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Pyritic Ore Deposits of the Yanahara District, Japan*

By

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with 5 Tables, 17 Text-figures and 3 Plates

ABSTRACT: The ores of the Yanahara Mine, which has hitherto been widely noted for its leading production of iron sulphide ore in Japan, are deposited only in the 'Yanahara complex' correlative to a member of the upper Permian including a complicated alternation of acidic tuff, slate, rhyolite, dacite, and so forth.

Modes of their occurrence are classified into two types such as the massive, and the disseminated ores, of which the former involvès mainly pyrite together with pyrrhotite and magnetite. The pyrite ore contained conformably in the Yanahara complex seems to have been formed through low-temperature hydrothermal replacement accompanied subsequently with cataclastic, and then thermal metamorphisms. The magnetite, and pyrrhotite ores are found concentrated around pyrite ore bodies and along the fractures cutting across the latter or along quartz porphyry dike, showing no evidence for metamorphism in their textures. Most of these ores seem to have been derived from interaction of the pyrite ore with hydrothermal solution ascending along the fissures distributed around or in the pre-existing pyrite ore bodies, and the formation of some of the pyrrhotite ore related to dikes might have been ascribed to thermal metamorphism.

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** Geological Survey of Japan.

I. INTRODUCTION

Since 1953, the writer has engaged in the research concerning the ore deposits of the Yanahara Mine for pursuing the subject of their "Werden" or "Sollen" in relation to the geological environments appeared in the surrounding area. The ore deposits are situated within specific strata occurred at Yanahara-cho, Kume-gun, Okayama Prefecture. They say that the deposits were discovered in 1603 by Tadamasa Mori, the lord of the Tsuyama Castle and worked for the first time in 1884. These deposits were formerly famous for production of limonitic ores enriched in their oxidation zone and are now well known for high content of the pyritic ores. The annual production of the mine has recently been estimated about 600,000 tons for pyrite ore, 33,500 tons for pyrrhotite ore and 30,000 tons for cupriferrous pyrite ore, remaining more than 27,000,000 tons of ores to be workable in an industrial scale.

Generally speaking, main events in the geological history of the inner zone of the southwestern Japan including the Yanahara district are considered to have been represented by (1) formation and development of the Chichibu geosyncline in Paleozoic, (2) deformation and metamorphism of the sedimentaries by the Akiyoshi (Variscan) orogeny and activity of the syntectonic basic rocks of the Yakuno type, (3) acidic magmatism in the late Mesozoic, (4) local deposition of the Triassic, Cretaceous and Tertiary formations, and (5) igneous activities appeared from Tertiary to Quaternary.

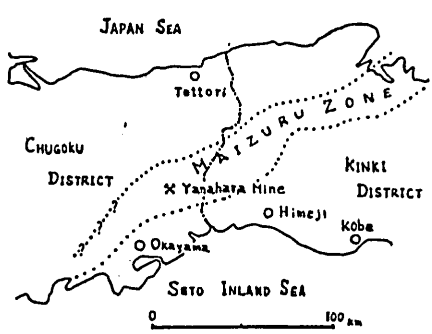

FIG. 1. Map showing the situation of the Yanahara Mine.

There are bulk of contact, and hypo- to meso-thermal ore deposits in the neiborhood of the late Mesozoic granitic batholith. Some meso-thermal and many epi- or xeno-thermal ones might have been formed by certain igneous activities in Tertiary to Quaternary. And it has hitherto been said that the cupriferrous pyritic deposits in crystalline schist as well as the bedded manganese deposits in the Paleozoic formation were related to the magmatism at the initial stage of the Chichibu geosyncline, but this remains yet to be reasonably certified.

In this report, the writer wants to make it clear that the Yanahara ore deposits formed previously by the magmatism at certain stage of the upper Permian were subjected to the subsequent cataclastic metamorphism in the late Permian to Eo-Triassic and then partially to the effects of igneous activities in the late Cretaceous, and furthermore regenerated partially by hydrothermal solution probably accompanied with the late Cretaceous granite.

II. ACKNOWLEDGEMENT

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III. PREVIOUS WORKS

Previous works dealing with the geology and the ore deposits of the Yanahara district are as follows:

S. OTSUKA (1893) is the first to give a short description on the ore deposit with respect merely to the limonite gossan formerly worked in an industrial scale, reporting that barium sulphate associated with the limonite ore might have come from barite contained in the pyrite ore primarily produced.

M. KUHARA (1920) describes in detail on the geology and the ore deposits. His study shows that the ore deposits under consideration were magmatic in origin and derived from differentiation of a basic magma.

T. KATO (1920) studies the deposits concerned especially in connection with magmatism and reaches the following conclusion: All of the igneous rocks appeared in the district were produced from a singular magma yielding mineralizer derived from differentiation of volatile materials for deposition of the pyrite ore at the last stage of the magmatic activity.

In 1952, H. MATSUISHI (1952–1953) first divides the igneous rocks into two groups such as one related to a basic magmatism in the early Mesozoic and the other connected with an acidic magmatism in the late Mesozoic to early Tertiary. He is of opinion that there was an intimate relation of ore deposition to the post activity of the former.

Y. HAYASE and his co-workers (1952–1954) investigate the electrical property of magnetite and pyrrhotite in this mine and find that minerals under consideration are characterized by suggesting thermal effects on the ore deposits after their formation.

Resently, N. OSHIMA (NAKANO, 1957, OSHIMA, 1954, 1958) and his stuffs of the Research Section of the Yanahara Mining Office have found the complex zone composed chiefly of rhyolite, andesite, tuff, shale and sandstone, and that the ore bodies are conformably situated in the complex zone. And OSHIMA (1958) points out that the ores of Yanahara are considerd to have been introduced within the openings resulted by crustal movement.

In addition to the above-mentioned works, there are many other short reports (KOCHIBE, 1895; FUKUCHI, 1902; YATSUMAKI, 1903; TAKIMOTO, 1950; HIGASHIMOTO, 1958; HORIKOSHI, 1958; OGUSHI, 1958).

IV. GENERAL GEOLOGY

Geology cropping out in the Yanahara district is composed of the unknown Paleozoic and the upper Permian formations, diabase and older quartz diorite, older porphyrite, lithoidite, granite, younger rhyolite, quartz diorite, quartz porphyry, younger porphyrite, and Tertiary formation, together with river, and talus deposits.

A. Stratigraphy

1. Paleozoic Formation

The Paleozoic formation is divided into those of the unknown Paleozoic and the upper Permian. The latter is subdivided into the upper member and the lower one here called the Yanahara complex.

(a) Unknown Paleozoic Formation

The formation occurring in the area adjacent to Yukinobu is the lowest member in the district, and composed chiefly of black slate accompanying schalstein and diabase. The slate and the schalstein are remarkably rich in micro- and minor foldings, and show semischist-like appearance.

The formation is conformable with the overlying Yanahara complex, and its lower limit is not distinct. No fossil is found in the formation yet.

(b) Upper Permian Formation

i. *Yanahara Complex*: The complex extending from Shimotani, Hisaki, Shimoyanahara, Yanahara, Kichigahara, Yasumiishi, Matsuo to Dodo is conformable with the overlying and underlying formations. The lower limit of the complex is represented by the lowest bed of sandstone and the upper limit, by the uppermost bed of limestone conglomerate.

In more details, the lower part of the complex is composed of an alternation of slate, basic to intermediate tuff, diabase and sandstone, and the upper part, of a complicated alternation of acidic tuff, slate, intermediate tuff, older rhyolite, dacite, sandstone, tuffaceous conglomerate and limestone conglomerate. Either tuffaceous or limestone conglomerates are included in the upper or the uppermost part of the complex.

The limestone conglomerate recognized in the neighborhood of Dodo is consisted of subangular to subrounded pebbles, some cm or less in diameter, of limestone, black shale, chert, quartz porphyry, basalt and sandstone associated with calcareous matrices. Many fossils are found out in the limestone pebbles and matrices. According to the determination by K. KONISHI (1952) and K. KANMERA (1953), the age of the limestone conglomerate is taken as the upper Permian.

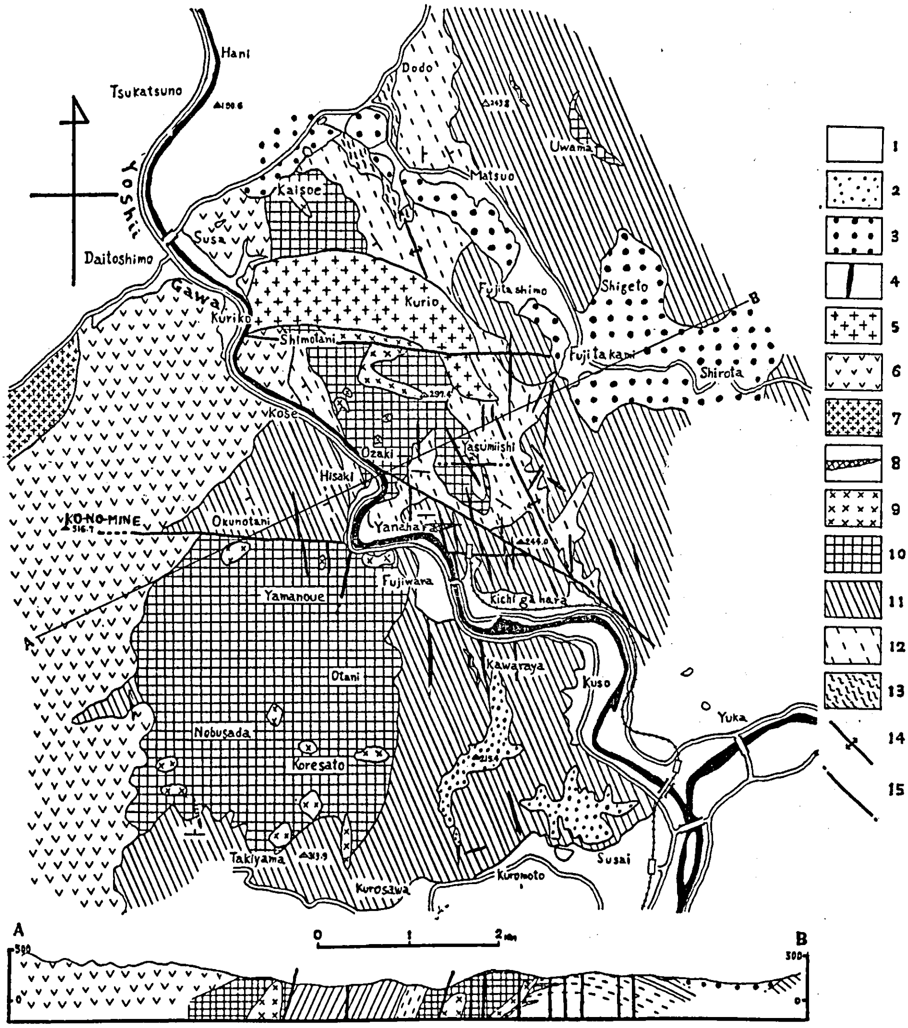

FIG. 2. Geological map of the Yanahara mining district.
1-Quarternary; 2 & 3-Tertiary formation (2-Gravel beds); 4-Dikes; 5-Younger quartz diorite; 6-Younger rhyolite; 7-Granites; 8-Older porphyrite; 9-Older quartz diorite; 10-Diabase; 11-Upper member of Permian formation; 12-Yanahara complex; 13-Unknown Paleozoic formation; 14-Anticline axis; 15-Faults.

The limestone conglomerate appeared in the vicinity of Hisaki is consisted of subangular to subrounded pebbles, 2 cm or less in diameter, of limestone, shale, sandstone, chert and quartz porphyry accompanied with matrices of acidic tuff. Fossils are found included both in the pebbles and in the matrices. The limestone conglomerate distributed around Yasumiishi is consisted of subangular to subrounded pebbles, some cm in diameter, of limestone, shale, basalt, sandstone, chert and quartz porphyry contained in matrices of calcareous shale and acidic tuff.

All of the limestone conglomerate are stratigraphically not basal but interbedded. In general, acidic tuffs are predominant in the southern part of the district including most of the ore deposits, and basic to intermediate tuffs are so in the middle part comprising the Yasumiishi deposit, while pyroclastic rocks are scarce in amount in the northern part of the district where none of the deposits has been found yet.

Microscopic inspection indicates that parts of basic tuffs are consisted of fragments of basalt and andesite associated with feldspar, chlorite, very little amount of quartz, sericite and magnetite. Acidic tuff is composed either of fragmental quartz and feldspar or of their tiny grains together with recrystallized quartz and feldspar, chlorite and sericite. Dacite, porphyritic in texture, is composed of phenocrysts of feldspar and a little amount of deformed and fragmental quartz included in holocrystalline groundmass containing aggregates of quartz and feldspar, biotite, chlorite, and ore minerals. The older rhyolite, spherulitic in texture, is consisted of microspherulitic or micrographic groundmass containing phenocrysts of quartz and feldspar with a little amount of biotite, sericite, chlorite, and ore minerals.

All of the rocks in the complex are characterized by their cataclastic textures. Quartz and feldspar crystals are crushed, and the former shows an undulatory extinction. Recrystallized grains of quartz and sericite, showing parallel orientation, are found in the slate and acidic tuff. And all of the rocks contain biotite occurring as aggregates of the fine flakes in random arrangement, suggesting their formation through thermal effects after dynamic metamorphism.

ii. *Upper Member of the Upper Permian Formation:* The member distributed from Hisaki, Kawaraya, Soda to Uwama lies conformably over the Yanahara complex and is covered unconformably by the younger rhyolite and the Tertiary formation.

In the western part of Hisaki, slate intercalated with acidic tuff and sandstone is predominant. The member is composed of slate either with subordinate amount of sandstone in the area adjacent to Kichigahara and Soda or with considerable amount of sandstone in the western part of Kawaraya and the southwestern part of Uwama.

2. Tertiary Formation

The Tertiary formation appearing in the vicinity of Fujita and Yukinobu covers unconformably the Paleozoic formation and the younger rhyolite. The formation in question is slightly tilted and is composed of conglomerate, sandstone, and an alternation of sandstone and shale with thin lignite seams in ascending order. The conglomerate contains the pebbles of slate, sandstone, diabase, quartz diorite and younger rhyolite. The very formation is determined as a part of the Miocene on the basis of the fossil assemblage contained and may be correlated to that occurring in the Tsuyama basin designated by J. YATSUMAKI (1903) and T. KATO (1922).

Gravel beds covering the flat planes, about 50～100 m high above the present river bed, are frequently found in the district, composing of rounded to subrounded pebbles of schist, slate, sandstone, quartz diorite, diabase, quartz porphyry and rhyolite. The size of the pebbles is generally 1～10 cm in length. The bed frequently intercalates thin seams of sand and clay, in which no fossil is found, and has been correlated to the gravel beds of the Miocene formation by T. KATO.

3. River Deposits and Talus Deposits

Gravels, sands and muds are found accumulated on the beds of the Yoshii river and some of its tributaries, and talus deposits, at Kichigahara and Kuso. These are of the Quaternary deposits.

B. Igneous Rocks

1. Diabase: Diabase occurs either as lava flows, intercalating conformably in the Paleozoic formation and associated with tuff, or as intrusives intruding into the Paleozoic formation and situating, in parts, concordantly or discordantly with the structure of the formation.

Commonly diabase is too crushed and too altered to indicate its original textures. The rock is composed of plagioclase, amphibole and accessory minerals such as quartz, chlorite, epidote, apatite, biotite and magnetite. Plagioclase and amphibole are crushed and altered. Amphibole and feldspar are replaced by chlorite and epidote filling the fractures developed within the former.

Aggregates of fine flakes of biotite are scattered in random orientation throughout the rock. Biotite replaces amphibole and chlorite, and is closely associated with actinolite replacing chlorite and amphibole, suggesting that biotite and actinolite might have been produced by thermal metamorphism.

2. Older Quartz Diorite

The rock is closely associated with intrusive diabase, and is situated commonly within, and sometimes in the border of, the diabase or rarely in the Paleozoic formation. Various modes of its contact with diabase are appeared, in places, being sharp, confused, plany or irregular. The rock is covered with younger rhyolite on one hand, and is intruded by younger quartz diorite on the other.

The rock is petrographically heterogeneous, indicating various—dioritic, quartz dioritic, granodioritic, granitic and aplitic—facies in different portions even within a unit mass. In view of this, differentiation is very conspicuous even in a small rock mass.

Under the microscope, the rock shows protoclastic feature in such a texture that large crystals of quartz and feldspar are crushed, and small grains of quartz and feldspar fill fractures in the former. The small crystals are not crushed, but each grain of quartz show an undulatory extinction.

The large crystals of feldspar are considered to have been subjected to bending, shifting and saussuritization producing zoisite, chlorite, sericite and albite. The feldspar is determined as oligoclase-andesine group by indices of refraction. The small crystals of feldspar are observed filling interstices of crushed and larger ones.

Hornblende indicates a sort of bent and crushed texture with severe alteration to chlorite, epidote and magnetite, and is replaced by biotite and actinolite.

Quartz is one of the main constituents in the granitic or aplitic facies, and, at the same time, an accessory mineral in the dioritic facies. The large quartz crystals are crushed and show a remarkable undulatory extinction, and their interstices are filled with small crystals of quartz and feldspar.

K-feldspar is abundant in the granitic and aplitic parts, but scanty in the other parts. Large crushed crystals of K-feldspar and noncrushed small ones are distinguishable from each other. The latter shows milmekitic intergrowth with quartz, and fills fractures of the former.

Both chlorite and epidote occur as alteration products of hornblende, probably ascribed to deuteric origin. Biotite and actinolite occur as aggregates of random-orientated fine crystals and replace chlorite and amphibole.

Thus the older quartz diorite is evidently characterized by its protoclastic texture, close association with the intrusive diabase, and conspicuous differentiation in situ. From its texture it seems clear that the rock was subjected to severe stress during intrusion and solidification, when minerals previously crystallized were crushed, and then crystallization of unsolidified portion of the magma as well as formation of small crystals of quartz and feldspar filling interstices of the early solidified and crushed crystals might have followed.

3. Older Porphyrite

The rock, occurring as dikes cutting across the Paleozoic formation, has a characteristic in its texture produced not by cataclastic metamorphism but by thermal effect.

Microscopically the rock shows such a porphyritic texture that holocrystalline groundmass is consisted of lath-shaped feldspar and interstitial quartz, while phenocrysts are composed of idiomorphic crystals of plagioclase. Biotite occurs as aggregates of fine flakes scattering throughout the rock, and replaces feldspar. Judging from its mode of occurrence, the biotite might have been secondarily produced by thermal metamorphism.

4. Lithoidite

The rock, occurring as dikes cutting across the Paleozoic formation, ore bodies, diabase and the older quartz diorite, shows no cataclastic texture, but contains aggregates of random-orientated fine flakes of biotite assumably produced by thermal metamorphism.

5. Granite

In the southern part of Daito, a stock of granitic rocks is exposed and covered by the younger rhyolite. Its relation to other rocks is not known because of its occurrence isolated in the younger rhyolite.

The rock mass is a sort of composite stock representing various facies such as hornblende-biotite granite, porphyritic granite and fine-grained granite within a continuously exposed mass in different portions. These are not cataclastic in texture, and show no evidence for thermal metamorphism.

In general, K-feldspar, quartz, plagioclase, biotite, apatite, magnetite, and so on are microscopically identifiable, and mineral assemblages, however, are dependent on the respective facies.

6. Younger Rhyolite

The western part of the district is covered by the younger rhyolite. The rock covers either the erosion surface of the Paleozoic formation or the syntectonic intrusives and is intruded by the younger quartz diorite, quartz porphyry and younger porphyrite.

The rock in question shows commonly a brecciated texture but rarely a non-brecciated facies in some places. Gradual transitions from one to the other are also clearly observed.

The younger brecciated rhyolite contains numerous angular fragments, ranging from some mm to some cm in their size. Under the microscope, features of fragments and of cementing materials are hardly distinguishable, but sometimes slaty or diabasic fragments are found. As T. Kato (1922) described, "Most of the fragments of the rhyolite are clearly derived from previously solidified portions of the effusive mass of the same lava, whereas those of slate and diabase might have been captured from any other source in the depth on the way of its extrusion."

The rock concerned is consisted of granophyric or microspherulitic groundmass associated with spherulite and abundant phenocrysts composed of quartz and feldspar in clear-colored and corroded state. Little amount of plagioclase, biotite, chlorite, epidote and calcite are recognizable as accessory minerals.

The rock shows such a texture as was produced not through dynamic metamorphism but through thermal effects given by the younger quartz diorite and the late Cretaceous granite, and is found cutting across the ore bodies.

7. Younger Quartz Diorite

The rock appeared as a stock penetrating into the Paleozoic formation, ore bodies, syntectonic intrusives and younger rhyolite is cut by the younger porphyrite.

It is homogeneous in petrographical feature, medium-grained and gray in colour. No textures produced by cataclastic and thermal metamorphisms are observable.

Under the microscope, the rock, holocrystalline, hypidiomorphic and granular, is composed of andesine-oligoclase, hornblende, and small amount of quartz and K-feldspar associated with accessory minerals such as apatite, epidote, allanite and magnetite.

8. Quartz Porphyry

The rock occurs abundantly as dikes with strike of N 10°~20° W, cutting across the younger rhyolite as well as across the older rocks and formations.

The rock composed of microgranitic groundmass together with phenocrysts of large crystals of quartz and feldspar has no texture or minerals suggesting the effects relating to thermal or cataclastic metamorphism. The dikes in question are found cutting across the pyrite ore bodies, and giving thermal effect on the latter, as are observed at the Yanahara main ore deposit.

9. Younger Porphyrite

Porphyrite occurs abundantly as dikes ranging from 2 to 3 m in width and cutting across the younger quartz diorite, quartz porphyry and other older rocks, but not across the Tertiary formation. In contrast to the quartz porphyry dikes, strikes of the younger porphyrite dikes are NS or EW. Lithologically, the rock concerned is considered to belong to a sort of auguite porphyrite.

C. Mutual Relationship of Igneous Rocks

As was mentioned in the paragraph of the previois works, M. Kuhara (1920), T. Kato (1922) and H. Matsuishi (1951, 1952) already described on the igneous activities appeared in the district. The writer here proposes some views on the problem from a standpoint different from those of the former investigators.

The igneous, and pyroclastic rocks distributed within the district are divided into the following:

(1) Basic tuff and diabase interbedded in the unknown Paleozoic formation,
(2) Diabase, dacite, rhyolite, basic to acidic tuff of the Yanahara complex and rhyolite, and acidic tuff of the upper member of the upper Permian formation,
(3) Diabase and older quartz diorite intruding into the Paleozoic formation during the tectonic movement,
(4) Older porphyrite and lithoidite which are later in stage than the cataclastic metamorphism, but earlier than the thermal metamorphism,
(5) Granite, younger rhyolite, younger quartz diorite, and quartz porphyry,
(6) Younger porphyrite which is later in stage than the quartz porphyry.

The rock of the group (1), which are, judging from their occurrence, considered to have been formed by the initial magmatism in the Chichibu geosyncline, are interbedded in the unknown Paleozoic formation. Those belonging to the group (2) might have been formed by igneous activity taken place in the sedimentary basin of the upper Permian deposited in the Chichibu geosyncline during the later period of its development.

Though the magmatism is often considered to originate acidic rock facies at the initial stage of its activity, there may also not be the case with certain places in the world (STILLE, 1940, KAY, 1951, GORAI, 1952). The initial volcanism of the Yanahara district is not peculiarly thought to have been acidic. On the other hand, striking is that the upper Permian formation is not associated with pyroclastics in other district of Japan (KANMERA, 1953), but the very formation of the Yanahara district is rich in the latter.

The rocks belonging to the group (3) are closely associated with one another and must have been differentiated from a single magma. The diabase appears to have intruded into the Paleozoic formation concordantly in most parts and discordantly in some parts. Most of the older quartz diorite is enclosed in the diabase and has a protoclastic texture. It thus seems to be conclusive that the group (3) might have been syntectonic intrusives. The group under consideration is able to correlate to the Yakuno basic rocks assumed as have been later than the upper Permian formation and as have intruded during the tectonic movement of the Maizuru zone at certain stage between the late Permian and Eo-Triassic. The period is believed to have been most important in the so-called Akiyoshi orogenic cycle corresponding to the Variscan orogeny in Europe (NAKAZAWA and Others, 1958).

The dikes of the group (4) are found cutting across the older rocks and formations with vertical or nearly vertical contact. Their activity seems to have been later than the tectonic movement and earlier than the thermal metamorphism given by the Cretaceous granite.

The rocks of the group (5) have a genetic relation to the igneous activity in certain period from the late Cretaceous to early Tertiary in the light of the general trend of igneous activities appeared throughout the Chûgoku district.

The younger rhyolite is correlative to the rhyolite, widely distributed in the Chûgoku district, of the late Cretaceous. The granite and the younger quartz diorite may belong to the 'Central plutonic rocks' named by G. Kojima (1957). Dr. Kato (1922) was of opinion that the quartz porphyry dikes were the offshoots or forerunners of the supposed cryptobatholith of Hiroshima-type granitic rocks.

The porphyrite of the group (6) is believed to have been formed later than the block movement producing EW fractures after the intrusion of the quartz porphyry, and older than the Tertiary formation.

In conclusion., the igneous rocks and the pyroclastic rocks of the Yanahara district are divided into six groups or six igneous activities clearly distinguishable from one another, whereas the view given by M. Kuhara (1920) and T. Kato (1922) is that all of the igneous rocks located within the district concerned are consanguineous and H. Matsuishi (1951; 1952) believes that those were derived twice from certain igneous activities.

D. Ore Deposits and Igneous Activities

In the Yanahara district, pyrite ore bodies are found cut by the younger porphyrite, quartz porphyry, quartz diorite, rhyolite and lithoidite, among which the quartz porphyry and younger quartz diorite seem to have played an important role in metamorphism of the ores at their contact, suggesting the formation of ore bodies earlier in stage than these rocks. The ores show a conspicuous mode of occurrences, e.g. in such a manner that they are conformably situated in the Yanahara complex and, however, are discordant with the country rocks.

Dikes or stocks of the diabase and the older quartz diorite cutting through the ore bodies are nowhere observable, and no ore body is situated in the rocks. The writer believes that genetically the pyrite ore bodies of the Yanahara Mine have no relation to the older quartz diorite on the basis of the following reasons: (1) the ores located in contact with or near the older quartz diorite indicate no evidences for such mineral compositions as are ordinarily expected, (2) their deposition seems to be not syntectonic with intrusion of the older quartz diorite and, (3) granting that the mineralizer came from the older quartz diorite, diabase previously solidified must have been mineralized to certain extent, and the ores in question might have been distributed in more close connection with the older quartz diorite.

It results in that the syntectonic intrusives must be those formed after deposition of the pyrite ores.

The pyrite ore bodies are found involved only in the Yanahara complex, and are situated conformably with the country rocks, being associated closely with tuff. From pretectonic textures of the pyrite ores it may be deduced that their genesis is to have been related to the volcanism of the Yanahara complex accompanying its own sedimentation.

E. Correlation of the Paleozoic Formation

It seems conspicuous that the unknown Paleozoic formation is older than, and conformable with, that of the upper Permian with only a slight interval of time.

As was determined by the fossil assemblage contained in the interbedded limestone conglomerate, the Yanahara complex is of the upper Permian. Both the matrices and limestone pebbles included in the limestone conglomerate contain the fossil assemblage representing the age of "Zone of Lepidolina" designated by K. KANMERA (1953). The member lying conformably over the Yanahara complex must be of the upper Permian and may be correlated, in parts, to the Kose (NAKAZAWA and others, 1954), the Nukada (NAKAZAWA and others, 1957) and the Maizuru formations (NAKAZAWA and others, 1958) of the Maizuru zone as well as to the Kuma formation in the southern Kyûshu (KANMERA, 1953).

Geologically, the Yanahara district is located in the Maizuru zone characterized by distribution of the late Permian formation and the intrusives of the Yakuno type (MATSUSHITA, 1950, 1953; NAKAZAWA and others, 1954).

F. Period of Dynamic Metamorphism

Only from the data of the Yanahara district, the age of the dynamic metamorphism seems to have been earlier than that of the older porphyrite and the lithoidite, and later than that of the upper Permian formation. But synthetic consideration on regional data obtained from the surrounding area appears to give a clue to more accurate determination.

K. NAKAZAWA and his co-workers (1958) investigating the Maizuru zone are of opinion that "an orogenic stage confirmed between the late Permian and Eo-Triassic is considered to have been most important in the so-called Akiyoshi orogenic cycle". It thus follows that the dynamic metamorphism associated with the orogenic movement in the district might have taken place in the late Permian to Eo-Triassic.

G. Period of Thermal Metmorphism

Biotite hornfels widely distributed in the Yanahara district are characterized by abundant biotite occurring as microscopic aggregates of random-orientated flakes scattered throughout the rocks. The grade of the thermal metamorphism is weaker in the northern part of the district and stronger in the southern part where Cretaceous granite of the Hiroshima-type is exposed. Since distribution of the hornfels is closely connected with that of the Hiroshima granite accompanying widely the aureole of the former, the thermal metamorphism recognized in the district might have been caused by the very granite. The occurrence of the hornfels suggests its relation to the granite to be a sort of a roof contact, and the batholithic mass of the intrusive is assumed to be concealed beneath the present surface. The contact metamorphism by the older quartz diorite is not discriminated, while, on the other hand, metamorphic aureole with only a narrow width by the younger one is observable.

H. Structures

1. Folds: The Paleozoic formation in the northeastern part of the district shows gentle folding, an anticlinal axis of which extends from Yukinobu to Kichigahara. The axes of the folds in the western part are recognized parallel to the Shimotani–Shimoyanahara line, and a gently synclinal folding is common in the southern part. The Tertiary formation is observed slightly tilted.

2. Faults: Those named the Kurio–Shimotani, the Ozaki–Shimotani, and the Okunotani–Fujiwara faults are remarkable in the district. There are many minor faults of EW and NS trends. NS faults are commonly older than those of EW strike. Some of NS faults cut across the pyrite ore bodies and some are filled with magnetite and pyrrhotite ores. EW faults also are found cutting through the pyrite, the magnetite and the pyrrhotite ore bodies. All of the faults are classified as normal faults.

V. ORE DEPOSITS

A. Classification of Ores and Ore Bodies

Ores of the Yanahara Mine are used to show massive, and disseminated occurrences, and the massive ores are divided into such groups as are mainly composed of pyrite, pyrrhotite and magnetite respectively, among which the former is most abundant and the latter two are less in their amount.

TABLE 1. ESTIMATED AMOUNT OF REMAINING ORES.

Ores	Tons	%	Contents (%)		
			Cu	S	Fe
Pyrite ore	24,978,232	90.6		50	
Disseminated pyrite ore in high grade	1,223,846	4.5		40	
Cupriferrous pyrite ore	151,800	0.6	2.0	47	
Pyrrhotite ore	1,165,630	4.3		37	56
Magnetite ore	25,959	0.1			61
Total	27,545,467				

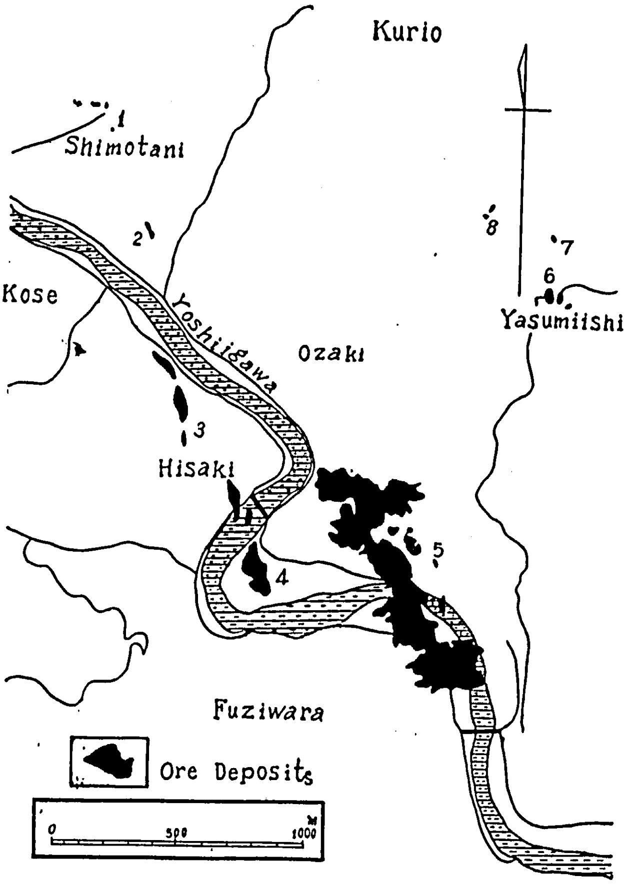

FIG. 3. Distribution map of the ore deposits.
1-Shimotani; 2-Hitashiro; 3-Hisaki; 4-Shimoyanahara; 5-Yanahara main deposit; 6-Yasumiishi; 7-Hoden; 8-Kanabori.

B. Forms of Ore Bodies and Occurrences of Ores

1. Disseminated Ores

Most of the disseminated ores are composed of pyrite as an essential ore mineral, and some are of pyrrhotite.

The pyrite ores of this type are scattered in the zone between massive ores and tuff with a width of several decimeters to more than ten meters and show gradual transition into tuff. Their contacts with the massive pyrite are, in places, gradual or sharp. There are similar cases in dissemination appeared between the older rhyolite and the massive pyrite with a narrow width, but the occurrence of this type is nowhere recognizable between the pyrite ore and slate.

Shape of the disseminated ore seems to be dependent on that of the space intervening between the massive pyrite ore body and tuff bed.

The disseminated pyrrhotite ores are situated along faults and around their massive bodies within a narrow zone.

2. Massive Ores

Pyrite ore bodies are lenticular or of irregular spindle in shape (Fig. 4, 10). Their volumes are 35m (strike) × 50m (dip) × 10m (width), 30 × 20 × 7, and 35 × 20 × 10, etc. at the Shimotani ore deposit, 120 × 50 × 15, 80 × 55 × 20, etc. at the Hisaki (Fig. 4), 90 × 100 × 30, etc. at the Shimoyanahara, that of No.

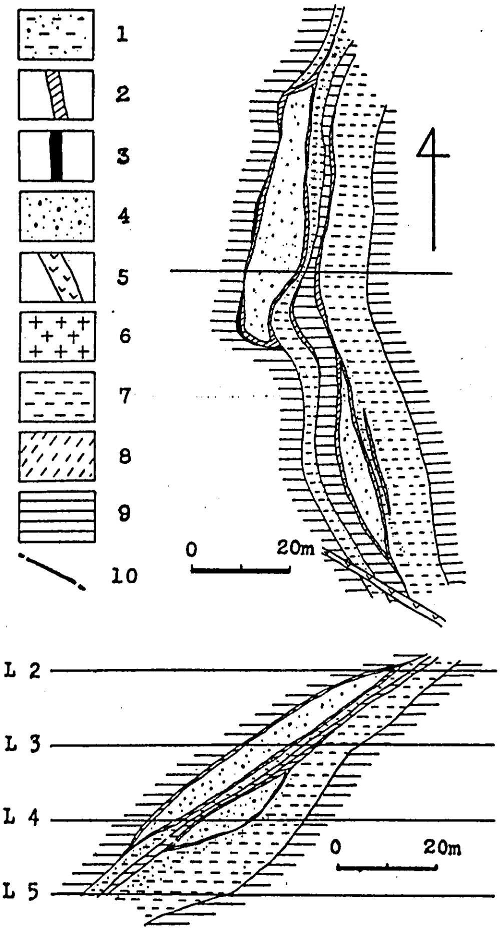

FIG. 4. Geological map on the 3rd level and cross-section of the Hisaki ore deposit.
1-Disseminated pyrite ore; 2-Pyrrhotite ore; 3-Magnetite ore; 4-Pyrite ore; 5-Porphyrite; 6-Quartz porphyry; 7-Acidic tuff; 8-Dacite; 9-Slate; 10-Fault. (This legend is drawn almost similarly in the figures of this report.)

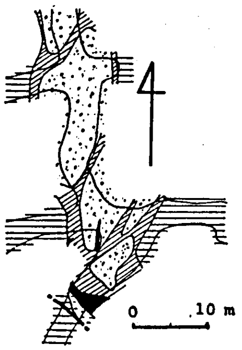

FIG. 5. Geological map on the 6th level of the Shimoyanahara ore deposit, showing relation among pyrite ore, pyrrhotite ore and magnetite ore.

I ore body is 250 × 200 × 150, No. II ore body has nearly the same dimension as the former, and that of No. III ore body is 400(+) × 300 × 100(+) at the Yanahara main ore deposit (Fig 10). The pyrite ore bodies occurred at Yasumiishi, Hoden, Kanabori, Hinotani and Hitashiro have nearly the same shapes and dimensions as those appeared at Hisaki and Shimotani.

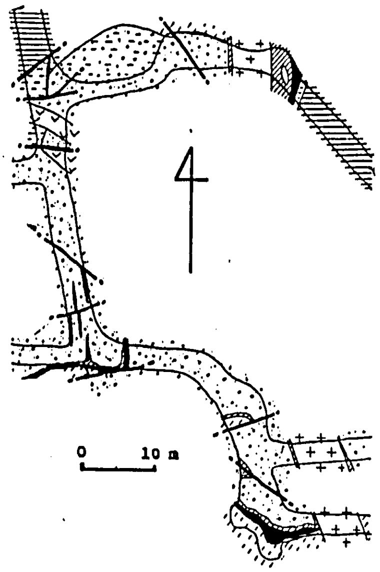

FIG. 6. Geological map on the 21st level of the Yanahara main ore deposit, showing the mode of occurrence of the border, vein, and dike pyrrhotite ores and the border magnetite ores.

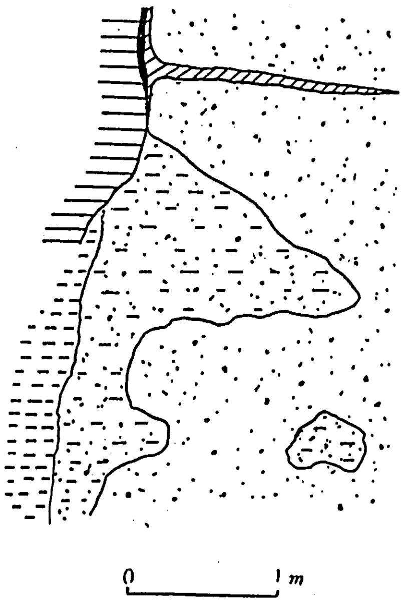

FIG. 7. Sketch showing the mode of contact between pyrite ore and acidic tuff, and relation between the pyrite ore and vein pyrrhotite ore. The contact is gradual, and the pyrite ore passes with transition into disseminated pyrite ore and further into acidic tuff impregnated with pyrite. The vein pyrrhotite cuts acrsos the pyrite ore.

Pyrrhotite ore bodies are situated around the pyrite ore bodies (the border pyrrhotite) (Fig. 4, 5, 6, 9, 10, 11, 12,), or along the fractures cutting across the pyrite ore bodies (the vein pyrrhotite) (Fig. 5, 6, 7, 9, 11), or along the quartz-porphyry dike intruding into the preexisting pyrite ore bodies (the dike pyrrhotite) (Fig. 6). The pyrrhotite ore bodies situated along fractures are closely connected with those situated around pyrite ore bodies (Fig. 5, 6, 7, 9, 11). All of the pyrrhotite ore bodies are always in contact with pyrite ore bodies, and not observable in a separated place distant from the latter.

It seems common that the border pyrrhotite ore bodies are of several centimeters to some meters in width, the vein pyrrhotite, of some centimeters to some decimeters, and the dike pyrrhotite, of 5∼10 cm.

Magnetite ores are often found situated around the border pyrrhotite and pyrite ore bodies (the border magnetite) (Fig. 4, 5, 6) along fractures of joints and faults cutting across pyrite ore bodies (the vein magnetite) (Fig. 5, 6, 11) and along quartz

FIG. 8. Sketch showing the mode of contact between pyrite ore and acidic tuff. The contact is gradual, and there are many replacement remnants of acidic tuff in disseminated ore.

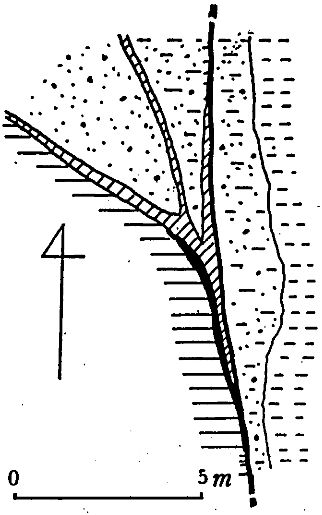

FIG. 9. Geological map on the 2nd level of the Hisaki ore deposit, showing details of relation among the pyrite ore, the border and the vein pyrrhotite ore, and the border magnetite ore. There are pyrrhotite ore around pyrite ore body, and between pyrite ore and disseminated pyrite ore. Magnetite ore is situated around the border pyrrhotite ore and along fault. The magnetite ore and the pyrrhotite ore are closely associated with each other. The border pyrrhotite ore and the vein pyrrhotite ore are connected with each other.

porphyry dike (the dike magnetite) (Fig. 6). Magnetite ore bodies are always associated with pyrrhotite and pyrite ores. Commonly the border pyrrhotite ores are observed between the pyrite, and border magnetite ore bodies (Fig. 5, 6), but sometimes the magnetite ores come into contact directly with pyrite ore. There are no ore bodies of magnetite isolated completely from the pyrrhotite, and pyrite ore bodies. This fact seems to suggest an intimate connection of the pyrite ore bodies with formation of the pyrrhotite, and magnetite ore bodies to be expected. The pyrrhotite, and the magnetite ores are similar to each other in the mode of occurrence and are considered to have been formed later in stage than the pyrite ore bodies.

C. Relation between Ores and Igneous Rocks

Generally speaking, pyrite ore bodies seem to be rich in amount in the places where acidic tuff is abundant, pyrrhotite ore, in the places where thermal metamorphism is relatively remarkable or in the vicinity of the younger quartz diorite or along quartz porpyry dike, and magnetite ore, in the places where the pyrrhotite ore is predominant.

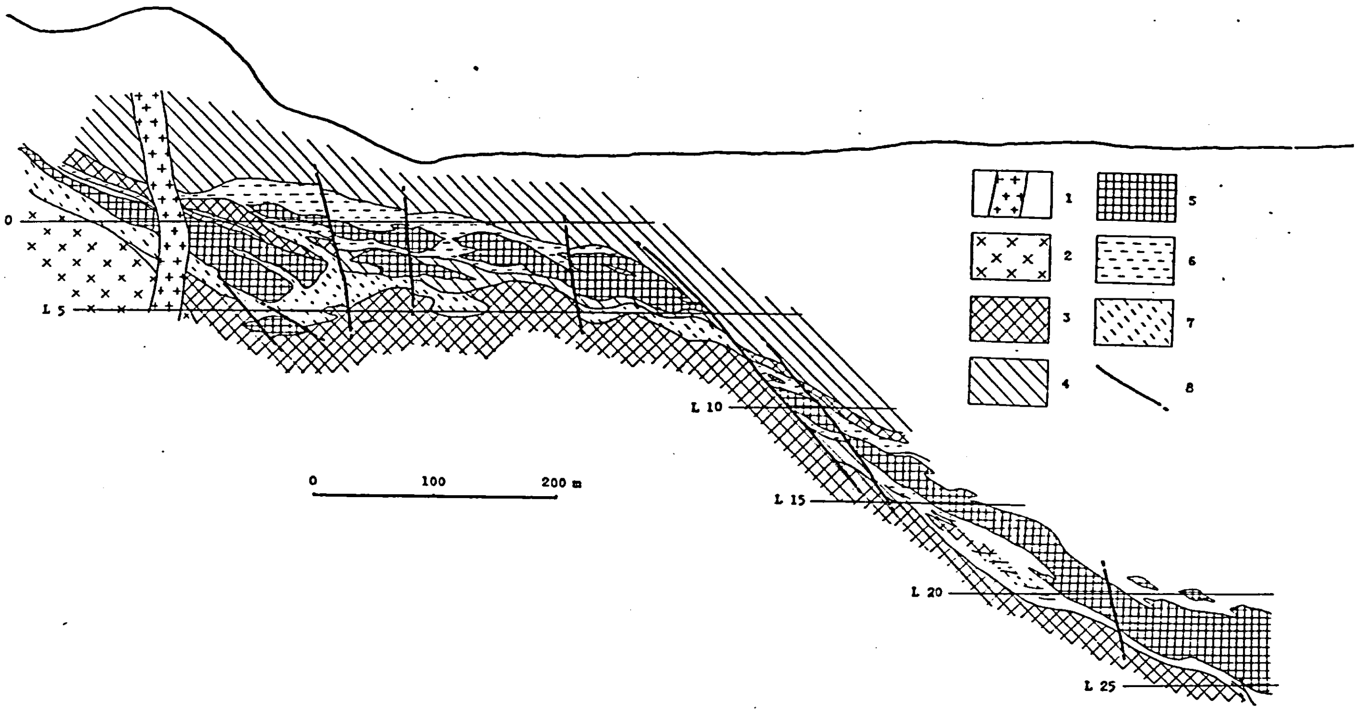

FIG. 10. Geological profile through the ore bodies of the Yanahara main ore deposit (after T. OSHIMA and partly revised by the writer).
1-Quartz porphyry; 2-Older quartz diorite; 3-Diabase; 4-Slate; 5-Ore bodies; 6-Acidic tuff and older rhyolite; 7-Dacite and tuff; 8-Fault.

D. Relation between Ores and Country Rocks

1. Pyrite Ore Bodies and Yanahara Complex

The Yanahara complex holding the thickness of 200~250m in an average shows the trends such as N 10°~20°W, 70°W at Shimotani, N 20°~30°W, 50~70°W at Hitashiro and Hisaki, NS~N 20°W, 10°~20°W at Shimoyanahara, EW, 20°~30°S at Yanahara, and N 20° W, 10°~20°W at Yasumiishi.

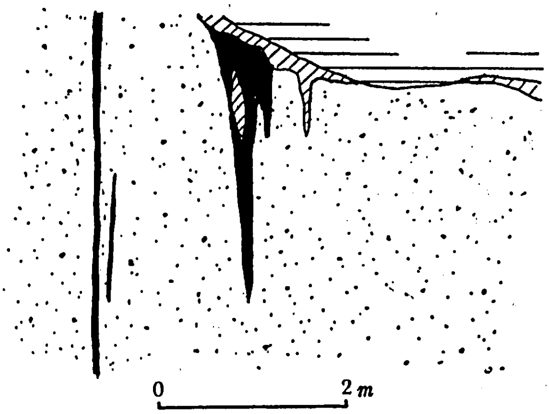

FIG. 11. Sketch showing the mode of occurrence of magnetite ore in pyrite ore, and relation among pyrite ore, pyrrhotite ore and magnetite ore, on the 6th level of the Shimoyanahara ore deposit. The magnetite ore is situated along fractures in the pyrite ore bodies.

Pyrite ore bodies are found situated conformably with the complex (Fig. 4). With increase of the ore bodies in thickness, the complex seems to become of more thickness and vice versa. The shape of the former also depends on the occurrence of the latter: for example, the ore bodies show acute foldings (Fig. 13) in accordance with the structure of the complex wherein boudinages of the former (Fig. 14) are also found contained.

The complex found at Shimotani is composed of slate, acidic tuff and older rhyolite, and intruded by diabase, older quartz diorite, younger quartz diorite and younger porphyrite. Most of the ore bodies are conformably situated between slate and acidic tuff, and, in parts, in slate. Both the younger rhyolite and the younger porphyrite are observed penetrating into the pyrite ore bodies.

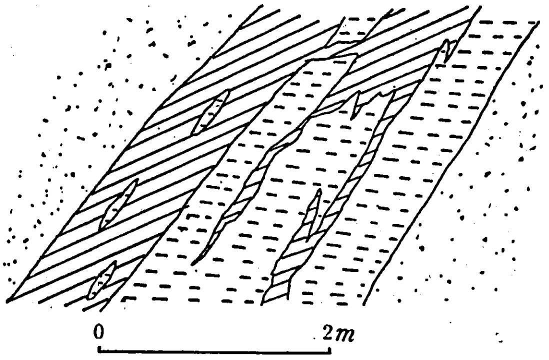

FIG. 12. Sketch showing the mode of occurrence of pyrrhotite ore on the 4th level of the Hisaki ore deposit. The pyrrhotite ore is situated between pyrite ore body and tuff or in tuff, and is discordant with tuff bed.

The complex distributed at Hitashiro and Hisaki is composed of acidic tuff, slate, older rhyolite, dacite, tuffaceous conglomerate and limestone conglomerate. Larger masses of ore bdies are situated between slate of the hanging wall and acidic tuff of the foot wall. In parts, there are ore bodies between slate and older rhyolite, and between slate and dacite.

The complex located at Shimoyanahara is composed of slate and acidic tuff. The ores are considered to be closely associated with acidic tuff, and indicate a transition from massive bodies, through their dissemination, and into acidic tuff impregnated with pyrite.

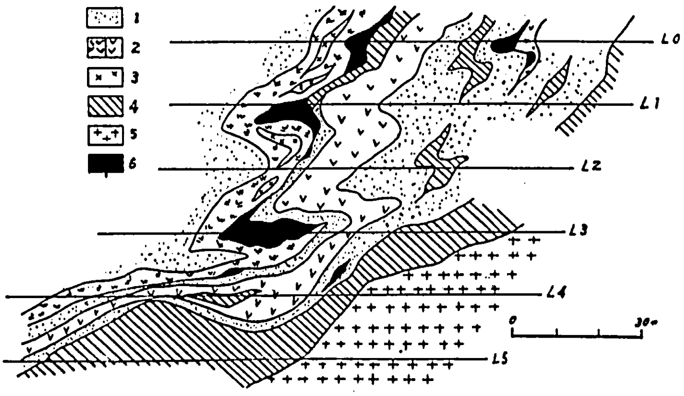

FIG. 13. Cross-section through the ore bodies of the Hitashiro ore deposit (after the Yanahara Mining Office and partly rivised by the writer).
1-Slate; 2-Acidic tuff and older rhyolite; 3-Dacite and tuff; 4-Diabase; 5-Older quartz diorite; 6-Ore bodies. The ore bodies and the country rocks are remarkably folded and deformed, and there are large ore bodies at the apexes of folds. The ore bodies are concordant with structures of the country rocks.

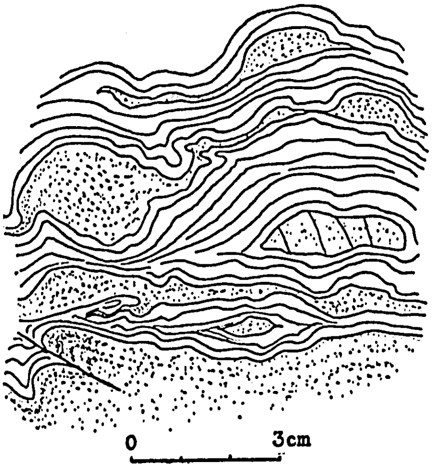

FIG. 14. Sketch showing boudinage and folding of pyrite ore bodies in a minor scale on the 2nd level of the Hisaki ore deposit. The pyrite ore bodies are remarkably sheared and deformed, and boudinages are resulted. Minerals in the ore bodies show more or less parallel arrangement.

The complex recognized near the Yanahara main deposit is composed of acidic tuff, intermediate tuff, slate, older rhyolite, dacite and tuffaceous conglomerate. Similarly, ore bodies are in a close relation to acidic tuff.

The complex observed near Yasumiishi is composed of basic to intermediate tuff, slate, acidic tuff, older rhyolite, diabase and limestone conglomerate. Ore bodies are also accompanied with tuffs.

2. Relation between Pyrite Ore Bodies and Wall Rocks

The relation of pyrite ore bodies to acidic tuff is commonly transitional (Fig. 7, 8, 9), and their contacts with slate, dacite and diabase are mutually well-demarcated (Fig. 14), while either gradual or sharp contacts of the ores are found in the case with the older rhyolite.

It is to be noted that, in certain parts where transition from the ores to their country rocks is continuous, the grain-sizes of the disseminated pyrite increase with approaching to the massive ore, that, in parts where pyrite grains are not so much abundant, the original textures of the wall rocks are partly reserved, and that, in parts where pyrite grains are numerous in amount, their original figures are scarcely reserved or are changed at all.

3. Relation of Pyrrhotite, and Magnetite Ore Bodies to Wall Rocks

The fact may be that magnetite ore bodies have no special connection with certain country rocks. Their contacts with slate are sharp and plany, and those with tuff and diabase are of complication. The ores under consideration are involved as impregnations in tuff and diabase.

The relation of pyrrhotite ore bodies to country rocks are similar to that in the case of magnetite. Their contacts with country rocks are sharp and plany, but some of pyrrhotite grains are impregnated in country rocks such as tuff or rhyolite.

E. Wall Rock Alteration

1. Hydrothermal Alteration Associated with Pyrite Mineralization Prior to Dynamic Metamorphism.

Sericite, chlorite and pyrite are contained in the wall rocks appeared near the pyrite ore bodies more abundantly than are far from them. Most of the minerals composing the wall rocks are replaced by sericite, chlorite and pyrite, showing a variation in their textures with approaching to the ore bodies.

Acidic tuff is gradually changed to quartz-sericite-pyrite rock near the contact of pyrite ore bodies. Where the rock is chiefly composed of quartz, sericite and pyrite with small amount of barite, chlorite, chalcopyrite and sphalerite, its original texture is almost vanished with such exception that relatively large corroded crystals of quartz are rarely found as relicts of acidic tuff.

Under the microscope, two kinds are discriminated in quartz contained in the rock. Relatively large crystals are crushed and replaced by pyrite, sericite and small crystals of quartz, of which the latter have a close association with pyrite and sericite, occurring as granular aggregates. From their occurrence both kinds of crystals are deducible to have been formed under the non-stress condition.

Sericite occurs in aggregates of random-orientated fine flakes, indicating weaker birefringence than those formed by dynamic metamorphism.

Pyrite, 0.1–0.5 mm in size, is granular, scattered throughout the rock in an intimate relation to sericite and shows either remarkably zonal or rarely colloform textures (Pl. 5) which are considered to have not been produced under the stress condition.

Barite is closely associated with sericite, pyrite and quartz. Chlorite, sphalerite and chalcopyrite are closely accompanied with sericite and pyrite.

The quartz-sericite-pyrite rock occurs within some centimeters to some decimeters around the pyrite ore bodies. Along the outer side the altered rocks contain feldspar, decreasing amount of pyrite and sericite and increasing amount of chlorite.

The older rhyolite near the pyrite ore bodies contains pyrite, chlorite and epidote. The alteration of the rock is not so noticeable as that of acidic tuff, and limitted within a narrow zone.

Near the pyrite ore bodies, both basic and intermediate tuffs are altered to chlorite-pyrite-quartz rock. Dacite is altered to chlorite-pyrite-quartz rock near the ore bodies. Sericite, chlorite, and a part of pyrite and of marcacite become more abundant in slate with approaching to the ore bodies.

Thus, the wall rock alterations surrounding the pyrite ore bodies are observed as sericitization, pyritization, chloritization, and silicification, the grade and mode of which depend upon the compositions and the textures of the original rocks. Acidic tuff is most extensively altered, and the alteration of the other rocks are not so remarkable. (1) The alterations are somewhat zonally distributed, showing a variation from the remarkably altered rock near the pyrite ore bodies, through the weakly altered part and at last into non-altered rock, and (2) As pyrite, sericite, chlorite, chalcopyrite, sphalerite, barite, marcasits, etc., are found confined in the remarkably altered rocks, the alteration must be concerned with the pyrite mineralization.

In the light of that sericite, chlorite, pyrite and quartz are (1) found similarly in many other mesothermal to epithermal ore deposits (SCHWARTZ, 1955) and closely associated with the ore bodies, (2) synthesized at relatively low temperature (MOREY and INGERSON, 1937; STRINGHAM, 1952), and (3) associated with low-temperature minerals such as marcasite, colloform pyrite and barite at the Yanahara Mine, the alteration under consideration might have been derived from action of a relatively low-temperature hydrothermal solution. In this case the fact may be that tuff was most favorable for alteration, and the other rocks were not so.

2. Dynamic Metamorphism of Wall Rocks

That the wall rocks including the pyrite ore bodies were subjected to a dynamic metamorphism subsequent to hydrothermal alteration is easily understood by microscopic observation.

Inspection of forms and internal structures indicated respectively by quartz, sericite and pyrite in the altered rocks near the pyrite ore bodies suggests that none of them was formed under the stress condition. It, however, is clear that they might have been crushed and replaced by crystals arranged in certain direction. Accordingly, the hydrothermal alteration might have taken place prior to a dynamic metamorphism.

Microscopically, granular aggregates and large crystals of quartz, aggregates of random-orientated fine crystals of sericites, granular pyrite grains, barite, and so forth are crushed and replaced or penetrated by lamellar quartz and regularly orientated sericite. Pressure shadow of lamellar quartz or sericite or chlorite are often developed around the crushed pyrite grains (Pl. 6).

3. Thermal Metamorphism of Wall Rocks

One more repetition of thermal metamorphism after dynamic metamorphism is reserved in the wall rocks. For instance, microscopic inspection conspicuously shows bulk of recrystallized biotite, in free arrangement, contained in the quartz-sericite-pyrite rock including some quantity of chlorite (Pl. 6). The biotite therein replaces both sericite and chlorite produced by hydrothermal alteration and dynamic metamorphism.

Where the thermal metamorphism is remarkable, pyrite grains in the rock indicate an appearance as if they were dissociated into pyrrhotite along its border or fractures. There are also the cases where most parts of pyrite grains show a variation into pyrrhotite, or pseudomorphs of pyrrhotite after pyrite are rarely found.

Dissociation of pyrite takes place at 650°C under I Atm (S pressure) (ALLEN and others, 1912, 1917; BURG, 1934), but the dissociation temperature in natural condition can not be determined (INGERSON, 1955; RAMDOHR, 1955).

Biotite crystals are found scattered also in the other altered rocks as well as in those showing no hydrothermal alteration. Biotite is frequently associated with cordierite considered to have been formed by thermal metamorphism.

4. Wall Rock Alteration Associated with Magnetite, and Pyrrhotite Mineralization (Wall Rock Alteration after Thermal Metamorphism)

The wall rocks containing the magnetite, and the pyrrhotite ore bodies are believed to have been affected by hydrothermal alteration after thermal metamorphism.

It seems that altered zone extends within some cm in width from the magnetite ore bodies. There are calcite, epidote, hornblende, biotite, chlorite, magnetite, quartz, and rarely albite and garnet. Sequence of deposition of the minerals is (I) quartz, (2) hornblende, calcite, magnetite, (3) garnet, epidote, magnetite, calcite, albite, biotite, chlorite, and (4) chlorite, calcite.

Quartz is xenomorphic granular, relatively coarse and does not show an undulatory extinction (Pl. 7). Hornblende is closely associated with magnetite (Pl. 7). Biotite is light green to greenish brown in color in thin section and associated with calcite and chlorite, being easily distinguished from those appeared in the hornfels. Calcite, rich in amount, associated with biotite, epidote and chlorite, is relatively coarse and shows remarkable polysynthetic twinning. Chlorite is associated with calcite, epidote and biotite. Albite shows a close connection with quartz, epidote and magnetite. Garnet is associated with calcite and epidote.

On the outer side of the severely altered zone, the wall rocks indicate the evidences for chloritization and carbonatization, whereas their original textures are reserved to certain extent.

It may be the fact that these alterations of the magnetite ore bodies are independent on the compositions and the characters of their wall rocks, since mineral assemblages composed of calcite, hornblende, epidote, etc. are appeared similarly in slate, tuff and diabase. Ca, CO, CO_2, H_2O, and some others sufficient to produce the minerals appeared in the altered zone in question might have been derived from any other source, since these constituents are originally not to be contained in the surroundings.

The wall rocks including the pyrrhotite ore bodies are altered to a sort of calcite-sericite rock with a zone of several cm in width from the ore bodies. Because of its indifference to the composition of the wall rocks similarly in the case of the magnetite ore bodies, the alteration must also be ascribed to an addition of materials from any other source.

F. Mineral Compositions of Ores

1. Pyrite Ore

Pyrite ore is essentially composed of pyrite accompanying subordinate amounts of chalcopyrite, sphalerite, tetrahedrite, arsenopyrite, quartz, chlorite, sericite and barite, and rarely of bournonite, galena, bornite, freibergite, chalcocite, and native gold. In an average, the ore under consideration contains 85~97% of pyrite, 3~15% of gangues, 3% or less of sphalerite and chalcopyrite (Tab. 3, Fig. 15). Chalcopyrite is more abundant in the ores appeared at Hisaki, Shimotani, and Hitashiro ore deposits than in those contained in the main body of Yanahara as well as in the Shimoyanahara and the Yasumiishi deposits, and commonly richer in the border parts of ore bodies than in their inner parts. Marcasite and arsenopyrite in small amount are found scattered throughout the ore body. Tetrahedrite is frequently included in the ores appeared in the Hisaki ore deposit and rarely in those located at the other ore deposits. The occurrence of bornite, bournonite, galena, freibergite, chalcocite and gold are scarce but ubiquitous.

TABLE 2. LIST OF MINERALS OCCURING IN THE YANAHARA MINE.

Pyrite Ore	Pyrrhotite Ore	Magnetite Ore
Ore Minerals	Ore Minerals	Ore Minerals
Arsenopyrite	Arsenopyrite	Arsenopyrite
Bornite	Bismuthinite	Chalcopyrite
Bournonite	Bournonite	Cobaltite
Chalcocite	Chalcopyrite	Galena
Chalcopyrite	Galena	Magnetite
Freibergite	Jamesonite	Pyrite
Gold	Jordanite	Pyrrhotite
Galena	Pyrrhotite	Sphalerite
Marcasite	Schapbachite	
Pyrite	Sphalerite	Gangue Minerals
Sphalerite	Stibnite	Albite
Tetrahedrite	Tetrahedrite	Biotite
		Calcite
Gangue Minerals	Gangue Minerals	Chlorite
Barite	Calcite	Epidote
Chlorite	Chlorite	Garnet
Quartz	Epidote	Hornblende
Sericite	Quartz	Quartz
	Sericite	Sericite

——Very abundant, ······ Commonly associated

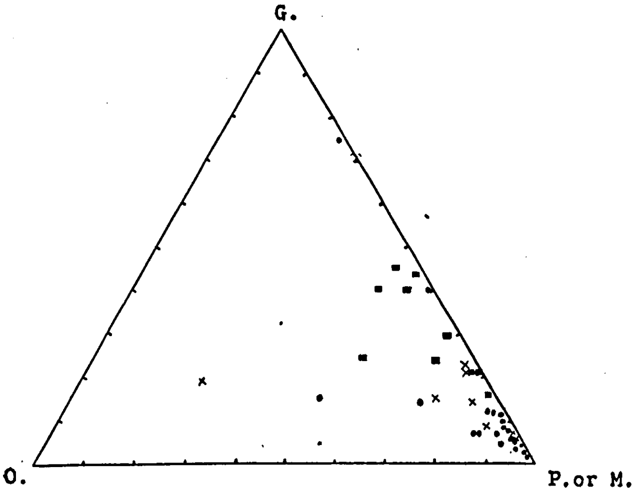

FIG. 15. Diagram showing composition of ores in the Yanahara Mine.

P. or M. -Pyrite for pyrite ore, pyrrhotite for pyrrhotite ore and magnetite for magnetite ore; G. -Gangue minerals; O.-Chalcopyrite, sphalerite and others; ●-Pyrite ore; ×-Pyrrhotite ore; ■-Magnetite ore.

For reference, the differences between the ores obtained from the Yanahara deposits and those from the Besshi (NISHIO, 1940; TSUNORI, 1950) and the Makimine deposits (TATSUMI, 1952, 1953) are summarized as follows: (1) chalcopyrite and gangues are less in amount in the former than in the latter two and (2) bornite, tetrahedrite, chlalcocite and gold are found not in Makimine but in Yanahara and in Besshi.

The gangues contained in the pyrite ore are compared to those in the pyrrhotite ore and in the magnetite ore (Tab. 2, 3, 4; Fig. 15). The results are that: (1) their contents in the former are very little, while those in the latters are considerable. (2) the gangue minerals accompanying the former are quartz, chlorite, sericite and barite, while those associating the magnetite ore are garnet, hornblende, biotite, calcite, epidote, albite and others, and those coexisting with the pyrrhotite ore are calcite, chlorite, epidote and quartz.

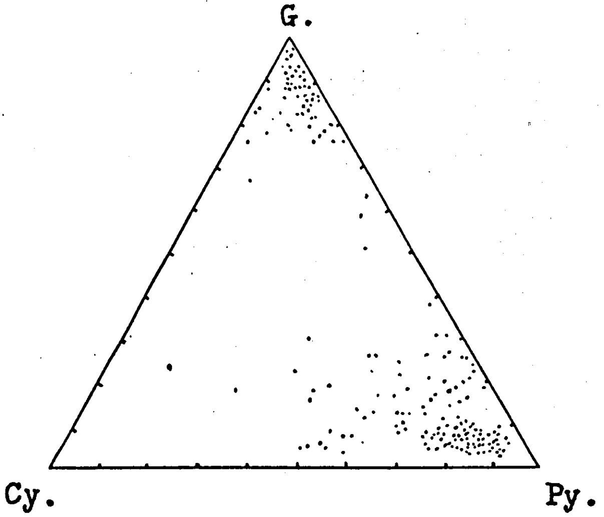

FIG. 16. Diagram showing composition of ores of the Besshi Mine (after S. NISHIO).

Py. -Pyrite; G. -Gangue minerals; Cy. -Chalcopyrite.

Grains of pyrite, not so remarkably crushed, are 1～0.5 mm in diameter and those accountably crushed, 0.5～0.05 mm. Generally, pyrite grains are coarse near the quartz porphyry dike and those of the magnetite and pyrrhotite ore are crushed and fine in other places. Large crystals of more than 5 mm in diameter occur near the pyrrhotite

TABLE 3. MINERAL COMPOSITION OF PYRITE ORE.
(*Vol. %*)

Ore Deposit	Pyrite	Gangue	Chalcopyrite	Sphalerite	Others
Yanahara main deposit	93.2	4.4	0.5	1.9	
	91.3	4.6	0.6		
	89.8	7.8		2.4	
	94.8	4.3		0.9	
	91.8	6.9	0.9	0.4	
	88.9	9.8	0.4	0.9	
Shimoyanahara	85.3	6.4	7.6	0.6	
	93.9	3.3	1.9	0.9	
	97.7	2.3			
	96.9	2.3		0.8	
	93.6	4.8	1.6		
Shimotani	88.8	6.5	3.6	1.2	
Hisaki	86.0	12.2	1.8		
	84.0	6.9	8.4	0.8	
	78.1	21.4	0.5		
	69.4	15.0	15.6		
	49.2	15.6	27.3	4.7	3.2
Yanahara main deposit	24.4	74.1		1.5	
Shimoyanahara	58.8	40.5	0.7		

ore bodies.

Pyrite is commonly xenomorphic and angular, but, in places, idiomorphic or hypidiomorphic granular. Polished and etched specimens of pyrite, not so remarkably crushed in the inner part of the ore bodies, show either a sort of zonal structure or rarely a colloform texture (Pl. 5). The grains of pyrite having these characteristics are furthermore crushed and sheared. Inspection of the fine-grained specimens in the same manner indicates that those are composed of partly crushed and relatively coarse ones and of many fine angular ones.

Crystals of the partly crushed pyrite are of octahedral habit (Pl. 1), while those are cubic, which are in places appeared, not crushed, and fill interstices of the crushed pyrite or replace the latter. There are the cases where pyrite fills fractures of quartz grains or replaces them, and where pyrite grains are cut, or replaced, or their interstices are filled, by quartz, chalcopyrite, sphalerite and tetrahedrite. Pyrite grains, where crushed severely, accompany pressure shadows of quartz, or are cut by veinlets of lamellar quartz (Pl. 6).

Near the contact with the pyrrhotite, and the magnetite ore bodies, pyrite ores are chiefly composed of some larger, and many finer, interlocked crystals of pyrite, showing no cataclastic texture. Interstices in pyrite grains are filled, or the grains are replaced, by quartz, calcite, chalcopyrite sphalerite and sericite, and, in places, cut by later veinlets of pyrite and calcite.

At the contacts with the pyrrhotite, and magnetite ore bodies, pyrite ores are cut or replaced by the formers respectively.

Some considerations on the pyrite are hereunder outlined. Pyrite shows commonly either zonal structure or octahedral habit and rarely colloform texture. Colloformed pyrites are generally contained in the low-temperature hydrothermal or the sedimentary ore deposits (RAMDOHR, 1955). According to the conclusion given by I. Sunagawa (1957), octahedral pyrite is considered to have been formed under suitable condition as well as with sufficient supply of solution, and cubie one, by dynamic metamorphism.

As are confirmed at the pyrite ore deposit of the Gojo Mine (HIGASHIMOTO, 1958) and the Ural district (ZAVARITSKY, 1950), the pyrites formed prior to dynamic metamorphism are octahedral or colloformed, but those formed during the metamorphism are cubic.

Thus, the similar conditions are to be expected in the case of the mineral obtained from the Yanahara Mine and, accordingly, the pyrite might have been crushed after its formation, and partly mobilized to be redeposited as cubic one.

From the fact that the pyrite ores appeared nearby the ore bodies of pyrrhotite or of magnetite and the quartz porphyry dike are not cataclastic in texture, their recrystallization may be ascribed to the action or effect of the subsequent dike or the ore bodies later formed.

Chalcopyrite, 0.05~0.01 mm in diameter, shows lamellar twinning, fills interstices of the octahedral or crushed pyrite and replaces them all. Moreover, the mineral is associated with the cubic pyrite and lamellar quartz as well as closely with sphalerite. Exsolution intergrowth of chalcopyrite with sphalerite is not found in the inner part of the pyrite ore bodies, but the former is included as exsolution blebs in sphalerite near the quartz-porphyry dike or the pyrrhotite, and the magnetite ore bodies.

Sphalerite, 0.05~0.01 mm in diameter and light-yellowish colored in thin section, must be a low-temperature one containing less than few percents of FeS (EDWARDS, 1954; KULLERUD, 1953). The mineral is closely accompanied with chalcopyrite, and fills interstices of pyrite grains and replaces them.

Sphalerite, reddish brown in thin section and appeared near the quartz porphyry dike or the pyrrhotite, and the magnetite ore bodies, contains more than ten percents of Fe (EDWARDS, 1954; KULLERUD, 1953). The color of sphalerite becomes lighter with the distance from the dike or the ore bodies. The deep colored specimens of sphalerite are found filling interstices of the recrystallized pyrite grains and replacing them. The sphalerite contains chalcopyrite as exsolution blebs. The exsolution texture and the deep color are probably due to the subsequent thermal effect of the dike and to deposition of pyrrhotite and magnetite.

Marcasite is granular, tabular or scaly (Pl. 5), and commonly shows the twinning, the lamellae of which are perpendicular to the direction of its elongation. The mineral concerned is associated with quartz and barite. It replaces pyrite, and is replaced by chalcopyrite, and sphalerite.

A scaly marcasite showing commonly a pseudomorph after pyrrhotite (EDWERDS, 1954; RAMDOHR, 1955) is obtained from other mines, where the mineral in question is fine-grained, random-orientated and is usually associated with replacement remnants of pyrrhotite and carbonate. Inasmuch as the scaly marcasite obtained from the Yanahara Mine, however, is (1) associated with quartz and barite, but not with carbonate, (2) not consisted of fine-grained aggregates in random orientation, (3) not associated with pyrrhotite relict, the very mineral seems not to be a pseudomorph of pyrrhotite. Because of being crushed, the mineral is believed to have been formed before the dynamic metamorphism. As was ascertained by LUDWIG, JOHNSTONE and ADAMS (DOELTER and LEITMEIR, 1920), marcasite seems stable under high pressure and retained in the cases of the metamorphosed cupriferrous pyrite ores of the Ural (ZAVARITSKY, 1950) and the Rammelsberg ores (RAMDOHR, 1953). But the mineral is transformable into pyrite when it is heated above 450°C under I Atm. in H_2S vapour (ALLEN and others, 1912, 1914, 1917). Its existence in the ore bodies of the Yanahara Mine may suggest that the ore bodies have never been heated above 450°C. Near the quartz porphyry dike and the ore bodies of magnetite and pyrrhotite the pyrite ores are not associated with marcasite, and their transformation from marcasite might have been attributable to the effect of dike or of a hydrothermal solution producing the magnetite, and the pyrrhotite ore bodies.

On the other hand, it appears common that marcasite is found in many low-temperature ore deposits or sedimentary rocks (RAMDOHR, 1955), and synthesized at 25° ~200°C in H_2SO_4 solution or 25°~300°C in HCl solution (ALLEN and others 1912, 1914).

Tetrahedrite occurs in the places rich in chalcopyrite, and is associated with sphalerite, chalcopyrite, galena and bournonite. It happens that the mineral comes into contact directly with galena but there is commonly bournonite between galena and tetrahedrite.

Galena is scarce in amount, and is associated with sphalerite, chalcopyrite and tetrahedrite.

Freibergite occurs in the ores rich in chalcopyrite, bornite and tetrahedrite, and is easily distinguished from bornite and orange bornite by its colour, isotropic character and etching reaction. It is brownish, perfectly dark under the crossed nicols, softer than chalcopyrite and bornite, and contains Ag detected by microchemical test.

Bournonite is associated with chalcopyrite, gelena and tetrahedrite, and occurs commonly between galena and tetrahedrite or in chalcopyrite.

Bornite, very scarce in amount, is associated with chalcopyrite, freibergite, tetrahedrite and sphalerite. Chalcocite, very scarce in amount, is associated with chalcopyrite as well as bornite, and replaces pyrite.

Gold, very scarce in amount, is associated with bornite, chalcopyrite and quartz (Pl. 5).

Arsenopyrite, idiomorphic and fine-grained, is found scattered in the ore bodies in small quantities, associating pyrite, filling interstices of pyrite grains and being replaced by chalcopyrite.

The gangue minerals involving the pyrite ore are genetically divided as follows; (1) quartz crystals as relicts of the orginal rocks, (2) quartz, chlorite, barite and sericite formed during pyrite mineralization, (3) quartz, sericite and chlorite formed by dynamic metamorphism, and (4) quartz and biotite recrystallized by thermal or hydrothermal effects.

The modes of occurrence of quartz are devided into four types: The first is granular and replaced by pyrite, the second is granular and closely associated with pyrite, the third is lamellar, cutting pyrite grains or showing pressure shadow around pyrite grains, and the fourth is granular, occurring in the pyrite ores near the magnetite, and the pyrrhotite ore bodies. The first and the second indicate the crushed appearance, and the first, the second and the third the undulatory extinction, respectively.

Chlorite, occurring as aggregates of fine flakes, is associated with quartz, and partly replaced by biotite.

Sericite is found not in the ore of high grade but in the ore containing considerable amount of gangue. There are two kinds of occurrence, one of which is of fine-flake showing random orientation and the other, cutting across the former, is of the similar in parallel arrangement.

Barite grains are associated with quartz as well as chlorite, fill interstices of pyrite grains and cut them in veinlets.

2. Pyrrhotite Ore

(a) Border Ore:

The ore is composed of pyrrhotite accompanying subordinate amount of chalcopyrite, sphalerite, arsenopyrite, jamesonite, stibnite, bournonite, tetrahedrite, galena, jordanite, bismuthinite, schapbachite, and gangues such as calcite, epidote, sericite, chlorite and quartz (Tab. 4. Fig. 15). Amount of chalcopyrite is variable in portions. Where chalcopyrite is abundant, there are jamesonite, bournonite, tetrahedrite, stib-

TABLE 4. MINERAL COMPOSITION OF PYRRHOTITE ORE
(*Vol. %*)

Ore Deposit	Pyrrhotite	Gangue	Chalcopyrite	Sphalerite	Magnetite
Yanahara main deposit	92.6	6.2	0.6	0.6	
	73.2	15.3	5.1	6.3	
	93.2	6.2		0.6	
	84.7	5.9			9.3
	76.1	20.9	0.1	2.9	
Shimoyanahara	75.1	22.5	2.3		
	80.2	13.9	5.9		
Hisaki	86.8	9.4	2.3	1.5	0.1
	23.9	19.7	55.9	0.5	

nite. The ore rich in galena contains bismuthinite, jordanite, schapbachite, calcite and chlorite.

Pyrrhotite, 0.15～0.5 mm in diameter, comes into contact mutually with chalcopyrite and sphalerite. It is cut or replaced by chalcopyrite, sphalerite, and galena, and includes minute idiomorphic crystals of arsenopyrite. At the contact of the pyrrhotite ore with the pyrite ore, the former cuts or replaces the latter (Pl. 7). And at its contact with the magnetite ore, it cuts or replaces the latter.

Chalcopyrite is closely associated with sphalerite and included in the latter. Polysynthetic twinning is very common in the mineral, and deformed or crushed textures of the twinning lamellae are not observed.

Sphalerite is reddish brown-colored in thin section, containing more than 10% of FeS. It includes bulk of minute exsolution-blebs of chalcopyrite (Pl. 7).

Jamesonite, 0.2～0.3 mm in width and 0.5 mm in length, includes fine idiomorphic crystals of arsenopyrite.

Stibnite is rarely found and is commonly associated with jamesonite.

Tetrahedrite and bournonite are very scarce in amount, and closely associated with chalcopyrite.

Galena is very scarce and associates jordanite, bismuthinite and schapbachite. Schapbachite, slightly harder than galena and bladed, is enclosed in galena, and shows the color very similar to that of the latter in air, but becomes more yellowish in oil.

Jordanite is exceedingly rare. Its color is little darker than that of galena. For few days after polishing, its surface gets rusty and becomes more darker than galena. It is closely associated with galena, and includes many minute idiomorphic crystals of arsenopyrite.

Bismuthinite is very rare, and is involved in galena.

As the gangue minerals chlorite, epidote, sericite and quartz are common. Calcite is also abundant and quartz is scarce. Calcite, epidote and chlorite fill interstices of pyrrhotite grains. These gangues have no texture to show the effects of thermal or dynamic metamorphism (Pl. 7).

(b) Vein Ore:

The ore has a character similar to that of the border pyrrhotite ore. It is composed of pyrrhotite associating certain amounts of chalcopyrite, sphalerite, arsenopyrite, calcite, chlorite, epidote and quartz, and demarcated sharply with the pyrite ore. It contains pretty amount of minerals bearing Ca and CO_2, and differs from the pyrite ore in that the latter has no relation to these constituents but a texture suggesting the evidence for dynamic and thermal metamorphisms.

(c) Dike Ore:

The ore under consideration (HIGASHIMOTO, 1958) is composed of pyrrhotite accompanying small amount of chalcopyrite, sphalerite, quartz, chlorite and sericite.

It occurs in the mode similar to that of the border pyrrhotite ore, and shows contacts with chalcopyrite and sphalerite respectively. Frequently it is cut by the veins of quartz and chlorite, and includes some minute idiomorphic crystals of arsenopyrite.

Chalcopyrite in the ore is closely associated with sphalerite, and included in the latter as exsolution-blades scattering widely and uniformly along crystallographic orientation of sphalerite.

The inclusions are finer and distrubuted more regularly than those in sphalerite of the pyrite ore.

Sphalerite is reddish brown-colored in thin section, and associated with chalcopyrite. It includes minute blebs or blades of chalcopyrite or, in parts, of pyrrhotite.

Quartz, chlorite and sericite cut across pyrrhotite in vein, and fill its interstices. The quartz is coarser than that in the pyrite ore, showing no undulatory extinction.

3. Magnetite Ore

The ore in question is divided into three groups such as the border, the vein and the dike magnetite ores, all of which are similar in composition to one another. It is composed of 48~84% of magnetite, 15~45% of gangues, and small amount of pyrrhotite, chalcopyrite and sphalerite (Tab. 5, Fig. 15). The gangue minerals are calcite, hornblende, biotite, chlorite, and rarely albite, garnet, quartz and so on. The formation stage of the ore is later than those of the pyrite ore, the dike pyrrhotite and the quartz porphyry dike, and earlier than that of the border pyrrhotite.

TABLE 5. MINERAL COMPOSITION OF MAGNETITE ORE
(*Vol. %*)

Ore Deposit	Magnetite	Gangue	Pyrrhotite	Chalcopyrite	Sphalerite	Pyrite
Yanahara main deposit	68.7	23.6	5.5	2.2		
	77.6	21.1	0.6	0.6		
	69.4	28.4	1.5	0.7		
	48.4	39.4	1.6		0.5	10.1
Shimoyanahara	55.2	43.1	0.6	1.1		
	84.3	15.2		0.5		
	49.7	44.1	4.6	0.5	0.5	0.5
Shimotani	52.9	24.1		15.2	0.8	
Hisaki	55.6	40.0	2.8		1.7	

(a) Border Ore:

Magnetite in the related ore is granular or scaly and closely associated with gangue minerals. It shows lamellar intergrowth with chlorite and biotite or generally mixing with gangue minerals.

At its contact with the pyrite ore bodies, the mineral cuts into and replaces the latter. And at the contact with the pyrrhotite ore bodies, it is cut and replaced by the latter.

Chalcopyrite in the ore is scarce in amount, and closely associated with sphalerite. It includes sphalerite-stars and is included in sphalerite.

Sphalerite is scarce, and includes minute blebs of chalcopyrite scattering uniformly in crystallographic orientation of sphalerite.

Pyrrhotite is included in magnetite as rounded blebs or replaces the latter.

Galena is scarce, and cuts across magnetite.

Gangue minerals are composed of abundance of calcite, considerable amounts of epidote, chlorite, hornblende, biotite and small amount of sericite scarcely together with quartz, garnet and albite. Quartz is considered earlier in stage than magnetite. Calcite, hornblende, biotite, chlorite, garnet, epidote and albite are closely associated and mixed with magnetite. Most of them seem to have been produced contemporaneously with magnetite and some of them are earlier or later than the latter.

(b) Vein Ore:

The mode of occurrence of magnetite in the ore (HIGASHIMOTO, 1958) is similar to that in the border magnetite ore.

But the pyrrhotite contained is abundant in the margin of the vein magnetite ore bodies, and believed earlier in stage than magnetite (Fig. 17), associating subordinate amount of chalcopyrite, sphalerite, quartz, chlorite and calcite. On the basis of its occurrence, the paragenetic relation and stage of formation it may be deduced that the mineral was formed by reaction of pre-existing pyrite ore bodies with hydrothermal solution.

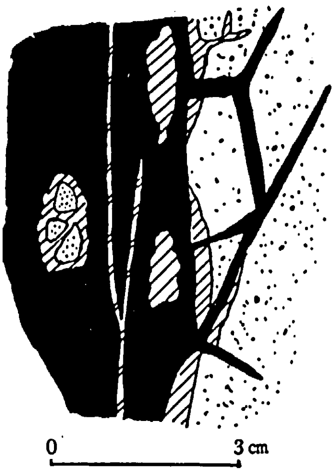

FIG. 17. Sketch of a hand-specimen on the 21st level of the Yanahara main ore deposit, showing relation among pyrite ore, pyrrhotite ore and magnetite ore. The specimen was taken at the contact between pyrite ore and the vein magnetite ore body. Magnetite ore fills fractures of pyrite ore, or includes replacement remnants of pyrite ore.

Chalcopyrite in the ore concerned is in close intimacy with sphalerite. The latter is deep red-colored in thin section, including minute exsolution-blebs of the former.

Gangue minerals are calcite, biotite, chlorite, and epidote, of which the former two are abundant. Lamellar intergrowth of biotite or chlorite with magnetite is often observed. The gangue minerals are always closely related to, and mixed with magnetite.

(c) Dike Ore:

The very ore (HIGASHIMOTO, 1958) is consisted of magnetite and gangues accompanying chalcopyrite, sphalerite, pyrite, pyrrhotite, galena, cobaltite and arsenopyrite in certain amount.

Magnetite, granular or scaly in habit, is closely enclosed in or mingled with gangue minerals. It replaces pyrite, and is replaced by pyrrhotite, chalcopyrite and sphalerite.

Pyrite in the ore occurs as aggregates composed of granular pyrite together with subordinate amount of quartz, chlorite, chalcopyrite and sphalerite. The pyrite in the aggregates is replaced first by pyrrhotite and then by magnetite and gangues.

Chalcopyrite occurs in veins replacing magnetite or as inclusions in sphalerite. In the latter case it is bladed, finer and more regularly arranged than that contained in the dike pyrrhotite ore. Moreover, it contains minute dendritic or skeletal crystals of sphalerite (Pl. 7).

Sphalerite, deep reddish in thin section, includes chalcopyrite and magnetite or is included in the former in close association.

There are two cases where pyrrhotite is accompanied with pyrite in aggregates, or replaces magnetite. In one case it is used to show weaker reaction with the standard reagents, higher reflection in air, finer size, and less brownish color than is observed in the other case.

Cobaltite, arsenopyrite and galena occur rarely within the magnetite grains.

Gangue minerals such as calcite, chlorite, biotite, epidote, sericite and quartz are fine-grained and mixed with magnetite.

G Some Considerations on Mixed Crystals and Exsolution (HIGASHIMOTO, 1958)

1 Sphalerite-Pyrrhotite:

The sphalerite appeared near the quartz porphyry dike is rich in minute exsolution-blebs of pyrrhotite. This relation is, because of being not recognizable in the ore far from the dike, probably due to thermal effect of the dike.

The sphalerite located near the dike is deeper in color and shows its variation in the respestive cases: that is, light yellowish green in the pyrite ore distant from the dike, reddish brown in the pyrite ore near the dike pyrrhotite, and deep red either in the dike pyrrhotite or in the dike magnetite. The change of colors and the textures showing exsolution may imply that the sphalerite was heated at high temperature by the dike and absorbed certain amount of Fe in its lattice, and that a part of Fe was exsolved as pyrrhotite while most of Fe was being fixed in the sphalerite (KULLERUD, 1953; EDWARDS, 1954).

2. Sphalerite-Chalcopyrite:

Exsolution intergrowth of sphalerite with chalcopyrite is observable in the pyrite ore either near the pyrrhotite, and the magnetite ore bodies or near the quartz porphyry dike. Commonly, sphalerite seems to play a role of host mineral for chalcopyrite, and the latter in the dike magnetite ore includes dendritic or skeletal crystals of the former.

Both forms and arrangement of chalcopyrite inclusions in sphalerite are regular and uniform in the ores of pyrrhotite and magnetite, but not so in the pyrite ore. The inclusions in sphalerite of the dike pyrrhotite and the dike magnetite ores are more uniformly and regularly distributed, showing nearly equal forms as well as finer sizes. The regularity, however, is observed only in the vicinity of the dike, suggesting the thermal effect of the latter.

The experimental data indicate that in dry reaction chalcopyrite begins to dissolve in sphalerite at 360°~650°C and forms a perfectly homogeneous solid solution at 500°~800°C (SCHWARTZ, 1931; BORCHERT, 1934; BUERGER, 1934; SUGAKI and YAMANE, 1952). Although the temperatures may be variable with certain factors such as mixing ratio of ZnS and $CuFeS_2$, occurrences, impurities and some others, and the above-quoted values are nothing but a result obtained from laboratory work, the existence of the exsolution texture in the Yanahara ores may point to that the pyrite ore bodies were subjected either to the effect of hydrothermal solution producing the pyrrhotite, and the magnetite ore bodies or to that of the dike, and that the pyrrhotite, and the magnetite ore bodies were formed at relatively high temperature.

H. Dissociation of Pyrite

Some of pyrrhotite occurs in some pyrite ore bodies appeared along the quartz porphyry dike which was probably formed at post-ore stage and possibly gave the thermal effect on the pyrite ore bodies, resulting in their dissociation to produce pyrrhotite.

Dissociation of pyrite has ever been reported concerning the ores from Eustis (STEVENSON, 1937), Ben Novis (NEUMANN, 1950), Harz (FREBOLD, 1926), Makimine (TATSUMI, 1952, 1953) and so forth, and studied in detail by many investigators. From some examples and experiments it appears noteworthy that the thermal effect of igneous rock is sufficient to decompose pyrite, and the latter may be dissociated at about 690°C under I Atm (ALLEN and others, 1912, 1917; BURG, 1934).

On the other hand, the temperature of intrusives were studied by Beiley, MCFARLAND and DAPPELES, and LOVERING (LOVERING, 1955). They summarize the results and estimate the intrusion temperature of basic rocks as 900°C, that of acidic rocks as 850°C, and that of dikes far from the center of intrusion as 700°C. At Yanahara, the dike is quartz porphyry, its intrusion temperature may be estimated 700°~800°C, and the dike pyrrhotite ore occurs commonly within 5~10 cm in width along the dike. It thus follows that the pyrite appeared therein might have been dissociated at 700°~800°C.

I. Formation of Magnetite

Magnetite is always in coexistence with considerable amount of gangue minerals such as calcite, hornblende, epidote, biotite, and so on accompanying the pyrite ore and wall rocks originally containing none of such components as Ca, CO, CO_2, H_2O and some others, suggesting formation of the gangues by accountable addition of these constituents from any other source. The materials introduced along fissures between the pyrite ore bodies and the wall rocks or in the pyrite ore bodies or between the dike and the dike pyrrhotite ore bodies might have reacted with iron sulphides, oxidized and deposited the latter to form magnetite, calcite, epidote, hornblende, chlorite, biotite, and others.

VI. ORIGEN OF ORES

A. Relation between Ores and Matamorphisms

It seems of course that, concerning a definite kind of ore deposit, its texture and paragenesis with other minerals are to be dependent on certain conditions controlling the system related, and accordingly, new relations may overlap the previous ones, though those were once stable, with addition of new factors (RAMDOHR, 1954; SCHNEIDERHÖHN, 1954; SCHROCKE, 1954).

In this sense, the transitions of the ores by metamorphisms in the Yanahara Mine are hereunder inspected.

1. Relation to Dynamic Metamorphism

In the Yanahara district, dynamic metamorphirm is believed to have happened during the period from the ends of Permian to Eo-Triassic, and to have been a sort of cataclastic metamorphism.

As is accountably expected, evidences for dynamic metamorphism are to be conspicuously shown in that the minerals forming the ore bodies are crushed, deformed and folded (RAMDOHR, 1954, 1955; SCHNEIDERHÖHN, 1954; SCHROCKE, 1954).

At the Yanahara Mine, some characteristics shown by folding, deformation and boudinage of the ore bodies (Fig. 13, 14), crushing of pyrite crystals, "*zerknitterungslamellierung*" of chalopyrite, crushing of quartz and recrystallization of pyrite, chalcopyrite, sphalerite, quartz, chlorite, sericite and so forth are observed, while, on the other hand, pressure shadows of quartz, chlorite and sericite are frequently developed around pyrite grains (Pl. 6).

From these facts it may easily be ascertained that the pyrite ore bodies were subjected to a cataclastic metamorphism. Formation of the pyrite ore and of the wall rock alteration products associated with its mineralization might have taken place at certain pre-tectonic stage.

T. OSHIMA (1953) is of opinion that the pyrite ores were formed by filling of the pre-existing potential openings produced by crustal movement; in other words, shapes of the ore bodies were controlled by pre-existing structures. At any rate, their characteristic shapes, for example, swelling at apexes of folds, boudinage and so on may also be resulted by crustal movement at post-ore stage owing to difference in competency of the pyrite ore and of the country rocks. Furthermore, in the light of the fact that the pyrite ore shows, as was alluded to already, the effects of an intense tectonic movement subsequent to its formation, the shapes resulted are supposed to be related not to the openings formed at pre-ore stage but to the crustal movement subsequent to ore formation.

This may also be the case with the magnetite ore and with the pyrrhotite ore from the similar reason.

2. Relation to Thermal Metamorphism

It is to be noted that temperature is an important factor to determine which species of minerals or how they are originated in an ore deposit, and its subsequent variation also may cause new assemblage or distribution of minerals in the respective cases. Recrystallization, redeposition, inversion, solid diffusion, mobilization, and so on of the related minerals may be derived by thermal effect, resulting in generation of new minerals and textures (RAMDOHR, 1954, 1955; SCHNEIDERHÖHN, 1954; SCHRÖCKE, 1954).

At the Yanahara Mine, the pyrite ore situated near the quartz porphry indicates transformation into the pyrrhotite ore due to the thermal effect of the dike concerned. At the same time, exsolution textures between chalcopyrite and sphalerite, and those between pyrrhotite and sphalerite are appeared, while, on the contrary, cataclastic texture of the pyrite ore is disappeared near the dike.

Most parts of the pyrite ores are characterized in the cataclastic textures without thermal effects and contain light-coloured sphalerite and marcasite, while their wall rocks as well as the disseminated pyrite ores seem to have been subjected to thermal metamorphism causing the formation of biotite hornfels. Some of the pyrite grains in the disseminated ores show dissociation into pyrrhotite.

The preceding facts may point to that the thermal metamorphism was severe enough to generate boitite hornfels and to change certain amounts of pyrite in the disseminated ores, but was not so enough to change the whole mass of pyrite at all.

Near the intrusion of younger porpyrite, younger rhyolite, older quartz diorite and diabase the pyrite ore bodies show no changes other than crushing.

The magnetite, and the pyrrhotite ores have no textures indicating the effects of thermal metamorphism. The stage of their formation seems to have been later than that of the thermal metamorphism.

B. Nature of Ore Solutions

1. Pyrite Solution:

The solution producing the pyrite ore is supposed to have been a hydrothermal solution derived in connection with the initial magmatism in the upper Permian, and characterized chemically by the contents of S, Fe, SiO_2, H_2O in higher percentages, Cu, Zn, Pb, Sb, and As in lower amount, and Au, Ag, and some others in extremely little amount.

As was stated already, the fact is that the pyrite ore is accompanied with certain amounts of marcasite, barite, sericite, colloformed pyrite and light-coloured sphalerite, among which the marcasite is associated with sericite and chlorite. According to the experiments of ALLEN and others (1912, 1914), the mineralizer concerned might have been nearly neutral in property, and its deposition temperature may be estimated under 150°C. After KURRELUD's experiment (1953), the sphalerite containing less than several percents of FeS may be estimated to have deposited under 200°C. The colloform of pyrite seems a characteristic suggesting its formation at low temperature.

In consequence, the paragenesis referred to above probably indicates that the solution precipitating pyrite and others was of low temperature and neutral to somewhat acidic in property.

2. Magnetite and Pyrrhotite Solutoins:

The occurrence of the magnetite, and the pyrrhotite ores as well as their gangue minerals suggest the related solution to have been similar to that for pyrite in nature, though its relation to temperature be not ascertainable.

It, however, seems sure that the solution forming the magnetite ore was of a comparatively high temperature, of a pneumatolytic or hypothermal property characterrized by the formation of garnet and hornblende at the initial stage, and of a hypothermal or mesothermal property characterized by the formation of calcite, epidote, biotite and chlorite at the main stage of ore deposition.

It may also be that the solution relating to the genesis of the border, and the vein pyrrhotite ore was of a composition similar to that of the magnetite ore and considerably rich in the constituents such as Ca, CO, CO_2, H_2O and so forth, but was of a moderate temperature.

C. Origin of Pyrite Ore

The origin of the pyrite ore occupying more than 90% of the Yanahara ores has long been the subject of discussion. M. KUHARA (1920) believed the Yanahara ore to be of magmatic origin, and T. KATO (1922) concluded that it was hypothermal. Recently, N. OSHIMA (1958) studied the deposits especially on their relation to structure, and considered that the ore was formed by filling of the openings generated by tectonic movement.

Although these authors thought all of the ores in the Yanahara Mine to have been formed by mineralizations or successive depositions at relatively high temperature, the writer reaches, as was alluded to in the previous peragraphs, a view distinguished from their opinions on genesis. There is a remarkable difference between the pyrite ore and the ores of magnetite and of pyrrhotite. Accordingly, the hypotheses given by the former authors must be revised.

The writer believes it most reasonable that the pyrite ore was formed by selective hydrothermal replacement of the rocks, especially, such as tuff of the Yanahara complex, at relatively low temperature before tectomic movement, because (1) the pyrite indicates a specific connection with acidic tuff, (2) it is rich in replacement remmants of tuff, (3) its contacts with tuff are commonly transitional, (4) it is associated with a considerably wide zone of disseminated pyrite ore and of alteration on both sides of the hanging and the foot walls, (5) the mineral assemblage of the ore suggests its formation to have been at relatively low temperature, (6) it shows the texture pointing to its formation at pre-tectonic stage, and (7) it has no evidence for its genesis from magmatic or hypothermal origin, or relating to fissure-filling.

D. Summary of Origin of Ores

The pyrite ore deposits are conformably situated in the Yanahara complex of the upper Permian, and seem to have been genetically related to the initial magmatism of the complex and to have been formed by hydrothermal replacement in certain shallower depth at low temperature. They were folded, crushed and recrystallized by the cataclastic metamorphism in the late Permian to Eo-Triassic age, and then affected through thermal metamorphism in the late Mesozoic as well as partially through action of a high-temperature hydrothermal solution.

The ore bodies of magnetite and of pyrrhotite are situated around the pyrite ore bodies along their fractures and along the quartz porphyry dike cutting across the former. Most of the ores seem to have been produced by interaction of the pre-existing pyrite ore with a hydrothermal solution ascending along the fractures distributed between themselves and the country rocks or in their own fractures. The genesis of dike pyrrhotite ore also might have been ascribable to thermal effect of the dike on the pyrite ore.

VII. COMPARISON OF YANAHARA ORE DEPOSIT TO OTHERS SIMILARLY CHARACTERIZED

Pyrite ores analogous to the Yanahara ores in their occurrences and paragenetic relations are well known from a number of mining districts all over the world. Some of them are considered hereunder.

In the inner zone of the south-western Japan, several bedded cupriferrous pyrite ore deposits are found distributed. The ores, situated conformably in the Sangun crystalline schist or the non-metamorphic Paleozoic formation, are lenticular in shape and believed to have been formed by hydrothermal replacement of sheared zones.

The Tsuboi (MITSUNO, 1952), the Tsuchikura (MIYAZAWA and others, 1953, TAKIMOTO, 1950), and the Minamitani ore deposits (NAKANO, 1932) occur in close association with diabase and basic tuff. The Minamitani ore deposits of the Akenobe Mine are assumed to have an intimate relation to thermal metamorphism producing magnetite and skarn minerals after their deposition.

The Saya, the Ohira, and the Aome ore deposits are included conformably in the formation composed of semi-schists from acidic tuff, basic tuff, diabase, sandstone and slate. The pyrite ores of these deposits are composed mainly of pyrite with subordinate amount of chalcopyrite, sphalerite, quartz, chlorite and so forth indicating cataclastic textures. Their occurrence, relation to the wall rocks, and textures are very similar to those of the Yanahara Mine.

In the outer zone of the south-western Japan are there many bedded cupriferrous pyrite deposits named the 'Besshi-type'. Most of them are found situated in concordant connection with green schist, and composed of pyrite accompanying subordinate amount of chalcopyrite, sphalerite, quartz, chlorite, rarely tetrahedrite, barite and bornite. G. KOJIMA (1956) found out that the ore deposits were situated only in the Minawa formation and considered their formation to be of exhalative-sedimentary origin. On the basis of the exisistence of apophyses cutting the country rocks and of discordant ore bodies, some authors (1937), however, reached a conclusion that the ore-bearing solution was derived from the syntectonic intrusives, resulting in the ore formation by thermal replacement of schists.

In the Mesozoic formation of the outer zone (TATSUMI, 1952, 1953) are there many pyrite ore deposits, of which the Makimine deposit is situated concordantly in phyllitic complex of the Makimine formation in genetic relation to basic igneous rocks, and is composed of pyrite with chalcopyrite, sphalerite, quartz, chlorite, and some others.

The deposit concerned seems to have been metamorphosed thermally by granite porphyry, the effect of which is considered to have produced the cubanite-bearing pyrrhotite ore. This case also is similar to those appeared at the Yanahara and the Minamitani ore deposits.

In the vicinity of the Gojo Mine, Nara Prefecture are there also abundance of bedded cupriferrous pyrite ore deposits (HIGASHIMOTO, 1958; KANO, 1958; SHIIDA and UMEDA, 1957) situated concordantly in the Tsuzurao formation consisted of shale, sandstone, tuff, chert, diabase and limestone. The ore bodies of the Gojo Mine are lenticular in shape, and are composed of pyrite, melnicovite-pyrite, chalcopyrite, sphalerite, galena, quartz and chlorite. Either the ore bodies or their country rocks are considerably sheared, and most parts of the former are cataclastic in texture, but there are some ores remaining colloidal forms in their inner part where shearing is not so remarkable. This texture is assumed as a characteristic for pre-tectonic (pre-cataclastic) agency, and radial, concentric and spherical arrangement are observable in the ores. The so-called "vererzte Bakterie" is also frequently found in the colloformed ores. The ores seem, in this case, to have genetically related to the initial magmatism, and are probably of exhalative-sedimentary origin (HIGASHIMOTO, 1958).

In U.S.A., the pyrite ores of Bradshow Mountain and Jerome, Arizona (LINDGREN, 1933) and Shasta County, California (HULIN, 1933; KINKEL, 1954) resemble the Yanahara pyrite ore in their characteristics, and are situated concordantly in the pre-Cambrian schists of sedimentary and igneous origin. The ore deposits of Shasta County, California are situated concordantly in the Paleozoic formation consisted chiefly of acidic tuff, rhyolite and slate, and are composed of pyrite with some chalcopyrite, sphalerite, tetrahedrite, quartz, barite and chlorite, suggesting their formation by replacement of the sheared zone.

In the sericite schists distributed along the west coast of Tasmania (LINDGREN, 1933) at Mount Lyell are there pyrite ore bodies composed mainly of fine-grained pyrite with some gangues of quartz and barite, in which 5 to 6 percent of copper in the form of chalcopyrite, more rarely bornite and enargite are also contained. It is supposed that the ore was formed by replacement of the sericite schist derived probably from dynamo-metamorphism of the Paleozoic acidic porphyry.

At Rio Tint of Spain (BATEMAN, 1927; FINLAYSON, 1910) are there the pyrite ore bodies estimated roughly as of the greatest scale in the world. They show a concordant relation to the Paleozoic formation, and are connected closely with quartz porphyry. Their baundary seems gradual. The ore is divided into the main massive ore containing 48 to 50% of sulphur and the disseminated one. The wall rock alteration is represented by sericitization and is most remarkable on the porphyry. The ore is composed chiefly of pyrite accompamying small amount of quartz, barite, chalcopyrite, sphalerite, tetrahedrite, galena, and so on. From these facts it seems clear that the ore of Rio Tinto is very similar to that of the Yanahara Mine. As to its origin, miscellaneous views have long been proposed by geologists. Specifically concerning magnetite and pyrrhotite present in certain deposits opinions seem to differ from one another in whether these minerals might have been due to the later metamorphic processes or to original deposition.

In the Ural district, U.S.S.R. (ZAVARITSKY, 1950) are there many pyrite ore deposits holding a close relationship with certain volcanic rocks. The fact is that the ore deposits in question were dynamically metamorphosed after their deposition. The grade of metamorphism is different in parts and its effect on the pyrite ore is evidently traceable.

Non-metamorphosed or weakly metamorphosed ore is colloidal in texture, and contains pyrite of pentagonal habit, marcasite, wurtzite and melnicovite-pyrite. It seems conspicuous that pyrite was crushed by dynamic metamorphism, and pentagonal pyrite, melnicovite-pyrite and marcasite were changed to cubic pyrite, while, on the other hand, chalcopyrite, sphalerite, quartz, sericite and chlorite were recrystallized.

Only few of the deposits are recognized to have been subjected to thermal metamorphism by dikes.

VIII. SUMMARY

The Yanahara deposits are situated in Yanahara-cho, Kume-gun, Okayama Prefecture, Japan.

Geologic compositions cropped out in the district concerned are as follows: the unknown Paleozoic formation, the upper Permian formation, the Tertiary formation, the river deposits and the talus deposits as sedimentaries, and the diabase, older quartz diorite, older porphyrite, lithoidite, granite, younger rhyolite, younger quartz diorite, quartz porphyry, and younger porphyrite as igneous rocks.

The Paleozoic formations were subjected to the dynamic or cataclastic metamorphism during the period from the late Permian to Eo-Triassic and to the thermal metamorphism by the Hiroshima granite in the late Cretaceous.

Igneous activities in the surroundings are classified into six groups, of which the initial magmatism in the upper Permian, the syntectonic magmatism in the late Permian to Eo-Triassic, and the igneous activity in the late Mesozoic to early Tertiary are most conspicuous.

The ores appeared in the Yanahara Mine are roughly divided into the massive, and disseminated ores, of which the former is futhermore subdivided into the pyrite, pyrrhotite, and magnetite ores.

The pyrite ore is situated in conformable relation to the Yanahara complex. The latter is correlated to the lower member of the upper Permian formation and is composed of a complicated alternation of acidic tuff, older rhyolite, dacite, slate, diabase, miscellaneous tuffs of basic to intermediate properties, limestone conglomerate and tuffaceous conglomerate. The pyrite ore is composed of pyrite with subordinate amount of chalcopyrite, sphalerite, marcasite, tetrahedrite, quartz, barite, chlorite, sericite, and others. The pyrite ore bodies are used to accompany a low-temperature hydrothermal alteration zone of wall rocks and seem to have been formed with genetic relation to the initial magmatism by hydrothermal replacement at low-temperature in the shallower depth. After their formation, those were cataclastically and then thermally metamorphosed.

The magnetite, and the pyrrhotite ores are closely associated with each other, and are situated around the pyrite ore bodies, along their fractures, or along the quartz porphyry dike cutting through the pyrite ore bodies. Most of the ores seem to have been generated by interaction of the pre-existing pyrite ore bodies with a hydrothermal solution ascending along fissures around or in the pyrite ore bodies, and some of the pyrrhotite ore, that is, the dike pyrrhotite ore might have been derived from thermal effect of the quartz porphyry dike on the pyrite ore.

The pyrite ore contains only small amount of gangues composed of quartz, chlorite, barite and sericite, but the magnetite ore contains considerable amount of gangues composed of calcite, hornblende, biotite, epidote, chlorite, garnet, chlorite, and so on, and the pyrrhotite ore contains intermediate amount of gangues composed of calcite epidote, chlorite, and others.

The pyrite ore is, because of its cataclastic texture, believed to have been pretectonic in stage, and its formation is earlier than the thermal metamorphism, but the magnetite, and the pyrrhotite ores are non-cataclastic, and deposited later in stage than the dynamic, and thermal metamorphisms.

The solution forming pyrite is supposed to have been low-temperature hydrothermal in property. The magnetite solution is of high temperature, and is characterized by high contents of Ca, CO, CO_2, H_2O, and some others. Nature of pyrrhotite solution seems to have been same as that of the former and is of moderate temperature.

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Abbreviations used in microphotographs of minerals

Ab-Albite
Bi-Biotite
Cp-Chalcopyrite
Ch-Chlorite
Ep-Epidote
Au-Gold
Gu-Gangue
Gn-Garnet
Hb-Hornblende
Mt-Magnetite
Mc-Marcasite
Pt-Pyrite
Po-Pyrrhotite
Qu-Quartz
Sp-Sphalerite

EXPLANATION OF Plate V.

Fig. 1. Pyrite grains in pyrite disseminated ore (pyrite-quartz-sericite rock), showing zonal structure (upper) and colloform texture (lower). L. 4, Hisaki. Etched by HNO_3. Polished section. × 100.

Fig. 2. Colloform pyrite occurring in the inner part of pyrite ore body. L. 21, Yanahara main deposit. Etched by HNO_3. Polished section. × 100.

Fig. 3. Zonal structure of pyrite occurring in the inner part of pyrite ore body. L. 21, Yanahara main deposit. Etched by HNO_3. Polished section. × 100.

Fig. 4. Marcasite associated with pyrite and gangue. L. 3, Hisaki. Polished section. × 100.

Fig. 5. Gold associated with chalcopyrite and gangue. L. 5, Hisaki. Polished section. × 100.

Fig. 6. Crushed pyrite occurring in pyrite disseminated ore. L. 21, Yanahara main deposit. Polished section. × 100.

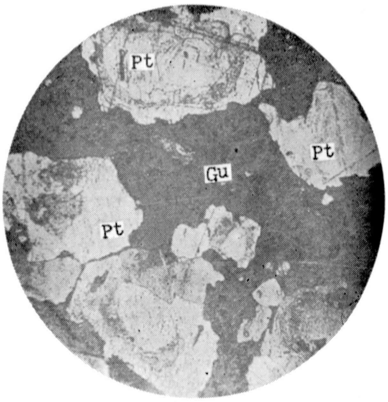

FIG. 1.

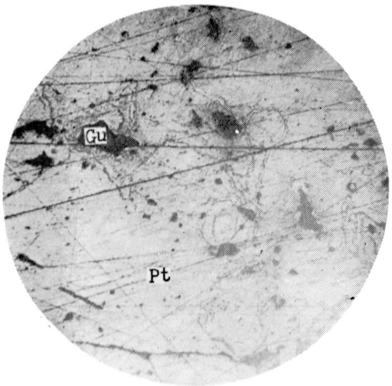

FIG. 2.

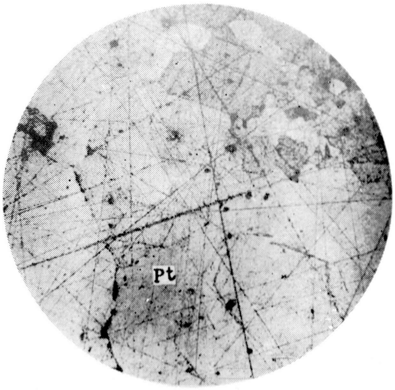

FIG. 3.

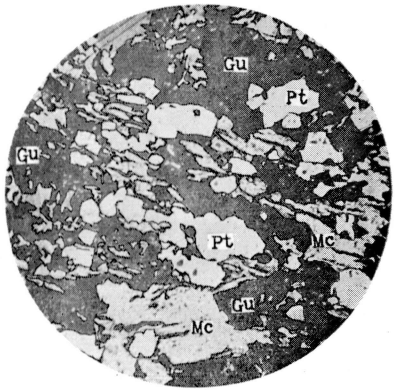

FIG. 4.

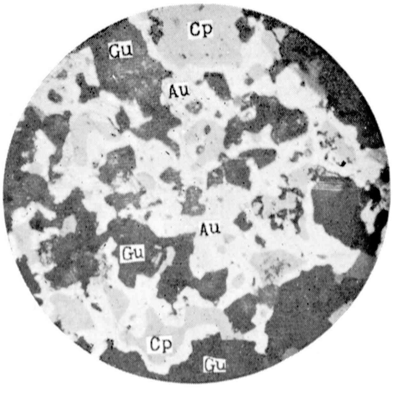

FIG. 5.

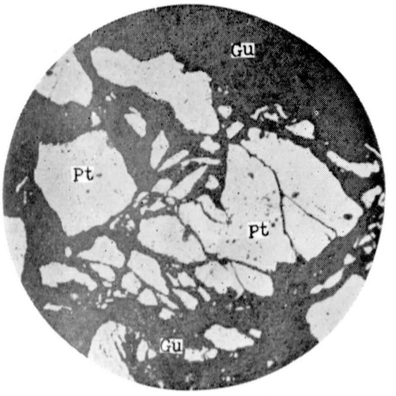

FIG. 6.

EXPLANATION OF Plate VI.

FIG. 1. Pressure shadow of quartz occurring in pyrite-quartz-chlorite rock. L. -10, Yasumiishi. Under crossed nicols. × 100.

FIG. 2. Relict crystal of quartz in pyrite disseminated ore (pyrite-quartz-sericite rock). It shows an undulatory extinction and is crushed and replaced by small crystals of quartz. L. 4, Hisaki. Under crossed nicols. × 100.

FIG. 3. Pressure shadow of quartz occurring in pyrite ore. L. 4, Hisaki. Under crossed nicols. × 100.

FIG. 4. Lamellar quartz cutting across pyrite ore in veinlets. L. 3, Hisaki. Under crossed nicols. × 100.

FIG. 5. Biotite replacing gangue of disseminated pyrite ore. L. 17, Yanahara main deposit. Under crossed nicols. × 100.

FIG. 6. Magnetite replacing pyrite, occurring at the contact between pyrite ore body and magnetite ore body. L. 6, Shimoyanahara. Polished section. × 450.

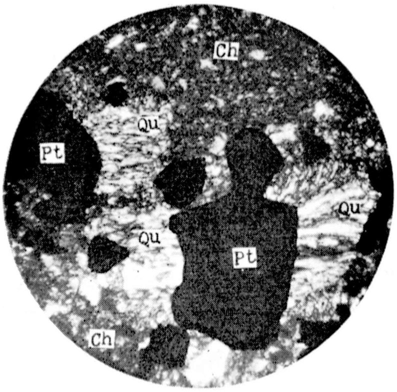

FIG. 1.

FIG. 2.

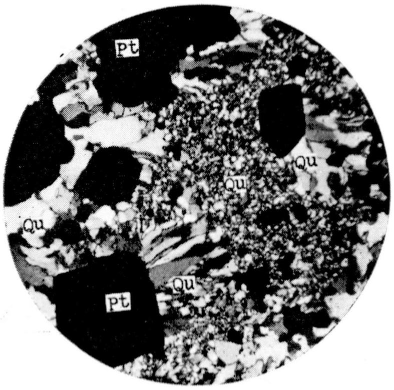

FIG. 3.

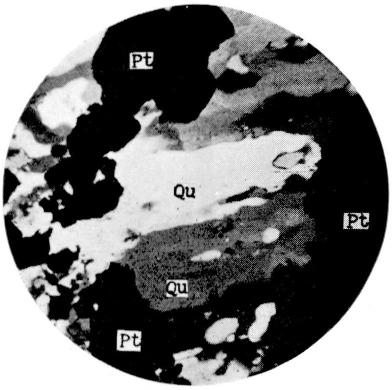

FIG. 4.

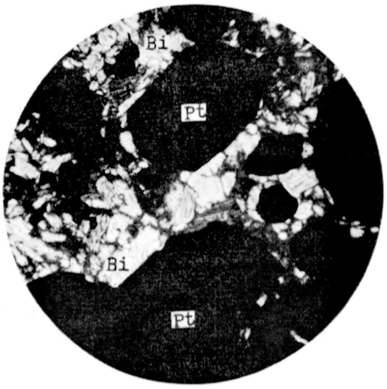

FIG. 5.

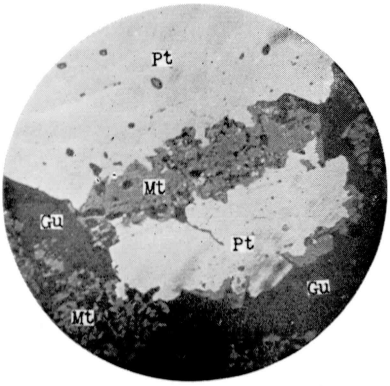

FIG. 6.

EXPLANATION OF Plate VII.

FIG. 1. Hornblende-magnetite rock occurring in alteration zone of wall rock including magnetite ore body. L. 21, Yanahara main deposit. Under crossed incols. × 100.

FIG. 2. Quartz-albite-epidote-magnetite rock occurring in alteration zone of wall rock containing magnetite ore body. The rock has no texture due to dynamic metamorphism. L. 21, Yanahara main deposit. Under crossed nicols. × 100.

FIG. 3. Garnet in magnetite ore. L. 1, Shimotani. Under open nicol. × 100.

FIG. 4. Skeletal crystals of sphalerite in chalcopyrite, occurring in magnetite ore. L. 17, Yanahara main deposit. Polished section. × 450.

FIG. 5. Exsolution blebs of chalcopyrite in sphalerite, occurring in pyrrhotite ore. L. 19, Yanahara main deposit. Polished section. × 150.

FIG. 6. Quartz crystals in pyrrhotite ore. They have no texture due to dynamic metamorphism. L. 17, Yanahara main deposit. Under crossed nicols. × 100.

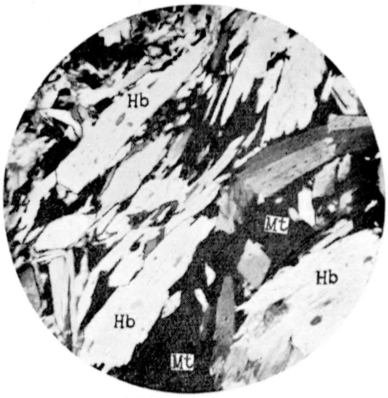

FIG. 1.

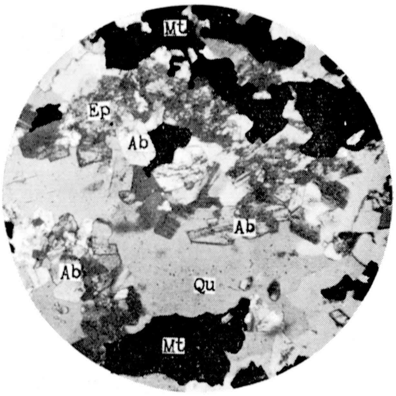

FIG. 2.

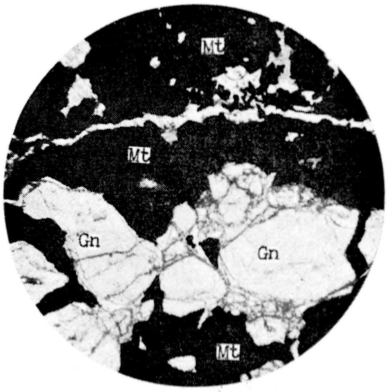

FIG. 3.

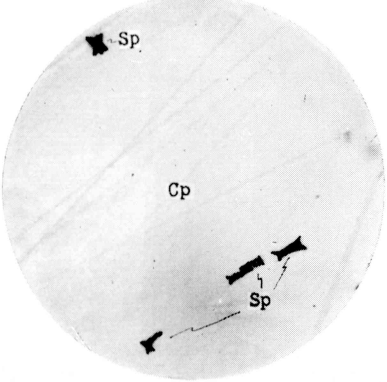

FIG. 4.

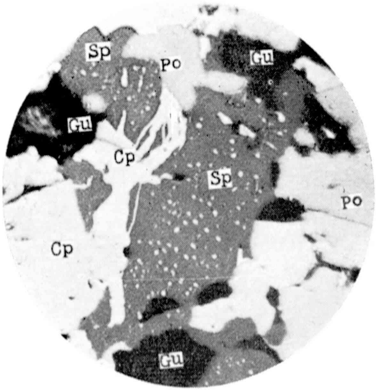

FIG. 5.

FIG. 6.