原 著 論 文

On the Thermal-Metamorphism of the Ore-Body of
the Yanahara Mine

Kitaro HAYASE* and Tadashi MARIKO*

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I. Introduction

One of the writers(K. HAYASE)has been studying the properties of pyrrhotite since about eight years ago, some results of which he applied to the geological problems of the Kawayama ore deposit (Yamaguchi Pref.), Chichibu ore deposit (Saitama Pref.), Ashio ore deposit (Tochigi Pref.), Makimine ore deposit (Miyazaki Pref.), Kamaishi ore deposit (Iwate Pref.), Sano ore deposit, and Tsuda ore deposit (Okayama Pref.).^{1),2),3),4)}

Professor Dr. Takeo WATANABE of Tokyo University once suggested that the magnetite and the pyrrhotite of the Yanahara ore deposit (Okayama Pref.) might be the products of thermal-metamorphism from the pyrite. The writers have made a study of the magnetite, the pyrrhotite, the dyke rocks and the country rocks of this ore deposit for the first four years in order to confirm this suggestion as a result of which they have become convinced that these minerals are undoubtedly the products of thermal-metamorphism from the pyrite. And they have been able to find out great possibilities for ascertaining such a thermal metamorphism by means of thermo-dynamic calculations.

II. Acknowledgement

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III. Outline of Geology and Ore Deposit

The Yanahara Mine, an iron-sulphide ore mine, belonging to Dowa Mining Company, is situated at Yanahara-machi, Kumegun, Okayama Pref., Japan.

According to Takayoshi OSHIMA,^{5),6)} this area is composed of clay-slate, diabase, so called "complex zone" rocks, epidote-quartz-diorite, biotite-quartz-diorite and some dyke rocks.

Epidote-quartz-diorite, the base rock, is covered by diabase. Clay-slate, which is mounted on the diabase, dips to the south, and its thickness is more than 300 meters in the southern section.

* Mining Department, Waseda University
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The rocks of "complex zone", which are composed of trachydacite and rhyolite and closely related to the ore deposit, exist near the boundary between diabase and slate, or as the intrusive bodies in diabase.

Northward from the ore deposit, biotite-quartz-diorite is distributed extensively, and in the vicinity of the ore deposit the out-crops of this rock are recognizable. Relation of this rock to the ore body has not been completely clarified, but the writers think this rock is a post-ore-intrusive body.

Numbers of the quartz-porphry dykes and porphyrite dykes cut across all the above-mentioned rocks and ore bodies.

Hornfelses are recognized in the rocks of "complex zone", clay-slate and diabase. Most rocks in this area have been altered by silicification, chloritization, albitization and mineralization.

The ore deposit is composed of many ore bodies. The Yanahara main ore bodies (No. 1, No. 2, No. 3 ore bodies) lie at the centre, while the Kanahori ore body, Hoden ore body, and Yasumiishi ore body are found as if forming a line in the northeastern part of this area. The Hisagi ore body and Shimoyanahara ore body form a parallel line to the main ore body on the west side.

In the northwestern part, the Shimotani ore body has also been prospected. The ore, in massive ore bodies in the complex zone, consists principally of fine granular pyrite, associated with pyrrhotite magnetite and minor chalcopyrite, zinblende, and galena. But especially the Hisagi ore body and Shimoyanahara ore body are so rich in copper that the average copper content of ore comes to be about 2% (Fig 1).

Fig. 1 Map of the location of the Yanahara Mine (shown by cross mark) and the geologic map of the Yanahara Mine area (based on the company maps of the Dowa Mining Company)
1- Gravel, 2 Breccia bearing Rhyolite, 3 Slate, 4 Diabase, 5 Biotite-quartz-diorite, 6 Epidote-quartz-diorite, 7 Complex-zone, 8 Ore-body, 9 Dyke-rocks

IV. Occurrence of Pyrrhotite and Magnetite

Almost all parts of the ore body are composed of compact ore of fine granular pyrite, but pyrrhotite and magnetite are recognizable very frequently in the surrounding parts of the ore body and at the boundary between pyrite ores and quartz-porphry-dykes which intrude into the ore body.

Both minerals are found in all ore bodies without exception. Especially in the Shimoyanahara ore body, Hoden ore body, the eastern side of the middle section of the Yanahara main ore body, and the western side of the lower section these two minerals are recognized in large quantity.

Generally speaking, pyrrhotite and magnetite show zonal distribution, and when they exist in the surrounding parts of the ore body,

Fig. 2 A Underground geology of the Yanahara Mine (21st level)

Fig. 2 B Underground geology of the Yanahara Mine (Yasumiishi)

1: Magnetite 2: Pyrrhotite 3: Pyrite

4: Quartz-porphry 5: Complex Zone

(Fig. 2A, 2B, Fig. 3, Fig. 4 in common)

Fig. 3 Underground geology of the Yanahara Mine (21st level)

the magnetite occupies the outer position and the pyrrhotite lies be-

tween the magnetite and the pyrite ore as shown in Fig. 2 A.

When these minerals are at the boundary between the pyrite and the quartz-porphry dyke, the magnetite exists in the dyke-rock-side, and the pyrrhotite is found along the pyrite-ore-sides as shown in Fig. 3.

The magnetite is associated with the pyrrhotite in all cases, but occasionally the pyrrhotite is found without magnetite (Fig. 2B). The writers could not discover any case of the magnetite coming in direct contact with pyrite without the pyrrhotite zone between them.

Ordinarily, the width of the magnetite and pyrrhotite zone is from about scores of cm. to scores of m., but the Hoden ore deposit, situated near the quartz-diorite which is distributed widely in the northern part of the Yanahara deposit, is largely composed of magnetite and pyrrhotite, but a small amount of pyrite can be seen along the lower part of this ore body.

There is a tendency that the magnetite and the pyrrhotite predominate in the narrower section of the ore bodies.

As a whole the magnetite and pyrrhotite zones cover the ore bodies in shell-like shapes, except for the contact parts of the quartz-porphry dykes, but rarely vein-shaped ore bodies of pyrrhotite can be found in the pyrite ore bodies. Even in that case, the pyrrhotite is elongated along a fissure from the pyrrhotite zone in the surrounding part of the pyrite ore body, and the front of it thins out in the pyrite (Fig. 4).

No ore body, composed only of magnetite or pyrrhotite, exists in the Yanahara deposit.

Under the microscope the following phenomena about the ores from the boundary parts between the pyrite and the pyrrhotite are recognized.

1) It seems that the pyrrhotite has eaten into the pyrite along the boundary of the pyrite grains and their cracks. Pyrite grains, remaining

Fig. 4 Underground geology of the Yanahara Mine (21st level)

in the pyrrhotite ground, show round shapes (Fig. 5).

2) It is extremely more difficult to get fine polished-surfaces of the pyrite grains of the ore taken from the boundary than those of other ores.

3) Such pyrite-grains show a remarkable optical anomaly. This optical anomaly of pyrite gradually decreases with the increasing of the distance from the boundary. Many descriptions about the optical anomaly of pyrite have been published, but most of them are of the pyrite grains from epithermal deposits and the polarization colours of them are written as being brown to dark gray. But the pyrite from this deposit shows the polarization colours of brown to brownish yellow and the optical anomaly is so distinct that this pyrite is frequently mistaken for pyrrhotite under crossed nicols (Fig. 6, Fig. 7). (We can recognize them because of differences in color of reflected light and hardness.)

4) Under a microscope of high magnification, it is recognized that countless minute holes are distributed over the polished surface of such a pyrite as shows optical anomaly, especially in the outer parts of the pyrite-grain.

5) Sometimes, the boundary parts of the pyrite and the pyrrhotite are rich in chalcopyrite.

The following facts about the boundary ores of the magnetite and the pyrrhotite are also recognized.

1) It seems that the magnetite has eaten into the pyrrhotite and minute granular or vermicular pyrrhotite grains are scattered in the magnetite-ground, retaining the original shapes (Fig. 8).

2) The pyrrhotite, remaining in the magnetite, is very porous and frequently indicates a short prismatic or hexagonal plate shape, and the surrounding magnetite grains of such pyrrhotite also show similar shapes, as they seem to be the pseudomorphs after the pyrrhotite (Fig. 9).

V. Magnetic Properties of Pyrrhotite

The chemical formula of pyrrhotite is expressed as $\text{Fe}_n \text{S}_{n+1}$ and it has been known for many years that the value of n has a range from 5 to 16.

HÄGG⁷⁾, JUSA and BILTZ⁸⁾, upon the studies of synthetic pyrrhotite concluded that there were some vacant positions of Fe atom in crystallattice of pyrrhotite, it contributing to a variety of n value. And they also discovered that the magnetic susceptibility of pyrrhotite increased with its atomic ratio of sulphur.

PEHRMAN⁹⁾, HAYASE and HARADA²⁾ ascertained that the magnetic susceptibility of natural pyrrhotite had the same relation with the atomic ratio of sulphur.

HARALDSEN¹⁰⁾, NISHIHARA and KONDO¹¹⁾ studied the temperature dependency of magnetism of pyrrhotite, and KYSKYRAS¹²⁾, SAITO¹³⁾ and GŌHARA also studied the same properties of natural pyrrhotite.

Fig. 10 Variation in the magnetic susceptibility of pyrrhotite (Kawayama Mine)

Fig. 11 Variation in the magnetic susceptibility of pyrrhotite (Tsuda Nine)

According to KY-SKYRAS, natural pyrrhotite can be classified into the following three groups by its temperature dependency of magnetism.

1) α -pyrrhotite (Peak Type)

Para-magnetic or weak magnetic pyrrhotites belong to this type, and they show a prominent peak between $200^{\circ} - 240^{\circ}\text{C}$ on $I-T$ curve, which is thought to be the consequence of the so-called γ -transition.

2) β -pyrrhotite (Weiss Type)

Pyrrhotite of this type has strong magnetism and indicates no peak on a $I-T$ curve, which is dependent on the so-called Weiss theory.

3) Mixed type pyrrhotite

This type is either a mixed crystal or a mixture of the above-mentioned two types of pyrrhotite, possessing the properties of both. The writers have also obtained similar results about natural pyrrhotite from Japan.

KYSKYRAS reported that the pyrrhotite, crystallized under a high temperature and a high pressure, had weak magnetism, but the pyrrhotite crystallized under low temperature, indicated strong magnetism. The writers studied the magnetism from Japan, and obtained such a result that the average magnetic susceptibility of the pyrrhotite from high temperature deposits was generally lower than that of the pyrrhotite from low temperature deposits.

According to the results obtained from the studies on the Kawayama, Tsuda and Sano Mine, the magnetism of pyrrhotite always shows the higher value in the outer parts of ore body than that in the middle parts (Fig. 10, Fig. 11, Fig. 12, Fig. 13).

The writers think that this fact means that the center of the mineralization was in the middle part of the ore body, and there was a gradient of temperature from middle parts to outer sides.

Fig. 14 Variation in the magnetic susceptibility of pyrrhotite of the Yanahara Mine on Shin-Shimoyanahara 9th level

Fig. 12 Variation in the magnetic susceptibility of the pyrrhotite (Tsuda Mine)

Fig. 13 Variation in the magnetic susceptibility of the pyrrhotite (Sano Mine)

Fig. 15 Variation in the intensity of magnetization of pyrrhotite of the Yanahara Mine on 17th level (A-A in Fig. 3)

Fig. 16. Intensity of magnetization-Temperature curve of pyrrhotite samples in Fig. 15

Fig. 14 and 15 show a tendency that the magnetism of pyrrhotite of the pyrite-sides is stronger than that of the opposite sides, which can not be recognized on the results of the studies about the Kawayama, Tsuda and Sano ore deposits.

Fig. 16 shows the I - T curves of the pyrrhotite, which indicate that the pyrrhotite of the pyrite-side is β -pyrrhotite and that of the middle parts is a mixed type and that of the magnetite-side is α -type. This phenomenon is to reveal that the pyrrhotite of the pyrite-sides contains more sulphur than that of the opposite sides

These results also indicate that the pyrrhotite on the outer sides of the Kawayama, Tsuda and Sano ore deposit, contains more sulphur than that of the middle parts.

The writers measured similarly the magnetism of the pyrrhotite of many ores which were sampled from the Yanahara deposit across the ore body with the results as shown in Fig. 14 and Fig. 15.

VI. Genesis of Pyrrhotite and Magnetite

According to the above explanation about the occurrences of the pyrrhotite and the magnetite, it may be certain that these minerals crystallized later than the pyrite. Thus, two theories concerning their genesis are advanced.

- 1) These minerals have crystallized from the different hydrothermal solutions to the one from which the pyrite has crystallized.
- 2) These minerals have been converted from pyrite by a pyrometamorphic action.

The principal reasons for the former idea are based on the fact that these minerals have an irregular distribution and that a sufficient quantity of secondary pyrometamorphic minerals can not be discovered in vicinal country rocks. But the writers support the latter idea which is considered to be much more probable than the former, for the following reasons:

- a) In spite of the rather irregular distribution of the pyrrhotite and the magnetite, the occurrence of these minerals is limited to the surrounding parts of the pyrite ore bodies and to the places along the quartz-porphyry dykes, which have intruded into the pyrite ore body and are therefore thought to be the post-ore intrusive bodies.
- b) When these minerals run across the pyrite (this phenomenon is rather rare) the tips of them thin out into the pyrite in every case.
- c) There is no ore body composed of pyrrhotite or magnetite only.
- d) The microscopic observations of the ores at the boundary between pyrite and pyrrhotite lead the writers to think that a pyrometamorphic action was given to the pyrite.
- e) The remarkable optical anomaly of the pyrite near the boundary of the pyrrhotite suggests the existence of an extraordinary state of the mineral.

f) The results obtained from measuring the magnetic properties of the pyrrhotite also lead the writers to think there is a gradual decrease of the sulphur content of the pyrrhotite from the pyrite side to the magnetite side.

g) Takeo WATANABE discovered cordierite in the country rocks near the Hisagi ore body, and he suggested the writers that this mineral was an evidence of pyrometamorphism.

From these viewpoints, the writers discussed probabilities as to the existence of pyrometamorphic action, which converted pyrite to the pyrrhotite and to the magnetite, by thermodynamical calculations.

A. Dissociation of pyrite and crystallization of pyrrhotite and magnetite

According to E. T. ALLEN and R. H. LOMBARD¹⁴⁾, and L. H. BERGSTRÖM¹⁵⁾, the relation between dissociation temperature and the vapour pressure of sulphur of pyrite is shown in Fig. 17. This Fig. 17 shows that pyrite dissociates at about 600°C when the vapour pressure of sulphur is still low, but its temperature gradually increases with sulphur-vapour-pressure, and at 1 atm. of sulphur-vapour the temperature approaches about 690°C.

If the sulphur-vapour-pressure is as high as 50 atm. pyrite will not be able to dissociate less than 800°C. If pyrite and pyrrhotite are heated with water at about 450°C to 800°C, these minerals will convert to magnetite as follows^{16), 17)}.

B. Thermodynamical calculation about the intrusive rocks and surrounding rocks

There are many studies^{20), 21)} on the theory of heat conduction as to temperature distribution in the ore body or in the surrounding rocks caused by heat coming from the intrusive rock bodies. The writers calculated the heat given to the ore or the country rock under such conditions that the magma flowed along the fissure and the temperature of the heat source was maintained for a remarkably long time. And later, the writers calculated the velocity of flow of the magma which should have given sufficient heat to the country rock.

The writers treated the temperature distribution in the country rock and the ore body as in a semi-infinitesimal solid when the temperature of its one side was constant. The temperature distribution in semi-infinitesimal solid under such conditions will be given by¹⁸⁾

$$\theta - \theta_1 = (\theta_0 - \theta_1) \left(1 - \frac{2}{\sqrt{\pi}} \int_0^{\frac{x}{2\sqrt{kt}}} e^{-\beta^2 \alpha \beta} d\beta \right) \dots \dots \dots (1)$$

Fig. 17 Dissociation pressure of the pyrite

Where θ temperature, at time t , of any point x in the solid.
 θ_0temperature of the heat source.
 θ_1temperature, when $t=0$.
 kthermal diffusivity. $k=K/C$
 Kthermal conductivity of semi-infinitesimal solid.
 ρdensity of semi-infinitesimal solid.
 Cspecific heat of semi-infinitesimal solid.
 βintegral function.

The curves showing a temperature distribution in semi-infinitesimal solid, for one year later, 10 years, 10^2 years and 10^3 years, later are illustrated in Fig. 18. Here the writers assumed that $\theta_1=50^\circ\text{C}$, $\theta_0=750^\circ\text{C}$ and $C=0.185$ (cal/g. deg), $K=0.0051$ (cal/cm. deg. sec.), $\rho=2.9$ (g/cm³.) for the country rock which is regarded as andesite or diabase, and $C=0.12$ (cal/g. deg.), $K=0.0902$ (cal/cm. deg. sec.), $\rho=5.01$ (g/cm³) for the pyrite²⁰⁾²¹⁾²²⁾.

It can be seen in Fig. 18 that the pyrite ore body will be easily heated to high temperature, whereas the temperature of the country rock will hardly rise to such a degree during the same time.

For example, in 100 years the pyrite may be heated to beyond 600°C up to 100m. distance from the heat source. On the other hand, the country rock will be heated to about 600°C up to only 30m. in 100 years.

Next the writers considered such a case that the dyke rock intruded into the pyrite ore body enclosed by the country rocks.

The condition of this case can be regarded as that of semi-infinitesimal solid ($x \geq -a$) composed of A material ($-a \leq x \leq 0$) and B material ($0 \leq x \leq \infty$), and the one side of which ($x=-a$) is held constant in temperature.

The following formulas¹⁹⁾ indicate the temperature distribution in A and B when $0 < \sigma < 1$.

$$\begin{cases} \theta_A - \theta_1 = (\theta_0 - \theta_1) - \frac{2(\theta_0 - \theta_1) \sin 2\varphi}{\pi} \int_0^\infty \frac{\sin \alpha (x+a) e^{k_A \alpha^2 t}}{\cosh 2\varphi \cos 2a} d\alpha \\ \theta_B - \theta_1 = (\theta_0 - \theta_1) - \frac{2(\theta_0 - \theta_1) \cosh 2\varphi}{\pi} \int_0^\infty \frac{(1 + \tanh \varphi) \sin \alpha (x+a) + (1 - \tanh \varphi) \sin \alpha (\mu x - a) e^{-k_1 \alpha^2 t}}{\cosh 2\varphi - \cos 2a\alpha} \frac{e^{-k_1 \alpha^2 t}}{\alpha} d\alpha \end{cases} \quad (2)$$

here θ_A temp. in A material (pyrite)
 θ_B temp. in B material (country rock)
 K_A heat conductivity of A
 K_B heat conductivity of B
 k_A heat diffusivity of A
 k_B heat diffusivity of B
 C_A specific heat of A
 C_B specific heat of B
 ρ_A density of A

Fig. 18 Temperature distribution in the pyrite ore body and the country rock when $t=10^0-10^4$ years (calculated on the basis of the formula(1))

— Pyrite ore body Country rock

ρ_B density of B

$\mu = \sqrt{k_A/k_B}$

$\sigma = \mu K_B/K_A = \tanh \varphi$

θ_0 temp. of high-temp. side (quartz-porphry dyke)

θ_1 initial temp. of A and B (pyrite and country rock)

The writers then applied the values of the physical properties of pyrite to those of A material, and those of country rock to B material*, and assumed $\theta_0=750^\circ\text{C}$, $\theta_1=50^\circ\text{C}$ to those formulas, and the writers obtained the result as shown in Fig. 19 (when $t=100$ years).

From this figure, the writers can deduce that all parts of the pyrite body can be heated to above 700°C , but that up to only 3 meters of the surrounding country rock along the boundary the temperature can approach 700°C in 100 years.

C. Probability of Such Condition of the Heat Source

Concerning the calculation of the above formulas, the writers assumed that the temperature of the heat source was constantly maintained.

This assumption means that a satisfactory flow of the magma in fissure gives suitable heat to the surrounding materials (pyrite and country rock).

Assuming that a magma** intrudes deep under the surface of the Yanahara district and that its thickness is about 1,000 meters, the heat, emitted from this magma while its temperature decreases from 950°C to 750°C , will be calculated as follows:

$$H_a = \frac{C \cdot \rho (950 - 750) T}{2} \dots\dots\dots (3)$$

where H_a emitted heat through 1 cm^2 of the surface of the magma*** while its temp. decreases from 950°C to 750°C

C specific heat of the magma ≈ 0.2 (cal/g. deg)

ρ density of the magma ≈ 3 (g/cm³)

T thickness of the batholith $\approx 10^5$ (cm)

then $H_a = 6 \times 10^8$ (kcal)

Assuming that the temperature of the magma is kept at about 750°C , the heat conducted to the surrounding rocks during 1,000 years will be also calculated as follows:

Fig. 19 Temperature distribution in the pyrite ore body and its surrounding rock when $t=10^2$ years (calculated on the basis of the formula (2))

* Refer to the factors on the case of the formula (1).

** Near the Yanahara ore deposit, out-crops of biotite-quartz-diorite are widely distributed. The writers are led to think this igneous rock is related to such a magma.

*** According to LARSEN, the temp. of rhyolitic lava was 573°C — 870°C , and he considered that the temp. of most rhyolitic magmas would be at about 600°C — 700°C . Therefore, the writers assumed the melting point of granitic magma which intruded into the Yanahara district as the quartz-porphry dykes and as the granodiorite, was slightly higher than this value.

$$H_b = C \cdot \rho \cdot A \dots\dots\dots (4)$$

where H_bheat given to the surrounding rock through 1 cm² of surface of the magma.

C specific heat of the surrounding rocks=0.2 (cal/g. deg).

ρ density of the surrounding rocks=3 (g/cm³).

A area between the temperature-distance curve in 1,000 years and the horizontal line of 50°C in Fig. 18 (when the initial temp. of the surrounding rock is about 50°C)=1,400(cm³.deg.).

$$\text{then } H_b = 8.4 \times 10^3 \text{ (kcal)}$$

This value is close to that of the emitted heat from the magma H_a . If the initial temperature of the surrounding rocks is about 150°C, requisite heat H_b will be less than 2.8×10^3 kcal. Assuming that the thickness of the magma is about 500 meters and its initial temp. is 850°C, and 1.5×10^3 kcal will be obtained as the emitted heat.

Thus, some parts of this magma can remain without being solidified for about 1,000 years, under the above mentioned conditions.

In any case, if a rather remarkable magma happens to intrude into the rocks at deep places, liquid-magma can be supplied from the parent magma to branch fissure (which has become quartz-porphyry dyke) for a considerable long time, say for 100 years, under suitable conditions.

Assuming that the temp. of dyke rock is kept at 750°C constantly, the heat H_c conducted to the ore body (thickness: 100 meters) and its surrounding rocks during 100 years will be calculated in the same way as shown in (4) by Fig. 19, curve A.

$$H_c = 7.2 \times 10^3 \text{ kcal/cm}^2 \text{ of the surface of the dyke rock.}$$

The heat H_d , emitted from the dyke rock (thickness: about 10 meters) while its temp. decreases from 950°C to 750°C, will be also calculated as follows:

$$H_d = 0.6 \times 10^2 \text{ kcal/cm}^2 \text{ of the surface of the dyke rock.}$$

And the heat H_e , conducted to the country rock during 100 years, is:

$$H_e = 3 \times 10^2 \text{ kcal/cm}^2 \text{ of the surface of the dyke rock.}$$

Now assuming that the distance from the parent magma to an ore body is 500 meters and the thickness of the ore body is 100 meters (Fig. 20), the liquid-magma must flow along the fissure at the following velocity so as not to get solidified during 100 years.

$$(500 \times H_e / H_d + 100 \times H_c / H_d) \div 100 = 128$$

$$\text{m/year} \div 0.35 \text{ m/day}$$

As this velocity is rather small, even though the viscosity of magma is relatively high, the existence of such a flow of magma is probably possible. The above calculation is done in the case where there is only one fissure, but if many fissures exist (more than 20 of quartz-porphyry dykes have been known near the Yanahara deposit), the lower velocity of flow than this value may be expected.

D. The quantity of the magma which flows out to the surface

Fig. 20 Cross-section, showing a typical dyke rock intruding into a pyrite ore body and its surrounding rock.

On the basis of the above calculation, the quantity of the magma, which flows out from the fissure to the surface during 100 years, is as follows; assuming the strike side length of fissure is 1000 meters.

$$1,000\text{m} \times 10\text{m} \times 12,800\text{m} = 128 \times 10^6 \text{m}^3$$

This volume of magma corresponds to about 380×10^6 ton. Assuming that this magma flows over the surface of an area of 4km^2 , its thickness is about 32m, and such a volcanic activity may be expected geologically.

E. Genesis of pyrrhotite and magnetite

According to the above-mentioned thermodynamic calculation, the following facts are revealed.

(1) If a quartz-porphyry dyke, 10 meters wide, intrudes into the pyrite ore body and a fresh fluid magma is supplied into this dyke from the parent-magma at the velocity of flow of about 0.35m/day, the magma of this dyke will exist as a liquid phase for at least 100 years without being solidified (assuming that the initial temp. of fluid magma is 950°C and melting point is less than 750°C).

These conditions may be expected if it is assumed that parent-magma, 1,000 meters thick, is intruding in this district as a batholith.

(2) If the temp. of the dyke rock, liquid magma in a fissure, is kept at 750°C for 100 years, the surrounding pyrite ore body will get to 700°C within 100 meters range.

(3) When pyrite is heated above 700°C , it will dissociate and convert into pyrrhotite under such a vapour pressure of sulphur less than 1 atm., but at the same time about 200 cc of sulphur vapour (at 1 atm.) will be separated from 1 cc of pyrite (5g in weight).

The pressure of this sulphur vapour becomes exceedingly high. Therefore, even if the pyrite ore body is heated to about 800°C , the dissociation of pyrite will not advance fully, unless there is a suitable path for the sulphur vapour to escape, because the dissociation pressure of pyrite under such temp. is only about 50–80 atm. Thus dissociation of pyrite will be dominated by the easiness of escaping of sulphur vapour.

On the basis of these assumptions, the peculiar distribution of the pyrrhotite and the magnetite, that they exist in the surrounding parts of the pyrite ore body or at the boundary between pyrite and quartz-porphyry dyke, can be explained.

The pyrrhotite, occurring in the shape of vein, will be found along a certain fissure, as sulphur vapour is able to escape through the fissure.

The magnetite can be also interpreted as the final product of pyrrhotite after its further dissociation.

F. On the metamorphism of the country rocks by intrusion of dyke rock

In the country rock near the pyrrhotite and magnetite zone, high temperature metamorphic minerals like cordierite, andalusite, hedenbergite, epidote, tremolite, biotite etc., are not fully recognized, but sericitization, chloritization, silicification and carbonatization are found predominantly. This phenomenon is believed to confirm the assumption that pyrrhotite and magnetite are not made from pyrite by the thermal metamorphism.

But the writers have reached a conclusion that even this phenomenon can be explained as having been brought about by the thermal metamorphism as follows:

(1) The temperature-distribution of the country rocks and pyrite ore body

intruded therein by quartz-porphyry dyke is illustrated in Fig. 18 and Fig. 19. It reveals to the writers that the country rocks are not heated so easily as pyrite ore body. Therefore even if the temperature of the ore body approaches the dissociation temperature of pyrite, the temperature of the surrounding rocks is likely to be still far lower than that of the pyrite ore body.

(2) Under a microscope, remarkable auto-metamorphism, such as sericitization or silicification, is observed in the quenching parts of quartz-porphyry dyke rock, and this metamorphism becomes slighter as it gradually moves toward the center parts of dyke rock.

(3) The temperature of formation of cordierite, epidote, andalusite etc. is thought to be higher than the dissociation temperature of pyrite. Thus, even if the pyrrhotite and magnetite are made from pyrite by thermal metamorphism, these high temperature metamorphic minerals will not always be made under such conditions.

(4) Even if these high temperature metamorphic minerals are crystallized by the thermal metamorphism, it may be that most of them would be decomposed into sericite, chlorite and others by the action which has brought out the auto-metamorphism of the dyke rocks.

From these view-points the writers are led to think that the fact that sufficient high temperature metamorphic minerals are not discovered in the surrounding rocks, can not be taken as a sufficient reason for assuming that pyrrhotite are not the products of the thermal-metamorphism from pyrite.

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Fig. 5 Microphotograph of the boundary part between pyrite and pyrrhotite which east into pyrite along the boundary of pyrite grains and their cracks, and pyrite grains, remaining in pyrrhotite ground, show round shapes.

Fig. 6 (polarizer only), Fig. 7 (crossed nicols) Microphotographs of the boundary part between pyrite and pyrrhotite, showing the anomalous pyrite

Fig. 8 Microphotograph of the boundary part between pyrrhotite and magnetite. Magnetite eats into the pyrrhotite and minute granular or vermicular pyrrhotite grains are scattered in the magnetite ground as remaining shapes.

Fig. 9 Microphotograph of the boundary part between pyrrhotite and magnetite. Magnetite shows a short prismatic or a plate shape as the shape of pyrrhotite.

py.....pyrite, po.....pyrrhotite, mag.....magnetite

柵原鉱山の黄鉄鉱体の熱変質について

(要 旨)

早瀬喜太郎・鞠子 正

岡山県柵原鉱山の黄鉄鉱鉱床はその大部分が微粒黄鉄鉱が緻密に集合した塊状鉱体からなるが、鉱体の外周及び鉱体を貫く石英斑岩脈と鉱体との接触部に屢々磁鉄鉱及び磁硫鉄鉱が分布する。これら磁鉄鉱及び磁硫鉄鉱の成因を知るため、その産状の肉眼的顕微鏡的観察、磁硫鉄鉱 ($\text{Fe}_n \text{S}_{n+1}$) の磁性の測定による硫黄原子率の変化の観察、熱伝導論による鉱体及び周囲岩石の温度分布の計算等を行い、柵原鉱山に産する磁鉄鉱、磁硫鉄鉱は黄鉄鉱がその生成後に熱変成作用を受けて生じた産物であると推論した。