A Contribution to the Knowledge of the Contact-Metamorphic Ore Deposits.

By

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Recently, the present writer has published the results1 of his investigation on the ore-deposits in the environs of Hanana-yama in the Oda mining district, Nagato Province, and intended to deduce conclusions as to some vital questions confronting the students of contact-metamorphic deposits at the present time. The present paper includes those conclusions drawn from the discussions and descriptions of the contact metamorphic deposits in the Oda district, many other conspicuous deposits of similar character in this country being repeatedly referred to.

The following three subjects are here treated: (1) Origin of the lime-silicates and ore-minerals in contact deposits. (2) Progressive change in the composition of metamorphosing solutions. (3) Duration of the mineralization in contact deposits.

1) Origin of the lime-silicates and ore-minerals in contact metamorphic deposits.

The origin of the lime-silicates and ore minerals in contact metamorphic deposits which mainly occur in limestone close to intrusive contacts has been long and repeatedly controverted.2 The introduc-

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2) There are too many papers on this subject to be exhaustively mentioned. The following may be regarded as representative:


tion of the sulphide and oxide ores into the limestone by the magma is, however, too obvious to be disputed, though some hold that the silicate gangue minerals are mainly the result of a recrystallization of constituents originally contained in the limestone.

The present writer has expressed his belief again and again in his papers on the Ofuku deposits and those in the environs of Ōda, that iron, silica, various rarer metals, mineralizers etc., i.e., the greater part of the elements composing the lime-silicate minerals and the entirety of ore-minerals of the contact metamorphic deposits


1) Leith, Uglow and others, opt. cit.


3) Loc. cit.
have been derived from the emanations from the magma. This is the view advocated for years by Kemp, Spurr, Vogt, Lindgren, Goldschmidt, Stutzer and many others.

The writer’s belief is chiefly based on his field observations and microscopic study, the most convincing field evidence being the presence of veinlets of the lime-silicate minerals ramified from the main deposits and cutting irregularly through the surrounding recrystallized saccharoidal limestone.

Fig. 1. Ideal section through the Umegakubo deposit.

L = Limestone.  
\( a = \) Oxidized ore, consisting of limonite and more or less oxidized copper ores and magnetite.  
\( b = \) Wollastonite and garnet (fresh), with sulphides.  
Cu content = 3% or less.  
Black portion = Partially oxidized ore, consisting of chrysocolla, malachite (rare), azurite (rare), chalcopyrite, bornite, tetrahedrite, magnetite, garnet and wollastonite.  
Cu 3%, Ca 20%, Fe 18%, SiO₂ 50%.

The contact metamorphic deposit of Umegakubo⁴ (Fig. 1) is entirely enclosed in limestone at a distance of about 300 meters from the contact with the granite-porphyry where the Mizudamari deposit lies. Between the two deposits numerous veinlets of wollastonite have been found in the saccharoidal limestone. These wollastonite veinlets (Pl. III, Fig. 4) represent probably communicating between the two deposits.

Garnet and hedenbergite veinlets, branching from the main deposit and cutting through the white crystalline limestone, have

⁴) Ōda District, loc. cit., p. 66.
frequently been noticed in the Yoboshi deposit. (See page 26(8)).

The Kitabira deposit (Fig. 2) is a large pipe-shaped mass of bedenbergite, garnet, ilvaite and others associated with various sulphide ore minerals, and is enclosed entirely in more or less recrystallized white limestone.

Fig. 2. Section through the Kitabira deposit.

L = Limestone. O = Oxidized ore = chiefly limonite.
P = Unaltered ore. I = Inclined shaft. S = Shaft.

The formation of these contact metamorphic deposits with the form of irregular masses and pipes, embraced in saccharoidal limestones somewhat away from the contacts with the intrusives, and of those veins consisting of wollastonite, garnet and other lime-silicates can not be explained by the assumption of recrystallization of impure limestones. It is most satisfactorily explained only by assuming that highly-heated solutions, charged with silica, iron and other metals and mineralizers, and expelled from the consolidating magma, travelled through fissures and cracks in recrystallized limestone, and resulted in those deposits and veinlets by a process of metasomatism at places where conditions were favourable.

Such veinlets of lime-silicates are not rare in contact deposits in other districts. The present writer has collected a fair number of specimens showing veinlets of wollastonite, garnet etc. cutting

1) E. Weinschenk: Grundzüge der Gesteinskunde, I, 1906, S. 134; "A similar narrow zone of reticulated garnet veins" was observed by W. Lindgren in the contact-metamorphic iron deposits at Encarnacion, State of Hidalgo, Mexico. (W. Lindgren: Mineral Deposits, 1913, p. 677).
through saccharoidal limestone, from numerous similar contact deposits in this country. A few remarkable examples are given below.

Pl. II, Fig. 2 is a specimen from the Yoshiwara mine, Prov. Buzen, Kyūshiu. The deposit of this mine is a rudely tabular one of contact metamorphic origin. It lies between a recrystallized saccharoidal limestone and a dark-green hornfels (metamorphosed slate), and is composed mainly of garnet associated with more or less epidote, wollastonite and other minor lime-silicates, mingled with abundant pyrite (crystallized in $\infty O\infty$ and $\infty O\infty O$), chalcopyrite, a little stibnite etc. The ore-bringer is a granitic rock exposed somewhat remote from the deposit. Numerous veins and veinlets of garnet, admixed with more or less sulphides, branch from the main ore-body and cut through the foot-wall limestone in a complicated manner.

Pl. II, Fig. 1 shows a specimen of a wollastonite vein penetrating a recrystallized saccharoidal limestone, collected at a contact deposit in the Sanno-také district, Prov. Buzen, Kyūshiu. Such veins are abundant in this district.

Garnet veins, often following bedding planes of limestone, ramifi-

![Diagram](image)

**Fig. 3.** Diagrammatic sketch of the Jishaku-yama deposit.

L = Limestone. G = Garnet-skarn associated with more or less epidote, wollastonite, pyrrhotite, magnetite, pyrite, chalcopyrite, etc.
ed from a large irregular mass of garnet in association with epidote, wollastonite, pyrrhotite, chalcopyrite, magnetite and others, are observed on a large scale at Jishaku-yama in the Sanno-také district, as shown by the diagrammatic sketch Fig. 3.

At the Asahi mine, Prov. Buzen, an irregular large mass of garnet admixed with small quantities of epidote, calcite and quartz; in association with pyrite, chalcopyrite and magnetite, is entirely enclosed in a dark-green hornfels (metamorphosed slate) somewhat apart from the contact with a granitic rock.

The writer has been much interested to learn from the studies of the Mackay copper deposits,\(^1\) Idaho, U. S. A., by Kemp and Umpleby, that "the garnetiferous copper deposits occur well within a granite-prophyry mass......In many places stringers of garnet-diopside-chalcopyrite rock have been followed out along joints 10 to 20 or even 100 feet into the granite-porphyry. In places, at the intersection of cross joints these open out into bunches of ore of minable size."

The last-mentioned two examples, among others, show that the garnetiferous deposits occur in rocks other than limestone in the form of irregular masses and veins. These are not decidedly cases of recrystallized impurities in limestone. They were formed by highly heated magmatic solutions charged with iron, sulphur, silica, copper, lime and others, ascending through fissures and cracks in the surrounding sedimentary rocks, as well as the upper crust of the consolidating magma. It is proved by microscopic study that metasomatism played at least a part in the formation of the deposits. The lime in the solutions was largely absorbed from the neighboring limestone.

\(^1\) J. F. Kemp and C. G. Gunther; loc. cit.
2) Progressive change in the composition of metamorphosing solutions.

J. E. Spurr, G. H. Garrey and C. N. Fenner\(^1\) were driven to the conclusion, on their study of the contact metamorphic deposit of the Dolores mine, at Matehuala, Mexico that the composition of the metamorphosing solutions changed in the order: (A) alumina-silica-lime, (B) silica-lime, (C) silica-lime-iron and other metals, (D) lime. Eliminating the lime which is thought to have been absorbed from the limestone, the composition of the solutions derived from the magma is (A) alumina-silica, (B) silica, (C) silica-iron and other metals, each stage being represented by the corresponding minerals deposited metasomatically. The established sequence of mineral depositions is as follows:—(1) Pale green, rarely white aluminous pyroxene, (2) pale reddish aluminous garnet (grossularite) and vesuvianite, (3) wollastonite, (4) dark green lime-iron pyroxene (hedenbergite), (5) yellow-brown, and dark green lime-iron garnet (andradite), (6) fluorite, quartz and metallic sulphides (and actinolitic hornblende), (7) metallic sulphides (and quartz and fluorite), (8) calcite.

On the other hand, the present writer, after studying the contact metamorphic deposits of the Ofuku mine, Prov. Nagato, Japan,\(^2\) arrived at the conclusion that the metamorphosing solutions were, in the first stage of mineralization (stage of wollastonitization), very siliceous (rich in silica and absorbed lime); in the second stage (stage of garnetization) they changed to rather basic ones, rich in iron and silica (with a little alumina and absorbed lime) and charged with the constituents of sulphide ores; and finally, in the last stage, the nature of the solutions became exceedingly basic, abundantly charged with the constituents of chalcopyrite, together with only subordinate amounts of silica and iron.

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1) J. E. Spurr, G. H. Garrey, and C. N. Fenner, loc. cit.
2) T. Katō, loc. cit.
In my recent paper,\(^1\) progressive change in the composition of metamorphosing solutions in some deposits in the Ōda mining district, particularly in the Yoboshi deposit, has been fully discussed. In the Yoboshi deposit, four stages of mineralization have been settled; namely, (1) stage of wollastonitization, (2) stage of the formation of the principal skarns or the main deposit consisting of hedenbergite, andradite, chalcopyrite and other important minerals,\(^2\) (3) stage of cobaltite-quartz vein formation (Pl. I, Fig. 3), (4) stage of the deposition of chalcopyrite veinlets (Pl. I, Fig. 1), occasional occurrence of hard clayey masses, containing abundant nodules of chalcopyrite in association with calcite and quartz, representing a product toward the end of this final stage of mineralization. The metamorphosing solutions in this case were thus very siliceous at the beginning of mineralization, but changed gradually to rather basic ones, charged with much iron and other rarer metals as well as silica. The deposit was formed mainly in this second stage. It is very characteristic that after the formation of the main deposit, the metamorphosing solutions changed again to very acidic ones for a while, and later, in the final stage, again became much charged with the constituents of chalcopyrite.

The stage of wollastonite deposition, succeeded by garnetization or by the stage of the formation of hedenbergite-andradite skarn usually associated with sulphide and oxide ores, has been recognized in some other deposits in the Ōda district, e.g., in Umegakubo, Ōgiri and Hanamoyama deposits.

All above conclusions are based upon field observations and microscopic examination, each of these stages of mineral deposition being represented by veins and veinlets penetrating the products of the preceding stages, with accompanied corrosion and replacement

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2) See PL. III, Figs. 1 and 2. Those are photomicrographs of hedenbergite skarn mixed with scheelite, fluor spar, residual calcite etc., showing paragenetic relations of those minerals. See, also, Pl. I, Fig. 2.
of the latter along the boundaries.

It has so far been noticed that the progression of changes of the metamorphosing solutions is not quite the same in all instances. But, as a rule, the first solutions expelled from a consolidating acidic magma seem to be siliceous, being commonly represented by wollastonite, wollastonite-diopside\(^1\) etc. The solutions show a tendency to change to basic ones, rich in iron, copper and other metals, in addition to a tolerable amount of silica, and are represented by such minerals as hedenbergite, andradite\(^3\) and others, with more or less sulphide and oxide ores. Towards the end of mineralization, the solutions contain much iron, copper and sulphur with very small amounts of silica and others, being represented by veins and veinlets of metallic sulphides in association with a little quartz etc. 

*In other words, the deposition of the lime-silicates containing little or no iron precedes the formation of those skarn minerals rich in iron. Sulphides and oxide-ores are formed contemporaneously with the andradite and hedenbergite, or at the closing epoch of their deposition, veins and veinlets of chalcopyrite and other sulphides often forming the final manifestation of metallization.*

3) *Duration of the mineralization in contact metamorphic deposits.*

The creation of skarn-forming minerals such as hedenbergite, garnet, wollastonite and others at or near the limestone-intrusive

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1) The wollastonite stage was preceded by the diopside and grossularite stages at the Dolores mine (Spurr and others, loc. cit.).

Wollastonite mass is often commingled with pale green diopside, as in the case of the Umegakubo deposit, the latter being always of earlier crystallization than the former (PL. II, Fig. 3; PL. III, Fig. 3).


At the Yoshiwara mine, Prov. Buzen, the wollastonite mass is the oldest lime-silicate, and is penetrated by garnet veinlets containing more or less sulphide ores, the latter being, in turn, sometimes cut by massive chalcopyrite veinlets. The same paragenesis has often been observed in many contact deposits in this country.
contacts is, as already stated, generally believed to be due to a process of metasomatism by emanations or highly heated solutions expelled from the magma.

Fig. 4. Ideal profile through the Yoboshi deposit.

Y=Yoboshi mine. A=Adit. M=Mizudamari basin.

In most contact deposits, investigated by the writer, garnet-hedenbergite-wollastonite skarns have not been found in the eruptive rocks with which they are genetically connected. Some of the deposits lie at the immediate contacts between limestones and igneous rocks, as those at the Yoboshi (Fig. 4), Mizudamari, Ōgiri and Hakujiki pits in the Ōda district, and many deposits in the Zōmeiki district, Prov. Nagato; some are enclosed entirely in limestone somewhat apart from intrusive contacts, as in the Umegakubo deposit (Fig. 1) in the Ōda district, and the Sasagatani deposit in the province of Iwami; some are spreading along bedding planes between slate and limestone, more or less apart from eruptive contacts, as in the Naganobori deposit in the Ōda district, and the Yoshiwara deposit in the province of Bizen and the main deposit of the Yakuki mine\(^1\) in the province of Iwaki; some are represented by

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1) The main deposit of the Yakuki copper mine, consisting of garnet, hedenbergite and other lime-silicates with associated ore-minerals, is found in limestone as well as along the bedding plane between limestone and metamorphosed slate.
metasomatically metamorphosed limestone lenses intercalated in other sedimentary rocks also somewhat remote from igneous contacts, as in the Ofuku deposits in the province of Nagato; while a few others are found in metamorphosed slate as in the deposit of the Asahi mine, Prov. Buzen. In the examples above enumerated, the deposits are commonly irregularly massive or rudely tabular in form, and often branch intricately into the surrounding rocks, particularly into limestone. But the boundaries between the skarn-masses and the eruptive rocks, when these are in contact, are generally sharply defined, no veinlets of skarn-minerals being recognized in the eruptives. These facts indicate that the formation of the main deposits or the chief skarn masses had, in these cases, terminated before the outer part of the magmas in the form of stocks or dykes consolidated sufficiently for the development of joints.

On the other hand, cases of contact metamorphic deposits formed after the solidification and jointing of the outer part of the batholiths have been repeatedly reported. For instance, in the Mackay copper deposits, according to J. B. Umpleby,1) "the principal metamorphism is later than the solidification of the porphyry enclosing the ore-shoots. The garnetization took place after the consolidation of at least the outer few hundred feet of the magma instead of while it was still viscous." In the case of the Dolores mine, according to J. E. Spurr and others,2) "numberless observations show that the metamorphosing solutions have penetrated the monzonite along fractures, and have metamorphosed the adjacent rock. . . . . . . . These pale-greenish bands, in many of which the nature of the original rock is still discernible, as for example, in the survival of the unreplaced quartzes, have an anastomosing vein-like form in the early stages, with monzonite between showing even its dark minerals

intact, in the later stages the rock is entirely replaced, and with difficulty recognizable."

It is evident, therefore, that the skarn formation in contact metamorphic deposits begins at the moment of magmatic irruption, and sometimes continues till the igneous rock at least partly consolidates.

The heat at the limestone-igneous contacts in the stages of the formation of the principal skarns must have been very high, far above the critical points of water and many haloids of heavy metals, and the magmatic emanations to which the formation of the deposits is due, consist of gases, water vapour and volatile compounds in which the metals are probably contained as chlorides or fluorides, thus forming "solutions in aqueous gas." The emanations may sometimes, when the consolidation of magmas has proceeded and the temperature has fallen gradually, be represented by superheated aqueous solutions or by solutions in a state of aqueo-igneous fusion carrying with them certain constituents of the magmas, such as silica, some heavy metals, alkaline metals and others; these magmatic extracts containing till much gaseous matters may act in a like manner as gaseous emanations on limestone and other rocks metasomatically, and result in wollastonite, garnet, hedenbergite and other lime-silicates and some ore-minerals. These minerals are, therefore, products of pneumatolytic and pneuma-lytogenetic stages.

As the intrusive magma has entirely consolidated, and the temperature has fallen to a limit, hydrothermal stages follow. The sericitization of the granite-porphyrty adjacent to the ore-deposits at the Mizudamari and Ōgiri mines in the Ōda district, and the chloritization accompanying pyritization in the same rock at Ōgiri, are, as discussed in my recent paper 1), evidently hydrothermal alterations. The hydrothermal stages in the mineralization of contact deposits are characterized by the lack of the lime-silicate minerals.

But the occurrence of veins and veinlets of sulphides and of ore-masses containing sulphides, quartz, calcite etc. sometimes in association with clayey matter, makes the deposits very valuable.

In general, it may be concluded that the mineralization in contact metamorphic deposits begins at the moment of magmatic intrusion, and continues till the entire mass of the intrusive solidifies. The formation of the main deposits, or of the principal skarns with contemporaneous sulphide- and oxide-ores, however, is confined to the early stages of mineralization, viz., pneumatolytic and pneumatohydrotogenic stages. In the subsequent stages, take place the hydrothermal alterations of the country rock and deposition of sulphide ores in association with quartz, calcite and others, but with no accompanying lime-silicates.

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Explanation of Pl. I.

Fig. 1. Specimen of hedenbergite skarn ore from the Yoboshi deposit in the Ōda district. 1/3 natural size.

The hedenbergite (H) occurs in radial and confused aggregates of prismatic crystals, with more or less chalcopyrite of the same period, the latter filling the interstices of the former. The hedenbergite is well crystallized against the residual calcite (C). Boundary between limestone (L) and the hedenbergite is sharply defined. The skarn as well as the surrounding limestone is penetrated by a vein of massive chalcopyrite (Ch), which manifests the last stage of metallization.

Fig. 2. Specimen of saccharoidal limestone adjacent to the Yoboshi deposit, penetrated by netted veins and veinlets.
consisting of hedenbergite, garnet and chalcopyrite. § natural size.

The veins and veinlets are developed along joints of the limestone, the more extensive ones (V) showing evidently metasomatic enlargement.

Fig. 3. Specimen of cobaltite ore from the Yoboshi deposit. § natural size.

Hedenbergite skarn (H) is impregnated with more or less cobaltite, and is penetrated by veins (QC) consisting of quartz and cobaltite. The formation of the quartz-cobaltite veins is decidedly later than the deposition of hedenbergite.

**Explanation of Pl. II.**

Fig. 1. Specimen of wollastonite vein (W) containing anhedral crystals of garnet (seen as black spots in the photograph), cutting through coarse granular limestone (L). Loc. Sanno-take, Prov. Buzen. § natural size.

Fig. 2. Garnet veinlets ramified from the main deposit of the Yoshibara mine, Prov. Buzen. They cut through saccharoidal limestone (L). § natural size.

Fig. 3. Specimen of wollastonite-diopside skarn, showing an orbicular structure. From the Umegakubo deposit in the Ōda district. About § natural size. The white ground is wollastonite (W). Dark bands and minute spots are diopside (D). Darker bands associated with the diopside bands consist of sulphides and magnetite (S). Note that the diopside spots are suspended in the wollastonite; on the left-hand side of the specimen a diopside band is torn and re-cemented by wollastonite. At the same place a sulphide-magnetite band terminates abruptly in the wollastonite. Microscopic and macroscopic examinations
show that the rhythmical structure is only apparent. Compare with the photomicrograph (Pl. III, Fig. 3) of the same specimen.

**Explanation of Pl. III.**

(Figs. 1, 2, 3 are photomicrographs)

**Fig. 1.** Hedenbergite skarn from the Ōgiri deposit, showing mode of occurrence of fluorspar (F) in residual calcite (C). H = hedenbergite. Polarizer only used. Magnified 50 diameters.

**Fig. 2.** Hedenbergite skarn with scheelite crystal (S). Polarizer only used. Magnified 50 diameters.

Scheelite is always of earliest crystallization, hedenbergite being hindered by it from full development. H = section of hedenbergite || c. H' = basal section of the same mineral.

**Fig. 3.** Wollastonite-diopside skarn from the Umegakubo deposit. Polarizer only used. Magnified 50 diameters.

This shows part of the orbicular skarn rich in diopside crystals (D). The interstices of the diopside crystals are filled with wollastonite fibres (W), and the interstices between the fibres of the latter are in turn filled with sulphides and magnetite (S). Sulphides occur also as streaks and veinlets (Sv).

**Fig. 4.** Specimen of wollastonite veinlet (W) penetrating saccharoidal limestone (L). ¾ natural size.

This was collected at a place about midway between the Mizudamari and Umegakubo deposits. Such veinlets are frequently found in limestone adjacent to the Mizudamari deposits, and represent probably communicating channels between the two deposits.