Mineralization in the Contact Metamorphic Ore-Deposits of the Ofuku Mine, Prov. Nagato, Japan.

by

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(I) Introductory Remarks :—

The Sanjō mine⁽¹⁾ near the village of Ofuku, formerly called Ofuku mine and once famous for the occurrence of beautiful crystals of scheelite, cuproscheelite, and many other contact minerals and oxidized ores, had long been out of work. Recently, however, new deposits have been found not very far from the same mine, and are now prosperously being worked.

This mine is known as Ofuku mine. It is a very small copper mine,⁽²⁾ but the ore-deposits worked there are fairly interesting geologically. The deposits belong to the contact metamorphic deposit, formed in sedimentary rocks at a small distance from the contact with an eruptive rock. They are accompanied by typical contact minerals which were deposited metasomatically from the metamorphosing solutions⁽³⁾ originated from the consolidating magma. The nature of the solutions has changed gradationally,

(1) N. Fukuchi: Mineral paragenesis in the contact-metamorphic deposits, found in Japan. *Beiträge zur Mineralogie von Japan*, herausgegeben von T. Wada. Nr. 3. 1907. pp. 88-89.

T. Suzuki: The explanatory text to the Yamaguchi sheet (in Japanese). *Imp. Geol. Surv. of Japan*. 1907.

(2) The copper production of this mine during the recent years has been as follows:

1910: 11604 pounds copper.

1911: 45956 „ „

(3) The terms 'metamorphosing solutions,' 'solutions' etc., which will appear repeatedly in this paper, are used according to J. E. Spurr, G. H. Garrey, and C. H. Fenner (Study of a Contact Metamorphic Ore-Deposit. The Dolores Mine, at Mate-

but in a marked degree, during the period of metamorphism, thus giving rise to a remarkable sequence of mineral depositions in the deposits.

It would be very interesting to compare the results of this work with the recent study of the contact deposits of the Dolores mine, at Matehuala, Mexico by J. E. Spurr and others.⁽⁴⁾

(II) Geology :—

The Ofuku mine lies about 1.5 kilometers west of Ofuku (or Ofuku-Kaneyama), a village due north of the railway station of Isa on the Ōminé Branch of the Sanyō Line. It is situated near the top of a mountain, 340 meters above the sea, and which makes a steep slope on the western side of the Asagawa valley. This valley in which the village of Ofuku lies, is a fault-valley, on both sides of which the topographic feature is remarkably different. The eastern side of the valley is a large plateau of limestone (Palaeozoic) with an average height of 300 meters. It terminates with a steep slope towards the valley. The western side of it is a mountainous region. Though it is sculptured and dissected to a stage of geographical maturity, the heights of the mountain tops are practically same, the average being about 350 meters above sea level. Thus, the plateau and the mountainous region belong to the same geographical cycle, and the difference of the topographic feature is chiefly due to the difference of the rock characters.

The prevailing rocks in the environs of the Ofuku mine are

huala, S. L. P., Mexico. Econ. Geology, Vol. VII, 1912. No. 5. pp. 444-484). It is certain that solutions expelled from a consolidating magma are so heated, especially at the moment of and a while after leaving the magma, that they exist in a superheated state saturated with mineralizers, or in a gaseous form (solutions in aqueous gas), the temperature being far over the critical temperature of water (364° C), [see, S. Arrhenius: *Zur Physik des Vulkanismus*, Stockholm, 1900.—Cited by J. H. L. Vogt: *Problems in the Geology of Ore-Deposits*. Genesis of Ore-Deposits, 1902. pp. 643-644.] To this point I shall recur later.

(4) See (3).

Palaeozoic sedimentaries—quartzite beds with intercalated thin limestone lenses—with a strike of NNE and a steep dip towards W. A dioritic rock (quartz mica diorite) is exposed on the eastern slope of the elevation, near the top of which the ore-deposits are found. The contact of the sedimentaries with the eruptive rock is observed at a distance of about 500 meters from the deposits.

Fig. 1. Geological Map of the Environs of the Ofuku Mine. Scale 1:25,000.

At the foot of the elevation, along the Asagawa river, low river terraces are developed. The terracial clayey, sandy and gravelly deposits are underlain by the quartz mica diorite, the latter thus occupying a meridional narrow zone with a width of about 1 km. along the western side of the river.

The quartzite is of Younger Palaeozoic age (Middle and Upper Palaeozoic System), and the dioritic rock is of Older Mesozoic intrusion.⁽⁵⁾

(5) T. Katō: The tourmaline copper veins of the Yakuōji mine, prov. Nagato, Japan. Journ. Geol. Soc. Tōkyō, Vol. XIX, 1912. p. 69.

Quartz Mica Diorite.—It is a medium-grained, gray to dark colored rock with abundant minute biotite scales. Under the microscope, it is composed essentially of well crystallized plagioclase crystals, crystals of biotite and hornblende, and quartz as mesostasis (Pl. I. Fig. 1).

Plagioclase occurs usually in idiomorphic crystals, but rarely in a hypidiomorphic form. It shows almost invariably polysynthetic twin-lamellae and a zonal structure. The cores are sometimes noticeably different from the shells, giving larger extinction angles (often 10 degrees or more). All plagioclases, however, belong to the family of labradorite as determined by the Fouqué method and by symmetrical extinction angles. Twinning according to the Carlsbad law is sometimes observed. The commonest size of the plagioclase is 1 to 2 mm, rarely up to 4 mm. Due to the formation of kaolinitic and sericitic matters, especially along the cleavage fissures, the plagioclase often shows a turbid appearance.

The dominant colored mineral is biotite. It occurs in well defined hexagonal plates with a size less than 1 mm in diameter. It is a common biotite with the optical angle of almost 0° , and exhibits strong absorption and marked pleochroism—dark brown to oil-yellow. It is sometimes altered to chlorite.

The next important ferro-magnesian mineral is hornblende which occurs in prismatic idiomorphic crystals with a size usually smaller than 1 mm in length. It is a common hornblende showing pronounced pleochroism; *b*=greenish brown, *c*=brownish green to bright green, *a*=yellow. Twinned crystals with the twinning plane (100) are fairly common.

In quantity, the biotite predominates far over the hornblende. The two ferro-magnesian minerals are sometimes corroded along the margin, and show a serrated or embayed outline. In general, both minerals are of the earliest crystallization among the essential constituents, though in some cases they are crystallized at the

same time as plagioclase or a little later than it, because we find the former minerals hindered in crystallization by the latter.

Colorless diopside is very sparingly found in crystal-aggregations, often in groups with biotite and hornblende crystals.

Quartz is not very small in quantity, and occurs always as xenomorphic mesostasis, filling the spaces between the above mentioned crystals. It is fresh, rich in minute liquid inclusions, and characteristically traversed by cracks.

Sparingly and rarely, orthoclase is found. It assumes never an idiomorphic form, but occurs sometimes with the quartz-mesostasis in micropegmatitic intergrowth and sometimes fills up the inter-spaces of the plagioclase and ferro-magnesian minerals in xenomorphic grains altogether with quartz grains. The alteration of the orthoclase to kaolin and sericite flakes is commonly observed.

Apatite, zircon and magnetite are the common accessory minerals. The first mineral occurs invariably in fine needle-shaped crystals, the second in minute short prismatic crystals and rounded grains, the third in rounded crystals. They are scattered irregularly and included in all of the essential constituents. The zircon, when enclosed in biotite and hornblende, shows a rather indistinct pleocloic halo around it.

Thus, the rock under consideration is a quartz mica diorite with monzonitic characters (tonalite).

Quartzite.—It is a very compact, flinty rock usually grayish in color, and sometimes more or less calcareous, especially near the ore-deposits. Under the microscope, it is composed of minute angular quartz grains (0.4 mm or less in diameter). Sometimes it is traversed by very fine veinlets of calcite, which make the rock more or less calcareous (Pl. I. Fig. 2). The calcite veinlets are most abundant in the quartzite just in contact with the ore-deposits and gradually diminish in quantity as the deposits are left further. Thus, they are evidently closely related to the

formation of the ore-deposits. The veinlets are composed chiefly of xenomorphic calcite grains often mingled with a little quantity of quartz which often shows an idiomorphic form.

Limestone.—The limestone intercalated in quartzite beds occurs in thin strata or in small lenses. At the mine, only small lenses of limestone are developed, which are closely related to the formation of the deposits. The limestone is generally metamorphosed to a saccharoidal crystalline variety, and in most cases it is partially changed into a wollastonite-rock by the metasomatic action of the metamorphosing solutions. Consequently, we often find a lentlular wollastonite-rock, intercalated in the quartzite and enclosing residuary saccharoidal limestone in rounded or irregular-shaped masses.

Metamorphism of the sedimentary rocks at the contact with the eruptive intrusion.—The quartzite shows no remarkable indication of metamorphism due to the tonalite intrusion. The limestone, however, at the contact with the same eruptive rock, as observed at a place about 500 meters from the main ore-deposit, is altered to a granular rock richly disseminated with greenish and reddish garnet crystals (rhombic dodecahedrons) and sulphide minerals, such as pyrite, pyrrhotite etc.

As examined under the microscope, isotropic garnet crystals (pale greenish and flesh colored, and microscopic up to several millimeters in diameter), biotite in hexagonal scales (strongly pleochroic—dark brown to dark green || to the cleavage track and yellow $\perp$ to it), and quartz grains and crystals with minute liquid inclusions are scattered irregularly and abundantly in a granular aggregation of calcite. The calcite grains are very large, attaining often a size of several centimeters in diameter. Of the sulphide minerals, with which the rock is richly impregnated, the pyrite often assumes a minute but well developed crystal (cube), while the pyrrhotite occurs usually in irregular small patches.

This rock is, no doubt, a regenerated limestone due to the contact metamorphism with an addition of silica, iron, magnesia, alumina and a small quantity of sulphides from the superheated solution⁽⁶⁾ originated from the consolidating magma.

(III) Ore-Deposits:—

In the environs of the main deposit now under work, we find almost everywhere quartzites impregnated with more or less sulphide minerals.

The main ore-deposit, however, is a lenticular saccharoidal limestone (with a width of 10 meters, and 40 meters or more in

A = Main ore lens. B = Oxidized ore lens, already worked out. C = Small oxidized ore lens. D = Cave with quartz-and limonite-stalactites.

(6) The recrystallization of the limestone was due to the action of heated steam expelled from the eruptive magma and pressed into it. The formation of contact-minerals such as garnet, biotite and sulphides, all or at least the last, is explained by supposing the presence of metallic compounds in the heated steam.

length), which is in greater part metamorphosed to wollastonite associated with garnet and sulphide minerals, as will be stated more fully in the next article. The workable portion of the deposit is not confined to the metamorphosed limestone, but the surrounding quartzite is often richly mineralized, being impregnated with various sulphides and traversed by veins and veinlets of massive chalcopyrite.

The formerly worked and now exhausted deposit was found at upper horizon and nearer to the surface than the present one (see Fig. 2 in the text). It was composed almost entirely of oxidized minerals, supplying very rich ores containing much malachite, chrysocolla, cuprite and others. It was probably of the same character as the present main deposit, the oxidation being due to the descending meteoric waters.

Another small deposit is exposed at the surface near the main adit (Fig. 3 in the text). It is a small lens composed chiefly of limonite, mingled with more or less oxidized copper ores such as malachite etc. It contains unaffected wollastonitized limestone masses, and is intercalated in quartzites (Fig. 3). It is, no doubt,

Fig. 3. Ore lens exposed near the main adit.

Q = Quartzite. L = Limonite.
W = Wollastonitized limestone.
M = Malachite.

a small limestone lens which had been metamorphosed and mineralized, and later oxidized by the surface-water.

Thus, the bigger deposits have been found always at those places where limestone lenses are intercalated in quartzites, and it is highly probable to find more deposits by further cross-cutting.

(IV) Contact Minerals and Ores, and Their Modes of Occurrence (With Conclusions) :—

The ore-deposits of the Ofuku mine are always accompanied by typical contact minerals such as wollastonite, garnet, vesuvianite, etc. The sulphide minerals found in the main deposit in association with them are chalcopyrite, iron pyrite, arsenopyrite, pyrrhotite, bornite, molybdenite with occasional oxidized ores as chrysocolla, malachite, cuprite, and limonite.

(A) Contact Minerals.

Wollastonite :—This is the dominant contact mineral. It is snow white in color and occurs in fibrous aggregations often assuming a radial or rosette structure. Under the microscope, it is always colorless and characterized by the position of the optical plane transverse to the cleavage in sections showing paralld extinction. Twinning parallel to the orthopinacoid is fairly common.

The lenticular limestone intercalated in the quartzite is usually almost entirely metamorphosed to a wollastonite-rock often containing remnants of unresorbed saccharoidal limestone in spheroidal and irregular forms. Microscopic study shows that the wollastonite was formed by the metamorphism of the limestone by the action of the magmatic solutions which added substances and replaced the original rock.

As observed at the main working (April, 1912), the quartzite surrounding the wollastonitized limestone lens, was also attacked by the metamorphosing solutions and replaced by

wollastonite. The wollastonite in the quartzite occurs in veinlets or in irregular masses (Pl. I. Fig. 4. and Pl. II. Fig. 1). The boundary between the quartzite and wollastonite-mass is commonly so indistinct that the latter passes gradually into a highly calcareous substance, a mixture of calcite and wollastonite, and then into a bleached and more or less calcareous quartzite, and at last to the unaltered gray quartzite with numerous microscopic calcite veinlets. When examined under the microscope, the indistinctness of the boundary between the quartzite and wollastonite-calcite mass is exhibited in a satisfactory way. The mass branches out into stringers and veinlets, consisting of wollastonite fibers and calcite grains. Quartz grains of the quartzite and the wollastonite fibers are very intricately commingled along the margins of the veinlets, showing clearly the metasomatic formation of wollastonite at the expence of quartz grains by the action of the solution (Pl. I. Fig. 4).

Mingled with wollastonite fibers, macroscopically pale greenish and microscopically colorless diopside in minute prismatic crystals, is very rarely and sparingly found. It is quantitatively insignificant and is evidently contemporaneous in formation with the wollastonite.

Among the minerals produced by metamorphism, wollastonite is of the earliest deposition, because it is often penetrated by veins and patches of darker colored minerals such as garnet and vesuvianite, and also by those of sulphide ores (Pl. II. Fig. 1 and 2). It is certain, therefore, that the heated solutions expelled from the consolidating tonalite magma were originally very rich in silica. They ascended through fissures and cracks in the quartzite, and where they encountered a limestone, they attacked it metasomatically and deposited wollastonite on the one hand, and became calcareous by the absorption of the limestone on the other. The siliceous solutions, which became thus calcareous, proceeded further and attacked even the quartzite on their journey up-

wards, resulting in the metasomatic deposition of wollastonite and calcite in it. That the solutions at the final stage of wollastonitization were exceedingly rich in lime and probably not in enough high temperature to produce wollastonite by the process of replacement, is indicated by the fact that near the termination of the wollastonite mass produced in the quartzite, there is developed more calcite than wollastonite, and it gradually passes into an irregular aggregation of calcite and quartz, which at last branches out into microscopic calcareous veinlets with quartz crystals.

Thus, the magmatic or metamorphosing solutions⁽⁷⁾ of the earliest stage were very siliceous (and calcareous).

Garnet and Vesuvianite:--Garnet plays as important a rôle as

(7) In the case of the Dolores mine, according to Spurr and others, the earliest metamorphosing solutions were aluminous and siliceous (and calcareous due to the absorption of limestone) corresponding with the compositions of aluminous pyroxene and grossularite, the succeeding ones being siliceous (and calcareous). These solutions, they say, perhaps correspond with the alaskite-quartz, quartz magma-solutions which represent the end-products of siliceous magmatic differentiation (J. E. Spurr and others, loc. cit. pp. 445, 473 etc.). In the case under consideration, the earliest solutions were siliceous (and calcareous), the aluminous and siliceous ones being almost entirely wanting.

The wollastonite plays a rôle of geological thermometer, its formation taking place, according to certain experiments in the dry way (A. L. Day, E. S. Shepherd, E. T. Allen, W. P. White, and F. E. Wright: *Am. Journ. Sc.*, 19, 1905 pp. 93-134, and 21, 1906, p. 89 etc.), between 800° and 1180°c under 1 atm. pressure (F. Beyschlag, P. Krusch, J. H. L. Vogt: *Die Lagerstätten der Nutzbaren Mineralien und Gesteine*, Band I. p. 349). According to C. Doelter, "Die untere Temperaturgrenze, bei der sich wollastonit bildet, wahrscheinlich beträgt sich zwischen 300°—400°; ich vermute, dass sie eher näher dem letzteren Punkt liegt, über dem kritischen Punkt für wasser," and "Wir können die obere Existenzgrenze des wollastonits mit 1100° annehmen....." C. Doelter: *Minerogenese und Stabilitätsfelder der Minerale*. *Tscherm. Min. Petr. Mitt.* XXV Band, 1906. 89—92.

In general, we can suppose that the wollastonitefels (both recrystallized and metasomatically deposited) in contact metamorphic deposits is formed at a temperature far over the critical temperature of water; in other words, the wollastonitization due to the contact metasomatism takes place by the action of highly heated solutions or solutions in aqueous gas. The process is, therefore, pneumatohydrogenetic or pneumatolytic metasomatism (refer, J. F. Kemp: *Ore Deposits at the Contact of Intrusive Rocks and Limestones*. *Econ. Geol.* Vol. II.

the wollastonite, as contact mineral. It forms a garnet-rock, variegated in colour due to the aggregation of varieties of different colours—deep red, brownish, dark greenish and yellowish. The garnet, forming a solid aggregation, is usually well crystallized. As observed in thin sections under the microscope, the rock consists of the rhombic dodecahedrons of very light yellowish to flesh colored garnet. The crystals, are, however, often overlapped (Pl. I. Fig. 3 and 5). It shows commonly optical anomaly, often consisting of a division of the crystal into birefracting segments, that are optically different (Pl. I. Fig. 5). A zonal structure due to the growth of layers with varying double refraction is remarkably developed. Sometimes, only the margins of garnet crystals are birefracting (usually pale flesh colored), while the centers are isotropic and greenish in colour.

As qualitative analyses show, the garnet under consideration contains much Ca and Fe and only trace of Al and Mg. It belongs to the andradite family.

The andraditefels is always associated with more or less calcite and quartz. They occur in masses and patches or as fillings of the interspaces of the andradite crystals. The garnet at the contact with the calcite and quartz grains is perfectly crystallized

1907. pp. 1—13; W. H. Weed: Ore-Deposits near Igneous contacts. Tr. A. I. M. E. Vol. XXXIII, 1903. pp. 715—746; W. Lindgren: Character and Genesis of Certain Contact-Deposits. Tr. A. I. M. E. Vol. XXX and XXXI, and also in "Genesis of Ore-Deposits," 1902. pp. 728 et seq; V. M. Goldschmidt: Die Kontaktmetamorphose im Kristianiagebiet. 1911. pp. 211—220).

Consequently, the earliest metamorphosing solutions in the case of the Ofukumi mine are superheated solutions containing much silicic acid or "solutions in aqueous gas" rich in silicon (either in free silicic acid or in silicon-haloids (V. M. Goldschmidt: loc. cit. p. 234)), corresponding in composition with the siliceous end-products of the magmatic differentiation of granitic rocks which are represented by quartz veins transitional to pegmatite-alaskite-veins (Spurr) (see, W. Lindgren: loc. cit. the article "Relation of pegmatite-veins to ore-deposits"). It must be noted that the case in question is concerned with the exhalation from the magma during process of cooling, wollastonitization and other mineralizations being absolutely confined to the sedimentary rocks near the contact with the eruptive rock, while the alaskite-pegmatite-quartz-veins are mostly found in eruptives themselves.

without any hinderance in growth. The quartz in the garnetfels is sometimes well crystallized with predominant prismatic faces, especially along the outer borders of the *fels*. Mingled with the andradite, a small amount of macroscopically green and microscopically colorless pyroxene (probably hedenbergite) occurs in minute prismatic crystals.

The andraditefels is sometimes impregnated with sulphide ores, as will later be fully discussed.

The deposition of andradite has taken place subsequently to the wollastonite-rock, because the former occurs in veins, veinlets and pipes penetrating the latter and also cutting limestones and quartzites. As observed by the unaided eye as well as microscopically, the garnet often fills up the cracks and fissures of the wollastonite in the form of veinlets and small pipes, along the margins of which the latter mineral shows indications to have been attacked and replaced by the former (Pl. I. Fig. 3. Pl. II. Fig. 2). In some specimens, the former fills up the interspaces of the latter showing an appearance as if the latter were imbedded in the former.

Occasionally, aggregations of minute columnar crystals of a dark brownish mineral with a bright vitreous luster occur in the wollastonitefels in the form of small nests and minute veinlets (Pl. II. Fig. 1). It belongs to the same generation as the andradite, because it is later in generation than the wollastonite and earlier than the lastly deposited sulphide veins, being cut by them as in the case of the garnetfels. It is, however, much more rarely and sparingly found than the garnet. Only imperfect prismatic faces are developed, which are often finely striated || ϵ . A parting transverse to ϵ is fairly common. No terminal face nor measureable prismatic face has been observed. It shows straight extinction. A section $\perp$ to ϵ shows a typical uniaxial interference figure. The character of double refraction

is negative, the optical character of the zone of ϵ being negative too. In thin sections, it is colorless or very light brownish colored, and exhibits *no pleochroism*. In very thick sections, it is very feebly pleochroic—reddish brown $\parallel \epsilon$, and brown $\perp \epsilon$ (absorption $\epsilon > \omega$). Double refraction is rather weak, but shows no abnormal interference colour. This mineral is nothing but vesuvianite.

The nature of the solutions in the stage of andradite (and hedenbergite and vesuvianite) deposition was different much from those in the stage of wollastonite formation. The source of the solutions, however, was the same—the consolidating tonalite-magma. It is certain, therefore, that the solutions have been gradually changed in character from what rich in silica and lime to what rich in silica, iron and lime with a small amount of alumina corresponding with the compositions of andradite and vesuvianite (and hedenbergite). This is a change from highly siliceous solutions to rather basic ones.

(B) *Metallic Ores.*

Metallic ores found in the ore-deposits of the Ofuku mine are, as already mentioned, chalcopyrite, iron pyrite, arsenopyrite, pyrrhotite, bornite, molybdenite and some oxidized ores, such as chrysocolla, malachite, cuprite etc.

Chalcopyrite is the principal ore worked there. It occurs always in massive state, no crystal being ever found. *Iron pyrite* occurs in cubic crystals imbedded in chalcopyrite or impregnated in gangues and rocks. Its size varies from microscopic up to several millimeters in diameter. Sometimes, it is found as minute irregular masses. *Arsenopyrite* occurs in masses or in crystals. Very large, though not perfect, crystals with a size of several centimeters in length have been abundantly found. *Pyrrhotite* is found always as small irregular masses. *Molybdenite* occurs in

minute scales with a diameter less than 1 mm, and is found usually in cumulations in gangues and rocks. *Bornite* occurs always in masses. It is a secondary mineral due to the alteration of chalcopyrite.

Chrysocolla, malachite and cuprite are found in the upper parts of the deposits, and sometimes in fissures and cracks of the unaltered sulphide minerals.

In general, two modes of occurrence of sulphide minerals are recognized, namely; (a) Disseminations, and (b) Veins and Veinlets.

(a) In some parts of the andraditefels as well as the quartzite surrounding wollastonitized limestone lenses, and rarely in the limestone, above mentioned sulphides are irregularly commingled and richly disseminated. These rock portions are worked as a copper ore. It is highly probable that the sulphides were deposited contemporaneously with the andradite or at least at the very close of its deposition, because they are intimately but irregularly intergrown with it, showing no trace of later infiltration. The presence of molybdenite suggests that the solutions were highly heated and contained more or less volatile metallic compounds.⁽⁸⁾ In limestones and wollastonite-rocks, sulphide dissemination is rather rare, occasional specks of pyrite and chalcopyrite showing evidently later impregnation.

(8) This stage corresponds with the third period (C) (silica-lime-iron and other metals) in the Dolores mine (J. Spurr and others : Loc. cit. p. 473 et seq.).

In the Ofuku deposits, garnetization with contemporaneous sulphide dissemination is due to the deposition from, and pneumatohydatogenetic or pneumatolytic metasomatism by the superheated solutions or "solutions in aqueous gas" too (Goldschmidt : Loc. cit. p. 213 et seq.). The presence of molybdenite suggests it. The fact that the garnetfels with accompanying sulphides occurs always in the contact zone not very far from the contact with the eruptive rock, and is never found in the tonalite itself, is explained by the supposition that from the still liquid magma the compositions of garnet and sulphides were blown into the adjoining rigid rocks, along the fissures and cracks caused by the shrinkage of the previously formed wollastonitefels (W. H. Weed : Loc. cit. p. 745), in the form of highly heated solutions or "solutions in aqueous gas" (refer, J. H. L. Vogt : Zur Classification der Erzvorkommen. Zt. f. Pr. Geol, 1895. p. 154).

It is certain that the metamorphosing solutions in the stage of andradite deposition were charged with more or less sulphides which had been almost entirely lacking in the previous stage. Toward the end of the garnetization, sulphide content in the solutions was very abundant, consequently they formed impregnations of sulphides in quartzite and other rocks on the one hand, while deposited andraditefels mingled with much sulphides on the other. That the solutions in this stage contained still an excess of silica and lime, is shown by the fact that the sulphide impregnation in the quartzite and the andradite-sulphide ore are always associated with abundant quartz (in massive state and crystals) and calcite.

(b) Veins and veinlets consisting almost entirely of chalcopyrite only, are often met with, cutting the wollastonitefels, andraditefels, quartzite and limestone (Pl. II. Fig. 1 and 2). They are characterized by the absence of other sulphides than the massive chalcopyrite, which often contains remnants of limestone, quartzite or contact minerals in the form of streaks and minute masses. The width of them is variable from less than 1 mm up to 10 cm or more, thus supplying a very rich copper ore. Microscopical examination of the boundaries between the enclosed patch or the surrounding rock and the chalcopyrite vein, shows the former to be more or less resorbed and replaced by the latter along the margins, this phenomenon being especially remarkable when the limestone is concerned (Pl. I. Fig. 6).

Quartz, though not very much in quantity and not always observable macroscopically, is invariably associated with the chalcopyrite vein, usually along the margins.

The vein, not only accompanied by more or less quartz along the selvages, but also is often bordered with a thin film of a macroscopically greenish black to coal black mineral. Even when the vein pinches, branches or grades into discontinuous patches

and spots, the black thin film is often developed around them. As examined under the microscope, the mineral is commonly massive and only rarely scaly in structure, scarcely transmitting light. Thin edges and minute scales, however, are more or less transparent, and show a dark green colour and very weak double refraction. The streak colour is dark olive green. Consequently, it is a chlorite very rich in iron (cronstedtite?).

The stage of chalcopyrite-vein formation is the last stage of mineralization due to the contact metamorphism in the Ofuku deposits. There is no room for doubt that the metamorphosing solutions in this stage were charged with abundant chalcopyrite altogether with more or less silica and iron, and that the solutions ascended through the fissures and cracks, formed in the previously deposited wollastonite and garnet rocks as well as the quartzite and limestone. They attacked the rocks along the cracks and widened them on the one hand, and deposited chalcopyrite on the other, the metasomatic action being naturally most intensive in the limestone. This final solutions,⁽⁹⁾ very basic in nature, were evidently derived from the solidifying or just consolidated tonalite magma, as are the cases with those in the stages of wollastonitization and garnetization.

The metamorphosing solutions, therefore, which were in the first stage of metamorphism very siliceous (rich in silica and absorbed

(9) Whether the solutions from which the chalcopyrite veins were deposited, were gaseous or liquid, I had no data to conclude. Examining the veins and veinlets of massive chalcopyrite in situ and in hand-specimens (Pl. II. Fig. 1 and 2), I can not help recollecting the deposits of Lökken and Sulitelma in Norway, visited by myself in 1910, where the 'Kieslagerstätten' are represented, in some portions, by massive chalcopyrite filling the cracks along the plane of schistosity or netted fissures (Beyschlag, Krusch, Vogt: Loc. cit. Bd. I, pp. 300-310; J. H. L. Vogt: Ueber die Kieslagerstätten von Typus Röros und Rammelsberg. Zt. f. pr. Geol., 1894, and Problems in the geology of ore deposits, already cited). At any rate, the solutions were of magmatic origin representing the last stage of contact metamorphism or of magmatic secretion. The fissures and cracks filled up by the chalcopyrite had been caused by the shrinkage of the metamorphic zone due to the cooling.

lime), changed in the second stage (stage of garnetization) to rather basic ones, rich in iron and silica (with lime and a little of alumina) and charged with more or less sulphide ores, and finally, in the last stage, the nature of the solutions became exceedingly basic, very rich in sulphide of copper and iron (chalcopyrite) with only subordinate amounts of silica and others.

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Japan, Sept., 1913.

Explanation of Plate I (Microphotographs).

- Fig. 1. Quartz mica diorite (Tonalite). Polarizer only used. Magnified 44 diameters. F=Plagioclase. Q=Quartz. H=Hornblende. B=Biotite.

Notice the idiomorphic plagioclase crystals, partially altered and showing a zonal structure.

- Fig. 2. Quartzite traversed by calcite veinlets. Nicols crossed. Magnified 44 diameters. C=Calcite veinlets.

The quartzite is composed of minute angular quartz grains.

- Fig. 3. Wollastonitefels intruded and replaced by garnetfels. Polarizer only. Magnified 44 diameters. G=Garnet. W=Wollastonite.

Wollastonite occurs, in this part, in aggregations of prismatic crystals. Notice the boundary between the two kinds of mineral-aggregation, which is very intricately zigzag.

- Fig. 4. Quartzite replaced by wollastonite. Polarizer only. Magnified 44 diameters.

Q=Quartzite. W=Wollastonite.

The quartzite surrounding wollastonitized limestone lenses was attacked by the metamorphosing solutions, giving rise to the formation of wollastonite. The solutions travelled through even very minute cracks in the rock, and deposited the wollastonite by a process of metasomatism.

Fig. 5. Garnet skarn showing optical anomaly, Nicols crossed. Magnified 44 diameters.

Division of crystals into segments showing different optical orientation is well shown.

Fig. 6. Crystalline limestone penetrated by chalcopyrite veinlets. Transmitted light. Magnified 44 diameters. C=Calcite. Black portion=Chalcopyrite. Notice the residuary calcite patches in the chalcopyrite.

Explanation of Plate II.

Fig. 1. Quartzite (Q) replaced by wollastonite (W), both being penetrated by massive chalcopyrite veinlets (Ch). Small patches of vesuvianite aggregation (V) are shown, which are later in generation than the wollastonitefels but also cut by the chalcopyrite veins. The gray portion on the lower and right sides of the specimen is the quartzite which is more or less calcareous with microscopic calcite veinlets. It passes over into the snow-white wollastonitefels on the left upper side, with a transitional zone (composed of quartz and calcite mingled with a small amount of wollastonite=QC) between them. Q'=Quartzite impregnated with sulphide ores.

About 1/5 natural size.

Fig. 2. A. Wollastonitefels (W) penetrated and replaced by garnetfels (G) in the form of veinlets, pipes etc.

4/5 natural size.

B. White crystalline limestone (L) penetrated by

massive chalcopyrite veinlets (black parts). The veinlets are accompanied by quartz grains and crystals, and bordered with thin films of dark greenish chlorite (not visible on the photograph). The limestone is impregnated along the veinlets with dark chlorite and quartz too.

4/5 natural size.