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601 Booth St,
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Dear Rod:

It was good to hear from you again. I hadn't realized you were in the States. My thesis has been submitted to the Survey here for publication & should be in print sometime within the next two years. Such is the incredibly slow movement of government wheels. I had prepared a paper for submission to Economic Geology but found that what I ended up with was a "Reader's Digest" version of the Survey Bulletin, so decided to forego the outside publication.

I have enclosed a copy of the abstract which summarizes my findings but without giving the supporting evidence. I'll try to answer your questions in the order you presented them:

1. I have absolutely no quarrel with Peter Eastwood's ideas as far as they go. Matter of fact, reading part of his paper sounds very similar to one or two of my chapters. His main weakness, I feel, is not explaining the role of limestone.

2. The intrusions are all of intermediate composition (see enclosed diagram) and all (except one) appear post-tectonic. The exception, interestingly enough, is ~~[illegible]~~ syn-tectonic & is associated with the Tasu deposit on the Queen Charlottes (latest estimates are ~40,000,000 tons of ore)

3. Mineralization is always post-intrusion. There is plenty of evidence to indicate that the outer edge of the intrusion, at least, was xlline (i.e. solid rock) at the time of mineralization. In this respect, the B.C. deposits resemble Mackin's observations at Iron Springs.

The difference is that in B.C., the deposits are generally found just <u>outside</u> the intrusion

4. Mineralization is only locally related to joints or faults within the intrusion. There is ample evidence to indicate that faults in the <u>country rock</u> have localized ore in several deposits.

5. The intrusion, in the vicinity of the orebodies, are generally altered to varying degrees; ranging from complete replacement by magnetite to incipient kaolinization of K-spar.

6. Garnet is of the grossularite - andradite series (see diagram). Skarn development always preceded ore but there was probably some overlap near the end of the "skarn stage".

7. I searched for, but could not find, Fe-gradients near the orebody. In the Prescott deposit, I could detect mineralogical zoning (see enclosed table) & hoped chemical analyses would show some gradients but such was not the case (see diagram Fig. 15). At the Merry Widow, I analyzed the intrusion in an attempt to detect Fe-gradation but to no avail (see enclosed diagrams & table). The fact that ① the centre of zoning at the Prescott is outside the intrusion - limestone contact and the intrusion itself lies within peripheral zones and ② no Fe-gradient could be detected at the Merry Widow, ~~that~~ led me to picture the ore moving up along the intrusion - country rock contact until it hit a favourable structural - chemical environment where it deposited magnetite. i.e. movement of Fe-bearing fluids was largely <u>up</u> rather than <u>out</u>.

8. Sulphides are generally contemporaneous with or later than the oxides and are generally more abundant on the "limestone - side" of the deposit. Pyrite & chalcopyrite are the most common.

I hope these comments will be of some help to you. Let me know if I can be of further assistance.

~~The title~~

I have long been interested in geothermometry & mineral zoning and the title of your thesis intrigues me. If you are planning to have several copies run off at little expense, may I put in my bid now for a copy?

You may be interested to know that Ray Yole is teaching at Carleton U. here in Ottawa; Al Stanley has joined the Geography Branch of Mines & Tech. Surveys & is working on glaciology; Bob Patterson is chief geologist at Texada; Gord Davis is making money hand over fist with Dynasty in the Yukon.

All is well here. Eleanor & I just had our 3rd child in Nov. so nobody is really standing still.

Best wishes,

Don.

P.S. I've also included a lot of extra diagrams, etc. which you may or may not want to use. I'd ~~send~~ loan you a copy of the thesis but it's out on loan elsewhere at the moment.

Abstract

Ore zones, skarn, host rocks, and associated intrusions of twelve magnetite deposits were studied in both field and laboratory to determine their mineralogical and geochemical characteristics, origin of the iron, and factors controlling emplacement of iron-bearing minerals.

Skarn in the coastal British Columbia region is composed mainly of garnet (andradite-grossularite), pyroxene (diopside-hedenbergite), epidote, and magnetite. Conformity to the Mineralogical Phase Rule is strong evidence that equilibrium was attained during skarnification. Magnetite is the major metallic mineral but chalcopyrite, pyrite, pyrrhotite, and arsenopyrite are locally abundant.

The temperature of intrusion is estimated to be in the range 900-800°C and stability relations of coexisting minerals indicate a temperature range of 800-450°C during skarnification. The pyrite-pyrrhotite geothermometer applied to eight specimens shows that ore deposition took place within the temperature range 550-400°C. The composition of arsenopyrite coexisting with pyrite and pyrrhotite in one orebody indicates a confining pressure of 2600 ± 1000 bars during ore formation.

A majority of deposits have replaced volcanic rocks near a contact with limestone. Several orebodies have formed entirely in limestone or, rarely, in an adjacent intrusion. Stocks adjacent to the magnetite deposits are generally of intermediate composition but range from gabbro to quartz monzonite. Local folds and faults are important physical ore controls; the presence of limestone is a major chemical control.

The immediate source of iron in these deposits is believed to be nearby intrusions. The ultimate source, however, is very probably underlying volcanic rocks which have been assimilated, in part, by an advancing pluton. Iron is considered to have been derived from plutons

adjacent to the orebodies and to have been carried to the sites of deposition as aqueous supercritical solutions of iron chloride. Magnetite was precipitated from the ore-forming fluid by an increase in pH brought about by reaction with limestone.

Changes in the chemical and physical nature of the ore-forming fluid during ore deposition are discussed in terms of temperature, density, pH, partial pressures of oxygen and sulphur, and composition. Hydrothermal processes operative in formation of the deposits were solvate apposition, metasomatism, and cavity filling.

The author proposes that the process by which skarn is formed be called skarnification i.e. the replacement by, conversion into, or introduction of skarn. The term would include all processes by which skarn may be formed such as contact metamorphism, contact metasomatism, or regional metamorphism.

constituent of epidote, water must be counted as an independent component. No carbonate minerals were formed during skarnification, indicating that CO_2 remained volatile during this process. Neither is there evidence indicating that perfectly mobile components (Thompson, 1955) were present during skarnification.

Therefore, a total of seven independent components ---- SiO_2, CaO, (Fe,Mn)O, MgO, Fe_2O_3, Al_2O_3, and H_2O ---- are the major constituents of skarn in this study. Seven components and four phases satisfy the Mineralogical Phase Rule and supports the theory that chemical equilibrium was at least approached during skarnification.

Fulfillment of the above criteria indicates only that equilibrium could have been obtained during metasomatism but does not prove that equilibrium did, in fact, prevail. Further tests, such as the distribution of trace elements among coexisting skarn minerals (Kretz, 1960), are required to show that equilibrium was attained during skarnification.

SUMMARY

The magnetite orebodies were formed adjacent to plutons of intermediate composition in response to chemical and physical changes in the ore-forming fluid caused in part by a decrease in temperature. The immediate source of the iron in contact metasomatic deposits is a nearby intrusion. The ultimate source, however, is very probably the Karmutsen volcanic rocks which, in part, have been assimilated by an advancing pluton. The ore fluid that originated in a nearby intrusion as a dilute aqueous supercritical solution consisted mainly of iron chlorides with lesser amounts of silica, magnesium, and aluminum. The initial temperature of the solutions approximated that of the intrusion (800-900°C). Movement to the sites of deposition was either along the intrusion-country rock contact, resulting in deposits immediately adjacent to the stock, or along faults, resulting in deposits several

hundred feet from the intrusive contact. Some orebodies may also have been formed by solutions migrating outward from the intrusion along a contact between limestone and volcanic rocks.

Skarnification, which probably took place in the temperature range 800-430°C, generally preceded the main stage of magnetite deposition. Conformity to the Mineralogical Phase Rule is strong evidence that equilibrium was attained during skarnification. Neutralization of iron chloride solutions by calcite resulted in precipitation of magnetite in the temperature range 600-500°C. Ore fluids, originally one phase, probably developed into a two-phase system at lower temperatures. These fluids increased in pH by reaction with calcite until they reached at least 7.8, the minimum stability pH of calcite. Magnetite first filled cavities in skarn and brecciated volcanic rocks; then diffusion into, and replacement of, volcanic rocks took place. Where the volume of host rock dissolved exceeded the volume of metasome deposited, cavities were formed, some of which were later filled by magnetite or by post-ore calcite and/or quartz.

The most favourable sites of deposition were along contacts between limestone and volcanic rock, particularly where local folding had brecciated the more brittle igneous rocks. Brecciated volcanic rock, relatively more permeable to ore-forming fluids and having a relatively large surface area, was a particularly favourable site of ore deposition.

REFERENCES AND SELECTED BIBLIOGRAPHY

Allen, V.T. and Fahey, J.J.
1952: New occurrences of minerals at Iron Mountain, Missouri - Amer. Min., vol. 37, pp. 736-743.

1957: Some pyroxenes associated with pyrometasomatic zinc deposits in Mexico and New Mexico - Bull. Geol. Soc. Amer., vol. 68, pp. 881-896.

Contact effects in the country rock are most striking where metasomatic deposits have formed; endomorphism of the pluton is not as noticeable.

A detailed study of the distribution of certain elements was made in the margins of the Coast Copper gabbro-diorite stock adjacent to the Empire Development Company deposits. This stock was selected because the contact is locally well exposed, outcrops are plentiful, and the rock appears fresh in hand specimen. Five-pounds of chip samples were collected at each of 22 stations at approximately 100 foot intervals along two lines. These lines began at or near the contact of Coast Copper gabbro and Bonanza Group volcanic rocks and extended roughly perpendicular to this contact for several hundred feet toward the interior of the intrusion. Nine samples were collected along Traverse "A" adjacent to the Merry Widow deposit; 13 samples were collected along Traverse 'B' which was parallel to 'A' but 1,000 feet farther south and remote from any known mineralized zone. The relations are shown in Figure 5. The samples were analyzed spectrographically for the ferride elements (Mn, V, Ti, Ni, Co, Cr, Fe) and for copper. Weight per cent magnetite in each sample was also determined and the results recalculated to weight per cent iron. Thus a clear distinction was made between total iron (Fe_t) and iron in magnetite (Fe_m). Results of these analyses are given in Table 6.

Values for Ti, Ni, and Cr are too inconsistent to attempt to correlate with distance from the contact. The method of least squares was used to fit a straight line to values for V, Mn, Co, Fe_m and Cu. In both traverses the correlation coefficient for these elements was less than 0.5, indicating that there is no systematic change in the concentrations of these elements away from the contact. In fitting a straight line curve ($y = a - bx$) to values of total iron (Fe_t), however, a correlation coefficient of 0.84 was obtained in Traverse 'A' and 0.67 in Traverse 'B' (Fig. 6). The intercept in both traverses is 8.5% Fe_t

but the slopes of the lines are small: 0.0017 in 'A' and 0.0021 in 'B'. A statistical test (Student's "t" distribution) showed that such slopes are not significantly different from zero and therefore the average value of Fe_t does not vary significantly from 8.5% for distances up to 800 feet from the intrusive contact. This indicates that the iron contained in the stock was not depleted toward the margins as might be expected if it had supplied the iron. In addition, there is no significant difference in iron content of the stock adjacent to the Merry Widow deposit (Traverse 'A') as compared to a place remote from the iron deposit (Traverse 'B'), and this further suggests that magnetite of the stock is genetically unrelated to magnetite of adjacent orebodies.

what about density changes

Magnetite constitutes between 1 and 11 weight per cent of the Coast Copper gabbro in this area. It replaces augite, the only other major iron-bearing mineral. Without further evidence there is no way of knowing whether such magnetite formed as a late magmatic mineral from the melt which produced the gabbro or whether it has replaced pyroxene as a result of a later period of iron metasomatism, such as that which formed the nearby Merry Widow and Kingfisher magnetite deposits. Magnetite in four samples from the gabbro has a titanium content ranging from 5.6 to 8.4%. In contrast, one sample from the Kingfisher deposit contains no titanium and magnetite from another small deposit in the area analyzed 0.0074% Ti. The contrast in titanium content of accessory and ore magnetite suggests different conditions of formation. Buddington et al. (1955) showed that Ti-rich magnetites are characteristic of rocks formed directly from a melt at high temperature and that, in such cases, magnetite formed as a primary differentiate. Pegmatites, on the other hand, were shown by the same authors to carry Ti-poor magnetite. It is possible, therefore, that magnetite in the Coast Copper gabbro was produced as a late magmatic mineral and magnetite in the orebodies as a hydrothermal mineral.

Table 6

Spectrographic analyses of gabbro in Traverses 'A' and 'B',

Coast Copper stock. (Analyst, W.F. White, Geol. Survey, Canada)

Dist. from contact (feet)	Sample number	% Mn	% V	% Ti*	% Ni	% Co	% Cr	% Fe_t	% Fe_m	% Cu
	Traverse 'A'									
55	1	0.12	0.042	1.6	NF	0.0043	0.0049	8.4	1.6	0.0064
140	2	0.11	0.037	0.99	"	0.0035	<0.003	6.7	3.2	NF
255	3	0.11	0.086	>2.0	"	0.0058	NF	8.8	3.8	0.022
340	4	0.16	0.092	>2.0	"	0.0072	"	11.1	5.9	0.015
395	5	0.17	0.068	>2.0	"	NF	"	11.2	3.9	0.0069
450	6	0.13	0.067	>2.0	"	0.0037	"	8.3	1.0	0.002
610	7	0.15	0.044	>2.0	"	0.0051	"	9.2	4.4	0.0050
700	8	0.19	0.030	>2.0	"	0.0046	"	10.4	3.6	0.0059
780	9	0.20	0.016	>2.0	"	NF	"	8.5	1.5	0.0058
	Traverse 'B'									
15	1	0.17	0.048	1.8	NF	0.0050	<0.003	9.0	3.7	0.0050
80	2	0.15	0.043	1.7	"	NF	NF	8.8	3.1	0.0039
160	3	0.15	0.074	>2.0	"	0.0068	0.0074	10.8	7.2	0.016
250	4	0.098	0.041	1.0	"	0.0053	<0.003	6.4	3.3	NF
325	5	0.12	0.049	>2.0	"	0.0069	0.0071	9.0	2.0	0.010
390	6	0.15	0.058	1.5	"	0.0049	0.0031	8.7	3.5	0.0029
440	7	0.17	0.072	>2.0	0.013	NF	NF	10.8	5.7	0.0096
540	8	0.15	0.067	1.9	NF	0.0057	"	7.6	4.6	0.0033
600	9	0.20	0.084	2.0	"	0.0061	"	12.7	8.3	0.013
680	10	0.11	0.050	1.4	"	0.0036	"	7.6	4.0	NF
740	11	0.20	0.063	>2.0	"	0.0039	"	12.2	4.7	0.013
820	12	0.17	0.033	>2.0	"	<0.002	"	10.2	3.2	0.0042
870	13	0.20	0.040	1.6	"	0.0065	"	8.5	1.8	0.0037

* Values for Ti are semi-quantitative only. Upper limit of method approximately 2%.

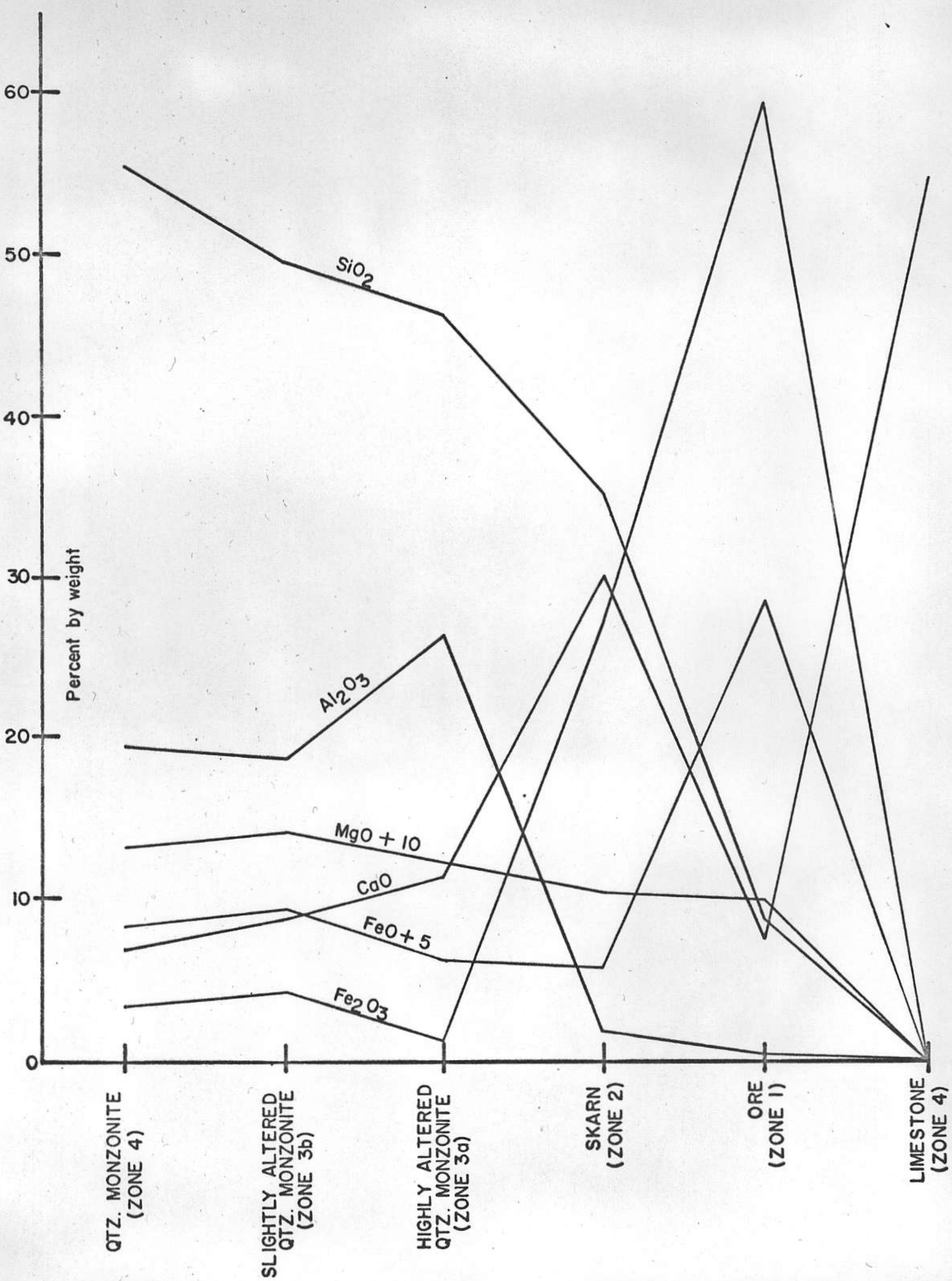

FIGURE 15

Prescott Mine, Texada Island. Diagram showing chemical changes across a contact between quartz monzonite and limestone. Zones correspond to those described in text, Table 12. Composition of ore zone was calculated on the basis of 75% magnetite, 25% skarn.

Zone 4 - Unaltered Zone

This is the outermost zone and is characterized by relatively unaltered country rock, either quartz monzonite or limestone. In quartz monzonite, plagioclase is slightly less calcic (An_{47}) than in adjacent subzone 3(c). Unaltered orthoclase makes its first appearance and quartz is much more abundant. Alteration is confined to slight chloritization of mafic minerals; chlorite is absent from subzone 3(c). Limestone is almost everywhere recrystallized in this zone but is otherwise unchanged.

These zones are summarized below:

Table 12

Prescott mine, Texada Island. General characteristics of zones developed within and around the orebody

Zone 1 - Ore Zone

magnetite; magnetite-rich skarn; sulphides.

Zone 2 - Skarn Zone

Subzone (a) garnet-rich skarn

Subzone (b) epidote (or actinolite) first appears;
sulphides increase locally toward limestone

Zone 3 - Alteration Zone

1. In granitic rock

Subzone (a) garnet-epidote skarn

Subzone (b) epidote-rich skarn; no garnet; granitic texture; plagioclase (or pseudomorphs) visible.

Subzone (b) appearance of quartz; rock is recognizable as an altered intrusion.

2. In limestone

Patchy development of skarn, pyrite, jasper.

Zone 4 - Unaltered Zone

Fresh quartz monzonite or recrystallized limestone.