model (e. g. Nir, 1964) but because of the hydrogen bomb tests in 1961 and 1962 a theory based on such a model is not applicable. For this reason a broader theory using an exponentially increasing value for tritium in the input area was developed and applied to determine the transit time and velocity of water circulation in the Coronation mine.

Transit times for the Coronation mine are contoured in Figure 2. The average velocity of the ground water ranges from 150 to 300 feet per year, in reasonable agreement with the velocities reported by Mawson (1964).

Interpretation of Transit Times

Interpretation of the contoured transit times is rather difficult. At first sight it appears that the gross porosity of the rock, that is the porosity

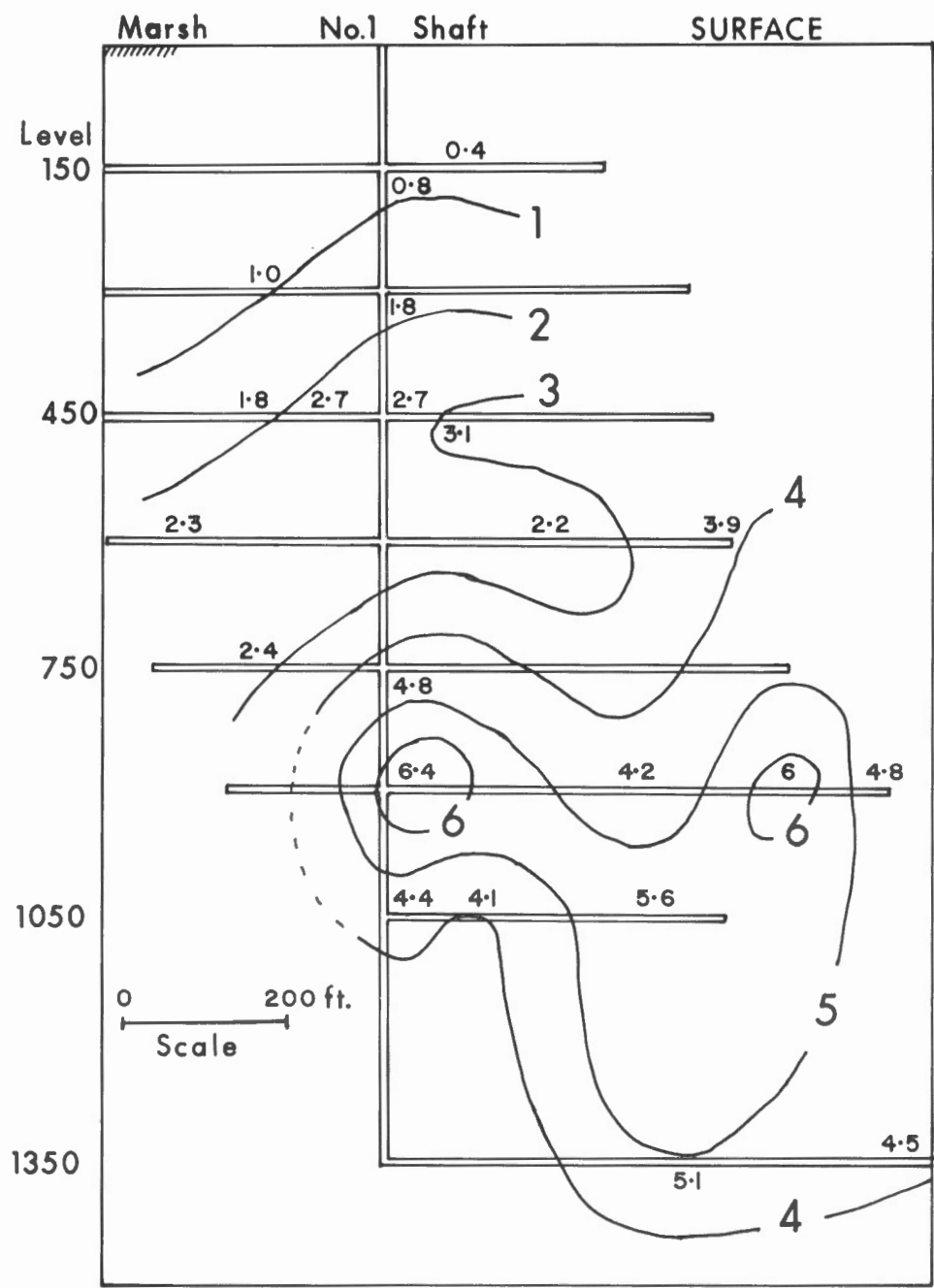


Figure 2. Coronation mine transit times and contours, in years. Section is looking N52° E.

TABLE 2
Tritium Content of Surface and Groundwater Samples
from the Coronation mine

Sample	Sampling Point	Sampling Date	T. U.
S-1	Phil Lake	August 1961	395 \pm 35
D-1	1,050 ft. level	August 1961	75 \pm 7
S-11	Phil Lake	July 1962	968 \pm 48
C-67-1	Rapid drip from borehole, 450 ft. level	July 1962	190 \pm 20
C-67-2	Trickle from borehole, 450 ft. level	July 1962	154 \pm 20
C-135-6	Drip from borehole, 600 ft. level	July 1962	98 \pm 10
No. 5	Very slow drip from roof, 750 ft. level	July 1962	61 \pm 8
C-50-3	Drip from borehole, 900 ft. level	July 1962	31 \pm 6
C-32-4	Very slow drip from borehole, 900 ft. level	July 1962	86 \pm 10
C-265-7	Rapid drip from borehole, 900 ft. level. Possible atmospheric contamination in lab.	July 1962	\leq 60
C-14-9	Slow drip from borehole, 1350 ft. level. Possible atmospheric contamination in lab.	July 1962	\leq 50
C-12-10	Water dripping from borehole, 1350 ft. level	July 1962	81 \pm 10
S-12	Phil Lake, south of rubble path	August 1964	2320 \pm 80
S-15	Phil Lake, north of rubble path	August 1964	2320 \pm 80
S-17	Loon creek near Loon Lake, about 9 mls. north of Phil Lake	August 1964	2300 \pm 50
21	Drip from borehole, 150 ft. level	August 1964	1720 \pm 50
22	Roof drip, 150 ft. level	August 1964	1245 \pm 40
11	Roof drip, 300 ft. level	August 1964	748 \pm 50
24	Slow roof drip, 300 ft. level	August 1964	1110 \pm 30
7	Very slow drip from borehole, 450 ft. level	August 1964	484 \pm 30
14	Water from same hole as in sample 7, after plugging hole overnight	August 1964	480 \pm 28
8	Drip from borehole, 450 ft. level	August 1964	718 \pm 30
9	Roof drip, 600 ft. level	August 1964	545 \pm 30
20	Very slow drip from borehole, 600 ft. level	August 1964	595 \pm 40
4	Slow roof drip, 750 ft. level	August 1964	535 \pm 44
13	Rapid drip from vertical hole, 900 ft. level	August 1964	1140 \pm 40
23	Very slow drip from borehole, 900 ft. level	August 1964	54
3	Moderate flow from borehole, 1050 ft. level	August 1964	187 \pm 33
10	Rapid drip from borehole, 1050 ft. level	August 1964	222 \pm 50
2	Very slow drip, 1050 ft. level	August 1964	96 \pm 35

of a very large volume of the rock including the effects of pores and fissures, is least at the 900 foot level. However, a more likely explanation seems to be that the apparent transit times are affected by mixing and contamination due to holes drilled from the surface and from the drifts at various levels. To help understand the pattern of water flows a three dimensional scale model of the Coronation mine was constructed showing sample sites and the paths traced by surface and underground boreholes. From such a model it became clear that at least one sample, No. 13, had become badly contaminated by a near intersection of an inclined borehole drilled from Phil Lake with one drilled from the 900 foot level. Furthermore several inclined holes drilled from Phil Lake penetrate to the 600 foot level, some of them again passing very close to inclined holes drilled from the 600 foot level. This may explain the rather anomolous appearance at the 600 foot level of the three year transit time contour. In addition, the depression of the transit time contours in the upper left hand portion of the figure, i. e. closer to the lake, would suggest contamination by inclined boreholes drilled from the lake.

It is quite possible that prior to the sinking of the main shaft some underground water flows were present. However, the evidence from the tritium content of the underground water samples suggests that these flows have been considerably influenced by the presence of the mine and that substantial contamination takes place. Since this disturbance is of very recent origin it is unlikely that there has been any significant effect on the heat flow data. Thus the effect of underground waterflows can be neglected.

Because of the importance to future work of knowing the variation of the tritium content of surface waters with time, water samples from Phil Lake have been collected in August of each year up to the present time; Phil Lake is large enough to smooth out high frequency fluctuations of tritium content in rainfall but is probably not large enough to smooth out monthly fluctuations. The data are shown in Table 3.

TABLE 3

Tritium Content of Phil Lake Surface Waters

<u>Date Collected</u>	<u>T. U.</u>
21st August 1961	395 \pm 35
19th July 1962	968 \pm 48
25th August 1964	2320 \pm 60
5th August 1965	1820 \pm 60
15th August 1966	1336 \pm 44
29th August 1967	1010 \pm 30

Acknowledgments

We wish to acknowledge the great assistance received from the mining and geological personnel of the Hudson Bay Mining and Smelting Company. This work was carried out with the aid of grants from the National Research Council and the Geological Survey of Canada; one of us (JPN) was in receipt of a Commonwealth Scholarship. The measurements of tritium were made by Isotopes Inc.

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No. 12 PALEOMAGNETIC STUDY OF THE
CORONATION MINE AREA

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ABSTRACT

Magnetic studies have been carried out on 88 surface and 157 underground samples from the Coronation mine area of northern Saskatchewan. The intensity of the surface samples was compared to trace element determinations from the same locality. A good correlation was found between the titaniferous constituent of the rocks and the intensity of magnetization. From the direction of the remanent magnetism, two virtual geomagnetic poles were determined - latitude $12^{\circ}54'$ North, longitude $158^{\circ}17'$ West; and latitude $23^{\circ}42'$ North, longitude $163^{\circ}45'$ West.

The sulphide ore specimens showed anisotropic susceptibility characteristics. A relationship was found between the measured maximum susceptibility values of the ore specimens and the direction of the tectonic forces which are considered to have formed the structure at the Coronation mine.

Introduction

This paper summarizes the results of a study of the magnetic properties of samples from well known Precambrian formations. The observed data give information for an interpretation of the magnetic field conditions in Precambrian times. The high magnetic intensity values indicate the importance of the study of remanent magnetization of rocks in areas where an interpretation of magnetic maps is to be made. The susceptibility properties exhibited by the studied samples are related to the tectonic conditions under which the rocks were deformed.

Geological Summary

The first group of 88 samples was collected on the surface from 44 sites. The sampled area extends from latitude $54^{\circ}30'$ to $54^{\circ}45'$ north and from longitude $102^{\circ}00'$ to $102^{\circ}15'$ west. Flin Flon, on the Manitoba-Saskatchewan boundary, is 5 miles east of the sampled area. The second group of 157 samples was collected underground in the Coronation mine. The mine is between Table Lake and Kaminis Lake, being southeast of the area described above.

A detailed account of the geology of the area has been published by Byers and Dahlstrom (1954). The collected samples represent three Precambrian lithological units.

1. The Amisk Group. This group comprises the oldest rocks in the region. The samples were taken from a member composed of massive pillowed basic lavas and flow breccias.

2. An intermediate to basic group of intrusive igneous rocks. This group includes quartz diorite, diorite, gabbro and metagabbro in the form of dikes, sills and stocks. The so-called Mosher-Birch Lakes metagabbro and the Birch-Table Lakes metadiorite formations were sampled.

3. Pyroxenite, peridotite and serpentine. These form small irregular bodies and long sill-like masses of ultrabasic rocks. Samples were taken from the Ruth-Table Lakes serpentized peridotite, which outcrops along the east shore of Table Lake.

The geology of the Coronation mine was described by Faulkner (personal communication). The deposit is on the slightly overturned eastern limb of an anticline, the axial trace of which has a northerly strike through Table Lake. The orebody is a replacement of an essentially concordant shear zone in a sequence of metamorphosed volcanic rocks. Those volcanic rocks consist of relatively massive altered dacites, andesites and andesite breccias. The orebody is composed of varying amounts of massive to disseminated pyrite, pyrrhotite and chalcopyrite, with minor amounts of sphalerite and some magnetite.

The samples were collected on the 300-foot, 600-foot, 700-foot and 900-foot levels. Both the ore and country rock were sampled on the 600- and 700-foot levels. On the other two levels, samples were taken only from the wall rock.

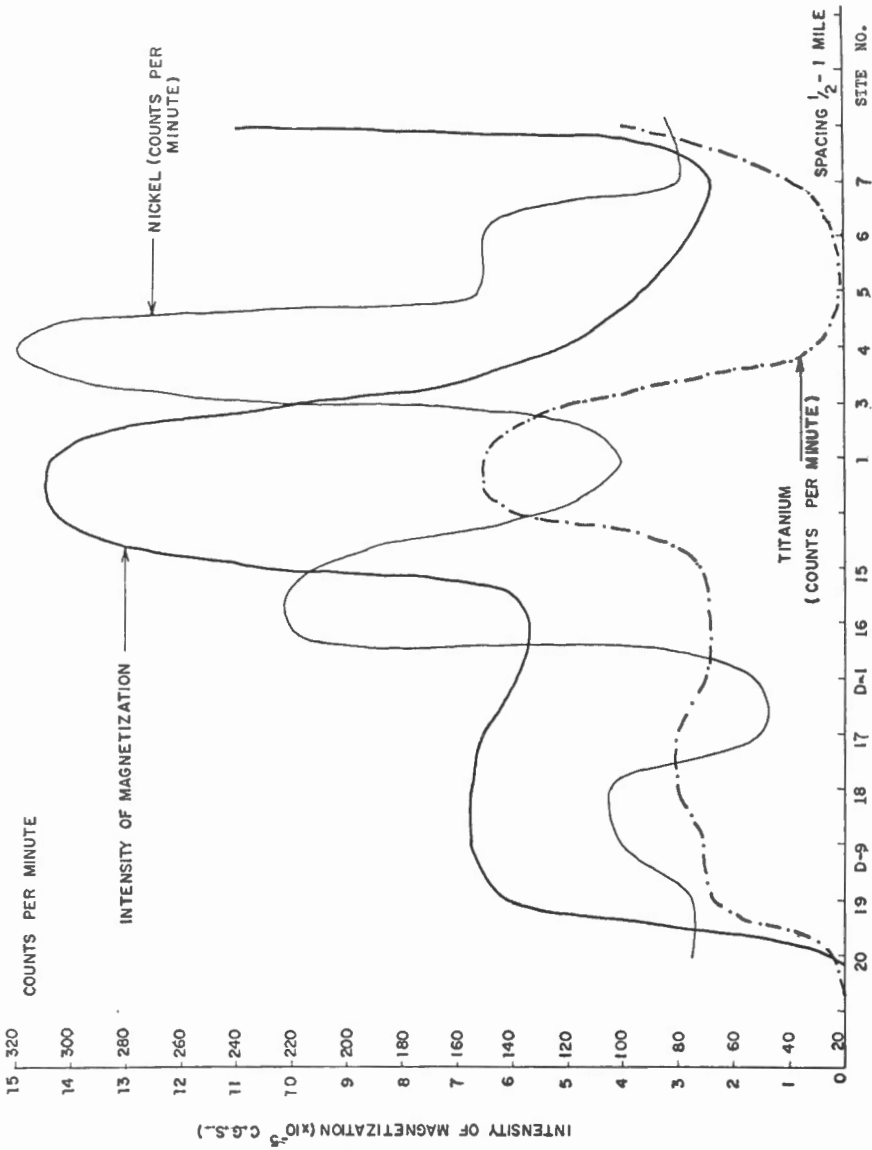


Figure 1. Magnetic intensity and counts per minute for titanium and nickel.

Sampling and Laboratory Investigations

The surface samples were collected using the method described by Graham (1949). A modified method was used for the underground samples (Hajnal, 1963). Because of the high magnetic disturbances in the mine, a transit was used instead of a Brunton compass. The orientations of the samples were determined from the azimuth of the survey lines which were established by mining surveys.

The intensity and the direction of magnetization was determined in a spinner magnetometer (Bruckshaw and Robertson, 1948). This apparatus was of the conventional rock generator type, in which the rock specimen was rotated opposite a fixed coil system at 25 revolutions per second. The instrument's maximum sensitivity was 1.5×10^{-5} cgs. The susceptibility measurements were carried out with a MS-3 susceptibility bridge (Geophysical Specialties Co.), with a maximum sensitivity of 3.5×10^{-6} cgs.

The studied specimens were magnetically cleaned by 50-, 100- and 200-oersted alternating magnetic fields. Then, after two weeks and a month in storage, they were remeasured. The surface specimens gave the same results after every measurement. It was concluded that they are free from soft components and are magnetically stable. In the case of the ore specimens, the observed data were different with every measurement. No measurable stable component was found.

Intensity Measurements

1. Surface Samples

The intensity of magnetization of the different lithological units can be classified as follows:

- (a) Amisk volcanics had intensity values from 2.5×10^{-5} to 2.7×10^{-3} cgs.
- (b) Mosher-Birch Lake metagabbro and Birch-Table Lakes metadiorite had values from 2.4×10^{-5} to 8×10^{-5} cgs.
- (c) Ruth-Table Lakes serpentinized peridotite had intensity variations from 5.3×10^{-4} to 2.68×10^{-2} cgs.

The Saskatchewan Research Council is presently conducting trace element determinations of rocks from the same area. Specimens were analyzed with an X-ray fluorescent spectrometer for several elements. The magnetic intensity values along a line across the sampled area were compared to the titanium and nickel contents of the rock. On Figure 1, the magnetic intensity and counts per minute readings for titanium and nickel are plotted. The titanium content and the intensity of magnetization curves show remarkable similarity. The titaniferous mineral content correlated well with the values of the magnetic intensities and their variations. No correlation can be found with the nickel content. Thus, it is very unlikely that any iron-nickel constituent contributes significantly to the magnetic behaviour of the samples.

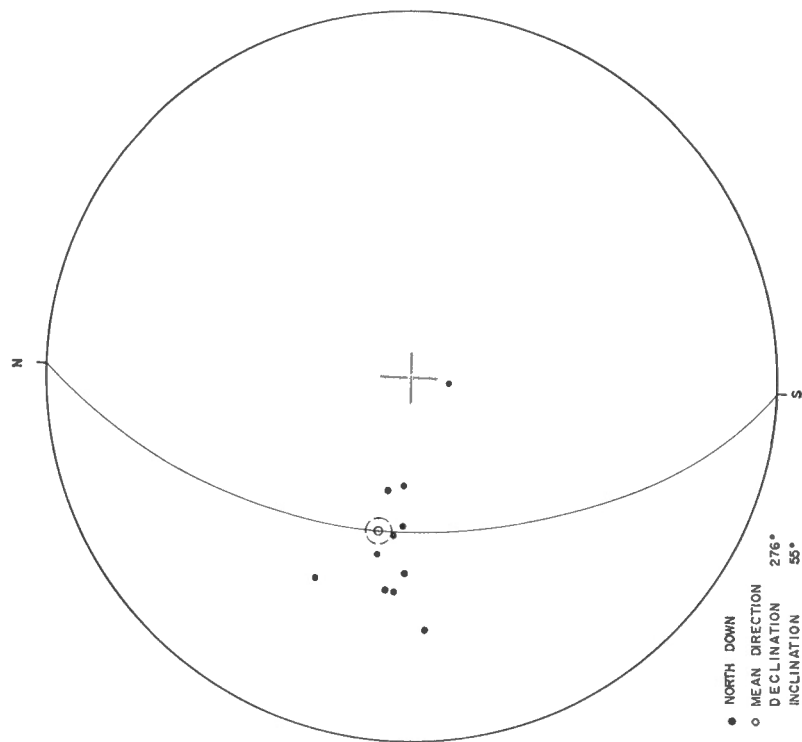


Figure 2. Amisk Group (volcanics).

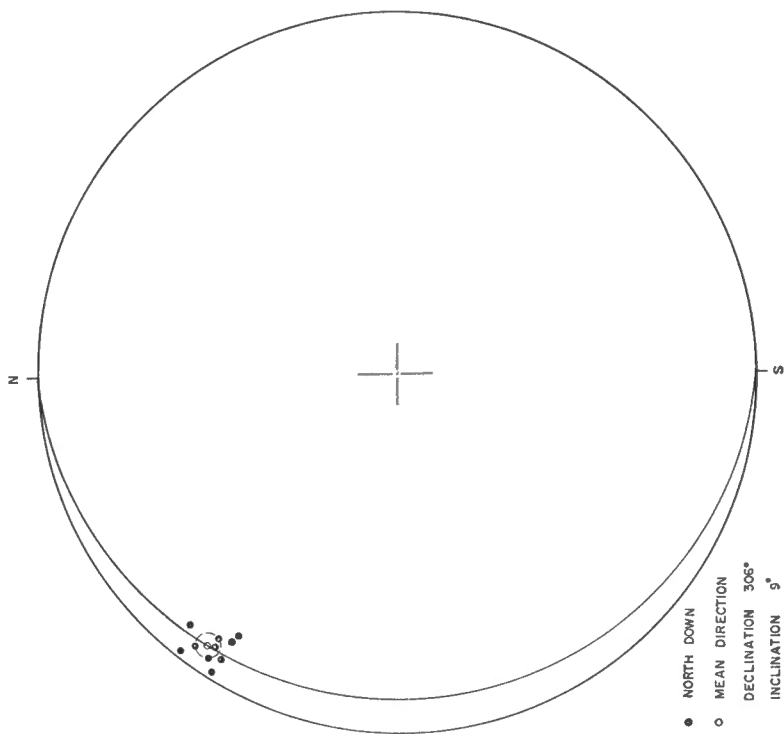


Figure 3. Mosher-Birch Lakes metagabbro; Birch-Lakes metadiorite.

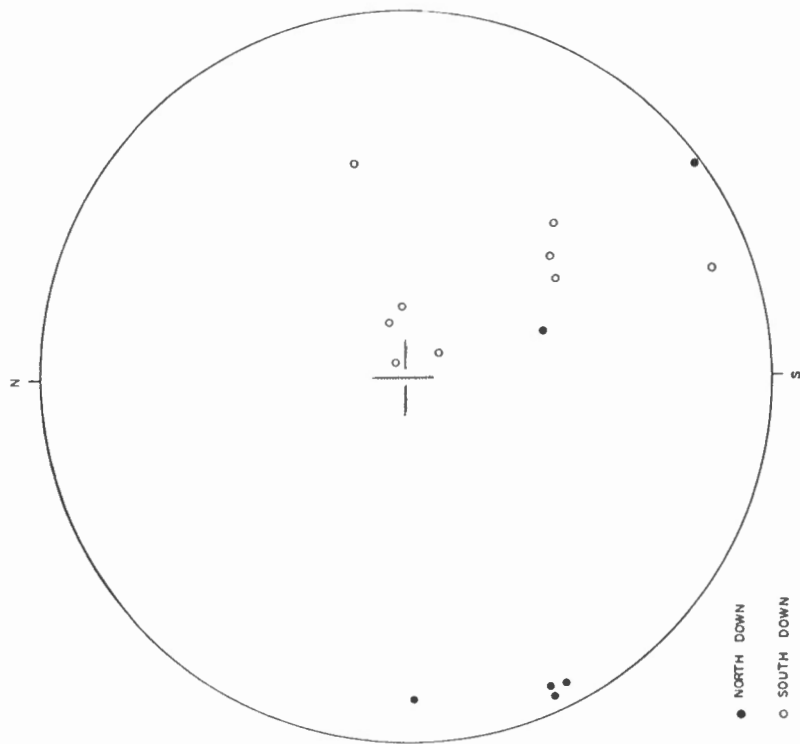


Figure 4. Ruth-Table Lakes serpentinized peridotite.

Magnetic declination and inclination values plotted on equal-area diagrams.

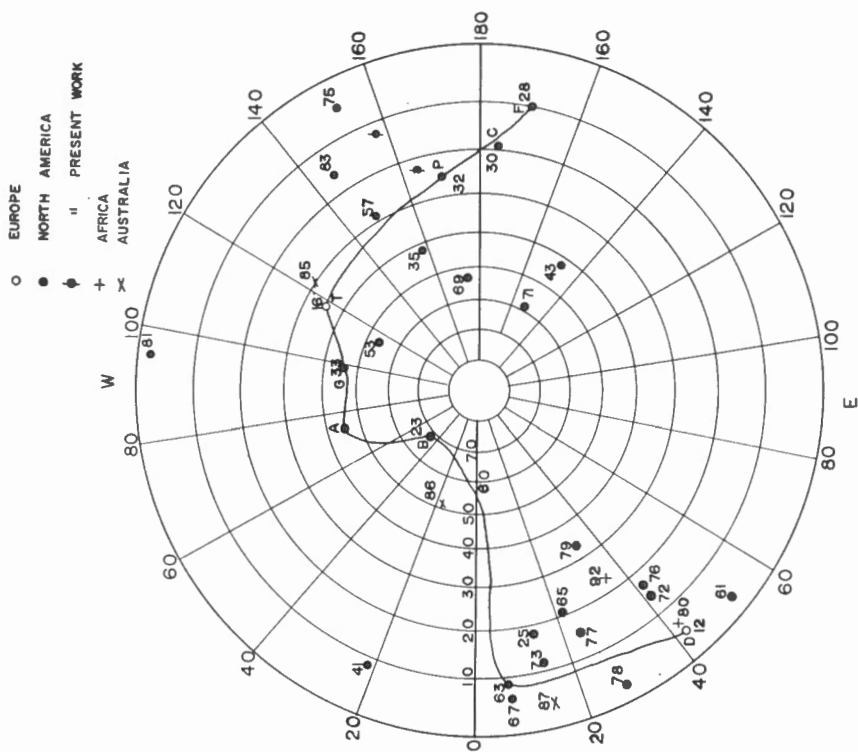


Figure 5. Plot of the listed data for the northern hemisphere.

Magnetic declination and inclination values plotted on equal-area diagrams.

2. Underground Samples

The wall-rock specimens do not show any measurable magnetization. The ore specimens ranged in magnetic intensity from 2.5×10^{-4} to 4.9×10^{-2} cgs. Although all the high intensity values are from the 600-foot level, no vertical or lateral trend is indicated in the obtained results.

Paleomagnetic Studies

The calculated magnetic declination and inclination values were plotted according to lithological units on equal-area diagrams (Figs. 2, 3 and 4). Using Fisher's (1953) statistical analysis, mean field directions were calculated for the Amisk Group, the Mosher-Birch Lakes metagabbro and the Birch-Table Lakes metadiorite. The results are shown on the respective diagrams. On Figure 4, the values from the Ruth-Table Lakes serpentinized peridotite specimens are extensively scattered. Thin-section studies on these rocks indicate not just a high degree of metamorphism, but also lineation and foliation. Many of the crystals of tremolite are bent and broken. Thus, strong deformation of the rock could explain the scattering of the direction of magnetization.

From the mean field directions, the positions of the virtual geomagnetic poles were determined as follows:

Amisk Group		Latitude $12^{\circ}54'$ north Longitude $158^{\circ}17'$ west
Mosher-Birch Lakes metagabbro	}	Latitude $23^{\circ}42'$ north Longitude $163^{\circ}42'$ west
Birch-Table Lakes metadiorite		

Recently, a large number of similar observations have been carried out on Precambrian rocks around the world. Most of the data were listed by Cox and Doell (1960). To compare the present results with the previous information, the listed data were plotted on Figure 5. The two poles determined by the present work fit in with the general arrangement and, more specifically, with the measurements made on the North American continent.

In general, it can be seen that all the paleomagnetically studied Precambrian formations are magnetized in directions significantly different from that of the present field. Although the extremely old age and alteration of some of the examined rock formations make some of the results questionable, the evidence strongly suggests that the earth's field was not parallel to its present direction in Precambrian times. There is some scatter of the calculated virtual geomagnetic poles, but they do not appear to be entirely random. Most of the poles fall in a region covering about one-third of the hemisphere and are concentrated in the vicinity of 160° west and 20° east.

No paleomagnetic studies were made of the ore samples, because they were found to be magnetically unstable. Sopher (1961) observed similar characteristics with the sulphides from the Sudbury Basin.

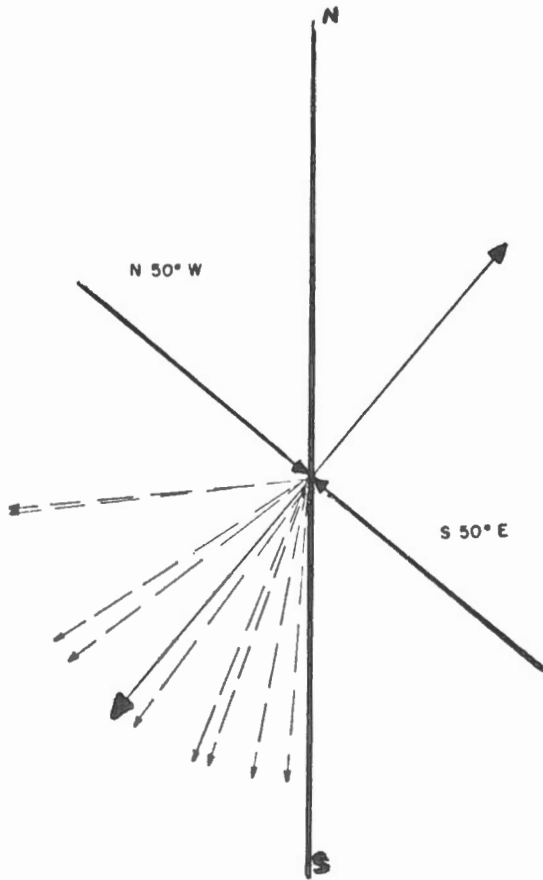


Figure 6

Susceptibility Measurements

Magnetic minerals can display anisotropic susceptibility characteristics. Uyeda (1963) found that both shape and crystalline anisotropy of susceptibility have an effect on the direction of the thermo-remanent magnetization. The regrowth of minerals in response to geologic stresses is a likely cause of both shape and structure susceptibility anisotropy.

According to these observations, all specimens used in paleomagnetic work should be tested for susceptibility anisotropy. Thorough investigation would involve susceptibility measurements in three directions and a computer program for calculations (Girdler, 1961). This could not be done due to a lack of facilities. However, a simple test for anisotropy was made using the following procedure. Two cores were drilled from a sample, one parallel with the direction of orientation and one at right angles to it. If the sample has a uniform composition, but the susceptibility value of the two cores from the same sample is different, this indicates that the sample has anisotropic susceptibility.

The measurements made on the Amisk Group indicated that there were no changes in susceptibility values within one sample. Similar conditions were found with the Mosher-Birch metagabbro and the Birch-Table meta-diorites. There were variations in susceptibility from 25×10^{-6} to 95×10^{-6} cgs., with respect to the different sites. These variations appear to be due to changes in composition, as indicated by the intensity measurements.

The Coronation wall-rock samples showed such weak susceptibility that no change within individual specimens could be measured. Every ore specimen, on the other hand, showed changes individually, and there was also a variation from site to site.

Nagata (1961) indicated that metamorphic rocks have greater anisotropic factors and high susceptibility directions associated with the dominant plane in the rock. When there is a linear structure, the direction of maximum susceptibility coincides with that of lineation. If this is a general condition, the observed susceptibility variations for the ore specimens should show a relationship to the acting stress which formed the shear zone in the Coronation mine. This shear zone is part of the Ross Lake fault system. The probable mechanics of faulting for the whole system were described by Byers (1962).

There are several theories to explain the origin of this fracture system. The most widely accepted one is a north-south counter-clockwise couple, the couple having a direction of $S5^\circ E$ and $N5^\circ W$. Figure 6 shows the approximate position of the horizontal compressive and tensile stress developed by the couple, as well as the direction of the measured maximum susceptibility values for the ore specimens. The diagram indicates that the compressive stress was responsible for the development of variations of susceptibility within the individual ore samples. The scattering can be explained by the imperfection of the method that was used, as the cores were drilled in randomly selected directions. It is very unlikely that any of them define the true maximum susceptibility direction, but it is seen that all the greater values of the measured susceptibility directions trend toward the southwest.

Conclusions

The main result of the magnetic measurements of the Precambrian rocks is that the estimated geomagnetic pole positions differ significantly from the position of the present geomagnetic pole, which agrees with previous measurements on Precambrian rocks. There is some scatter of the calculated virtual geomagnetic poles, but they do not appear to be entirely random. Many more observations are needed to make a definite interpretation. However, the present evidence supports the suggestion that the earth's field in Precambrian time was not parallel to its present direction.

The present susceptibility measurements indicate that tests for susceptibility anisotropy are a necessary part of the investigation of magnetic properties. The results show the importance of the anisotropic behaviour in geological interpretation of magnetic data. It may be possible to explain the different stress conditions acting at certain times by using this method.

The practical use of the study of intensity of magnetization is connected with exploration. Studying the intensity of magnetization in an area of an airborne magnetic survey may influence the interpretation of magnetic

maps. The remanent component of magnetization can be oriented in any direction, therefore increasing or decreasing significantly the induced component. Thus, an anomaly may not represent the true concentration of high susceptibility materials such as magnetite.

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No. 13 A PRELIMINARY INTERPRETATION
OF THE CRUSTAL STRUCTURE
WEST OF FLIN FLON

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ABSTRACT

Six crustal seismic recordings were made at sites along the Hanson Lake Road, in an area to the northwest of the Coronation mine. In addition gravity readings were also made at one mile intervals between Milepost 110 and Milepost 224. A preliminary interpretation of the seismic data suggests a two layer upper crust with a 6.0 km/sec. layer overlying a 6.4 km/sec. layer at 10 km and possibly an increased total thickness of crust of the order of 40 km. This layering in the upper crust may be a feature of the Churchill structural province, as a similar velocity layering has been found in southern Saskatchewan and Alberta. Because of the irregular areal disposition of the gravity stations, no quantitative interpretation of this data was attempted, but all of the anomalies could be satisfactorily explained in terms of changes of rock type in the upper few kilometres of the crust.

Introduction

Recent geophysical evidence, particularly in the Soviet Union (Kosminskaya, 1967), has shown that different tectonic zones are associated with crustal blocks of different structure and thickness. The larger blocks are often characterized by distinct upper mantle properties and a crust-upper mantle block may form the basic unit for certain zones. There is also evidence for a possible relationship between metallogenic provinces and crust-upper mantle blocks. Information on the crustal structure in the vicinity of Coronation mine and other ore deposits in the Flin Flon area may therefore be of assistance in explaining their origin.

Investigation of the crustal structure in the Flin Flon area was commenced in 1961, in a joint project between the Institute of Northern Studies, University of Saskatchewan and the Department of Geology, University of Manitoba. Deep seismic soundings were made at seven recording sites in an approximately north-south line between Flin Flon and Mafeking, Manitoba. In 1964, additional seismic records were obtained along this same line by the University of Manitoba and a crustal cross-section based on an analysis of the travel time data for direct, head and converted head waves has been reported by Hall and Brisbin (1965). The data were interpreted in terms of a two layer crust; the depth to the Conrad discontinuity varying from 15.5 ± 1 km near Flin Flon to approximately 10 km near Mafeking, while the depth to the Mohorovicic discontinuity varies from 34 ± 1 km to 31 ± 1 km over the same distance. This decrease in depth to both discontinuities occurs across the boundary between the Churchill and Superior Precambrian provinces. Wilson and Brisbin (1960) had previously interpreted the gravity high in this region as being associated with a major crustal upwarp at the boundary of the provinces. It is therefore possible that the Superior and Churchill provinces are characterised by different thicknesses of layers.

In 1964, six seismic records were also obtained at sites along the Hanson Lake Road by a seismic crew from the University of Saskatchewan using the same shots as recorded by the University of Manitoba. In the following summer of 1965, gravity measurements were made at one mile intervals along the Hanson Lake Road. The main purpose of this paper is to present the data obtained in the seismic and gravity surveys and to make a preliminary interpretation of the crustal structure in the Churchill province, west of Flin Flon.

Fieldwork

Location of shotpoint and recording sites

The location of the shotpoint and seismic recording sites are shown in Figure 1. All of the shots were fired at a depth of 100 feet in the flooded workings of the North Star mine, in the bottom of Lake Thompson, Manitoba. The charges consisted of 50-pound boxes of Geogel, which were roped together in a column and lowered into the workings from a boat. One charge of 100 pounds, three charges of 400 pounds, one charge of 500 pounds and one charge of 600 pounds were used; the charge size being increased with increasing shotpoint to recording site distances. A detailed plan and cross-section of the shot location is given in Hall and Brisbin (op. cit.).

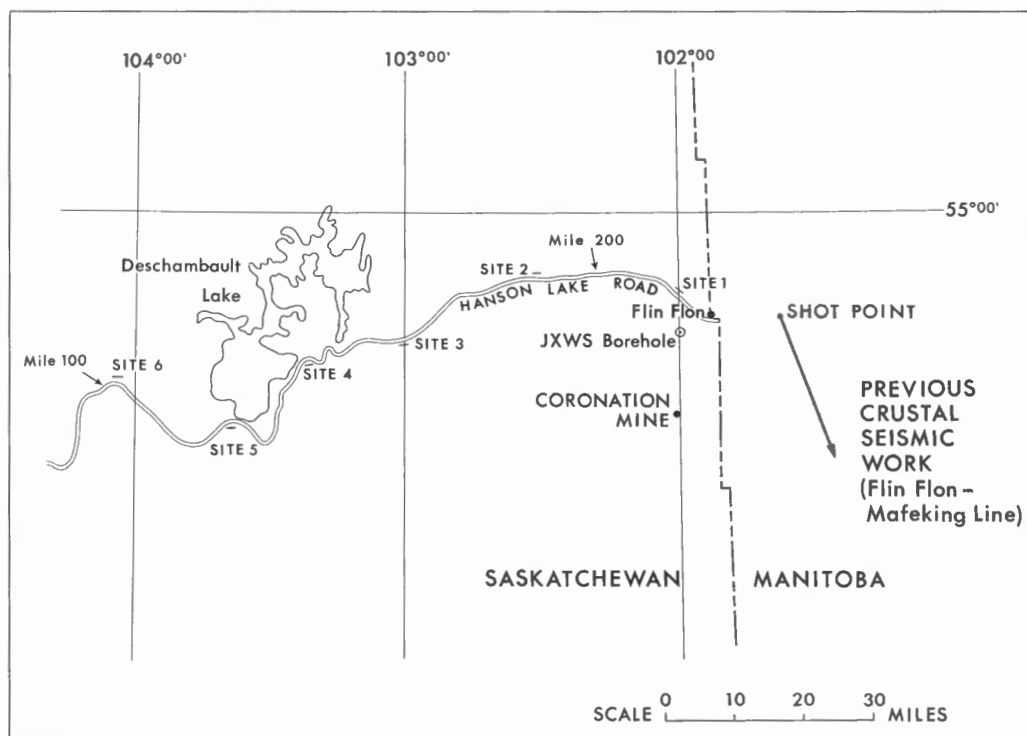


Figure 1. Location map.

In-line spreads of geophones were laid at each of the recording sites. The distance between the first and last geophone was restricted to 0.89 km because only this amount of cable was available. All the spreads were arranged to be as nearly parallel to a radial line from the shotpoint as possible; their actual orientation being obtained subsequently from the Saskatchewan Department of Natural Resources road plans of the Hanson Lake Road. Recording site 1 was established on acidic to intermediate lavas of the Amisk Group, while recording site 2 was established on a Pleistocene sand and gravel deposit, which covers rocks of the Amisk Group. Recording site 3 was located along the road where granodiorite outcropped. Dolomites and sandstones of Upper Ordovician age underlie drift deposits at recording sites 4, 5 and 6. The shotpoint and recording sites were tied in by survey traverses to bridges, benchmarks or other features which could be identified on topographical maps of various scales. The positions of each site was then

transferred to Department of Energy, Mines and Resources maps of scale 1:253,440 and the distance between shotpoint and recording site measured. All distances are considered to be accurate to ± 0.1 km, which is sufficient for this type of investigation.

Gravity stations were established at each milepost along the Hanson Lake Road from mile 110 to mile 225, and the data plotted on a Saskatchewan Department of Natural Resources map of scale 1:253,440. The elevation of each station was obtained by series levelling connections to Geodetic Survey of Canada Bench Marks.

Recording equipment and procedure

A twelve-channel recording system, consisting of Southwestern Industrial Electronics, P. T. 100 amplifiers, coupled to a VRO photographically recording oscillograph, was used to obtain seismograms at each location. McManis (1961) has given a detailed description of the amplifier and filter section of this equipment, which is a broadband recording system with an essentially flat, frequency response between 5 and 500 cps. Recordings were made at a paper speed of 5 inches per second, with the record length varying from 30 to 60 seconds. WWV radio receivers, manufactured by Specific Products, provided an absolute time signal at the shotpoint and recording locations.

The seismic waves were detected by ten Geospace, HS1, 2 cps vertical-component geophones; one, HS1, 2 cps, radial, horizontal-component geophone and one, HS1, 2 cps, transverse, horizontal component geophone, all arranged in an in-line spread. It was necessary to bury the geophones to a depth of about one foot to provide good ground to geophone coupling and to lessen the effects of wind noise.

Gravity measurements were made with a Lacoste-Romberg, thermostatically-controlled gravimeter, which has a sensitivity of approximately 0.01 milligal. The closed loop method of surveying between control stations was used, with readings to check the drift of the gravimeter being taken every two hours. Gravity values were referred to the Canadian gravity control network by including the Dominion Observatory, primary station, excentre connection (station 9460-60), at Flin Flon, in the first loop.

Results

Seismic data

All events were 'picked' on the basis of distinct amplitude and frequency change of the seismic traces. Each event was timed at the centre of spread to the nearest 0.01 second. Table 1 contains the times for the 'well defined' arrivals on the six records.

Table 1

Record No.	1	2	3	4	5	6
Distance from SP in km	29.3	59.6	93.1	115.2	141.2	165.7
Times of events in seconds	4.88	9.84	15.44	19.11	23.08	26.96
	5.08			19.26	23.50	27.69
	6.21			20.20	24.03	28.59
	8.36			21.84	25.39	29.26
	9.26			22.26	26.21	46.84
	9.90			37.66	42.65	47.85

It was only possible to pick the first arrival of seismic energy on record 2, as the high background noise level at this site completely obscured later arrivals. On record 3, the WWV time signal was inadvertently cross-fed to all of the recording channels and it is again only possible to distinguish the first arrival of seismic energy. The events on the other four records may be split into two groups of arrivals. The first group were all recorded at times within 3 seconds of the first arrivals while the second group were much later, appearing at times that are about twice the first arrival time. These respective times suggest that the first group of waves has travelled predominantly as compressional waves and the second group as shear or possibly boundary waves. This conclusion is supported by the relatively high frequencies of the first group, 8-20 cps, compared to those of the second group, 5-10 cps. Reduced travel times of the first group of arrivals (i.e. the difference between the actual travel time of the event and the time required for a wave to travel an equivalent distance at 6 km/sec) are plotted against distance in Figure 2. There are too few events in the second group for a similar representation of their travel times to be useful.

It is possible to fit two straight lines to the first arrival times (A and B in Fig. 2), which can then be interpreted as representing a two-layer model in the upper crust. Least squares slopes of these lines give velocities of 6.0 km/sec and 6.4 km/sec. for the two layers respectively. Secondary arrivals at recording sites 4, 5 and 6 were also included in the determination of the best straight line fit for the first layer. Well shooting data for the JXWS, Flin Flon borehole 'A', at Meridian Lake (Fig. 1) support the velocity value for the first layer (Geophysical Logs, 1966). An average vertical velocity of 6.0 km/sec. was obtained for the 10,000 feet (3.03 km) section of rocks penetrated by this borehole. A thickness of 9.5 km for the first layer satisfies the delay times associated with the headwaves from the second layer.

Because of the lack of 'well defined' secondary arrivals, it is difficult to obtain reliable information on the deeper structure of the crust. However, some of the secondary arrivals at recording sites 4, 5 and 6 do follow an 8 km/sec trend on the reduced time plot, which is a characteristic velocity for the upper mantle. If the first events, associated with this trend, are taken to represent the Pn head wave, then a crustal thickness of approximately 40 km is indicated. Support for a crustal thickness of this magnitude

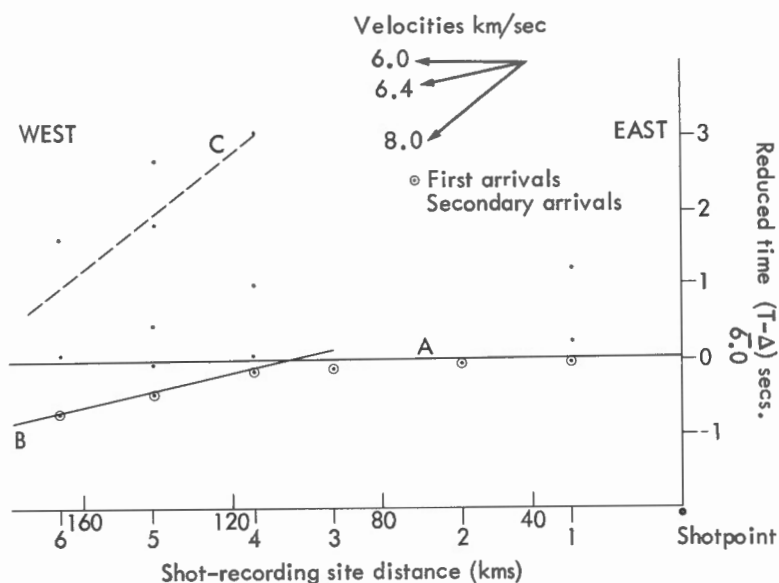


Figure 2. Reduced time plot.

is given by the last events recorded at sites 4, 5 and 6, if these events with an apparent velocity of 4.7 km/sec are identified as S_n head waves.

The few events which have not been identified, and others which were not 'well defined' enough to pick on the seismic records, may represent an intermediate layer in the deep crust, or alternatively converted wave arrivals. The presence of an intermediate layer would increase the estimate of crustal thickness. There is insufficient evidence to support such an interpretation with the data available.

The duration of some of the 'well defined' events may also be a result of the interference of two distinct phases. For example, the events associated with the 6.0 km/sec layer, at sites 4, 5 and 6, may contain a contribution from the wide angle reflections from the second layer. From the calculation of theoretical times, these wide angle reflections would only be delayed by a tenth of a second or so after the arrival of the direct wave and, at the distances involved, would have a similar apparent velocity.

Gravity data

Bouguer anomaly values were obtained from the gravity observations by making corrections for elevation, the Bouguer slab effect using a density

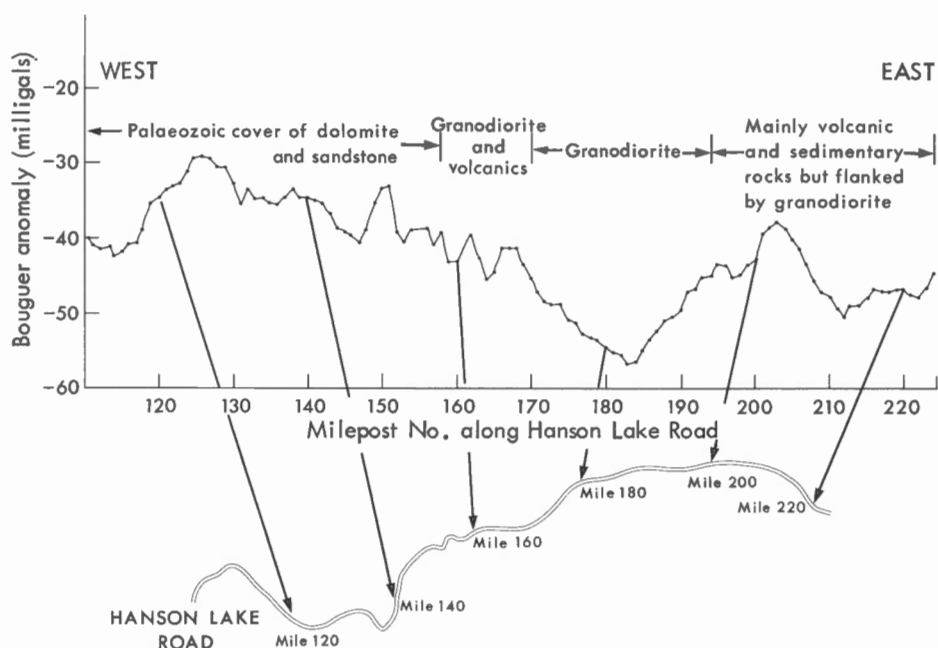


Figure 3. Bouguer anomaly values along Hanson Lake Road.

of 2.67 gm/cc and latitude. Because of the lack of maps with contoured elevations, no terrain corrections were made, introducing errors of possibly a tenth of a milligal or so in the absolute value of Bouguer gravity at a particular station. The Bouguer anomalies are plotted against distance along the road in Figure 3, which also shows the plan of the road and the near surface rock type in the vicinity of the road.

Because of the variable directions taken by the Hanson Lake Road, the gravity data represents essentially spot values. It is therefore impossible to make reliable estimates of the dimensions of subsurface rock units from this scattered data and no quantitative interpretation has been attempted.

A loose correlation of the relative magnitude of the gravity anomaly with rock types at various locations along the road is shown in Figure 3. For example, the lowest values were obtained between mile 175 and 190, in the vicinity of granodiorite. Higher values, to the east, are associated with the exposed volcanics and metasediments. However, to the west, the values again increase and it is difficult to reconcile this increase with the Ordovician

dolomites and sandstones which outcrop in this area. In this case, the rise in gravity values may be due to an increase in the proportion of basic volcanic rocks underlying the Paleozoic cover, south of Deschambault Lake. Such rocks are exposed in areas to the north and east of the lake. All of the anomalies can be explained in terms of variations in thickness of rocks in the upper part of the crust. No further interpretation is justified until an areal coverage of gravity data is obtained.

Discussion of Seismic Results and Conclusions

From the seismic data available, it appears that the upper crust in this area is divided into two layers represented by velocities of 6.0 km/sec and 6.4 km/sec. Velocities of the order of 6.4 km/sec, at a pressure equivalent to a depth of 9.5 km, have been obtained in laboratory measurements of samples of gneiss (Christensen, 1965) and diorite (Volarovich *et al.*, 1967). Velocities of the order of 6 km/sec have been obtained for a great variety of rocks at pressures equivalent to those in the first layer. The 6 km/sec. velocity probably represents the average of a whole sequence of rocks of various composition, representing the many rock types mapped in the area. One explanation of the two layer model is that the first layer represents a sequence of metasedimentary granitic and volcanic rocks of relatively low velocity, overlying an older crustal layer of either dioritic composition or gneissic equivalents of acidic to intermediate rocks. The thickness of 9.5 km, derived from the seismic data, is compatible with geological information for the area. The exposed thickness of the Amisk group has been estimated as probably in the order of 21,000 feet (6.4 km) by Byers and Dahlstrom (1954). The steep isoclinal folding of the strata would tend to increase the vertical extent in depth of the rocks, so that a thickness of 9.5 km is an acceptable value for the whole sequence, with the relatively low velocity indicating a predominance of rocks of acidic composition in the overall vertical section.

It is interesting to note that a similar layering in the upper crust has been found in seismic crustal studies in southern Saskatchewan and Alberta. Cumming and Kanasevich (1966) have presented a model, for a reversed seismic refraction profile between Swift Current and Suffield, which contains three crustal layers beneath the sediments, in the following sequence:

Depth below surface	2.02- 2.24 km	Velocity	6.16 km/sec.
" " "	10.4 -12.5 km	"	6.5 km/sec.
" " "	33.4 -35.5 km	"	7.15 km/sec.
" " "	43.2 -46.9 km	"	8.08 km/sec.

If the increased depth of burial is taken into account, and some lateral variation in composition is allowed, the two upper layers correlate well with the 6.0 km/sec. and 6.4 km/sec. layers interpreted from the results along the Hanson Lake Road. As both locations belong to the Churchill province, this type of layering in the upper crust may be characteristic of this particular structural province.

The paucity of the data makes the interpretation of 40 km for the crustal thickness of questionable reliability. The possibility does exist however that the Churchill province, west of Flin Flon, is characterised by an increased thickness of crust. This increased thickness may be associated

with major fractures in the crust. However, before the crustal model can be considered as established, additional seismic and gravity data will have to be obtained.

Acknowledgements

The author wishes to express his thanks to Dr. A.R. Byers and Mr. D.J. Gendzwill for critically reading the manuscript.

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No. 14

A GRAVITY SURVEY IN THE
AMISK LAKE AREA, SASKATCHEWAN

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Saskatchewan Research Council
Physics DivisionABSTRACT

A gravity survey was carried out over an area of about 200 square miles near Amisk Lake, Saskatchewan, including the Coronation Mine. Eight hundred and forty gravity measurements were made and densities of 1585 rock samples were determined. The gravity field was found to be almost wholly determined by the densities of outcropping rock units assuming moderate extrapolations to depth. The acidic to basic volcanic and intrusive rocks of the Amisk group need extend to depths ranging from 3 to 4.7 kilometers to explain the gravity anomalies. Below this depth the volcanic rocks either rest on lighter rocks or have substantial quantities of acidic material emplaced in them, suggesting that basic Amisk rocks grade downward into Kisseynew type material. Seismic data, though scanty, tend to support this conclusion. A gravity interpretation chart is presented for determining the thickness of a slab with uniformly varying density.

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INTRODUCTION

A gravity survey was carried out in part of the Amisk Lake area of Saskatchewan in the summers of 1965 and 1966 as part of a continuing investigation by the Saskatchewan Research Council. The Coronation mine is included in the gravity map area. The objective was to study the gravity field as it is affected by certain aspects of the local and regional geology. The map area extends from latitude $54^{\circ} 33.8'$ to $54^{\circ} 47.3'$ north and from longitude $101^{\circ} 50.9'$ to $102^{\circ} 23.1'$ west. The dimensions are 21.9 miles east-west by 15.3 miles north-south. The gravity survey covers approximately the central two-thirds of the map area. Except for the thin strip east of the Provincial border, the map lies within the areas described in Saskatchewan Department of Mineral Resources reports No. 14 and 62 (Byers *et al.*, 1954 and 1965). The many large, island-dotted lakes in the area provide ready access by boat and good elevation reference, eliminating the need for much levelling.

To aid in the interpretation, densities were determined for 1585 samples of rock.

This work has been supported entirely by the Saskatchewan Research Council and is one of a series of investigations of the Amisk Lake-Flin Flon area by the Saskatchewan Research Council and the University of Saskatchewan. The work will also be part of a Ph.D. thesis in geological Sciences at the University of Saskatchewan. Both the University and the Saskatchewan Research Council have consented to this publication.

In particular I would like to thank Dr. K. B. Burke and Dr. A. R. Byers of the University of Saskatchewan, and Dr. J. R. Smith of the Saskatchewan Research Council for advice and discussion freely given concerning this paper. The Hudson Bay Mining and Smelting Company provided a grade profile for the Coronation mine railroad and access to their property for survey purposes. K. McConnell of the Dominion Observatory established a number of gravity control stations at convenient points within the map area and provided a quantity of unpublished gravity data for a large surrounding region.

GRAVITY SURVEY AND REDUCTION

The gravity readings were made with a La Coste Romberg thermostated gravity meter, serial No. 52, with scale constant 1.045 milligals per unit in the range of interest, readable to 0.01 unit. Due to its thermostated design, the meter had a very low drift rate amounting to only $1/2$ milligal in almost two months of operation. The calibration was verified at Primary Gravity stations established by the Dominion Observatory at Regina, Saskatoon, Prince Albert, and Flin Flon. The total gravity field was taken with reference to the Flin Flon area control stations of the Dominion Observatory. Data from these 25 control stations are included in the Bouguer map, Figure 5. The gravity field at the Flin Flon C.N. Railroad station (Primary Gravity Station 9463-60) is $981.39164 \text{ cm/sec/sec}$ (McConnell, 1965). The raw gravity data were corrected for drift and tide. Free air and Bouguer corrections using density 2.67 were made to sea level. The Bouguer anomaly is calculated with respect to the International Gravity

Formula, $g_o = 978.049 (1 + .0052884 \sin^2 \phi - .0000059 \sin^2 2\phi)$. Extreme values of -12.7 milligals maximum and -41.8 milligals minimum were found. About 840 gravity stations were read.

A station spacing of about 1/2 mile was desired but the terrain prevented this in many areas, whereas much closer spacing was achieved in some localities. The overall station density is nominally 4 stations per square mile in those parts of the map area which were surveyed.

Terrain corrections were not applied. Accurate topographic maps are unavailable. Steep-sided rocky knobs or ridges rise 20 to 30 feet above the level of swamps and lakes. The depth of the swamps is unknown, but the depth of most lakes is shallow, generally less than 30 feet with the exception of certain portions of Amisk Lake that exceed 115 feet in depth (Saskatchewan Department of Fisheries). As care was taken to read the gravity meter well removed from steep slopes or cliffs and since the station spacing was broad and a contour interval of 1 milligal was desired, it was felt that neglect of the terrain correction was justified.

LEVEL SURVEY

Elevations were taken with rod and level along the roads in the area. Lake levels were established, thereby providing good elevations for all points along the shore. The Hudson Bay Mining and Smelting Company provided a railroad grade profile for elevations along the Coronation mine railroad. For points away from roads or lakeshores an American Paulin Surveying "Terra" Altimeter was used in conjunction with a recording base barograph to correct for barometric variations. Both instruments are readable to 1 foot elevation. In tests on known elevation points, the altimeter achieved an accuracy of ± 3 feet. Absolute elevations were obtained from points established by the Topographical Survey of the Department of Mines and Technical Surveys (now the Department of Energy, Mines and Resources). Accuracy of elevations varies from 0.1 foot on roads to 0.5 foot on lakeshores to several feet for barometric points.

The maximum and minimum elevations recorded are 1138.9 feet on the road from Schist Lake to Flin Flon and 958 feet on Schist Lake. The elevation of Amisk Lake was 969.8 feet in July, 1965.

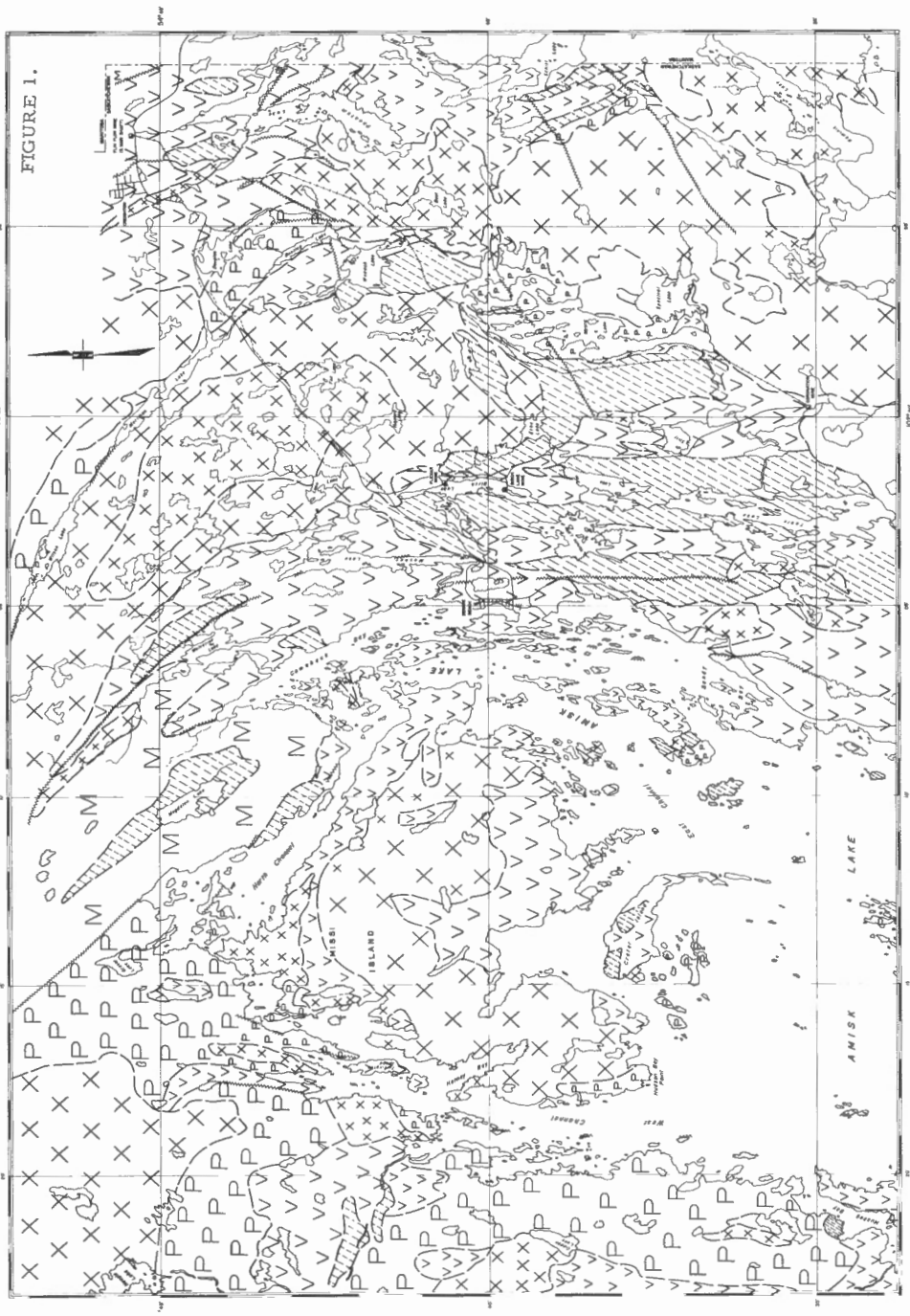
ROCK DENSITIES

A large number of samples of rock were collected from the area east of Amisk Lake by J. R. Smith (1964) and his assistants during 1960-1962 for geochemical analysis. These rocks were collected as nearly as possible on a 1/4 mile grid and chosen to represent the most abundant rock type at each locale. Each sample was freshly broken on all or all but one of its sides. The densities of 1585 of these rock samples were determined for the gravity study. The samples, weighing from 200 to 500 grams each, were weighed in air and water to compute specific gravity which was then correlated with the rock type. The porosity of these igneous and metamorphic rocks is very low and was therefore not considered when calculating specific gravity.

A table of densities arranged according to the legend of the geological map follows. The rock names are meant to be descriptive as to both

Table of Densities

Rock Type and Location	Number of Samples	Mean Density gr/cc
<u>Ordovician Sediments - no samples</u>		
<u>Precambrian</u>		
<u>Intrusive Rocks</u>		
Acidic Intrusive Rocks		
Phantom Lake Granite	34	$2.656 \pm .017$
Reynard Lake Microcline Granodiorite	83	$2.669 \pm .022$
Reynard Lake Biotite Granodiorite	104	$2.676 \pm .025$
Reynard Lake Border Zone	197	$2.811 \pm .080$
Mystic Lake Pluton	176	$2.789 \pm .077$
Annabel Lake Pluton	21	$2.791 \pm .057$
"Quartz-Eye" Diorite	24	$2.727 \pm .112$
Grey Diorite	33	$2.925 \pm .078$
Basic Intrusive and Ultrabasic Rocks		
a) Ultrabasic Rocks		
Serpentinities	25	$2.728 \pm .101$
Undifferentiated Ultrabasic Rocks	4	$2.833 \pm .118$
Meta Pyroxenite and Peridotite	5	$2.988 \pm .054$
Boundary Intrusion	10	$2.956 \pm .095$
b) Basic Intrusive Rocks		
Wolverine Lake, east side of	15	$3.033 \pm .043$
Cable Lake to Amisk Lake	33	$3.004 \pm .075$
Table Lake, west side of	76	$2.956 \pm .076$
Ruth Lake, east side of	41	$3.042 \pm .066$
Mystic Lake, west side of	98	$2.974 \pm .084$
Schist Lake, west of West Arm	9	$3.001 \pm .062$
<u>Missi Series</u>		
Arkose	5	$2.682 \pm .043$
<u>Amisk Group</u>		
Acidic to Intermediate Volcanic and Pyroclastic Rocks		
Lava, west and south of Wekach Lake	11	$2.707 \pm .036$
Lava, east and north of Wekach Lake	14	$2.719 \pm .041$
Tuff, west and south of Wekach Lake	7	$2.738 \pm .025$
Tuff, east and north of Wekach Lake	7	$2.756 \pm .032$
Basic Volcanic and Pyroclastic Rocks		
Tuff and Agglomerate, west & south of Wekach Lake	10	$2.868 \pm .110$
Tuff and Agglomerate, east & north of Wekach Lake	25	$2.902 \pm .098$
a) Lava, Greenschist Facies		
Eastern Islands and Shore Amisk Lake	185	$2.918 \pm .108$
Schist, Phantom, and Douglas Lakes	161	$2.936 \pm .096$
b) Lava, Epidote-Amphibolite Facies		
Konuto Lake Unit	35	$2.932 \pm .062$
Ruth, Birch and Stitt Lake Unit	57	$2.939 \pm .084$
South of Wekach Lake	22	$2.979 \pm .058$
c) Lava		
Mosher, Wolverine Lakes	58	$2.961 \pm .085$



EXPLANATION

<div></div>	PALEOZOIC ROCKS Ordovician Dolomite and Basal quartz Sandstone
<div>XX</div>	INTRUSIVE ROCKS Mainly Acid Intrusive Rocks of Pre,Syn,and Post Tectonic age, Minor basic dikes and sills
<div></div>	Basic intrusive sills and dikes and ultrabasic rocks
<div>MM</div>	MISSI SERIES Arkose, greywacke, quartzite and conglomerate
<div>PP</div>	AMISK GROUP Acid to intermediate Volcanics and Pyroclastics, Greywacke, minor basic lavas and intrusives
<div>VV</div>	Basic Volcanics and Pyroclastics, minor sediments and acid to basic intrusives
<div></div>	GEOLOGICAL CONTACT

FAULTS
SCALE 1" = 2 miles



GENERAL GEOLOGY
OF THE
AMISK LAKE AREA
SASKATCHEWAN

SASKATCHEWAN RESEARCH COUNCIL
PHYSICS DIVISION

location and rock type. The number of samples is given, followed by the mean density and standard deviation of each group. There are 31 groups. The mean density of the 1585 samples is 2.862.

GEOLOGICAL SKETCH

The geology of the area has been investigated by a number of people. Byers and Dahlstrom (1954) and Byers, Kirkland and Pearson (1965) give the most detailed account of the geology of the entire area. The following brief account is based mainly on these two reports. Other investigators are listed in the references. On the basis of density characteristics of the various rocks, the writer has simplified this geological description from those given in the published reports. See the geological map, Figure 1.

Amisk Group

The oldest rocks in the area are the Precambrian lavas, pyroclastic and sedimentary rocks of the Amisk group. On the basis of specific gravity they have been divided into two major groups, one made up largely of andesitic to basaltic lavas and pyroclastic rocks with only minor amounts of dacitic to rhyolitic rocks, the other group consisting largely of dacitic lavas and dacite breccia interlayered with minor agglomerate, tuff, rhyolite, trachyte, and andesite. Because of similar density, acidic pyroclastic rocks and the Amisk sediments are included with the dacitic group. The basaltic group (marked with V's on Figure 1) underlies much of the central and eastern portions of the map area.

The dacitic group (marked with P's on Figure 1) is most common in the western part of the map area, diminishing in quantity towards the central and eastern parts of Amisk Lake. Greywacke and argillite of the Amisk group outcrop in a belt extending from the north end of Amisk Lake to the north edge of the map area. Pyroclastic rocks with interbedded lavas and minor intrusions extend in an irregular belt from Mystic to Wilson Lakes and make up some of the islands in Amisk Lake.

The total thickness of the Amisk group is estimated in the order of 21,000 feet made up of 10,000 feet of basic volcanic rocks, 7,000 feet of acidic to intermediate flows and breccias and 4,000 feet of clastic sediments (Byers and Dahlstrom, 1954, p. 25).

Amisk rocks are mainly steeply to vertically dipping and isoclinally folded. A series of anticlines and synclines occur across the map area with steep to vertical axial planes striking north in the southern part and swinging northwest in the northern part. Major anticlinal folds are occupied by large granodiorite intrusions. Several synclinal structures have been described in the eastern parts of Amisk Lake. The fold axes plunge either north or south.

Missi Series

Conglomerate, arkose and greywacke of the Missi Series outcrop north of Amisk Lake, in the northeast corner of the map area, and in a few

small isolated patches not shown on the map. The sediments were derived from the underlying Amisk group. An estimated minimum thickness for the sediments in this area is 5000 feet. A conglomerate lies at the base and in narrower bands at several horizons in the series, grading upward into arkose and greywacke. An unconformity exists between the Amisk and Missi deposits with angular relations observed at some but not all contacts. In most places the Missi rocks are in fault contact with or intruded by surrounding rocks. The Missi rocks north of Amisk Lake are folded isoclinally into the Magdalene Lake syncline whose axial plane strikes northwest, dips vertically to steeply southwest, and plunges northwest in the map area.

Basic Intrusions

Intermediate, basic and ultrabasic sills and dikes (diagonal dashed line) are intrusive into the Amisk rocks and some are also found cutting Missi strata. Pyroxenite, peridotite, and serpentinite, although undifferentiated on the map, are found in a more or less continuous belt along the islands and east shores of Table Lake and Ruth Lake. Ultrabasic rocks outcrop also on the southeast shore of Cable Lake, the islands of Mosher Lake, and southeast of the east bay of Wolverine Lake. Smith (1964) suggests from aeromagnetic evidence that the west half of the basic intrusion which extends northward from Cable Lake may be underlain by ultrabasic rocks at no great depth. Serpentinities are low in density.

The basic intrusive rocks lying between Amisk and Mystic Lakes range from meta-diorite to meta-gabbro in composition. Wohlberg (1964) indicates that the body lying east of Ruth and Table Lakes was originally composed of pyroxene and calcic bytownite. Other basic intrusions are mainly meta-gabbro and porphyritic meta-gabbro. The highest measured densities were found in the basic intrusive rocks.

The structure of the basic intrusions is massive in some places and gneissic in others. Density zoning seems to occur, at least in the intrusion along the east shore of Amisk Lake. Wohlberg (op. cit.) considers the zoning in the Ruth Lake sill as primary and from this concludes that the sill was intruded before regional deformation had ended.

The Boundary Intrusions are a related group of rocks mainly basic in composition. They are the youngest basic intrusions in the area and are contemporaneous with the Phantom Lake granite. Only the largest of these is shown on the map at the north end of Phantom Lake. It is composed mostly of peridotite. A small gravity high occurs over this body along with a pronounced magnetic anomaly.

Acidic Intrusions

The acidic intrusive rocks denoted by X's on the map include a wide variety of compositions, structural settings, and ages. Numerous minor porphyritic dikes and sills intrude the Amisk rocks and in some areas, notably the Hannay Bay area and the central eastern part of Missi Island, constitute more than 50 per cent of the bulk of the rock. Some of the islands of the east channel of Amisk Lake are composed largely of porphyritic intrusions. A "Quartz-eye" diorite underlies the southern part of the southwest

peninsula and the north central part of Missi Island but is undifferentiated on the map from the porphyritic intrusions. The "Quartz-eye" diorite also outcrops in several locations in Comeback Bay and between Table Lake and Amisk Lake. "Quartz-eye" diorite cuts Amisk and Missi rocks.

Granodiorite forms large intrusive masses underlying much of the area. They are generally elongated parallel to the regional structure and show conformable relationships to the country rocks. They are considered to be syntectonic with the major regional deformation and occupy anticlinal positions. One batholith, the Reynard Lake mass, which extends from Mystic Lake to the north edge of the area is a zoned structure with a low density core (outlined on the map) of porphyritic microcline granodiorite. Surrounding the core is a discontinuous zone of low density biotite granodiorite enclosed by a contaminated border zone. The contaminated border zone is a heterogeneous complex of volcanic, sedimentary, granodioritic and other intrusive rocks. Angular inclusions of country rock and of the intrusive rocks themselves are abundant. Contacts with volcanic rocks are sharp but contacts with basic intrusions are sometimes difficult to define because many of the rocks of the contaminated border zone are essentially foliated amphibolites closely similar to the amphibolitic intrusion west of Mystic Lake (Smith, 1964).

The Mystic Lake pluton which lies largely between Kaminis and Mystic Lakes is not so well defined as the Reynard Lake mass. It consists mostly of hornblende granodiorite with variable quantities of mafic minerals and quartz. Some areas along the west boundary of the Mystic Lake pluton are quartz diorite that gives rise to prominent aeromagnetic anomalies.

A portion of the Annabel Lake pluton is in the map area northeast of Meridian Lake. It consists of relatively uniform, foliated, relatively mafic rich, hornblende granodiorite (Smith, 1964).

A portion of the Wolf Lake mass, mainly biotite granodiorite, lies on the west edge of the map area northwest of Oddan Lake.

Albite granite forms a small boss-like intrusion north of Stitt Lake.

The Neagle Lake intrusion occupies the northwest corner of the map area. It and the two smaller intrusions between it and Amisk Lake are post-tectonic in age. The Neagle Lake body is largely granodiorite but ranges from granodiorite to gabbro in composition.

The Phantom Lake granite underlies the southern part and southwest shore of Phantom Lake and intrudes Amisk rocks and the Mystic Lake pluton. It is composed of low density pink to reddish porphyritic microcline granite. It is outlined on the map to distinguish it from the Mystic Lake pluton. A distinct gravity minimum is associated with this rock. The Phantom Lake granite intrudes and is intruded by the Boundary Intrusions.

Phanerozoic Rocks

Flat lying Ordovician dolomite and sandstone overlie the older Precambrian rocks along the southern edge of the map area. Unconsolidated Pleistocene glacial deposits are irregularly distributed over all younger formations.

Faults

Many faults, described by Byers and Dahlstrom (1954, pp. 78-82) and Byers, Kirkland and Pearson (1965, pp. 49-56), cut the Precambrian rocks in this area. The Ross Lake fault which is in the extreme northeast corner of the map area is the most prominent fault (in its area) and has been traced by detailed mapping for over 25 miles. Strike slip movement on this fault has been estimated in three different places as 3,300 feet, 1,650 feet, and 1,650 feet, all left-handed movements. A reverse dip slip movement has been estimated in three different places at 600 feet, 850 feet, and 1,750 feet, all with the east side moving up with respect to the west wall.

The Cliff Lake fault, a mile or two east of the map area, is a reverse fault with dip slip movement of at least 3,000 feet with the east side thrust up and to the west.

The Creighton Creek fault and the Triangle Lake fault are both just north of the northeast corner of the map and these faults also show left hand strike movement and reverse dip slip with the east side moving up and to the north.

The Annabel Lake fault, an east striking fault several miles north of the map area, has drag folds near it indicating the north side to have moved up and to the southwest with respect to the south side.

The West Channel fault zone through the west channel of Amisk Lake is indicated to have a reverse oblique movement shown by tension fractures and drag folds. The west block or hanging-wall has been moved up and to the southeast.

The above named faults are all those listed by Byers et al. with the sense or amount of movement defined.

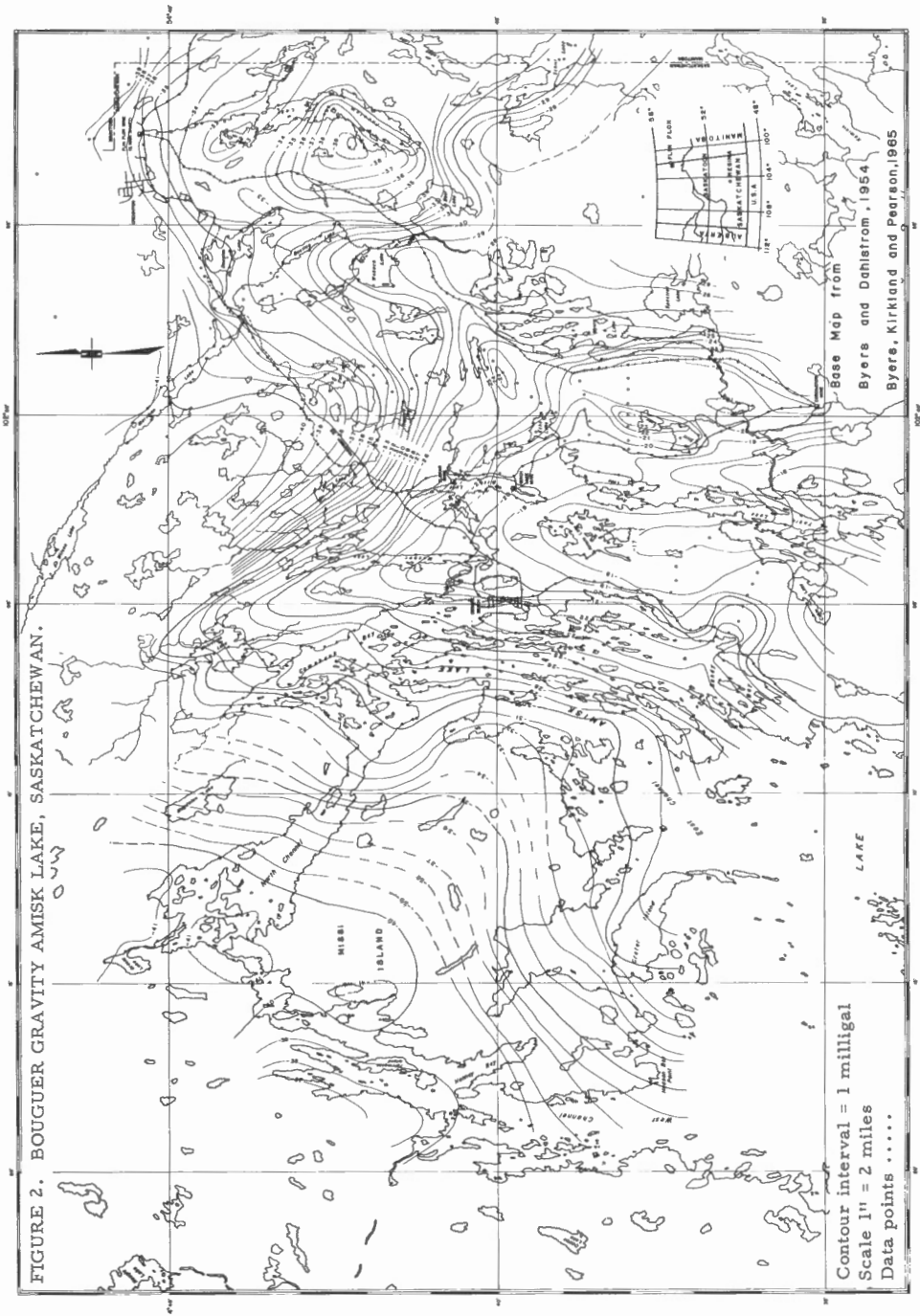
The MacDonald Creek fault which forms the southwest contact of the block of Missi sediments north of Amisk Lake must have a large dip slip movement with the west side moved up since it has cut out the entire basal conglomerate (about 600 feet thick) of the Missi series in the Magdalen Lake syncline.

Similarly the positions of the Mosher Lake fault and the Wilson Lake fault, which form parts of the northeast contact of the same unit of Missi rocks, suggest that the northeast walls of these two faults have moved up with respect to the southwest walls, at least where the faults cut Missi rocks, although the movement has not been sufficient (in these cases) to remove entirely the basal Missi conglomerate.

In spite of the lack of direct evidence for these inferred movements, there are two reasons to suggest them. First, the suggested movements would have preserved the existing Missi sediments from erosion. Second, if the west block had been moved down along the MacDonald Creek fault, one should expect to find the missing Missi rocks somewhere along the downthrow side. Only one small patch of Missi conglomerate appears southwest of the MacDonald fault and it has been preserved there by local down faulting, consistent with the suggested west side up movement of the major fault.

A number of faults have been mapped along the eastern islands and shore of Amisk Lake, more or less in line with the MacDonald Creek and Mosher Lake faults but no movements have been determined for these.

Numerous other faults occur in the area but no data has been given as to their individual movements or possible cumulative movement. Froese



(1963) shows that the joints and minor faults in the Coronation Mine area are the result of a local compressional force oriented in an east-northeast by west-southwest azimuth. Most of the movements are strike slip with very little dip slip component. We shall assume that they do not cancel the movements on the faults described above.

This fault pattern suggests that the Missi sediments north of Amisk Lake and the Amisk volcanics to the southeast have been let down by a series of steeply dipping reverse faults on the east, west, and north sides. Gravity anomalies, discussed later, support this theory.

GRAVITY INTERPRETATION

The Bouguer gravity map, Figure 2, in the Amisk Lake area is dominated by a pronounced gravity "high" which is centered along a zone through Table, Konuto, and Mosher Lakes. The anomaly falls off rapidly towards the north end of Wolverine Lake. The anomaly has a broad flank extending to the west shore of Mystic Lake and a finger extends northeast through Wekach Lake. This gravity high is directly correlated with the outcrop area of basic and ultrabasic dikes and sills. A smaller gravity high is found over the ultrabasic Boundary Intrusion at the north end of Phantom Lake.

Pronounced gravity minima occur over most of the mappable acidic igneous intrusive rocks in the area. The gravity field displays a continuous decrease from east to west across Amisk Lake and the acidic volcanic rocks become more abundant towards the west side of the lake.

Deep Seated Sources

Although the anomaly appears to be associated with the outcropping rock types, the possibility remains that the major portion of the anomaly is due to some density distribution at great depth and that the surficial geology contributes only some local detail to the gravity field.

Hall and Brisbin (1965) give the following data for the area south-east of Flin Flon:

	<u>P Wave Velocity</u>	<u>Density</u>	<u>Depth to Top</u>
Granitic Layer	$6.15 \pm .05$ km/sec	2.82 gm/cc	0
Basaltic Layer	$6.65 \pm .10$ km/sec	2.95 gm/cc	15.5 ± 1 km
Upper Mantle	$7.90 \pm .10$ km/sec	3.34 gm/cc	34 ± 1 km

Using a regional Bouguer map drawn from Dominion Observatory regional gravity data only (25 points), the above listed values, and the method given by Smith (1960) to determine the limiting depths of gravity anomalies, the following estimates were made:

1. The minimum permissible density contrast capable of producing the anomaly is 0.0425 gm/cc provided that the contrast extends from surface to unlimited depth.

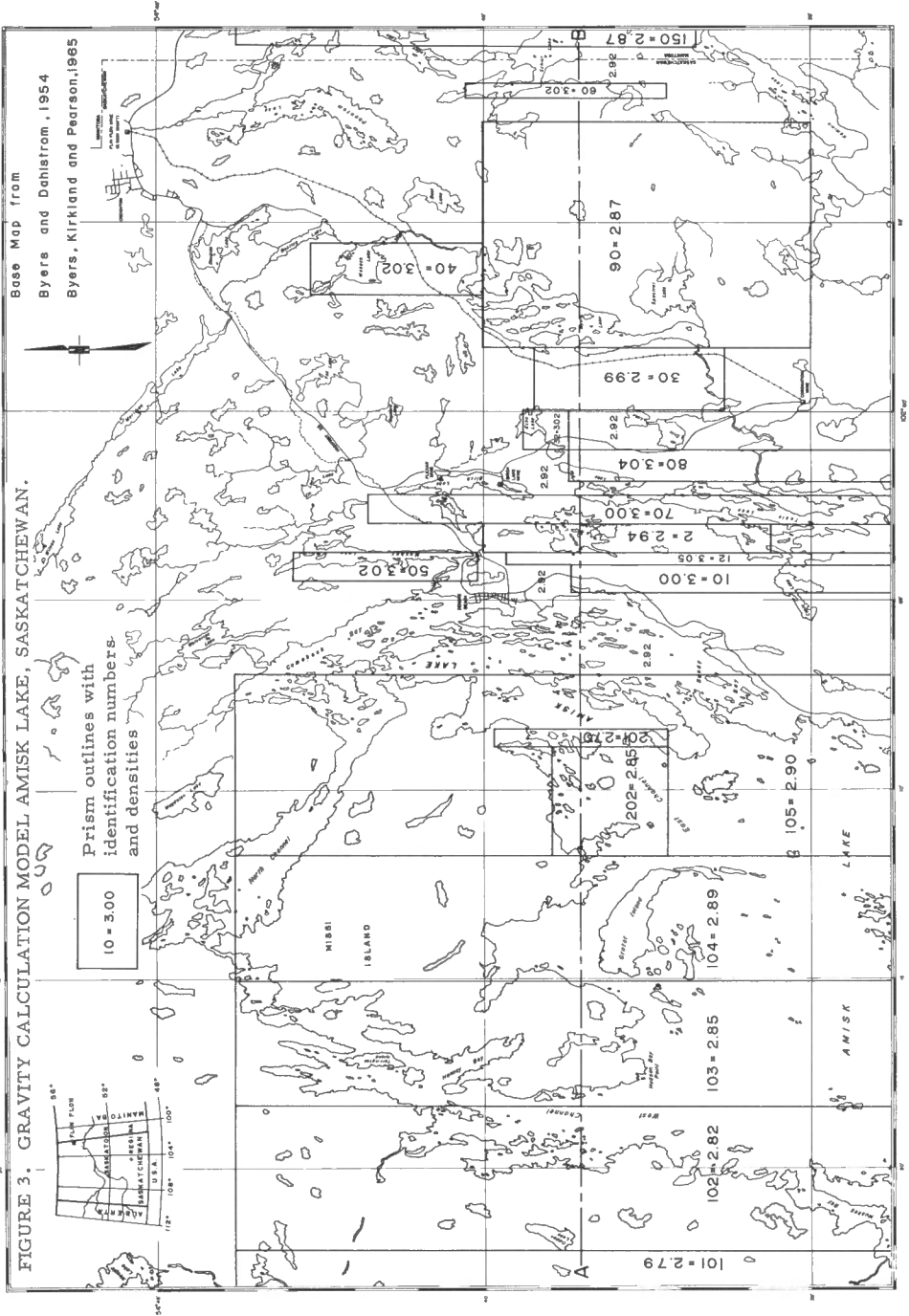


FIGURE 3. GRAVITY CALCULATION MODEL AMISK LAKE, SASKATCHEWAN.

Figure 4

GRAVITY INTERPRETATION

PROFILE A - B

Points from Observed Field

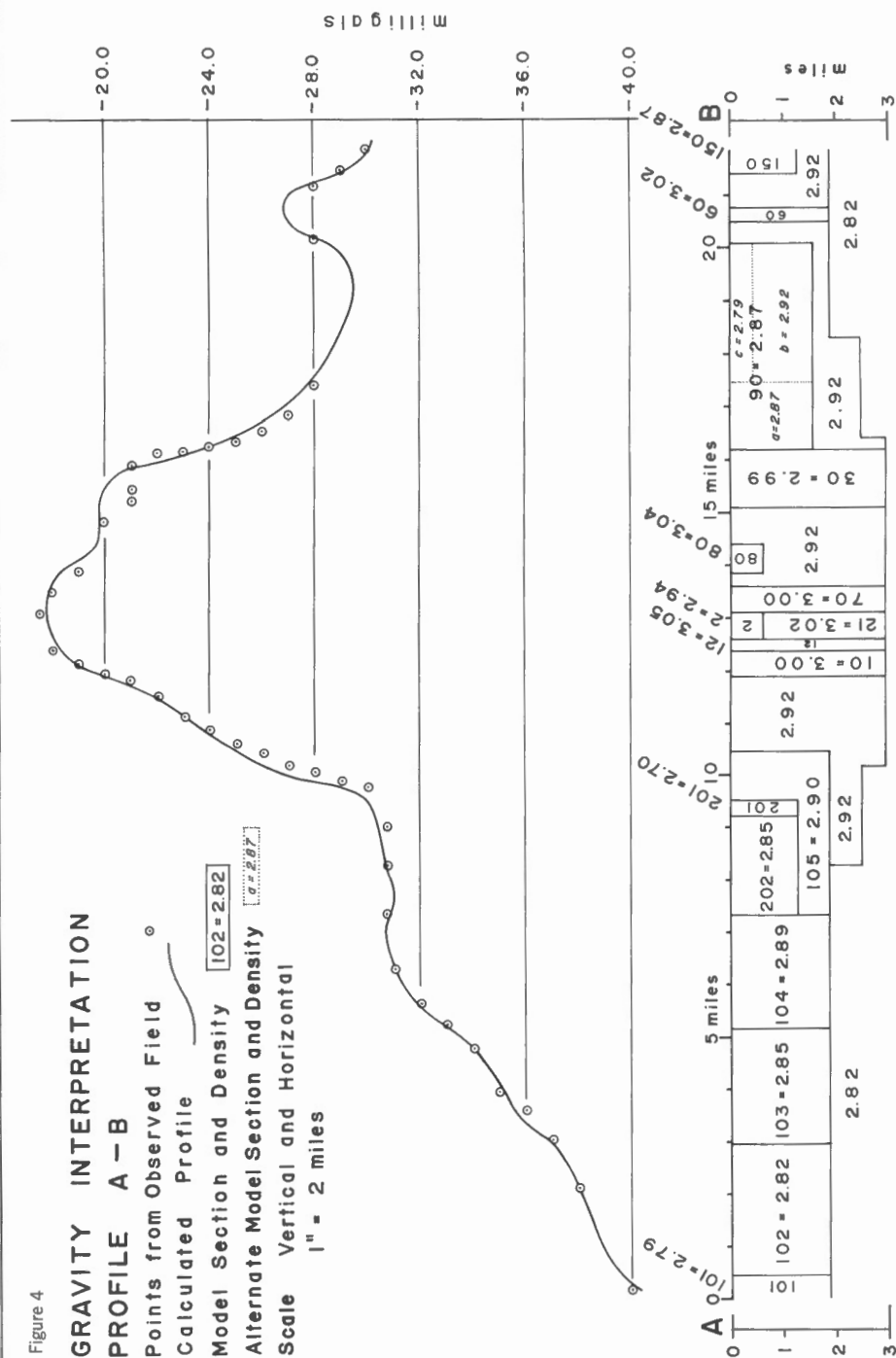
Calculated Profile

Model Section and Density

Alternate Model Section and Density

Scale Vertical and Horizontal

1" = 2 miles



2. If the anomaly were due to relief on the basaltic layer (Conrad discontinuity) and the maximum density contrast were taken as 0.13, the basaltic layer would have to rise from a depth of 15.5 km to a depth of 4.0 km to explain the anomaly.
3. If the anomaly were due to relief on the upper mantle surface (Mohorovicic discontinuity) and the maximum density contrast were taken as 0.39, the upper mantle surface would have to rise from a depth of 34 km to a depth of 12.9 km to explain the anomaly.

These estimates show that if the anomaly were due, in any substantial part, to relief on the Conrad or Mohorovicic discontinuities, extreme amounts of upward relief would be required, respectively 11.5 km and 21.1 km. However, the fault pattern discussed earlier suggests downward movement rather than upward. Furthermore, if most of the field were due to deep sources, the residual field would be inadequate for any reasonable depth of the surficial rocks.

Therefore it may be concluded that little or none of the Bouguer positive anomaly is due to deep seated sources.

Shallow Sources

Depth estimates were made on some of the sharp anomalies such as the steep gradients along the east channel of Amisk Lake and along the west shore of Mystic Lake. By the method of Smith (1960) the depth to the top of the body causing the east channel anomaly is less than 1,500 feet. Evidently the basic intrusive rocks outcropping on the east shore of Amisk Lake are the cause. Similarly, the anomaly along Mystic Lake is due to the contacts between a basic intrusive sill, a thin strip of basic volcanic rocks and the acidic volcanic and pyroclastic rocks that underlie most of Mystic Lake. Using a method developed by the writer for interpreting gravity anomalies of dipping contacts, the vertical extent of the contact between basic and acidic rocks is estimated variously at 2.6 to 4.6 kilometers depending on the density contrast allowed. The variability is caused partly by the fact that the contact is not a simple plane.

Model Interpretation

Since deep crustal sources are ruled out, and since the density of rocks in this area varies almost directly with the basicity of the rock (except for serpentinites), it may be said that the gravity is largely explained in terms of the outcropping geology. The amplitude of the anomalies, however, depends on the depth extent of the rock formations. Three factors are important here, the density assigned to the rock units, the thickness of the units, and the dip of the beds. Measured densities of 1,585 rock samples from the Amisk Lake area are tabulated earlier in this report. Thicknesses of the various volcanic and intrusive units and their dips are given by Byers et. al. All dips are steep to vertical.

For this report a single east-west profile about 4 miles north of the Coronation mine has been interpreted. The interpretation model and results are shown in Figures 3 and 4.

In gravity studies of this nature, it is common practice to remove a "regional gravity" effect from the Bouguer map before proceeding to interpret the "residual". This was not done in the Amisk Lake study because the gravity variations seemed to be almost totally controlled by the outcropping rock units. In a sense, this study is interpreting the "regional effect" as it might be considered in a more localized survey.

The interpretation method is by curve matching and the calculations were carried out on the University of Saskatchewan IBM 7040 computer. The equation for the gravity effect of a three dimensional rectangular prism was derived and programmed in Fortran IV by D. Nágy of the Dominion Observatory.

Prisms comprising the model were chosen on the basis of the shape of the outcropping rock units and extended to depths sufficient to obtain the required gravity anomalies. The model was chosen to fit conditions most closely along the axis of the profile and only approximately at points away from the profile. The reader should bear in mind that the blocky appearance of the model is a limitation of the computing method and that equally good interpretation could be achieved with curved and slanting contacts. Such an interpretation would be much more costly and no less ambiguous. Densities were assigned on the basis of measured densities insofar as possible. Exceptions to this are blocks No. 90, 101, 102, 103, 104, 201, and 202. No densities were available for these blocks, except block 90, because they fall outside the area of Smith's sampling. No gravity points occur within the Mystic Lake pluton so block 90 includes both the Mystic Lake pyroclastics and the Mystic Lake pluton. The density corresponds to the pyroclastics. If the density of granodiorite were used, the thickness would be considerably less as shown by the alternate interpretation on the profile. The alternate interpretation would produce very nearly the same gravity effect as calculated for the first interpretation, but since no gravity points exist in that area, neither one can be verified.

Block 201 corresponds to an acidic igneous dike and was assigned an appropriate density. Block 202 corresponds to an area covered mostly by water but since a few narrow acidic dikes occur on the shore of Missi Island it is assumed that sufficient acidic material is present to lower the bulk density and produce the flattening in the gravity field. Blocks 105, 104, 103, 102, and 101 were assigned their densities to take account of the increasing proportion of acidic rocks westward across Amisk Lake. The densities of blocks 101 and 102 are higher than the density for acidic lava listed earlier because the acidic rocks in this area have undifferentiated basic lavas and intrusive rocks in them. Blocks which are not terminated within the borders of the map area are terminated a few miles beyond.

The density for the material lying immediately under the Amisk volcanic rocks was taken as 2.82 for several reasons; the rock at 3 km depth in a hole drilled in the center of the Reynard Lake pluton is similar to the Reynard Lake contaminated border zone whose density is 2.81; the average density of all samples taken from the East Amisk area is 2.86.

The mean value 2.86 may be considered unbiased or properly weighted insofar as Smith's (1964) sampling is representative. The sampling was intended to be as representative as possible but was subject to uncontrollable factors such as topography. Probably the value 2.86 is somewhat too high.

Two hypotheses were tested in computing model profiles. The first was that the basic and ultrabasic dikes and sills are deep seated with their roots extending to the basaltic layer. The second hypothesis was that the dikes and sills are limited in depth and the required anomaly amplitude is made up by a thickening of the basic Amisk volcanics. Both models produced satisfactory fits to the observed data but the second was chosen for two reasons. The basic dikes and sills were intruded before the regional folding had ended (Wohlberg, 1964) and therefore may be far removed from any root or feeder dike that exists or might have existed. Secondly, the regional faulting discussed earlier is compatible with a thickening of the Amisk volcanics in the area east of Amisk Lake.

Basic Dikes and Sills

The maximum gravity anomaly is found over the basic intrusions, (blocks 10, 12, 21, 30, 32, 40, 50, 60, 70, and 80) but in the Amisk-Mystic Lakes area the intrusion with the highest density, 3.042 (block 80, east of Ruth and Table Lakes) is not under the peak of the anomaly. To obtain the shape of the observed curve, and still use the measured densities, it was necessary to assume the Ruth Lake sill to be limited in depth (1 km) and extra mass (block 21, Figure 4), added at depth below the Konuto Lake (block 2) greenstone belt, implying that basic intrusive material is there also. The small negative anomaly observed on the west side of the Mystic Lake sill (block 30) is due to a small acidic intrusion. No attempt was made to fit this anomaly. The shape of these bodies need not be square and blocky to fit the gravity anomaly. Rounded and tapered forms would do nicely but are much more difficult to compute. Therefore, geological intuition can be used to alter the square appearance of the model providing only that the mass concentrations remain relatively undisturbed.

The mass of the basic intrusive rocks is insufficient to explain the amplitude of the gravity anomaly unless the intrusions extend to great depth. Since this is unlikely from structural considerations, a downward bulge of basic volcanic rock was added instead to make up the difference. A total of 4.7 km of basic volcanic and intrusive rocks is inferred in the Amisk-Mystic Lakes area with somewhat lighter material below.

Acidic Lavas

Three kilometers of vertical thickness of rock are required to match the observed gravity field over the west half of Amisk Lake if the assumed densities are correct. If the acidic lavas on the west shore of Amisk Lake (block 102) are assigned the density of acidic lavas on the east shore (2.707) instead of the value used (2.82), the vertical thickness required would be reduced to 1 1/2 or 2 kilometers. The larger value was used because some basic rock has been included with the acidic volcanics. The geophysical model therefore indicates that the density contrasts observed at the surface disappear within a few kilometers of depth and are replaced by or change into material with density so homogeneous that it does not substantially effect the gravity field. A density of 2.82 has been assumed for this underlying material for reasons listed earlier. If the material were heavier

or lighter, the only alteration required to the gravity interpretation would be an increase or decrease in the amount of downwarping required in the Amisk-Mystic Lakes area. The density of the rock may very well decrease with depth but such a horizontal stratification is not detectable from considerations of the local Bouguer anomaly.

Pyroclastic and Granodioritic Rocks

East of Mystic Lake, there are relatively few gravity points to interpret. Therefore, the interpretation of the form of the Mystic Lake pluton is not very satisfactory. The entire block 90 has been assigned a density of 2.87, appropriate for the pyroclastics in Mystic Lake. The Mystic Lake granodiorite samples have an average density of 2.79. If the interpolated Bouguer gravity across the Mystic Lake pluton is fairly realistic, then only 700 meters of granodiorite (block 90C) would be adequate to explain the anomaly. The postulated density distribution is shown as an alternate interpretation on the profile. Qualitative support for this contention is shown in the Boot Lake area where the gravity anomaly is seen to increase southward towards the center of the pluton reaching values larger than are found over nearby Amisk volcanic rocks. Hence, at least in the area north from the interpretation profile, the Mystic Lake pluton is thin and lacks any low density core as found in the Reynard Lake body. This interpretation is contrary to Smith (1964, p. 14) and Byers *et al.* (1965, p. 35) who suggest the exposed surface is near the original roof of the pluton and that the body is structurally lower than other large intrusions, its central core not yet exposed.

The lavas and basic intrusions outcropping along the west arm of Schist Lake do not require any excess material at depth to explain their gravity effect. The basic intrusions (block 60) in particular seem to be quite limited in size in comparison to the Table Lake, Ruth Lake bodies.

Block 150, east of the West Arm of Schist Lake was included because rocks east of the map area become more acidic in composition.

Interpretation Chart for Variable Density Slab

An interpretation chart (Figure 5) has been prepared by the writer to interpret the gravity effect of a two-dimensional strip with density varying uniformly across its width and with densities in the semi-infinite slabs on either side constant and equal to the value reached at the edges of the varying strip.

On this chart K is the density gradient in the strip measured in grams/cc per kilometer, L is the width of the strip, H is the vertical thickness, and dv/dx is the horizontal gradient of gravity in milligals/kilometer at a point half way across the strip. The top of the slab is at surface. The equation which has been derived and used for this chart is

$$dv/dx = GKL \left[\ln \left(\frac{4H^2}{L^2} + 1 \right) + 4 \frac{H}{L} \tan^{-1} \frac{L}{2H} \right]$$

where G is the gravitational constant. If L is very large this expression simplifies to $dv/dx = 41.9 KH \text{ mg/km}$.

NOMOGRAM FOR HORIZONTAL GRAVITY GRADIENT
DUE TO A STRIP OF VARYING DENSITY



$K = \frac{d\rho}{dx}$ $\frac{\text{gr/cc}}{\text{km}}$ $\frac{dg}{dx}$ in $\frac{\text{milligals}}{\text{km}}$

L and H in km

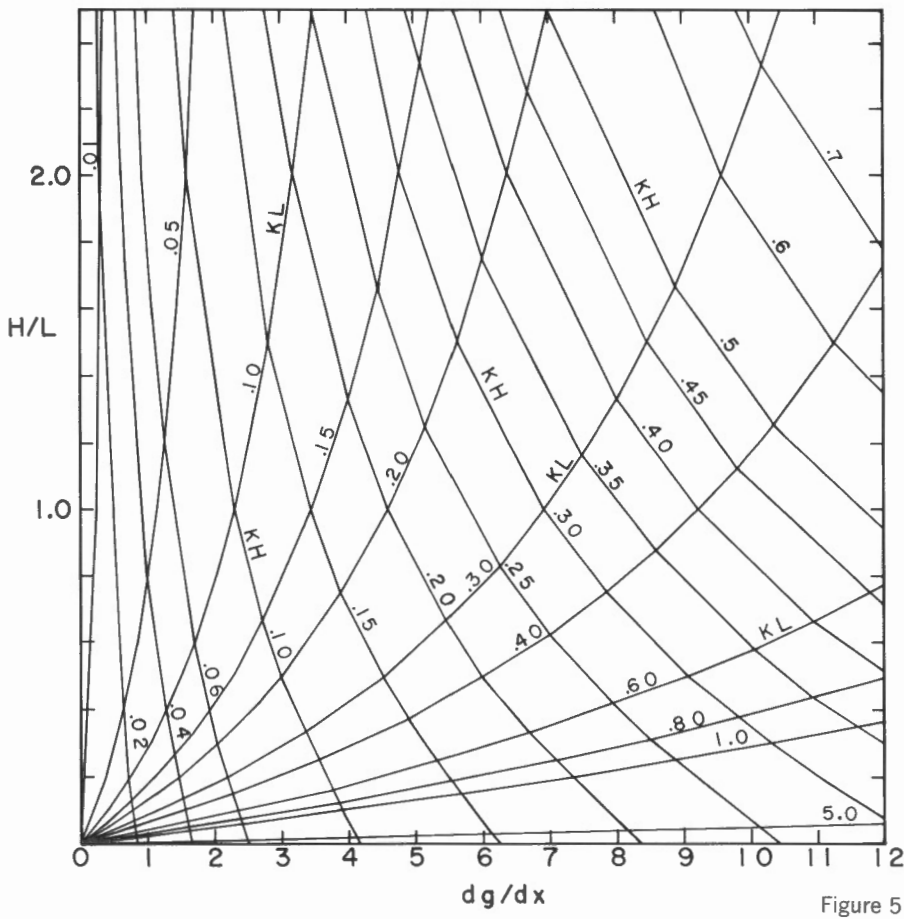


Figure 5

To use the chart, consider a map area where the gravity slope is uniform for some distance and where the density of outcropping rocks changes gradually. Estimate the two gradients and the width of the density gradient. Form the product KL and find the intersection of KL and dv/dx on the chart. Read the value of H/L or KH from the chart and compute H . Notice that the method is not very sensitive to changes in L and that small values of KH depend mainly on the value of dv/dx . Also, the product KL represents the total density contrast. Of course, the chart can be used in reverse to compute gravity gradients for assumed thicknesses. For the gravity profile on the west side of Amisk Lake, $dv/dx = 1 \text{ mg/km}$, $K = .01 \text{ gr/cc/km}$, $L = 10 \text{ km}$, $KL = 0.1 \text{ gr/cc}$, $H/L = .29$, and $H = 2.9 \text{ km}$ depth which agrees substantially with the depth indicated by the model calculation.

Seismic Velocities and Densities

Figure 7 is a chart published by Volarovich *et al.* (1967) using data on magmatic rocks from Kazakhstan and incorporating the results of Birch (1954) and Hughes (1964). This diagram shows that the compressional wave velocity of rocks increases with both pressure and the density of the rock, as is well known.

Figure 6 is a plot of the distances and first arrival refraction times of the Hanson Lake Road seismic profile (Burke, 1968) which passes immediately north of the Amisk Lake area. Also plotted is the expected arrival curve if the velocity were to increase downward at the rate of 0.126 km/sec per kilometer depth. The rate of 0.126 km/sec/km is interpolated from Figure 7 assuming a density of 2.86 .

The seismic velocity of basic igneous and metamorphic rocks such as outcrop in the Amisk Lake area should be in the order of 6.1 km/sec according to Volarovich, increasing to about 6.6 km/sec at a depth of 5 km . The shot-point for the seismic surveys of Burke, and Hall and Brisbin was at Thompson Lake, Manitoba, located in Amisk volcanic rocks quite similar to those around Amisk Lake. Yet the velocities to depths of 10 km and 15 km were found to be 6.0 and 6.15 km/sec , respectively. Evidently something must happen at relatively shallow depths to nullify the expected increase in velocity due to pressure. This inference from the seismic data supports the gravity interpretation. Moreover, it implies a decrease in density of the rocks at a depth of a few kilometers.

Velocities of 6.0 to 6.15 km/sec at pressures in excess of 1000 bars are characteristic of certain varieties of granite or gneiss (Clark, 1966). The requirements of density, pressure, and velocity are also met by some metamorphic sedimentary rocks, for example, quartzite or slate (Christensen, 1965).

OTHER INVESTIGATIONS

For purposes of comparison, findings of some gravity investigations of other Precambrian greenstone areas are listed below.

Grant, Gross, and Chinnery (1965) have found the Red Lake greenstone belt in northwestern Ontario to taper sharply to a depth of $25,000$ feet (7.6 km). The Red Lake belt outcrops in an area approximately 35 miles by 18 miles.

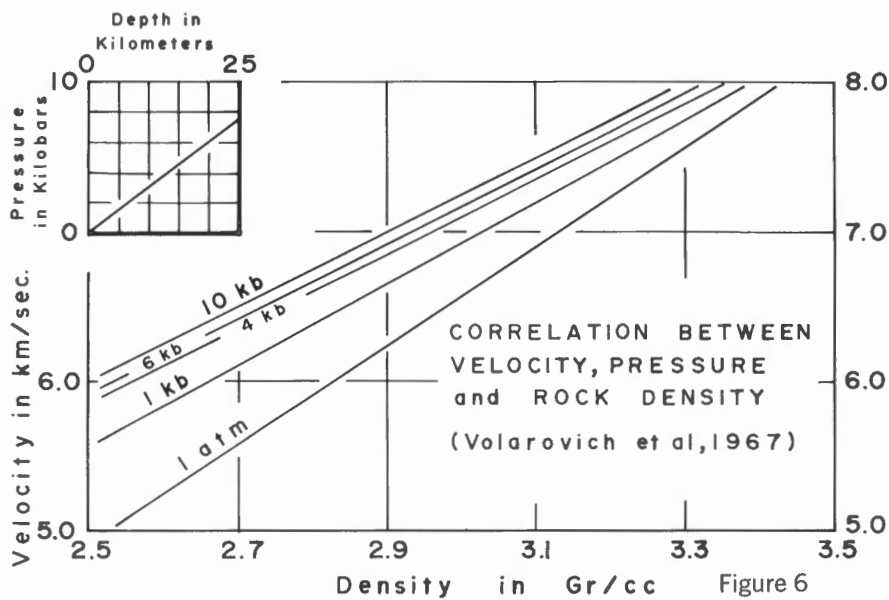


Figure 6

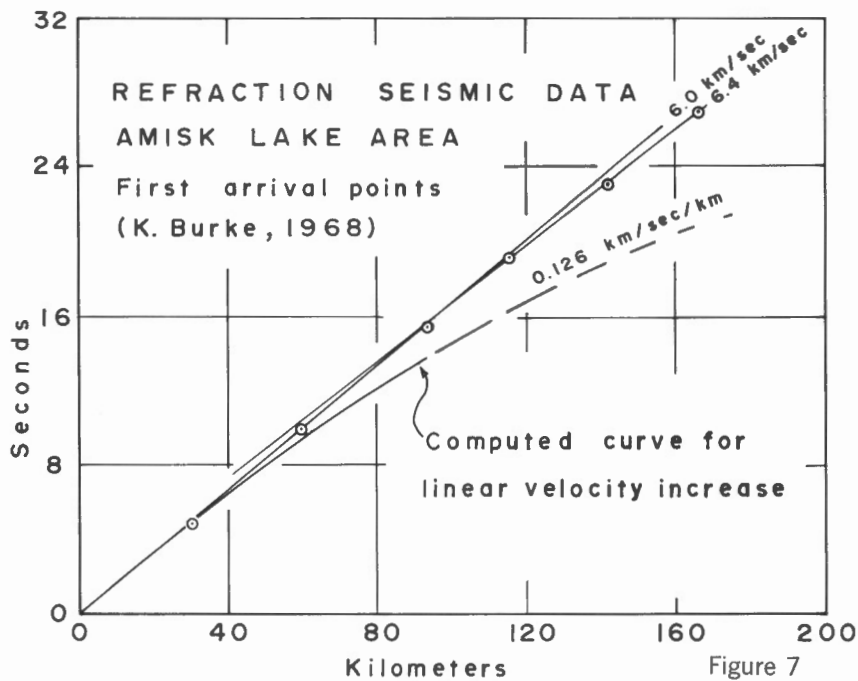


Figure 7

Innes (1960) finds average depths of 4.1 and 6.4 kilometers for different parts of the greenstone belt extending from Lake of the Woods to Dryden, Ontario. In each of these examples low density rocks are presumed to underlie the greenstones.

On the south coast of Norway, Smithson (1963) has investigated an area of Precambrian gneisses, meta-sediments, basic and acidic intrusions. He found the dense meta-sediments to be lying over granite gneiss, the meta-sediments varying in thickness from 0.5 to 7 kilometers. Two post tectonic granites intruding the meta-sediments have thicknesses ranging from 2 to 5 kilometers, depending on the meta-sediment thickness, and appear to be diapiric differentiates of the underlying granite gneiss.

Bott and Smithson (1967) suggest that many deep-level granites, usually restricted to the Precambrian, appear to be thin or lenticular. They cite a number of cases where gravity evidence indicates depths of 2 or 3 kilometers for Precambrian granites.

CONCLUSIONS AND DISCUSSION

The major conclusions to be drawn from the gravity study are

1. The densities associated with the steeply dipping basic to acidic Amisk volcanic rocks have a limited depth. The density contrasts disappear and may gradually merge into a material with more or less homogeneous lower density at a nominal depth of 3 km. This conclusion is supported by seismic data which indicates that the density of outcropping volcanic rocks does not persist to depths as great as 10 km but decreases at quite shallow depths.
2. The basic volcanic and intrusive rocks in the area between Mystic and Amisk Lakes have been displaced downward almost 2 km so that the maximum depth along the line of profile is nominally 4.7 km. Major faults mapped on the surface tend to support this sense of movement. Here also, the lower contact is possibly gradual and there may be no sharp density contrasts in the vertical direction.
3. The Mystic Lake granodiorite pluton is probably less than 1 km in thickness along the gravity profile but the scarcity of gravity observations in this area prevents any satisfactory interpretation.

An objection to the foregoing interpretation comes from a consideration of the structural geology. Detailed mapping in the area (Byers and Dahlstrom, 1954) has shown that the stratigraphic thickness of the Amisk group of volcanic rocks is about 21,000 feet (6.4 km) and these rocks are now vertically dipping and isoclinally folded. Therefore the 3 km depth indicated by gravity is quite inadequate to contain the troughs of the synclinal folds that have been mapped, if the entire stratigraphic thickness were involved in each fold.

However, Byers and Dahlstrom (op. cit., p. 25) state that the thickness of 21,000 feet is approximate and exact figures are impossible to obtain due to the complex isoclinal folding. They also point out that the basalt and andesite lavas outcrop in and around Amisk Lake, especially to the east and

northeast of the lake while the rhyolite and dacite lavas and clastic sediments are found generally west and northwest of the lake. "The general distribution of the volcanic strata and sedimentary rocks would indicate that the Amisk period of volcanism closed with the production of intermediate lavas and pyroclastics, and a gradual transition from volcanism to sedimentation, with the deposition of greywacke mainly to the west and northwest of the Amisk Lake area, and interfingering of sediments and volcanic rocks to the east." (Ibid.) Little or no intermediate or acidic lavas or clastic sediments occur along the axes of the defined synclinal structures along the eastern islands and shore of Amisk Lake. Therefore the entire stratigraphic sequence is definitely not involved in each fold.

Large quantities of the different rocks were eroded at various times before and after their final deformation. Certainly there is an unconformity between Amisk and Missi rocks, and the present surface is very deeply eroded. Froese, (1968) from studies of the metamorphic minerals, concludes that the rocks in the Coronation mine area were metamorphosed at temperatures of 550° to 600° centigrade and 2-4 kilobars pressure, equivalent to 6.5 to 13 kilometers depth. Part of this pressure may have been due to tectonic forces but most of it probably came from depth of burial since rocks at high temperature cannot sustain high stress differences for long periods and will flow, tending to restore a lithostatic equilibrium. Jeffreys (1962, p. 210) concludes that stress differences of at least 1.5 kilobar can exist in the outer 50 km of the earth and 150 bars below 50 km. The Coronation mine area then could have had a lithostatic load from 0.5 kilobar to 4 kilobars corresponding to depths of 1.7 km to 13 km.

A considerable quantity of rock has been removed since the Hudsonian orogeny, and an unknown amount in pre-Missi time. Structural considerations alone, therefore, do not preclude the geophysical interpretation.

The large acidic igneous bodies of pre, syn, and post-tectonic age, which intrude the Amisk and Missi rocks, imply the existence of a wide-spread source of acidic igneous rock under most or all of the area. Geophysical evidence indicates the existence of a low density material at a few kilometers depth under the basic volcanics. This could be the older material on which rocks of the Amisk Group were deposited. If so, then any such pre-Amisk formation might be expected to crop out in anticlinal structures. This has not been observed in the Amisk Lake area although Bateman and Harrison (1945) found such a unit surrounding the Wabishkok Lake dome of granodiorite gneiss in Manitoba, about 15 miles northeast of Flin Flon. This assemblage of quartz-oligoclase gneiss and hornblende gneiss and schist has an apparent thickness of about 1,500 feet computed perpendicular to the schistosity. The gneiss and schist assemblage underlies altered pillow lavas of the Amisk group and is itself intruded by the granodiorite gneiss. Since this "pre-Amisk rock" is relatively thin and underlain by intrusive granodiorite gneiss, it seems unlikely to represent any extensive pre-Amisk basement.

Granitization at depth would solve the problem of the synclinal troughs by changing them from dense to lighter material. There seems to be no definite evidence for granitization of basic Amisk rocks, although temperature and pressure in the most deeply buried portions of the Amisk group would certainly have been higher than the 550° C and 4 kilobars found by Froese at the present erosion level. Progressive granitization with depth

would also contribute to a uniform seismic velocity with depth and density contrasts would tend to be smoothed.

Granitic intrusions at depth, similar to presently outcropping granodiorites but physically smaller and occurring more frequently with depth would tend to produce the necessary density distribution. At great depth, the rock might have the character of a migmatite or injection gneiss. At shallower depth some of the granitic layers of the migmatite lens out and disappear. Other lenses or sheets of granitic material coalesce into larger tongues and some of these join to form large intrusive bodies which penetrate to the surface. In such an interpretation, the rocks at great depth would have been subjected to high pressure due to depth of burial and high temperatures due to both depth and the heat of granitic intrusions. Rocks of the Amisk group then could extend to depths greater than 3 km but would become increasingly metamorphosed and intruded by numerous small granitic plutons. The Amisk rocks at depth then would resemble Kisseynew rocks. Kisseynew rocks are the metamorphic equivalent of Amisk and Missi strata and are characterized by higher metamorphic grade, gneissosity, lit-par-lit injection of granitic material, numerous pegmatite dikes and generally more granodiorite intrusions of batholithic dimension or smaller than are found in areas underlain by Amisk or Missi rocks (Byers, Kirkland and Pearson (1965) and Bateman and Harrison (1945)).

In summary the geophysical evidence presented here indicates that lower density rocks exist at depths of 3 to 5 kilometers below the Amisk rocks but provides no conclusive evidence as to their nature. Detailed seismic measurements could possibly add more definitive information.

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No. 15 TRACE COPPER AND ZINC IN THE
CORONATION MINE OVERBURDEN

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ABSTRACT

Podsol soil horizons developed on Pleistocene glacial sediments overlying the Coronation mine orebody were analyzed for copper and zinc spectrophotometrically, using biquinoline-isoamyl alcohol and dithizone carbon tetrachloride reagents.

Copper and zinc are concentrated in the A_0 and C horizons, whereas the A_1 , A_2 and B horizons are leached. Of economic significance is the fact that the C horizon contains a copper anomaly, in excess of 100 times background, directly over the orebody. Due to the erratic distribution of high copper concentrations in the A_0 horizon with respect to the orebody, that horizon is not considered as a reliable prospecting datum.

INTRODUCTION

Under certain conditions, metallic ore deposits are accompanied by primary halos of trace elements in unweathered rock surrounding the ore-bodies or by secondary halos in weathered rock, alluvium, soil or vegetation above or near the mineralized zones. Where such halos occur, chemical analysis, as applied to the detection of trace elements, is a valuable prospecting aid, permitting the detection of mineralization of possible economic value.

During the summer of 1955, Byers (1956) used the Bloom method (1955) to determine, semi-quantitatively, the total heavy metal content of the soil in the vicinity of the Coronation mine. At the same time, samples for later testing in the geochemical laboratory at the University of Saskatchewan were collected at intervals of 100 or 25 feet, depending on the proximity of the mineralized zone, along lines which crossed the zone at intervals of 100 feet. Holes were dug with a spade to a sufficient depth to reach the parent material or C horizon of the soil profile - usually 24 to 30 inches below the surface. Samples were then taken from each soil horizon and placed in polyethylene bags. The samples were collected after the forest cover of spruce and poplar had been removed but before mining operations had disturbed the soil.

The Coronation mine is approximately 13 miles south-southwest of Flin Flon, from which it is reached by a gravelled highway and a mine railroad.

Geology of the Mine Area

The Coronation ore zone is a sulphide replacement of part of an essentially concordant shear zone in a sequence of metamorphosed basic to intermediate volcanic rocks belonging to the Amisk Group of Precambrian age (Figure 1).

The orebodies are confined within a zone 900 feet long, up to 200 feet wide and 1,000 feet in depth. The strike of the zone is northwest and the dip is 75 degrees southwest. The individual ore shoots plunge steeply south.

The ore consists of disseminated to massive pyrite, pyrrhotite and chalcopyrite, with minor amounts of magnetite, marcasite and sphalerite. To the end of 1963, 1,145,301 tons, with an average grade of 4.50 per cent copper and 0.23 per cent zinc, had been mined. The upper part of the ore, as revealed by stripping and development work, is highly oxidized to depths of 5 to 15 feet. This oxidized material consists of a mixture of iron oxides, malachite, a little azurite, and unweathered non-metallic gangue minerals, and is overlain by 5 to 20 feet of glacial sediments.

Nature of the Overburden

The overburden in the vicinity of the deposit consists of a thin basal layer of till overlain by glacio-lacustrine deposits of clay, silt and sand. These sediments, wherever they occur at the surface, have undergone podzolization, the dominant soil-making process in northern Canada. Leaf

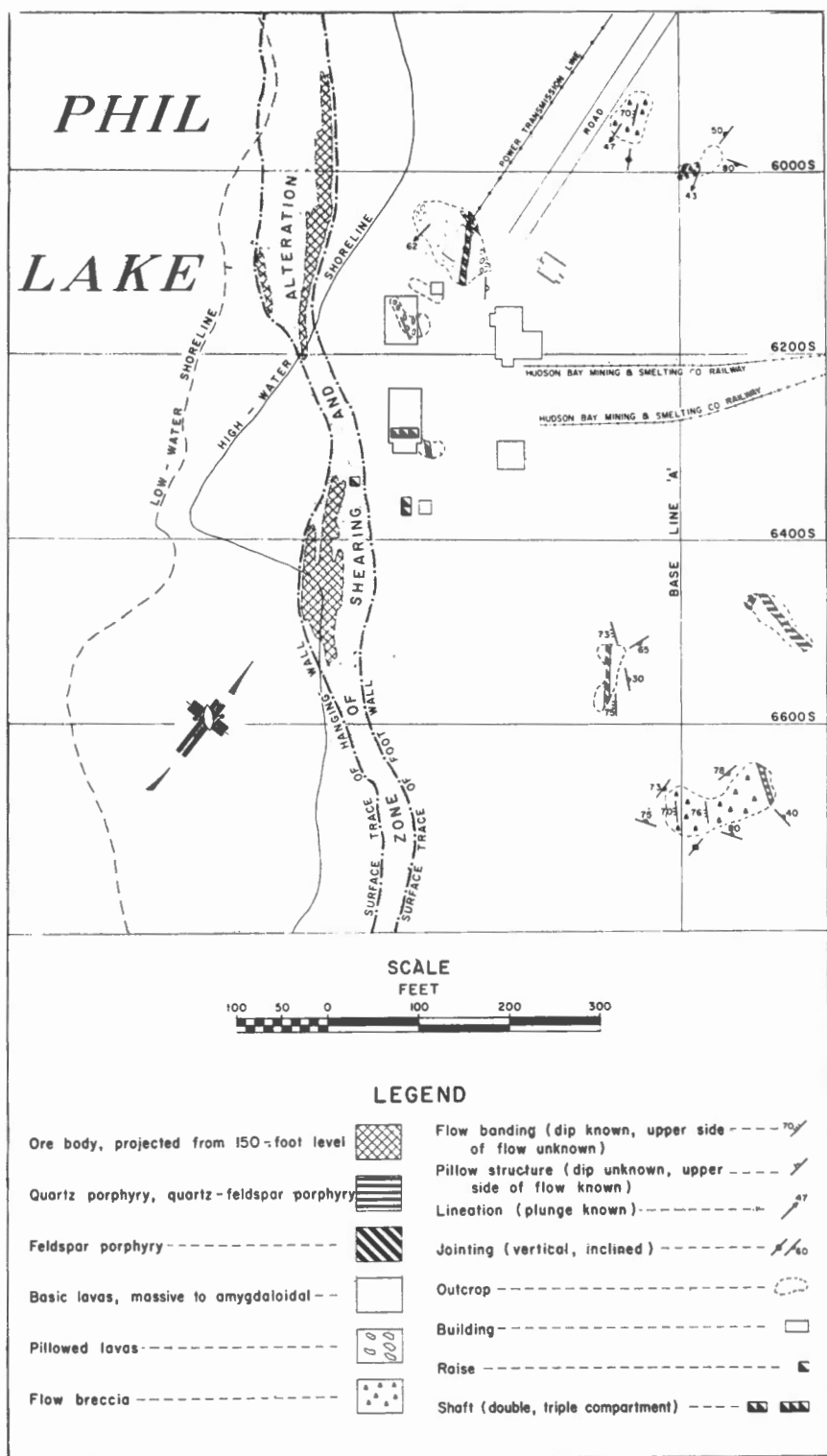


Figure 1. Surface geology at the Coronation mine.

Table I—Podsol Profile in the Coronation Area

Horizon	Thickness in inches	Description
A ₀₀	1—2	Leaf material, original structures definable
A ₀	2—5	Partly decomposed leaf matter
A ₁	0—1	A mixture of humus and minerals or ash and minerals where the A ₀₀ and A ₀ horizons have been burned.
A ₂	2—10	Light grey with pale brown streaks; mainly silty to sandy; horizontal platy structure
B	6—25	Greyish brown; often with moderate content of calcium carbonate, especially near base; often a blocky and nutty structure
C		Generally some shade of grey; layered to massive structure, depending on nature of parent glacial material.

debris and partly decomposed organic material accumulates on top of the soil. The downward movement of water through the organic cover and upper layer, or A horizon, of the soil tends to remove part of the calcium and magnesium carbonates, some of the mineral elements, and fine clay-size particles. These constituents are deposited in the B horizon, the zone immediately below the A horizon. Below the B horizon lies the parent material of the soil, referred to as the C horizon.

A generalized description of the Podsol profile, as developed in the area of the Coronation mine, is shown in Table I.

Sample Preparation

The soil samples were first pulverized in an alumina hand mortar to break up any clay nodules. If organic material was present, the samples were heated in porcelain dishes to ash the organic content. Each sample was passed through a 100-mesh stainless steel sieve. A 0.2-gm. portion of the minus 100 mesh fraction was mixed with 1.0-gm. of potassium pyrosulphate and then fused. The fused product was digested in 4 ml. of 6N(1:1) HCl for 1 hour in a water bath at a temperature of about 100° C. The solution was filtered into a 25-ml. flask and diluted to volume.

Copper Determination

The 2,2' biquinoline method, as first reported by Breckenridge (1939), was used, and the procedure followed for the determination of the copper in the samples was essentially the same as that outlined by Almond (1955) for soils and rocks.

The copper-biquinoline complex was extracted into isoamyl alcohol and the solution placed in an absorption cell. The amount of absorbance at a wave length of 546 mμ was determined using a Beckman Model D. U. spectrophotometer. The amount of copper present was determined from a standard

**Table II—Content of Copper and Zinc in the Soil Profile
and Underlying Bedrock**

Soil Horizon	Cu ppm Range	Cu ppm Average	Zn ppm Range	Zn ppm Average	Average Cu/Zn Ratio
A ₀	22—1725	324	4—800	22.8	14.2
A ₁	38—808	53.9	1—10	5.7	9.5
A ₂	30—89	48.5	1—8	5.5	8.8
B	9—55	30.8	2—9	5.6	5.5
C	8—76	37.2	2—12	6.4	5.8
Bedrock*	30—380	132	50—130	78	1.7

*Data supplied by Dr. J. R. Smith, Saskatchewan Research Council

curve representing a plot of absorbance vs known concentrations of copper prepared under the same conditions as the sample solutions.

Zinc Determination

The dithizone method, as described by Sandell (1959), in which zinc reacts readily to form the primary dithizonate, which is soluble in carbon tetrachloride, was modified in order to eliminate any interference by iron (Scott, 1963).

An aliquot of the solution previously prepared for the copper determination was further diluted and treated with hydroxylamine hydrochloride, thus reducing Fe^{3+} to Fe^{2+} , to prevent oxidation of the dithizone. Ammonium hydroxide was used to neutralize the solution and precipitate the iron as $\text{Fe}(\text{OH})_2$. The latter was dissolved by an acetic acid buffer (pH=5.5), which contains citric acid, to complex aluminum, and by phosphoric acid to complex iron. Sodium diethyldithiocarbamate was added to prevent interference by copper and other heavy metals.

The zinc was extracted from the solution by dithizone in carbon tetrachloride, and the solution was filtered into an absorption cell. The amount of absorbance at a wave length of 535 mμ was determined spectrophotometrically. The amount of zinc present was determined from a standard curve representing a plot of absorbance vs known concentrations of zinc prepared under the same conditions as the sample solutions.

Distribution of Cu and Zn in the Normal Soil Profile

Table II summarizes the results of 104 analyses of samples of normal soil in the vicinity of the mine and indicates the amount of the background content of copper and zinc in the soil profile away from the orebody. The data, as supplied by Dr. J. R. Smith, on the content of copper and zinc in the bedrock represent analyses of 150 samples taken over a considerable area of the volcanic rocks in which the Coronation deposit occurs, but they do not include samples from the wall rocks adjacent to the ore zone.

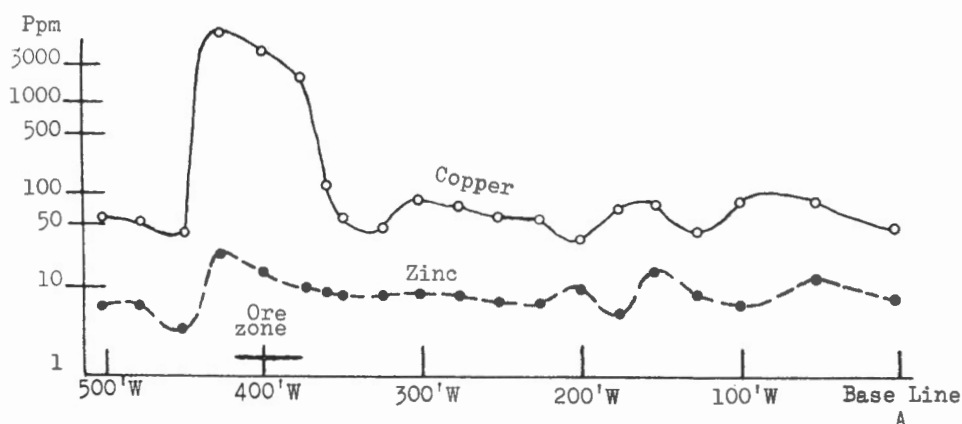


Figure 2. Profile-section on line 6400S, showing the variation of copper and zinc in the C soil horizon.

The following statements concerning the average amounts of copper and zinc in the soil profile may be made.

1. The A_0 or organic leaf horizon contains six times as much copper and four times as much zinc as any of the lower horizons.

2. The amounts of copper and zinc decrease from A_0 to B in the soil profile, with the C horizon, or parent material, containing somewhat more copper and zinc than the B horizon. The Cu:Zn ratios behave in a similar manner.

3. The A_2 horizon contains essentially the same amounts of copper and zinc as the A_1 .

4. The content of zinc is more constant than that of copper.

5. With the exception of the A_0 horizon, the content of copper in the soil profile is much less than in the underlying bedrock, and the amount of zinc in all the soil horizons is very much less than in the bedrock. There is also a marked difference between the Cu:Zn ratios of the soil profile and that of the bedrock.

The Bloom method indicated that the B horizon contained more heavy metals than the C horizon (Byers, 1956), whereas the present study indicates the reverse. This is probably due to the use, in the present study, of a hot acid leach solution which extracted more of the copper and zinc from the sample. The Bloom method, which employs a cold ammonium citrate solution, extracted only the heavy metals adsorbed on the soil particles and not the copper and zinc contained in the silicate structures of the minerals of the soil. The slightly higher content of copper and zinc in the C horizon as compared to the B horizon is probably the result of a difference in pH between B and C, the C horizon being more basic and thus favouring the precipitation of the metals leached from the upper horizons.

The decrease in the Cu:Zn ratio from the A_0 to the B horizon indicates the greater solubility and mobility of zinc compared to copper as the two metals move down through the soil profile.

The marked difference between the content of copper and zinc in the unmineralized bedrock and that in the normal soil profile away from the

orebody is due to the fact that the soil consists of transported material which is not related to the immediately underlying bedrock and that the bedrock is essentially unweathered.

Distribution of Cu and Zn in the Soil over the Orebody

Figure 2 shows the variations in copper and zinc in the C horizon along line 6400S, which crosses directly over the south orebody, where the thickness of overburden ranges from 5 to 16 feet. The location of the orebody is indicated by an increase in the content of copper to over 100 times normal background, but there is only a slight increase in the amount of zinc. The ratio of Cu to Zn is 238, compared to an average of 5.8 for the C horizon in the normal soil beyond the limits of the ore zone. This undoubtedly reflects the high proportion of copper to zinc in the ore as well as the removal of zinc by groundwater during the weathering of the ore zone.

The A₁, A₂ and B horizons show similar anomalies, but only in the order of 8 to 10 times background level.

The content of copper and zinc in the A₀ horizon is so erratic and high in the normal soil profile that no anomaly is indicated over the orebody.

Two other lines which crossed the mineralized zone show only a slight increase in the content of copper in the soil profile, the maximum anomaly being 4 times normal background. One section, at 6300S, crosses the ore zone between the south and north orebodies; the other, at 6100S, crosses the north orebody where the overburden is more than 20 feet thick.

Conclusions

Copper and zinc are concentrated in the A₀ horizon and to a much lesser degree in the C horizon immediately below the B horizon of the soil profile. However, the content of copper and zinc in the A₀ horizon varies so much from place to place and shows so little relationship to the ore zone that it is not considered to be of diagnostic value.

The C horizon represents the most favourable sampling datum for the following reasons:

1. It consists of fairly uniform material, whereas the upper horizons tend to be discontinuous and heterogeneous in their mechanical and mineralogical properties.
2. The C horizon is generally not disturbed or contaminated by organic material.
3. It displays the largest anomaly.

Acknowledgments

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No. 16 HELICOPTERBORNE ELECTROMAGNETIC, MAGNETIC
AND RADIOMETRIC SURVEY
CORONATION MINE, SASKATCHEWAN

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ABSTRACT

In conjunction with the research study of the Coronation mine recommended by the National Advisory Committee on Research in the Geological Sciences and coordinated by the Geological Survey of Canada, Canadian Aero Service Limited performed a detailed, low-altitude airborne survey over a block of ground encompassing the Coronation mine.

The in-phase/out-of-phase airborne electromagnetic data are compared with "horizontal-loop" ground data with reference to: size and nature of conductors detected; criteria in selection of targets for drilling. Information provided by Hudson Bay Mining and Smelting Company on their drilling of the numerous conductors in the area is employed in this comparison.

The merits of combining a sensitive airborne magnetometer with an airborne electromagnetic unit are discussed. The magnetic data are considered very important in assessing conductors as prospects for commercial sulphide deposits in this area of numerous electromagnetic anomalies.

The "Coronation" survey illustrates the value of EM in-phase measurements in detecting high-conductivity bodies and in providing diagnostic information concerning the geological nature of conductors.

Radiometric records are used to aid in the positioning of conductivity and magnetic anomalies and as an aid in interpreting the nature of certain conductors.

INTRODUCTION

At a meeting of the Canadian Exploration Geophysical Society in Toronto on March 22, 1960 the members were advised that the Geological Survey of Canada was coordinating a comprehensive geological and geophysical study of the Hudson Bay Mining and Smelting Company's "Coronation" mine (Figure 1), and that participation by exploration and survey companies was being invited. This study had been recommended by the National Advisory Committee on Research in the Geological Sciences and was being directed by Dr. D.R.E. Whitmore of the Economic Geology Division of the Geological Survey of Canada.

Canadian Aero Service Limited offered to survey the mine area with its geophysically-equipped S-55 helicopter. Since ground electromagnetic surveys performed by Hudson Bay Mining and Smelting Company had located numerous conductors besides the one which became the "Coronation" mine, an opportunity presented itself for determining whether airborne in-phase electromagnetics and airborne magnetics could distinguish the copper-bearing conductor from the others.

The detailed surface mapping program (400 feet per inch) which Dr. Whitmore was to initiate during the summer of 1960, and the library of drill log information to be made available by Mr. Albert A. Koffman of Hudson Bay Mining & Smelting Co., would provide a maximum amount of geological information on the area being studied. This would eventually permit the appraisal of the airborne geophysical data to be made in a much more positive manner than is normally possible.

Both from the point of view of Canadian Aero Service Limited and of the Geological Survey of Canada, a detailed, low-altitude, combined in-phase electromagnetic and magnetometer survey seemed highly desirable. It was consequently planned that this program would be accomplished during the summer of 1960 when the Canadian Aero survey unit was in the Flin Flon area.

Survey Program

The survey was flown on the morning of August 20, 1960. Dr. Whitmore arranged to have the power turned off at the mine for the occasion. As it developed, everything was blacked out west of Flin Flon so all the residents found themselves contributing to the scientific study for a few hours.

Forty-six productive traverses were flown over an irregular block in the vicinity of the Coronation mine. The block extended two and one-half miles northward from the southern end of McNally Lake, and averaged one and one-half miles in width. Line spacing was four hundred feet throughout, with the exception of the special traverses spaced at two hundred feet over the Coronation orebody. Line direction averaged east-west, but was varied somewhat to accommodate changes in formational strike.

In addition to this continuous block surrounding the Coronation mine, thirteen traverses were flown over the Birch Lake orebody, and over other known sulphide occurrences in the vicinity of Birch Lake and Mosher Lake.

The entire survey required two hours of flying time with the S-55 helicopter. Navigation was by visual recognition of ground detail on air

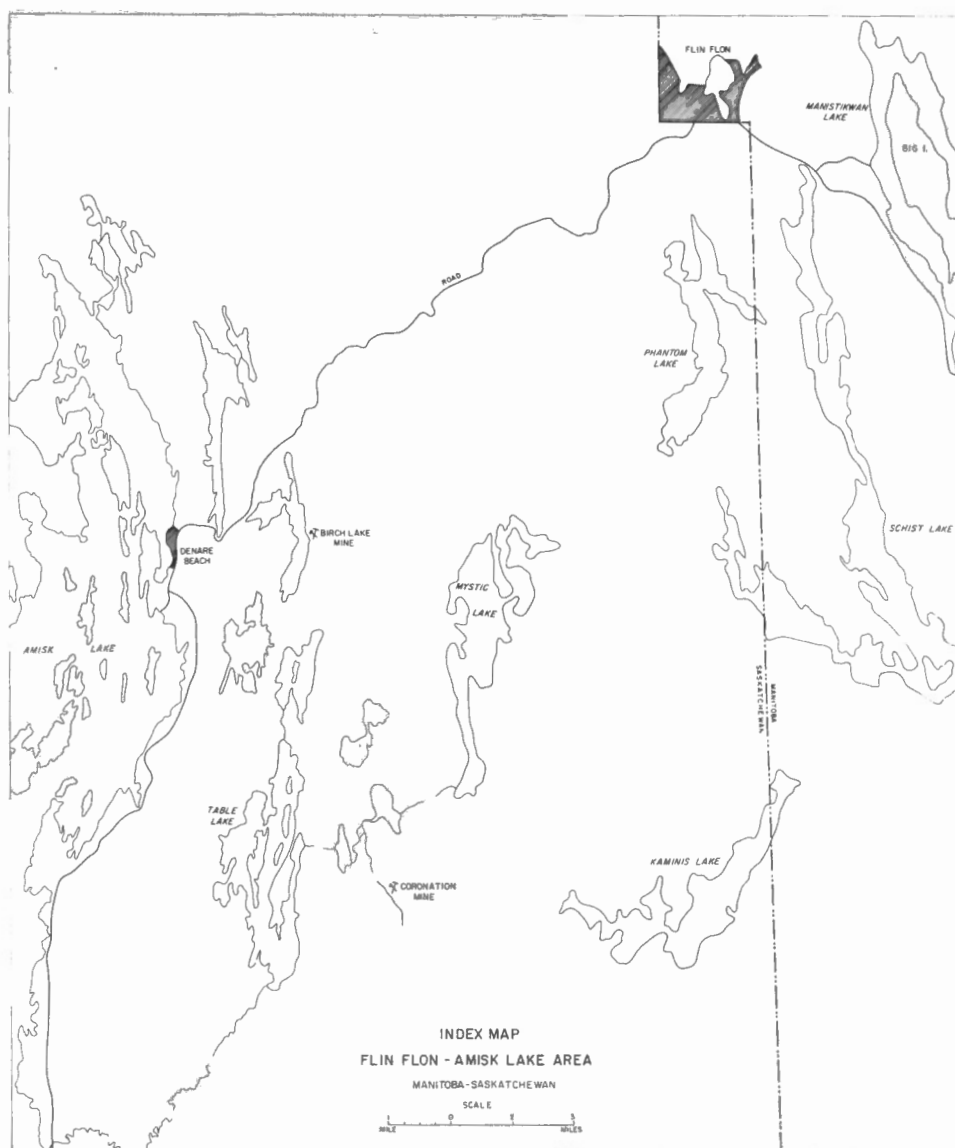


photo enlargements. The flight strips employed by the navigator were at a scale of 1320 feet per inch, an enlargement of four and one-half times from the original photo scale. No difficulty was experienced in flying 400-foot spaced traverses. Mean terrain clearance for most of the survey is estimated to be 160 feet, from an examination of the radio-altimeter record. The north-south-trending ridges and valleys exhibit relatively low relief so it was not difficult to maintain proper clearance. With few exceptions 140 and 180 feet were the limits of the terrain clearance.

Each of the three traverses across the Coronation orebody was flown at two different terrain clearances: once at the normal 160 feet, and once about 50 feet lower.

Survey Equipment

The geophysical equipment employed on the "Coronation" program is our standard airborne survey unit, consisting of the following:

- (a) In-phase/out-of-phase electromagnetic unit;
- (b) Gulf Mark III total-intensity magnetometer;
- (c) Atomic Energy Commission scintillation counter.

Auxiliary equipment carried includes: a fiducial counting system; an APN-1 radio altimeter; two Aeropath continuous-strip cameras - one with wide-angle lens, and one with standard lens. A six-channel Brush recorder, and a single-channel rectilinear Gulf recorder chart the data.

The Brush recorder plots simultaneously the following:

- (a) the in-phase and quadrature components of the secondary electromagnetic field;
- (b) the variations in total intensity of the earth's magnetic field;
- (c) the distance between the geophysical equipment and the land surface;
- (d) the variations in the gamma radiation from the earth's surface;
- (e) the fiducial marks which synchronize the geophysical measurements with the continuous-strip record of flight path.

The rectilinear recorder is used to present an extra large-scale plot of the total intensity magnetic data to facilitate the preparation of isomagnetic contour maps.

In-Phase/Out-of-Phase Electromagnetic Unit

The airborne electromagnetic detector is the unit developed by Newmont Exploration Limited, and acquired from them by Canadian Aero Service in 1958. It employs a coaxial coil arrangement with the axis of the coils paralleling the line of flight. Both coils are mounted rigidly on the aircraft with the transmitter forward and the receiver aft. On the Sikorsky S-55 helicopter employed during the "Coronation" survey a coil separation of sixty feet is attained. Operational frequency is 390-395 c. p. s.

Both in-phase and quadrature components of the secondary electromagnetic field are measured. The almost fixed spatial relationship between the two coils, plus a precise compensation system, permit the measurement of a very small in-phase component of the secondary field in the presence of a very large primary field. An instantaneous sampling technique is used to make the in-phase and quadrature measurements.

The instrumental noise level on most of the "Coronation" survey was such that an in-phase anomaly of thirty parts per million (of the primary) could be readily distinguished. Out-of-phase anomalies of only 15-20 p. p. m. were easily discerned. These are the normal instrumental sensitivities.

The measurement of the in-phase component plus the high resolution and sensitivity attained are considered the most important attributes of this unit. The in-phase measurement at a given frequency responds to a higher



Figure 2. Geophysically-equipped Sikorsky S-55 Helicopter.

range of conductivities than does the quadrature measurement, ensuring that very high conductivity bodies will not be missed. The ratio of in-phase to quadrature components is a function mainly of conductivity.

Gulf Mark III Magnetometer

The airborne magnetometer is the well-known Gulf Mark III total-intensity instrument developed by Gulf Research and Development Company. It is a saturable core, "flux-gate" type of magnetometer.

Sensitivity of the instrument is such that anomalies of only 2-3 gammas amplitude can normally be recognized on the ten-inch rectilinear tape record. This sensitivity is very valuable in a magnetometer which is used in conjunction with an airborne electromagnetic unit as it permits detection of relatively small amounts of magnetic material - information which is indispensable when appraising the electromagnetic results. This ability of the Gulf magnetometer to detect small amounts of magnetite or pyrrhotite is enhanced in the airborne survey unit under discussion by the low terrain clearance which is attained.

Scintillation Counter

The Scintillation Counter used is the one designed by The Atomic Energy Commission of Canada, and produced by Measurement Engineering Limited of Arnprior, Ontario.

Radiometric measurements are made in conjunction with the electromagnetic-magnetic survey chiefly as auxiliary location information. The scintillation counter record provides an excellent means of distinguishing swamps and lakes from dry ground, and outcrops of certain types of rock

(chiefly acidic) can be recognized. These data have proved to be very valuable in areas of difficult path recovery (poor photo quality or lack of distinct photo features) when precise locations are required.

As will be seen in the "Coronation" survey, the radiometric data can also serve to show the relationship between certain electromagnetic anomalies and certain physiographic features.

Aircraft

The Sikorsky S-55 helicopter (Figure 2) employed on the "Coronation" survey is the original carrier of this survey unit. For a survey of the type described here it is an ideal carrier. The short flight lines require frequent turn-arounds, and the helicopter permits a minimum of waste flying in this situation. Furthermore, since the survey area was close to the base of operations, the three-hour range of the helicopter did not impose any limitations.

Data Presentation

Our standard form of map presentation has been used for the "Coronation" data. This system of presentation is based on the premise that the most definitive characteristics of a conductivity anomaly are the in-phase amplitude and the ratio of in-phase to out-of-phase amplitudes.

Note that the in-phase amplitude figures appearing on the map are normalized for altitude variation. This is very important since anomaly amplitude decays rapidly with increasing altitude (of the order of an inverse cube at our operational terrain clearance). As mentioned above the "Coronation" area is considered to be relatively flat topographically, and for the most part terrain clearances were maintained between 140 and 180 feet. To emphasize the need for altitude correction, even over relatively flat terrain, we would point out that an increase in altitude from 140 to 180 feet would cut the parts per million amplitude of an anomaly in half.

The data presentation is essentially a plot of individual anomalies, rather than a contour map. The following quantities are plotted for each anomaly:

- 1) normalized in-phase amplitude;
- 2) in-phase/out-of-phase ratio (using symbols which correspond to ranges of ratio);
- 3) half-peak width (for single conductors), and zone boundaries for broad conductive zones;
- 4) gamma amplitude of associated magnetic anomaly (if any).

When anomalies appear only on the quadrature component the in-phase amplitude figure and the ratio symbol are replaced by the notation "OP" and a mark indicating the position of the out-of-phase peak if it is well defined. We do not normally calculate normalized quadrature amplitude figures, although it could be done.

It has proved very convenient to indicate associated magnetic anomalies directly on the electromagnetic map. Magnetic association is

Interpretation of Airborne Em Data

A. "Coronation" Block (Figure 3)

Most of the conductors within the large block surveyed are characterized by broad, low amplitude, out-of-phase anomalies with no discernible in-phase response. In the eastern part of the area several bodies exhibit sufficiently high conductivities to yield substantial in-phase anomalies. Among these is the "Coronation" orebody. On several conductors, chiefly those with the stronger in-phase responses, associated magnetic anomalies occur.

Several of the broad out-of-phase zones obviously coincide with lakes (e. g. zones A, B and H). Others (e. g. C, D and F) coincide with lakes in part but extend beyond. Examination of the scintillation counter record shows that these broad "OP" anomalies coincide with radioactive lows. This is true over land as well as over lakes. The evidence, then, is overwhelming that these broad, weakly conducting zones correspond with lakes and swampy ground.

In an exploration survey for massive sulphides these areas would in general be considered of no interest. The obvious interpretation is that conducting overburden under lakes and in swampy valleys is responsible for the small conductivity contrasts observed.

In any survey, however, such zones must be watched closely for local changes in characteristics. If sharp in-phase or out-of-phase anomalies are detected locally, or if a local association of magnetic and EM anomalies becomes apparent, there may well be bedrock conductors beneath the surface conductor. These conditions are clearly demonstrated in this survey.

The best example is at the "Coronation" mine itself. The sulphide conductor lies precisely at the edge of an out-of-phase zone corresponding with the lake. On traverse 28 (SW) (Figure 4) no clearly-defined out-of-phase anomaly is visible over the orebody, whereas the in-phase trace shows it very clearly. This happens, of course, because the in-phase component is not sensitive to low conductivity contrasts such as that exhibited by the lake or lake-bottom, but it is sensitive to conductivities in the massive sulphide range.

If only the out-of-phase component had been measured on this profile it would be necessary to rely on the magnetic record to suggest that something of interest was happening locally, and this is much less positive evidence than the direct conductivity indication of the in-phase component.

The combination of the two features (sharp in-phase peak and closely associated magnetic anomaly) is the most encouraging set of circumstances. In any exploration survey this feature would definitely warrant follow-up on the ground.

Near the southern extremity of the block, within the weak out-of-phase zone designated "I", in-phase anomalies were detected on three traverses (two of these are shown at the top of Figure 5). The out-of-phase profiles on these traverses were essentially similar to those elsewhere along the zone, but the in-phase anomalies distinguish two local bedrock conductors of markedly higher conductivity. There appears to be one conductor about 800 feet long, and a second small one seen on only one traverse. The long, stronger one lies along the flank of a large magnetic high so it is

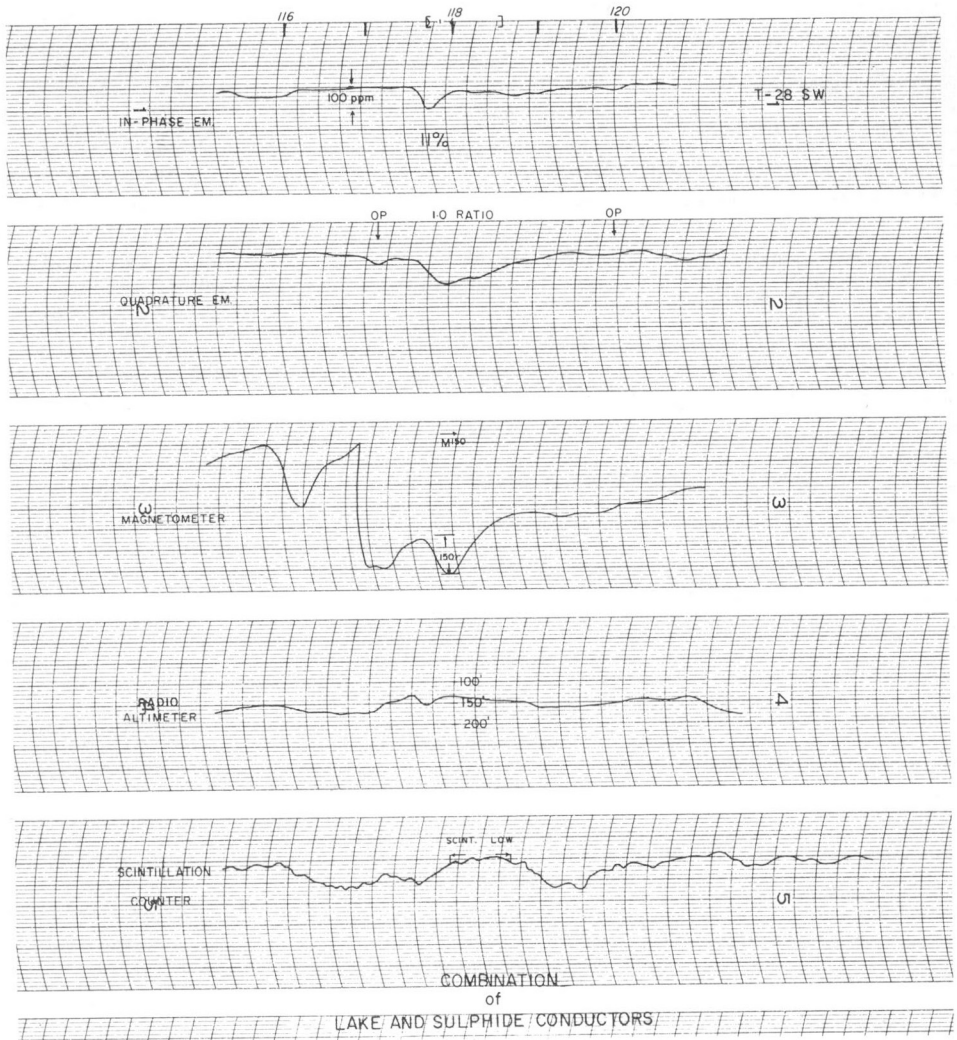


Figure 4

probably at or near a contact. There is no obvious magnetic high coinciding exactly with the conductor, but a very small magnetic anomaly could be lost in the steep gradient of the large magnetic feature. In any event, in a "hot" area such as this these in-phase anomalies would unquestionably rate ground examination.

Besides this anomalous zone and the "Coronation" conductor itself, one other conductive zone would have been included as a high priority target if this had been a normal exploration survey. The zone designated "J" contains at least two highly-conducting bodies. The electromagnetic response is almost exclusively in-phase; the quadrature anomalies are insignificant. The two profiles shown on Figure 6 are typical. Note the clear-cut, coincident magnetic anomaly of 200 gammas.

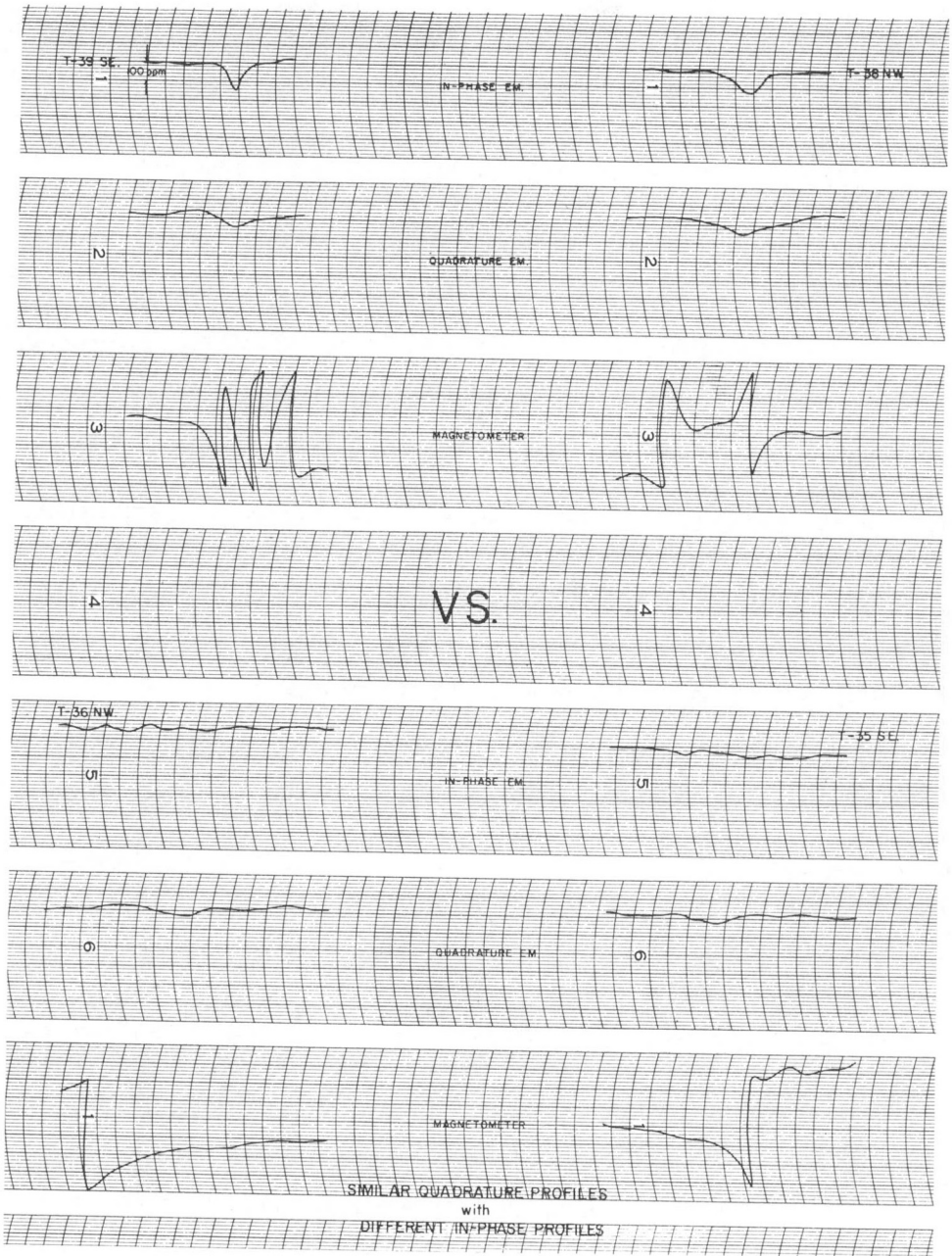


Figure 5

There are several other locations which would be noted as "second-class" prospects. Space does not permit a complete discussion of these. In general, however, they are places where the electromagnetic and (sometimes) magnetic characteristics suggest a local bedrock conductor but the

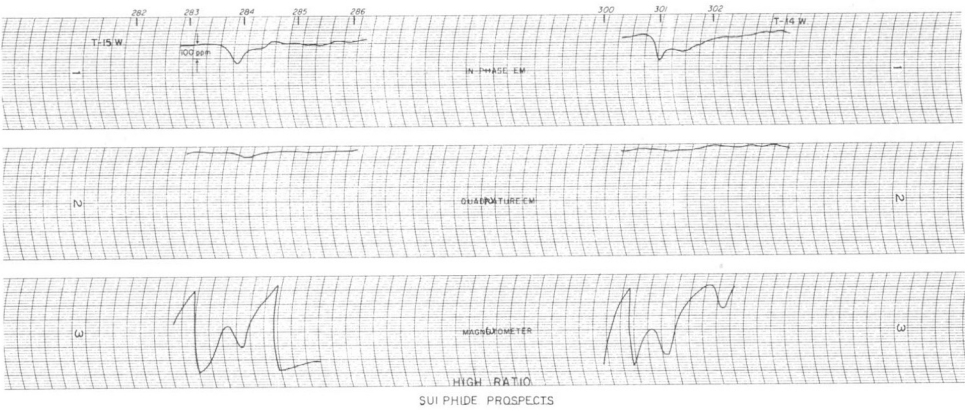


Figure 6

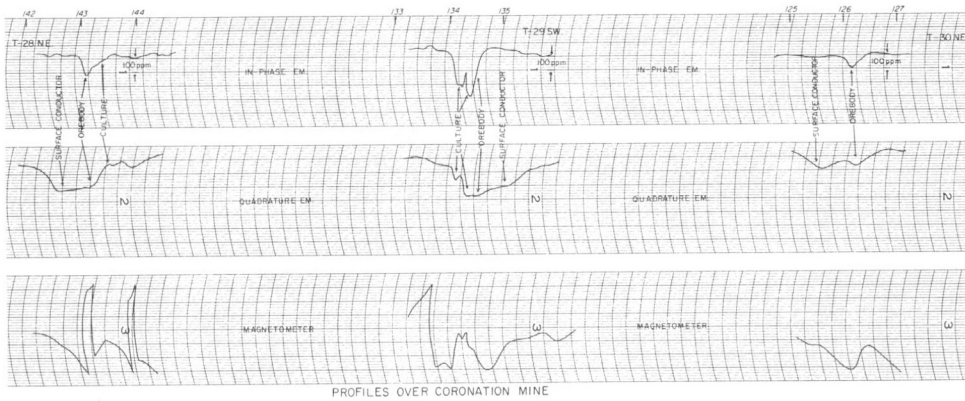


Figure 7

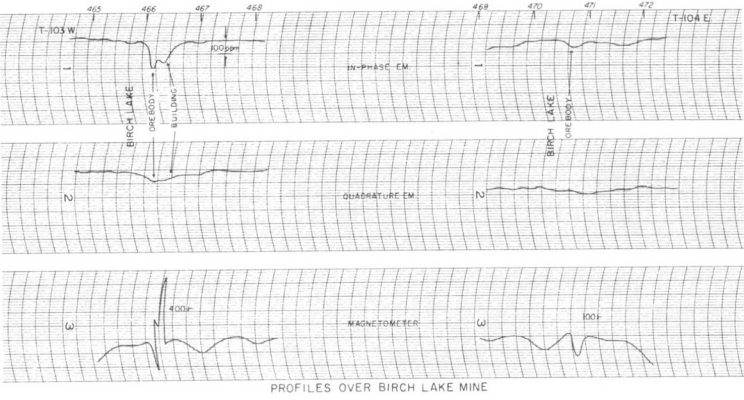


Figure 8

electromagnetic response is not strong enough to be typical of massive sulphides. These, then, would be given a much lower priority in the ground follow-up program.

B. "Coronation" Mine

Arrangements were made to have the power turned off during the survey of the mine in order to eliminate the strong electromagnetic anomalies produced by power lines and transformer stations. This unquestionably helped, but there were still appreciable electromagnetic anomalies for some of the "cultural" features in the vicinity of the mine. To eliminate these effects it was necessary to make a very careful examination of the film record so that each peak in the multiple electromagnetic anomalies could be accurately positioned with respect to buildings, roads, etc.

As viewed on the original profiles, most of the electromagnetic anomalies are quite complex (Figure 7). However, when they are carefully positioned it is immediately apparent which are due to the sulphide body and which are due to man-made conductors. All of the "cultural" anomalies coincide with certain buildings or other features, and these same features can be seen on various traverses. The sulphide conductor is the conductor closest to the lakeshore on all six traverses, and it is the only conductor which does not coincide with cultural features on the film.

If this had been a normal airborne exploration survey the "Coronation" conductor would definitely have been selected as an excellent prospect for massive sulphides on the basis of the following characteristics: 1) limited length; 2) high conductivity; 3) related local magnetic anomaly.

The airborne electromagnetic data indicate that the conductor length is greater than 450 feet and less than 900 feet. The southernmost anomaly is very weak so we would assume that it is at or near the southern end of the body. The northern extremity would be placed between traverses 27 and 28.

The ratio of in-phase to out-of-phase components appears to be of the order of 1.0 to 1.5 on most traverses. It is difficult to determine these values precisely on some lines because of the interference from the cultural anomalies and from the surface conductor corresponding to the lake. Experience has shown that massive sulphide conductors generally give anomaly ratios of 1.0 or greater, and since the ratios here are at least 1.0 they are clearly in the sulphide range.

Normalized in-phase amplitude figures are small in comparison to those obtained over huge orebodies such as the Brunswick and Heath Steele in New Brunswick (about one-sixth their size); and they are of the order of one-half the anomaly amplitudes at Stall Lake and Chisel Lake. The interpretation then would be that massive sulphides were very likely the source of the anomaly, but that a body of relatively small dimensions should be expected.

The positional relationship between the sulphide conductor and the magnetic anomaly is consistent on all traverses with the peak of the magnetic anomaly occurring about 100 to 120 feet west of the electromagnetic peak. In length the magnetic and electromagnetic anomalies correspond perfectly, so there is no question that the two are directly related.

We suggest that the westerly dip of the sulphide body is responsible for the offset of the magnetic anomaly to the west. The shape of the magnetic

anomaly clearly indicates a westerly dip. Presuming that the same body is both ferro-magnetic and conductive, the peak of the magnetic anomaly would be expected to be farther down-dip than the electromagnetic peak. The amplitude of the magnetic anomaly (150-200 gammas) is of the order to be expected from pyrrhotite, so pyrrhotite may give rise to the magnetic anomaly and also contribute to the conductivity anomaly.

Rough estimates of conductor width based on a comparison with empirical curves give fifteen feet for the anomaly on traverse 28 - SW (north part of conductor), and one hundred feet on traverse 30 - NE (near south end of conductor). Using these width figures, curves derived from model studies yield conductivity values of 4 mhos/metre on traverse 28, and 1 mho/metre on traverse 30. No estimates were possible on the traverses over the central part of the body due to the interference from the "cultural" anomalies.

C. "Birch Lake" Mine

Two traverses were flown across the "Birch Lake" orebody (Figure 8), one (traverse 103) directly over the main buildings, and the other (traverse 104) about 150 feet farther north just at the edge of the island on which the mine is located.

The electromagnetic anomaly on traverse 103 has two peaks, and both exhibit in-phase to out-of-phase ratios greater than 2.0. The eastern peak coincides with a sharp magnetic anomaly of 400 gammas and is presumably due to massive pyrrhotite and other sulphides. On the film the western EM peak coincides with a building and it presumably is due to the building rather than a bedrock conductor.

The normalized in-phase anomaly amplitude of the "Birch Lake" conductor is about fifty per cent higher than the strongest response over the "Coronation" body, and the ratio is also somewhat higher. The magnetic anomaly is twice as large as the largest one over the "Coronation" body.

The northern traverse picked up a single conductor of comparable ratio, but lower amplitude, which must be the northern part of the "Birch Lake" ore zone. On this traverse the amplitude of the coincident magnetic anomaly has diminished to 100 gammas.

Comparison of Ground Em and Airborne Em

A. "Coronation" Block

The ground electromagnetic survey of the area was conducted by Hudson Bay Exploration and Development Company using Boliden "horizontal-loop" equipment. It was this survey which led to the discovery of the "Coronation" mine. Mr. A.A. Koffman of Hudson Bay has kindly made available the results of his company's ground electromagnetic program in the vicinity of the mine, and it is these data which will be compared to the "in-phase" airborne electromagnetic data.

The Boliden unit is well-known as the first widely-used horizontal loop electromagnetic equipment measuring both in-phase and out-of-phase components of the secondary field. It employs a 45-inch diameter transmitting coil, a 26-inch receiving coil, and is usually operating at coil separation of two hundred feet. Operational frequency is 3600 c. p. s.

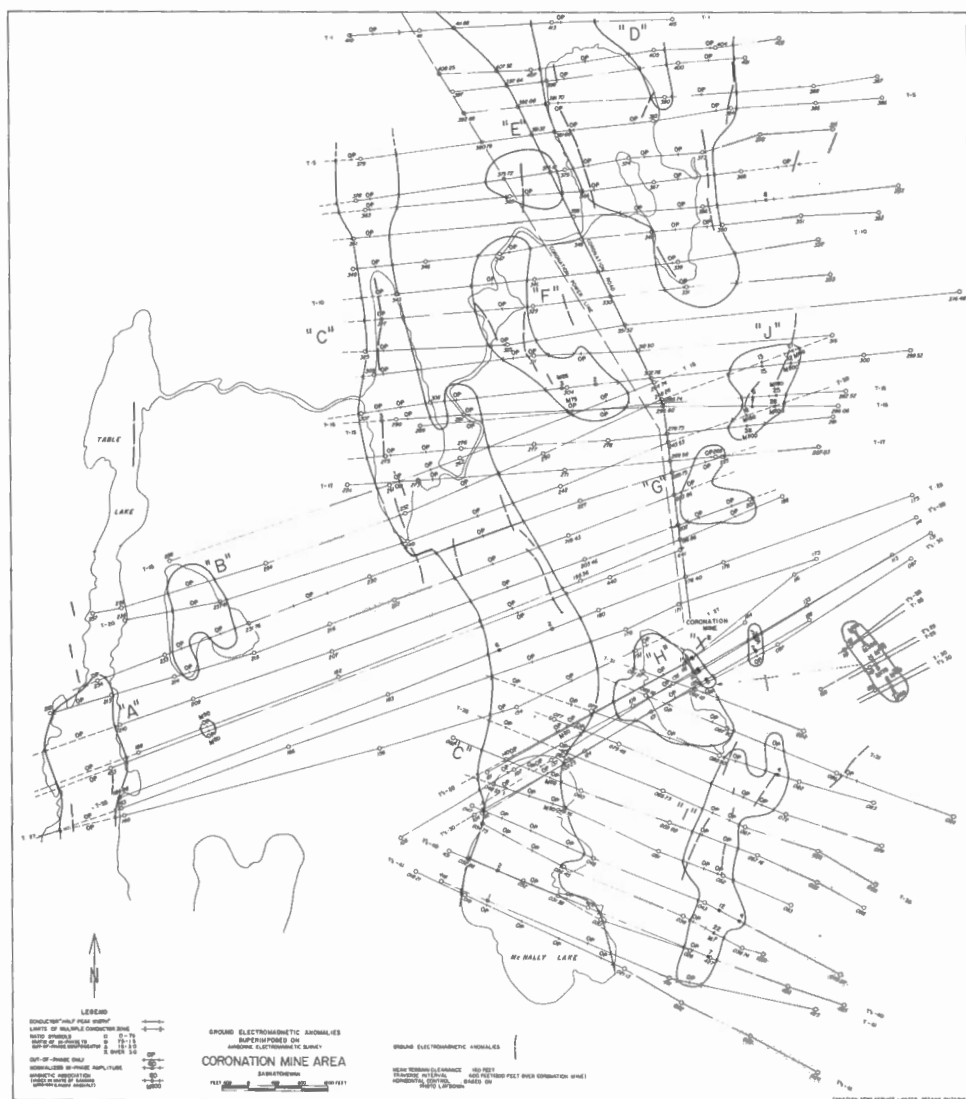


Figure 9. Ground electromagnetic anomalies superimposed on airborne electromagnetic survey.

In the ground survey conducted by Hudson Bay Exploration and Development Company the picket lines were 200 feet apart. Readings were taken every one hundred feet on non-anomalous traverses and every fifty feet to detail conductors when they were detected. Except in the vicinity of anomalies, only the in-phase readings were plotted, so we do not have out-of-phase readings everywhere. With the exception of a small piece of ground at the southern tip of the airborne survey area the entire area is covered by the ground electromagnetic results made available to Canadian Aero.

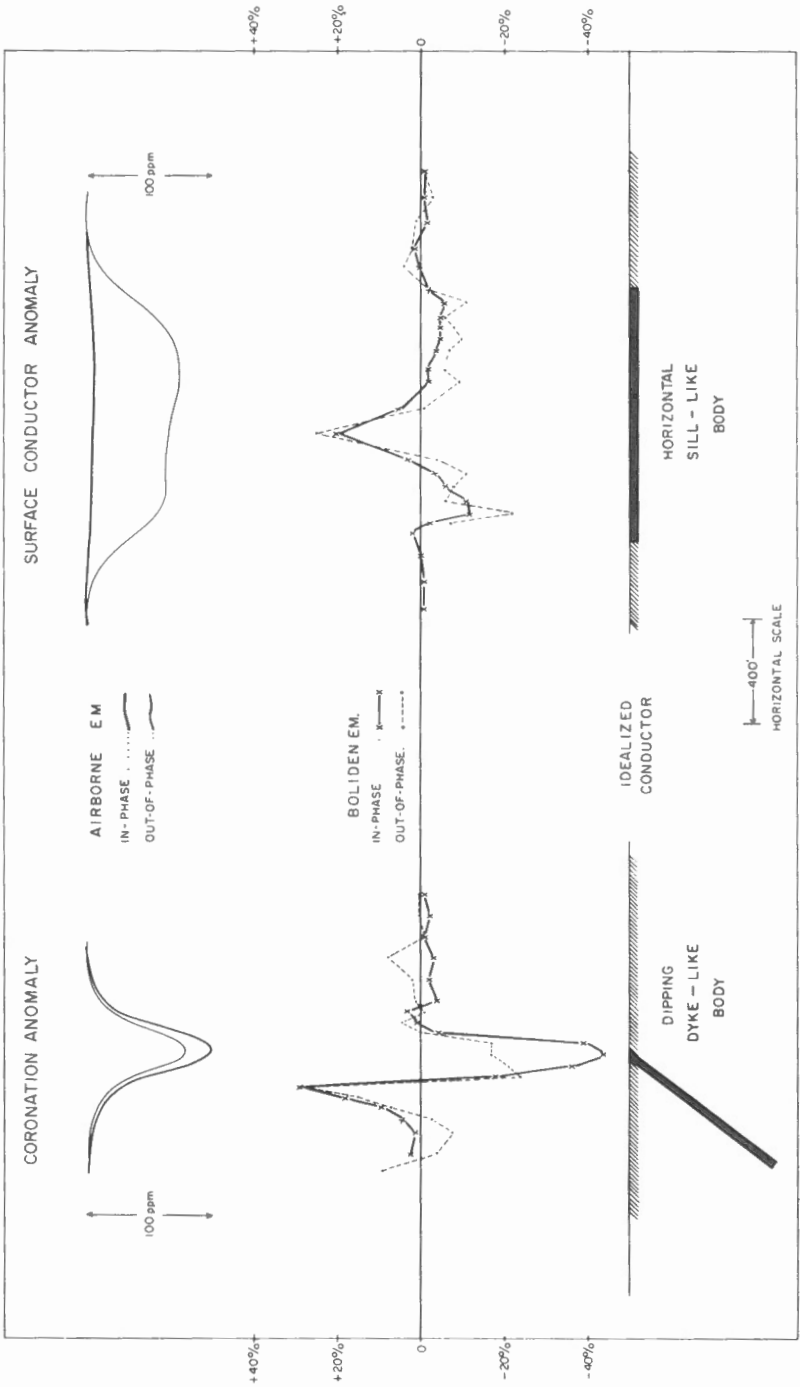


Figure 10

Certain conductors were indicated on the Hudson Bay map which we received. These are the ones which are shown on Figure 9 superimposed on the airborne electromagnetic map. In the course of Hudson Bay's exploration of this area many of these anomalous zones were drilled.

A cursory examination of the anomalies marked on the ground electromagnetic map shows two important facts:

- 1) The two best anomalous airborne electromagnetic zones also give the best anomalies on the ground (largest in-phase amplitudes and largest ratios of in-phase to out-of-phase readings).
- 2) Most of the other anomalies fall within the extensive out-of-phase zones mapped by the airborne electromagnetic unit, and on the broader "OP" zones they fall consistently near the boundaries.

A thorough examination of the ground electromagnetic results shows clearly that the anomalies fall into two distinct categories, differing both in:

- (i) ratio of in-phase to out-of-phase response;
- (ii) anomaly shape.

The two zones corresponding to the "good" airborne anomalies J and X have the characteristic shape of single dyke-like bodies: a sharp negative flanked by positive shoulders. Ratios range mainly from 1 to 4 with the J zone exhibiting generally higher ratios than the "Coronation" conductor (as on the airborne survey).

The majority of the other ground anomalies are of markedly lower ratio and different shape. The examples shown on Figure 10 illustrate the difference. Note the 2 : 1 ratio on the negative peak over the "Coronation" conductor, and note the positive shoulders on either side of the negative. The asymmetry of the positive shoulders reflects the dip of the conductor.

The so-called "Surface Conductor Anomaly" was obtained over one of the lakes in the area (the same lake corresponds with a broad out-of-phase anomaly on the airborne EM map). This profile illustrates the basic shape of the majority of the ground anomalies which correspond to the broad out-of-phase airborne anomalies. Note that it consists of negative peaks over the edges of the flat-lying conductor with positive values in between. The amplitude ratios on the negative peaks are mainly in the range of 0.5 to 1.0.

Once the character of the anomalies from the surface conductors is recognized it then becomes apparent that most of the anomalies which had originally been indicated on the ground electromagnetic map are actually the negatives which occur along the edges of the surface conductors (that is, conducting overburden, conducting lake-bottom deposits, conducting swamps) and they are not due to local dyke-like conductors at all.

When the ground electromagnetic data are perused, many more of these negatives can be found than were picked originally, and most of them fall into the basic pattern portrayed on Figure 10. There are, of course, variations on the basic pattern, but this is to be expected due to the inhomogeneities, varying widths and varying thicknesses of the surface conductors.

For instance, as a surface conductor narrows, the positive central portion of the anomaly narrows and eventually disappears. The remaining negative is then similar in shape to that from a steeply dipping sulphide body, but has a lower ratio. Another instance of irregularities on the basic pattern is the wide divergence in the amplitudes of the two negative peaks on some zones. This occurs due to differences in the thickness and/or conductivity between the two edges.

Referring again to Figure 10, let us see how the airborne anomalies compare with the ground anomalies for the two different types of conductors described above. On the "Coronation" anomaly the airborne and ground systems both give single, sharp negative peaks. Due to the different coil orientations and to the difference in the height-coil separation relationship between the two systems, the basic anomaly shapes are of course different. The asymmetry displayed by the positive shoulders on the ground profile reflects dip very effectively. The airborne profile shows only a slight asymmetry in the negative peak (it is usually advisable to rely on the airborne magnetometer profile to provide dip information). The ratio of in-phase to quadrature is roughly twice as high on the ground profile; experience shows that this is the normal relationship between the ratios of the two systems for dyke-like conductors of reasonably high conductivity.

The anomalies corresponding to the horizontal sheet-like conductor exhibit characteristic shapes for the particular coil orientations and height-coil separation relationships employed. The striking difference between the two systems is the marked insensitivity of the in-phase trace of the airborne unit to this type of conductor. We suggest that two factors are involved, namely coil orientation and frequency.

On the ground the horizontal transmitting loop couples ideally with the flat-lying surface conductors and would be expected to generate larger secondary fields (proportionately) than the vertical transmitting coil of the airborne unit. The Boliden frequency is 3600 c. p. s. in contrast to 390 c. p. s. on the other, so the (proportionate) response from a poorly-conducting body is higher. Presumably then both frequency and coil orientation contribute to make the in-phase response to flat-lying, low-conductivity bodies much stronger for the ground unit.

Note, however, that the ratio of in-phase to out-of-phase response on the Boliden profiles is markedly lower on the negative peaks of the surface conductor anomaly than on the "Coronation" anomaly. This is a measure of the conductivity difference between the two types and is one of the factors to consider when appraising ground electromagnetic anomalies.

In concluding our comments on the comparison on the Boliden survey and the airborne "in-phase" electromagnetic survey in the "Coronation" block, we would generalize as follows: The same pattern of conductors is shown by both surveys. Both on the ground and from the air most of the anomalies fall into two main groups, one of which is considered very likely to indicate sulphides, and the other very likely to indicate surface conductors. On both surveys there are exceptions - those "in-between" anomalies which are obviously not first-class prospects, but which at the same time cannot be dismissed without further explanation.

CONCLUSIONS

The study of the combined electromagnetic, magnetic and radio-metric airborne survey in the "Coronation" area and the comparison of the airborne electromagnetic results with the ground electromagnetic map lead to the following conclusions:

- 1) The "Coronation" orebody would definitely have been located if this airborne system had been used in the original exploration survey, provided only that the line spacing was close enough to put a line across the

conductor. The orebody is one of three conductive zones which would have been selected as first-priority prospects on the basis of their electro-magnetic and magnetic characteristics.

2) The in-phase measurement proved to be extremely valuable in the detection of all three prospects. It was demonstrated that if only the out-of-phase measurement had been made it would not have been possible to single these out as the most important targets. In two cases conducting surface material generated out-of-phase anomalies of comparable magnitude to the anomaly from the bedrock conductor. The shape of the important out-of-phase anomaly was thereby distorted so that it was very difficult, and on some traverses impossible, to recognize.

In the third zone there was fortunately no surface conductor, but the conductivity was sufficiently high that the electromagnetic response was almost exclusively in-phase. Even with the undisturbed background the out-of-phase anomaly was barely discernible. At higher frequency or with conducting overburden it would have disappeared completely.

3) The value of the simultaneously recorded magnetic information is unquestionable. Both of the orebodies in this area (Coronation and Birch Lake) have coincident or closely-parallel magnetic anomalies on every traverse across them.

Although the three conductors mentioned above would have been picked as potential sulphide occurrences on the basis of their in-phase electromagnetic properties alone (one of them, in fact, was) the presence of a magnetic anomaly makes the selection that much more positive.

It is significant that the out-of-phase surface conductor anomalies do not have associated magnetic anomalies. This negative information in combination with the scintillation counter data aided in recognizing these anomalies for what they were.

From these comments it is evident that measurements of the magnetic field are very helpful in the interpretation of any electromagnetic survey, whether airborne or terrestrial.

4) The airborne geophysical survey was at least equal to the ground electromagnetic survey in providing diagnostic information on the nature of the conductors detected, and was in some instances superior. Recognition of the highly-conducting sulphide zones was equally easy on both. Recognition of the surface conductors was easier from the air. The advantage enjoyed by the airborne geophysical system in this comparison is to a large degree due to the addition of magnetic and radiometric data which were not available to support the ground electromagnetic data. The remaining advantage resides in the different anomaly shapes which the two electromagnetic systems obtain over flat-lying surface conductors: the ground electromagnetic anomaly is not always so readily recognized and can under certain conditions be mistaken for an anomaly (or anomalies) from bedrock conductors.

5) The advent of "diagnostic" airborne in-phase equipment and the use of this equipment in conjunction with airborne magnetometers and scintillation counters have drastically altered the role of airborne electromagnetic surveys in the overall exploration program. No longer is the airborne electromagnetic contribution restricted to indicating generalized conductive areas requiring exhaustive detailing on the ground. Recognition of different types of conductors and selection of specific targets can now be accomplished from the air.

ACKNOWLEDGMENTS

The author wishes to express his appreciation to Dr. D. R. E. Whitmore of the Geological Survey of Canada for his aid and cooperation in the assembly of geophysical and geological data used in the preparation of this paper. The author is also indebted to Mr. Albert A. Koffman of Hudson Bay Exploration and Development Company for making available the results of their ground electromagnetic survey which was used as a basis of comparison for this paper.

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No. 17

CALCULATION OF ORE RESERVES
IN THE CORONATION MINE*

R. B. Cairns

Chief Geologist, Mining,
Hudson Bay Mining and Smelting Co., LimitedABSTRACT

The Coronation copper sulphide deposit, which had a length of 600 feet, maximum width of 65 feet, and vertical range of 1,050 feet, was delineated from surface by 55 diamond-drill holes which intersected the zone at approximately 100-foot intervals. Using this basic data, the orebody was divided into 25 blocks for a volume and grade estimate which was done in the space of a few hours and gave a reserve figure of 825,000 tons at 5.08 per cent Cu. Development work, and the drilling of 261 underground holes, furnished data for a revised estimate which required three days to calculate on the basis of 90 ore reserve blocks and gave a figure of 722,000 tons at 4.83 per cent Cu. Each subsequent revision involved up to 150 blocks and occupied a geologist's time for one week. When the orebody was completely mined out, total production had been 1,412,861 tons at 2.25 per cent Cu, which yielded an amount of copper metal 43 per cent higher than originally estimated. The increase was due largely to the lowering of the cutoff grade from 2.00 per cent Cu to 0.90 per cent Cu during the latter, low-cost stages of mining. The original ore estimate proved to be a realistic one upon which to base production plans.

In view of this experience, it does not appear that a computerised data processing technique is warranted in the evaluation of a deposit of this size and type because the number of individual ore reserve blocks is comparatively small and the greater part of the estimating procedure is interpretive.

* Presented at the C. I. M. M. conference on Ore Reserves Estimation and Grade Control held at l'Esterel, Quebec, September 1967.

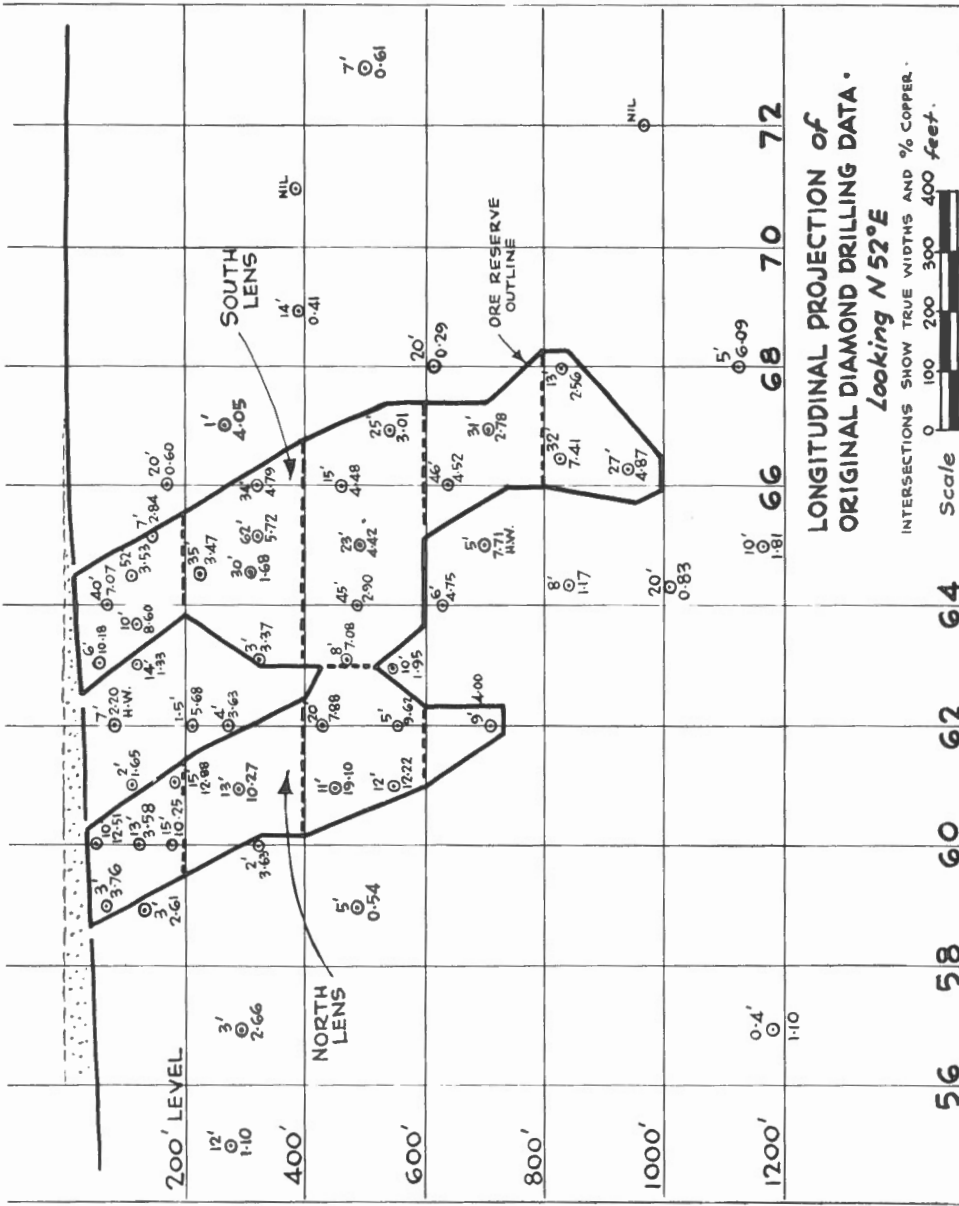


Figure 1.

Data from Surface Diamond Drilling

The Coronation orebody was discovered in 1953 as the result of an electromagnetic survey carried out in northern Saskatchewan at a location 13 miles southwest of Flin Flon, Manitoba. The orebody had no visible surface expression and was delineated by 55 inclined surface diamond-drill holes. These holes intersected the ore zone at intervals of approximately 100 feet over a strike length of 700 feet and to a maximum depth of 1,100 feet, as shown in Figure 1. Cross-sections were drawn at right angles to the longitudinal projection and at 100-foot intervals. Figure 2 shows a cross-sectional view of the South Lens at Section 66+00 as outlined by surface drilling. The ore occurred as two main shoots aligned in a northwest strike and associated with a zone of alteration which has a regular dip of 70 degrees to the southwest. These shoots were called 'North Lens' and 'South Lens' and were joined along strike at the 450-foot level on Section 63+00 (see Fig. 1).

Calculation of Ore Reserves from Original Data

On completion of the surface drilling program in 1954, a calculation of reserves was made in the conventional manner. The outline of the orebody was drawn on the longitudinal projection, and on the cross-sections, by fitting a cut-off line at a minimum mining width of five feet and a minimum grade of 2.00 per cent copper. Fitting of the outline was also influenced by the expectation that the orebody would have a southerly plunge to conform with lineation measured on nearby rock outcrops. For calculation purposes, the North Lens and the South Lens were separated at Section 63+00 and then each lens was divided into ore reserve blocks by horizontal slicing at 200-foot vertical intervals. Level plans of the orebody were constructed at 50-foot intervals from surface to the 1,000-foot level at a scale of 40 feet to one inch.

The North Lens consisted almost entirely of massive sulphides and specific gravity measurements of specimens gave a tonnage factor of 7.75 cubic feet per ton. It was decided to use a safer figure of 8.3 cubic feet per ton, which is the standard factor for massive sulphide ore in the Flin Flon area and which allows for the unforeseen inclusion of some patches of gangue material.

The South Lens contained 30 per cent sulphide disseminated in a cordierite-anthophyllite rock. The specific gravity of this material indicated a tonnage factor of 9.71 cubic feet per ton but a safer figure of 10 was used in the calculations.

The calculations were done very simply. The five level plan areas in each ore reserve block were measured with a planimeter and their average was multiplied by the height (200 feet) to give the block volume. This volume was then reduced to a tonnage figure by applying the appropriate tonnage factor. To obtain the grade of each block, the assays of all drillhole intersections within the block outline were averaged proportionally to their widths. Block tonnages were totalled, the overall grade was figured as a weighted average of block grades, and a 10 per cent waste dilution factor was applied to the total.

The total reserve thus calculated was: 825,000 tons averaging 0.044 oz. Au, 0.16 oz. Ag, 5.08 per cent Cu, 0.4 per cent Zn.

Revision of Estimate after Underground Development

At January 1, 1959, development had been done from two shafts on levels established at 150-foot intervals down to the 1,050-foot level, and the lower part of the zone of alteration had been explored from a drift on the 1,350-foot level. A total of 261 underground diamond-drill holes had given information at approximately 50-foot centres in most parts of the orebody. Using the data from these drill intersections, together with results from mapping and sampling of drifts and raises, the first revision of the original ore estimate was made. This time the calculations were based on vertical cross-sections which had been drawn at 50-foot intervals and, in some parts, at 25-foot intervals. All of the information from the logging, mapping, and sampling of drillholes and workings was plotted on the sections at a scale of 20 feet to the inch, and ore outlines were drawn to a minimum copper grade of 2.00 per cent. Figure 3 shows Cross-section 66+00 at this stage, and may be compared with Figure 2. The North and South Lenses, together with additional, smaller lenses in hangingwall and footwall, were divided into mining units by the main levels, and then into vertical slices by the cross-sections. The volume of each slice was obtained by multiplying the average of the two end areas by the perpendicular distance between sections. In view of the greater amount of detailed information available, a third tonnage factor was introduced: a factor of 9 cubic feet per ton was used for ore slices in which the mineralization was heavier than 'disseminated' but not completely massive. The grade of each slice was the average of assays on both end sections, proportional to assay widths. The total number of slices, or individual blocks, was 90, and these were accumulated by levels and by lenses into a final total tonnage and average grade. After adding 10 per cent anticipated waste dilution, the total was: 722,000 tons at 0.06 oz. Au, 0.20 oz. Ag, 4.83 per cent Cu, 0.2 per cent Zn. As shown in Figure 4, the general outline of the orebody was similar to the original outline shown in Figure 1 but, when the more detailed information was taken into account, the calculated reserve of copper metal was 17 per cent less than the original estimate.

Comparison of Ore Estimates with Production

During the five-year productive life of the mine, 161,000 tons of new ore averaging 3.00 per cent copper were discovered outside the original orebody outline. Furthermore, it was found that the cut-off grade could be lowered to 0.90 per cent Cu in the latter stages of mining when horizontal pillars were being recovered by the cheaper, long-hole method. These pillars were blocked out to include low-grade material along their margins, and then were blasted into the slopes below. The lower cut-off grade was applied when drawing these slopes to dilution. The final outlines of the mining operation are illustrated by Figures 3 and 5, which show Cross-section 66+00 and the longitudinal projection.

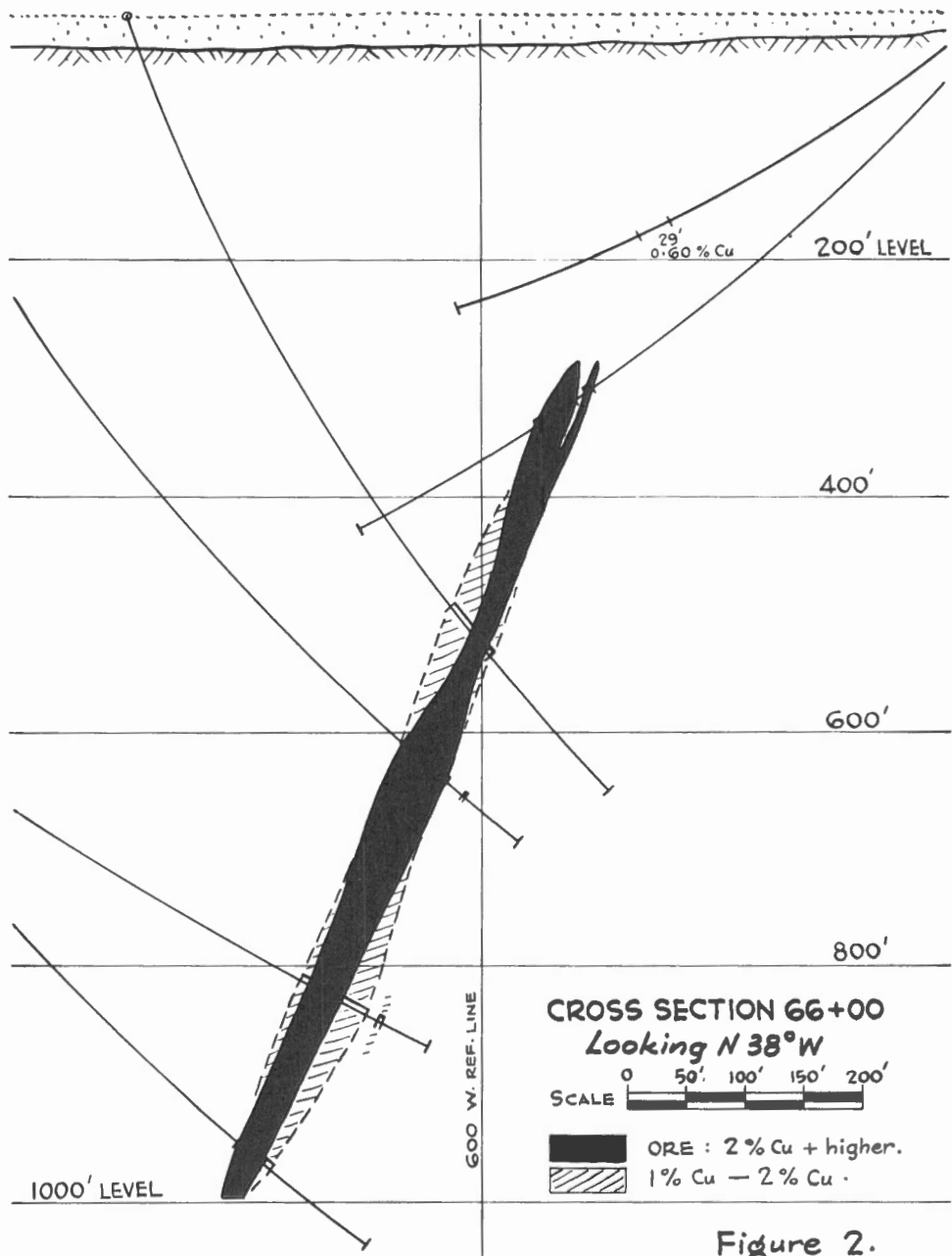


Figure 2.

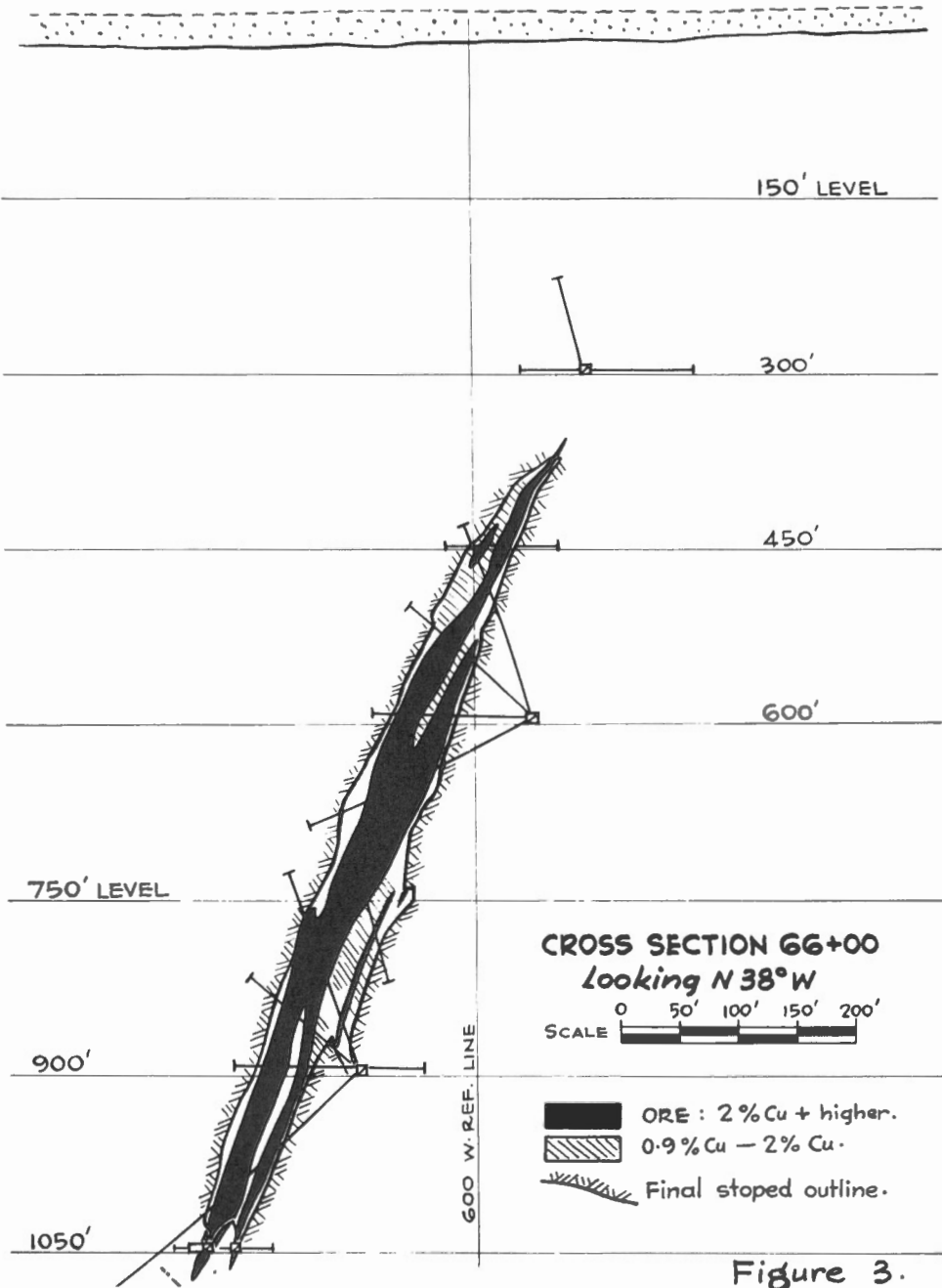


Figure 3.

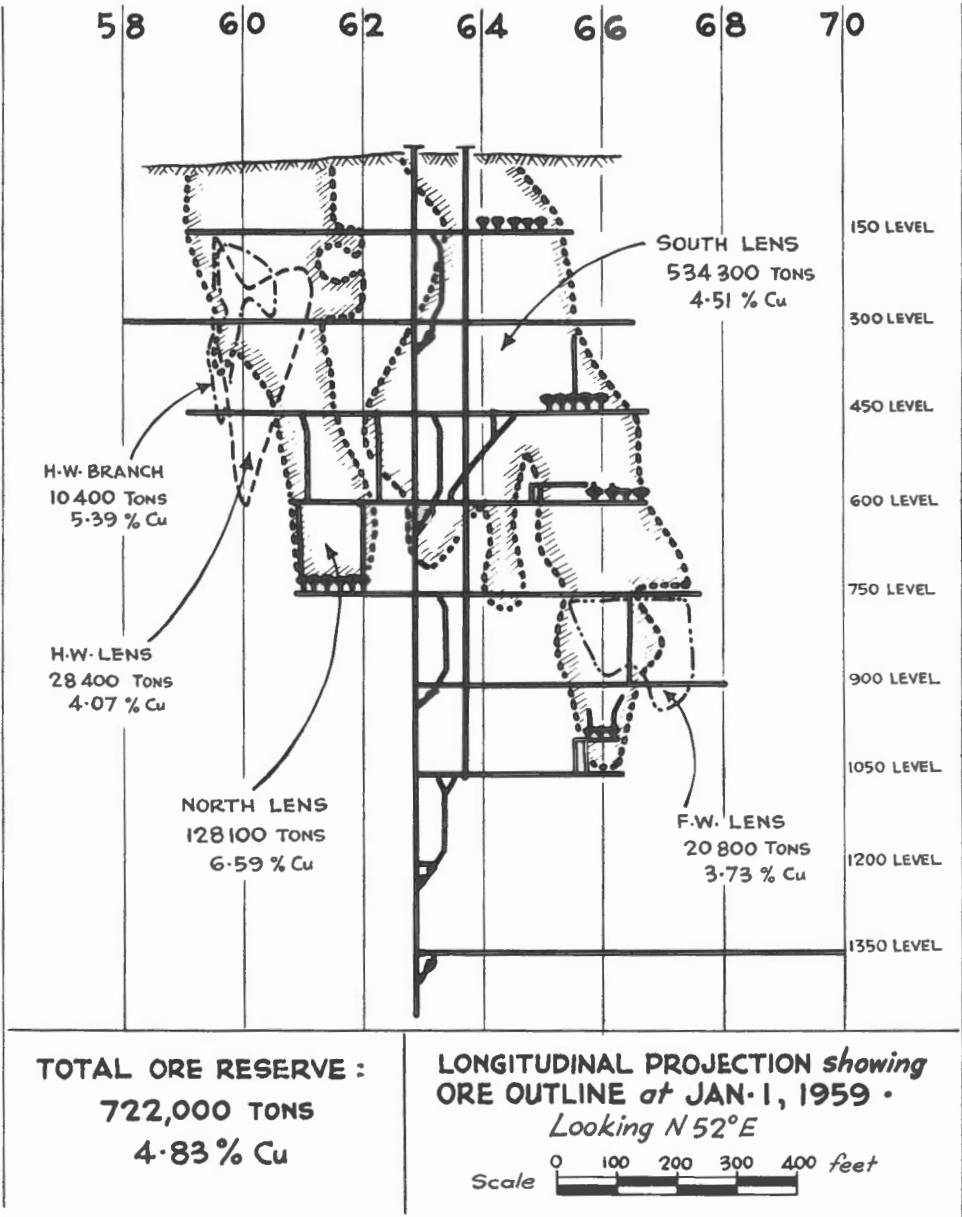
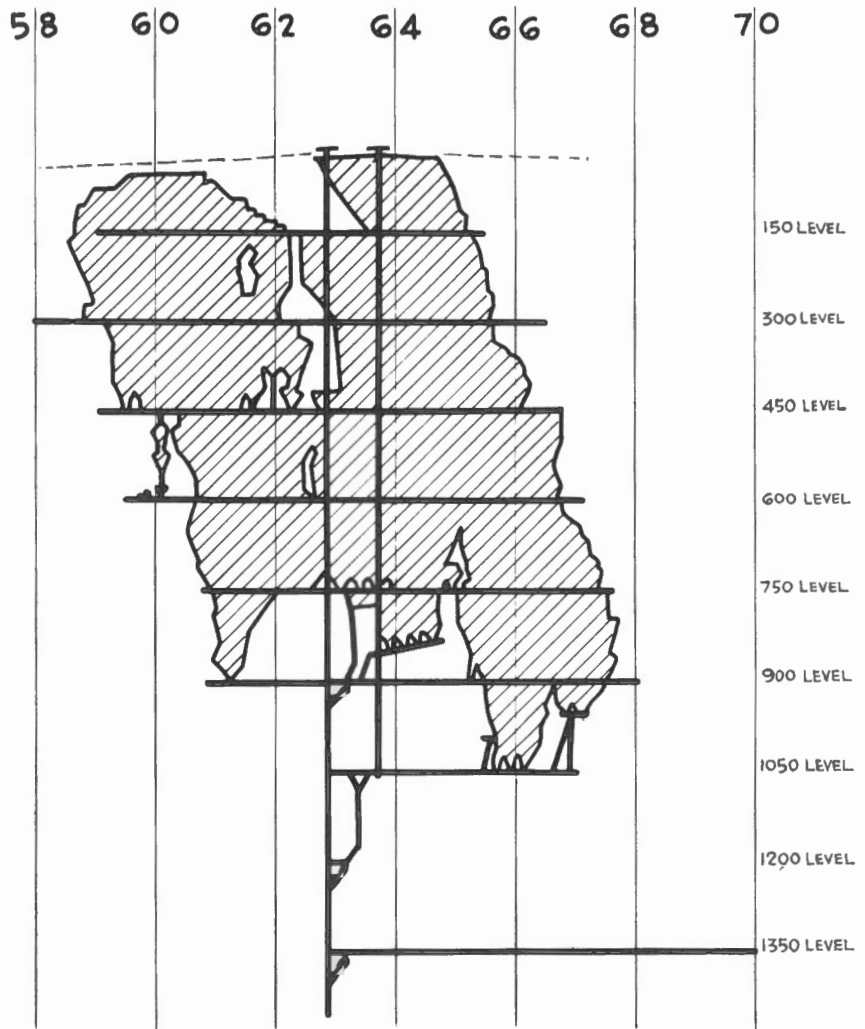


Figure 4.



LONGITUDINAL PROJECTION *showing*
FINAL STOPPED OUTLINE •
Looking N 52°E

Scale 0 100 200 300 400 feet

Figure 5

Final comparative results were:

	<u>Tons Ore</u>	<u>Per cent Cu</u>	<u>Cu Content: tons</u>
Total Production	1,412,861	4.25	60,000
Original Estimate	825,000	5.08	42,000
Difference	587,861	3.07	18,000
New Ore Found	161,000	3.00	4,800
Overdraw on Original	426,861	3.10	13,200

Conclusions

The original reserve estimate, using a planimeter and desk calculator, was done in the space of a few hours. This estimate, based on 55 drillhole intersections, required that the orebody be subdivided into 25 blocks for the volume calculation and into only nine blocks for the grade calculation. No further refinement was warranted and later experience proved that the original estimate was a realistic one upon which to base production plans. The first estimate based on more detailed underground information subdivided the orebody into 90 individual blocks and occupied one geologist's time for about three days. Each subsequent revision of the reserve figure as mining progressed involved up to 150 individual blocks and occupied the geologist's time for one week.

A program for calculating the Coronation ore reserve on the I. B. M. 1620 computer from the original drillhole data formed the basis of a B.Sc. thesis, "A Preliminary Study of the Use of a Digital Computer in Evaluating Ore Reserves in Metal Mines", by R. B. Robertson at the University of Manitoba in 1965. This work showed that the basic data measurements could be made by an experienced person in about two hours, that the FORTRAN program could be written in two days, and that computing time would be 15 minutes. Compared with the original manual calculation, the computer gave a result which was 12.5 per cent higher in tonnage but only 8.5 per cent higher in copper content.

In view of the experience outlined above, it does not appear that a computerised data processing technique is warranted in the evaluation of a deposit of this size and type because:

- (a) The number of individual ore reserve blocks is comparatively small.
- (b) The greater part of the estimating procedure is interpretive, involving detailed changes in the outline of mineable ore as development and mining proceed. This requires the drawing of revised plans and sections, which are required for mining layouts in any case. The actual work of calculating tonnage and grade, then, is relatively minor.