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CONTACT METASOMATIC IRON-COPPER DEPOSITS

OF BRITISH COLUMBIA

A Term Paper for Geology 375

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April, 1966

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An interesting, well documented, and well illustrated report of a peculiar group of deposits. The organization of the report is very good, also the content and balance among sections. The report indicates a thorough survey, summary, and analysis of the literature.

Your style of writing needs improvement. It is jerky, rather than smooth, owing to use of too many parenthetical expressions, departures from normal word order, and peculiarities of punctuation. Choice of words is not always apt. Study the editing carefully. Readability of a report is important.

EMC

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Introduction

Contact metasomatic iron-copper deposits are very abundant in British Columbia. However, to date most of them have proved to be only modest sources of iron, copper, gold and silver. Most of the deposits are primarily ores of iron but there is a complete spectrum through those where copper and other sulfides are serious contaminants to those that are primarily ores of copper.

Prior to 1950 production from this type of deposit was negligible, but since the Second World War the rapidly expanding Japanese industry has provided a market for the metals from these deposits. Moreover were it not for this market it would be questionable if any of these deposits would be mined at present, for they are some of the smallest iron mines in the world (see Table 1).

The present economic outlook for these deposits is somewhat uncertain. Since individual orebodies tend to be quite small, their life is short; hence, if a company is to stay in business it must have a high discovery rate. The generally small economic reward is not, of course, an incentive for extensive exploration.

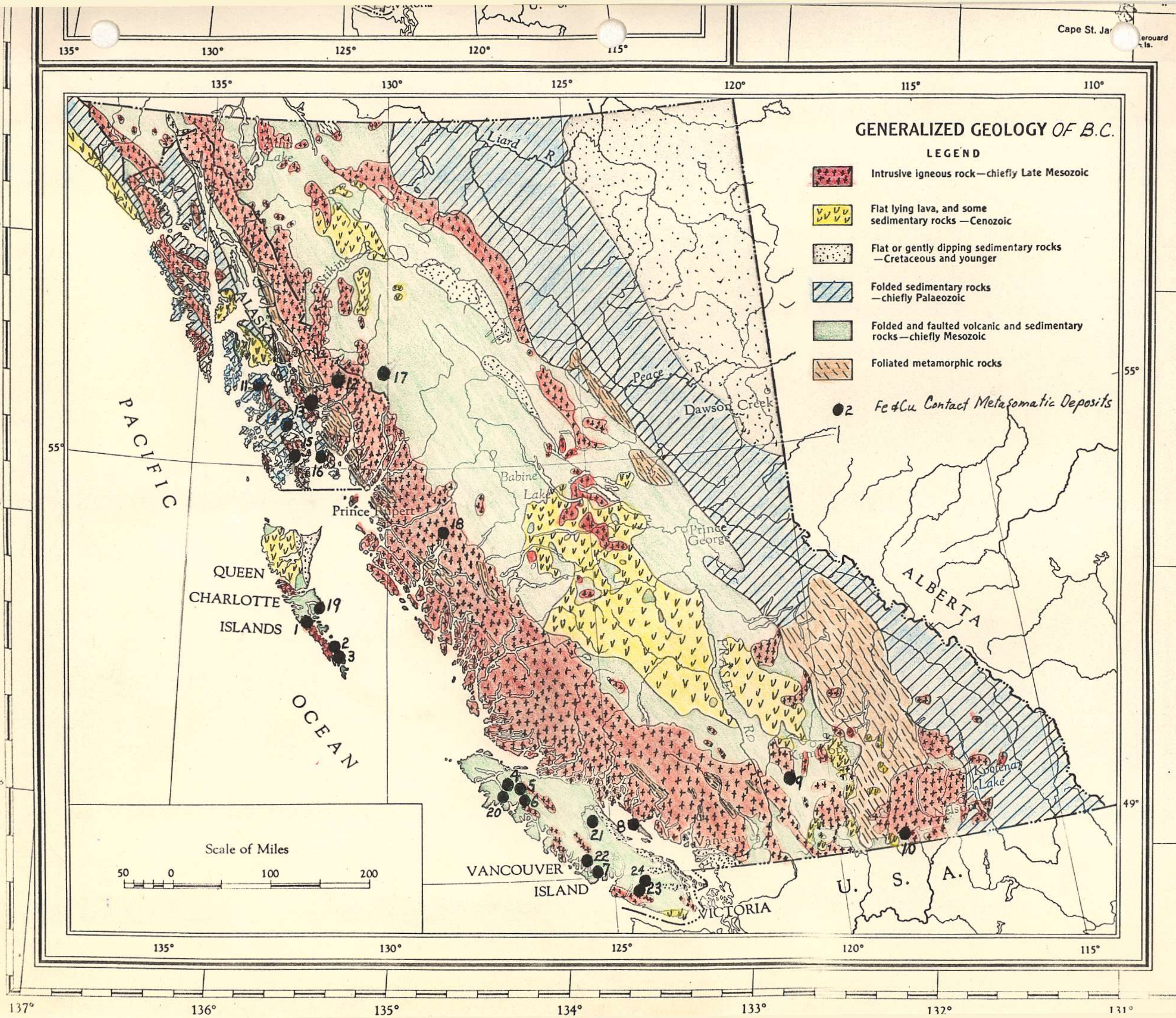
The small size of deposits is not the only factor that could have major economic influence on this industry. As mentioned above, most if not all of these mines would probably not be in production today if it were not for the Japanese market. Japan needs metals and British Columbia has metals to sell; however, there is only a gentlemen's agreement between the two countries. Japan has agreed to consume British Columbia's ores as long as British Columbia does not put restrictive policies on export of mineral commodities. So far this arrangement has been very satisfactory. Nevertheless, this situation could change when Australian iron ore becomes readily available, or when British Columbia decides to restrict exportation of certain mineral commodities. The latter could occur if it were decided that British Columbia should not be so dependent on export revenue but rather should establish secondary industries.

Even though the mines are small, they are very important to the economy of British Columbia. At present about 2 million tons of iron concentrates worth approximately 20.5 million dollars are shipped annually to Japan. All of these concentrates come from the contact metasomatic-type deposits.

This paper will be restricted to a description and discussion of the origin of the deposits near the coast, since these are the ones being mined. However, it should be understood that this same general type of deposit occurs in other parts of the province, but cannot be mined for economic reasons. There are a few exceptions where the deposits are copper ores. Craigmont mine (Figure 1) is an example, but even here the iron concentrates are not shipped because of the high transportation costs of such a bulk commodity.

Location of Deposits

The location of the deposits is shown on Figure 1 and their names with brief descriptions are given in Table 1. All the economic iron and iron-copper deposits occur in areas where belts of Upper Triassic limestone are cut by Coast Intrusions. Where either one or the other is missing, there is a noticeable lack of this type of deposit. For example, no significant orebodies of this type have been found along the eastern contact of the Coast Mountains plutonic complex from the Fraser River area north to the Portland Canal area. Many seemingly suitable intrusions occur in this region, however, there is a lack of Upper Triassic limestone. Experience has indicated that deposits tend to occur in clusters. Thus mines usually consist of a number of orebodies


GENERALIZED GEOLOGY OF B.C.
LEGEND
Intrusive igneous rock—chiefly Late Mesozoic
Flat lying lava, and some sedimentary rocks —Cenozoic
Flat or gently dipping sedimentary rocks —Cretaceous and younger
Folded sedimentary rocks —chiefly Palaeozoic
Folded and faulted volcanic and sedimentary rocks—chiefly Mesozoic
Foliated metamorphic rocks
2 Fe & Cu Contact Metasomatic Deposits
PACIFIC OCEAN
QUEEN CHARLOTTE ISLANDS
VANCOUVER ISLAND
VICTORIA
ALASKA
ALBERTA
U. S. A.
Prince Rupert
Prince George
Dawson Creek
Peace R.
Liard R.
Stikine R.
Babine Lake
FRASER R.
Kamloops
Kootenay Lake
Nelson
Vancouver
Scale of Miles
50 0 100 200
Cape St. Ja

2a.
Figure 1

Table 1

LIST OF PROPERTIES SHOWN ON INDEX MAP

Mines and Probable Mines	Type	Comments
*1. Tasu Mine	Fe-Cu	>40,000,000 tons 37% Fe (½-⅕ is Cu ore)
*2. Jib Mine	Fe-Cu	>8,000,000 tons 49.5% Fe
*3. Jedway Mine	Fe	4,700,000 tons 42% Fe
*4. Benson River Area		
a. Coast Copper Mine	Cu-Fe	
b. Empire Mine	Fe	> 4,000,000 tons
*5. Nimpkish Mine	Fe	depleted in 1963 2,400,000 tons mined)
*6. Zeballos Iron Mines	Fe	
*7. Brynnor Mine (Kennedy Lake)	Fe	probably >15,000,000 tons (?)
*8. Texada Mines	Fe-Cu	over 14 yrs prod. 8,300,000 tons mined from 3 pits
*9. Craigmont Mine	Cu	>26,000,000 tons 1.82% Cu & 20% Fe in oxides
+10. Phoenix District	Cu	old district mainly depleted > 5,000,000 tons .7% Cu reserves left - poor in Fe oxides
A. **Prospects**		
+11. Shakan Penn.	Fe(?)	
12. Head of Bradfield Canal	Fe	
+13. Ernest Sound Area	Fe	
+14. Kasaan Penn. (Mt. Andrew Mines)	Cu-Fe	old district
+15. Moira Inlet	Cu-Fe	old district
*16. Gravina Island	Cu-Fe	
*17. Unuk River (Max Property)	Fe-Cu	probably >15,000,000 tons medium grade Fe with minor Cu
✓18. Iron Mountain	Fe	> 5,500,000 tons 22% Fe
*19. Iron Duke	Fe	
✓20. Power River Area	Fe-Cu	
*21. Iron Hill	Fe	depleted mine
*22. Tofino Creek	Fe-Cu	
*23. Bugaboo	Fe	many small deposits >5,000,000 tons 56% Fe
24. Blue Grouse (Cowichan Copper Mines)	Cu	depleted - prod. >8,000 tons Cu. conc.

* - deposits known to occur in or near Upper Triassic limestone

\+ - deposits known to occur in calcareous Paleozoic rocks

✓ - deposits known to occur in Mesozoic vol. rocks without evidence of limestone units

A. - very little information is available on Alaskan deposits and in many instances have other mines nearby.

Exploration and Mining Problems and Techniques

Exploration for these deposits has proved to be exceedingly difficult. Since the orebodies consist mainly of magnetite, one would expect that they could be located easily using airborne magnetics, but this has not been the case. The problem is two fold. First, the deposits and hence their magnetic anomalies are usually much smaller than the normal flight interval. Thus for adequate coverage, flight lines have to be exceedingly closely spaced. Secondly, the coastal areas, where most of the exploration is being carried out, are very rugged. Hence elevation control is almost impossible to achieve unless one resorts to helicopters which are very expensive.

Even after an anomaly or some showings have been discovered, major problems still exist. Geophysical and geological ground work are hampered by the jungle-like undergrowth and heavy rainfall that are characteristic of most of the coast. It has also been found from experience that tonnage estimates based on anything but very closely spaced drill holes are of little value. Deposits are characteristically irregular and typically end abruptly; hence area of surface outcrop may give no indication of the size of the deposit, and projections far beyond drill holes are not warranted. A few companies have had economic failures by not doing sufficient drilling before starting their operations.

The existence of large skarn zones has proved to be one of the most useful guides to ore. Most extensive skarn zones have associated orebodies of reasonable size.

Meaning?

Both open-pit and underground mining methods are presently in use. However, the types used are restricted mainly to those which are relatively inexpensive, such as normal open-pit, glory hole, unsupported stope and random pillar methods.

General Geology of Coastal British Columbia

1. Introduction

Because most areas along the coast are mountainous, highly irregular coastlines characterized by islands and fiords result. The mainland is bordered by the Coast Mountains, which extend for approximately 100 miles inland, and the axes of the main islands are also mountain chains called the Insular Mountains. Lowlands border a few shorelines, but in general they are less than 10 miles wide. Nevertheless, they are important because they mark the edges of major tectonic depressions, such as Hecate Strait and the Strait of Georgia.

Even though over one half of Vancouver Island is not yet mapped, it has been generally established that the coastal areas are underlain by rocks ranging in age from middle Paleozoic to Recent (see Figure 2). ~~However,~~ Mesozoic rocks are by far the most abundant (see Figure 1). In general, the oldest rocks are found in the cores of the mountain ranges; the younger rocks occur on their flanks closer to the shorelines. This generalization does not hold for areas such as Southern Vancouver Island, which have suffered repeated deformation.

2. Regional Tectonic Setting

The regional tectonic setting of much of western British Columbia remains to be worked out. It has been established, however, that at least three fairly widespread periods of deformation, ranging from Lower Jurassic to Recent, have affected parts of the area. In most regions, however, the rocks have suffered only moderate deformation. Intense deformation has been restricted to fault zones and intrusive contacts.

Most of northern Vancouver Island has been subjected to only one period of deformation, that was probably Jurassic or Lower Cretaceous in age, whereas southern Vancouver Island and adjacent areas have also been affected by post-Tertiary deformation. The Queen Charlotte Islands have suffered at least two periods of deformation that, in general, were more intense than their southern counterparts.

Deformation accompanying the emplacement of the great batholithic masses of the Coast Mountains was generally intense but, in most regions, was restricted to a zone within a few miles of the contacts. Thermal gradients near these areas were generally steep. Probably most of the Coast Intrusions and associated deformation are Upper Jurassic and Lower Cretaceous in age; however, some are pre-Middle Jurassic and others cut Upper Cretaceous sedimentary rocks. Most of the present mountain chains were probably initially uplifted during the Coast Range orogeny (pre-Middle Jurassic to post-Lower Cretaceous (21, p. 60)).

Some important features of the regional tectonic setting that should be stressed in regard to the ore deposits are as follows:

1. Most areas never suffered intense regional metamorphism (greater than lower greenschist facies) or deformation.

2. Most areas were always reasonably elevated; high level with only minor areas were depressed. being subjected to deep level conditions.

3. Most of the tectonic events, including ore deposition, were probably over by Middle Cretaceous time, (the ore deposits under consideration are being spatially and probably genetically related to intrusions of Jurassic and/or Lower Cretaceous age).

Dangling participle

Lithologic Units

The main lithologic units of western British Columbia are shown in Figure 2. Although this diagrammatic stratigraphic section is probably ~~generally~~ correct, in general, it should be emphasized that there are many local variations and also that the geology of a large part of the area under consideration remains to be mapped and studied.

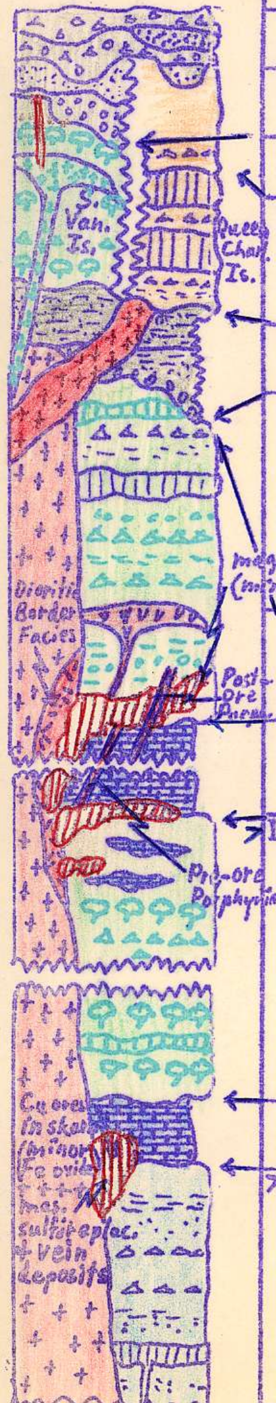
For most of the region, the sequence from upper Paleozoic to Middle Jurassic is as follows: several thousand feet of sedimentary rocks overlain by about 1,000 feet of siliceous, crinoidal limestone, overlain by at least 10,000 and perhaps greater than 15,000 feet of sodic basalts, overlain by 1,000 to 4,000 feet of massive limestone and calcareous sediments, which in turn is overlain by 3,000 to 10,000 feet of intermediate volcanics and interlayered sediments. In a few places where rocks of similar ages are exposed to the east of the Coast Mountains, comparable sequences containing Permian limestone, Triassic basalts, Upper Triassic limestone and Jurassic intermediate and acid volcanics have been recognized. Younger rocks, however, show much greater diversity.

Poor sentence, cumbersome. Break it up.

Both ~~of the~~ main limestone units are sheet-like in nature ~~and~~ and represent intervals when most of the area was tectonically quiet. Their origin is still somewhat in doubt; however, since they contain abundant benthonic fauna, at least in part they are bioclastic in origin. On southern Vancouver Island the Upper Triassic limestone is a series of large lenses. On a regional scale the only significant lithologic difference between the limestones that has been recognized is that the Permian limestone is generally more siliceous.

The basaltic volcanics between the limestones are probably a mixture of subaqueous flows and associated pyroclastics and less abundant terrestrial counterparts. Preliminary investigations

DIAGRAMMATIC STRATIGRAPHIC SECTION OF COASTAL AREAS OF BRITISH COLUMBIA



Thickness	Age	General Lithology	Names: S. Van. Is.	N. Van. Is.	Texada Island	Queen Char. Is
0-1000'	Pleist.	glacial deposits				
>500'	Mid. Olig. & Up. Mio.	S.S. & congl.	Sooke Fm.			
	Early Olig.	basic intr.--some highly differentiated; minor Cu deposits	Sooke Intr.			
>6000'	Eocene	S. Van. Is.--pillow lavas, breccias etc. Queen Char. Is.--pyrocl. breccias, rhy. ash flows, dacites, basalts, and minor S.S.	Metchosin Volc.			Masset Fm.
0-10,000'	Cret.	shallow water marine & continental S.S., shales, congl. *with coalbeds*	Nanaimo Grp. (Up. Cret.)	Low. Cret.		
	Late Jur. & Ear. Cret.	gabbro to granite but mainly qtz. dior. & granodior. both syntectonic (concordant, foliated, assoc. migmatites, mod. to deep seated) & post-tectonic (discordant, massive, high level) -assoc. faulting, folding & meta.	Coast Intrusions			
3,000' to 10,000'	Ear. & Mid. Jur.	andesitic pyroclastics, flows, & vol. intrusions-some clastic sediments -in places rhyolites and dacites	Van. Vol.	Bonanza Gr.		Yakoun Fm.
1000' to 4000'	Upper Tri.	mas. lms. which in places grades upward into thin-bedded carbonaceous lms. and argillites	Sutton Lms. (lenses)	Quatsino Lms.	Marble Bay Fm.	Kunga Lm (2 member
>10,000	Triassic	sodic basalt flows, pillow lavas, breccia and aquagene tuffs -minor lms. nr. top of section -some small magnetite bodies -Mid. Van. Is. Section (top) 12,000-15,000 pillow lavas; >100' pillow breccia; 7000'-10,000' mas. flows with amyg. tops, > 1000' *pillow* breccias, tuffs, & lavas	Van. (& Franklin Cr.) Volcanics	Karmutsen Fm.	Texada Fm.	Karmutsen Fm.
1000'	Lower Permian	crinoidal lms. & calcareous seds.	Sicker Lms			
>8000'	Permian & older(?)	thin bedded, cherty argillaceous and feldsp. tuffs, fine vol. breccia, greenst. some and. bas. flows and lms. -some radiolarian cherts, Mn beds & two localities with known cherty Fe-fm.	Sicker Volcanics			

Figure 2 6a.

indicate that the rocks contain typically about 11 to 13% iron oxides (FeO and Fe_2O_3).

The Coast Intrusions are known to cut all units older than Lower and Middle Jurassic. On northern Vancouver Island they are overlain unconformably by Lower Cretaceous sediments, and on southern Vancouver Island they are overlain unconformably by Upper Cretaceous sediments. However, a few intrusions , usually grouped with the Coast Intrusions, are known to cut these same Upper Cretaceous sediments. This stratigraphic information plus a few radiometric dates indicate that most of the Coast Intrusions in the far west were emplaced during Middle and Upper Jurassic epochs,and a few were emplaced during the Cretaceous period.

The intrusions are both syntectonic (concordant, foliated, etc.) and post-tectonic (discordant, massive, etc.) and range in composition from granite to gabbro (Figure 3). However, the great majority are quartz diorite and granodiorite.

Eastwood (5, p. 131) has noted that the intrusions commonly have a dioritic or basic border facies near the magnetite deposits. Several authors have recently suggested that the Coast Intrusions contain considerably more iron near the magnetite deposits, which are in post-Permian rocks, than where they cut Permian rocks (5,11,15,and 18). There are few analyses available to test their hypothesis. Nevertheless, eight chemical analyses cited by Fyles (6) indicate that the combined iron oxides range from about 1 to 6 percent where the intrusions cut Permian rocks while Sangster's (15) and Eastwood's (5) data indicates the intrusions contain from 3 to greater than 12 percent combined iron oxides where they cut the upper Triassic and Lower Jurassic rocks. The latter authors suggest that the increase in iron content is due to the assimilation of vast amounts of the iron-rich Permo-Triassic sodic basalts.

Figure 3 requires further comment and should be discussed in this ¶

Figure 3 (after Sangster (15))

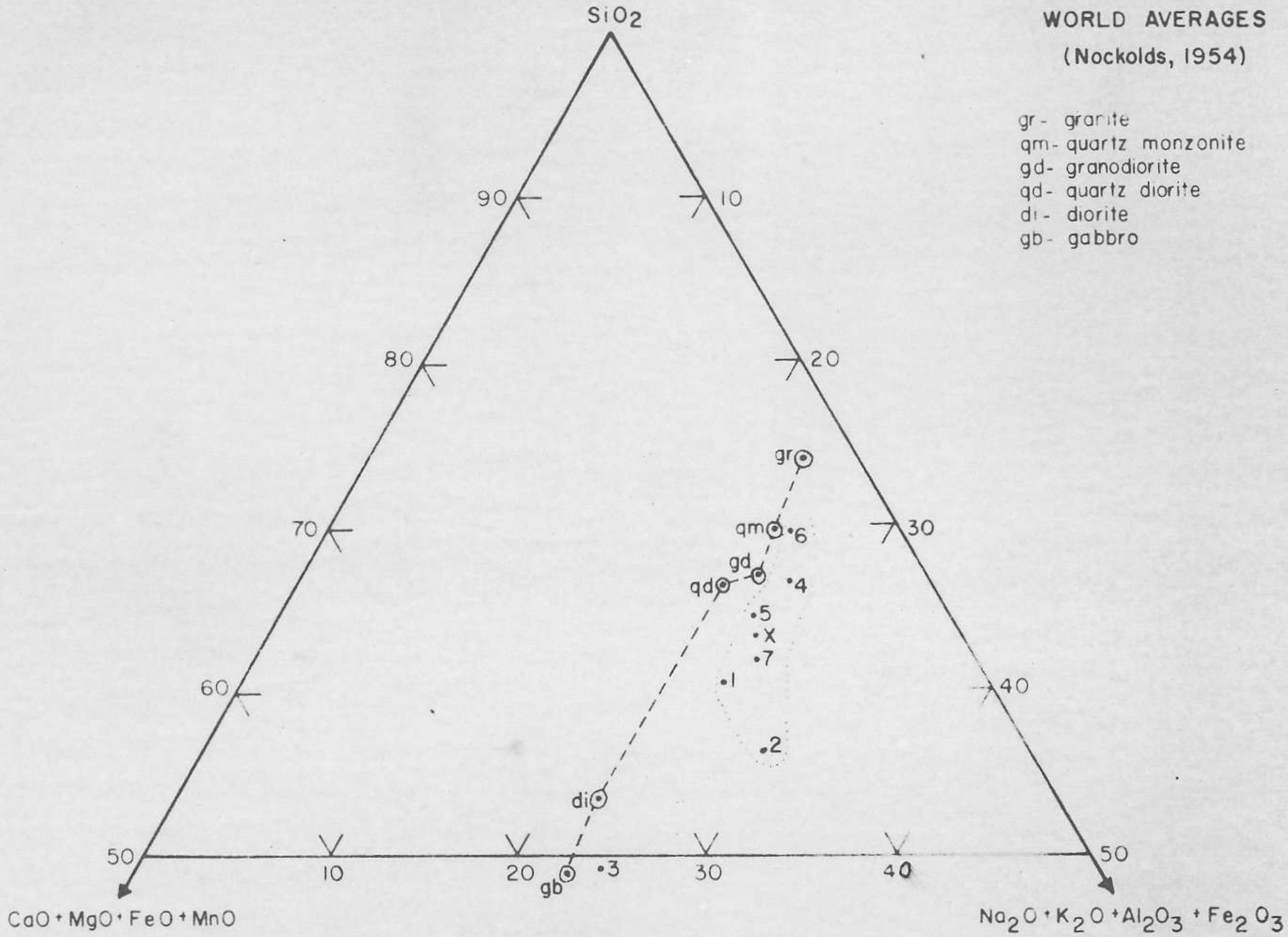


FIGURE 3

Diagram showing compositions of intrusions adjacent to contact metasomatic magnetite deposits. Numbers refer to analyses, Table 12.
Composition 'X' is arithmetic average of analyses encircled by the dotted line.
World averages of the granite-gabbro series are also shown for comparison.

Mineral Deposits

1. General Description

The ore deposits, in most districts, consist of massive fine-grained to dense magnetite and minor sulfides in garnet-pyroxene-epidote-amphibole skarn. Almost ~~invariably~~ the orebodies occur within 500 feet of the contact of a Coast Intrusion. As a rule they occur well down the flanks of post-tectonic, epizone plutons; however, some occur in roof pendants and a few are thought to be associated with syntectonic, mesozone plutons. Tasu, the largest deposit found to ~~this~~ date, is considered to be associated with a syntectonic batholith (19). Relatively basic pre- and post-ore porphyry dikes have been ~~commonly~~ localized commonly in the mineralized area.

2. Size and Shape of Orebodies

~~Generally~~ individual orebodies are relatively small, ranging from less than one-half million to a few million tons. Only in a few mines do individual bodies exceed ten million tons.

Orebodies are typically very irregular and, at many localities, end abruptly. Their shape is generally ~~an interplay~~ of a number of concordant and discordant forms related to bedding and structural features. ~~Some of these forms~~ are tabular-lensoid or lensoid swarms conformable with bedding, tabular discordant parallel faults and other planar structural zones, and pipe-like discordant localized along zones of structural weaknesses. The concordant lensoid ~~shapes~~, parallel to stratigraphic units, are most common. ~~In~~ some mines the bodies are nearly as wide as they are long, while in others their length is much greater than their width.

3. Structural and Stratigraphic Controls

Both structural and stratigraphic controls have been important in determining the sites of deposition. Deposits ~~have been~~ localized in areas of intense deformation, both along faults and breccia-pipe systems. Eastwood (5, p. 143) suggests that the reason for most of the deformation found in re-entrants of intrusions is that may have been caused by the difference in structural response to intrusion of the brittle, massive volcanics and the more plastic limestone. In many instances, however, evidence of pre-ore structures has been obliterated by the extensive metasomatism; hence, the importance of structural controls cannot be fully evaluated.

The presence of abundant pre-ore pre and post-ore porphyry dikes, localized near the ore bodies, also tends to indicate that conduits were periodically opened to the magma chamber below. Since, at many mines these dikes are thought to be penecontemporaneous close in time with ore deposition, there is reason to believe that these structural conduits were very important in determining the migration paths of the ore-bearing solutions.

As shown in Table 1, all of the economic iron-copper deposits are found in or near the Upper Triassic limestone; therefore, the conclusion that this limestone was an extremely important stratigraphic control on deposition seems inescapable. As mentioned above, the shape of individual orebodies or skarn zones, in many places, is primarily a function of lithology. Hence "microstratigraphic" controls were therefore also important.

Eastwood (5, p. 127) states that the susceptibility to skarnification varies with rock type. He gives the following series in decreasing order of susceptibility: (1) pyroclastics, (2) andesite lavas and intrusions, (3) Island Intrusions, and (4) limestone.

Such features, as garnet and epidote alteration rims on pre-ore andesite dikes occurring in unskarnified limestone, were used to determine this series.

A very strange series, in view of the fact that the ... were introduced in bulk

4. Mineralogy of the Skarn and Ore

The mineralogy of the skarn and ore tends to be relatively simple and uniform. The skarn consists chiefly of garnet (andradite-grossularite) (see Figure 4), pyroxene (diopside-hedenbergite) and epidote. Actinolite, serpentine, chlorite, anthophyllite, K-feldspar and calcite occur in minor but variable amounts. Sangster (15, p. 59) concludes that since seven major independent components (SiO_2, CaO, (Fe, Mn)O, MgO, Fe_2O_3, Al_2O_3 and H_2O) and only four major phases (garnet, pyroxene, epidote and magnetite) were involved in skarnification, the Mineralogical Phase Rule was obeyed and thus, equilibrium was probably maintained. However, it should be pointed out that since the garnets are commonly zoned, in a strict sense, complete solid-fluid equilibrium could never have been achieved. Therefore, if equilibrium existed, it had to be restricted to the solid-fluid interfaces of the garnets, and individual garnet crystals could not have re-equilibrated with changing physical-chemical conditions in the fluids.

In all deposits magnetite is the most abundant ore mineral but chalcopyrite, pyrrhotite, and arsenopyrite are locally abundant. Hematite, bornite, and sphalerite have been found in some deposits. In all orebodies the magnetite is characteristically very low in titanium. In many deposits there are minor amounts of scaly magnetite which could be pseudomorphic after hematite.

5. Paragenetic Sequence and Mineral Zoning

The general paragenetic sequence in most deposits was: 1.) epidote, 2) garnet, 3) magnetite, 4) sulfide, 5) calcite and quartz (post-ore cavity and vein fillings). There was some overlap.

Figure 4 (after Sangster (15))

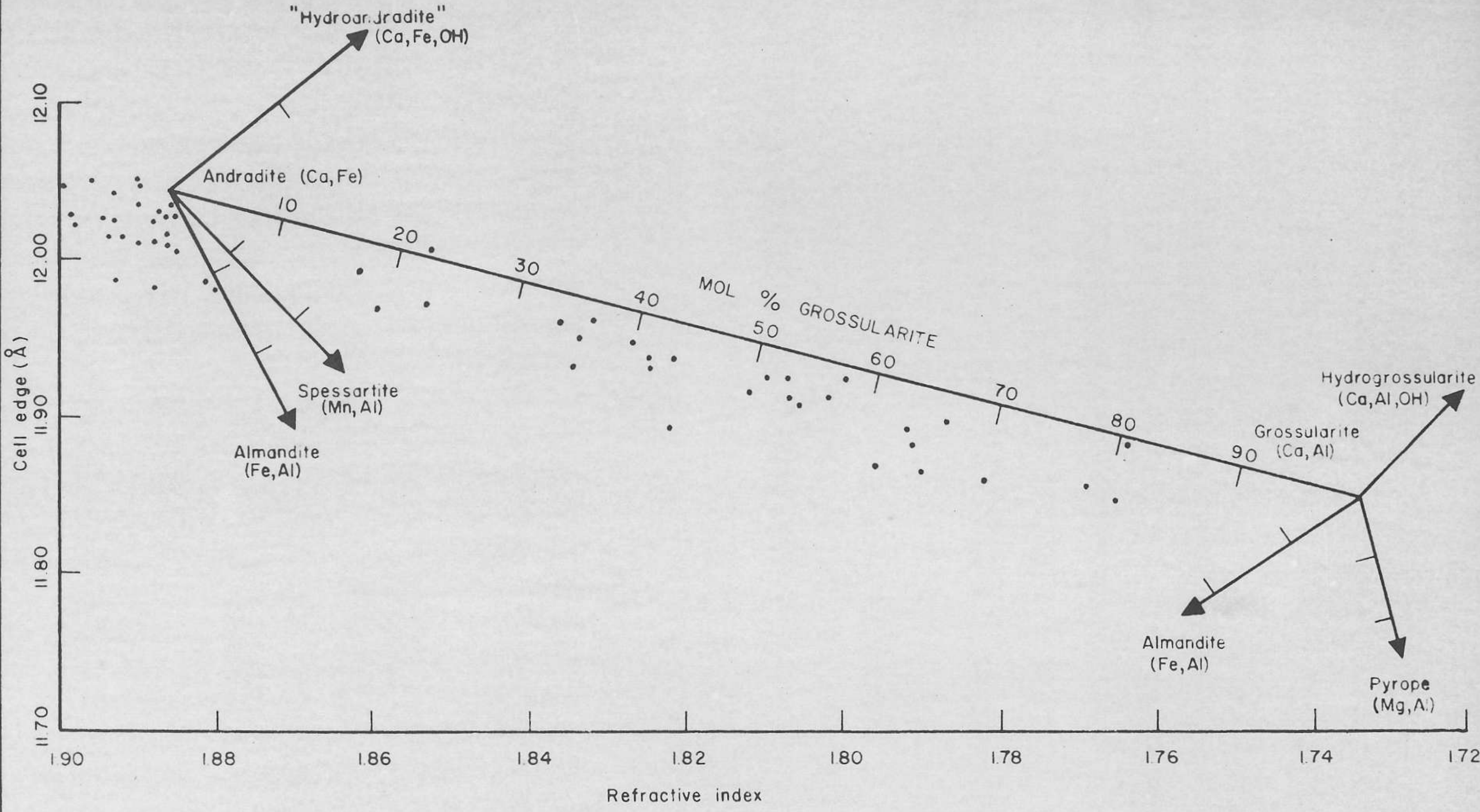


FIGURE 4

Composition of garnet in skarn as determined by cell edge and refractive index. Values for end members taken from Skinner (1956). Diagnostic components shown beside each sub-species.

In some deposits there is conspicuous mineral zoning from recrystallized limestone or relatively unaltered intrusive rock, to epidote or actinolite skarn (alteration), to garnet skarn, to the magnetite orebodies. Sulfides are generally most abundant in the outer skarn zones. The zoning occurs on both orebody and hand specimen scales. However, to some degree this zoning is irregular and somewhat dependent on the host rock. For instance, magnetite bodies in limestone may have little or no associated skarn, with the epidote zone being completely missing. In these deposits the garnet is usually restricted to the immediate vicinity of the magnetite and, in many places, occurs only in the interstices. Skarns formed from basic lavas are dominantly green rocks consisting of epidote, actinolite, chlorite, and minor anthophyllite with garnet occurring only in the most intensely skarnified areas. As a rule magnetite occurs disseminated throughout all the skarn zones; hence, the rigid zonal pattern does not hold true in detail.

6. Empire Mine

A brief description of the Empire Mine is included since it illustrates many of the characteristic features of the deposits (Figures 5 and 6). Typical structural and stratigraphic controls are present. The Merry Widow deposit consists mainly of irregular sheets and lenses of ore and skarn which have replaced volcanic rocks near the intersection of the Upper Triassic limestone and a fault zone. The Kingfisher ore zones are small, nearly circular, pipe-like bodies of magnetite localized along the same fault zone as the Merry Widow orebody and the small Raven deposit is simply part of an elongated mineralized zone of disseminated magnetite that probably lies along another fault.

Figure 5

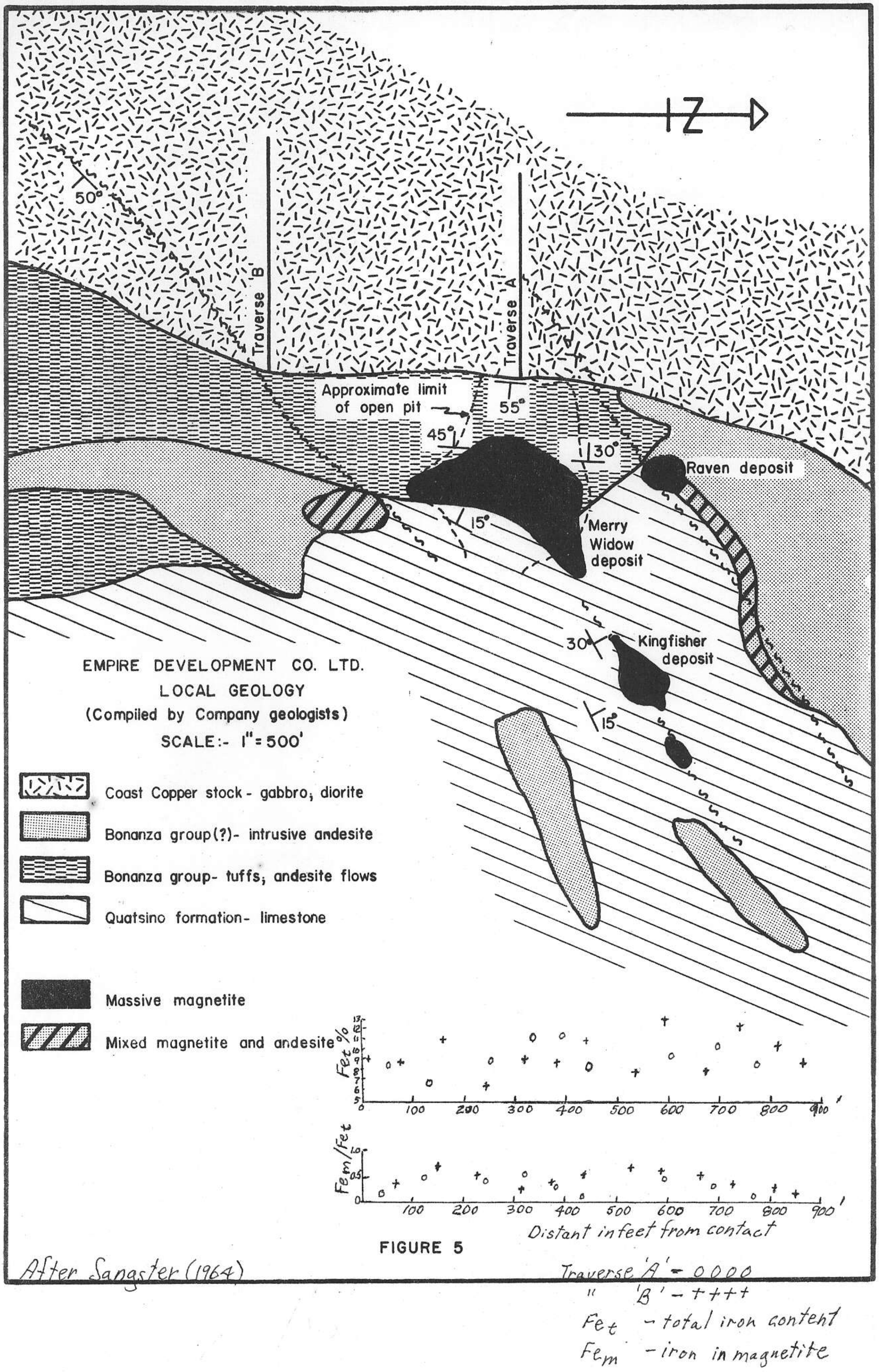


FIGURE 5

Figure 6 (after Sangster (15))

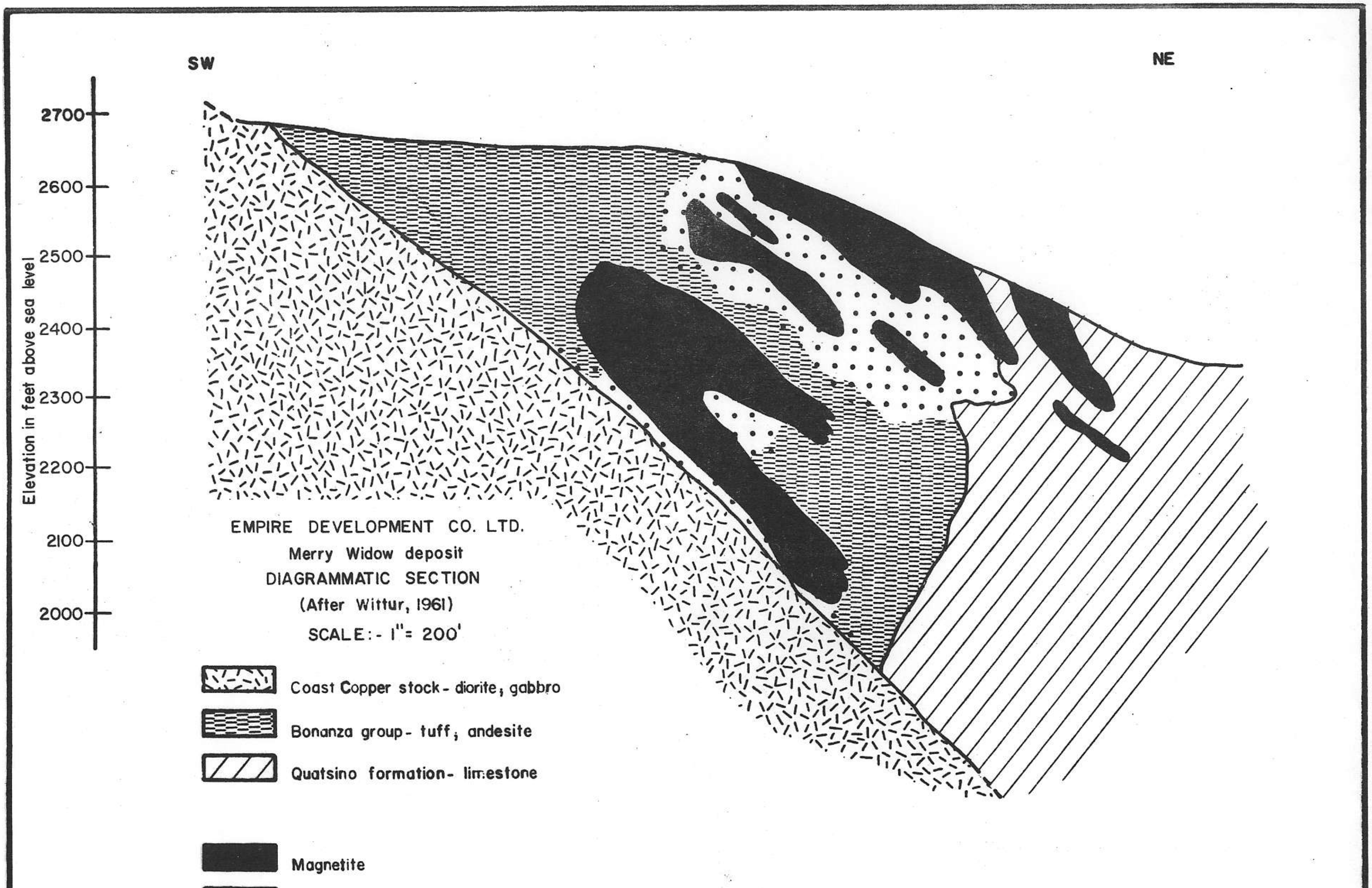


FIGURE ~~17~~ 6

Sangster (15) has studied the variation in iron content of the Coast Copper stock away from the Empire deposits (Figure 5). His statistical tests show that there is no significant trend in iron content (av. 8.5%) with distance. He has also shown that the stock magnetite (1 to 11 wt. %) is much higher in titanium than that of the adjacent orebodies. The stock magnetite was found to contain from 5.6 to 8.4% titanium; whereas the orebody magnetite was found to contain less than .0074%. Textural features indicate that the stock magnetite is late magmatic; hence the deposits probably formed under physical-chemical conditions that were quite different from the late magmatic conditions of the stock. It should be kept in mind, however, that the variation in P-T conditions could be simply a reflection of distance from the contact.

Origin of the Deposits

1. Introduction

There are many features of the deposits which should be reconciled by any hypothesis of the origin of the ores. These features are summarized as follows:

1. All deposits show a close spatial relationship to Coast Intrusions and Upper Triassic limestone.
2. The Upper Triassic limestone was a much more favorable horizon for deposition than the Permian limestone.
3. Volcanic rocks and pre-ore dikes were replaced by skarn and magnetite in preference to other intrusive rocks and limestone.
4. In general skarn development was not extensive in limestone.
5. The general paragenetic sequence was from (1) recrystallized limestone or relative unaltered volcanic or intrusive rocks, to (2) epidote and garnet skarn, to (3) magnetite, to (4) sulfides.

I would add here the striking fact that the ore bodies are mostly in rocks other than limestone. This raises some intriguing problems of source and manner of migration of quantities of Ca into the volcanics.

6. Both pre-ore and post-ore porphyry dikes and more basic (dioritic) border facies in the main intrusions seem to have been localized near the deposits.

7. Orebodies have been emplaced in grossly different tectonic environments, being associated with both mesozone, syntectonic and epizone, post-tectonic plutons.

8. Extensive zones of iron depletion have not been found in the immediate vicinity of the orebodies.

9. Many deposits occur in highly deformed re-entrants of intrusions, and pre-ore faults and breccia-pipes have been important structural controls on deposition.

10. Most of the deposits were probably emplaced well down the flanks of the intrusions; ~~while~~ only a few were emplaced in roof pendants.

11. The outer parts of the main plutons must have been solid before the skarnification and mineralization had ceased. However, these bodies were probably still near magmatic temperatures during ore deposition.

12. Most deposits are remarkably poor in hematite and quartz.

13. The stock magnetite adjacent to the Empire deposits is very much higher in titanium than that of the orebodies.

2. Source of Heat and Solutions

Sangster (15) has estimated that the temperature of intrusion was in the range of 900°-800°C and that the temperature of skarnification was in the range of 800°-450°C. From the pyrite-pyrrhotite relations, he estimated that ore deposition took place between 550°-400°C. Although his temperature indicators are of dubious value and his pyrite-pyrrhotite temperatures definitely cannot be accepted, it is reasonable to conclude that his temperature estimates are of the correct order of magnitude. Hence, the temperatures of skarn and ore formation were very much higher than those that can be accounted for by the geothermal gradient. Moreover, they were very close indeed to those of intrusion. It is reasonable, therefore, to conclude that the heat source for

I.e., for lack of concrete data! Essentially you say that his estimates are reasonable, though without any basis in fact!

ore deposition was the nearby intrusion. It also follows that the intrusions were still near magmatic temperatures while the ores were forming.

Thus we pile assumption on assumption

Holser's and Schneer's (p.375) studies of the solubility of magnetite in dilute, HCl-bearing, aqueous solutions at high temperatures and pressures have indicated that significant amounts of iron can be dissolved in acid but ~~can~~not ~~be dissolved~~ in neutral or alkaline solutions. They found also that solutions containing Na_3BO_3, $NaHCO_3$, NaCl, or NaOH cqnnot carry significant quantities of iron (p. 375). They also demonstrated that limestone can precipitate magnetite and hematite from these solutions. Their results, the ~~consideration of~~ the importance of limestone in the formation of contact metasomatic-type deposits, and the fact that no one has given a reasonable, alternate explanation of the transport and depositional processes involved, all strongly suggest that the ore-bearing solutions were originally acid in nature. This single feature tends to indicate that it was highly ~~unlikely~~ improbable that the bulk of the ore-forming fluids were derived from the country rock. The intrusions, however, would be quite plausible sources. This argument is based on the belief that aqueous solutions, long in contact with rocks, should be alkaline or neutral, except, perhaps, in near surface environments.

The logic is open to question.

Not very satisfactory, is it? If the ore bodies were all in ls., neutralization by ls. would be easier to accept. But they aren't! Perhaps the ls is only important as a source of Ca.

3. Source of Iron

When considering the source of the iron, it is useful to entertain the possibility that the ultimate and immediate sources are quite distinct. Since, both the Permian and Upper Triassic limestones have been cut by the Coast Intrusions, and only the Upper Triassic limestone contains economic iron and iron-copper deposits, it is logical to conclude that incorporation of the iron-rich Permo-Triassic basalts by the intrusions was a necessary requisite for ore formation. Although this hypothesis must remain highly speculative until more evidence is gathered, no alternate explanation seems apparent.

Both Sangster (15) and Eastwood (5) strongly favor the adjacent intrusions as the immediate source of the iron. However, their evidence is not convincing, and they have not explained how the iron was "released" from the intrusion. Eastwood (5) has pointed out that the Brynnor orebodies at Kennedy Lake are probably separated by one and one-half miles of intrusion from the Triassic basalts, which are the only other reasonable source for the iron. This relationship, however, is true only for these deposits. At other localities solutions probably migrated up contact zones; hence the writer sees no reason to believe that other rocks could not have made significant contributions to the iron content of the solutions.

From present knowledge it seems probable that the solutions were derived from the intrusions beneath the orebodies. In normal water-saturated magmas, the volatile constituents would tend to move to areas of lower temperature and pressure; that is, outwards and upwards. In the British Columbia deposits there are three features which indicate that lateral migration of solutions was insignificant in the vicinity of the orebodies:

1. Study of known conduits indicates solutions moved mainly upwards.
2. There is a noticeable lack of iron depletion zones adjacent to the deposits.
3. The late magmatic magnetite in the stock adjacent to the Empire deposits has a much higher titanium content than that of the orebodies, indicating that the conditions of formation of the two were very different.

4. Mechanisms of Deposition and Replacement

Holser and Schneer, as mentioned above, have demonstrated the possible importance of limestone in deposition of contact metasomatic magnetite. According to ~~Follow-ing~~ their hypothesis, dilute, HCl-bearing iron-bearing acidic solutions, initially, would attack and dissolve the limestone until the increase in pH ~~were~~ was sufficient to cause the precipitation of either magnetite or hematite. The fugacity of oxygen would determine which of the two oxides would form.

This simple mechanism accounts completely for the formation of the deposits in the limestone; however, it does not explain why skarn ~~is formed not why the skarn~~ and ore preferentially replaced volcanic rocks adjacent to the limestone.

Sangster (15) has given a satisfactory explanation of these relationships. The limestone provided the essential chemical control for deposition, and the volcanics provided the essential physical control. The volcanics, being much more brittle than the limestone, were more highly fractured and brecciated during deformation. These fractured and brecciated areas provided permeable zones for solution passage and extensive surface area to facilitate replacement. The skarn was simply an intermediate step in the rock transformation. However, the relationships tend also to indicate that the skarn minerals were more stable than the magnetite under the initial high temperature and low "intensity" (of iron-metasomatism) conditions.

Sounds good, but is really meaningless

The process of replacement was basically one of iron metasomatism. Iron, in a series of stages, replaced all other cations in the host rock. Without ~~benefit of~~ a detailed discussion

Actually, Rod, this mechanism is far from satisfactory, because it is only half a mechanism. One might accept, with some reservations, the mechanism of precip. of Fe by $CaCO_3$, although after reaction the iron is required to move some distance before formation of Mgt. However, what is the chemistry of replacement ~~of~~ and removal of skarn silicates?

of the crystal chemistry, this replacement can be viewed simply as an exchange of cations and the change of bonding between closely-packed and reasonably closely-packed oxygen atoms. If sufficient activation energy were available, the replacement and accompanying diffusion would simply be processes whereby there was a continuing tendency of the crystals to maintain equilibrium with the ore-bearing fluids.

5. <u>The "Deuteric Release" Hypothesis</u>

Mackin (12) and more recently Mackin and Ingerson (13) have proposed the "deuteric release" hypothesis as a general mechanism of ore deposition. An essential part of their theory requires that early-formed mafic constituents in a magma be altered by late magmatic solutions, thus freeing some of their metal ions to form ore deposits. Another essential feature of their hypothesis is that suitable structures be formed in the crystallizing magma to permit the escape of the late magmatic solutions.

Since this hypothesis seems to be well founded for the Iron Springs area, it is constructive to consider whether or not this mechanism might have been instrumental in the formation of the British Columbia deposits. Table 2 shows some of the similarities and differences of the two sets of deposits. From the available information it would seem that the differences are more numerous than the similarities.

The reasons for these differences may lie in the general nature of the intrusions. As Mackin and Ingerson have pointed out, a prime requisite for the "deuteric release" mechanism

OK as a statement of general principles but what is the precise application to the ores under discussion?

Table 2

A Comparison of Certain Features of the Iron Springs and British Columbia Deposits

Iron Springs	British Columbia
1. deposits are of second order magnitude containing greater than 100 million tons reserves	1. size of individual deposits or districts is much smaller, generally ranging from 1 to 15 million tons
2. orebodies are associated with high level Tertiary laccoliths (related ignimbrites)	2. orebodies are associated with both high and moderately deep level stocks and batholiths, probably of Jurassic age
3. deposits occur mainly near the top of the intrusions	3. deposits occur mainly along the sides of intrusions (a few in roof pendants)
4. the associated intrusions are granodiorites that originally contained a normal or slightly less than normal concentration of Fe oxides (~3.0%)	4. the associated intrusions are intermediate in composition with a slightly higher than normal concentration of Fe oxides (~8.5%)
5. ore has replaced limestone with little associated skarn	5. ore has mainly replaced volcanic rocks with extensive associated skarn - some deposits have formed in limestone with little associated skarn
6. there are large Fe depletion zones near the deposits (~20 vol. % of the rock has lost ~30 wt. % of its Fe)	6. there are no obvious extensive depletion zones near the orebodies
7. probably both lateral and upward migration of solutions were significant	7. the solutions probably moved chiefly upwards
8. sites of deposition were governed by zones of selvedged joints formed in upbulged areas of the intrusions -through-going faults released the solutions	8. there is no obvious cooling joint control on deposition; however, permeable structures in the country rock definitely influenced the sites of deposition -also deposits tended to be concentrated in highly deformed re-entrants in the intrusions
9. sulfides were concentrated near the outer parts of the ore	9. sulfides were concentrated near the outer parts of the ore
10. if, as hypothesized, the solution were endogenous to the intrusions, there was not an unlimited supply of solutions to form the ores.	10. source, amounts and concentrations of solutions remain unknown

OK

would be the presence of biotite and hornblende phenocrysts that were formed at depth. It is probable that these phenocrysts would be out of equilibrium with the late magmatic solutions in high level environments; hence it is easy to visualize how they would be altered and destroyed by these solutions. However, it is equally difficult to visualize how the mafic constituents of generally equigranular, massive intrusions of stock and even batholithic dimensions could be grossly out of equilibrium with the interstitial liquid of the semi-consolidated magmas. Mackin and Ingerson suggest that this is the general reason why orebodies are not formed by batholiths. Perhaps Sutherland Brown, Sangster, Eastwood and Jeffery are correct in assuming that the abnormally high iron content of the intrusions was fundamental in the formation of the deposits, even though their detailed mechanisms of ore deposition remain unknown.

6. Summary

In conclusion, it seems reasonably certain that both the heat (energy) and the solutions were derived from the adjacent or underlying Coast Intrusions. However, the source of the iron is somewhat more of a problem. A satisfactory mechanism for the release and transport of the iron from the intrusions has not been presented. Moreover, since Sangster suggests that most of the solutions migrated up the contact zones, it is quite conceivable that the volcanic country rocks could have contributed considerable iron to the solutions.

Even though the immediate source of the iron is somewhat in doubt, the Permo-Triassic basalts seem to be a reasonable ultimate source. Much chemical and geologic work, however, remain to be done to test this hypothesis.

Transportation of the iron in dilute, HCl-bearing, aqueous, acidic solutions, as described by Holser and Schneer, accounts for the apparent importance of ~~the~~ limestone in causing iron deposition . Volcanic rocks near the limestone were probably preferentially mineralized because they were relatively permeable to the ore-forming fluids, provided extensive surface area for replacement, and were more susceptible to replacement than ~~were~~ other rocks in the area.

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