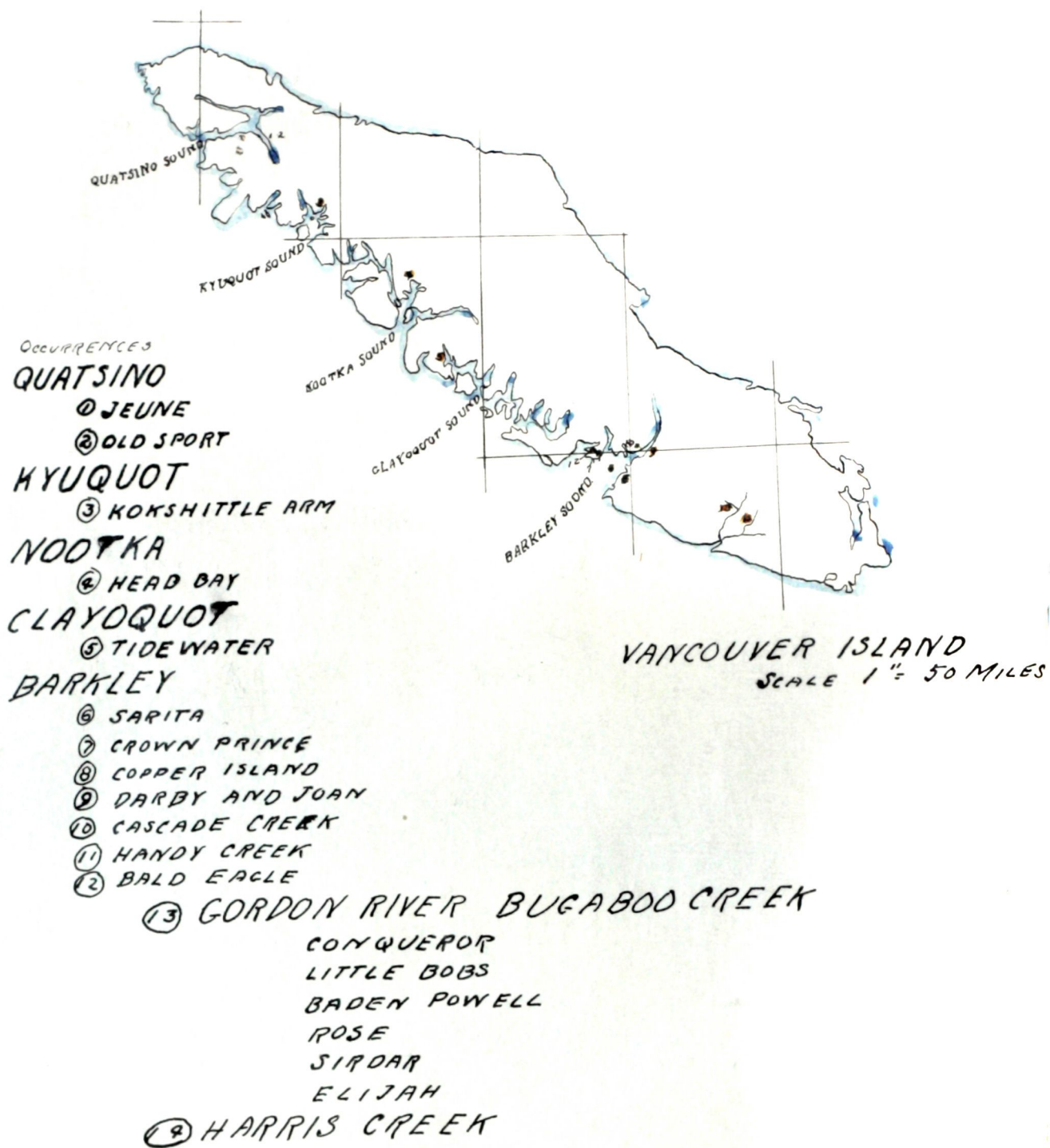


*The Magnetite Occurrences of
the West Coast of Vancouver Is-
land, B. C.: their Contact Meta-
morphism and Ore Genesis*

*by
Freleigh Fitz Osborne*

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PLATE I



*accepted
R. W. Brach*

THE MAGNETITE OCCURRENCES
OF THE WEST COAST OF VANCOUVER ISLAND, B. C.:
THEIR CONTACT METAMORPHISM AND ORE GENESIS

-- By --

FRELEIGH FITZ OSBORNE

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DEGREE OF MASTER OF APPLIED SCIENCE

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THE MAGNETITE OCCURRENCES
OF THE WEST COAST OF VANCOUVER ISLAND, B.C.:
THEIR CONTACT METAMORPHISM AND ORE GENESIS

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FORWARD AND ACKNOWLEDGMENTS

During the field season of 1924, the writer had the good fortune to be employed on the iron-ore survey of the Province of British Columbia, carried on by the Geological Survey of Canada. The work, which was a continuation of that begun by Dr. G.A. Young, of the Geological Survey, was confined to the occurrences on the West Coast of Vancouver Island. This work was under the supervision of Dr. W.L. Uglow of the University of British Columbia, and the writer wishes to acknowledge his indebtedness to him for assistance in all stages of the preparation of this thesis. Acknowledgment is also due to Dr. V. Dolmage of the Geological Survey, for discussion of West Coast geology and access to unpublished maps of the shoreline in the vicinity of some of the occurrences.

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from 1902. The iron ores were the subject of a special examination by Einar Lindeman in 1907; the results were published as Canada, Department of Mines, Mines Branch Publication No. 47, 1910. The earlier work is summarized by W.M. Brewer in British Columbia Department of Mines, Bulletin No. 3, 1917. "Iron Ores of Vancouver and Texada Islands."

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-- SUMMARY AND CONCLUSIONS --

The magnetic iron-ore on the West Coast of Vancouver Island, is of the contact metamorphic type, formed by the intrusion of rocks of Upper Jurassic age into the rocks of the Vancouver group, consisting of limestones and volcanic flows and tuffs. The intrusive is of varying lithology from granite to diorite, but the magnetite occurrences show a preference for the more basic type. Following the intrusion of the plutonics the equilibrium both within the intrusive and within the intruded rock was disturbed. In the intrusive, this is evidenced by the formation of fine grained or porphyritic contact facies^{by} contact zones of different composition, or the alteration of certain already formed minerals in the rock. In the intruded rock the readjustment may take the form of recrystallization, or less noticeable alteration. As the igneous rock consolidates materials are given off, which enter the contact zone and form silicates and

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SUMMARY AND CONCLUSIONS

ore. The variation in the mineralizers, as shown by the minerals deposited is very marked, although there is a tendency for silicates to form before the ore, especially in limestone. The observed variations point to the concentration of the last stage product of crystallization of the magma and the mineralizers within the intrusive; and diffusion into the contact zone. The emanations characterized by the elements of lower atomic weight reach the contact zone first. They also, as a rule, are the more chemically active, and can so deposit first. The heavier elements may reach the contact zone and not be able to deposit because they cannot maintain their concentration. Under special conditions, especially when the intruded rock approaches the intrusive rock in composition, magnetite, even in the presence of the more siliceous emanations may deposit first^{or} simultaneously. This metamorphism and deposition of magnetite takes place from tenuous solutions at temperatures from 1000° to 600° Hematite. . was probably formed close to 500° or below, and the sulphides with the possible exception of pyrrhotite at lower temperatures still. Silicates may be just as effective in the deposition of ore as limestone.

THE MAGNETITE OCCURRENCES OF THE
WEST COAST OF VANCOUVER ISLAND, B. C.
THEIR CONTACT METAMORPHISM AND ORE GENESIS

INTRODUCTION

PHYSICAL FEATURES OF VANCOUVER ISLAND

Vancouver Island is the largest island of the West Coast of North America, and is completely surrounded by navigable waterways. The West Coast is deeply indented by fiords; the principal ones of which are: Barkley, Clayoquot, Nootka, Kyuquot and Quatsino Sounds. Inside the sounds, deep water is found very close to the shore and mountains rise quite abruptly to heights up to three thousand feet to form the Vancouver Range, the backbone of the Island. This range has a general N.W. and S.E. trend so the fiords cut across it almost at right angles. Below Barkley Sound, the large inlets are not present and as you go south the mountains do not rise to as great heights, until south of Port San Juan the topography is notably more subdued and a narrow coastal plain appears.

CLIMATE

The climate of the West Coast is very equable. The rainfall is heavy, but snow is not common and does not remain for long periods.

GEOLOGY OF VANCOUVER ISLAND

LEECH RIVER SERIES

The oldest known rocks on the West Coast are the Leech River Series, a highly metamorphosed set of rocks,



Below points to Sarita River Mouth. Occurrence

-- From the summit of Copper Island. --
View of Valley of Sarita River
Barkley Sound.

- Plain-table and alidade used in mapping iron ore -
deposits.

* * *



-- Sydney Inlet-Clayoquot Sound --
Showing character of Inlets with steep
slope to water.

* * *

INTRODUCTION

mostly slates, of unknown age, exposed only in a narrow belt at the south end of the Island.

VANCOUVER GROUP

The next younger rocks belong to the Vancouver group as defined by Dawson. These rocks are of Jurassic and Triassic age. The group includes three formations. (1) The lowest one, known as the Nitinat formation, consists of non-fossiliferous marbles and amphibolites. (2) Overlying these a thick series of volcanic material, the Vancouver volcanics, is found, flows, and clastic materials predominate but sills and dykes occur. This series is of varying basicity from rhyolites to basalts but with a marked tendency for the more basic ones to predominate, while the rhyolitic types are rare.

SUTTON FORMATION

Intercalated in the Vancouver volcanics are a number of lenses of limestone, more or less recrystallized to marble, the Sutton Formation. In places this formation contains fossils, but there is still some doubt as to the correct age. Dawson (1) refers these limestones to the Alpine Triassic, Olapp places them in the Jurassic and calls the fauna the Sutton Jurassic, while G.C. Martin (2) consider them Upper Triassic in age.

- | | |
|----------------|--------------------|
| ① Dawson, G.M. | Geol. Surv., Can. |
| Sum. Rept. | 1886 pp. 7B-11B. |
| ② Dolmage V. | Geol. Surv., Can., |
| Sum. Rept. | 1920 p. 15A |

INTRODUCTION

COAST RANGE INTRUSIVES

Intruding the older rocks is a complex of igneous rock, probably representing an offshoot of the Coast Range Batholith and therefore of Upper Jurassic ^① age. The intrusives are of varying lithology from granite to diorite; - the most common types being quartz ~~z~~ diorite, granodiorite and diorite. In general the diorite, which Clapp calls the Beale diorite, represents an earlier marginal facies of the intrusive and often is intruded by the later more acid rocks. In some cases the contacts are sharp and in others they are irregular, showing the diorite was intruded by the acid plutonics before it was consolidated completely. These rocks are the most important on the West Coast, because most of the mineralization is due to them.

LATER ROCKS

Cretaceous beds are found in small areas on the West Coast, but the areas are far from continuous. As far as known no metallic ores are found in them. In the Tertiary, Oligocene-Miocene sediments were deposited at the south end of the Island. Igneous activity of this time is shown by the Metchosin volcanics and the Sooke gabbro group. The Sooke gabbro caused some mineralizations, but it is not as important as that due to the rocks of Coast Range age.

① Schofield, S.J. Geol. Surv., Can., Memoir
No. 132, p.8.

INTRODUCTION

THE MAGNETITE OCCURRENCES SITUATION AND DEVELOPMENT

Most of the magnetite properties examined are within three miles of navigable water. The most important exceptions to this statement are the claims on Gordon River, Bugaboo Creek and Harris Creek. The claims are now reached by trails from the water; in some cases little more than blazed lines. Owing to the length of time which has elapsed since the development was done on most of the properties, the trails are now overgrown with typical coast vegetation, salmon berry, salal and devil's club, so practically new trails must be cut. The dense growth also obscures the work done on the claims. Open cuts, trenches and test pits are overgrown and filled with surface debris. Tunnels and shafts are inaccessible due to caving or to water. The combination of dense vegetation and the heavy drift mantle makes detailed examination of the deposits difficult and in most cases impossible without further exploratory work.

TOPOGRAPHY OF OCCURRENCES

The examination of the magnetite occurrences showed the influence of ore deposits on topography. Although none of the individual deposits covered a large area, the number of observed deposits made up for this deficiency. The deposits are all of the contact metamorphic type and therefore have a tendency to resist subsequent ^① metamorphic processes. Of all the minerals of the deposits magnetite is the most resistant.

① Leith, C.K. & Mead, W.J. "Metamorphic Geology"
1915, p. 264.



*
- Maiden-hair -
 Fern

- Elijah M.-

Bugaboo Creek

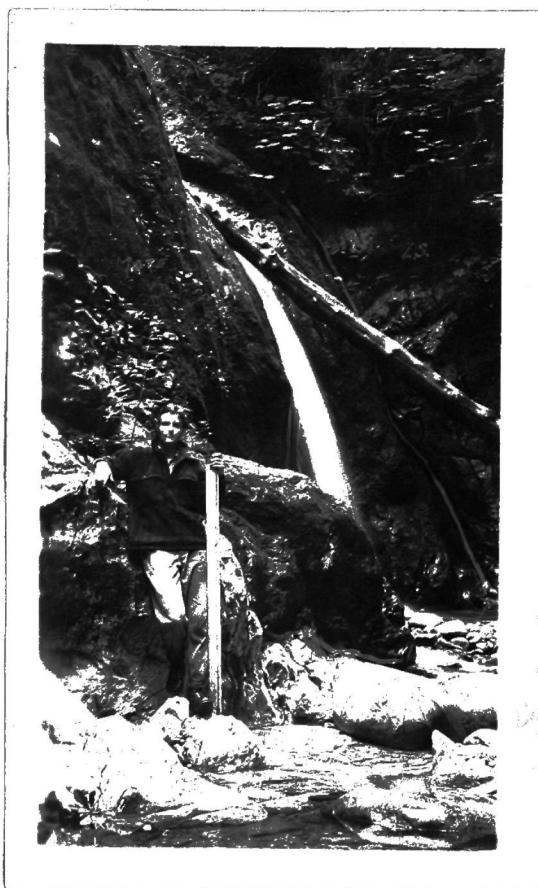
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This illustrates the luxuriant growth found in some of the valleys. These ferns are growing on soil about four inches thick on the surface of weathered limestone at about 45°. This shows the ease with which the surface may be covered by vegetation especially in moist places.



Magnetite in Limestone

Head Bay - Nootka Sound



-- Falls over Magnetite --

- Outcrop Bugaboo Creek. -

Showing Limestone
magnetite contact

INTRODUCTION

on account of its hardness, homogeneity and resistance to weathering, especially when pure, so it stands out in relief against the common country rock, such as diorite and limestone. This characteristic results in the formation of prominent topographical features such as: steep bluffs, tops or caps of ridges and waterfalls^① in streams. The resistance of the magnetite is so noticeable that a general statement may be made, that where ore-bodies are intersected by the present surface, some prominent topographical features will be present. It can be seen that this conclusion has an important bearing on the probable continuation, on the surface, of exposed ore bodies.

APPEARANCE OF THE ORE BODIES

The pure magnetite, where exposed, has a characteristic steely blue colour, and usually shows a rather smooth surface. The normal colour may be obscured by a "rusty", that is limonite, stain due to the decomposition of iron bearing sulphides or silicates. This rustiness is an important criterion for determining the purity of the ore. A steely blue outcrop is not necessarily a pure outcrop, because running water will remove the limonite, or, in certain cases, the roots of the mosses may remove it. Under these conditions, where porous magnetite is found, it may be due to the removal of sulphides, silicates or calcite.

① PLATE IV

INTRODUCTION

GEOLOGY

All the ore occurrences examined belong to the contact metamorphic type, that is, they are due to the intrusion of the rocks of the Coast Range age into the rocks of the Vancouver group with consequent mineralization along the contact, usually confined to the intruded, but in some cases extending into the intrusive rock as well. In most cases observed, the intrusive is a hornblende diorite. The deposits are divided into a number of classes which will be discussed in detail later.

HOW THE CONDITIONS ON VANCOUVER ISLAND AFFECT THE VALUE OF THE ORE

A brief review of how the conditions on Vancouver Island affect the value of the iron properties of the West Coast will be given. The first problem to be met is that of transportation: as stated before, most of the deposits are within three miles of navigable water, so if a short railroad or tramway were built to the shore, shipments could be made by water. In order that the ore could be loaded, a harbour is necessary so the deposit must be on one of the sounds rather than on the open coast. Outside of the sounds severe storms are common from October to March, so it is doubtful if at all regular shipments could be made by scow. Special barges might be used, but even then shipments might be hazardous and uncertain. Barkley Sound is the only sound at present connected to the East Coast by railroad, so ore mined on it might be shipped to Port Alberni, the railroad terminus, and then

INTRODUCTION

transhipped. The ore from Gordon River, Bugaboo and Harris Creeks, might be shipped directly to Victoria, if a projected railroad were built. If ore were mined from any known occurrence on the West Coast, it would be a very expensive matter to market it due to its isolation. If a smelter were established there, essentially the same transportation problem would have to be met in taking in coal and taking out the manufactured product. Barkley Sound appears to be the only location which, at the present time, is at all feasible for such an undertaking.

The climate is such that mining operations could be carried on all the year around.

The next condition to be considered is the geology. The deposits are all of the contact metamorphic type, one that is noted for its irregularity. This irregularity combined with the heavy soil mantle makes exploration difficult and expensive. Measurement of magnetic properties by the dip needle or magnetometer may be of value where the drift is thick, but they tell nothing of the quality of the ore. The ore may be less valuable for a number of reasons. It may contain excessive amounts of sulphides necessitating roasting, or siliceous impurities may be present which makes special furnace treatment necessary. In some occurrences, copper minerals are found with the iron, where these are present in sufficient quantity it may pay to concentrate the ore and smelt the iron and copper separately.

CLASSIFICATION OF DEPOSITS

CLASSIFICATION OF MAGNETITE OCCURRENCES

The occurrences examined are in the rocks of the Vancouver group where they have been intruded by the rocks of Coast Range Batholith age. The iron ores are found in all the formations of the Vancouver group, and in some cases, in two types in the same deposit. The type of country rock mineralized is used as the basis of classification. Under these headings they fall into three groups; deposits in limestone, deposits in volcanics, and deposits in limestone and volcanics. The table given below shows the distribution of the types and the claims belonging to each. In the intrusives a marked tendency for diorite^① to be responsible for mineralization of the magnetite occurrences was noted, but this rule had exceptions. More acid phases of the plutonics were represented by granites, monzonites, quartz monzonites, granodiorites and quartz diorites.

① Clapp G. H. Loc. city. Mem. No. 13. p. 190.

CLASSIFICATION BY TYPE

<u>CLAIMS</u>	<u>COUNTRY ROCK</u> <u>MINERALIZED</u>	<u>INTRUSIVE</u>	<u>REMARKS</u>
<hr/>			
Conqueror	Nitinat Limestone	Beale Diorite	
Little Bobs	"	"	"
Baden Powell	"	"	"
Rose	"	"	"
Sirdar	"	Quartz	"
Elijah	"	Beale	"
A Harris Crk. Claims	Sutton (?)	"	"
Sarita Rv.	Nitinat	"	"
Rob Roy	Sutton	"	"
Prince Charlay	"	"	"
Glengarry	"	"	"
Stormont	"	"	" } wrong
B Copper Island	Vancouver Volcanics	"	"
Crown Prince,	"	"	"
Sechart	"	"	{ ? }
Darby & Joan	"	"	{ ? }
Cascade Crk.	Limestone Volcanics	Diorite	
Kokshittle Arm	"	" (?)	} CuFeS ₂ Fe ₂ O ₃
Handy Creek	"	"	"
Old Sport	"	"	"
Bald Eagle	"	" (?)	" + (?)
C. Tidewater	"	"	Granodiorite
June	"	"	Diorite + (?) Cu ₂ FeS ₄

CLASSIFICATION BY SOUNDS

<u>Gordon Rv.</u>	<u>Claim</u>	<u>CLASS</u>
Bugabook Crk.	Conqueror	A
Harris Crk.	Little Bobs	A
	Baden Powell	A
	Rose	A
	Sirdar	A
	Elijah	A
	David	A
	Harris Crk. Claims	A
<hr/>		
Barkley Sound	Sarita Rv.	A
	Copper Is.	B
	Crown Prince	B
	Darby & Joan	B
	Cascade Crk.	C
	Hangy Crk.	C
	Bald Eagle	C
<hr/>		
Clayoquot Sound	Tidewater	C,
<hr/>		
Noetka Sound	Head Bay	A
<hr/>		
Quatsino Sound	June	C,
	Oldsport	C

MAGNETITE DEVELOPED IN LIMESTONE

The contact metamorphic deposits in limestone are the most common type and the one most noted in the literature. In general, the statement may be made that deposits in this rock have a tendency to be purer and more regular than those in other country rock. On the West Coast of Vancouver Island the claims that belong to this group are: Those on Gordon River, Bugaboo Creek in the Nitinat limestone including; Rose, Little Bobs, Baden Powell, Conqueror, Elijah and David; The Sarita River^① claims also belong to the Nitinat limestone. The magnetite at Head Bay, Nootka Sound, occurs in the Sutton limestone and it is probable that the limestone of the claims on Harris Creek belong in it, but this is not certain. The intrusive responsible for mineralization in this group is, in all cases observed, the Beale diorite. The effects of the intrusion are of two kinds, the endothermic or changes in the intrusive; and the exothermic or changes in the limestone, due to the intrusive.

① Clapp C.H. Geol. Surv. Can., Mem. 13, p. 189.

ENDOTHERMIC EFFECTS

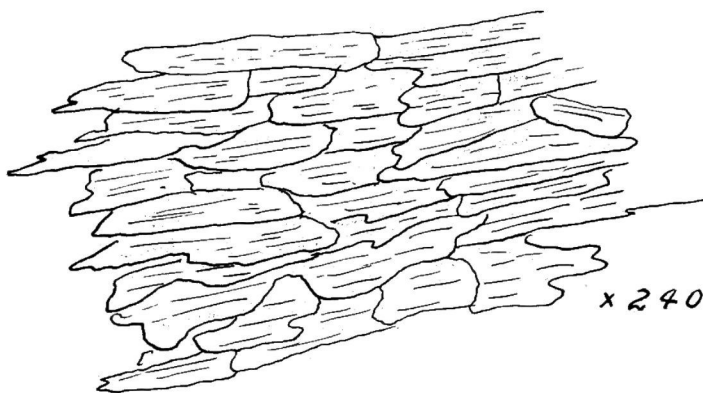
In many cases, pronounced endothermic changes are noted in the intrusive. This effect is not confined to contacts with limestone, but is also found along contacts with other rocks, although it is usually most markedly developed along the limestone contacts. The most common change is a decrease in size of grain in the intrusive close to the contact. This is often, but not necessarily, accompanied by darker colour in the diorite, due to

MAGNETITE IN LIMESTONE
Endothermic Effects

a large increase in the content of dark ferromagnesian minerals. In some cases porphyritic phases may represent the intrusive at the contact, and it is only by a consideration of the mineralogical composition and its field relations that its true nature can be ascertained. "Solutions" derived from the magma of the diorite itself may cause an alteration of the intrusive². These can be divided into two types, those which act before the magma is completely consolidated, and those acting after consolidation. The first case has not yet been fully worked out, so all the effects have not been described, but it seems probable that the formation of alteration products in feldspars, of "injection perthites" and of typical contact metamorphic minerals, as a primary constituents of an igneous rock may be due to this. The alteration of plagioclase to more acid feldspars along the margins is probably also due to this action. To what extent this last stage alteration may be governed by the position of the contact is difficult to say, but it seems to have a marked influence in many cases. A detailed petrographical study of a suite of specimens from the intrusive close to a contact would probably throw some light, not only on these last stage phenomena, but also on the nature of the magma and some of the causes of contact metamorphism. The alteration after consolidation is represented by epidofization and silicification in the diorite, often along joint cracks. Occasionally garnet may be developed and magnetite may occur in the intrusive.

**Fig. A.**

Diorite, Conqueror M.C. showing formation of new plagioclase (P) along the margins and within old altered feldspars (F). Where the new feldspar is close to the old one or within it, they are in parallel orientation, but against the hornblende and pyroxene (M) this is not so. This is a common alteration close to the contact but not to this extent.

**Fig. B.**

A thin section showing the pronounced schistosity developed by the parallel orientation of diagenesis formed at the Tidewater under conditions of contact metamorphism.

MAGNETITE IN LIMESTONEEXOTHERMIC EFFECTSMARMORIZATION

In all cases near the ore occurrence the limestone has recrystallized. This alteration may be either regional or contact, because the limestone is now a series of roof pendants in the plutonics and no field evidence is at hand to show whether the limestone was marmorized before the intrusion. In its recrystallized form the limestone is of varying texture from grains of almost lithographic fineness to some over one inch across, showing pronounced polysynthetic twinning. Some silicates were formed including garnet, (grossularite) diopside and tremolite, probably by recrystallization of impurities. Variation in the alteration of the limestone seems, to a large extent, to have been governed by variation in the properties of certain beds, although it is very difficult, at present, to ascertain original bedding.

SILICATE ZONE

The zones of contact metamorphic silicates on the West Coast are relatively narrow, none of them are more than a few feet thick. The commonest product of metamorphism is a mixture of garnet, epidote and quartz, with minor amounts of other silicates as tremolite and diopside. The distribution of the silicate zone is governed by several factors: original bedding, attitude of the contact and brecciation of the limestone. In many cases the distribution of the silicate zone

MAGNETITE IN LIMESTONEEXOTHERMIC EFFECTS -- SILICATION

is parallel to the original beds of the limestone, suggesting a preferential replacement of certain zones due to texture or composition. Another important feature is the attitude of the contact. A vertical contact does not seem favourable for silication or ore deposition; one exposed on the ELIJAH M.C., Bugaboo Creek, showed silicates only where an apophysis of the diorite cut the limestone and so formed a trap for the contact metamorphosing agents. No very general statement can be made from the field observations that a flat contact favours the formation of large silicates zone, but this would appear to be a favourable place for mineralizers to escape. The brecciation of the limestone also to a large extent influences the distribution of the contact silicates. Where the brecciation in the limestone was widespread the silication seems to have followed it enclosing blocks of the country rock.

METALLIZATION

In a number of cases, the deposition of the magnetite was, in part, contemporaneous with the silication, although it had a tendency to extend beyond the time of formation of the garnet zone. The contemporary time of formation of silicate and ore may to large extent account for the banding observed in some deposits although preferential replacement of original beds by silicate and magnetite in most cases was present. If limestone with 40% Ca O and a density of 2.6 is acted on by mineralizers

MAGNETITE IN LIMESTONEEXOTHERMIC EFFECTS-- METALLIZATION

which remove CO_2 and CaO , and introduce Fe_2O_3 , FeO , SiO_2 to form a contact rock of density 3.0 containing 25% CaO , depending on amount of CaO removed, there will be a contraction of volume, and magnetite may be deposited to make up for it. This may account for the irregular banding of some of the silicates and are observed in some of the occurrences. The later magnetite may in part replace the earlier silicates so the relation of contemporaneously deposited magnetite may be obscured. The occurrence of blebs of silicates in the magnetite may be explained as due to this replacement, or they may represent impurities in the limestone, which was being replaced, recrystallized under the influence of the solutions depositing the ore.

Clapp^① postulates the formation of the magnetite of the Gordon River Bugaboo Creek claims as due to concentrated magnetite solutions, "virtually magnetite magmas" which brecciate the limestone as a dyke would. If the nature of magnetite is considered, it seems difficult to see how magnetite can exist in a monominerallic magma, as magnetite. To the writer it would seem that these "apophyses" of magnetite represent replacement of limestone following, rather than causing, brecciation. The way the magnetite is formed is shown clearly at Head Bay, Nootka Sound. It is found in dyke-like^② or vein-like masses in the limestone. Actinolite in lenses parallel to the wall, with fibres running from wall to wall, is found in the magnetite. The silicates probably represent impurities in the limestone which during the interaction of the iron bearing solutions with the

① Clapp C.H. ① Geol. Surv., Can. Mem. 13 p. 193.

② PLATE IV

MAGNETITE IN LIMESTONE

EXOTHERMIC EFFECTS--METALLIZATION

calcite, were deposited as silicates. In a section across the magnetite vein a banding can be seen with corresponding similar bands on each side, suggesting that as the magnetite was introduced as some soluble iron salt, it interacted with the limestone along the vein and was deposited. From the distance it had travelled, it must have been very thin or gaseous.

SULPHIDES

In the contact deposits, beside the silicates and magnetite, sulphides, especially those of iron and copper iron, are developed. The principal sulphide minerals are: pyrrhotite, pyrite and chalcopyrite. All these are developed later than the magnetite with the exception of pyrrhotite, which in someⁱⁿ stances, may have been formed contemporaneously with the magnetite. The conditions that control the distribution of the minerals along the contact could not be worked out. An example of this is at Sarita River. Here marble forms the top of a low ridge with a general East and West trend. This has been intruded by the Beale diorite so an undulating, almost flat contact is partially exposed. At the West end of this ridge, a body of high grade magnetite with little sulphide is found, but as the deposit is followed east, pyrite and pyrrhotite appear, with a corresponding decrease in magnetite. These sulphides seem to have a greater tendency than the magnetite to replace the silicated zone of the limestone. Another property is situated about one half mile east of the large magnetite body, apparently on the same limestone-diorite contact, although it is separated by an area of drift. Here pyrrhotite, chalcopyrite,

MAGNETITE IN LIMESTONE

EXOTHERMIC EFFECTS

and pyrite are developed but no trace of magnetite is to be seen. The only explanation that can be made seems to be that the sulphides are formed, under suitable condition, when the sulphur is present in the mineralizers in some form.

LATE GANGUE MINERALS

Following the metallization some veins of quartz were formed. Calcite veins also occur in the ore, a few are mineralized by chalcopyrite and pyrite but the majority are not mineralized, some of them probably being due to meteoric water. Some veins of hydrous silicates are also found cutting the ore, of these serpentine and chlorite have been identified and probably others are present.

MINOR INTRUSIVES

Minor intrusives are found in the vicinity of these occurrences, at the Conqueror M.C. a porphyrite dyke occurs cutting the ore. Small dykes and sills are found at Head Bay, but they are earlier than the mineralization, because they confine the ore and are themselves mineralized. These minor intrusives are probably from the same magma that produced the mineralization. In certain cases, the diorites are themselves intruded by apophyses of more acid plutonics so possibly some of the mineralizers from them may have caused alteration in the diorite.

SIRDAR M.C.

The Sirdar M.C. does not strictly belong in this class, but its location in the Bugaboo Creek group make this the best

MAGNETITE IN LIMESTONEEXOTHERMIC EFFECTS

place for it. The magnetite here is a complete replacement, except for a few fragments in the ore, of a roof pendant or block of the Nitinat limestone by a quartz-diorite.

ORE DEPOSITS ASSOCIATED WITH THE VANCOUVER VOLCANICS

The deposits associated with the Vancouver volcanics and apparently not related to limestone, are much less important than those in limestone, both on account of the larger amount of impurities and because of smaller size and greater irregularity of the distribution of the ore. These deposits are of great scientific interest because they show the variable effects of contact metamorphism. The volcanic rocks are of two types; flows and tuffs. Some small beds of limestone may have been included in the volcanics and also, possibly, some intergrading^① types such as calcareous tuffs, which are known to occur on Vancouver Island. The tendency of rock types to approach one another and the intrusive in composition during contact metamorphism made it difficult to identify the original character of the contact metamorphosed rock.

The difficulty encountered under the microscope^③ was even greater, therefore the rocks had to be named on the basis of limited field observation adjacent to the deposits.

① Delmage V. Geol. Surv. Can. Sum. Rept. 1920. p. 15A.

② Van Hise C.R. V.S.G.S. Mon. No. 47 - "A Treatise on Metamorphism" p. 713.

③ Pirsson L.V. Am. Jour. of Science 4 Series vol. 40.
"The Microscopic Character of Volcanic Tuffs"
pp. 191-211 (1915)

MAGNETITE IN VOLCANICS

The principal deposits belonging to this class are:

The claims on Copper or Tzaartoes Island; the Crown Prince Mining Claim, Sechart; The Darby and Joan M.C., Alberni Canal. All these occurrences are on Barkley Sound. They all show different characters so it is necessary to describe them separately.

COPPER ISLAND

On Copper Island, magnetite in the Vancouver volcanics is exposed close to the summit. The deposits are apparently related to the Beale diorite, but the Saanich granodiorite passes very close to the deposit so contact effects of it may be superimposed on those due to the earlier diorite. The contact effects observed were various and will be discussed separately. It is impossible to discuss these processes in the order in which they took place, because the evidence^{for it} is lacking.

SILICATION WITH CONTEMPORARY MAGNETITE DEPOSITION

One of the most interesting contact effects observed was found at the very top of the island; here magnetite and a garnetite rock are found in a banded structure. Observed in detail the thickness of the bands of magnetite and the garnetite was from one quarter to four inches. The bands of silicates were far from continuous, but rather consisted of a series of irregular parallel lenses having the general dip of the volcanic rocks of the island, with complementary lenses of magnetite between them. The garnetite was found to consist of a mixture of andradite and grossularite with minor amounts of quartz and epidote. The original character of the volcanics could not be determined but it was either a flow or

MAGNETITE IN VOLCANICS - COPPER ISLAND

a tuff. If it were a tuff, the banding might be accounted for as a relic of an original bedding structure; even in a flow it is possible that metasomatism might take this form.

The following is the origin that suggests itself to the writer. Whatever the nature of the original rock it probably had a density very close to 2.6. The density of the magnetite lenses, as determined, was about 3.6. If the constituents of a rock of density 2.6 recombine to form a rock of density 3.6 the loss of volume is equal to $\frac{3.6 - 2.6}{3.6}$ or about one-third. This is about the ratio of the exposed magnetite in the banded structure to the total mass suggesting, that in this case, the formation of the silicates took place under the influence of solutions which contemporaneously deposited magnetite to make up for the volume contraction. That the formation of the magnetite took place simultaneously with, rather than later than the garnet, is shown under the microscope and also by the intimate intergrowth of garnet and magnetite. A further point in support of this mode of origin is found if the chemical analysis of an andesite, the average volcanic rock of the Vancouver group, is compared with analysis of grossularite and andradite. A mixture of the two garnets with the exception of CaO , SiO_2 and Fe_2O_3 corresponds almost exactly to that of the volcanic. The excess of silica forms the quartz of the contact rock while lime and ferric oxide have been introduced. The iron was derived from the solutions which caused the metamorphism and introduced the magnetite. The lime, that was being introduced at the same time, was probably also derived from the mineralizers, which had obtained it from

MAGNETITE IN VOLCANICS - COPPER ISLAND

limestones occurring elsewhere in the series on Copper Island. This absorption^① of limestone has been noted in a number of cases and introduced to account for contact silicates in non calcareous rocks. This case seems to show very definitely the effects of the solution where ore is deposited simultaneously *with silicates*

BANDED STRUCTURE DUE TO REPLACEMENT OF BEDS

A banded structure of magnetite and the silicates was commonly observed in the deposits replacing volcanics. The bands were much thicker and more regular than those described as due to silicification and contemporary formation of the magnetite. These are apparently due to metasomatic action on bands in the volcanics so some are replaced by garnet, epidote, quartz, diopside and others by magnetite. It is possible that, in part, the action described as taking place in the case where the narrow banding occurs may have been active here, but although the formation of the magnetite was in part contemporaneous with the silicates, some of it replaced earlier silicate minerals and formed veins in the silicated bands. Some of the ore also shows veins of quartz and epidote cutting it.

BANDED CONTACT ROCK

Beside the banded silicates and magnetite, banding of the silicates alone was observed. One exposure on Copper Island showed a rock apparently of volcanic origin in bands six inches

① Clapp, C.H. "Geology of Victoria and Saanich Map-Areas, Vancouver Island." Geol. Surv., Can. Memoir 36, p. 50.
Reesler Trans. A.I.M.E. Vol. 61, 1918. p. 101.

MAGNETITE IN VOLCANICS - COPPER ISLAND

thick, epidotized and apparently bleached, alternating with bands of similar thickness, consisting of epidote and quartz with small amounts of garnet and vesuvianite. The volcanic was apparently a tuff because it is difficult to see how a flow could be so uniformly banded with such even thickness. The adjacent bands must have been of very dissimilar composition or texture to yield such different metamorphic products. It is conceivable that the series might represent a lit-par-lit injection of a basic magma with a large amount of mineralizers into tuffs. After the injection the mineralizers might escape into the porous rock and form the bands of silicates. The notable absence of amygdules is against this mode of formation.

OTHER CONTACT EFFECTS

Besides the banded structures other contact effects were found. In some cases the andesites were altered to epidote along irregular lines and then replaced by magnetite. In other cases, they are feldspathized and silicified, with fragments of original feldspars remaining. The new feldspars were in all cases more acid than the old showing the addition of sodium in some form and the removal of calcium.

CROWN PRINCE M.C.

The general features of the Crown Prince Claim are essentially the same as those of Copper Island except that in this case the intrusive is not visible, unless small dykes of granite cutting the ore belong to it. The banding of silicates

and gangue found at Copper Island is also found here.

FELDSPATHIZATION OF TUFFS

From their appearance in the field, the rocks of the Crown Prince claim were originally tuffs. Under conditions of contact metamorphism a rock resembling a biotite gneiss is produced. In thin section the rock is seen to have suffered marked feldspathization and some contemporaneous silicification. The original feldspar phenocrysts, near andesine-labradorite, are deeply altered to an indeterminate mixture of probably, paragonite and zoisite, so they have a marked cloudy appearance. These phenocrysts have been altered to or replaced by more acid plagioclases, near oligoclase-andesine and probably more acid. The new feldspars occur irregularly in the old and often completely replace them so all that can be seen of them is their "ghost" formed by the zoisite-paragonite. In several cases the new feldspars were found in alternate twinning lamellae of the old. This process again shows the marked introduction of soda.

Hornblende and pyroxene occur in the feldspathized tuffs, probably one of these was an original constituent of the rock. Several of the pyroxenes observed had cores of hornblende, and also hornblende rims suggesting that perhaps, under conditions of contact metamorphism, hornblende may be altered to pyroxene and that following this the pyroxene may be uranitized.

Actinolite is of later introduction, and veins the mosaic formed by the new feldspars and the quartz. Small masses of garnet are also found in the feldspathized rock and, in isolated cases, small stringers of garnet cut it suggesting that the feldspathiza-

MAGNETITE IN VOLCANICS - CROWN PRINCE

tion represented an earlier stage of the contact metamorphism, but this is not certain.

DARBY AND JOAN

The Darby and Joan claim on Alberni Canal is totally different from the two previously described occurrences in this class. The magnetite occurs in a garnetized and epidotized zone in the rosette porphyrite of the Vancouver volcanics. It is possible that the mineralized area may represent a completely replaced lense of limestone. No intrusive is visible close to the claim, but the extensive alteration of the porphyrite to greenstones suggests, that the mineralization may be due to a concealed intrusive, although it is not impossible that the metamorphism may be due to the porphyrite itself. Material from the garnetized zone under the microscope shows idiomorphic garnet with interstitial magnetite and quartz, so no definite conclusion as to the relative age of them can be drawn but some of the magnetite apparently has a tendency to replace garnet, suggesting that, at least in part, the magnetite is of later formation. The alteration of the porphyrite is difficult to work out because of the fine grain of the minerals. The feldspar phenocrysts are altered to paragonite-zoisite, the groundmass is now a felted mass of actinolite and epidote with a few grains of some mineral of high relief and low interference colour, probably zoisite or clinozoisite. Small garnets are also found.

DEPOSITS DEVELOPED IN BOTH VOLCANICS AND
LIMESTONE

In several cases, both rocks of the Vancouver volcanics and the Sutton limestone have been mineralized and replaced. Various of the deposits described in limestone and in volcanics may belong here, but the occurrence of the other type of rock can not be recognized due to contact metamorphism. The Tidewater Copper Company's mine, Clayoquet, and the June mine, really belong in this class, but due to several exceptional features they will be described later. The deposits which belong here are: the Sunshine group; Cascade Creek, Barkley Sound; the Defiance M.C., Handy Creek, Barkley Sound; Waterloo M.C., Kokshittle Arm, Kyuquot Sound; the Old Sport Mine, Quatsino Sound. Where the intrusive is visible, it is a diorite, and in the case of the Waterloo^① M.C. diorite is exposed a short distance from the occurrence.

In all these deposits the contact metamorphic effects extended into both rocks. In the deposits on Barkley and Kyuquot Sounds, there is a marked tendency for the contact effects to be more noticeable and far reaching in the volcanics than in the limestone, probably due to the difference in composition and permeability to solutions. The Old Sport group was not visited but from Dolmage's^② description it appears that silication is more intense in the limestone next to the volcanics than in the volcanics.

① Dolmage V. Geol. Surv. Can. Sum. Rept. 1920 p. 21A

② Dolmage V. Geol. Surv. Can. Sum. Rept. 1920 pp. 33B-35B

MAGNETITE IN LIMESTONE & VOLCANICS

In the deposits the commonest metallic mineral is magnetite. Hematite later than the magnetite was found in the Barkly and Kyuquot Sound localities. In all the cases, chalcopyrite occurs which is younger than the hematite. Pyrite is also found but its relation to the hematite is not clear. At the Old Sport pyrrhotite occurs, especially close to the diorite contact, and is more or less complementary to the chalcopyrite.


BALD EAGLE CLAIM

A deposit which probably should be in this class is the Bald Eagle M.C., Sechart, Barkley Sound. On this claim no volcanics are exposed next the ore, but they are found close to it. The texture of the ore, the impurities in it, and a banding closely resembling that found in ore replacing volcanics suggest that it may be a nearly complete replacement of volcanics near limestone. The limestone, exposed near the ore, has a zone of silicates consisting of tremolite with minor amounts of garnet and olivine along its contact with the diorite but no magnetite developed in it. In the same deposit a mass of coarse granite or pegmatite consisting of quartz and feldspar, extensively garnetized, is found next the ore, but its precise relationship to the ore-body is not clear. Due to the common association of the magnetite with diorite observed in the other deposits it is probable that the mineralization here may be due to it.

TIDEWATER M.C.

The geology of the Tidewater Copper Company's mine at Sydney Inlet, Clayoquot Sound is rather complex, and there are unusual features so it is made, with the June Claims, Quatsino Sound, a separate type. The geology is described by Dolmage^① and, in part, the following brief description of the general features of the deposit is from his description. To quote from his description -

"The mountain on which the ore-bodies are situated is composed of light grey granodiorite up to about the 1500-foot contour."

Slides of this rock show it to vary from a granite to a granodiorite in composition. On the top of the hill over the ore-bodies limestone occurs. In contact with it on the lower side are a series of andesites:  the contact has a shallow dip, and is slightly undulating. The andesites are, in general, openly folded but locally steep dips are encountered. Below the andesites a series of schistose rocks, with a flat dip are found, these were observed to grade laterally into porphyritic types similar to porphyrite dykes in the limestone and andesites, so they are thought to represent contact metamorphosed dykes or sills younger than the andesites. The ore-bodies occur in the limestone, andesites and the sill forms, as replacements of them.

CONTACT METAMORPHISM OF THE LIMESTONE AND ANDESITE

The limestones are marmorized and small garnets and grains of diopside are developed in them, apparently by recrystallization.

① Dolmage V. Geol. Surv., Can., Sum. Rept. 1920 pp. 20-21A.

TIDEWATER MO.

tallization of impurities. Mica, probably near phlogopite, is formed in small stringers by the introduction of material.

Locally, the limestone is altered to ¹⁰⁻³⁰ masses of garnet and epidote.

In the volcanics the commonest alteration noted is the formation of garnet, epidote, quartz and diopside, in some cases, original banding of the rock is preserved in them. It was noted that the volcanics seemed to have a greater tendency to develop contact silicates than the limestone, perhaps due to a greater distance ^{of the limestone} from the intrusive.

CONTACT METAMORPHISM OF SILLS

The alteration of the sills could not be worked out completely because a complete suite of specimens was not available, however the early stages are suggested by an alteration observed in a porphyrite dyke. The alteration of the porphyrite may have been, in part, or all, endothermic. The rock has been acted on by solutions which altered pyroxene to hornblende. The basic feldspars, near andesine -labradorite, forming the phenocrysts have been, in part, altered to a mixture probably of paragonite and zoisite and replaced by a more acid plagioclase, near oligoclase. The new feldspars resemble small pegmatite masses but they are found within the basic ones, and in some cases residuals of the andesine-labradorite are found in parallel optical orientation ^① in the oligoclase suggesting a replacement by tenuous solutions. After this alteration hornblende was introduced in parallel zones so a pronounced gneissic structure is developed. That this stage took place in the sills is probable,

① For a somewhat parallel case see Foye W.V. - Ec. Geol. Vol. 11, p. 668.

TIDEWATER

but a thin section showing it was not available. The next stage in the alteration of the sills gives a dark green, fine grained schistose rock. Under the microscope the schistosity is seen to be due to elongated light green grains with prominent cleavage, showing a pleochroism from green to light green and a high extinction angle. This mineral was determined as a pyroxene near diallage^①. Minor amounts of quartz and an indeterminable feldspar were also found.

The diallage schist is altered, apparently by solutions, along channels, the majority of them parallel to the schistosity but some cutting across it. This alteration changes the schist to a gray, fine grained, cherty appearing rock so all traces of schistosity are lost. All intermediate stages between the schist and the cherty rock are present. Under the microscope with even the highest magnification available it is difficult to work out the mineralogy of the cherty rock. A mineral, apparently a feldspar, but its basicity could not be determined made up the larger mass of the rock. A colorless pyroxene and some garnet and quartz made up the remainder. The whole rock is cut by veins of colorless pyroxene, near diopside.

The next process is a further alteration of the rock by solutions. This order is beautifully illustrated in the hand specimen. A mass of diallage schist is altered along certain lines to the cherty material and inside this a narrow zone of andradite garnet is found, definitely later than the other al-

① For a description of diallage occurring under somewhat similar conditions see -Miller, W.J. - "The Magnetic Iron-ores of Clinton Co. N.Y." Ec. Geol. Vol. 14, pp. 514 - 533.

terations. . The next stage is a further formation of contact silicates so large masses of the rock are eventually replaced by garnet and epidote with minor amounts of diopside or hedenbergite. The period of metallization followed and probably to some extent overlapped it.

The first metallic to be formed was magnetite, following it bornite was deposited. Chalcopyrite was formed later than the bornite as seen both under the microscope and in the hand specimen. The order found in the case of the Tidewater is essentially the same as that found by Dolmage^o at the Marble Bay Mine, Texada Island. The bornite is commonly replaced along joints and contact with other minerals, by covellite and sometimes chalcocite. The alteration is only occasionally noted in the chalcopyrite and in no case observed, was the alteration found along the contact of bornite and chalcopyrite, which, if the covellite were formed later than the chalcopyrite, would be a favourable place for it to form. The explanation that would seem to cover the case is that the copper sulphides, in part, were formed before the deposition of the chalcopyrite but that some action extended beyond this time so a little of freshly deposited chalcopyrite was altered.

The alteration of the limestone and andesite probably followed essentially the same order of, formation of silicates, then metallization but the change could not be worked out in as great detail.

^o Dolmage V. "The Marble Bay Mine, Texada Island, B.C."
Ec. Geol. Vol. 16, Pl. 12, p. 384.

TIDEWATER

The complexity of the metamorphic process outlined above may be due to emanations from several intrusives below the ore-bodies. Endothermic effects in the sills may account for some of the alteration in them.

THE JUNE MINE

The June or Jeune group of claims is about four miles from Quatsino Sound. Limestones and volcanics have been intruded by a diorite; a more acid intrusive occurs near the claim and it probably is responsible for many of the effects observed in the diorite, volcanics and limestone. The contact effects on the volcanics are not extremely marked; some quartz, epidote and garnet are developed and they are mineralized by magnetite and sulphides. The way in which the magnetite replaces the volcanics, along stringers and around grains is of interest because it suggests that the iron must have been introduced in very tenuous solutions or in some form approaching a gas. No very extensive mineralization of the limestone was observed, but it was found to be largely replaced by clear, coarse grained quartz, resembling that of pegmatite dykes or igneous rocks.

REPLACEMENT OF DIORITE

The most notable feature of this deposit was a replacement and mineralization of the diorite. This process was noted in other occurrences but not so extensively developed as here. It followed some lines of weakness such as a joint crack, so it can be observed in all stages from a narrow line to one embracing large amounts of the diorite. The first alteration

JUNE GROUP

is the introduction of magnetite which, in most cases, replaces the ferromagnesian constituents of the rock, although it is rarely found replacing feldspars. This replacement must have been by very tenuous solutions or by gases because of the preferential replacement of certain constituents, and due to the fact that on the polished surface no ~~visible~~ connection is visible between the magnetite masses. The basic plagioclase is largely replaced by pyrite and pyrrhotite, in some cases this replacement seems to have chosen alternate twinning lamellae in the feldspar. Bornite followed the iron sulphides and some quartz veins observed were probably related to it. Covellite and chalcocite are found in the bornite but in this case they were not observed at all in the chalcopyrite, so they were judged to have formed before the chalcopyrite, which was later than the bornite. Fine grained quartz with pyrite, in contrast to the clear, coarse grained quartz related to the bornite, cuts all the ore minerals. Other non-metallic minerals include a dark-green, fine columnar epidote which appears as an alteration of the plagioclase, apparently following the formation of the pyrrhotite. Serpentine is found in veins cutting the other minerals. It may be an alteration of the early minerals or of later introduction.

The origin of the mineralizing solutions could not be worked out; whether they were from the diorite itself or the more acid intrusive. It is peculiar that the diorite should be replaced when ten feet away a limestone occurs, but it is probable that the limestone does not extend very far below the surface.

MINERALOGY - METALLIC

Before discussing the contact metamorphism, in general, the properties of the minerals found and peculiarities in them will be described; so descriptions to use in the discussion of contact metamorphism and ore-genesis may be kept together.

To determine the minerals present and their ages, polished surfaces were prepared of over twenty-five pieces of characteristic ore. The general results will be summarized below under the particular mineral species. In the polishing of the ore, not much difficulty was experienced. The majority of the minerals in the section were hard, so that they could be ground to a good surface rapidly by means of a steel lap, using "Wellsworth Emery No. 180". It was found, that if little water were used, and the emery run until fairly dry, much better results could be obtained. After this treatment, it was put on another steel lap with "Wellsworth Emery No. 303", and ground until all the scratches were removed. The polishing was carried on on a steel lap covered with fine linen, revolving at high speed. Chromic oxide mixed to a stiff paste with water or liquid soap was the polishing agent. The surface was held on this lap with considerable pressure until the lap was nearly dry, then a further application of the chromic oxide made. Most of the polishing

MINERALOGY - METALLIC

of the hard minerals took place when the lap was nearly dry and in this case the soap was of advantage because it dried more quickly on the lap. The specimens were mounted on glass slides with plasticine and examined under a Leitz mineralogical microscope, fitted with a prism illumination. An arc lamp with condensing lense was found useful for oblique illumination to supplement the vertical illuminator under medium power objectives. By means of the oblique illumination, minerals which could not be determined otherwise were easily made out, such as the nature of some of the gangue minerals.

In the determination of the paragenesis of the minerals in the section, a constant difficulty was encountered, due to, not only the hard metallic minerals present, but also to the hard silicates, such as garnet, which tend to have idiomorphic form. With these minerals and softer ones in the same section there is a constant tendency for the softer ones to be called younger^①. This probably accounts for the obscure time relations noted between pyrrhotite and magnetite.

The commonest metallic mineral found in the deposits was magnetite. This mineral has the composition usually written Fe_3O_4 - H 5.5-6.5 G 5.2. It crystallizes in the isometric system as octahedrons and dodecahedrons. It is strongly magnetic and in some cases has polarity. In the surfaces from Vancouver Island magnetite is usually the oldest metallic mineral. In general it is slightly later than the garnet

① Gilbert G. "The Relation of Hardness to the Sequence of Ore Minerals" Ec. Geol. Vol. 19, pp. 668-673.

minerals. The size of grain varies from some one-half inch across to some too fine to see, and with difficulty distinguishable under the microscope. One difficult thing to account for observed under the microscope was the different appearance of grains. In the case of the claims at Head Bay, Nootka Sound, in one of the small veins in limestone, the magnetite in the centre of the vein is much lighter than that at the two sides. No visible impurities can be detected under the microscope. Adjacent grains of different colors might be accounted for by different optical orientation of the plane of the section, as an octohedral plane and a cubic plane but no apparent reason can be found why, on opposite sides of a vein, a different orientation should hold from that in the centre. The obvious explanation would be a slight change in the composition of the depositing solutions at the time of deposition. Broderick,^① for a similar case, but observed in adjacent grains of similar orientation, comes to the conclusion that it may be due to a solid solution of Fe_2O_3 in Fe_3O_4 . In the Nootka Sound case there was not much difference in the etch figures produced on the surface by hot hydrochloric acid. Unfortunately accurate chemical analyses could not be made. In a great number of cases, adjacent magnetite grains had a different color, but their orientation could not ^{be determined so conclusion could} be drawn from them. In some cases these grains etched very differently with hot hydrochloric acid.

No titanium minerals were found either by etching or blowpipe tests.

① Broderick T.M. "Some of the Relations of Magnetite and Hematite." Ec. Geol. Vol. XIV. 1919. p.362.

In several places "geniculated" magnetite was found. This type was named because of the resemblance to the geniculated twins of rutile. Examination of specimens failed to show any simple crystal face in the isometric system, which could form the twinning plane so it was concluded the structure was not due to twinning. One explanation is that it was produced by interference of individual crystals during growth, and the longitudinal furrows on the individual grains are due to the oscillatory combination of the dodecahedron and the octohedron.

The magnetite with polarity, constituting the variety ledestone is of interest, because of its relative rarity. Two occurrences were noted on the West Coast. At the Sunshine group on Cascade Creek, Barkley Sound, magnetite with a strong polarity was found. At the Black Prince claim, about one mile from the above locality, more ledestone was found, ^{but} its polarity was relatively weak. Pieces from both localities were polished and etched. The two magnetites were of totally different character. That from the Sunshine Group polished with a pitted surface. It was relatively pure with only a small amount of quartz later than the magnetite. ~~that~~ it tended to have a somewhat parallel arrangement throughout the surface. On etching, this surface showed a parallel arrangement of etched bands ~~with~~ ^{with} pronounced cracks ~~and~~ etched deeper between them. In one case, a radiating structure was observed, resembling that in specularite, but no hematite could be found in the section. A similar structure was found in some of the magnetite at Head Bay even more highly developed than this, but it showed no trace of polarity. The

MINERALOGY - METALLIC

specimens from the Black Prince M.C. showed a mass of very pure magnetite consisting of grains from one-half a millimeter to one centimeter in diameter, intergrown with one another. Apparently when this magnetite was being formed, numerous centres of crystallization were set up so the equidimensional grains grew until they interfered with one another. The faces represented are, therefore, not crystal faces, but contact faces. Under the microscope the grains appear different colors, and on etching the color contrast is greater. No zoning is observed within the grains.

Specularite or specular hematite occurs in several places. Under the microscope it shows needle like forms which are not as easily etched, by hot concentrated hydrochloric acid as the magnetite crystals. In all cases, where found, the hematite formed later than the magnetite with needle like projections cutting the grains of magnetite giving angular outlines to the pieces. For a somewhat similar occurrence, Broderick^o suggest these may be replacements of magnetite. ^{along octahedra / p. 197-8.} The relation to the sulphides is not clear, except in the case of the Waterloo M.C. where the chalcopyrite is younger. In all cases the specularite was formed by magmatic solutions or alteration of earlier magnetite under deep seated conditions. It could not be formed by weathering because of the unoxidized condition of the sulphides near it. Some of the hematite was slightly magnetic but this is probably due to included magnetite.

^o Broderick T.M. "Some of the Relations of Magnetite and Hematite" Es. Geol. Vol. 14, 1919, p. 362.

MINERALOGY - METALLIC

Pyrrhotite was found to be the most common sulphide in the deposits. In certain cases it was found to constitute practically the entire mineralization along the contact as at the small occurrence, described on Sarita River. On the polished surface, the mineral appeared as; veins in the magnetite and garnet, or as disseminated grains in them. These small grains never showed crystal boundaries and since they were almost structureless as viewed under the microscope, it was very difficult to determine the relative ages of the pyrrhotite and the enclosing hard mineral. The hand specimens where the pyrrhotite occurred as stringers often proved more valuable in telling the relative age than the polished surface. In general the conclusion arrived at was that the pyrrhotite was in most cases later than the magnetite.

Pyrite occurred as stringers in the ore, as a filling for joint cracks, and as disseminated ^ograins with a strong idiomorphic tendency. In some cases pyrite of several generations was found. The most usual occurrence was for it to be just later than the pyrrhotite and occurring as veins in it, however when pyrrhotite did not occur pyrite often did, in which case it occurred as grains or veins in the magnetite and garnetite. In some cases the pyrite occurred after chalcopyrite associated with veins of calcite or quartz; but it was more usual for it to precede the copper iron sulphide.

Chalcopyrite belonged to the last stage of sulphide mineralization, except when small amounts of pyrite appear of later formation. Under the microscope this mineral is easily recognized by its softness and color. It is almost



Fig. A. Camera lucida drawing of section from June Mine, showing forms of pyrite (P) replacing pyrrhotite (M). The tendency to develop idiomorphic form is noticeable. The spherical structure seen in the two grains was noted in several places, but it could not be explained.

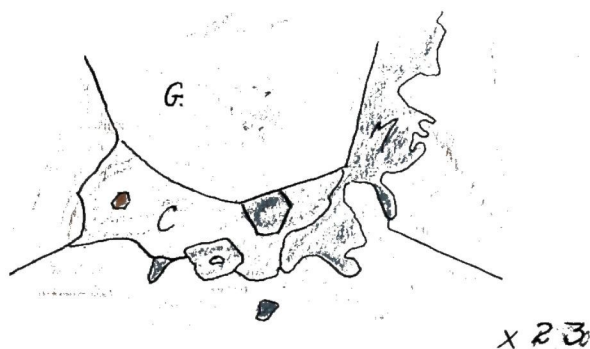


Fig. B. June Mine. Magnetite (M) showing idiomorphic form replacing calcite (C) interstitial to idiomorphic grossularite (G). The magnetite is also replacing the garnet.

MINERALOGY - METALLIC

entirely structureless and seldom shows crystal ^{faces} forces, then usually against a soft mineral such as calcite. In some cases where cut by later quartz veins the line of the veins showed curious angular displacements suggesting a following of some structure as cleavage or parting, but since it is negative to the usual reagents, it was not etched. One peculiar structure between magnetite and chalcopyrite was noted at the June group of claims. Here masses of magnetite were found which showed in cross section, concentric elliptical bands of chalcopyrite. The whole structure was about four inches across the major axis. Under the microscope the chalcopyrite was seen to be definitely later than the magnetite. The only explanation that would seem at all feasible is, that the magnetite was formed and then subjected to stress so concentric lines of weakness were formed. Later copper bearing solutions came along and took advantage of this to deposit.

Bornite was found only in the two localities, namely the Tidewater and June. In both these localities it was definitely earlier than the chalcopyrite although at the June one occurrence suggested a later generation of bornite but the evidence was not conclusive and it was met only in one place in one section.

Covellite and chalcocite were found as primary minerals in the bornite. They occurred as small stringers and veins in the bornite, sometimes apparently parallel to the octohedral cleavage of that mineral. The evidence would point to the formation of the covellite and chalcocite, before the introduction of the chalcopyrite.

MINERALOGY - METALLIC

Galena was found as small cubes in the altered limestone at the June.

The above list constitutes the primary metallic minerals observed in the magnetite occurrences. In general the average paragenesis of the minerals for all the deposits would be magnetite, pyrrhotite, pyrite, bornite, chalcopyrite. Locally there might be variations, but this list, except for the bornite, corresponds to Olapp's^o list for Southern Vancouver Island.

^o Olapp, C.H. Geol. Surv., Can., Mem. 13, p. 168.

MINERALOGY - NON-METALLIC

In the case of the non-metallics, the paragenesis is more difficult to determine because thin sections of the contact metamorphosed products were not available. The identity of the transparent minerals was determined by inspection and by the examination of powder in oil using Larsen's^① tables. A few were determined by their optical properties in thin section, where these were available.

① Larsen E.S. "The Microscopic Determination of the Nonopague Minerals"
U.S.G.S. Bull 679 - 1921.

Garnet is present in the deposits both in massive and in crystal forms, showing the dodecahedron, and icositetrahedron. The commonest form that occurs is the red calcium iron garnet, andradite. The calcium aluminium garnet, grossularite, occurs quite commonly but does not form as large bodies as the andradite. Quite often the two minerals occur together and can only be separated under the microscope, by the different indices of refraction. The garnet does not show preference for any type of intruded rock, but apparently developed equally well in any of them. In general, garnet appeared to have been formed before the metallic minerals were deposited, but probably in most cases there was some overlapping in their time of formation.

Epidote is another very common constituent in the contact zone, occurring often intimately mixed with the magnetite. More often it occurs as an alteration of the volcanic rocks invaded, often extending long distances from the contact. It is quite often found as alteration of the intrusive rock, especially along fissures. No attempt was made to distinguish epidote formed by "contact metamorphism"^o, and that formed later, "as in fissure veins,"

In the amphibole group actinolite and tremolite were found in some quite large crystals but they did not occur as plentifully as the epidote. Some hornblende may have been formed by contact metamorphic process, but it was found impossible to distinguish between the product of contact metamorphism and the product of normal uralitization.

^o Lindgren W. "Metasomatic Processes in Fissure Veins"
Tr. A.I.M.E. Vol. 30, pp.610-611 - 1901.

MINERALOGY - NON-METALLIC

In the pyroxene group several individuals were found. Diopside is of quite common occurrence in the contact metamorphosed volcanics, but it is quite easily overlooked in the field. In several localities a dark green mineral resembling diopside was found, probably hedenbergite or an intermediate mineral. No wollastonite was observed but Dolmage^① reports some from the West Coast.

Some vesuvianite was found under the microscope in a mass with epidote and quartz.

Chlorite and serpentine were observed in a number of places. They occurred later than the ore and in some cases are probably secondary, formed by the alteration of earlier contact, silicates. Exact relations of these were difficult to determine due to their softness and tendency to be removed during the polishing of surfaces.

In several cases under the petrographical microscope small grains of minerals thought to be clinozoisite or zoisite were found. On account of the high magnification required, it could not be distinguished whether the extinction was parallel or nearly so.

Quartz is of very frequent occurrence in the deposits of the West Coast. It is found in the masses of contact metamorphosed rock containing epidote and diopside. It also occurs as veins cutting the ore in many of the deposits and is later than the majority of the mineralization although it is occasionally found with pyrite.

① Dolmage V.M. G.S.C. Sum. Rept. 1920 p. 15A

MINERALOGY - NON-METALLIC

Calcite occurs as residual fragments of limestone in the contact metamorphosed rock and ore and also as veins cutting the ore zone. Some calcite crystals found were due to recent solutions and deposition from meteoric water.

Titonite was observed in several slides of both the igneous rock and the contact metamorphosed product.

Plagioclase near oligoclase and more acid was found as an alteration product in some of the slides. The new feldspars seemed to be developed in the older more basic ones whether by the replacement of the old feldspars bodily by the new ones, or by the removal of lime and addition of soda to the more basic ones.

CONTACT METAMORPHISM - GENERAL

Before discussing the contact metamorphism of the magnetite deposits it is as well to review the existing ideas of this process and the definitions of the word. The word metamorphism is, itself, a much abused term; it has been defined by various authors with various applications so now, when metamorphism is mentioned, the exact meaning of the author has to be judged from the context or from a definition. Contact metamorphism has also suffered from the usages imposed upon it. The definition^① adopted by probably the majority of geologists is.

"Contact metamorphism comprises all metamorphic changes due to contact with or proximity to any body of eruptive (igneous) rock, the new crystallizations not being definitely directed by dead weight stress."

This definition is obviously intended to include the alteration, where materials are derived from the magma. Certain geologists would confine contact metamorphism to the effects due to heat and mineralizers without accession of material from the magma; this effect is usually, simply called recrystallization. The case where much material is contributed by the intrusive is called contact metasomatism. Barrell^② further divides the metasomatic processes into, pneumatolytic and hydrothermal, depending whether the emanations are above or below the critical point for water vapour. Probably one reason for the confusion in the definitions of contact metamorphism and its phases, is the difficulty in determining which process was the one most active, and so one

① Daly R.A. "Metamorphism and its Phases". Bull, Geol., Soc., of Am. Vol. 28, 1917 p, 405.

② Barrell, J. "Geology of Marysville Mining District Montana." U.S.G.S. Prof. Paper No. 57, pp.116-117, 1907.

CONTACT METAMORPHISM - GENERAL

term is used to cover the several processes. In the same way, the distinction between pneumatolytic and hydrothermal alteration is very difficult to make so that, in many cases, these terms are used interchangeably.

RECRYSTALLIZATION

There is a disagreement among geologists as to the relative importance of the different processes of contact metamorphism. Recrystallization, or the case where not much material has been introduced from the magma, has been proved in a number of cases. By this process limestone is altered to marble and shale to hornfels. The products of recrystallization along igneous contacts are so similar to those which are due to the less severe regional metamorphism that it is often difficult to separate the two effects. This may account for the overlooking of recrystallization under conditions of contact metamorphism. Another reason for the overlooking of recrystallization is that the alteration, by emanations from the intrusive, is usually much more striking and also due to the fact that they may replace or alter the recrystallized material.

MAGMATIC CONTRIBUTION

The effect of introduction of material from the magma is usually so striking that all geologists must admit its importance in the formation of the contact zone. To discuss how the emanations from the magma are given off to the contact zone, and the origin of the mineralizers it is necessary to follow the

CONTACT METAMORPHISM * GENERAL

changes in an intrusive from the molten state to consolidation. If a normal magma is started with, it is thought that it has a large quantity of gases associated with it such as; chlorine, water vapour, carbon dioxide, fluorine, sulphur, and other volatile constituents, which reduce the fusion point of the melt and the viscosity. It is well known that in the crystallization of igneous rocks the accessory minerals, magnetite, pyrite, pyrrhotite, rutile, titanite, ilmenite are the first to form. The first crystallization of the metallics has always been difficult to explain because the same magma may form ore-bodies from its mineralizers, as a last product. Certain geologists,^① against the evidence of many petrographers, would even reverse the order of accessories first, and make them of later introduction by the mineralizers.

The processes advanced as the most prominent in the igneous rock magma are; magmatic differentiation due to liquation and the principle of supersaturation above the amount necessary for the formation of eutectics. To these may be added many minor processes which have been postulated for the formation of peculiar rock types.

If the rigid principle of the formation of eutectics is held, it is almost impossible to account for some igneous rocks. As an example, a chip of a rock from Clifton Point, Copper Island,

^① Tolman, C.F., and Rogers, A.F. "A study of the Magmatic Sulphide Ores." Stanford Univ. Publication 1916. pp. 20-21. Review Ec. Geol. Vol. 12, pp. 623-637.

CONTACT METAMORPHISM - GENERAL

showed phenocrysts of quartz which was the first rock forming mineral to crystallize. Plagioclase phenocrysts were formed next, and the quartz was corroded and embayed and then a micropegmatite which apparently altered the feldspar made up the groundmass. This case demonstrates how an eutectic may be passed and a mineral deposited which is unstable in the remainder of the magma. Vogt^① points out the tendency for the glass matrix of a rock to approach a eutectic composition. This oscillation about eutectic composition demonstrates how the "eutectic" may not be in equilibrium with the already deposited minerals which explains why a rock may be altered by its own "eutectic juices." Colony^② believes that the last stage residuum, approaching a eutectic, may with the mineralizers produce important effects on the already formed minerals such as; the formation of "injection perthites", and the formation of actinolite, brotite, chlorite, at the expense of earlier ferromagnesian minerals. In the case where the end stage product extends into the intruded rock, its importance cannot be overlooked. This tendency toward the formation of eutectics would account for the rather notable tendency for the contact zones along different intrusives to be rather similar, a fact which has been urged by a number of supporters of the recrystallization hypothesis as a strong argument for similar impurities in the

① Vogt J.H.L. "The Physical Chemistry of the Crystallization and Magmatic Differentiation of Igneous Rocks"
Jour. of Geol. Vol.31, 1923. pp.232-252 - pp.407-419.

② Colony R.J. "The Final Consolidation Phenomena in the Crystallization of an Igneous Rock"
Jour. of Geol. Vol.31, pp.169-178.

② PL V A -

CONTACT METAMORPHISM - GENERAL

intruded rock so that similar silicate contact zones are formed.

The changes in the magma show a tendency toward an equilibrium from the molten state until it is consolidated. The proximity to an intruded rock will have a marked influence on the processes which go on in the magma, so variations in the intrusive may be noted. Fine grained contact facies due to rapid cooling, caused by the escape of mineralizers or chilling because of the proximity of the intruded rock are common. Porphyritic facies or marginal facies of different composition may be due to the absorption of wall rock upsetting the equilibrium in the rock. *and space*

← This absorption^o of wall rock, especially limestone has been noted in many cases with the resulting production of peculiar rock types. It seems probable that this interaction would modify, to a large extent, the content of the mineralizers and also cause their emanation to be somewhat irregular.

The effect of the intrusive on the country rock is usually so much more noticeable than the endothermic effects, that contact metamorphism is often applied to this phase alone. After the magma is in place in the intruded rock, and as consolidation begins, a heat wave travels out; this wave in some cases, produces a recrystallization, and a general readjustment of the country rock. It travels out slowly and the temperature

① Daly R.A. "Genesis of the Alkaline Rocks. " Jour. of Geol. Vol. 26. pp.97-134.
 "Origin of the Alkaline Rocks."
 Jour. of Geol. Vol. 21, pp.87-118.

CONTACT METAMORPHISM - GENERAL

gradient is steep, so that before it has travelled a long distance a considerable part of the intrusive had consolidated, so there is a collecting of the last stage of crystallization product, and the mineralizers which are released and enter the country rock. The reasons the intruded rather than the intrusive rock is attacked, are two, chemical and textural. The emanations are derived from the intrusive and as a result are more nearly in equilibrium with it, so they prefer to attack a rock of another composition.

← However, as shown in the consideration of the processes in the igneous rock, the mineralizers may not be in equilibrium with the intrusive, and so it may be attacked. The texture of the intrusive is usually close grained, while the country rock is relatively porous either, as an original character, or due to the heat wave from the intrusive.

In individual deposits variation in the composition of the emanations may be traced by the order of deposition of the minerals. No rule seems to hold except that, in general the more acid emanations precede the more basic ones, but exceptions to this have been noted many times, even in the one deposit. On account of this variation in the contents of the emanations several authors,^① especially those working on the iron-ores of Eastern United States, have postulated the differentiation of the last stage material and the mineralizers into two poles, one acid and one basic. According to this view the more acid

① Colony R.J. "Magnetite Iron Deposit of South Eastern New York" New York State Museum Bulls. 249-250. 1925.

CONTACT METAMORPHISM - GENERAL

pole would represent a normal pegmatite, using it as the name of a product about as acid as a granite, and the basic one would contain the iron and other basic metals. They use pegmatite also as a name for the basic different^{er}iate, which is unfortunate because it leads to confusion. In the case of the contact metamorphic magnetite there is not the striking evidence for differentiation of the mineralizers and the last stage residuum into poles; but the two types seem to come off together. The reason why overlapping of the solutions is common, will be discussed in connection with the contact metamorphism on Vancouver Island.

FORMATION OF SILICATE ZONE - VANCOUVER ISLANDCONTACT METAMORPHISM ON VANCOUVER ISLAND - FORMATION OF SILICATE ZONE.

In considering the contact metamorphism of the magnetite occurrences of Vancouver Island, the type of field-work done must be borne in mind. A series of isolated occurrences were examined; the purpose of the examination being mainly economic so the work was confined to a limited area close to the ore bodies. The lack of broad field work made it relatively impossible to determine the order of some of the processes on a broad field basis.

Taking the occurrences all together, it is impossible to find evidence of recrystallization without addition of material except in the case of the limestone which was marmorized. This recrystallization may have been due to an earlier regional metamorphism, but in certain cases, a gradual increase in size of grain as the intrusive contact is approached suggests, that although it may have been altered to marble by regional metamorphism that it subsequently was recrystallized under the influence of the intrusive.

The action of emanations from the magma is much more important both as a contact metamorphosing agent and as the source of the metallic minerals of the contact zone. A noticeable feature of the deposits of the West Coast is the small size of the garnet zone formed. In many occurrences elsewhere, the garnet zone forms important rock units in the contact deposits, along intrusives of the same basicity as those of Vancouver Island. The only explanation that may be advanced is that the magmas

FORMATION OF SILICATE ZONE - VANCOUVER ISLAND

which produced the contact metamorphism were relatively high in iron bearing mineralizers so the zone due to the more acid part was not large. That some of the more acid products were present is shown by the formation of some silicates and the alteration of the basic feldspars of the intrusive to more acid forms along the margins and cracks. These emanations are characterized by their high content of, sodiums in some form, and of silica. The other common elements are also present, but they are subordinate in amount to these in their effects. In the limestone contact zones of Vancouver Island, minerals containing soda are relatively rare although soda lime feldspars^① are found in some cases, but in the contact zones of other formations the albite molecule is often noted. The reason for the small amount of soda in the limestone is that more stable compounds can be formed with the lime and iron, so the soda passes out and may reach the surface as sodium chloride which is often noted in fumarolic deposits.

The deposits associated with the rocks of the Vancouver volcanics show fairly wide zones of alteration. The volcanics are of about the same basicity as the rocks which intrude them, so their alteration may be very similar to that which goes on in the igneous rocks. For this reason, the formation of more acid feldspars at the expense of old ones in the contact metamorphism of the volcanics, is ascribed to the same cause that produces the alteration in basicity of the feldspars in the intrusive, that is, it is the result of the end stage products of the final consolidation^②

① Clapp, C.H. Geol. Surv., Can. Mem. 13, p. 49.

② Colony, R.J. Journ. of Geol. Vol. 31. pp. 169-178.

FORMATION OF SILICATE ZONE - VANCOUVER ISLAND

of the igneous magma. During this feldspathization, some silicification takes place, showing that the solutions must have been rich in sodium and silicon. Later then the feldspathization, and probably under more intense metamorphism, there is a change in the character of the mineralizers, so they contain more lime and iron and the "contact silicates" are formed. The lime may have been derived from the magma or perhaps from limestones, through which the mineralizers passed. Under certain conditions, the magnetite appears to have been introduced with the contact metamorphosing solutions, but in general the acid solutions tend to be first: In the Tidewater several cycles were gone through. The first was under the influence of the acid solutions when feldspars were formed. During the next stage, these materials, introduced, were removed and magnesium iron and lime added to form diallage. After the formation of the diallage, some of the components were removed, and soda reintroduced to form feldspars again.

← — — — Following this andradite which required a large accession of iron was formed. The complexity of the alterations at the Tidewater may be due to emanations from several intrusives or to reversal in the character of emanation from one.

RELATION OF SILICATES TO MAGNETITE

As noted previously, there is no fixed relationship between the time of formation of the silicates and the magnetite. In the contact deposits of Vancouver Island, there is no evidence for the differentiation of the material from the mineralizers into two poles. According to the prevailing notion of the nature of the mineralizers and the end stage products of crystallization, they are characterized by their mutual solubility and motility. These properties seem to exclude differentiation by processes similar to those in the magma.

A theoretical explanation may be given which seems to satisfy the observed irregularities in the emanations. From their nature, it seems probable that the agents producing contact metamorphism collect within the margin of the intrusive. Contact metamorphism is generally supposed to take place at such a depth that open fractures cannot exist in the rock, therefore the mineralizers must escape by the incipient or microscopic fractures in the intrusive. Due to the fine character of the cracks they act similarly to porous porcelain, that is, the solutions must diffuse through them to reach the intruded rock. It is also probable that some diffusion may take place through the massive intrusive itself, but no experimental results bearing on this point are available. All elements and oxides do not diffuse with the same speed; in general the lower the atomic or molecular weight of the substance, the faster it diffuses.

① For gases and dilute solutions this rate equals $K \sqrt{\frac{1}{\text{molecular weight}}}$ -
Wallace J. "Introduction to Physical Chemistry"
1919 p.89.

RELATION OF SILICATES TO MAGNETITE

This would apply either in a solution or in a gas. The effect of this would be that the mineralizers containing the lighter elements as sodium and silicon would diffuse out more rapidly than the mineralizers with the heavy bases and iron.^o As a result the mineralizers which produce the silication would act on one spot much before the basic emanations arrive. The time interval between the silicates and magnetite would vary with the distance the minerals had to diffuse and the place where they were given off so, under certain conditions, the magnetite depositing and the silicating mineralizers may be contemporaneous in their action.

Besides the rate of diffusion other properties of the mineralizers will influence the formation of the contact zone. One of these is the concentration of the material in the zone of reaction, and the other is the chemical activity of the elements.

———— The more chemically active elements are, those of lower atomic weight, and they are also the ones that diffuse fastest. These elements reach the zone of contact metamorphism first, and so begin to react so their concentration in the zone is reduced, but due to their high rate of diffusion a steep concentration gradient will be maintained and there will be a relatively rapid renewal of material. In the case where the elements of higher atomic weight are present they reach in the zone of deposition, but due to slower rate of diffusion the concentration cannot be maintained. So, until after the concentration of the chemically more active elements is reduced, there is no chance for the less active ones to deposit. It can be seen that with an easily

RELATION OF SILICATES TO MAGNETITE

replaced rock such as limestone, that the effect on the siliceous emanations will be most rapid so they will, in general, form the silicated zone before the magnetite is deposited. This accords with the facts because in the deposits in limestone, there was a greater tendency to have the silicate definitely earlier than the magnetite. In the volcanics the presence of silicates already in the contact zone may allow the magnetite to deposit before or contemporaneously, with some of the silicates. By the Mass Law the high concentration of silicates would tend to inhibit deposition of further silicates so even in the presence of the acid emanations magnetite might deposit.

The later introduction of the magnetite may also be explained mechanically by this process. The acid emanations may diffuse out, and then the magnetite solutions be deposited in another place or relatively wide solution channels may be established, so it could press out by ordinary flow.

ORE DEPOSITION

The chemistry of the deposition of magnetite is discussed following the discussion of the silicates, because of its general tendency to form later than they. As an introduction, a brief discussion of the chemical properties of magnetite is given.

In composition magnetite usually conforms to the general formula Fe_3O_4 or ferrous ferric oxide. As represented by the formula, magnetite contains 72.4% iron, and 27.6% oxygen. It often differs from this theoretical value even when pure, due to its ability to form solid solutions with ferric oxide, hematite. To quote from "The Oxides of Iron," -

"Ferric oxide (hematite) dissociates at high temperatures, giving off oxygen and leaving a homogeneous product which may be considered as a solid solution of magnetite, Fe_3O_4 , in hematite (Fe_2O_3). The proportion of magnetite in the product depends upon the temperature and oxygen pressure above the oxides. The lower the oxygen pressure, and the higher the temperature, the more magnetite is found in the solid solution. The reaction is strictly reversible for magnetite readily takes up oxygen at a temperature of 300° until the equilibrium proportion at the temperature in question is attained. Magnetite is therefore chemically unstable under atmospheric conditions, although it may remain unoxidized for long periods."

The melting point of magnetite is 1538°C ^②, which is different from that of Doelter ^① who gives $1190^\circ - 1225^\circ\text{C}$ which is obviously too low because magnetite formed on the lining of a copper converter is not melted at this temperature.

① "The Oxides of Iron" The Carnegie Institution at Washington, Year Book No. 15, 1916, p.137.

② Hodgeman and Large - "Handbook of Chemistry and Physics"

③ "Data of Geochemistry" - U.S.G.A. Bull 695, p.287.

ORE DEPOSITIONFORM OF IRON IN MINERALIZERS

Just what form the iron is in in the magma is difficult to say. The average composition^① of igneous rocks shows an excess of ferrous over ferric iron, and, therefore, probably much of the iron in the mineralizers is in the ferrous form. The formation of magnetite as an early product of crystallization in the magma shows the presence of the ferrous as well as ferric iron. The two times of formation for the iron oxides may be assumed to be due to iron in two forms in the magma; one of which forms the rock minerals, and the other goes into the mineralizers in some form. This is probably a ferrous or ferric fluoride or chloride or a mixture of them. The emanations are thought to be the iron halides because these elements show strong chemical affinity and are fairly stable. The halides are known to occur in the magma by the presence of minerals containing them, and they are also common in volcanic emanations.^② From the predominance of ferrous iron in the consolidated rock, some geologists^③ have argued that the iron in the mineralizers is in the ferrous form, and that the high ferric oxide content in the contact zone, is due to oxidation by limestone. Following this explanation, one would expect that along intrusive contacts with non calcareous sediments that the ratio of ferrous to ferric oxide would be greater than in the limestone contact zone. The composite straight-line diagrams of the changes in

① Clarke F.W. Washington, H.S. "Average Composition of Igneous Rock". National Acad. of Sc. Vol. 8 #5, P. 108-115. 1923.

② "Data of Geochemistry". U.S.G.S. Bull. 695. p.256.

③ Butler, B.C. "A Suggested Explanation of the High Ferric Oxide Content of Limestone Contact Zones." Ec.Geol.Vol.18. pp. 398-405.

regional and contact metamorphism in "Metamorphic Geology" by C.K. Leith, and W.J. Mead, were compared. They show that in almost all types of metamorphism ~~that~~ there is an increase in ferric oxide content, especially when there is a relative increase in total iron. The only marked exception is in the case of the contact metamorphism of clays and slates, Plate 10, where, when there is not much increase in total iron, the ferrous exceeds the ferric. The study of these plates shows that, in general, the conditions that obtain in contact metamorphism, are such that ferric oxide is formed, whether by introduction of ferric salts from the magma, or by oxidation of ferrous salts which would be subject to the same conditions as the introduced iron.

- ORE DEPOSITION -ORE PRECIPITATION BY LIMESTONE

The Chemistry of the formation of magnetite in contact zones has been discussed in several places. Leith and Harder in the "Iron Ores of Iron Springs District, Utah", U.S.G.S. Bull. #338, assume the iron was introduced as ferrous chloride and write the following equation.



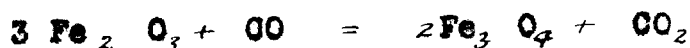
Magnetite is soluble in the hydrochloric acid, so it could not precipitate until the concentration of the acid is decreased by interaction with limestone. It may also be lost by diffusion^① because it tends to diffuse much more rapidly than the iron oxide through porous rock. Leith and Harder exclude ferric chloride from the reaction because they say it can only form ferric oxide, by the following reaction:



It seems probable that this does not represent the only reaction that takes place in the contact zone. With a reducing agent such as carbon, the carbon dioxide may be reduced.



This reaction^② does not take place at all at temperatures below 600° C. but at 800° C. it proceeds rapidly. With CO in the contact zone, the ferric oxide will be altered to magnetite by the following reaction:

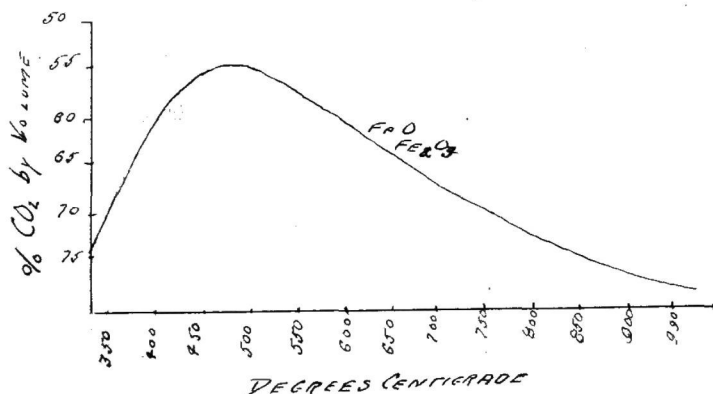


① Sullivan E.C. U.S.G.S. Bull #312, P.10.

② Winchell A.N. "Petrographic Studies of Limestone Alteration at Bingham." Trs. A.I.M.E. March, 1924.

ORE PRECIPITATION BY LIMESTONE

More data is available for this reaction as shown by the following curve.^①



At 800° only about 25% CO by volume is required to reduce the hematite. The ferric oxide would not be completely converted to the ferrous oxide, but the works of Sosman and Hostetter^② shows magnetite would form.

As the curve shows, at 500° the maximum concentration of CO is required to affect the reduction of the ferric iron and since this is also below the temperature of the free formation of CO by carbon, hematite is the most stable, so it is formed.

The upper limit of temperature is more difficult to define. The critical points of many minerals in the contact zone have not been determined. One mineral which occurred in the contact deposits on Vancouver Island, tremolite^③ cannot form above 1000° - 1100° , so the probable temperature range is from 1000° to 600° with a probable preference for the higher end

① Findlay - "The Phase Rule and its applications". P.309.

② "The Oxides of Iron." "The Dissociation of Hematite in Air". Journ. Am. Chem. Soc. Vol. 38 pp.807-833, 1188-1198.

③ Allen & Clement. Am. Journ. of Sc. 4th Series. Vol.26, p. 101. 1908.

- ORE DEPOSITION -

ORE PRECIPITATION BY LIMESTONE

because, there, magnetite can form most easily. Hematite forms close to 500° or lower.

An attempt was made to find the conditions under which sulphides form, but no definite information could be found. Investigation of the sulphides, as of the iron oxides, have not been made because they are not so important in iron blast furnace practices. The only conclusion that could be drawn is that pyrrhotite, the ferrous sulphide, can form at a higher temperature than the ferric sulphide, pyrite; and that in general, pyrite forms before chalcopyrite.

- ORE DEPOSITION -

ORE PRECIPITATION BY SILICATES

The chemistry of the precipitation of magnetite by rocks, other than limestone, is not well understood. The only work in this branch of the subject is on the precipitation of minerals at low temperatures as related to agricultural chemistry, and the chemistry of secondary enrichment. This application of experiments carried on at low temperature to conditions of high temperature may give results that are misleading. From the field evidence and the evidence of the mineralogical microscope it is seen that iron bearing solutions do replace other than carbonate rocks and precipitate magnetite. If as before it is assumed that the iron is introduced as ferrous or ferric fluoride or chloride reactions to cause a precipitation may be worked out. Any one of these salts is completely hydrolysed in water giving the corresponding hydroxide and the acid. The presence of a natural silicate with the alkali, or alkaline earth, metals hastens this precipitation, as shown by Sullivan^① in several papers. The basis of the silicates are taken into solution and hydroxides oxides or silicates are precipitated depending on the strength of the base deposited. Sullivan's work was mainly on the copper salts but his experiments show that iron reacts similarly.

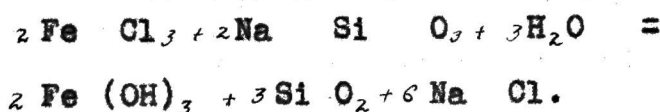
① Sullivan E.C. - "The Interaction Between Minerals and Water Solution." U.S.G.S. Bull 312. "The Chemistry of Ore

Deposition". Ec. Geol. Vol. 1, pp.67-76. "Experiments on the Separation of the Constituents of a Solution by Filtration Through a Mineral Filter". Ec. Geol. Vol. 3, p.750.

- ORE DEPOSITION -

ORE PRECIPITATION BY SILICATES

Some of the minerals which gave this effect are: feldspar, amphibole, augite, biotite, garnet, vesuvianite and olivine. Even quartz^① has the power of taking iron from ferric acetate solutions. At the high temperature at which the formation of the magnetite takes place it may be supposed that the silicon left will be removed in solution and magnetite deposited especially if free fluorides are present. A reaction involving ferric chloride and a simple alkali metal silicate may be written:



If fluorine were present a soluble salt of hydrofluosilicic acid would be formed. From this quartz might be deposited. Under the conditions of high temperature and low oxygen pressure the ferric oxide would easily be dehydrated and reduced. If a ferrous halide were the form of the salt it would give magnetite by dehydration of the hydroxide without reduction.

No data regarding the temperature at which the deposition in the silicates took place could be found, but it seems probable that it took place at as high a temperature as in the limestone.

① U.S.G.S. Bull, 312, p.20.



Camera lucida sketch of Magnetite (M)
replacing volcanics June Mine. In
the sketching it was necessary to omit
many fine veins of magnetite surrounding
grains of the rock.

- ORE DEPOSITION -

PHYSICAL CONDITIONS OF THE SOLUTIONS

So far the possible reactions producing the magnetite have been discussed. The physical conditions, except that the emanations were at a high temperature have not been discussed. At 900° water would be well above its critical point and due to its pressure it would act almost as a solution so the use of "solutions" is probably not incorrect. Clapp^① suggests that the magnetite was formed from very concentrated solutions "virtually magnetite magma", which, of course, must have been very viscous. No facts in support of this view could be seen in any of the deposits. Direct evidence in the shape of flow structure, orientation of contact silicates or limestone fragments, which under this hypothesis would constitute xenoliths, is lacking. On the other hand, there is much evidence that the iron bearing solutions were very tenuous. In the replacement of the diorite at the June mine the magnetite replaced, preferentially, the ferromagnesian constituents of the rock without visible solution channels existing between the masses of magnetite. In the replacement of volcanics^② on the same claim the method of replacement of certain grains in the rock suggests the agents must have been very thin, either as gases or a very tenuous solutions. At Head Bay, Nootka Sound, the banding of the ore and the distance it has penetrated along a joint or bedding plane again suggests a very tenuous solution.

① Clapp, C.H. Geol. Surv., Can. Mem. #13.

② PLATE V II.

- ORE DEPOSITION -

PHYSICAL CONDITIONS OF THE SOLUTIONS

All the polished surfaces from the different deposits support the idea of tenuous solutions.

Definite information regarding the temperature of formation of the silicates could not be found but it seems probable that they were derived from solutions the same temperature, or higher than that of the solutions producing the magnetite. The emanations producing the silication were just as thin as those producing the magnetite as shown by their ease of diffusion, and the way in which they were observed to penetrate some of the minerals of the original rock as along cleavage planes in feldspars.

MAGNETITE OCCURRENCES OF THE WORLD

The writer made a brief review of some of the literature on the occurrences of magnetite the world over, to determine the position of the contact metamorphic deposits as a source of ore. A brief summary of the geology of the more important types and of some of the principal localities is given. Magnetite may be divided into two classes, on the basis of its present commercial value, the titaniferous and the non-titaniferous ore. The titaniferous ore is not commercially valuable at the present time, on account of the lack of an efficient method of reduction, so the outline will be largely confined to the non-titaniferous ore.

MAGNETIC SEGREGATION TYPES

Magnetite is a common accessory in igneous rocks of all basicity, so it is not remarkable that the segregation of material should produce ore-bodies. These are more common from bodies of igneous rock corresponding in basicity to a gabbro but as a rule, are titaniferous. Exceptions have been noted where non-titaniferous magnetite occurs as a segregation, or titaniferous magnetite is of contact metamorphic origin.

"PEGMATITE TYPE"

The non-titaniferous magnetite formed by the contri-
bution of iron, in some form from the magma, is the most widely distributed and the commercially most valuable source of magnetite as an ore of iron. Ries^o divides these into: --

o Ries, H. "Economic Geology" 4th Edition 1916, p.504.

"PEGMATITE TYPE"

1. Benticular deposits in metamorphic rocks.
2. As more or less lense shaped or tabular bodies in igneous rocks.
3. As replacement of limestone not of contact metamorphic character.
4. Contact metamorphic deposits.
5. As veins.

Only the last two divisions, under this scheme are definitely defined, and it seems easier to regard them all of the same types, and the defined types, contact metamorphic deposits and veins as only a special case of it. The problematical forms will be discussed first followed by the specific case, contact metamorphic.

The non-titaniferous magnetites of the Eastern United States have long formed a puzzle for the geologists and various origins have been postulated for them. They are associated with Pre Cambrian rocks which have been highly metamorphosed so their origin is not clear until the relations of the rocks are worked out. Probably a good many of them are of contact metamorphic origin, but since contact deposits are not common in that district, and the wide alteration often accompanying contact metamorphism may obscure the true nature of the rock this origin may be overlooked. The explanation that receives the most support, at present, is that the magnetite was formed from solutions allied to pegmatites and containing the iron in the mineralizers. The character of the gangue minerals feldspar, quartz, amphiboles and apatite is urged in support of this view, but precisely the same minerals may be developed under conditions of contact metamorphism, as shown on Vancouver Island. In the Adirondack magnetite

MAGNETITE OCCURRENCES OF THE WORLD"PEGMATITE TYPE"

Newland^① comes to the conclusion that some of the ore may be a segregation from a granite, similar to those in the gabbro, but that the magma had a sufficient concentration of silica for the titanium to form titanite. However, a large part of the ore body was formed by the introduction of iron by later "pegmatite" solutions. Miller^② in discussing the origin of the magnetite of Clinton Co., New York, comes to the conclusion that diallage was formed by the leaching of iron from hypersthene and hornblende by the action of "pegmatite" solutions. The iron deposited as magnetite later. The similarity of the process in this case to that observed in some deposits on Vancouver Island, under conditions of contact metamorphism is noticeable.

For the magnetite of North Carolina, including the Cranberry magnetite, W.S. Bayley^③ postulates a similar origin to those of New Jersey, which he says are of pegmatitic origin, although in this case the feldspars are altered to epidote, another analogue to the processes in contact deposits. Grout^④ comes to the conclusion that the magnetite of Northern Minnesota is a direct contribution from the magma as "pegmatites."

① Newland, D.H. "On the Association and Origin of the Non-titaniferous Magnetites in the Adirondack Region." Ec. Geol. Vol. II, pp. 763-773.

② Miller, W.J. "Magnetic Iron-Ore of Clinton County, New York." Ec. Geol. 14, pp. 509-535.

③ Bayley, W.S. "The Magnetites of North Carolina - Their Origin." Ec. Geol. Vol. 14 pp. 509-535.

④ Grout F.F. "Magnetite Pegmatites of Northern Minnesota." Ec. Geol. Vol. 18, pp. 253-269.

MAGNETITE OCCURRENCES OF THE WORLD"PEGMATITE TYPE"

Leith^① provisionally classified the Atikokan magnetite and the deposit near Bathurst N.B., in this group. Throughout the whole group the resemblance to contact metamorphic ore bodies is noticeable.

The huge magnetite deposits of Lapland; Kiirunavaara, Luossavaara, Toluvaara and Gellivare are very difficult to explain both on account of their huge size and their apparently unique features. Per Geijer^② believes the ore bodies represent a magmatic product somewhat similar to the pegmatite type of Eastern United States. Daly^③ believes the deposit is a differentiation in situ of a quartz porphyry. Geijer's theory of the origin seems to be better able to account for the facts especially the presence of apatite in large amounts. Other occurrences have been classed with these by Geijer including: Grangeberg in Central Sweden, Solberg and Lyngrot in Southern Norway, and the Blagodatsky type of the Eastern Ural Mountains. The deposits of this group are few in number, and no fully satisfactory explanation of their origin has yet been given.

CONTACT METAMORPHIC

Contact metamorphic deposits, or the specific case where the mineralizing solutions come from an intrusive mass and extend into and replace another rock type with perhaps some replacement of the intrusive, as well, are common. The deposits

- ① Leith, C.K. "The Iron Ores of Canada". - Jour. Canadian Mining Institute. Vol. 11, 1908, pp.94-95.
- ② Geijer Per. "Some Problems in Iron Ore Geology in Sweden and America." Ec. Geol. Vol. 10, pp.299-329.
- ③ Daly, R.A. "Origin of Iron-Ores at Kiruna, Sweden." G.S.A. Trans. Vol. 26, p.99, 1915.

MAGNETITE OCCURRENCES OF THE WORLDCONTACT METAMORPHIC

may be developed at the contacts of rock with intrusives of any basicity but in the deposits important for their iron content there is a tendency for the intrusive to be of medium basicity. Due to lack of uniformity in rock nomenclature and to the use of "granite" for any, light colored, plutonic rock an exact comparison of the basicity in the intrusives could not be made. According to the literature contact, deposits may be found along rocks such as granite, monzonite, quartz-monzonite, but there is a tendency for more of the iron ores to be found along contacts of granodiorite, quartz diorite, diorite and their perphyritic equivalents. All the contact metamorphic ore-bodies are noted for their irregularity, both in the distribution of ore and the gangue contact silicates. The ore is commonly mixed with such amounts of iron or copper iron sulphides that it often requires roasting before use.

These ores are of such wide distribution that all the occurrences cannot be listed but a few of the more important type localities will be mentioned. The distribution of the contact metamorphic deposits in America is so striking that Eckel^o says:

"We might summarize the matter by saying that almost every known iron deposit along the Pacific Coast, from Alaska to Southern Chile, and from the coast back to the eastern-most mountain range, falls into the class of deposits."

^o Eckel, E.C. "Iron Ores Their Occurrence Valuation and Control". 1944 p.87.

MAGNETITE OCCURRENCES OF THE WORLDCONTACT METAMORPHIC

These relations are true in general, but exceptions may be noted. The more important localities in the United States are: Iron Springs,^① Utah; The Barth Iron^② Ores; The magnetites of Shasta Co., California^③; and the occurrence near Fairview N.M., and Dillsbury, York Co.,^④ Pa. Many smaller deposits might be added to the list.

In Canada many contact metamorphic deposits are found especially in the West. Among the best known ones are those of Texada Island.^⑤ In Eastern Canada, especially Ontario contact deposits are commonly found.

Outside of United States and Canada, many contact metamorphic iron ore deposits are known. In the following occurrences noted the information was obtained from "Iron Ore Resources of the World", published by the International Geological

- ① Leith, C.K. & Harder, E.C. U.S.G.S. Bull 338.
- ② Jones, J.C. "The Barth Iron Ore Occurrence" Ec. Geol. VOL. 8, pp. 247.
- ③ Prescott Basil - "Mgts ore of Shasta Co. Calif." Ec. Geol. Vol. 3, p. 465.
- ④ Smythe, D.D. - "A contact metamorphic Iron Ore Deposit Near Fairview N.M." Ec. Geol. Vol. 18, pp. 410.
- ⑤ Harder, E.C. - "Structure and origin of the Magnetite Deposits near Dillsbury York Co. Pa." Ec. Geol. Vol. 5, pp. 599-622, 1910.
- ⑥ McConnell, R.G. "Geol. Surv. Can. Mem. #58, 1914.
- ⑦ Pope E.J. - "Investigation of Magnetic Iron ores from Eastern Ontario". A.I.M.E. Tr. Vol. 29, pp. 372-405 - 1900.
"Report of Ontario Iron Ore Committee" Toronto 1923 Appendix.

MAGNETITE OCCURRENCES OF THE WORLDCONTACT METAMORPHIC

Congress of 1910, Stockholm. Magnetite occurs in a zone apparently extending south from Mexico into Peru. In Mexico the deposits are in limestone, where it has been intruded by diorite, monzonite, porphyrite, and granite. In Cuba^o, important deposits are found in limestone due to the intrusion of diorite. Outside of America, important occurrences of contact metamorphic ore bodies are known in Sweden, Russia, Hungary, Japan, Australia, and China. Many other countries have this type of deposit, indeed they seem to occur almost anywhere where there is extensive igneous intrusion and not too great a removal of the contact zone by erosion.

"IRON FORMATION"

Magnetite formed by the contact metamorphism of iron formation in the Pre Cambrian rocks is of rather a common occurrence in areas of extensive igneous intrusive. It is possible that some magnetite may be formed by regional metamorphism, but it is more common under conditions of contact metamorphism. The ore of this type is, as a rule, rather impure due to an excessive amount of siliceous impurities in the form of quartz, amphibole and other silicates. In Eastern North America there are a large number of deposits belonging to this type. They are found in Sweden, Norway, Brazil and South Africa.

o Papers by Kepp, Lindgren, Ross and others. A.I.M.E. Trans. 56.
1916.

MAGNETITE OCCURRENCES OF THE WORLDIRON FORMATION

Grout^① comes to the conclusion that due to the intrusion of a gabbro, the magnetite formed in the Gunflint formation was fused; but his melting point is two to three hundred degrees too low.

Occurrences of black sand are fairly common but not, at present, of commercial value. These deposits are derived by the concentration of accessory minerals, or of other magnetite occurrences. Often where the magnetite ^{sands} forms large bodies, they are titaniferous.

An occurrence of interest from its peculiarity rather than its commercial importance is that found about a fumarole^②. The magnetite occurs as octohedra, lining a vent in the pumice. The purity of the pumice precludes the possibility of the derivation of the iron from it so the magnetite must have been deposited by emanation from the fumarole under conditions of low oxygen pressure and rather high temperature. A notable feature was the occurrence of halite on the faces of, and intergrown with the octohedra of magnetite. Fluorite was also found in considerable quantities by analysis.

Magnetite in all its occurrences is formed at high temperature either as a direct product of the magma or due to the metamorphic effects of the magma on previously existing iron minerals. The wide areas of igneous activity favour the production

① Grout, F.F. Ec. Geol. Vol. 18, p. 253.

② "Fumarolic Incrustations in the Valley of Ten Thousand Smokes." Geophysical Laboratory - Wash. #541, by E.G. Zies.

MAGNETITE OCCURRENCES OF THE WORLDIRON FORMATION

of magnetite, while conditions of weathering favour the production of the higher oxides and hydrates.

COMMERCIAL VALUE OF MAGNETITE

An attempt was made to determine the proportion of magnetite, used as a source of iron, derived from contact metamorphic deposits. More than general results could not be obtained because if the statistics are available, the ore is not separated into the types, or if the amount of magnetite is listed the localities where it was mined are not given, so the geology of the deposits cannot be found. Figures for United States^① show that of a total production of iron-ore, for the year 1923, of 69,351,442 tons, that 2,190,624 tons, or 3.16% of the total ore produced was magnetite. Of mines producing over 100,000 ^{tons only 170,042} tons, or 1.2% of the total ~~was~~ from contact metamorphic deposits, the remainder being from the magnetite type of the Eastern U.S. From the remainder of the smaller producers ^{of magnetite}, no figures are available, but from the distribution of the localities it seems probable that about 11% is from contact metamorphic deposits, and that part of this production is used as flux. In Canada^②, the iron ore produced in 1923 was 20,739 tons, and the principal part of this was magnetite from Moose Mountain, Ontario.

① "Mineral Resources of the United States 1923." Pt. 1 pp.295-329. Advance chapter.

② "Mineral Production of Canada 1923" Bureau of Statistics 1924.

MAGNETITE OCCURRENCES OF THE WORLDCOMMERCIAL VALUE OF MAGNETITE

In Sweden with a production of 5,597,707 tons of iron ore in 1923^o the larger part - probably 85%, is magnetite produced from the Lapland type of deposit and a small amount of ore from the contact deposits.

Among the smaller producers of iron ore, it is probable that contact metamorphic magnetite is more important than in the United States. An instances of this is Japan, where magnetite from contact deposits is mined for use in the blast furnace. The tendency at present seems to be to use easily available hematite as an ore, and to only use magnetite to form a mixture with the other ore. Doubtless, as the easily available high grade hematite bodes become depleted, the smaller contact metamorphic ore bodies will become more valuable as a source of iron, but at present, they are rather minor producers.

o "Skandinaviska Kreditaktiebolaget." Stockholm, Quarterly Rept. Jan. 1925.

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