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GEOLOGY AND MINERALIZATION OF THE SUIAN DISTRICT, TYÔSEN (KOREA).

The Geology of the Suian Gold Mining District.

(3rd Report).*

By

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With 41 Plates and 12 Text-figures

Contribution from the Department of Geology and Mineralogy,
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* 1st Report: On the brucite-marble (predazzite) from the Nantei mine, Suian, Tyôsen (35). 2nd Report: Kotoit, ein neues gesteinsbildendes Magnesiumborat (36).

Chapter I

INTRODUCTION

The object and scope of the paper.—The most important geological feature of the Suian district is the stock-like intrusion of granitic magmas into the Pre-Cambrian sediments. As a result of this intrusion various kinds of metamorphic rocks and minerals were produced by thermal, pyrometasomatic and hydrothermal action. The present paper purports to describe the granitic and metamorphic rocks and mineral deposits of the district and to clarify the details of the history of magmatic activity and ore-deposition. In particular, the discussion of the progressive metamorphism of carbonate rocks and of the paragenesis of gold-copper-bismuth ores as well as of boron-magnesian minerals will be given special attention in this paper. Detailed description of the individual minerals will be given in a separate paper.

Location.—The Suian (Suan)[1] district, Kôkai-Dô[2], a famous gold mining district in Tyôsen, is in the central part of the Tyôsen-peninsula, about 75 kilometers east-south-east of the city of Heizyô (Pyeng Yang)[3], approximately at latitude 38°50′ and longitude 126°18′. The location of the district is shown in Fig. 1.

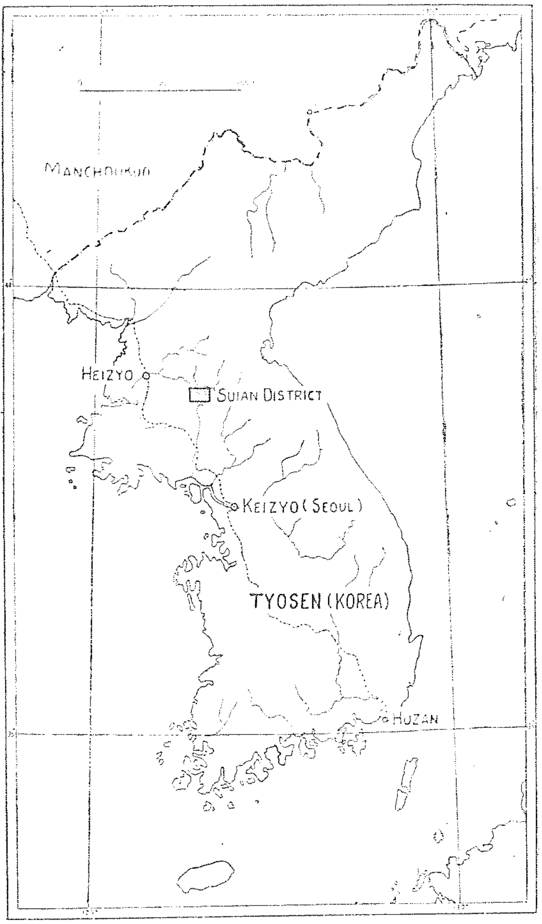

Fig. 1. Index map showing the location of the Suian district.

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1) 遂安　2) 黃海道　3) 平壤

Previous Works.—As the Suian district has been the scene of active gold mining operations for more than a century, geological surveys for mineral resources were frequently carried out by many geologists. While foreign companies held the concession of the Suian district, the area was examined by European and American geologists.

In 1903 the mode of occurrence of gold in the contact zone of the Suian stock was first explained briefly by Dr. R. Beck (1) in his text book, where an account is given by the observations of Bauer, a German traveller.

In 1903 Dr. Nakazima (24), then a mining geologist of the Mitsui Company, made a geological survey of the Kotudô1) (Hol Kol or Hol-gol) mine, which is the oldest mine in the Suian district. His report, however, has not as yet been published.

In 1907 Professor T. Iki and S. Suzuki (9) surveyed the area when a general geological survey for mineral resources was undertaken in Tyôsen.

Later, the material collected by Nakazima and by Iki was given over to the late Prof. B. Koto (18). He examined the material in his laboratory at Tôkyô and gave detailed petrographic descriptions of rocks and ores from the "Hol-gol" gold mine in 1910. He concluded that the "Hol-gol" deposits should be assigned to the category of the contact-metamorphosed deposits. In addition, he noted the abundant occurrence of "ilvaite" which was later identified as ludwigite by Shannon (25, 26).

Shortly after the commencement of mining operations in the concession by the Seoul Mining Company, the company requested Dr. D. F. Higgins (5, 6, 7) to make a topographic and geologic survey of the district. This survey was made in 1911 and in 1913, and his reports were presented to the company in 1914. A part of his work was also published in the "Economic Geology" in 1918. In his reports, a somewhat detailed genetical consideration of the geology and genesis of the gold deposits were given. It should be noted here that he gave a new mineralogical name "collbranite" to the so-called "ilvaite" of Kotô, regarding it as a new mineral, pyroxene rich in iron. The geological map of the contact zone, to which the name "Collbran contact" was given by Higgins, was printed on the scale of 1:18000.

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1) 笏洞

In 1914 E. Tamura and Y. Turumaru(27), geologists of the Geological Survey of Tyôsen, published a report on the geology of the Suian district. Then, at the time when the Hol-gol deposits were believed to be almost exhausted, the late Dr. Malcolm Maclaren (20), was invited by the company to see whether the concession was worth further exploitation. Maclaren studied the deposits of the "Collbran contact" and concluded that the "Suan mine" (the old name for the present Kotudô mine) was approaching exhaustion while the operations at the Tul Mi Chung mine[1] (The Nantei mine), on the other hand, were rapidly expanding. Although he noticed the structural control of ore deposition and the zonal distribution of ore deposits, his attention was but little directed to the scientific problems involved. He paid no attention for instance, to the mineral paragenesis of rocks and ores.

In 1919 A. R. Weigall and J. F. Michell-Roberts(31), mining engineers of the Seoul Mining Company, outlined the geology and ore deposits of the district in their report on the technical questions of mining in the Suian concession.

Since then no important article dealing mainly with the general geology of the Suian district has appeared, although there have been many short articles on the minerals and the mining in the district. In 1921, E. V. Shannon (25, 26) reexamined the "collbranite" from the Hol Kol mine and identified it as ludwigite. Furthermore, many papers on the various minerals from the Suian district were published by several investigators such as Z. Harada (3, 4), H. Inuzuka(10), K. Kinoshita and N. Nishihara(12–15), Wada(30), Watanabe(32–38) and others (28, 29).

Although C. B. Foster(2) studied the Tul Mi Chung geology in 1934, his report was not published. Occasionally reports on the technical operations of this mining district were published by Isikawa(11), Lemon(19), Weigall and Mitchel-Roberts(31), and others.

Present Investigation.—In 1930, Professor Takeo Kato of the Tôkyô Imperial University first directed the writer's attention to the study of pyrometasomatism in the Suian district.

The writer spent about two and a half months during the summer of the year 1930 in the field for a geological survey and the following

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[1] 楠亭鑛山

six months for the laboratory investigation of the rocks and ores. His first report on the geology and ore deposits of the district was presented as a graduation thesis at the Geological Institute of the Tôkyô Imperial University in the spring of the year 1931. As his work was incomplete at that time, he decided to make a further detailed study. The work has been continued till now. In the meanwhile, in 1931, he became a member of the staff of the Department of Geology and Mineralogy of the Hokkaidô Imperial University. The successive field work was undertaken in August, 1931, from June to August in 1934, from August to September in 1939 and in April, 1941. In these periods the greater part of his work was concentrated on the study of the surface and underground geology of the Kotudô and Nantei areas. The periods intervening between the field seasons were spent, from time to time, in the laboratory examination of the material from the district at the Hokkaidô Imperial University. Furthermore, a part of the material was also studied at the laboratory of the Institute of Mineralogy and Petrography at the University of Berlin, while he was staying in Berlin in 1937–1938.

Acknowledgments.—The writer takes particular pleasure in expressing his sincere thanks to Prof. Takeo Kato of the Tôkyô Imperial University, at whose suggestion the present investigation was undertaken, for helpful criticism and advice during the work.

He also wishes to thank Professor K. Uwatoko of the Tôkyô Imperial University, Professors J. Suzuki, Z. Harada and Y. Sasa of the Hokkaidô Imperial University for their kind advice and criticism.

He owes a debt of gratitude to the mining engineers of the Suian mining district, who gave hearty assistance in many ways during the field work. To Messers S. Nakakura and K. Unemura of the Hôkô Mining Company; T. Ben and K. Kin of the Kotudô Kinkô Kumiai; K. Seike, S. Kato and B. Sonoki of the Nippon Mining Company; S. Satô of the Seoul Mining Company, the writer is especially indebted. The late Dr. S. Kawasaki, the former Director of the Geological Survey of Tyôsen (Korea), and Dr. I. Tateiwa, the Director and other officers of the Survey did everything in their power to facilitate this work and he wishes here to express his sincere thanks to them.

At the University of Berlin, Professor Paul Ramdohr and Dr. Hugo Strunz offered valuable suggestions and advice while the writer was staying at their institute.

Thanks are also due to Prof. T. Itô of the Tôkyô Imperial University, for his kind advice and permission to reproduce two color plates of the kotoite-marble prepared for his book entitled the "Japanese Minerals in Pictures".

The writer is very much indebted to Drs. T. Yosioka and S. Miyagi of the Hitati Research Institute, Professor S. Nagai of the Tôkyô Imperial University, Dr. K. Tamura of the Ôsaka Industrial Laboratory, Dr. H. Inuzuka of the Research Laboratory of the Tôkyô Sibaura Electric Co. and Dr. T. Asayama of the Syôkôsyô Ceramic Laboratory, who kindly supplied him with the chemical data of the rocks and ores.

Finally, the writer wishes to acknowledge grants from the Huzita Research Funds of the Imperial Academy which made a part of his field work possible and from the Japan Society for the Promotion of Scientific Research which enabled him to carry on his laboratory investigations.

Physiography.—The physiographic features of the Suian area are somewhat rugged in contrast to those of Heizyô district known as "Rakuro-peneplain1)".

The average height of the peopled area in the district is about 300 meters above sea-level. A long ridge, running in a N.W.N. direction, at the highest point of which is located the summit of the Gensinsan (Unjinsan)2) (1119.8 m.), divides the mapped district into two regions; the northern and southern regions.

In the writer's opinion it is possible that the present features of the district represent a stage of maturity. In the northern region most of the streams run northward for a distance of 3–5 kilometers, forming transversal valleys, and then change their courses towards the east and join to become the Ukô3) which in turn flows into the Daidô-Nankô,4) the greatest river in the vicinity which runs from east to west. The widths of the valleys are relatively narrow and the area of deposition is usually small; and the villages and farmsteads are confined to these narrow spaces along the river. On the northern side of the Ukô, the Tyôma-San5) range runs nearly parallel to it.

On the other hand in the southern regions, the rivers generally flow in the reverse direction and moreover the valleys are com-

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1) 樂浪準平原 2) 彥眞山 3) 禹江 (U-gang or Oo-Kong) 4) 大同南江 (Nam Tai Tong Kang) 5) 頂馬山

paratively wide. There is therefore a larger population and agriculture is much more developed.

The morphological features of the district have close relationship to the general geologic structure. The present physiographic appearance of the district has been controlled principally by two dominating factors, the character of rocks and the geologic structures. The quartzite beds invariably become high and long cliffs to the south, forming usually long continuous ridges while the limestone and dolomite present relatively low and broad surfaces.

Between the northern and the southern regions granitic rocks are exposed and form characteristic features in contrast to the surrounding sedimentary rocks. Owing to homogeneity and to greater resistance to weathering action, the radial valleys have been developed in the central Gensinsan area where the granitic rocks are found, while in the sedimentary area the river-courses are always determined by the general trend of sediments except in some cases where, for example, dip faults determine the river-course as in the Kotudô valley. A few transversal valleys, furthermore, have been formed by antecedent rivers as in the case of the Nantei valley and others.

Recent uplift is generally shown by the river-terraces at 50–100 meters above the present surface of the river-water, on which the old gold hill-placers (or terrace-placers) are found. (For example, along the Rituri1) river and Naikinri2) valley).

Chapter II

GENERAL GEOLOGIC FEATURES OF THE SUIAN DISTRICT

In the north-western part of Kôkai-Dô in Tyôsen the older sediments, consisting mainly of extraordinarily thick limestone and dolomite with some intercalations of slate, quartzite, etc. are extensively exposed. Recently a considerable part of this area has been stratigraphically and paleontologically studied by many geologists. According to the researches of Prof. S. Nakamura (22,23), S. Matsushita (21, 23), N. Ikebe (8) and other, this series of great carbonate-

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1) 栗里 (Pamini-jang or Pai Mi Chang)   2) 内金里

rocks is now divided into the Syôgen[1] (Proterozoic or Sinian) and the Tyôsen system[2] (Cambro-Ordovician). These thick sediments are now rearranged into a complicated structure with foldings and thrust-faultings on various scales. Moreover, on account of contact metamorphism caused by the later intrusions of granitic magmas, the stratigraphic relations of the sediments in the Suian district have been largely obliterated. As no fossil has been found in them except some doubtful algal remains (*Collenia* sp.), the detailed stratigraphic order is not exactly determinable. However, the writer believes that the sediments in the Suian district will be grouped into the same horizons as those of the Syôgen district where the Syôgenian sediments (after Prof. S. Nakamura) are typically developed.

For these reasons, geological mapping is most difficult in this field. More exact and extensive surveys are necessary before we can find out the details of stratigraphic relations.

Archean rocks

Kokulian granites[3] *or "Grey gneiss".*—The Pre-Cambrian basement complex consisting of orthogneiss and paragneiss is well exposed in the south-western area of this region, a part of the So-hô-san[1] massive as shown in Fig. 2. The orthogneiss in this area is probably of magmatic origin and is very rich in dark xenoliths of sedimentary origin. These rocks underlie the thick sediments of the Syôgen system with a remarkable unconformity. Thus the rocks are now believed to be among the oldest in the Tyôsen peninsula and are correlated with the Archean rocks to which Professor S. Nakamura (23) has given the name "Kokulian granites".

Macroscopically the rocks consist chiefly of greyish orthogneiss and highly metamorphosed sediments such as augen-schist, mica-schist, etc. The latter two were evidently intruded or caught by the former. Under the microscope the paragneiss shows granoblastic and porphyroblastic structures. Bent plagioclase (andesine) is often found. The biotite is also often bent and shows very strong pleochroism X//straw yellow Y, Z//reddish brown. Absorption is $X<Y$ & Z. The biotite has abundant pleochroic haloes around small crystals of zircon. Quartz is generally present and shows un-

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1) 祥原系　2) 朝鮮系　3) 高勾麗花崗岩　4) 甑峯山

dulatory extinction. The so-called "augen" of microcline is often found.

Proterozoic rocks (Syôgenian rocks)

*The Tyokken series.*1)—The Tyokken series (22) named by S. Nakamura for Tyôkken village, west of Rituri, rests unconformably on the basal complex above mentioned. The series crops out in the southwestern part of the district and extends continuously westwards into the type-locality of the Tyôkken sediments. It comprises several formations as explained below. However, these formations are not separated in stratigraphic order in the accompanying geological map (Plate XLVI(I)). The lowest bed of the series is a white fine-grained quartzite of 20–30 meters thickness and called "Syoganri quartzite"2) by N. Ikebe(8). The sediments overlying this quartzite are yellow to brown coloured micaceous phyllite, called "Tyokken mica-schists"3) and banded slaty limestones which are more or less crystalline and dolomitic. These sediments dip towards the north, gently in the lower part and steeply in the upper-horizon near the Suian intrusive mass and strike generally NW-SE.

The upper part of these formations consists of the dark bluish crystalline limestones, locally called "Nantei-limestone4)" (Tul Mi Chung limestone, after D. F. Higgins (6, 7)), which grades into calcareous slate and quartzite beds which are called "Rendaihô quartzite5) by N. Ikebe.

Syôganri quartzite.—Petrographically the Syôganri quartzite is very light in color and has beautiful and distinct cleavage parallel to its bedding plane. Microscopically the rock is very fine-grained and consists mainly of granular quartz with very small amounts of sericite and sometimes shows marked schistosity.

Tyokken mica-schists.—Immediately overlying the Syôganri quartzite some peculiar metamorphic rocks appear. The rocks consist of mica-schists with intercalated siliceous bands; the former is usually light-grey to light yellow in color and finely layered. Under the microscope the micaceous part shows a lepidoblastic or granoblastic texture. Felsic bands consist of polygonal quartz and albite-oligoclase. The darker mafic band is mainly composed of

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1) 直峴統 2) 祥岩里珪岩 3) 直峴雲母片岩 4) 楠亭石灰岩 5) 蓮臺峯珪岩

sericite and biotite. The rocks are probably recrystallized from shaly sediment with lenticular layers of siliceous sandstone. (Plate LI (VI) fig. 2).

Tyokken limestones[1].—The carbonate rocks of the Tyokken-series are occasionally intercalated with the mica-schists mentioned above and their distribution is indicated on the geological map (Plate. XLVI(I)). Petrographically the rock consisting of calcite and dolomite, is almost crystalline and shows a well-marked banded structure. In the upper horizon of the Tyokken series the carbonate rocks become very dark in color and have many flakes of phlogopite and occasionally anhedral grains of quartz. This part of the formation was named "the Tong Am limestone"[2] by D. F. Higgins (5, 6).

The upper part of the banded or slaty limestone imperceptibly becomes calcareous slate to which the name "the Tul Mi Chung limestone"[3] has been applied by D. F. Higgins (5). Because of the selective weathering of bands having different mineral composition, the siliceous part stands in relief above the calcareous band as shown in Plate LI (VI), Fig. 1.

Rendaihô quartzite.—Near the village of Nantei a series of rocks consisting of siliceous slate and quartzite conformably overlies the carbonate rocks described above. The formation ranges from 50 to 70 meters in thickness. Because of the close resemblance of its lithologic characters to those of the Syôganri quartzite both have often been interpreted as being stratigraphic equivalents by different authors. However in the vicinity of Rituri the same kind of quartzite apparently overlies the mica-schists and limestones as mentioned by N. Ikebe (8). So it is possible that the quartzite and siliceous slates developed in the Nantei area are also stratigraphically higher than the Syôganri quartzite. The Rendaihô quartzite is one of the prominent cliff-forming sedimentary rocks of the Suian district. Its petrographic character is very similar to that of the Syôganri quartzite.

Sidôgû Series[4] (*Kotudô dolomite*[5]).—The Sidôgu series with which the sedimentary rocks of the district are correlated was named by S. Nakamura from Sidôgu-village situated in the vicinity of Syôgen. The series consists mainly of dolomite and limestone with some layers of slate. It consists usually of several formations

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[1] 直峴石灰岩
[2] 銅岩石灰岩
[3] 楠亭石灰岩
[4] 祠堂隅統
[5] 笏洞白雲岩

grading into one another. The geologic structure of this district is also highly complicated, so that it is impossible to show the subdivisions on a geologic map. The lower part of the series consists of grey, crystalline dolomitic limestones, grading into the white or grey massive dolomite of the middle part. The upper part of the series is composed of grey, thinly bedded limestone with Collenia, (Plate LI (VI), Fig. 3), banded dolomite (Pl. L (V), Fig. 2), and characteristic massive dolomite which is especially well developed in the Kotudô valley. According to Ikebe, the thickness of the Sidôgû series of the Syôgen district is about 1000 meters.

*Kuken Series.*1)—In the northern part of the district the carbonate rocks of the Sidôgu series are conformably overlain by the Kuken slaty rocks which can be divided into two formations, mainly the Suian slate2) and the Sekitauturi quartzite3). The name of the series, Kuken, was given by S. Nakamura because of its original type occurrence at the Kuken pass near Syôgen.

The Suian slate is the formation composed essentially of black or greyish green slate. It develops extensively in the western part of the Kotudô fault. The Sekitaturi quartzite consists of a very fine grained hard, slaty quartzite and grey to black siliceous slate (Pl. L (V), Fig. 3).

Metadolerite dykes and sills.

The basic dyke-rocks and sills which have hitherto been described as dolerite, gabbro-schist or "Green dykes" by previous investigators, are widely scattered throughout the area where the Syôgenian rocks crop out. According to S. Nakamura and his co-workers, dykes of this kind have not been discovered in the post-Syôgenian rocks of the Kôkai-Dô. Therefore it is believed that the dykes were injected before the Paleozoic sediments were deposited. As shown on the geological map (Pl. XLVI (I)) the direction of the longer axis of the exposed masses coincides generally with the regional trend of the country rocks.

Petrography.—Megascopically it is dark green in color, distinguished easily by its color from the surrounding rocks. Weathered portions are composed of dark olive-green colored soil. When fresh, small grains of iron ores with metallic lustre and other green mafic

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1) 駒峴統 2) 遂安粘板岩 3) 石達里珪岩

minerals are noticeable in the rock, and a few felspathic minerals can be discriminated.

Under the microscope the original structures and textures of igneous rocks are almost lost. Very rarely the thick tabular form of the original plagioclase is shown in thin sections. Judging from the faint palimpsest structure the original rock is probably dolerite or diabase. The original plagioclase has now commonly been altered into fine aggregate of albite and quartz, and rarely retains its original form. The unaltered feldspar occurs in long laths and shows polysynthetic albite-twinnings, though minute secondary minerals are scattered through it. Its chemical composition is roughly estimated as An_{55} by the maximum symmetry extinction method. Amphibole occurs in two forms, namely in rudely idiomorphic form with ragged outline showing the characteristic uralite-form and in fibrous form (Plate LVII(XII), Fig. 1). Biotite grains also occur in small amounts. Intimately associated with amphibole and biotite and iron opaque minerals are usually found. Although the remnants of the original minerals were not found, these minerals are probably metamorphosed products derived from the original pyroxene. Occasionally quartz or calcite occurs in small patches. Titaniferous iron-ores are very abundant and change their form into leucoxene grains with black lamellae of rutile. Idiomorphic apatite is universally present and always fresh. As to the metamorphosed products of metadolerite in the inner contact aureole of the Suian granite, a brief note will be given later.

The Mesozoic Intrusive Complex (The Suian Intrusive Complex)

General features.—The igneous activity of the Suian district has produced two principal classes of rocks: (1) major intrusives and (2) minor intrusive rocks. The distribution of the various rocks is shown on the accompanying map (Pl. XLVI(I)). The major intrusive rocks comprise 3 quartz diorites, 2 porphyritic granodiorites and a granite-porphyry. Numerous minor intrusive dykes are intruded into both the major rocks and sediments of the aureole. The central and higher part of the investigated area is composed of porphyritic plutonic or hypabysal rocks forming a very interesting igneous complex. The major igneous mass, to which the writer gives the name "The Suian Igneous Complex[1]", has an elongated outcrop 13 kilometers in length and 8 kilometers in breadth at the widest part, giving a total outcrop of about 75 square kilometers; the body of the complex therefore belongs in size to the group of stock as defined by R. Daly. This stock-like intrusion was named by B. Kotô the "On-Jin-San stock" (Gensin-San Stock) after the highest mountain in the district.

The long axis of the main mass runs from west-north-west to east-south-east and is roughly parallel to the regional strike of the country, as shown in fig. 2. To the west of the main mass a comparatively small outcrop of a similar kind of granitic rock is seen. This outcrop is probably a cupola of the main mass, which has been concealed under the country rocks between two masses, so that the metamorphic effect on the country rocks is very strong in that part. The total length of contact of the stock to which the name "Collbran contact" has been given by D. E. Higgins, is 45 kilometers. There are several areas of sediments or roof pendants entirely enclosed within the stock. As shown in fig. 2, the Suian stock is surrounded entirely by a contact aureole within which the various kinds of metamorphic rocks and related ore deposits are found. The details of the petrographic investigations of igneous rocks, metamorphosed rocks and ores will be given in the following chapters.

Age of the igneous activity.—As the intrusive rocks cut nothing younger than the metamorphic rocks of the Syogenian rocks, no direct evidence of the age of the magmatic activities is available. However the igneous rocks in question resemble petrographically those of the Bukkokuzi (or Hukkokuzi) igneous group[2] of the late-Mesozoic age, developing extensively in Tyôsen peninsula. Moreover the Suian intrusives clearly modified the major regional geologic structure previously controlled by the Taihô[3] orogenic movement of Jurassic age (Kobayashi (16) and Konno (17)). Since there is no effect of crushing nor sign of cataclastic effect in the igneous rocks of the district, the writer believes that most probably the igneous activity of the Suian district must have been later than that of the Taihô orogeny. It must, therefore, be concluded that most probably the igneous activity of the Suian district must have belonged to the period of Bukkokuzi igneous activity.

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1) 遂安火成岩體　2) 佛國寺火成岩類　3) 大寶

Cenozoic rocks

The Tertiary or Quaternary basalts.—In many places the basalts occur as dykes or in small masses. Some of these basalt-dykes cut both the Suian intrusive rocks and their country rocks, so it is the youngest eruptive in the field in question. The basalt in the Saziri[1] valley shows many accidental inclusions of dolomite-marble, hornfels and granitic rocks and it looks like igneous breccia while many of the narrow dykes are free from inclusions. As many basalts in the field show common petrographic characters, a detailed description of basalt from Saziri valley and from the Nantei mine will be given as representative. Basalt in the Saziri valley is megascopically very dark in color and has many phenocrysts of olivine, pyroxene, hornblende, and feldspar. Occasionally it has abundant amygdaloidal cavities in which chalcedonic quartz and zeolites are often found. Under the microscope the minute lath-shaped micro-crystals of feldspar and dark vitreous matters are seen to fill the space between the phenocrysts (Pl. LVI (XI), Fig. 4). Principal constituents of the basalt are olivine, titaniferous augite, barkevikitic hornblende, and plagioclase. Although B. Kotô (18) and D. F. Higgins (5) recognized some rare minerals known to occur in alkaline basalts, the writer could not find any of them except titaniferous pyroxene and anorthoclase which are often found in the margins of plagioclase when seen in sections.

Basalt in the Nantei mine.—Basalt dykes found in the vicinity of the Nantei mine are almost holocrystalline and equigranular and their principal phenocrysts are beautiful titaniferous augite and decomposed olivine. Their groundmass is also made up of the same kind of augite and multiple twinned plagioclase of 0.5 mm. in length. The plagioclase having a marginal zone of anorthoclase is long-prismatic and its composition may correspond to that of labradorite. Titaniferous augite is comparatively low-double-refractive and often shows zonal structure. Olivine is partially or entirely changed into aggregates of greenish yellow serpentine with very low-double-refraction, iron ore and calcite. Ilmenite is very abundant and often carries a leucoxene margin. Angular quartz is sometimes found as xenocryst in the basalt, which is believed to be taken from the siliceous country rock at the time of its intrusion. Since the ore-

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1) 沙峙里

bodies of the Nantei mine are apparently cut by dykes without marked alteration, the intrusion of basalts has nothing to do with the origin of ore deposits. As to the age of their intrusion no evidence is available, except the occurrence of the allied basalt-flows of the Quaternary age in the Kokusan-Sinkei[1] district, (Fig. 2) about 10 kilometers east of the town of Suian.

Quaternary sedimentary rocks.—The Quaternary deposits of the district consist of alluvial river sand and gravel. In some parts of these deposits, especially near or in the Suian stock, the gold placer deposits have been discovered as shown in fig. 2.

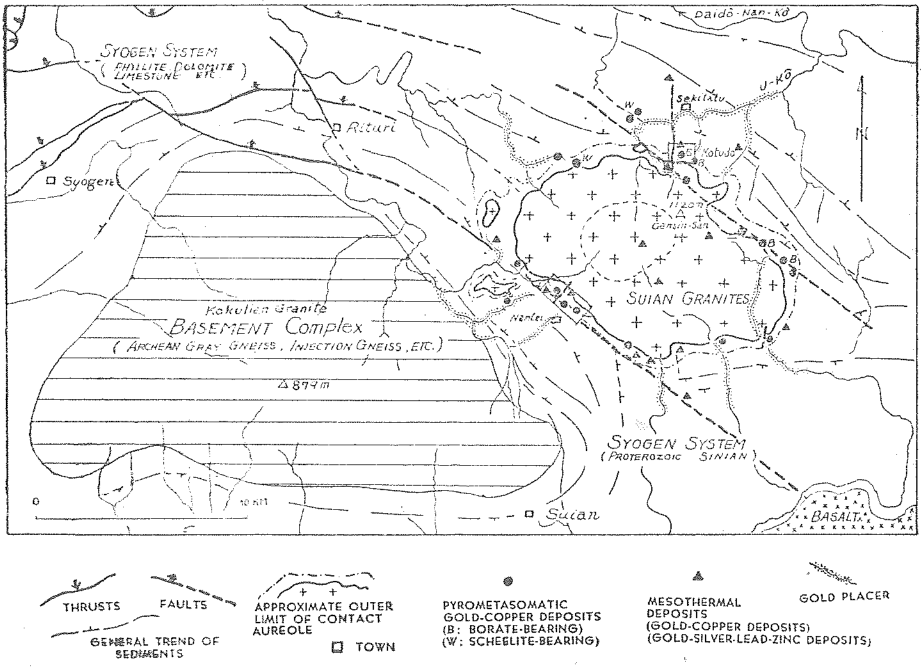

Fig. 2. Outline map of the Suian district showing the general features of the regional geology and the distribution of the mineral deposits.

Geologic structure.—The complex structure of the Suian district is principally the result of two kinds of deformation: (1) folding and faulting by Taihô orogenic movement; (2) gradual upheaval of the mountain region by the normal faulting of a later age. The structural relations of the igneous rocks will be mentioned in a later chapter

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[1] 谷山一新溪

and fissures to which the mineralization is known to be related will also be explained in the chapter dealing with mineral deposits.

During the period of the orogeny of the Taihô phase (the interval between the lower-Jurassic Daidô epoch and the Cretaceous Taihô epoch), the Syogenian and pre-Syôgenian rocks were intensely folded along axes which trend in NW-SE direction. Thrusts trending in the same direction were also developed in many parts of the district. After or succeeding the period of this deformation, the emplacement of granitic magmas took place, probably during the period of the Bukkokuzi (or Hukkokuzi) igneous activity. In consequence of these intrusions, minor faults were produced in the contact zone, which have important bearing on the ore-deposition of the district. Since then the district was uplifted till recently and some normal faults trending NW to WE were also produced. It should be mentioned here that igneous rocks such as quartz-porphyry or felsite and also basaltic rocks of the Tertiary or Quaternary age are found as dykes along these normal faults. In the accompanying outline map (Fig. 2) the important faults and fault zones of the Syôgen district are shown.

Summary of geologic history.—The geologic record of the Suian district begins sometime during the pre-Syôgenian. In Tyôsen the pre-Cambrian time has been divided into the Archeozoic and Proterozoic eras. It is believed that the Syôgen system in Kôkai-Dô belongs definitely to Proterozoic while the gneisses and schists underlying the Syôgen system with marked unconformity cannot be dated exactly. However the rocks lithologically resemble the so-called "Kôkulian granites" or "Grey-gneisses" representing the Archean rocks, which have been thought to be the oldest rock in the Tyôsen peninsula. Therefore the details of the geologic history of the pre-Syôgenian cannot be given here. It can be said however that intense injections and intrusions of granitic magmas took place before the deposition of the Syôgenian rocks. The formation of the latest metamorphic rocks of pre-Syôgenian was probably accompanied by an uplift and was followed by a long period of erosion. After this old land was worn down to peneplains the Syôgenian sea spread over them and might have covered the greater part of the district. From then until the middle Ordovician period the district represented an older geosyncline zone called the Heinan geosyncline.¹⁾

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1) 平南地向斜

Repeated withdrawals and invasions of the sea due to the oscillation of the earth's surface may have also occurred during the long period of deposition of "Rakuroan sediments[1] (after T. Kobayashi, 1940) in which the groups of rocks, Syôgenian and Cambro-Ordovician, are included.

Owing to the lack of the younger sediments in the district, it is impossible to state here the geologic events since the late-Paleozoic era. Although the data of later folding and igneous activity cannot be established directly by the available field evidences, the similarity of the structures of the Suian district with that of the adjacent Heizyô-Syôgen district, indicates that major geologic structures of both districts were probably produced by the same dynamic activity at the same time. Therefore the period of deformation of the sediments in the Suian district may be suggested by the data obtained in the adjacent field.

According to S. Nakamura and S. Matsushita (21, 22, 23), N. Ikebe (8) and others the Syôgen system of Heizyô districts in Kokai-Dô together with the Paleozoic group was intensely folded and thrusted by the late Mesozoic orogenic movement, i.e. during the Taihô phase (post lower Jurassic Daidô epoch—pre Cretaceous Taihô epoch). The axes of these folds and the trend of these thrusts extend from the Syôgen to the Suian district. Thus, the major deformation of the Syôgenian in the Suian district is concluded to have taken place in the Taihô phase. As to the igneous activity of the Suian granites no positive data were uncovered except the fact that major intrusions accompanied the deformation of the Syôgen sediments. On the other hand it is known that the period following the Taihô phase represents the most important period of igneous activity (called Bukkokuzi igneous activity) in the Tyôsen peninsula. It is assumed, therefore, that the granitic rocks of the district were also intruded during the same period of activity of the Bukkokuzi igneous group. The emanations from these granitic magmas formed many important metalliferous deposits of the district in question. Judging from the mode of occurrence and texture of the igneous rocks and ores, they were probably formed under a moderately thick cover.

Since the late-Mesozoic igneous activity the district has probably stood above the sea and eroded gradually. As to the age of the

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1) 樂浪堆積岩類

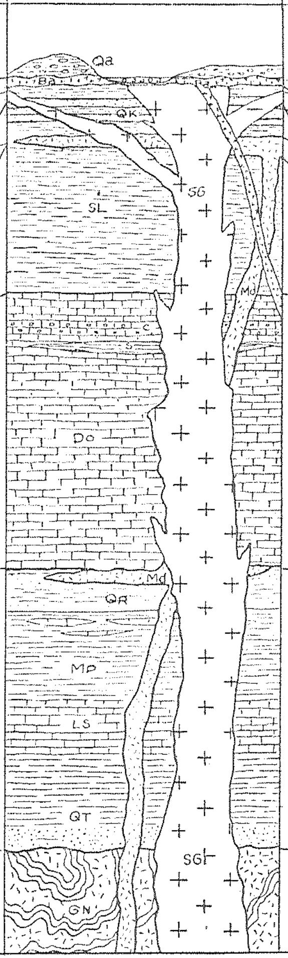
AGE			FORMATION	SYM BOL	COLUMNAR SECTION	LITHOLOGY	THICKNESS IN METERS	RELATION OF ORE DEPOSITS
QUATERNARY			ALLUVIUM	Qa		River and terrace gravel, sand.		Gold placer
			Unconformity					
TERT. or QUAT.			BASALT DYKES	Ba		Olivine basalt		
MESOZOIC (BUKKOKUZI)			SUIAN IGNEOUS COMPLEX	SG		Porphyritic granodiorite, Granite porphyry, etc.		Gold-copper mineralization.
PRE-CAMBRIAN	UPPER-PROTEROZOIC (SYÔGEN)		METADORELITE	Md		Metadolerite	200-	Country rock of the Sekitaturi deposits.
		KUKEN SER.	SEKITATURI QUARTZITE	Qk		Gray siliceous slate, Quartzite.		
			SUIAN SLATE	Sl		Black phyllitic slate.		
		SIDÔGU SERIES	KOTUDÔ DOLOMITE	Do		Thinly bedded crystalline limestone. Collenia limestone (c) Bluish gray or black slate (s) Massive dolomite. Bluish gray banded limestone.	500- 1000	Country rock of the Kotudô deposits. Country rock of the Nantei deposits.
		TYOKKEN SERIES	RENDAIHÔ QUARTZITE	Qr		Whitish quartzite.	500- 700	
			TYOKKEN MICA-SCHISTS	Mp		Grayish mica-schist with siliceous lenses.		
			TYOKKEN LIMESTONES			Banded micaceous limestone		
			SYÔGANRI QUARTZITE	Qt		Whitish quartzite		
			Unconformity					
	ARCHEAN		KOKULIAN GRANITES (GRAY-GNEISS)	Gn		Paragneiss. Injection- gneiss Migmatite.		

Fig. 3. Diagrammatic columnar section for the Suian district.

basaltic intrusions or extrusions, no positive evidences for determinig it exactly were obtained. However, the basalts in question are considered to be the allied members of Quaternary basalts developing extensively in Tyôsen. Recent uplift has been marked by the presence of river terraces while no trace of glaciation has been observed in this district. General geologic history is diagramatically shown in the columnar section of fig. 3.

Chapter III

THE SUIAN INTRUSIVE COMPLEX

As explained in the preceeding chapter, the stock of the Suian district is roughly elliptical in form and its dimension is approximately 8×13 kilometers. This igneous mass is a composite stock of granitic rocks. The main mass, to which the name, the Suian granite[1] (the Suan granite after Higgins(5, 6, 7) and Maclaren (20)) is given, is pierced in its central part by a rounded fine-grained granitic mass (the Hitiseidai granite[2] or Chil Sing Dai granite) about five kilometers in diameter. As shown in fig. 2 the longer axis of the major stock runs from NW to SE, roughly parallel to the regional trend of the country. Because of good exposures along the contact the relation between the intrusives and country rocks are generally well observed everywhere both on the surface and underground. Although the country rocks strike sometimes parallel to the igneous contact, cross-cutting relations are usually observed. Along the northern contact, dips are usually towards the country rocks in low angles except at the Kotudô mine. On the other hand along the contact near Nantei dip of contact plane is towards the igneous rock as shown in Plate (XLIX(IV). From the distribution of the abundant roof-pendants in the north-eastern part of the intrusive mass and from the absence of large xenolithic masses in the south-western part, it is assumed that the south-western part of the Suian mass is floored.

Within the igneous rocks near the contact, small xenolithic rocks from the wall rocks were often found in abundance. This fact suggests that the process of Daly's "piecemeal stoping" was important

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[1] 遂安花崗岩 [2] 七星垈花崗岩

at the time of the emplacement of the magma. As the structural behaviors of the igneous masses show very interesting facts about the mechanism of the intrusion, special investigations have been carried on by Mr. T. Isikawa of our Institute since 1941.

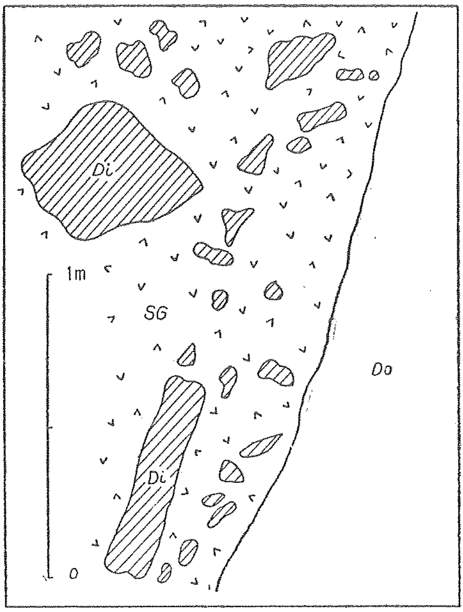

Fig. 4. Sketch showing distribution of inclusions of diopside skarn (Di) in the Suian granite (SG). Note characteristic lack of orientation ! Nantei South mine, −30 m level.

Suian granite (porphyritic hornblende-biotite-granodiorite).— The Suian intrusive stock is mainly composed of this kind of rock except in the central part, i.e. south-west of Hitiseidai and also in a narrow zone of marginal facies. The exposed surface shows very characteristic features when decomposed as shown in Plate LII (VII) Fig. 1. Rounded phenocrysts of orthoclase project from the surface because of its higher resistance to the weathering agency than the matrix. The writer's field examination shows that the distribution of phenocrysts is generally very even and average volume percentage of phenocrysts of the rock is 8 per cent.

Megascopically, it is of a light-rose color and shows a coarse texture (Pl. LIII (VIII), Fig. 1). The principal components can easily be recognized by the naked eye. In immediate contact with the sediments its porphyritic texture frequently disappears. Many dark inclusions are present as xenolith or autolith.

The characteristic features of the Suian granite is its porphyritic texture due to the presence of large rounded phenocrysts (ovoids) of microperthitic orthoclase, up to 5 cm in diameter. Petrographically the rocks resemble very closely the pyterlite[1] of Finland, an allied rock of the famous Rapakivi granite (Backlund (40)). As shown in Plate LIII (VIII), Fig. 1, the microperthitic phenocryst exibits occasionally its crystal form and in some outcrops it is often mantled by oligoclase (see Pl. LIII (VIII), Fig. 2) as in the case of a typical "Rapakivi granite." Although the "Rapakivi or "pyterlite" texture has not been mentioned by the previous writers, it is the most characteristic and common texture of the Suian granite.

Microscopically, the texture of the groundmass is granular. Plagioclase is stout-prismatic 2 mm. in length and more or less euhedral against orthoclase and quartz. Zonal structure is common (Plate LII (VII), Fig. 2 and 3). The composition of plagioclase varies from An_{30} to An_{18}, which was determined on the universal stage. The mineral is usually fresh and free from secondary minerals and it shows polysynthetic twinning after albite-law. As a phenocryst, orthoclase (microperthite) is flat prismatic or rounded while orthoclase occurs also in the groundmass and intersticial spaces (Pl. LIII (VIII), Fig. 2). The large crystals of phenocrystic orthoclase always carries abundant inclusions of plagioclase, hornblende, biotite and subhedral to enhedral quartz. Therefore the orthoclase-phenocrysts can not be considered as the earliest crystallized minerals from the liquid-magma. Consequently the larger size of this mineral is likely to be attributed to the fact that the centres of crystallization were relatively few at the time of solidification, as suggested by K. Sugi (109). And as in the case of the Rapakivi granite in Finland, which was described by B. Popoff (91), peculiar anhedral quartz (the so-called "aussenkonkaver Quarz") is also observed in the orthoclase-phenocrysts (Pl. LIII (VIII), Fig. 2). Orthoclase-phenocrysts show a micro-perthitic intergrowth, as if formed by the paul-post action along the cracks of orthoclase.

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1) Rapakivi-granite without oligoclase mantles. Lit. Wahl, W.: Fennia 45 (1925).

The perthitic plagioclase which occurs as fine lamellae, is more acidic in composition (albitic) than the larger idiomorphic plagioclase.

Quartz occurs abundantly in the groundmass and is generally euhedral against orthoclase. The intersticial spaces are commonly filled up with these minerals. Judging from its crystal form the quartz might have been crystallized as a higher temperature form.

The diopside is colorless in thin section and often bordered by hornblende-rim. It occurs especially in the Suian granite near the contact against the dolomite. From the mode of occurrence of diopside-bearing rocks the formation of crystals of diopside may have been caused by contamination of the dolomitic sediments. Hornblende is irregularly bounded and its characteristic prismatic cleavage is sometimes shown in the section. The association of hornblende with biotite and magnetite is usually seen. Pleochroic scheme of hornblende is as follows: X // pale greenish yellow, Y // brownish-green, Z // olive-green. Extinction angle is $c \wedge Z = 20°$. Optical character is negative and 2V is large.

Biotite is much more abundant in amount than hornblende, and has a brownish tint with distinct pleochroism.

$Z \doteqdot Y$ // dark brown, X // pale straw yellow;

absorption is $Z = Y > X$; $2V = 0°$. Green chlorite is frequently found as an alteration product parallel to its cleavage planes.

As accessory minerals, pyrite, magnetite, ilmenite, apatite, zircon, allanite, titanite, and others are present. Small grains of idiomorphic cubic pyrite are very rarely found, but widely scattered throughout the rock. Apatite is always acicular or stout-prismatic and closely associated with biotite. Zircon and allanite are also found with biotite. In order to determine the opaque minerals some polished sections of the Suian granite were examined under the reflecting microscope. Microscopic relation of magnetite to later ilmenite is shown in Plate LII (VII), Fig. 4. The analysis of the Suian granite from the Saziri valley, made by A. Kannari, together with its norm and mode1) is shown in Table I. The chemical and mineralogical composition accords well with the classification of the rock as "granodiorite."

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1) The mode was determined by the Rosiwal's method using the Leitz's integrating stage.

TABLE 1

Analysis of the Suian granite, Saziri valley.
Analyst: A. Kannari.

d	2.68	Norm		Mode vol.%	
SiO_2	67.59 %	qu	24.62	Q.	24.0
TiO_2	0.40	or	13.36	Or.	27.3
Al_2O_3	15.99	ab	33.56	Pl.	36.4
Fe_2O_3	1.45	an	17.80	Hrb.	2.8
FeO	2.01	c	0.51	Biot.	9.0
MnO	0.15	hy	6.63	Access.	0.5
MgO	1.82	mt	2.08		100.0
CaO	3.59	il	0.76		
Na_2O	3.94				
K_2O	2.30	Class I.4.2.4.			
P_2O_5	tr.				
H_2O+	0.91				
H_2O-	0.02				
Total	100.17				

Hitiseidai granite (*Biotite granite-porphyry*).—Entirely surrounded by the Suian granite another kind of granitic rock is found. This rock is called "Chil Sing Dai (Hitiseidai) Granite" by D. F. Higgins (7), who considered that this granitic mass is of later intrusion than that of the Suian granite. Several xenoliths of the Suian granite are enclosed in this rock near the contact as shown in Fig. 5 and in Plate LIX (IX), Figs. 1–3. Therefore the writer also considers that this mass represents a later separate intrusion.

Megascopically it is also porphyritic in texture but its groundmass is more fine-grained than that of the Suian granite. Moreover the density of distribution of the phenocrysts in this rock is much smaller than that of the latter. Pinkish phenocrysts of orthoclase sometimes attain 3 cm. in length and have a lighter color than the phenocrysts of the main porphyritic granite. Owing to the presence of deuteric chlorite in radial aggregates, the color of the rocks is usually green. The typical Rapakivi ovoids are very rarely found as phenocrysts.

Under the microscope it is seen to be porphyritic in texture and to consist of oligoclase, orthoclase, quartz and biotite. Biotite and chlorite are usually present in the groundmass.

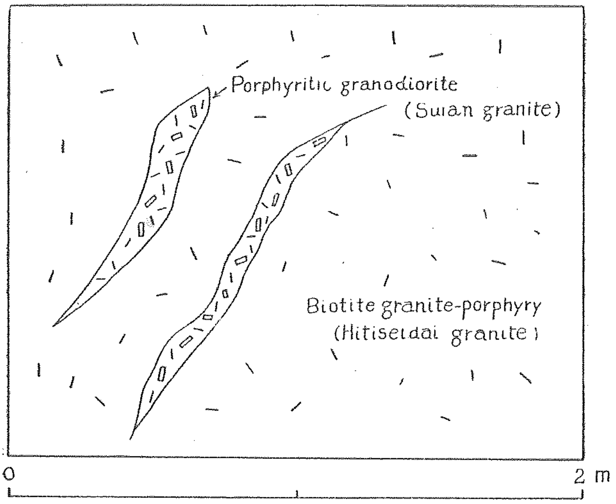

Fig. 5. Sketch of the rock face on the floor of the Tyôdô[1] valley, showing the elongated blocks of the Suian granite enclosed by the Hitiseidai granite.

Plagioclase is subhedral to euhedral against quartz and orthoclase and is often decomposed into zeolite, epidote, kaolin, etc. The composition was also estimated as An_{36}-An_{15} on the universal stage. Zonal structure of the plagioclase is very common. Phenocrystic orthoclase has similar characters to that of the Suian granite. Interstices of the groundmass are also filled with anhedral orthoclase.

Although quartz is not abundant as phenocryst, idiomorphic one appears in large quantities. Inclusions of titanite and magnetite are very common. Biotite is the principal primary mafic mineral in this rock. Closely associated with the fresh yellow to brown biotite green chlorite is found here and there. Chlorite is the characteristic mineral in the rock and is an alteration product derived from the original mafic mineral such as biotite. Epidote is also sparingly present as a secondary mineral. As accessory minerals magnetite, pyrite, ilmenite, and titanite are scattered throughout the groundmass. The analysis of this rock is given in Table II.

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1) 長洞

TABLE 2

Analysis of the Hitiseidai granite.
Analyst: A. Kannari.

d	2.61	Norm		Mode vol.%	
SiO_2	71.69 %	qu	27.81 %	Q.	29.0
TiO_2	0.20	or	20.03	Or.	37.9
Al_2O_3	15.56	ab	37.23	Pl.	29.4
Fe_2O_3	0.46	an	4.73	Biot. etc.	3.7
FeO	1.00	c	2.96		100.0
MnO	0.15	hy	5.84		
MgO	1.81	mt	0.70		
CaO	0.97	il	0.56		
Na_2O	4.41	(Class I.4.2.4.)			
K_2O	3.41				
P_2O_5	tr				
H_2O+	0.70				
Total	100.36				

The Minor Intrusive Rocks

Nantei quartz-diorite[1] (Weigall-granite after D. F. Higgins or quartz-diorite after M. Maclaren).—Closely associated with the Nantei ore-bodies, the much finer-grained granitic rocks occur. Although the mass is comparatively small the variation in composition is very marked. Boundary to the other rocks is often obliterated by the faults and obscured by the covering of the weathered soils on the surface. (See Plates XLVIII(III)–XLIX(IV)). This small mass is often cut by the later quartz or calcite veins. Megascopically the rock is of darker color and is equigranular in texture.

Under the microscope it is observed that the variation of mineralogical composition, texture and structure is marked in different parts of the mass (Pl. LVI(XI), Fig. 1). The typical rock is of granodioritic to quartz-dioritic composition with granitic texture. Plagioclase in the rock is more basic than that of the main porphyritic granodiorite (the Suian granite). It is thick tabular to equant, enhedral to subhedral against other con-

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1) 楠亭石英閃綠岩

stituents. The layers of zoned crystals, which usually show albite-twinning unvariably, have indistinctly defined boundaries. Periclin twin is rarely found. The inner part of the plagioclase is rather basic and has a composition corresponding to laboradorite, while the outer part is andesine. Saussuritization is usually confined to the inner core. Anhedral orthoclase is very sparingly present and fills the interstices of the other constituents. At the junction of plagioclase the myrmekite is frequently formed. Quartz is also anhedral and fills the interstices of the rock. Granophyric intergrowth of quartz with feldspar is also found. As accessory minerals the following minerals are noticed: titanite, ilmenite, hematite, etc. A chemical analysis of the quartz-diorite from the Nantei mine is given below.

TABLE 3

Analysis of the quartz-diorite, Nantei mine.
Analyst: A. Kannari.

d.	2.86		Norm	
SiO_2	52.08 %		or	7.79
TiO_2	1.05		ab	29.89
Al_2O_3	18.82		an	31.71
Fe_2O_3	0.09	di	$CaO.SiO_2$	5.81
FeO	5.46		$MgO.SiO_2$	3.41
MnO	0.39		$FeO.SiO_2$	2.11
MgO	6.06	hy	$FeO.SiO_2$	2.37
CaO	9.20		$MgO.SiO_2$	4.02
Na_2O	3.54	ol	$2FeO.SiO_2$	3.46
K_2O	1.35		$2MgO.SiO_2$	5.35
P_2O_5	tr		mt	0.23
H_2O+	2.50		il	1.97
H_2O-	0.20		II.5.3.4	
	100.74			

Quartz-diorites.—Near the Dôgan mine[1] the small masses of quartz-dioritic rocks crop out. Microscopically the rock resembles the quartz-diorite in the Nantei mine and suffers from intense

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1) 銅岩坑

fracturing. As the writer was not able to make a detailed examination, exact descriptions can not be given. The geologic relation of the Dôgan quartz-diorite to the Suian granite is quite similar to the relations of "Weigall Granite" to the latter. Separate masses of small intrusions of quartz-diorite are also found as dykes or small stocks near the villages of Rakkenri and of Dôgan (Plate LVI(XI), Fig. 2). They are thought to be precursors of the Suian granite. The mineralization also took place in the vicinity of rocks.

Kotudô granite[1] (*Hol Kol granite*).—On the hill south-west of the eastern open-cut of the Kotudô mine a non-porphyritic granitic rock occurs in irregular form. At the margin of the contact the rock grades into an aplite which has abundant miarolitic cavities, from which considerable amount of gases possibly escaped into the sediments. Rounded xenoliths (Pl. LXIV(XIX), Figs. 1–2) consisting of skarn minerals are abundantly seen in the eastern open-cut. Under the microscope the rock is essentially composed of quartz, orthoclase and plagioclase with very subordinate amounts of biotite. Similar igneous rock is also found in the Saziri valley.

Nantei quartz-porphyry[2] (*Tul Mi Chung quartz-porphyry*).—This rock occurs as a small stock or boss between the Suian granite and hornfels back of the Nantei Kita-Ko[3] (the North mine). As the boundary between it and the other igneous masses is always obscured by faults or soils on the surface, the mutual relation of the igneous rocks cannot be exactly determined. On the other hand the relations of the Nantei quartz-porphyry to the Suian granite, which were observed in the underground workings of the Dôgan mine suggests that the former intruded into the latter. Distribution of phenocrysts shows some regularities. The size of phenocrysts and density of distribution decrease toward the hornfels contact (See the geological map (Pl. XLVIII(III)), and the isometric diagram (Pl. XLIV(IV)) of the Nantei mine).

It is megasopically light yellow to brown in color and has many phenocrysts of orthoclase and quartz. The phenocrysts of mafic minerals are generally absent. Sometimes the rock is cut by the later quartz-veinlets.

Under the microscope it shows that the holocrystalline groundmass consists mainly of felsic minerals (Pl. LV(X), Fig. 3). Mafic

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1) 笏洞花崗岩 2) 楠亭石英斑岩 3) 楠亭北坑

constituents rarely occur. In some cases the rock contains dark patches of mafic minerals such as hornblende and biotite which are considered as small xenocrysts. Phenocrystic orthoclase is usually euhedral with Carlsbad-twinning. Quartz is the most abundant mineral and is crystallized into an ordinary hexagonal bipyramid, i.e. a higher modification. Due to corrosion by magma it frequently shows as rounded or eaten form and loses its original crystal outlines. The groundmass consists of very fine-grained quartz and intersticial orthoclase. Sometimes opaque ores such as pyrite, magnetite etc. are found.

Quartz-porphyries.—A number of dykes of porphyritic rocks are found intruding into both the sediments and the Suian granitic rocks. The location of the porphyry dykes is shown on the geological map (Pl. XLVI(I)). Only the representative rocks will be described here. In the west valley of the Dôgan mine, in the vicinity of the Rakken village and also in Zyosô-dô[1] several quartz-porphyry dykes are found. The rocks which occur near the Rakken village, are very light in color with small phenocrysts of quartz 2–3 mm in length and usually fractured into splintary and angular blocks. Photomicrographs of the quartz-porphyries are shown in Pl. LV(X), Figs. 1–2. Although their texture is slightly different from that of the Nantei quartz-porphyry, the rocks may be similar off-shoots from the main granitic stock.

Several porphyry dykes, which intrude into the sediments in the northern part of the district, have all undergone intense alteration (Pl. LV(X), Fig. 4). The rocks are usually white or light grey in color owing to sericitization. Under the microscope porphyritic texture is distinct because of the presence of quartz and feldspar phenocrysts. The biotite-phenocrysts, now altered into chlorite or sericite, are also seen. In the groundmass a large number of sericite-needles are observed. The genetical relation of the quartz-porphyries to mineral deposits is not clear.

Aplites. Aplitic veins, dykes and small masses are found in the area occupied by the Suian granite. The aplitic bodies vary in width from a centimeter to fifty centimeters, and do not continue along the strike. Several irregular aplitic bodies are especially developed in the marginal zone of the Suian granite. In several

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1) 汝草洞

places aplites occur also in the sedimentary region. Petrographically aplitic rocks in this area may be divided into two groups: (1) granite-aplites and (2) alkali granite-aplite.

(1) Granite-aplites.—Pale colored marginal facies, apophyses and veins are widely distributed in association with the Suian granite. In the Nantei area the aplite veins cut the diopside (salite) skarn and contain abundant xenoliths of the same rock as shown in Pl. LVIII(XIII), Fig. 1. Dykes of aplite are particularly abundant near the Tenzi[1] prospect, where the aplites are commonly tourmaliniferous.

(2) Alkali-granite-aplites.—Interesting igneous groups are the aegirine-bearing alkaline igneous rocks found in the northern contact aureole. They form dykes or irregular bodies in the Kotudô dolomite near the Suian granite in the vicinity of the Suzuran-prospect (See Pl. XLVI(I) and Pl. XLVII(II)). Rock with similar features has also been found as a marginal facies of the Suian granite in the Suzuran cross-cut tunnel.[2] It grades into the syenitic aplite at the very place of contact against the wall rock, the brucite-marble. These rocks are whitish in color and consist of microcline-microperthite, quartz, euhedral alkalin-pyroxene and markedly zoned anhedral alkali-pyroxene which fills the intersticial spaces of other constituents. Under the microscope it is observed that the pale green diopsidic core of the pyroxene is zonally surrounded by aegirine-augite and aegirine. In some parts especially near the contact of aplites with dolomites, several minerals such as phlogopite and diopside are also found. It should be noted here that alkali-granite-aplites are not rare in the contact aureole between granite and dolomitic rock as recorded by Zavaritsky (123), and by Hatch and Rastall (64). Their mode of occurrence indicates that assimilation of dolomitic sediments by granite magmas took place.

Felsite and felsite-porphyry.—The light colored siliceous rock found west of the Saziri prospect, was considered by D. F. Higgins (6), to be quartzite of sedimentary origin. However the rock proves to be a kind of felsitic igneous rock according to the writer's observation. It is white or grey in color and contains abundant fragments of country rocks. The rock frequently shows flow structure. Under the microscope it is seen that sporadic occurrences of corroded

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1) 天峙 (Kung Kol)　2) 鈴蘭立入

phenocrysts of quartz are set in very fine-grained and devitrified felsic groundmass as shown in Pl. LVI(XI), Fig. 3. The rock was probably injected along the fault zone late in the history of the Suian intrusive cycle. Numerous dykes of felsite and felsite-porphyry have also been found in the underground workings at the Nantei mine. They may be off-shoots from the Nantei quartz-porphyry.

Chapter IV

METAMORPHISM AND METASOMATISM

Introduction.—As already mentioned in the preceding chapter the sedimentary rocks of the Suian district, except alluvial deposits, more or less suffered a regional metamorphism during the period of late-Mesozoic orogeny. However, metamorphic influences of later granitic magmas were so intense that the effects of the regional metamorphism in the contact aureole have been obliterated by thermal actions caused by this later magmatic activities. Within the contact zone of the main intrusive mass recrystallization of the original rocks due to the heat of the magma took place extensively without any remarkable interchange of materials among the sediments or between the sediments and the invading magma. This metamorphic process will be referred to as thermal metamorphism in the sense of Harker(63), or as normal contact metamorphism, in the sense of V. M. Goldschmidt(58). On the other hand many evidences of transfer of materials from magma into newly formed rocks have also been noticed in the same contact aureole. Mineralogical change of these metamorphic rocks indicate that a large quantity of materials which emanated from the magmas contributed to their composition. The principal process operating in these changes is metasomatic in nature. These changes may be divided into two types: (1) Pyrometasomatism (in the sense of Lindgren) mainly recognized in the inner contact aureole near the intrusives and (2) hydrothermal action characterized by the introduction of various substances, such as sulphides at the latest stage of the magmatic activity.

In this chapter the typical rocks, formed by thermal metamorphism and pyrometasomatic and hydrothermal actions, will be described.

Thermal contact metamorphism of non-carbonate rocks

As explained in the chapter dealing with general geology a considerable part of the Syôgen system is cut by the later Suian granite. Consequently many kinds of interesting metamorphic rocks are developed in its contact aureole. However, as a systematic study of these rocks has not been undertaken by the writer, only the occurrences of the most important rocks will be mentioned here. In general, slaty or phyllitic sediments found outside the contact aureole grade into the spotted rocks in the vicinity of the igneous masses, while this spotted appearance further disappears within the inner contact aureole.

Hornfels derived from argillaceous rocks.—The metamorphic changes of this kind of rock near the contact, as the main intrusive mass is approached, can be shown in the following order:—(1) Zone of spotted slaty or phyllitic rock; (2) Zone of biotite-hornfels; and (3) zone of andalusite-(corundum)-hornfels.

In the first zone of the spotted rocks the original slaty or phyllitic rocks have been hardened and minute spots are recognized on the surface of the exposed rocks.

In the second zone minute flakes of brown biotite are well developed, increasing in size as they approach the contact. The spots similar to those in the first zone are preserved in this zone as is shown in the photomicrographs of the spotted biotite-hornfels found near the Goyô mine (Pl. LX(XV), Fig. 1).

In the third zone of andalusite-(corundum)-hornfels various kinds of coarse-grained hornfels occur instead of fine-grained spotted rocks. This zone may be called the zone of true hornfels, as mentioned by C. E. Tilley(113). As pointed out by V. M. Goldschmidt in his study of contact rocks in Christiania district and also by C. E. Tilley(113) in the Comrie area, the hornfels of the Suian district may be classified according to their mineral assemblages. The following hornfelses have been recognized by the writer: (1) Andalusite-cordirite-hornfels (Goldschmidt's class 1), (2) Andalusite-cordierite-plagioclase-biotite-hornfels (Goldschmidt's class 2), (3) Plagioclase-diopside-hornfels (Pl. LX(XV), Fig. 2) (Goldschmidt's class 7).

In the immediate vicinity of the Suian granite in the northern part of the Nantei mine the belt of characteristic biotite-bearing hornfelses are exposed nearly parallel to the contact. The rocks have a brownish color due to the presence of an abundance of biotite flakes. These rocks are frequently penetrated by the aplitic veins. Megascopically, the rocks are hardened, often splintery and greyish brown in color. Their external appearance differs in different places. In the Nantei Mine the rocks are usually schistose and, moreover, are injected or intruded by minute aplitic veins (Pl. LVII(XII), Fig. 3) or by the Nantei quartz-porphyry (Pl. LI(VI), Fig. 4). Slender needles of tourmaline are often present in some parts of the rocks (Pl. LX(XV) Fig. 3). The hornfelses found in Kotudô area are usually massive and fine-grained. Under the microscope the hornfelses are seen to be fine-grained and holocrystalline. They consist essentially of quartz, orthoclase, biotite, chlorite, muscovite, andalusite, and tourmaline. Biotite occurs in small flakes its pleochroic scheme being: X=light yellow, Z & Y=dark brown. Muscovite is also developed in the siliceous hornfels from Kotudô. Orthoclase fills the interstices between the quartz and biotite. Idioblastic plagioclase is sparsely found among the minerals mentioned above. Andalusite builds long prismatic crystals showing distinct cleavage as shown in Pl. LIX(XIV), Fig. 2. Long or short prismatic tourmaline occasionally appears in these rocks.

Besides free-silica hornfelses mentioned above several kinds of the silica-poor hornfelses have also been observed by the writer. The combination of minerals in these rocks are as follows: Tilley's Class (d) Corundum-spinel hornfels (Pl. LIX(XIV), Fig. 3), (e) Corundum-spinel-andalusite hornfels (Pl. LIX(XIV), Fig. 4). Because silica-poor hornfelses are rarely found in Tyôsen, the writer intends to give some description of the constituent minerals.

Andalusite.—It builds long prisms with distinct cleavage and magnetite is abundantly contained in it. (Pl. LIX(XIV), Figs. 1–2).

Corundum.—The anhedral crystals of corundum are found abundantly in these rocks. Idioblastic crystals are rarely observed. The mineral is usually more or less pleochroic as given here: ε= sapphire-blue, ω=colorless. A parting parallel to the base can be clearly seen in Pl. LIX(XIV), Fig. 4.

Spinel.—Rounded or irregular crystals of spinel are often associated with corundum or magnetite. Spinel (hercynite) in the hornfelses is generally colored green.

Orthoclase is one of the principal constituents of hornfelses and is found in groundmass. Plagioclase and biotite are also found.

Several representatives of hornfelses belonging to these classes are recorded from the contact zone near the Nantei mine and are also found as xenoliths. A specimen of andalusite-corundum-spinel hornfels which was injected by the Suian granite, was collected by the writer at the contact, north of the Minami-Kô (South mine), Nantei (Pl. LIX(XIV), Fig. 3).

Thermal metamorphism of carbonate rocks

As the dolomite of the Sidôgû series was intruded by the Suian granite the commonest metamorphosed rocks in the contact aureole of the Suian district also dolomitic in their composition. In the northern part of the contact east of the Kotudô valley, a series of metamorphosed dolomite is found and here dolomitic rocks with a small amount of siliceous and aluminous impurities are predominant. In this part the thermal effects of the Suian granite can be studied in detail by microscopic investigation of a series of rocks obtained on the eastern ridge of the Kotudô valley¹⁾ from the Sekitaturi²⁾ to the contact near the Suzuran prospect.

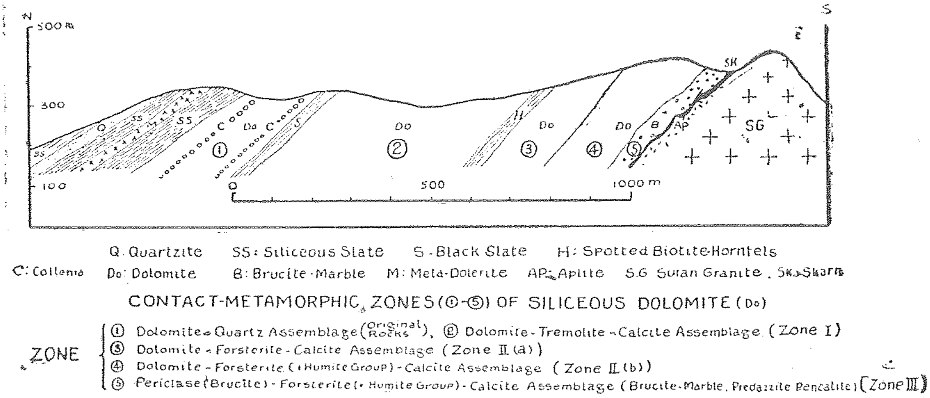

Fig. 6. North-south section along the eastern ridge of the Kotudô valley, showing the contact-metamorphic zones.

In the accompanying north-south section (Fig. 6) the relation of the dolomite and the Suian granite is shown. The progressive changes of siliceous dolomites in the contact aureole can be presented in the following order: (1) zone of quartz-bearing dolomite, (2)

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zone of tremolite-bearing dolomite, (3) zone of forsterite-dolomite-marble, (4) zone of development of minerals of humite group in forsterite-dolomite-marble, (5) zone of brucite-marble. (Cf. Pl. LXI (XVI) and LXII(XVII)).

(1) *Zone of quartz-bearing dolomite* (*Original rock*).—As the thermal effects of the Suian granite are not conspicuous in this zone, the rocks obtained may represent the original grade of regional metamorphism. Under the microscope the siliceous dolomite found in this zone is seen to consist essentially of quartz, dolomite and calcite. Attention must be directed to the direct contact relation of quartz and dolomite in a thin section as shown in Pl. LXI(XVI), Fig. 1. As to the argillaceous sediments in this zone, which are represented by black slaty rocks no conspicuous sign of thermal effects are recognized.

(2) *Zone of tremolite-bearing dolomite* (Zone I).—The signs of contact metamorphism in the siliceous dolomite are the disappearance of quartz in direct contact with dolomite and the development of tremolite as shown in Pl. LXI(XVI), Fig. 2. The size of the grain in the constituent minerals of the rocks is somewhat coarser than in those of the rocks belonging to the first zone.

(3) *Zone of forsterite-dolomite-marble* (Zone II(a)).—When this third zone is entered, the tremolite directly associated with dolomite is not found and forsterite becomes one of the important constituent minerals. The constituents increase in size as the granite is approached, and there are signs of that the rocks have been bleached in this zone. Under the microscope the rock is seen to consist essentially of dolomite, forsterite and calcite. As pointed out by Teall (111) and later by Tilley (112), intimate association of forsterite and new-formed calcite is a characteristic feature of the metamorphosed siliceous dolomite. The forsterite crystals may be entirely bordered or partly surrounded by calcite-rim. The forsterite-dolomite-marbles from the eastern ridge of the Kotudô valley always have this feature as shown in Pl. LXI(XVI), Fig. 3, Pl. LXII(XVII), Figs. 1–2. Thin sections of these rocks show that all of the constituent minerals have always mineralogical features similar to those described by Tilley (112).

At the part where the original dolomite was intercalated with more siliceous layers, forsterite-diopside bands have been well developd as shown in Pl. LX(XV), Fig. 4.

(4) *Zone of development of minerals of the humite group in forsterite-dolomite-marble* (Zone II(b)).—In this zone the bleaching of the rocks is seen to be perfect. As the contact is approached, the clinohumite or chondrodite is usually associated with forsterite as shown in Pl. LXII(XVII), Fig. 3. The distinction between the third and fourth zones can not be seen very clearly in the field; the boundary line in fig. 6 thus indicates the approximate position of the zonal border. It should be noted here that the partial replacement of forsterite by minerals of humite group is also seen. In this case the twinning lamellae of clinohumite or chondrodite are parallel to cleavage (010) of forsterite (Pl. LXII(XVII), Fig. 3). In the vicinity of the Kotudô ore-bodies the rocks in the fourth zone are often penetrated by ludwigite-clinohumite veins as seen in Pl. LXVI(XXI), and are also replaced by the kotoite-marble.

From a genetical point of view this zone should be included in the preceeding zone because the mineralogical change characterizing this zone has been caused chiefly by pneumatolytic actions of magmatic emanations. It is widely known that pneumatolytic actions always superpose on the thermal alteration near the contact of igneous rocks. In the Suian district, however, distinct changes of texture and mineralogical compositions are observed in forsterite-dolomite-marble, so that the writer established here the fourth zone.

(5) *Zone of forsterite-brucite-marble* (*forsterite-periclase-marble*) (Zone III)).—This zone is characterized by the disappearance of dolomite and lies in the innermost contact zone of the Suian granite. As a result of the thermal effect the partial dissociation of dolomite molecule took place and periclase was formed with the escape of CO_2. As the periclase is very unstable, the resulting rock usually suffers from hydration. Thus the new- formed periclase in the marble has been changed to brucite. The similar metamorphosed dolomite called predazzite or pencatite has been described by various authors: (Dunham (48), Harker (62, 63), Hunt(65), Joplin(70), Osborne(89), Peters(90) and Rogers (97, 98)). The present writer has also reported the occurrence of brucite-marble in the Nantei area and gave a short description some years ago (35). Some consideraitons of the genesis were also given in that paper. In the case of the thermal metamorphism of a pure dolomite the resulting rock should consist of brucite and calcite in equal molecular proportions. When silica and alumina are present

in the original dolomite-rock, the resulting rock may consist of forsterite (chinohumite), usually altered to serpentine, spinel, periclase (brucite) and calcite. Many examples of the series of brucite-bearing rocks have been found in the inner contact zone of the Suian granite, especially near the Kotudô mine (Pl. LXII(XVII), fig. 4), the Suzuran1) prospect and the Naikinri2) prospect and also in the Nantei area. It should be noted here that some of andalusite-bearing hornfelses which occur in the third zone of the metamorphosed argillaceous rock and some skarn rocks are always associated with the brucite-marble. A fine example showing the above zonal arrangement of metamorphosed dolomite in small scale, has been observed near the dyke of quartzporphyry in the Dôgan mine, Nantei (Fig. 7).

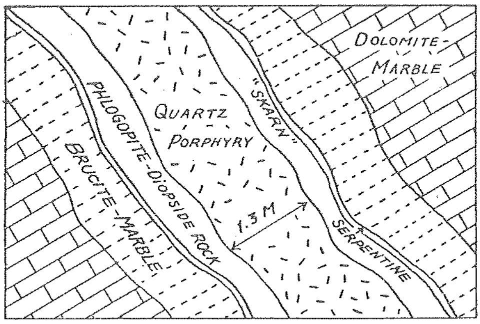

Fig. 7. Sketch of a quartz-porphyry dyke, Dôgan mine, showing development of skarn masses along its both sides. The zoning of thermally metamorphosed dolomite is also well shown in small scale.

Progressive metamorphism of siliceous dolomite.—Recently the problem of progressive metamorphism of siliceous dolomite has been systematically studied by N. L. Bowen (43) with the aid of the composition tetrahedron. Thirteen possible steps of increasing decarbonation, taking place at successively higher temperatures at any given pressure were recognized by him. Ten minerals such as tremolite, forsterite, diopside, periclase, wollastonite, monticellite, åkermanite, spurrite, merwinite, and larnite were considered as indicators of the grade of metamorphism. Although only five minerals out of the ten indicators selected by Bowen have been actually found in the Suian district, the progressive metamorphism

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of the siliceous dolomite may be well traced in the metamorphosed dolomites within the contact aureole of the Suian granite.

According to the writer's microscopic observations and also from the chemical composition shown in table 4, the dolomites found near the Kotudô mine usually contain a very small amount of impurities such as silica (less than 3%), alumina (less than 1.5%) and iron oxides (less than 0.5%). If we use the Bowen's composition diagrams (Fig. 8) for explanation, the chemical compositions of the dolomites in question will be represented by a point near A. These diagrams show clearly the mineral assemblages of the metamorphosed siliceous dolomites which occur in the Suian contact-zone.

TABLE 4

No.	1	2	3	4	5	6	7	8	9
d	2.88								2.87
SiO_2	2.75 %								
Al_2O_3	1.26								
Fe_2O_3	0.23								
CaO	31.03	30.28	32.03	26.04	30.08	31.08	37.93	30.66	30.41 %
MgO	20.30	21.29	20.46	21.05	20.31	20.96	18.74	21.00	21.87
B_2O_3[1]	1.00	0.56	1.40	1.33	1.33	0.63	6.44	2.94	
Na_2O	0.40								
Ig. loss	42.40								47.72 (CO_2)
	99.37								100.00
$\frac{CaO}{MgO}$ (mol. ratio)	1.10	1.02	1.13	0.89	1.07	1.07	1.46	1.05	1.00

(1) Forsterite-dolomite-marble near the kotoite-marble, 1000 Syaku-level, N.O.B., Kotudô mine. Analyst, K. Tamura, Osaka Indust. Lab.

(2–8) Dolomite-marbles, the country rocks of N.O.B., Kotudô mine. Analyses made in Hitati Res. Inst. (By courtesy of Dr. S. Miyagi).

(9) Theoretical composition of the pure dolomite.

When attention is turned to other kinds of metamorphic rocks of the Suian district, it will be found that many interesting rocks have not yet fully been studied. For instance, it is observed that metadolerite has been changed to its hornfelsic facies with the development of biotite, basic plagioclase, hornblende, etc., in consequence of the disappearance of some former constituent minerals as shown

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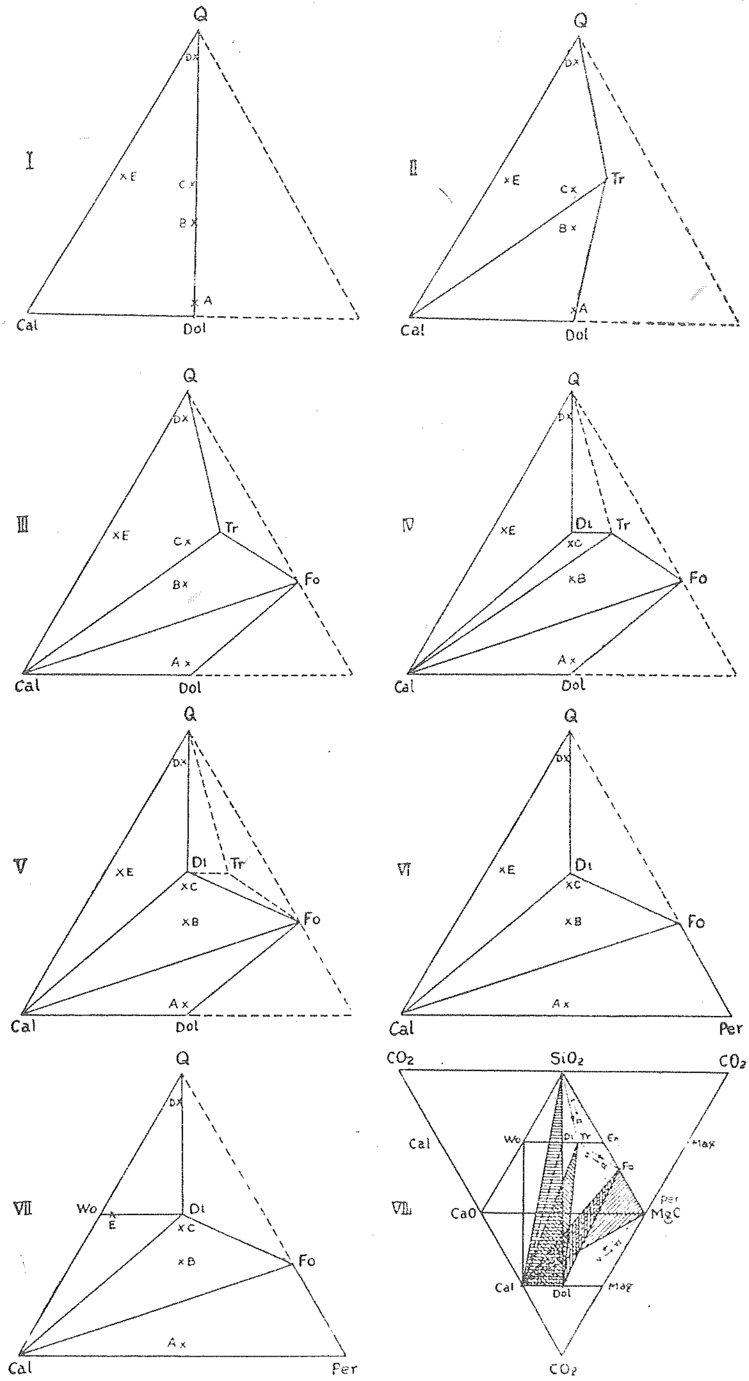
[1] B_2O_3 content in dolomite-marbles may be ascribed to the presence of a small amount of boron-minerals of pneumatolytic origin in the analysed samples.


I
Q
D×
×E
C×
B×
×A
Cal
Dol
II
Q
D×
×E
C×
Tr
B×
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Cal
Dol
III
Q
D×
×E
C×
Tr
B×
Fo
A×
Cal
Dol
IV
Q
D×
×E
Di
Tr
×C
×B
Fo
A×
Cal
Dol
V
Q
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Q
D×
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Di
×C
×B
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Per
VIII
CO₂
SiO₂
CO₂
Cal
Wo
Di
Tr
En
Mag
Fo
CaO
Per
MgO
Cal
Dol
Mag
CO₂

Fig. 8

Fig. 8. A series of projected composition diagrams (I–VII) showing the progressive metamorphism of siliceous dolomite (after Bowen (43)). Skelton diagram (VIII) of tetrahedron, illustrating composition of phases in metamorphosed, siliceous magnesian limestone, and showing the successive steps of metamorphism. Q, quartz; Cal, calcite; Dol, dolomite; Mag, magnesite; Per, periclase; Fo, forsterite; En, enstatite; Tr, tremolite; Di, diopside; Wo, wollastonite.

Point A represents the composition of a slightly siliceous dolomite. Rocks having such a composition are commonly found in the Suian district.

Points B & C represent siliceous dolomites.

Point D represents the composition of a carbonate-bearing quartzite. The wollastonite-diopside-quartz assemblage has been noticed among the metamorphosed rocks in the Nantei area.

Point E represents the composition of a siliceous limestone, example of which is very rare in the Suian district.

The diagram I, showing the mineral assemblages of the original rocks.

The diagram II, showing the mineral assemblages of the metamorphosed rocks of the contact zone (I). (Fig. 6)

The diagrams III, IV, and V, showing the mineral assemblages of the metamorphosed rocks of the contact zone (II). (Fig. 6)

The diagrams VI and VII, showing the mineral assemblages of the metamorphosed rocks of the contact zone (III). (Fig. 6).

I–II : Paired composition diagrams of reaction equation,
$3CaMg(CO_3)_2+4SiO_2 \rightleftharpoons CaMg_3(SiO_3)_4+2CaCO_3+4CO_2$
[Dolomite] [Quartz] [Tremolite] [Calcite]

II–III : Paired composition diagrams of reaction equation,
$CaMg_3(SiO_3)_4+5CaMg(CO_3)_2 \rightleftharpoons 6CaCO_3+4Mg_2SiO_4+4CO_2$
[Tremolite] [Dolomite] [Calcite] [Forsterite]

III–IV : Paired composition diagrams of reaction equation,
$CaMg_3(SiO_3)_4+2CaCO_3+2SiO_2 \rightleftharpoons 3CaMgSi_2O_6+2CO_2$
[Tremolite] [Calcite] [Quartz] [Diopside]

IV–V : Paired composition diagrams of reaction equation,
$2CaCO_3+3CaMg_3(SiO_3)_4 \rightleftharpoons 5CaMgSi_2O_6+2Mg_2SiO_4+2CO_2$
[Calcite] [Tremolite] [Diopside] [Forsterite]

V–VI : Paired composition diagrams of reaction equation,
$CaMg(CO_3)_2 \rightleftharpoons CaCO_3+MgO+CO_2$
[Dolomite] [Calcite] [Periclase]

VI–VII : Paired composition diagrams of reaction equation,
$CaCO_3+SiO_2 \rightleftharpoons CaSiO_3+CO_2$
[Calcite] [Quartz] [Wollastonite]

in Pl. LVII, Figs. 1 and 2. In order to compare the grades of metamorphism of various rocks the writer has made a rough correlation table of two different types of metamorphic zones recognized in the Suian contact zone, as shown below.

TABLE 5

Table showing the rough correlation of two types of metamorphic zones recognized in the Suian contact aureole.

Grade of metamorphism	Zone	Siliceous dolomite	Zone	Argillaceous rocks	Remarks
	Original rock	Quartz-bearing dolomite	Original rock	Black slate, phyllite	Siliceous limestone, metadolorite, epidiorite
Low	I	Tremolite-bearing dolomite-marble	I	Micaceous (sericite) phyllite Spotted slaty or phyllitic rock	Quartz-bearing crystalline limestone
	II (a)	Forsterite-dolomite-marble	II	Spotted biotite hornfels	Diopside-tremolite skarn
	II (b)	Forsterite-dolomite-marble with clinohumite, etc.	III	Biotite-hornfels (Tourmaline-bearing)	Biotite-hornblende-plagioclase rock derived from metadolerite, garnet skarn, diopside skarn, wollastonite skarn
High	III	Forsterite-brucite-marble (Pencatite, predazzite)		Andalusite-(Cordierite)-hornfels, Corundum-hornfels	

Pyrometasomatism, pneumatolytic and hydrothermal metasomatism

In the case of the thermal metamorphism the rocks near the contact were simply effected by the magmatic heat. At the Suian contact, however, other kinds of altered rocks which may have been formed by a transfer of material from the magma. Such a process of rock alteration at igneous contact has been termed "pyrometasomatism" by W. Lindgren (8) and Knopf (75) and "pneumatolytic metasomatism by V. M. Goldschmidt (58) because the metasomatic action of emanated substances at high temperature from the magma played an important rôle.

In the Suian district calc-magnesian silicate rocks usually called "skarn" are sporadically developed along the contact between carbonate rocks (especially, impure carbonate rocks) and the igneous rocks. Important skarn masses are indicated on the accompanying geological map. (Pl. XLVI(I)).

It may, however, be noted that while some materials are introduced into the carbonate rocks from the magma, yet the new-formed metamorphic minerals are dependent principally upon the original composition of the replaced rock. On the other hand the products of pyrometasomatism also depend on the composition of the fluid causing alteration and also on the prevailing temperature and pressure during the alteration.

In the case of the Suian district where the dolomitic rocks are dominantly developed, abundant calc-magnesian minerals are found. Among the metasomatic rocks in this district the writer discovered an interesting series of rocks which were produced by boron-fluorine-pneumatolysis. Genetically, the writer classified the metasomatic rocks into three groups: (1) Rocks formed by boron-fluorine-pneumatolysis, (2) pyrometasomatic rocks (skarns), and (3) hydrothermal-metasomatic rocks.

(1) Rocks formed by boron-fluorine pneumatolysis.

The rocks which belong to this group are the most interesting rocks in the Suian district. Although it has widely been known that products formed by boron-fluorine pneumatolysis, such as tourmalinization, axinitization etc. are commonly developed in the contact zone of many granitic rocks as has been described by Fitch (52), Goldschmidt (58) and others (see Lit. (61)), examples of occurrence of borates in dolomitic rocks are comparatively rare throughout the world.

In the northern contact zone of the Suian granite, where the Kotudô dolomite are well developed, various kinds of borate minerals have been discovered by the writer. Especially, the Kotudô orebodies are surrounded by a very interesting marble containing abundant magnesium borates such as ludwigite, kotoite, szaibelyite, etc. Among these, a new mineral, kotoite ($Mg_3B_2O_6$), was discovered by the writer (36, 37) at this place in 1939. The name, kotoite, was given in honor of the late Professor Bundjiro Kotô,[1] who studied the rocks and ores of the Hol-gol (Kotudô) mine in 1910.

Kotoitization.—As will be described later, tubular or pipe-like ore-bodies consisting of diopside, chondrodite, phlogopite, etc., have been found in the vicinity of the Kotudô granite (Pl. XLVII (II)). These ore-bearing skarn-masses are bordered by a compact rock consisting essentially of calcite and kotoite. Therefore this rock may be called kotoite-marble, and the process of its formation, kotoitization. Macroscopically the rock is white to creamy in color or may locally be stained brown by accessory minerals. It is very difficult to distinguish the kotoite-marble from an ordinary dolomite-marble in the field, especially in the underground working. On the polished surface of the specimen taken from the boundary between the kotoite-marble and the dolomite-marble, the two rocks can be easily distinguished as shown in Plate LXVI (XXI). Among the many ore-bodies of the Kotudô mine, the diopside skarn of the Northern ore-body (N. O. B.)[2] is entirely enclosed in the pipe-like body of the kotoite-marble (Fig. 9).

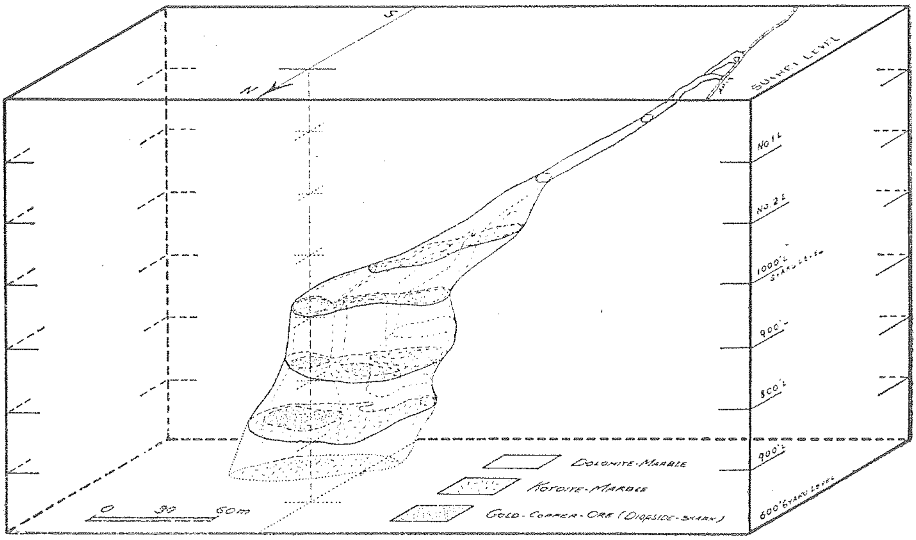

Fig. 9. Block-diagram showing the zonal arrangement of minerals in the pipe-like deposit of the Northern ore-body (or New ore-body), the Kotudô mine.

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1) 小藤文次郎教授

2) N.O.B. (北鑛體) is formerly called the New Ore-body or Hakkin-Kô Ore-body. (白金坑鑛體)

Although the boundary surface between the pipe and the wall rocks appears to be extremely uneven as shown in Fig. 10, its boundary position can be definitely determined in the underground working. It is also microscopically observed that the boundary between the kotoite-marble and the wall rock (dolomite-marble) is sharply defined as shown in Pl. LXX(XXV), Fig. 1. It has been observed that the vein-like kotoite-marble occasionally penetrates the wall rock, the dolomite-marble. Thus, this fact indicates that the former has replaced the latter. On the other hand the kotoite-marble itself has been replaced by irregular masses of diopside-skarn containing important metallic minerals. As shown in Pl. LXV(XX), the major trend of the diopside-skarn is always roughly parallel to the original planes of stratification which are represented by bands of ludwigite. Between the skarn and the kotoite-marble a narrow reaction zone showing a peculiar paragenesis of boron minerals is always well developed (Pl. LXVII(XXII)).

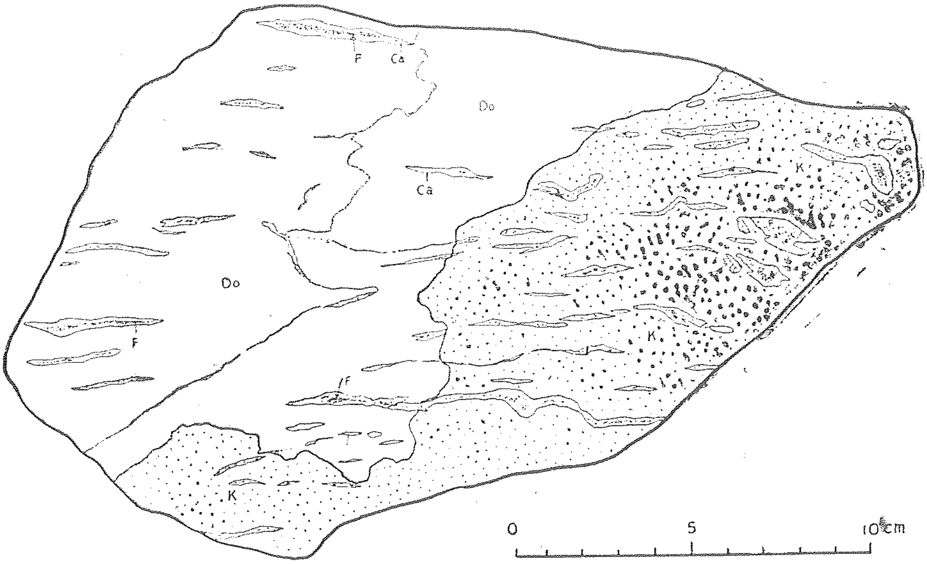

Fig. 10. Tracing of polished specimen from the Northern ore-body, showing the relation of kotoite-marble (K) to dolomite-marble (Do). Note that the original siliceous layers in the dolomite are well preserved by many streaks now consisting of forsterite (F) and calcite (Ca). Boundary line between the dolomite-marble and the kotoite-marble is very sharp. The former rock has been replaced by the latter as a result of boron-pneumatolysis.

The petrographic description of the kotoite-marble is as follows:

Kotoite-marble. When fresh it is a compact, white to cream-colored rocks, but on weathering its characteristic features become well developed. Many small hollows containing a fine powdery substance and projectings of resistant minerals may be noticed on the weathered surface of the rock. Under the microscope the rock is seen to be crystalloblastic (Pl. LXIX (XXIV) and to consist essentially of kotoite and calcite with subordinate amounts of forsterite, clinohumite, spinel, ludwigite and other borates.

Kotoite.[1] This mineral, a magnesium-borate, is one of the most important constituents of the marble and constitutes 25–35% of the rock. As shown in Pl. LXIX (XXIV), many detached grains of kotoite, 20–50 grains, are oriented in the same direction, embedded in a groundmass of mozaic aggregate of calcite. As the mineral resembles forsterite or diopside to some degree both in color and in optical properties in thin sections and occurs always in minute grains, its own properties had not been determined till the writer separated it from the matrix. According to his investigation, the following properties have been reported (See Lit. (36), (37)). Chemical formula: $Mg_3B_2O_6$ (or $3MgO \cdot B_2O_3$). Chemical composition of the kotoite from Kotudô: SiO_2 1.32%, Al_2O_3 0.26%, Fe_2O_3 0.20%, FeO 0.61%, CaO 0.18%, MgO 62.78%, B_2O_3 35.20%, H_2O 0.05%, Total 100,60%; Theoretical composition of $Mg_3B_2O_6$: MgO 63.46% B_2O_3 36.54%; Morphology: rhombic, fine-grained (0.1–0.2 mm), subhedral to anhedral. Cleavage perfect, parallel to (110), parting parallel to (101) is sometimes developed. Hardness=6½. Density=3.11. Optical properties: Colorless. $\alpha=1.652$, $\beta=1.653$, $\gamma=1.673$, $\gamma-\alpha=0.021$. (+) $2V=21°$, $\varrho>\nu$, Axial plane parallel to (010). Z=c. Under the hydrothermal condition this mineral is probably unstable and may be altered into a hydrous borate as seen in Pl. LXX (XXV), Fig. 2.

Calcite. This mineral constitutes about 60% of the rock. The interlocking grains are very irregular in outline, showing sometimes polysynthetic twinning lamellae. The distinction between calcite and dolomite was shown by Lemberg's method and also proved by their refractive indices. Dolomite which occurs in the wall rock, dolomite-marble, has never been found in direct contact with kotoite.

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1) 小藤石

Forsterite. It forms anhedral elongated grains parallel to c or tabular grains parallel to (100) with distinct cleavage parallel to (010). Grains reach a maximum length of 2 mm., and are usually coarser than those of kotoite. The refractive indices are α=1.638, β=1.651, γ=1.669, γ–α=0.031. (+) 2V=84°. Density 3.22. As explained in the preceding section treating wtih forsterite-dolomite-marble, the forsterite is usually entirely or partly surrounded by the calcite area in which kotoite is not found.

Clinohumite. This mineral occurs sparsely in the marble, sometimes, being associated with forsterite. This is usually anhedral with moderate refractive index and shows characteristic polysynthetic twinning on (001). On a hand specimen its color is pale yellow to brown while in thin section colorless or pleochroic with X= pale golden yellow, Y= almost colorless, Z= pale yellow with X>Z>Y. X makes an angle of 9–10° with twinning plane parallel to (001).

Spinel. This mineral is very fine-grained and euhedral or rounded. It is found isolated in calcite or in forsterite. Separated grains of spinel are pale green to ruby in color.

Ludwigite. This mineral is one of the most important borate minerals in the Kotudô mine. It occurs as minute patches or streaks or in bands in the kotoite-marble (Pls. LXV(XX), LXVI(XXI), LXVII(XXII) and LXVIII(XXIII)). Acicular or prismatic crystals in radiated masses are usually embedded in calcite free from inclusions of kotoite. As shown in Pl. LXXI(XXVI), Fig. 2, prismatic to acicular crystals of ludwigite are surrounded by calcite and both are enclosed in the groundmass consisting of calcite and kotoite. The mineral is nearly opaque in thin section, but when the section is very thin, its pleochroism is distinct from dark green to reddish brown. X // dark green; Y // green; Z // reddish brown, (// to the elongation).

Unknown minerals. There are two unknown minerals found in the kotoite-marble. Unfortunately, due to the difficulty of isolating these minerals from the rock and also to their scarcity, the exact determination has not yet been accomplished by the writer. One of these is fibrous and colorless in thin section with high birefrigence. The other is brown in color and prismatic to acicular in form. Their mineralogical nature is now under investigation.

Sulphides. A few minute specks of metallic minerals were observed in the specimens. Under the reflecting microscope two

TABLE 6. (1) Chemical Analyses

No.	1	2	3	4	5	6	7	8	9
d	—	—	—	—	—	—	—	—	—
SiO_2	3.56	3.38	2.56	14.24	3.60	2.46	3.64	2.71	2.24
TiO_2	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.03	n.d.
Al_2O_3	0.21	0.21	0.09	0.31	0.32	0.07	—	0.67	0.48
Fe_2O_3	0.31	0.29	0.23	0.37	0.46	0.29	0.26	0.27	0.62
MnO	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.05	n.d.
CaO	34.10	34.72	33.50	34.02	34.24	34.42	33.94	33.23	33.43
MgO	21.28	20.30	21.62	14.52	21.20	22.68	21.14	22.66	24.32
B_2O_3	11.98	10.59	14.63	7.36	12.02	12.71	12.39	12.49	12.28
K_2O	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.05	n.d.
Na_2O	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.63	n.d.
F	tr.	tr.	tr.	tr.	tr.	—	tr.	n.d.	n.d.
Ig. loss	27.82	29.78	27.10	28.38	27.42	27.90	27.54	27.41	26.76
Total	99.26	99.27	99.73	99.20	99.26	100.53	98.91	100.20	100.13

(2) Calculated Mineralogical Composition

No.	1	2	3	4	5	6	7	8	9
Calcite	60.7	61.9	59.8	—	61.1	61.4	60.6	59.3	59.7
Kotoite	32.5	28.8	33.8?	—	32.5	34.5	33.7	34.1	33.2
Ludwigite	0.5	0.5	0.6	—	0.8	0.5	0.5	0.5	1.1
Forsterite	8.3	7.9	6.0	—	8.4	5.8	8.5	6.3	5.3
Spinel	0.3	0.3	0.2	—	0.4	0.1	—	0.9	0.7
Total	102.3	99.4	100.4	—	103.2	102.3	103.3	101.1	100.0
$\frac{CaO}{MgO}\left(\begin{matrix}\text{Mol.}\\ \text{Rat.}\end{matrix}\right)$	1.15	1.23	1.11	1.68	1.16	1.09	1.15	1.05	1.00

Explanations

(1) Kotoite-marble, Cross-cut tunnel 600 Syaku-level (600 feet level), N.O.B.
(2) Kotoite-marble, Cross-cut tunnel 600 Syaku-level, N.O.B.
(3) Kotoite-marble, north Cross-cut tunnel, 700 Syaku-level, N.O.B.
(4) Impure kotoite-marble, stope-face, 700 Syaku-level, N.O.B.
(5) Kotoite-marble, 4-gô-kiriha, (No. 4 Stope), 1000 Syaku-level, N.O.B.
(6) Kotoite-marble, 4 gô-kiriha, 800 Syaku-level, N.O.B.
(7) Kotoite-marble, 4 gô-kiriha, 900 Syaku-level, N.O.B. Analyses, (1)–(7) quoted from T. Yamasaki and Y. Yamada; Report of investigation on kotoite, Rep. Central Lab. Gov. Tyôsen. 21 (1941) No. 1, 1–16.
(8) Kotoite-marble. Analysis made at Syôkôsyô Ceramic Laboratory. (After T. Asayama).
(9) Kotoite-marble, N.O.B.
(10) Kotoite-marble, N.O.B.
(11) Kotoite-marble, N.O.B.
(12) Kotoite-marble, N.O.B.
} Analyses reported by S. Nagai, Tôkyô Imp. Univ.

of the Kotoite-marble

No.	10	11	12	13	14	15	16	17	18	19
d	—	—	—	—	—	—	2.86	2.87	2.86	2.85(cal.)
SiO_2	7.64	5.11	1.98	2.96	2.98	2.39	3.63	2.0	2.2	—
TiO_2	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	—
Al_2O_3	1.55	0.14	0.22	0.61	0.68	1.10	0.82	0.4	0.4	—
Fe_2O_3	0.25	1.08	0.65		0.80	0.25	0.33	2.8	1.1	—
MnO	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	—
CaO	34.73	29.26	34.01	33.70	32.03	34.90	34.43	39.2	38.4	34.28
MgO	23.93	28.01	25.00	15.75	21.58	22.18	22.75	17.3	18.8	24.64
B_2O_3	9.83	9.60	11.34	11.26	15.12	9.50	9.39	8.3	9.0	14.19
K_2O	n.d.	n.d.	n.d.	2.06	n.d.	0.42	n.d.	n.d.	n.d.	—
Na_2O	n.d.	n.d.	n.d.		n.d.		n.d.	n.d.	n.d.	—
F	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	—
Ig. loss	21.76	26.89	26.69	34.21	26.86	29.23	28.81	30.0	30.1	26.89
Total	99.69	100.09	99.89	100.55	100.05	99.97	100.06	100.0	100.0	100.0

of the Kotoite-marble (in weight percentage)

No.	10	11	12	13	14	15	16	17	18	19
Calcite	49.5	61.2?	60.7	60.1	57.2	62.2	61.4	69.5	68.5	61.17
Kotoite	26.7	25.6	30.5	30.8	40.8?	25.8	25.4	21.4	23.9	38.83
Ludwigite	0.4	1.9	1.2	—	1.4	0.4	0.5	3.2	1.9	—
Forsterite	17.9	12.0	4.6	6.9	7.0	5.6	8.6	5.3	5.1	—
Spinel	2.2	0.2	0.3	—	1.0	1.5	1.1	0.6	0.6	—
Total	96.7	100.9	97.3	97.8	107.4	95.5	97.0	100.0	100.0	100.00
$\frac{CaO}{MgO}\left(\begin{matrix}Mol.\\Rat.\end{matrix}\right)$	1.04	0.75?	0.98	1.55	1.06	1.13	1.09	1.63	1.46	1.00

of Table 6

(13) Kotoite-marble, 1000 Syaku-level, N.O.B. Analysed in Chemical Lab. of Takeda-Tyôbei Syôten.

(14) Kotoite-marble, N.O.B. Analysed in Hitati Res. Inst. (By courtesy of T. Yosioka and S. Miyagi).

(15) Kotoite-marble (No. S. 1563), 1000 Syaku-marble, N.O.B. Analysis made by K. Tamura, Osaka Ind. Lab.

(16) Kotoite-marble (No. S. 260), N.O.B. Analysis made in Res. Lab. Tôkyô-Sibaura Elect. Co. (By courtesy of H. Inuzuka).

(17) Kotoite-marble (No. S. 260), N.O.B.: The calculated chemical composition from the mineralogical composition determined by Rosiwal's method.

(18) Kotoite-marble (No. S. 839), Stope face, N.O.B., calculated chemical composition from the mineralogical composition determined by Rosiwal's method.

(19) Theoretical value for $Mg_3B_2O_6{:}3CaCO_3$, supposed kotoite-marble derived from pure dolomite ($MgCa(CO_3)_2$).

kinds of sulphide paragenesis are noticed: (1) association of chalcopyrite-bornite-klaprothite-wittichenite-native bismuth, and (2) association of pyrrhotite-cubanite-chalcopyrite with valleriite-bismuthinite-native bismuth-native gold.

Chemical composition.—With cold dilute hydrochloric acid the marble effervesces freely and is partly soluble in the acid. It is almost perfectly soluble in hot strong acid leaving a small amount of residue. This solution gives a strong test for boron. Due to the simplicity of mineral composition the approximate composition of the kotoite-marble can be calculated from the results obtained by the micrometric measurements. The approximate results of the micrometric survey carried out by the writer are as follows: calcite, 65%–70%; kotoite, 20–35%; forsterite, 5%; and ludwigite and other accessories ±3%. From the result of two analyses by Rosiwal's method (Specimens No. S. 260 and No. S. 839) the approximate chemical composition of the specimens was calculated by the writer. (See Table 6, No. 17 and 18). Since the kotoite was discovered by the writer, specimens of the kotoite-marble have been chemically studied by many investigators. More than fifteen samples taken from various parts of the Northern Ore-body were analysed by them. The results of the analyses are tabulated here in Table 6. In this table the approximate mineralogical composition calculated from analytical data by the writer, are also given. From this table it is clear that the chemical composition of the kotoite-marbles shows comparatively constant values and their molecular ratio CaO: MgO is kept constant.

Chemical changes involved in kotoitization.—From the above description and chemical analyses it is suggested that the kotoite-marble has an intimate genetical relation to the dolomite-marble. The kotoite-marble shows a remarkable decrease of ignition loss (CO_2) and a great increase in boric acid. The most striking feature of these analyses is, however, that in general the ratio of CaO to MgO in these rocks does not vary very much. Besides, both types are not rich in silica and alumina, these being contained usually in about the same quantity. Therefore the important chemical changes involved in kotoitization have been the elimination of carbon dioxide and the introduction of boric acid. Due to the greater reactivity of magnesian than of calcic component of dolomite the introduced boric acid may have combined only with the former component.

The amount of eliminated carbon dioxide and introduced boric acid may thus depend upon that of the magnesite molecule of the replaced dolomite. In this respect the processes of kotoitization resemble that of so-called dedolomitization of dolomite. When pure dolomite is suffered by kotoitization the resulting rock may be a "pure" kotoite-marble consisting only of calcite and kotoite. The equations representing the formation of periclase-marble (brucite-marble, pencatite) and "pure" kotoite-marble are shown below:

$$1)\qquad \underset{\text{(Dolomite)}}{CaMg(CO_3)_2} \rightarrow \underbrace{\underset{\text{(Calcite)}}{CaCO_3} + \underset{\text{(Periclase)}}{MgO}}_{\text{PERICLASE-MARBLE}} + CO_2$$

$$+H_2O \rightarrow \text{BRUCITE-MARBLE (PENCATITE)}$$

$$2)\qquad \underset{\text{(Dolomite)}}{3CaMg(CO_3)_2} + B_2O_3 \rightarrow \underbrace{\underset{\text{(Kotoite)}}{Mg_3B_2O_6} + \underset{\text{(Calcite)}}{3CaCO_3}}_{\text{KOTOITE-MARBLE}} + 3CO_2$$

When silica and alumina are present in the original dolomite, thermally metamorphosed product of the impure dolomite may accompany forsterite and spinel. As stated before the original dolomite which has now been change to the kotoite-marble, had a small amount of silica and alumina as detrital material. It may also be considered that the original rock in question was thermally changed into forsterite-spinel-dolomite-marble before kotoitization began under the influence of magmatic heat and emanation. That is, in the case of impure dolomite, dedolomitization (formation of forsterite and spinel) probably preceeded kotoitization. Consequently a part of the magnesia molecules of the original dolomite was first consumed to form forsterite and spinel and only the remaining MgO molecules were available for the formation of kotoite. This is the reason why the kotoite-marble produced from the pure dolomite shows the highest value for B_2O_3 content (refer to Table 6).

Reaction zone between kotoite-marble and diopside skarn.

As mentioned before the kotoite-marble forming a pipe-like body called "the Northern Ore-body" of the Kotudô mine has been internally replaced by irregular masses of diopside skarn. (See Pl. LXV (XX), and Text-fig. 9). The diopside skarn is usually bordered by a narrow reaction rim, 2–5 mm in width. In this part the paragenesis of minerals distinctly differs from that of the adjacent part. Macroscopically this zone is not marked, but under the microscope the thin section shows that kotoite was unstable and decomposed into secondary borates in this reaction zone. Although the original texture of the kotoite-marble has been preserved in this zone, acicular ludwigite, prismatic fluoborite ($Mg_3B_2O_6 \cdot 3Mg(OH,F)_2$ and also acicular szaibelyite ($HMgBO_3$) have been newly formed and are scattered throughout this zone. In some cases clinohumite occurs abundantly in this zone. Thus the paragenesis may be as follows: ludwigite-szaibelyite-fluoborite-clinohumite-calcite (Pl. LXVII(XXII), Pl. LXVIII(XXIII), Figs. 1–3, Pl. LXX(XXV), Figs. 3–4).

Ludwigitization.—This process is represented by the formation of ludwigite[1], a magnesium-iron-borate, $3MgO \cdot B_2O_3Fe_3O_4$. When a large amount of iron is present in the host rock or when the supply of iron is large, the metamorphic products formed by boron-pneumatolysis may be different from those formed by kotoitization. In this case the new formed borate may be ludwigite instead of kotoite (Pl. LXXI(XXVI), Fig. 1 and 3). Although the ludwigite occurs sparsely in the kotoite-marble as described before, the occurrence of magnetite in association with kotoite has never been noticed by the writer. On the other hand where the ludwigite is abundantly present, kotoite disappears and magnetite is found. The intimate association of magnetite with ludwigite is well shown in Pl. LXXI(XXVI), Fig. 3. In some cases the szaibelyite occurs in this type of rock.

It should be noted here that the characteristic minerals belonging to humite group, formed by fluorine-pneumatolysis, are always associated with the borates described above. Indeed, the boron-fluorine pneumatolysis associated with acidic igneous rock is the most widespread type of pneumatolysis in the world. Although the characteristic boron mineral, tourmaline, is commonly found in the metamorphosed argillaceous sediments near the granitic rocks in many districts, it has, however, been seldom reported that abundant magnesium-borates have been found in pneumatolized dolomitic rock.

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1) Ludwigite from the Kotudô mine (Hol Kol) was first described by E. V. Shannon (25). Owing to the difficulty of identification the mineral was once mistaken for lievrite by B. Koto (18) and was later thought to be a new mineral "collbranite" belonging to the pyroxene group by D. F. Higgins (7).

Paragenesis of the magnesium-boron minerals.—When the boron-fluorine emanations are introduced into dolomite, minerals such as kotoite, ludwigite, szaibelyite, fluoborite, humite group, etc. may be formed. Several examples of this interesting paragenesis have been studied by such investigators as Ahlfeld, Mosebach and Oehmichen (39); Emmons and Calkins (49), P. Geijer (53, 54, 55), Gillson (57), Johnston and Tilley (69), Shannon (25, 26), Watanabe (36) and Willbourn (121, 122). Among these investigators Per Geijer studied especially fully the paragenesis of the borates at various localities and further noticed that the $Mg(F, OH)_2$ molecule has played an important rôle in the formation of the minerals of the humite-group, fluoborite and orthite. As mentioned by Per Geijer the minerals of the humite group have been regarded as a series of molecular combination of Mg_2SiO_4 with $Mg(OH, F)_2$. At Tallgruvan, Sweden, he gave the following paragenesis of minerals: chondrodite ($2Mg_2SiO_4 + Mg(OH, F)_2$), — fluoborite ($3MgO \cdot B_2O_3 + 3Mg(OH \cdot F)_2$) —ludwigite ($3MgO : B_2O_3 + Fe_3O_4$) —magnetite ($Fe_3O_4$) and suggested that these minerals may be interpreted as molecular compounds, although the occurrence of kotoite ($3MgO \cdot B_2O_3$), was not known at that time. The discovery of kotoite adds one more member to the above paragenetic group and confirms his interpretation.

Tourmalinization.—The commonest type of boron-pneumatolysis may be tourmalinization. In the metamorphic equivalent of argillaceous sediments near the Suian granite contains usually small prismatic to acicular crystals of tourmaline. As shown in Pl. LX (XV), Fig. 3, tourmalinization of the hornfels was especially intense in proximity to the tourmaline-quartz veins which fill the old channels of supply.

Pyrometasomatism of the carbonate rocks (Skarnization).

In the Suian district so-called skarn rocks consisting essentially of lime-magnesian silicate minerals are often found near the intrusive rocks (Plate XLV(I)). These rocks are usually associated with carbonate rocks and are often found along faults, fissures and other structually weak zones of this district. The skarn rocks are also found as veins even in the Suian granite at the Saziri valley, west of the Kotudô mine (Pl. LXIII(XVIII), Figs. 3–4). And it is often seen that xenolithic masses of carbonate-rocks have been partly or perfectly converted into the skarn rocks (Pl. LXIV(XIX), Fig. 1).

Petrographically the composition of skarn rocks are very complex being represented by the following paragenesis: forsterite, forsterite-spinel, forsterite-diopside, diopside, diospide-chondrodite (Pl. LXXII(XXVII), Fig. 3), chondrodite (Pl. LXXII, Fig. 2), diopside-phlogopite, phlogopite (Pl. LXXIII(XXVIII), phlogopite-chondrodite, diopside-garnet, garnet (Pl. LXXIII(XXVIII), Fig. 2), diopside-scapolite, diopside-garnet-scapolite, garnet-scapolite (Pl. LXIV (XIX)), garnet-vesuvianite, diopside-wollastonite, wollastonite, etc. Besides these minerals skarn rocks also contain a series of minerals such as serpentine, tremolite, actinolite, epidote, clinozoisite and others. Calcite (lamellar calcite), quartz and kali-feldspar (adularia) are also found in these skarns. As will be described later many kinds of metallic minerals are often found in the skarn rocks forming important ore-bodies of this mining district. These metallic minerals, sulphides and gold, however, are regarded as having been formed later than the silicate minerals of the skarn rocks as shown in Pl. LXXIII(XXVIII). On the other hand there are many skarn-masses in which no metallic mineral has been developed. The writer intends to describe only the important type of the skarn rocks in the following pages.

Skarn rocks of the Kotudô mine. Nearly parallel to the E–W contact of the Kotudô granite and along the N–S fault-zones the skarn rocks are well developed, especially on the side of forsterite-dolomite-marble. A part of the skarn rocks extend also into the igneous mass. Geological relations of the skarn are shown on the geologic sketch-map (Pl. XLVIII(II)) and sections (Text-figs. 11 and 12). Sulphide ores are commonly associated with the diopside-skarn. In some parts of the Eastern ore-body, very coarse-grained skarn occurs. It should be noted here that the formation of the skarn may be controlled by the location of old faults or fissure zones. Generally boundaries between the skarn and the wall rocks are well-defined. In the Eastern open-cut the relation of the skarn rocks to the igneous mass is well shown (Pl. LXIII(XVIII), Fig. 1). Here the various kinds of skarn rocks are zonally developed. From south to north, that is to say, from the igneous body to the country rock, the arrangement of the rocks is as follows: (1) Kotudô granite, (2) scapolite rock, (3) green diopside-scapolite rock (Pl. LXIII(XVIII), Fig. 2), (4) scapolite-garnet-diopside rock (Pl. LXIV(XIX), Figs. 3 and 4), (5) phlogopite rock (6) white diopside-tremolite-phlogopite rock (with sulphides) (7) diopside-chondrodite rock (8) chondrodite rock with borates (9) kotoite-marble (10) forsterite-dolomite-marble (the wall rock).

It may be considered that volatile matters such as boron, fluorine and chlorine now contained in the skarn minerals such as scapolite, clinohumite, datolite, etc., had played an important rôle in the formation these skarn rocks. In the western part of the mine the skarn rocks are well developed along the north-south Kotudô fault and also east-west contact. The paragenesis of the skarn rocks coincides generally with those of the eastern part described above except in the absence of scapolite. Ludwigite, however, occurs more abundantly. Along the Kotudô fault the writer found a garnet skarn especially rich in gold (Pl. LXXIII (XXVIII), Fig. 2). In addition to these skarn bodies, a large complex pipe (called Northern Orebody) consisting of kotoite-marble and diopside-skarn, has been found in the Kotudô dolomite (Text-fig. 9, Pl. LXVII (XXII)).

Skarn rocks of the Nantei mine.—In this mine skarn masses are not uniform in their composition. The distribution of skarn rocks is well shown in Pl. XLIX (IV).

(a) Skarn rocks in the contact aureole of the Suian granite.—Along the immediate contact of the Suian granite rudely tabular masses of skarn rocks and sulphide ores are well developed. The boundary surfaces between the porphyritic granodiorite and skarn is sharply defined and relatively even, while between limestones and skarns it is very irregular. In some cases angular xenolithic blocks of the diopside skarn are found in the Suian granite as shown in Pl. LVIII (XIII), Fig. 2 and 3. Greater parts of the skarn masses consist of green diopside (salite) and garnet (Pl. LXXXIII (XXXVIII), Figs. 1–2). Therefore the color of the skarn masses is dark green to dark reddish brown corresponding to their mineral composition. The grain size of the mineral is not uniform, being from 1 mm to 10 mm. Principal constituent minerals of the skarns are as follows: diopside, salite (pyroxene), andradite, deep green hornblende (iron-rich amphibole) (Pl. LXXXIII (XXXVIII), Fig. 4), vesuvianite, scapolite, epidote, phlogopite, forsterite, spinel, zoisite, clinozoisite, adularia, quartz, calcite, ore-minerals, etc.

(b) *Skarn rocks in the contact zone of the Nantei quartz-diorite.*—The mineral association of the skarn in this zone is somewhat different from that of the skarn above described. The endomorphism of the igneous mass has been observed in this zone.

i) *Skarns in the igneous rock (endomorphic rock).* — The outer part of the quartz-diorite has been greatly metamorphosed into the skarn mass. The boundary between the eruptives and skarn is not sharp. Every gradational facies has been found in the transitional zone. Megascopically it resembles the original quartz-diorite. However, the rock is penetrated by light greenish veins in which some sulphide minerals occur. The microscope reveals that it is equigranular and consists of plagioclase (laboradorite), pyroxene (diopsidic augite), hornblende, biotite, titanite and sulphide-ores. In some parts of these igneous masses, the skarn rock is essentially composed of plagioclase and consists of euhedral diopsidic pyroxene and white feldspathic minerals.

ii) *Skarn rocks formed in the carbonate-rock (exomorphic rocks).* —Salite-garnet skarn which is undoubtedly derived from magnesian limestone occurs in the vicinity of the quartz-diorite. Near the southern contact an interesting skarn consisting of pyroxene, garnet, titanite and plagioclase, was found. Salite-garnet (andradite) skarn are also abundantly found. In this area the wollastonite rock was rarely discovered. In the western contact zone the geologic relation has been highly obliterated by the later faulting, so the distribution of skarns and ores has been much more complex than in the other part. The garnet-salite skarn in this zone, however, shows petrographically similar characters to those described above.

Skarn rocks in the Saziri valley.—Some interesting skarn rocks are found in the contact zone of the Saziri valley, about 1 km. west of the Kotudô mine. They contain the following minerals: actinolite, epidote, scapolite, garnet, specularite, tourmaline, quartz, orthoclase (adularia) and calcite. The texture of the rocks varies from place to place. As shown in Pl. LXIII (XVIII), Figs. 3–4, it is observed that the Suian granite is penetrated by veins of skarn minerals along its joints and fissures. The veins often show characteristic symmetrical banding due to successive deposition of minerals. As seen in Pl. LXIII (XVIII), Fig. 4, the alteration of the wall rock is not marked. The mode of arrangement of the minerals is represented in the following order from wall to center: the wall rock (the Suian granite (the porphyritic granodiorite))—titanite-epidote-salite-garnet-scapolite rocks—long fibrous scapolite.

In the vicinity of these veins a large mass of skarn rocks is developed at the contact between the carbonate rock and the intrusive.

The mineralogical composition of this skarn mass generally coincides with that of the skarn veins. Tourmaline is often found in this skarn-mass. Hematite and quartz are not rare. It is occasionally observed that skarn veins in the Suian granite join with these skarn masses found in the contact zone. From the field relation it can be said that both the skarn veins and the skarn masses must have been formed after the solidification of the outer part of the Suian granite.

(2) Hydrothermal-metasomatic rocks

Hydrous silicate rocks.—The rocks in this group are characterized by the presence of hydrous silicates: serpentine, talc, chlorite and minerals of zoisite group together with carbonates. Where the skarn rocks consisting mainly of anhydrous silicates, were attacked by later hydrothermal solutions, the rocks underwent great changes and finally became assemblages of hydrous silicate minerals. In this case the process may be similar to the so-called "diaphthoresis" or breaking-down process. As observed at the Kotudô mine, serpentine and talc together with carbonate minerals occur sporadically in the chondrodite-diopside-tremolite-phlogopite skarn of the Eastern ore-body accompanied frequently by ore-minerals. The process of the formation of these hydrous silicates undoubtedly is diaphthoretic. The hydrous silicate rocks consisting of chlorite, talc, zoisite, etc. are also abundantly found in the Nantei mine. Compared with the minerals from Kotudô, these minerals are richer in iron, so the rock is dark green to greenish grey in color. On the other hand, serpentine-talc-veinlets are also formed by hypogene solutions along the fissures or joints of dolomite-marble. It may be said that these hydrous silicate minerals were formed chiefly by the hydrothermal solutions in a later stage of pyrometasomatism, that is to say, through the mineralization connected with building-up processes.

Sulphide metasomatism.—The carbonate rocks and the lime-magnesian silicate rocks (skarn rocks) described in an earlier section of this paper have been often replaced or cut by sulphide minerals together with gold and bismuth minerals as a result of the action of magmatic fluid which was emanated from the magma at the latest stage of its activity. As in the case of the Suian district it is generally accepted that the formation of silicate minerals (skarn minerals) generally proceeded sulphide-metasomatism. Sulphide metasomatism may have taken place after the formation of silicate-minerals. As these resulting rocks which contain metallic minerals, are considered to be ores, detailed descriptions of them will be given later.

Chapter V

MINERAL DEPOSITS

General features.—The later stages of the late-Mesozoic intrusive cycle in the Suian district were characterized by the deposition of gold-copper ores from fluids, the distillates or the last residues from the crystallizing magmas. As has been explained before, the formation of ore followed the skarnization (pyrometasomatism). The period of ore formation, therefore, is classed as the second metasomatic period. From the genetical point of view the ore deposits of the Suian district may be classified as follows:

(1) High-temperature (pyrometasomatic or contact-metasomatic) deposits: (gold-copper-bismuth-deposits).
(2) Moderate-temperature (mesothermal) deposits.
    (a) Replacement deposits (gold-copper-deposits).
    (b) Veins (gold-silver-lead-zinc deposits).

As the ore deposits of this district have not been changed very much by the action of meteoric waters, only hypogene mineralizations are dealt with in detail in this chapter.

In the present study the paragenetic relation of constituent minerals of ores were studied both in the field and in the laboratory. The gangue minerals and their interrelation have been studied in thin sections and polished hand specimens. Relations between gangue minerals and between these and opaque minerals were investigated with the polorizing petrographic microscope. The determination of the opaque minerals were done by the mineralographic method developed by Schneiderhöhn-Ramdohr (100) and Short (105). The relations of the metallic minerals to one another were easily studied with a polarizing reflecting microscope.

High-temperature (pyrometasomatic or contact-metasomatic) deposits.

The deposits belonging to this group are generally considered to have been formed under comparatively high pressure and at high temperature. The important deposits of the Kotudô and Nantei mines are the best examples of this group. Several small deposits are found at Tenzi, Naikinri and other prospects. These deposits are generally found in the immediate vicinity of the Suian granite and associated intrusive rocks.

Although close association of skarn rocks with ores is commonly observed in the district, there are many large skarn masses almost free from ore minerals. Such barren skarn rocks are extensively developed in the north-eastern contact of the Suian granite. As in the case of ore-bodies of the Nantei and Kotudô mines, along faults or fissure zones which represent structurally weak zones, irregular, rudely tabular, or pipe-like masses of skarn minerals intergrown with sulphides and gold, are found. As shown in Plates XLVII (II) and XLIV(V) and Text-figs. 11 and 12, the whole mass of the skarn rocks is not uniformly mineralized and the ore minerals commonly occur either in bunches or in dissemination. In general, high temperature mineral association is usually observed near the contact. As distance from the contact increases, characteristic features of high temperature ore deposits are lost and are shown by those formed at moderate temperature. Some of the ore-bodies of the Nantei mine show this transitional character.

Age relations.—As in the Nantei mine the salite and diopside skarn rocks are penetrated and cut by the aplitic dykes which seem to be related to the Suian granite. In the Minami-Kô (the South mine) the skarn ores are cut by narrow dykes having the characteristic porphyritic texture of the Suian granite. On the other hand the quartz-diorite mass of the Nantei mine is partly skarnized.

As has been the case in other pyrometasomatic deposits, both macroscopic and microscopic observations show that sulphide minerals were deposited later than silicate minerals in this district. (See Pl. LXXII (XXVII), Figs. 3–4; Pl. LXXIII (XXVIII), Figs. 1–3; Pl. LXXXIII (XXXVIII), Fig. 2). Therefore, the period of mineralization may be divided into two stages: (1) silicate stage (to-gether with oxide stage) and (2) sulphide stage. However, this division does not necessarily mean a time-break between the two stages. The process of the formation of silicates and of sulphides may have been continuous in many cases.

Description of ores

(1) Ores at the Kotudô mine

a) Oxide ores near the E–W contact.—Closely associated with phlogopite, forsterite, humite and other skarn minerals, a small amount of magnetite is found. Magnetite here does not come into direct contact with sulphides, although pyrite and pyrrhotite occur in the same skarn rocks. Magnetite is frequently octahedral in form and is 1–2 cm. long. Under the microscope it is rounded or octahedral in shape and is often wholly enclosed in calcite. According to the miners, it is possible for the amount of magnetite to increase in the deeper part of the Kotudô mine. The stage of magnetite formation is likely to be contemporaneous with that of skarn minerals. Magnetite is also found in ludwigite-bearing marble of the Western ore-bodies.

b) Sulphide ores (gold-copper-bismuth ores) of the Northern ore-body (N.O.B.).—Ore minerals are usually found in diopside-clinohumite-phlogopite-skarn which are generally enclosed in kotoite-marble. Mineralogical character of the ores is very complex. The following constituent ore-minerals are identified under the reflecting microscope: (1) pyrite(FeS_2), (2) pentlandite((Fe, Ni)S), (3) pyrrhotite(FeS), (4) cubanite($CuFe_2S_3$), (5) valleriite($Cu_3Fe_4S_7$), (6) chalcopyrite($CuFeS_2$), (7) bornite(Cu_5FeS_4), (8) bismuthinite (Bi_2S_3), (9) klaprothite($Cu_6Bi_4S_9$), (10) wittichenite(Cu_3BiS_3), (11) native bismuth(Bi) and (12) native gold (Au.).

From the observed paragenetic relation the above minerals must be divided into two classes: (1) iron-rich paragenesis; pyrite-pentlandite-pyrrhotite-cubanite-valleriite-chalcopyrite-bismuthinite-gold, and (2) iron-poor-paragenesis: pentlandite-chalcopyrite-bornite-klaprothite-wittichenite-native bismuth-gold. The paragenesis shows that the deposits were formed at high temperature. Among the paragenetic relations of various ore minerals, the most important and interesting paragenetic relations will be explained here.

Pentlandite-pyrrhotite. Small grains or flame-like crystals of pentlandite occur in pyrrhotite. Flame-like pentlandite may be interpreted as a product of unmixing (Pl. LXXIX (XXXIV), Fig. 2).

Cubanite-chalcopyrite. It is generally known that these sulphides (Cu-Fe-sulphides) can form a solid-solution at a higher temperature (+ 450° ?) and break down again into two at a lower. (cf. Newhouse (84), Ödman (88), Ramdohr (92, 93), Schwartz (102, 103) and M. Watanabe (118, 119). Typical examples of crystallographic intergrowth of cubanite with chalcopyrite as shown in Pl. LXXIV (XXIX), Figs. 3–4 indicate that both minerals are products of the unmixing of a solid-solution.

Valleriite-chalcopyrite. Valleriite always occurs in chalcopyrite and has never been found in pyrrhotite and cubanite. (cf. Ödman (88), 95). The mineral may have been formed by partial decomposition of iron rich chalcopyrite at higher temperature or by the introduction of iron into chalcopyrite (See Pl. LXXIV(XXIX), Figs. 1–2).

Pyrrhotite-bornite. Although both minerals are found in the same diopside-skarn of the Northern ore-body in some cases, they do not occur together in the same continuous sulphide-mass. Here, the antipathic relation of bornite to pyrrhotite is also striking as expressed by Gilbert (56).

Native bismuth-wittichenite-klaprothite. When native bismuth is found in bornite-bearing ores, it is entirely or partially surrounded by wittichinite or klaprothite. As will be mentioned later these Cu-Bi-minerals (klaprothite and wittichenite) may be interpreted to be reaction-products formed by the reaction of bismuth in liquid state with bornite or chalcopyrite (Pl. LXXVI(XXXI), Figs. 1 and 2; Pl. LXXVII(XXXII), Figs. 2 and 3).

Klaprothite-bornite. Rod-like inclusions of klaprothite are often found in bornite. The similar texture has been explained by Krieger (76) as having been caused by the unmixing of a solid solution (Pl. LXXVIII(XXXIII), Fig. 4).

Bornite-chalcopyrite. Chalcopyrite occurs in two forms. Massive chalcopyrite with drop-like bismuth is found without any regularity, while lamellar chalcopyrite is oriented crystallographically in bornite which is weakly anisotropic as explained in Pl. LXXVI(XXXI), Fig. 2). A similar texture has been described by Reuning(96) in the ores of the Natas mine, and by Brinkmann(44) in the ores of the Henderson mine, both of which were formed at high-temperature. The writer also interprets it as texture due to the unmixing of a solid solution as pointed out by Reuning(96) (Pl. LXXVII(XXXII), Figs. 1–2).

Native bismuth. As shown in Pls. LXXV(XXX), LXXVI(XXXI), LXXVII(XXXII), LXXVIII(XXXIII), bismuth occurs in irregular and drop-like form in chalcopyrite, bornite and sphalerite. Phlogopite is often penetrated by veinlets of bismuth. From these occurrences of native bismuth it is suggested that the bismuth in liquid state was separated from the ore-forming fluid above its melting point (271°C). Thus, the temperature of the melting point of bismuth may be used as a geologic thermometer. (Ref. Bowen (41), Ramdohr (94), and Seifert (104).

Bismuth-gold. As shown in Pl. LXXV (XXX), Fig. 1, fine grained white gold (probably electrum) is associated with drop-like bismuth. The writer considers that the gold was dissolved in bismuth liquid at a higher-temperature.

Gangue minerals. The following gangue minerals of skarn ores which have replaced the kotoite-marble are identified by the writer: (1) diopside, (2) clinohumite, (3) phlogopite, (4) tremolite, (5) serpentine and (6) calcite. Among these diopside is the most abundant gangue mineral in the ores. The texture of gangue minerals indicates that the silicate minerals have been replaced by metallic minerals (Pl. LXXII (XXVII), Figs. 3–4, Pl. LXXIII (XXVIII), Figs. 1–3 and Pl. LXXVIII (XXXIII), Fig. 1).

c) Gold ores of the Eastern ore-body (E.O.B.).—Ore minerals are found in diopside-chondrodite skarn rocks as bunches or irregular masses. The identified ore minerals are as follows: (1) pyrite, (2) pentlandite, (3) millerite, (4) pyrrhotite, (5) chalcopyrite, (6) bornite, (7) wittichenite, (8) bismuthinite, (9) tetradymite, (10) sphalerite and (11) gold. The mineralogy of the Eastern ore-body is also very complex. As very interesting textures and paragenesis have been observed, a brief account of them will be given here.

Pentlandite-pyrrhotite. At higher magnification, it is observed that small parallel blades of pentlandite are oriented in pyrrhotite (Pl. LXXIX (XXXIV), Fig. 1). The texture may be caused by the unmixing of a solid solution of FeS and NiS.

Sphalerite-chalcopyrite. Mutual relations of these minerals are very complex. Star-like sphalerite which has been called "Zinkblendesternchen" by Ramdohr (92, 93, 100) was found in chalcopyrite (Pl. LXXXI (XXXVI), Figs. 1 and 2). Small oriented needles of sphalerite, exsolved products of a solid solution, are also found abundantly in chalcopyrite (Pl. LXXXI (XXXVI), Fig. 5). On the other hand sphalerite found in bornite-ore contains abundant spots of chalcopyrite probably formed by the unmixing of a solid solution as shown by experiments done by Buerger (45) and Nakano (83) (Pl. LXXX (XXXV), Fig. 3).

Sphalerite-pyrrhotite. Small worm-like inclusions of sphalerite are observed in pyrrhotite. Therefore some of sphalerite-crystals have probably been formed earlier than pyrrhotite (Pl. LXXXI (XXXVI), Figs. 3–4).

Chalcopyrite-pyrrhotite. Under the microscope it seems that pyrrhotite has been replaced by chalcopyrite (Pl. LXXX (XXXV), Fig. 4, Pl. LXXXI (XXXVI), Fig. 3). However, vein-like masses of pyrrhotite are found between the grain-boundaries of chalcopyrite grains which often show beautiful characteristic twinning lamellae (Stevenson (108) (Pl. LXXX (XXXV), Figs. 1–2, Pl. LXXXI (XXXVI, Fig. 5).

Pentlandite-millerite. The occurrence of nickel minerals in the Kotudô ores has not yet been reported. It is, however, recognized by the writer that nickel minerals (pentlandite and millerite) occur in small quantities in many parts of the ore-bodies. The pentlandite represents one of the earliest ore minerals and was replaced by later sulphides and gold. Millerite occurs only in the proximity of pentlandite and is clearly later than the latter (Pl. LXXIX (XXXIV), Figs. 3–5).

Tetradymite.[1] This minerals is locally very abundant. Where it is present abundantly, it is embedded in calcite which fills the interstitial spaces of diopside. Under the microscope it is also seen that small flakes of tetradymite are often associated with bismuthinite and gold.

Gold. Gold is present as an important metallic mineral in free state. The distribution of gold in minerals is not simple. The gold is often associated with chalcopyrite as shown in Pl. LXXXII (XXXVII), Figs. 2 and 4. Small grains of gold are also enclosed in pyrrhotite as shown in Pl. LXXXI (XXXVI), Fig. 4 and Pl. LXXXII (XXXVII), Fig. 3. It is interesting to note that gold was often intimately associated with tetradymite and also with bismuthinite, (Pl. LXXXII (XXXVII), Fig. 1. The high grade gold ore obtained from phlogopite skarn at the 700 syaku-level includes the following minerals: pentlandite, millerite, sphalerite, chalcopyrite, bornite, wittichenite, and gold. In this ore the gold together with other sulphides was deposited along the cleavage planes of pentlandite and the former

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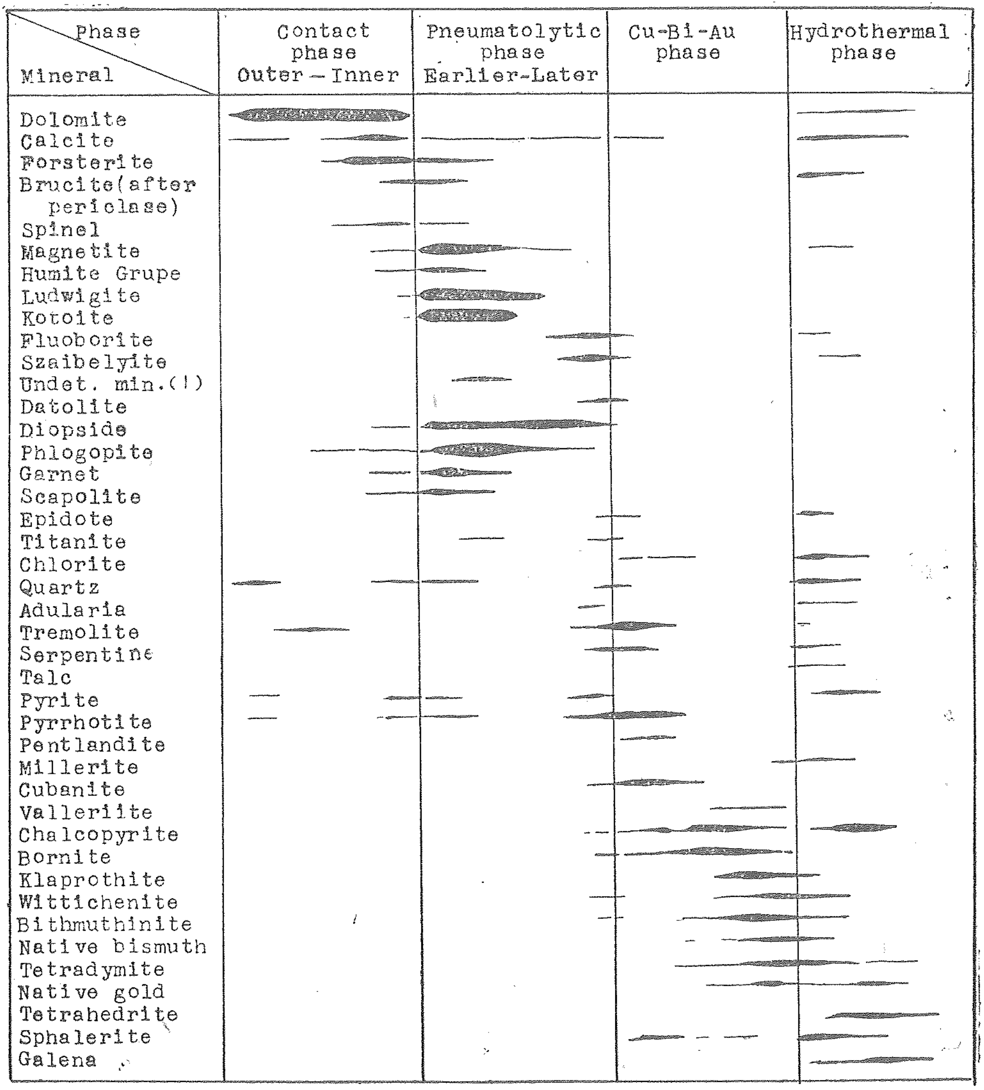
[1] According to the recent investigations on Bi-Te-S minerals, the following minerals have been known as distinct species: tellurbismuth (Bi_2Te_3), tetradymite (Bi_2Te_2S), grünlingite (Bi_4TeS_3) and joseite (Bi_3TeS). Their mutual identification is so difficult under the microscope that the Bi-Te-mineral described in this report is not strictly confirmed.

TABLE 7

Paragenetic table showing the sequence of metamorphic and hypogene mineral development in the gold-copper-bismuth deposits of the Kotudô mine, Tyôsen.



minerals are clearly later than the latter (Pl. LXXIX(XXXIV), Figs. 3–4).

Gangue minerals.—These minerals include ludwigite, kotoite, fluoborite, szaibelyite, diopside, tremolite, chondrodite, clinohumite, phlogopite, serpentine, talc and datolite. Between these ore-bodies and the wall rock (dolomite-marble) a narrow zone of new-formed calcite is usually developed as shown in Pl. LXXII(XXVII), Fig. 1.

d) Gold ores of the Western ore-bodies (W.O.B.).—Mineralogically the gold ores of these ore-bodies may be classified into three groups: (1) pyrometasomatic gold-ore in diopside-phlogopite skarn (2) pyrometasomatic gold-ore in garnet skarn and (3) mesothermal replacement ores in dolomite. The first group resembles the ores of the Eastern ore-bodies while the second shows some different features. The third group will be described later.

Gold ore in garnet skarn ("garnet ore").—The ore occurs in tabular form and lies along the Kotudô fault. The following minerals were identified; hematite (secondary), pyrite chalcopyrite, klaprothite, bismuthinite, tetradymite, gold, garnet, and calcite. Under high magnification native gold is easily seen in polished sections and is especially associated with bismuth-tellurium minerals such as bismuthimite and tetradymite.

In conclusion, the paragenetic relation of the minerals observed at the Kotudô mine are shown in Table 7.

(2) Ores at the Nantei mine (Tul Mi Chung mine)

The ores are mineralogically very complex. The following hypogene metallic minerals were identified: magnetite, specularite, pyrite, pyrrhotite, löllingite, arsenopyrite, molybdenite, chalcopyrite, bornite, klaprothite, bismuthinite, tetradymite, gold, tetrahedrite, sphalerite, and galena. The paragenesis shows that deposition of sulphides was later than skarnization and deposition of oxides. The Nantei ores can be genetically classified into the following four groups: (a) pyrometasomatic ores in igneous rocks, (b) pyrometasomatic ores in metamorphosed sediments, (c) replacement-ores in marble, and (d) mesothermal veins. In this section only (a) and (b) will be described.

(a) *Pyrometasomatic ores in igneous rocks.*—Along the fissures or fracture zones of the quartz-diorite gold and copper ores consisting of copper sulphides and gold are found, especially in "A" ore-body. The original constituents of igneous rocks like apatite, zircon, orthoclase etc. are found as remnants in the ores. The ores are often penetrated by veinlets of calcite in every direction. The ore-minerals identified are as follows: pyrrhotite, arsenopyrite, chalcopyrite and molybdenite.

Pyrite occurs abundantly and often develops its crystal form.

Arsenopyrite shows strong idiomorphism.

Chalcopyrite is one of the most important ore minerals and is closely associated with gold and silver.

Molybdenite is locally found in great quantities.

(b) Pyrometasomatic ores in metamorphosed carbonate rocks. —The most important high grade gold ores belong to this group. The principal constituent ore minerals are as follows: magnetite, hematite, pyrite, molybdenite, arsenopyrite, löllingite, pyrrhotite, chalcopyrite, bornite, klaprothite, bismuthinite, tetradymite, sphaerite, and gold.

Magnetite and hematite. The minerals are found in andradite-salite skarns of "B" ore-body and are usually cut or replaced by later sulphides.

Chalcopyrite-bornite-klaprothite. These minerals occur in specks or streaks in the salite skarn of the "B" ore-body The minerals are usually found, filling the interstitial spaces, minor cracks, and cleavages of salite-crystals. Crystallographic intergrowth of bornite with chalcopyrite is seen on polished sections. The texture shows that the bornite has been replaced by chalcopyrite along cleavage planes. A small amount of klaprothite is found in bornite.

Arsenopyrite and löllingite. These minerals are the characteristic minerals of the Nantei mine. These are often embeded in the hornblende or in chalcopyrite as small specks.

Pyrite. The mineral occurs in minute cubes or rounded-grains, being often surrounded by chalcopyrite. From its occurrence pyrite may be said to be a mineral formed earlier than chalcopyrite.

Pyrrhotite. This mineral is also replaced by chalcopyrite and pyrite (Pl. LXXXIV (XXXIX), Fig. 1).

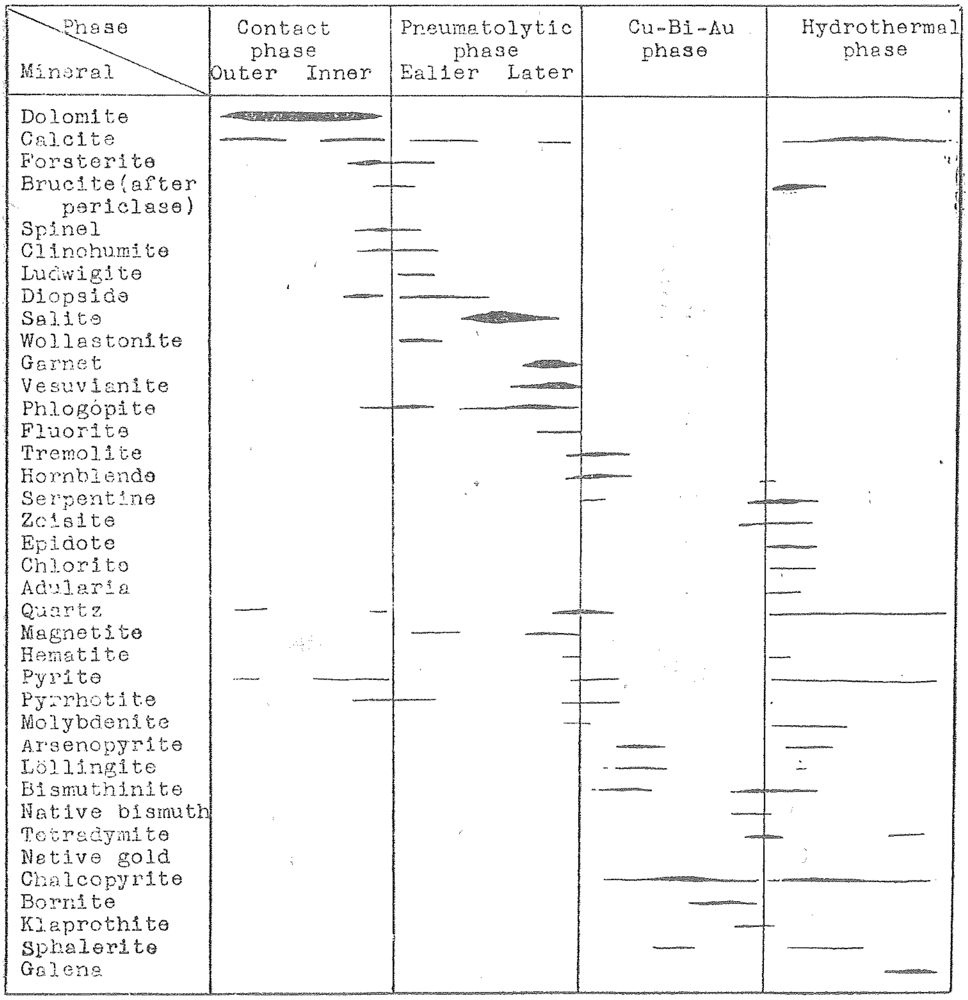
Sphalerite and galena. These minerals are rare. Chalcopyrite is replaced by them.

Molybdenite. Ill-developed crystals of molybdenite occur in the small patches or streaks extensively in pyroxene-skarns (Pl. LXXXIV (XXXIX), Fig. 2).

Gold-tetradymite-bismuthnite. As in the case of the Kotudô ores, the close association of these minerals is the most striking feature of the gold ores in the Nantei mine. Many photomicrographs show

TABLE 8

Paragenetic table showing the sequence of hypogene mineral development in the gold-copper-bismuth deposits of the Nantei mine.



the mutual relation of these minerals (Pl. LXXXIV (XXXIX), Figs. 3–4). As shown in the photographs the mode of occurrence of gold is characteristic, that is usually associated with tetradymite and bismuthinite. Gold particles are usually so fine that it is impossible to see them with the naked eye. The difficulty of milling of the gold ores of the Nantei mine may be attributed to this fact.

The paragenetic relations of all kinds of minerals found at the Nantei mine are shown in Table 8. It should be noted here that the Nantei deposits are characterized by the scarcity of boron and halogen minerals in contrast with the abundant occurrence of these minerals at Kotudô.

(3) Ores at the Naikinri[1] prospect and the Sakusui[2] mine

Ore deposits so far discovered in the vicinity of the Naikinri village belong to the class described as the pyrometasomatic type. Mineralogically the ores found in this district are very complex in composition. The ore-bodies are found in the belts of impure dolomite in the eastern part of the contact aureole of the Suian granite. The following hypogene minerals were identified by the writer: pyrite, pyrrhotite, chalcopyrite, bornite, sphalerite, bismuthinite, tetradymite, bismuth, gold, ludwigite, forsterite, chondrodite (clinohumite), serpentine, brucite, diopside, tremolite, epidote, adularia, quartz, calcite, etc.

Gold. Gold particles found in this district are usually very coarse and can be identified even by the naked eye. Microscopic investigation reveals the fact that the mode occurrence of the gold ores of this district is also characterized by the intimate association of gold, bismuthinite and tetradymite (Pl. LXXXII (XXXVII) Fig. 5).

Tetradymite. This mineral is always found in association with bismuthinite. Under the microscope it is seen that tetradymite sometimes contains minute inclusions of unknown minerals. Myrmekitic intergrowth of unknown components with tetradymite is occasionally observed.

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[1] 内金里 (Sang Dai) [2] 作水鑛山

(4) Ores at Tenzi[1] prospect

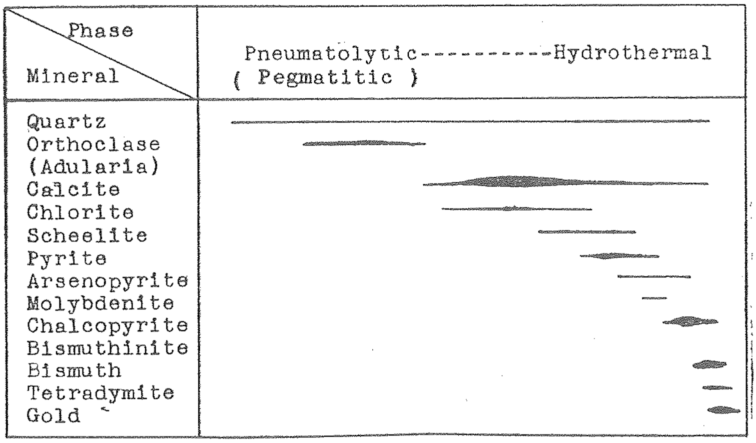
The ore deposits of the Tenzi prospect are located in the northwestern part of the Suian contact zone. Recently several tubular and pipe-like deposits of the pyrometasomatic type have been discovered and are being exploited. The mineral paragenesis of these deposits resembles in some respect that of the Kotudô mine. The ores of the pipe-like deposits, however, are characterized by their complex mineral paragenesis. The following minerals were identified: magnetite, pyrite, arsenopyrite, chalcopyrite, sphalerite, molybdenite, bismuthinite, tetradymite, gold, scheelite, diopside, phlogopite, quartz, adularia, and calcite.

Gold. Under the microscope it is seen that tetradymite and bismuthinite includes very fine particles of gold.

Scheelite. This mineral is not common. From the paragenetic relation it seems that the scheelite was deposited earlier than sulphide minerals. Orthoclase with an adularia-habit occurs in the proximity of scheelite (Pl. LXXXV(XL), Fig. 1). The general paragenesis of the minerals are shown in Table 9.

TABLE 9

Paragenesis of gold-copper-tungsten-bismuth ores from the Tenzi (Kung Kol) prospect.



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[1] 天峙 (Kung Kol)

Moderate-temperature (mesothermal) deposits.

a) *Replacement deposits in carbonate rocks.*—The deposits falling into this group are characterized by the presence of hydrous skarn minerals. The ores are usually associated with carbonates (calcite and dolomite) and hydrous silicates (chlorite, serpentine and talc). The deposits are very irregular in form and stock-like and are found in carbonate rocks. Just below the hanging wall of impervious hornfels or schist, the chemically reactive carbonate rocks have been intensely mineralized and altered into mesothermal ores. Fine examples of this category are seen in the deposits found in the Dôgan mine where the sulphide bodies have replaced the upper part of the dolomite which lies immediately under the biotite hornfels (Pl. XLIX(IV)). The sulphide bodies are also found in the crushed or fractured zone of the carbonate rocks. As in the case of the Western ore-bodies in the Kotudô mine the mineralized dolomite rocks are developed along the Kotudô fault-zones. Similar deposits are also found at the Keisyakoku[1] prospect. Mineralogically the sulphide masses of the mesothermal deposits are somewhat simpler in composition than those of the pyrometasomatic deposits. Paragenesis indicates that these ores may have been formed at moderate temperature. The following examples will be described below: (a) Ores of the Western ore-bodies at the Kotudô mine, (b) mesothermal replacement ores at the Dôgan mine, and (c) mesothermal replacement ores at Minami-Kô (South mine) of the Nantei mine.

(1) *Mesothermal ores of the Western ore-bodies at the Kotudô mine.*—As shown in Fig. 11, the sulphide-impregnated masses are found in the brecciated dolomite along the fault zones. The trend of these tabular masses coincides with the strike of the Kotudô-fault. The following minerals were identified: chalcopyrite, tetrahedrite, sphalerite, galena, gold-silver, dolomite, and calcite. Characteristic minerals of moderate temperature deposits are tetrahedrite and galena.

(2) *Mesothermal replacement ores at the Dôgan mine, Nantei.*—Just below the flat contact between hornfels and dolomite several tabular sulphide bodies have been discovered (Pl. XLIX(IV)). The constituent minerals identified are as follows: chalcopyrite, tetrahedrite, sphalerite, galena, molybdenite, and gold-silver. The rela-

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2) 慶射谷探鑛所 (Kung Chai Kol)

tion of tetrahedrite to chalcopyrite is shown in Pl. LXXXIII (XXXVIII), Fig. 3.

(3) *Mesothermal replacement ores at the Minami-Kô (south mine), Nantei.*—In the northern part of the Minami-Kô, the sulphide ores replacing marbles have been prospected. The ores, however, contain comparatively little gold and much silver. The sulphide ores consist of pinkish sphalerite, galena, arsenopyrite, löllingite, chalcopyrite and calcite with a small amount of quartz. These sulphide masses extend into the upper and northern fissure zones between hornfels and the Nantei quartz-porphyry where a typical quartz-calcite vein is developed (Pl. XLIX(IV)).

b) *Veins (gold-silver-lead-zinc deposits).*

General features.—Although the gold-deposits of the Suian district have generally been regarded as typical "contact metasomatic" deposits, there are several exceptions among them. In the area where the hornfels, slaty to phyllitic rocks are developed as well as in the igneous area, several deposits belonging to the category of the true vein have been discovered. Their most common mode of occurrence is along fissures parallel to the joints of igneous rocks and slates.

Among these, the Goyô1) and Eikô2) veins are the most important. The strike of the Goyô veins are nearly north-south and perpendicular to the contact plane of the Suian granite. The veins dip steeply and are possibly inclined toward either the east or the west. The length of the veins is more than 100 meters. Characters of the hypogene ores of the Goyô mine will be explained later. The Eikô veins consisting of quartz, pyrite, galena, sphalerite, etc. strike N–S and fill the joint fissures of the slaty wall rock. Huei3) veins, however, occur within the area of the Hitiseidai granite, their general strike is nearly north to south, and the dip is steep. As mentioned before some vein-like deposits have also been found in the Nantei mine. Recently gold-quartz-sericite veins have been worked in the Suian granite, near the Saziri village.

Character of the hypogene ores.—The hypogene ores of veins in the Suian district consist largely of zinc, lead and iron sulphides (pyrite or pyrrhorite), with gold and silver. The important gangue minerals are quartz, siderite ,ankerite (manganiferous) and sericite. Subordinate amounts of copper are contained in the veins.

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1) 梧陽　2) 永興　3) 富榮

Gold-silver ores at the Goyô mine.—The hypogene ores of the gold-silver veins at the Goyô mine consist of the following minerals: pyrite, pyrrhotite, sphalerite, arsenopyrite, chalcopyrite, galena, gold, quartz, siderite and sericite.

Pyrite. This mineral is a prominent constituent of the ores, occurring as disseminated cubes and crystalline masses. The pyrite crystals have been fractured and cemented by later sulphides and by gangue minerals (Pl. LXXXVI(XLI), Fig. 3).

Sphalerite. Sphalerite is abundantly present and it includes pyrite. Sphalerite crystals have been fractured and the fractures have been cemented by later sulphides. It has also been penetrated by chalcopyrite (Pl. LXXXVI(XLI), Fig. 1). Occasionally on the crystal surface of sphalerite arsenopyrite-crystals have grown (Pl. LXXXVI(XLI), Fig. 4).

Arsenopyrite. This mineral occurs in many places and it is especially abundant in the northern part of the Goyô vein. The arsenopyrite crystals have been cemented or partly replaced by chalcopyrite (Pl. LXXXVI(XLI), Fig. 4).

Chalcopyrite. This mineral is relatively common in the ores and it occurs in irregular masses and replaces the earlier minerals. Sphalerite-stars are occasionally found in chalcopyrite (Pl. LXXXV (XL), Fig. 4).

Pyrrhotite. This mineral, far from being rare, is found especially in the northern part of the veins.

Galena. The galena is one of the most important constituents of the ores. This mineral cements fractures of pyrite and very often includes particles of gold (Pl. LXXXVI(XLI), Fig. 2 and 3).

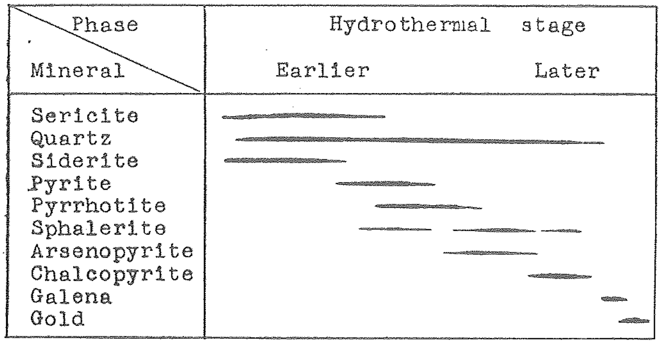
Gold. Native gold is often found in galena (Pl. LXXXVI(XLI), Fig. 2). The contact face between pyrite and galena was a favorable place for its deposition.

Gangue minerals. The following minerals were identified: quartz, siderite and sericite. Quartz is the most important constituent of the ore. Occasionally siderite occurs abundantly. Association of siderite and pyrrhotite is not rare.

Wall rock. Biotite hornfels and slate have been intensely sericitized as shown in Pl. LXXXV(XL), Fig. 3. Field and microscopic investigations suggest the following paragenesis: (1) sericitization and silicification of wall rock accompanied by development of pyrite, (2) pyritization, (3) deposition of pyrrhotite, sphalerite and a little later arsenopyrite, (4) crystallization and replacement of chalcopyrite and galena with gold. These relations are shown in Table 10.

TABLE 10

Hypogene mineral sequence in the gold ores from the Goyô mine.



Superficial alteration of the ores.—Owing to the climatic conditions and also to the rapid erosion, ore deposits of the Suian district have not been greatly effected by supergene alteration. In particular the supergene minerals, except a small amount of chalcocite (Pl. LXXVIII (XXXIII), Fig. 3), do not occur in the Kotudô mine. At the Nantei mine oxidized copper minerals were found in the upper parts of the ore-bodies. It is, however, impossible to study these parts because the upper part of the ore-bodies has now been entirely stoped out. Oxidized minerals found at the Nantei mine are as follows: malachite, chrysocolla, azurite, cuprite, native copper and limonite.

Chapter VI

GENETICAL CONSIDERATIONS

Thermal metamorphism and metasomatism.—On the origin of the skarn rocks there have been many discussions among the students of ore deposits. The relative importance of the agencies of heat and material transfer has long been discussed, yet to this day the problem remains unsolved. Some investigators such as Uglow(114), Leith(77), etc. have emphasized the effect of thermal actions and concluded that the greater part of skarn rocks were produced from impure limestone through recrystallization without any material exchange. On the other hand, investigators such as Lindgren (78, 79, 80), Umpleby (115), Kato (71, 72, 73), Suzuki (110), Kennedy (74), Dunham (48), Fitch (52), and Schmidt (99) have expressed the oppinion that there were active transfers of materials like silica, iron, etc. from the magma to the country rocks at the time of skarnization. There is now a great accumulation of literature on this subject and it is impossible to summarize all of them in this paper. It should, however, be noted here that intermediate opinions are also held by many workers. It is pointed out by them that the substance of some skarn minerals are partially accounted for by magmatic emanations, while the chemical natures of new-formed skarn minerals are also controlled by the chemical composition of the original rocks.

It is generally recognized that the metamorphic processes are of two types, thermal (or normal) metamorphism and metasomatism. The metasomatism of carbonate rocks by magmatic substances at high temperature was called "pyrometasomatism" by W. Lindgren (81) and Knopf(75). In the Suian district the features of metamorphic minerals show that their composition depends upon the original rocks. As the most predominant country rocks are dolomitic rocks, the various kinds of magnesian minerals, such as forsterite, chondrodite, brucite, spinel, phlogopite, diopside, kotoite, etc. are abundantly found, while some calcic minerals such as andradite, wollastonite, vesuvianite, are occasionally found in metamorphosed calcareous rocks. In this district transfer of material from the intrusive magmas to the country rocks also unquestionably took place. The metasomatic introduction of silica, iron, boron, fluorine and chlorine into sediments has been recorded in many minerals found in the contact aureole of the Suian granite.

Time relation and physico-chemical condition.—As to the sequence of events, many investigators have repeatedly discussed the data obtained from the field which they had studied. Thermal metamorphism and pneumatolytic action of gases and dilute vapors are generally considered to have taken place first at the earlier stage of the intrusion of magma and intense metasomatism came thereafter. Although the importance of pyrometasomatism was once minimized by Spurr (106, 107), Lindgren recognized its importance and stated that the development of hornfels, the recrystallization of limestone, introduction of silica, the formation of lime-iron silicates, the growth of the iron oxides, and the sulphide phase, all form a continuous series and are caused by one and the same agency, i.e., the transfer of heat and substance from the intrusive.

With regard to the Suian district the writer has endeavored to establish the sequence of magmatic activities, metamorphism and mineralization. At the contact the Suian granite is generally fresh and little altered except in the area where the sulphide minerals occur, while small masses of quartz-diorite, which are regarded as precursors of the Suian granite, have been altered greatly and changed into skarn masses. At the Nantei mine it has been observed that the skarn masses have been cut by the Suian granite and its allied aplites, while veins of skarn minerals penetrated the Suian granite at the Saziri valley. These facts indicate that there was a long period of skarnization and that this process began early in the beginning of crystallization of the magma and continued at least till after the outer part of the granitic stock had consolidated. At the Kotudô mine the pneumatolized dolomite rocks, i.e., kotoite-marble, ludwigite-bearing marble have been replaced by later typical lime-magnesian silicate rocks (skarn rocks). Therefore this fact suggests that the boron-fluorine pneumatolysis preceeded the skarnization.

In regard to the ore-formation the metasomatic process may be separated into two periods; (1) period of silicatization (skarnization) and (2) period of metallization (formation of hydrous silicates and sulphides together with gold and bismuth minerals). However, it seems that these two periods were, in some cases, continuous. That is to say, the formation of sulphides followed the silication as part of a continuous process of mineralization. As mentioned earlier, the sulphide ores of the Northern ore-body of the Kotudô mine, are found within the irregular pipe-like bodies of kotoite-marble. It seems to the writer that such complex pipe-like bodies may have been formed by a long continued single mineralization-process at relatively high temperature. The field observation indicates that the products of the first type of metasomatism, i.e.

the skarnization are usually confined to the area adjacent to the igneous bodies. On the other hand distribution of the resulting products due to the second type of metasomatism (metallization) has been especially controlled by the structural conditions of the country rocks.

As has been discussed by Niggli and others, the behavior of a magma at the later stage of solidification may be different according to the external conditions of the magmatic chamber. Judging from the petrographic characters of the igneous rocks of the Suian district the depth of solidification of the magmas was probably intermediate, because the eruptive rocks in question generally show the hypabyssal character. No quantitative data as to the pressure could be obtained by the writer, although Koto (18) and Higgins (7) estimated the pressure at the time of the formation of the ores. As to the prevailing temperature at the time of mineralization, paragenetice relations of some minerals will throw light on this question. As mentioned in the proceeding chapters the following may be considered as geologic temperature indicators (Table 11).

TABLE 11

Data for geologic thermometry.

	Observation	Example	Phenomenon	Temperature	Investigator
(1)	Anomalous garnet	Kotudô, Nantei	Disappearance of interference color of garnet	800°	H. E. Merwin (104)
(2)	Cubanite-chalcopyrite intergrowth	N.O.B., Kotudô	Unmixing of a solid solution	ca. 450° ?	G. M. Schwartz (102, 103) P. Ramdohr (94)
(3)	Sphalerite-chalcopyrite intergrowth	N.O.B. E.O.B. Kotudô mine	Unmixing of a solid solution	350-400°	N. W. Buerger (45)
(4)	Pentlandite-pyrrhotite	E.O.B. Kotudô	Unmixing of a solid solution	high	W. H. Newhouse, P. Ramdohr (94)
(5)	Drop-like bismuth	N.O.B. Kotudô	Melting point	271°	P. Ramdohr (94)
(6)	Low-quartz in skarn rocks	Kotudô Naikinri	Inversion	−573°	
(7)	Periclase-marble	Kotudô Nantei	Dissociation of dolomite molecule	+800°	Kôzu, Takane & Ômori

It should be noted here that the above phenomena also depend upon the prevailing pressure. Seeing from the mineral paragenesis and the data listed above, it may be, however, concluded that the important mineral deposits of the Suian district were formed at relatively high temperature. In conclusion the time relations in the metamorphic process of the Suian district may be summarized in order as follows:

(1) Thermal metamorphism of the country rocks.
(2) Crystallization and the formation of metamorphic minerals by pneumatolysis.
(3) The formation of anhydrous silicates (skarnization). } (Pyrometasomatism)
(4) The formation of hydrous silicates and sulphide minerals. }
(5) Hydrothermal metasomatism and vein-formation.

The nature of the ore-forming fluid.—In the previous section the transfer of materials from the magma into the surrounding sediments and the time-relations of the processes of mineralizing fluid were discussed. It now remains for us to consider the nature of the fluid and its behavior in the sediments. In connection with the genesis of ore deposits the following observation obtained in the field and at the laboratory may be summarized.

(1) The common skarn minerals are frequently associated with halogen and borate minerals.
(2) The halogen minerals are scapolite, fluorite, phlogopite, minerals of humite group, etc.
(3) The borate and borosilicate minerals such as kotoite, ludwigite, fluoborite, szaibelyite, datolite, tourmaline, etc. are found in the contact aureole.
(4) Copper-iron-bismuth sulphides together with gold and silver are present.
(5) The close association of gold with bismuth and tellurium minerals is a characteristic feature of the ores.
(6) Hydrous silicate minerals were formed at later stage of the mineralization.
(7) The sericitization of the wall rock of the gold-silver veins is seen.

As to the mode of transfer it was believed by V. M. Goldschmidt (58), A. Harker (63), W. Lindgren (81) and others that the heavy metals were introduced as halogenides. The writer also considers that a part of the heavy metallic elements was introduced as halogenides from the intrusive magmas into the carbonate rocks found in the contact zone of the Suian district, because abundant contact minerals like chondrodite, clinohumite, scapolite, etc., which contain an appreciable amount of halogen elements, are found in association with mineral deposits of high temperature type. The problem of the mode of transfer of silica, however, has been much discussed but not yet fully solved. (cf. Bowen (42), Fenner (50), Graton (59), Greig, Merwin Shepherd (60), Kennedy (74), Niggli (85, 86, 87), Schmidt (99). According to Lindgren (78, 79, 81), V. M. Golschmidt (58), Weed (120), et al). The processes of skarnization and metallization at the igneous contact are thought to be the result of the introduction, due to the rapid lowering of pressure at the time of intrusion, of emanated volatile components into sediments from the surface of the intrusive magma, which contained volatiles in large quantities. But Spurr (160, 107) considered that ore-generating solutions, (gaseous or aqueous) rich in SiO_2, Fe_2O_3, Al_2O_3, sulphides, etc., which came up from the deeper zones of magmatic differentiation through fissures or faults after the solidification of outer part of magma, supplied various materials into the sediments. The above variations in processes may be due mainly to difference in the physical conditions at the time of consolidation of the magma.

Recently the nature of the ore-forming fluid has been the subject of discussion among many geologists and petrologists such as Bowen (42), Fenner (50, 51), Graton (59), Ingerson and Morey (67, 68) and others. Although no unanimous opinion has been established, Bowen and Fenner advocated the theory that acid gases emanated from the magmatic liquid and played an important rôle on the formation of ore-deposits. According to Fenner, gaseous transfer of substances from magma may take place during the cooling process, while, according to Bowen, gases may be expelled by boiling from the volatile-high residual pegmatitic liquid at a later stage of the magmatic activity. The phenomena have also been well interpreted on the ground of physico-chemical principles by P. Niggli (85, 86) and W. Q. Kennedy (74). According to Niggli, the processes of skarnization and metallization may be ascribed to the distillation caused by the crystallization of refractory components in the system of magmatic solution consisting of volatile and non-volatile or refractory substances. The development of great pressure in the magma as a result of crystallization has also been noted by G. W. Morey (82), Niggli (61, 85, 86, 87) and others. As in the case of the Suian intrusive complex, under less deep-seated condition where the outer pressure of the magmatic system was lower than the inner pressure, the residual liquid of the crystallizing magmas might have boiled and evolved acid vapours at the temperature of so-called second boiling point.

Regarding the succession of minerals, Niggli considered that the phenomenon is similar to that occurring in distillation-tubes, that is to say, fractional distillation. Consequently various kinds of lime-silicates and oxides in the contact aureole may be produced from such distillates combining with original substances of wall rocks. On the other hand, a greater part of the sulphides formed the later than the silicate and oxides, is probably precipitated from the condensed liquid of the emanated gases, or directly from the residual liquids, which are poured into the sediments. In regard to the mode of transfer, he considered that the greater parts of the oxides and sulphides are probably transferred as vapour or gases such as halogenides, borates, etc. as already considered by V. M. Goldschmidt (58), and Ingerson and Morey (68). These vapours or gases are caught by the chemically reactive carbonate rocks and a part of these remains in the contact-minerals with the expulsion of CO_2. After the pneumatolytic formation of silicates, metallization of various sulphide ores takes place in the silicates from the watery solutions which represent the condensed part of the emanated gases or which came up later from the inner part of the residual magma. This explanation may well be applied to the case of the ore-formation in the Suian mining district. As to the chemical character of the vapour phase from boiling pegmatitic residual liquid, Bowen states that the vapor formed by the boiling may be acidic, in that it contains an excess of HCl, HF, H_2S, CO_2, H_3BO_3 H_2SO_4 and other ores or less volatile acids. He considered therefore that elements in the gas would be H, O, Cl, Si, F, S, B, K, Na, Fe, Ti, Al, together with Sn, Pb, Cu, Zn, and a number of others. Furthermore, direct evidence of the gaseous transfer of ore-forming elements was also observed by Zies (124) at Katmai.

In the Suian district the pyrometasomatic deposits are characterized by the presence of halogen-minerals, borates, anhydrous lime-magnesian silicates and iron oxides, and also by the association of gold, bismuth, and tellurium with some sulphides, while the mesothermal replacement deposits and veins are characterized by the occurrence of hydrous silicates and zinc-lead sulphides and by the intense sericitization of wall rocks. From these available facts and above considerations, it seems that at Suian the emanated fluids, which were probably formed by the boiling of the crystallizing granitic magmas, were acid when they left and contained elements H, O, Si, F, Cl, B, S, Te, Al, together with Cu, Fe, W, Bi, Mo, Zn, Pb, Ag and Au. These acid vapours, which were expelled through weak zones, faults, or fissures in the country rocks, attacked the carbonate rocks near the contact and formed sporadically the important pyrometasomatic gold-copper deposits in them.

As has been discussed above, it is possible that gases were able to transfer non-volatile components in the early metasomatic stage, because the amount of borates and halogen-bearing minerals which remain in country rocks of the Suian mineral deposits, are probably sufficient to account for the great quantity of such introduced substances as SiO_2, Al_2O_3, K_2O, and various metallic elements. Recently Fenner (51) has pointed out that boric acid, one of the most important mineralizers in magmas, does not generally form stable petrogenic minerals and that the important borate deposits of the world are found only on the surface in many volcanic circumstances. It is, however, remarkable that a great quantity of boric acid has remained in the metamorphosed dolomites of the Suian contact zone, as if the dolomite acted as blotting paper for the boric acid contained in the magmatic emanations.

Besides, it is inferable that the emanated fluids were sometimes also rich in water as in the case of the Traversella deposits described by W. Q. Kennedy (74), because hydrous silicate minerals are usually associated with skarn minerals and ore-minerals of such deposits as the Nantei ores. In such cases, these waterly fluids, which were probably formed by the boiling, supposedly exceeded the critical temperature of water (not of the magmatic solution) immediately after they have escaped from the magma. Therefore they could also transport a considerable amount of of the non-volatile materials as discussed by Ingerson (67), Morey (68) and others. These gaseous emanations, being usually acid, might have later condensed and become alkaline hydrothermal solutions as a result of the neutralising action of the wall rock substances. Consequently, most of minerals of the mesothermal deposits were probably precipitated from the condensed hydrothermal solution. It is, however, considered probable that some ore-forming fluids were also generated from the residual magmas in the latest stage of the magmatic activity. In conclusion, it is generally said that the ore-forming fluids showed all stages from the pneumatolytic to the hydrothermal. It should be mentioned here that gold-bismuth-tellurium paragenesis suggests that gold may have been easily transported by the magmatic emanations in the presence of bismuth and tellurium, as shown by many examples studied by such investigators as Buschendorf (46, 47), Hüttenhain (66), Reuning (96), and Warren (116, 117).

Spatial distribution of ore-bodies. — It has been generally observed in many mining districts that different types of ore deposits are zonally arranged with reference to the central igneous body. It is suggested that the change in temperature and pressure, outward and upward from the igneous body, a source of ore-forming fluid, has affected the deposition of minerals. It is also generally held that the copper zone lies nearer the igneous mass than the lead-zinc zone. Although various kinds of ore-bodies are found around the igneous complex of the Suian district, pyrometasomatic deposits characterized by the presence of gold-copper-bismuth minerals, are generally situated in the immediate neighbourhood of the Suian granite as shown in Text-fig. 2 and Pl. XLVI(I), while many mesothermal deposits are found at places more distant from the contact. Some of the mesothermal deposits, however, occur in contact with the pyrometasomatic deposits as observed at the Dôgan mine, Nantei and at the Western ore-bodies of the Kotudô mine.

Ore deposits found on the NW-ES fractured and fault zones which run nearly parallel to the trend of the sedimentary rocks, are not zonally arranged to correspond with the types of ore deposits. Therefore there are factors other than distance from the igneous body that have controlled the distribution of ore-bodies. As mentioned in the earlier chapter the ore deposits of the Suian district were not formed concurrently but successively in different stages. As is commonly known, the high temperature pyrometasomatic deposits of the district were formed earlier than the low temperature hydrothermal deposits. Thus it might be possible that many places where the earlier ore-deposition took place at higher temperature, were repeatedly fractured and mineralized by later ore-forming solutions. In that case the two types of deposits would be found together in the same place, as observed at Nantei and Kotudô. In those cases the time factor must be more important than the distance from the igneous body. It must be also considered that the downward or inward migration of the isotherms was caused by the loss of heat at the contact during the cooling of the intruded magma (Schneiderhöhn(101)). Another important factor that influenced the distribution of ore-bodies is the nature of the host rocks and local geologic structures. As carbonate rocks are chemically reactive, the gold-copper zone in dolomites or in limestones is confined to the neighbourhood of the contact surface of the Suian granite.

Chapter VII

LOCAL DESCRIPTIONS OF IMPORTANT MINERAL DEPOSITS

The ore deposits of the Suian district have been exploited chiefly for gold and copper but silver has also been obtained. Though scheelite-deposits (see Pl. LXXXV(XL), Fig. 2) were once actively prospected near the Sekitaturi village, 2 km. north-west of the Kotudô deposits during the period of the first World War, they were abandoned later. As molybdenite occurs in large quantities in the Nantei mine, the mineral has recently been mined.

History of mines.—The Suian mining district has long been famous for gold-production in Tyôsen. In former days the gold mining was carried on by the old royal family of Tyôsen. Although T. Yamaguti, a Japanese, obtained the right to mine the minerals in 1901, it was again returned to the old royal family. In 1905 the concession was formally granted to A. L. Pearse, an Englishman, who assigned his rights to the Korean Syndicate of London. The next year the Suian concession was granted to the tripartite combination of the Korean Syndicate (British combination), Collbran and Bostwick (an American firm) and Mitsui & Company (a Japanese firm). After the prospecting of the mining area the Japanese group withdrew and the concession was operated by the others. After two years of dissapointing results the Korean Syndicate gave the mining rights to Collbran and Bostwick who organized the Seoul Mining Company in 1908. In the beginning actual work was done by them at Kotudô (Hol Kol) and the mine was called the "Suan mine" for the following several years. During the prosperous period of the "Suan mine," prospecting was actively carried on by the company. Then promising deposits were discovered near the village of Nantei (Tul Mi Chung). The Nantei mine (Tul Mi Chung mine) was opened in 1913 and closed in 1925. Later this mine was reopened by Fraser and Folks. Again the property was sold to the Nippon Mining Company[1], the name "Suan mine" or Suian mine"[2] was applied to the "Tul Mi Chung mine". On the other hand, the old "Suan Mine" located at Kotudô (Hol Kol), was once closed and then reopened by Koreans during the years 1921–1932. In 1932 the property was transferred to the present owner (the Hôkô Mining Company,[3]) and is now called the Kotudô (Hol Kol) mine[4]. There are many other small mines and prospects in the districts which are shown on the geological map (Plate XLVI(I)).

(a) The Kotudô mine (the Hol Kol mine or the old Suan mine) (Plate XLVII (II), Plate L (V) Fig. 1, and Text-fig. 11 and 12)

The Kotudô mine is situated in the northern part of the district where the thick dolomite beds of the Sidôgû series were intensely metamorphosed by the intrusions of granitic magmas. The Kotudô granite is exposed along the E–W ridge separating the Kotudô and Saziri valleys. The Kotudô valley is the meridional one along which a small town has been developed. The major igneous contact lies at the northern side of the E–W ridge and the distribution of dolomites and argillites is bounded by the meridional dip fault called the "Kotudô fault". The slicken-side of this fault is well exposed, dipping 55°–60° to the east in the open-cut of the western ore-body. The ores found in this fault zone have been almost entirely stoped out. As will be mentioned later, genetically two different types of ores are recognized in this mining area. In the northern strip of the Eastern ore-body at the Main adit level and in the Northern ore-body of the western zone, gold-copper ores are now mined by the Hôkô Mining Company. The forms of these ore-bodies are irregular but generally roughly tabular and parallel to the contact and fault zones.

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1) 日本鑛業株式會社 2) 遂安鑛山 3) 寶光鑛業株式會社 4) 笏洞鑛業所

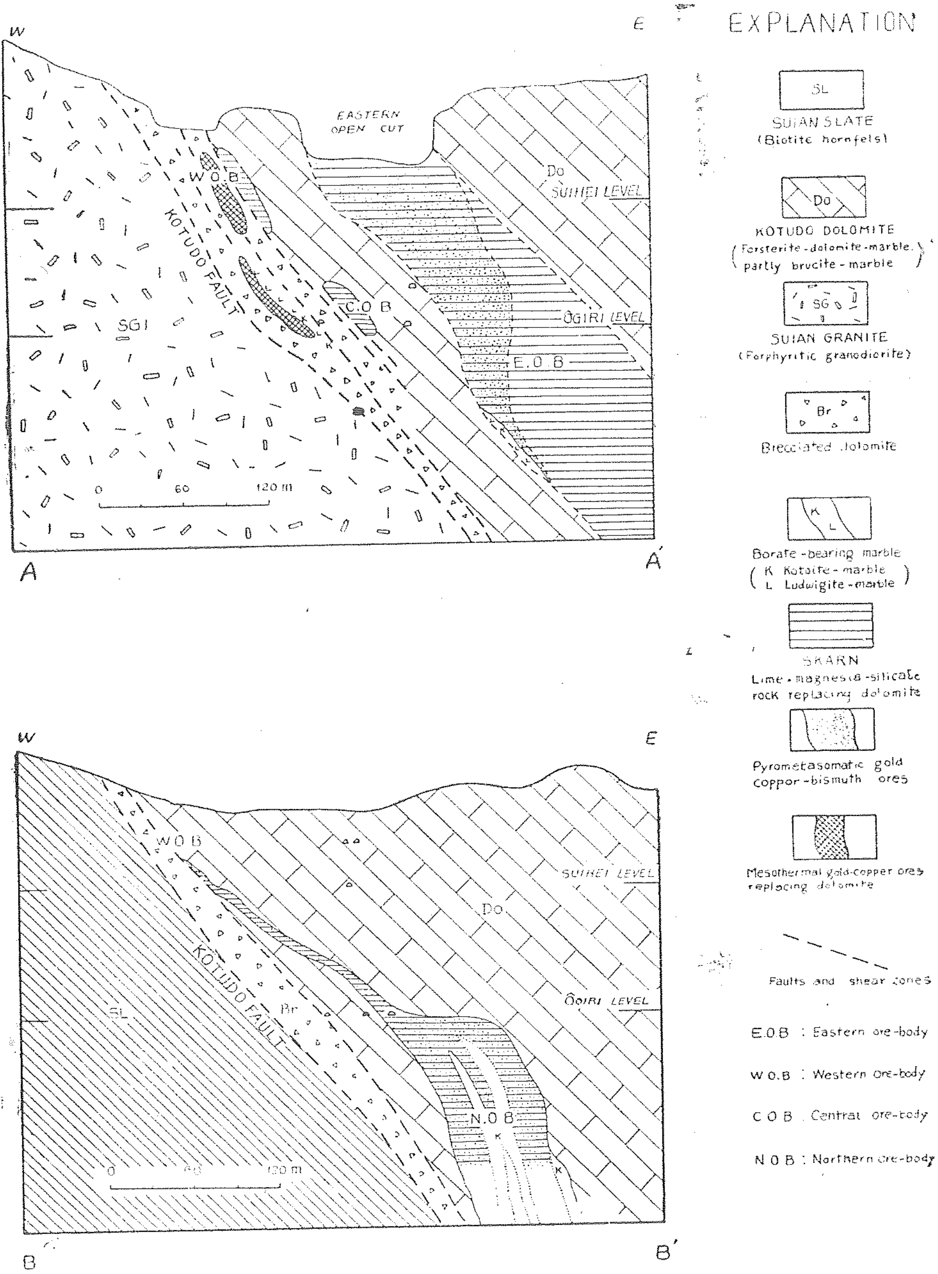

Fig. 11. Cross section of the Kotudô mine. The position of the sections is shown on Pl. XLVII (II), line A—A′ and line B—B′.

(1) *The Eastern ore-bodies.*[1]

A garnet zone 3–6 m. in width and a lime-magnesian silicate zone, which was called "Schist" by the miners, are developed in the area between the Eastern ore-bodies and the intrusive rocks. The zone next to the "Schist" is the skarn zone, called "Ore-formation", consisting mainly of diopside, tremolite, phlogopite and ore-minerals. The wall rocks of the "Ore-formation" are forsterite-dolomite-marble and occasionally kotoite-marble or ludwigite-bearing marble.

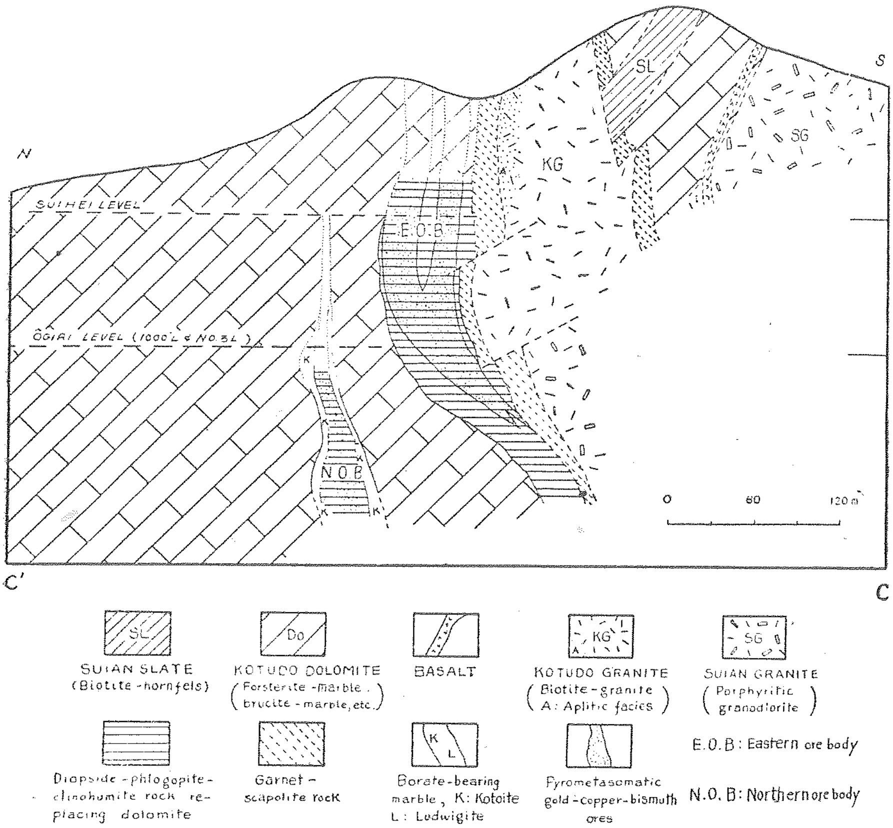

Fig. 12. Cross section of the Kotudô mine. The position of the N-S sectien is shown on Pl. XLVII (II), line C—C'.

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1) 東鑛體

(2) *The Western ore-bodies.*[1]

Separated by several fault-zones from the Eastern ore-bodies, the mineralized area ("Formation") of Western ore-bodies is developed along the fault planes which run meridionally from Kotudô to Sekitaturi and dip toward the east about 60°. The ores in the Western ore-bodies may be classed into two groups; (1) pyrometasomatic ores (garnet ores) and (2) mesothermal ores. The latter type is usually found in brecciated dolomite and consists mainly of chalcopyrite, tetrahedrite, sphalerite, galena, while the former is characterized by the presence of chalcopyrite, bismuthinite, tetradymite and gold.

(3) *The Northern ore-body*[2] (*New Ore-body*).

The Northern ore-body which was discovered by Koreans in 1924 shows very striking features and is pipe-like in form (Text-fig. 8). The mineralogical features of this deposit are very complex. The wall rock of this ore-body is white forsterite-dolomite-marble. The pipe-like body consists of kotoite-marble which encloses skarn masses consisting of diposide, clinohumite, etc. Black streaks of disseminated ludwigite bands in the kotoite-marble show the original plane of stratification. The plane dips 55°–60° towards the east with the strike running E–W. The ore is very complex in mineralogical composition and consists of pyrite, pyrrhotite, cubanite, chalcopyrite, bornite, bismuth-copper-sulphosalts, gold and silver.

The average composition of ores from 1500 samples taken from E.O.B. and W.O.B. by miners by analysis was determined as shown in Table 12 (Weigall and Mitchell-Roberts (31)).

TABLE 12

Siliceous insoluble residue	73.70%	CaO	4.00%
Bi	0.075	MgO	10.15
Fe	2.70	S	1.60
Cu	0.92	P_2O_5	0.02
As	trace	CO_2	0.02
Al_2O_3	1.98	Loss undet.	2.92
Au	1 dwt. per ton.	Ag	0.6 oz. per ton

Several analyses of the typical ores from the Kotudô mine are also given below.

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[1] 西鑛體 [2] 北鑛體 (新鑛體, 又は白金坑鑛體)

TABLE 13

Analyses of ores from the Kotudô mine.

No.	A	B	C	D	E
Spec. No.	152	200	202	256	
SiO_2	36.68%	23.66%	18.75%	37.98%	46.95%
Al_2O_3	7.85	2.48	1.93	2.83	2.57
CaO	28.32	18.28	8.86	19.11	19.43
MgO	3.27	12.89	13.18	23.73	23.33
Fe	12.59	9.55	16.50	1.38	1.72
Cu	0.67	10.05	13.73	1.05	1.92
Pb	0.00	0.00	0.00	0.00	0.00
Zn	tr.	tr.	tr.	0.19	0.25
Bi	0.22	0.72	3.67	0.10	0.21
S	0.62	10.13	16.87	0.55	1.29
Total	90.22	87.76	93.49	86.92	97.67
Spec. No.		200	202	257	
Au	—	0.00356	0.0747	0.00358	0.00210
Ag	—	0.00533	0.01726	0.01042	0.00461

A. Gold ore (garnet skarn), No. IL. Western ore-body.
B. Gold-copper-bismuth ore (diopside skarn), No. IL., Eastern ore-body.
C. Gold-copper-bismuth ore (diopside skarn) No. IL., Eastern ore-body.
D. Gold-copper ore (diopside skarn) No. 3L., Northern ore-body.
E. Gold ore (diopside skarn).
A–E. Analyses made in the Fuel and Ore Dressing Laboratory, Gov. of Tyôsen through courtesy of late Mr. B. Kagaya.

(b) The Suian mine (the Nantei mine or the Tul Mi Chung mine)[1]

The Suian mine, which has also been known as the Nantei-mine, is situated in the south-western part of the contact zone of the Suian granite and is now owned by the Nippon Mining Company.

Topography and local geology.—The mining area is situated in the northern part of the Nantei village at the foot of the south-western

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[1] 遂安鑛山 (楠亭鑛山)

slope of the Gensinsan mass. The north-eastern part of the mapped Nantei area (Pl. XLVIII (III)) is generally elevated and contains biotite-hornfels and eruptive masses. The main contact of the Suian granite with the hornfels runs parallel to the general trend of rocks. Underlying the hornfels, brucite-marble and dolomite-marble are exposed, with its general strike running NW-SE and its dip with low-angle towards the NE, and are locally replaced by skarn and ore-minerals. The general trend of the geologic structure is disturbed by minor intrusions such as quartz-porphyry, granite-porphyry, quartz-diorites and also by many faults in the central part of the mining area.

On the basis of the distribution of the ore-bodies, the places, where the mines are worked, are subdivided into three groups: (1) Minami-Kô (South mine[1]), (2) Kita-Kô (North mine[2]) and (3) Dôgan mine (Tong Am mine[3]). The characteristic features of ore-bodies in this mine differ greatly from those of the Kotudô ore-bodies. The non-porphyritic and somewhat basic intrusives which were called the "Weigall granite" by the miners and called "quartz-diorite" in this report and the Nantei quartz-porphyry and granite-porphyry, played an important role in the deposition of the ores. A large number of ore-bodies are found near these intrusive masses. Sometimes ore-bodies occupy the boundary zone between hornfels and marble. The location and forms of ore-bodies were controlled by the geologic structure and many important ore-bodies are found along the faults or shear zones.

i) *Minami-Kô* (*South mine*).

The ores have been found in three separate bodies: "A" ore-body, "B" ore-body, and "14Q" ore-body. "A" ore-body is found in the sheared zone of quartz-diorite and consists of pyrite and chalcopyrite ores and skarn minerals. The form is very irregular and is often penetrated by later calcite-veins. "B" O.B. is the largest ore-body in this mine, its maximum width being about 30 m. The ore minerals are usually associated with the salite-andradite skarn and are also found in streaks or patches in the slightly altered marble which consists of bluish or dark greyish calcite and serpentine. The ore-body in 16 J of No. 1 X.C.T. is entirely surrounded by the limestone, its trend being nearly parallel to the

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[1] 南坑 [2] 北坑 [3] 銅岩坑

local N-S fault zone. The ores are composed of pyrite, pyrrhotite, arsenopyrite, löllingite, bismuthinite, tetradymite, sphalerite, galena, and gold. Garnet(andradite) and salite are the most abundant gangue minerals found in these ores. These skarn masses often became epidote-zoisite rocks which have been replaced by chalcopyrite, pyrite, pyrrhotite, etc. Some hydrothermal veins consisting of galena, calcite and quartz, are also found in fissure zones near the contact. The vein-type deposits are clearly younger than the skarn type because the latter is penetrated by the former.

ii) *Kita-Kô (North mine)*.

Here the quartz-diorite is divided into small masses in which irregularly shaped ore-bodies are found. The contact minerals together with sulphide ores are also deposited in the brucite-marble underlying the flatly dipping eruptives. As a result of repeated faulting after the formation of the ore-bodies their original form has become largely obscure. Pyroxene (diopside) is the most important gangue and occurs with serpentine, zoisite, chorite, quartz and calcite. The outer wall of the skarn ore-bodies is composed of serpentine-calcite marble (ophicalcite). The metallic minerals resemble those of the Minami-Kô.

iii) *Dôgan-Kô (Tong Am mine)*.

This mine is situated at a distance of about 800 meters from the Kita-Kô. The ore-bodies lie in the boundary zone between the impervious hornfels and chemically reactive marble. The boundary plane is nearly horizontal, dipping flatly towards the north. The mineralogical composition of the ores differs somewhat from that of the ores at the Minami-Kô and Kita-Kô and paragenesis shows that deposits were formed at a relatively low temperature. The typical ore of this type contains galena, sphalerite, chalcopyrite and occasionally molybdenite together with gold. Recently skarn ores have been found near the contact of the Nantei quartz-porphyry and also along felsite-dykes.

Analyses of ores from the Nantei mine are shown in Table 14.

(c) Goyô mine[1]

The Goyô mine, the property of the Tôyô Takusyoku Co., is located 5 kilometers south-east of Nantei. This property was dis-

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1) 梧陽鑛山

covered comparatively recently. The country rocks at the mine are mainly argillaceous phyllitic or slaty rocks which are now thermally metamorphosed, however, into biotite-hornfelses or schists. The spotted biotite-hornfels, and calcareous rocks are also developed. A series of four parallel veins, which trends N 20° E. and dips almost vertically was found in the fissures along the cleavage planes of the hornfels. Close to the ore-veins the rock is much altered by sericitization and impregnated with pyrite. The ore minerals are pyrite, pyrrhotite, chalcopyrite, sphalerite, arsenopyrite, galena, and gold, and are associated with gangue minerals such as quartz, siderite and sericite.

TABLE 14

Analyses of ores from the Nantei mine
(After Weigall and Michel-Robert (31)).

	A	B
Insol.	57.17%	%
SiO_2	0.07 (sol.)	67.07
Fe	4.90	7.45
Al_2O_3	2.15	0.69
Cu	1.78	1.18
CaO	12.27	10.76
MgO	4.40	1.43
S	2.15	1.76
Bi	—	0.11
Pb	—	0.05
As	0.12	0.37
Zn	—	0.36
CO_2	10.16	—
undet.	4.83	—
	100.00	91.23
Insol.		
SiO_2	37.84	
Al_2O_3	2.23	
Fe_2O_3	5.59	
CaO	7.26	
MgO	2.89	
Alkali	1.06	
	57.17	

Chapter VIII

SUMMARY

The Suian mining district lies in the central part of Tyôsen. The dominant geologic feature of the district is the igneous complex which represents the stock-like intrusion of granitic magmas in the late-Mesozoic era. As a result of the igneous invasions a series of ore deposits was formed during the later stage of the igneous activities near the granitic rocks.

The greater part of the sedimentary and metamorphic rocks of the Suian district were formed before the major granitic intrusions. They range in age from Archean to Proterozoic. The Proterozoic rocks (Syôgen system) are composed mainly of dolomite, limestone, slate, phyllite and quartzite and cover the Archean gneisses (Kokulian granites or Grey-gneisses) unconformably. In particular, the sedimentary rocks were folded and thrusted by an orgenenic movement during the period of the Taihô phase (post lower-Daidô series—pre upper-Cretaceous).

After this movement probably during the period of the Bukkokuzi igneous activity granitic magmas invaded the sedimentary area under roof-rocks which formed a layer of moderate thickness. The granitic bodies cut across the trend of the folds of the sediment at the southern and western contact, while the roof rocks dip away from the intrusive rocks in the other parts.

The granitic mass is a composite stock and consists mainly of two different types of granitic rocks. The main granitic rock, the Suian granite, which is found in the peripheral portion of the stock, represents the porphyritic granodiorite. The rock is composed of plagioclase, orthoclase, quartz, hornblende, and biotite and is characterized by the presence of large ovoids of microperthitic orthoclase which are occasionally mantled with plagioclase. Its texture resembles that of pyterlite or Rapakivi granite in Finland. This peripheral rock is pierced by the later granite-porphyry, the Hitiseidai granite, which is more acid than the former. Furthermore, a large number of minor intrusives, aplite, quartz-porphyry, etc. are developed in the area, but no typical pegmatite has been found. As a result of magmatic heat and of material supply from the magmas, various interesting metamorphic and metasomatic rocks have been formed in the contact aureole.

The ore deposits of this district are usually situated in the area adjacent to the Suian intrusives, especially in the area where the carbonate rocks come in contact with the igneous rocks. The principal ore deposits contain gold, copper and bismuth. They may be genetically divided into three groups: (1) pyrometasomatic deposits (high-temperature type), (2) mesothermal replacement deposits (moderate-temperature type), and (3) mesothermal veins (moderate-temperature type).

(1) The pyrometasomatic deposits constitute the most predominant ore deposits in the district. They are commonly found near the contact of the Suian granite. The ore-bodies are very irregular in form, consisting of lime-magnesian-silicate gangue minerals (skarn minerals), copper-bismuth sulphides and gold. The greater part of the gold and copper production of the Suian mining district has come from ore-bodies of this type. In some pyrometasomatic deposits, borate minerals, such as kotoite, ludwigite, etc., are abundantly found as gangue minerals. The mineral paragenesis of the pyrometasomatic deposits indicate that they were undoubtedly formed at high temperature.

(2) Mesothermal replacement deposits are the next important type in this district. They are commonly found in the dolomite near the pyrometasomatic deposits and are usually situated a little farther away from the contact. Tetrahedrite-sphalerite-galena association is characteristic in these deposits.

(3) The veins in this district are mainly gold-silver quartz veins, and show many of the characteristic features of the mesothermal deposits. They are usually found in slaty or phyllitic rocks.

It has been pointed out that most of the pyrometasomatic deposits of the Suian district are located nearer the Suian granite than the mesothermal deposits. However, the zonal arrangement of different kinds of ore-bodies with reference to a central igneous mass is not typically represented in this district, probably because the mineralizations were successive in the same places. It is also probable that the influence of the geologic structure and the character of the host rocks were likewise important contributing factors to the present spatial distribution of ore-bodies.

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Plate XLVI (I)

Plate XLVI (I)

Geological map of the Suian district, Kôkai-Dô, Tyôsen.

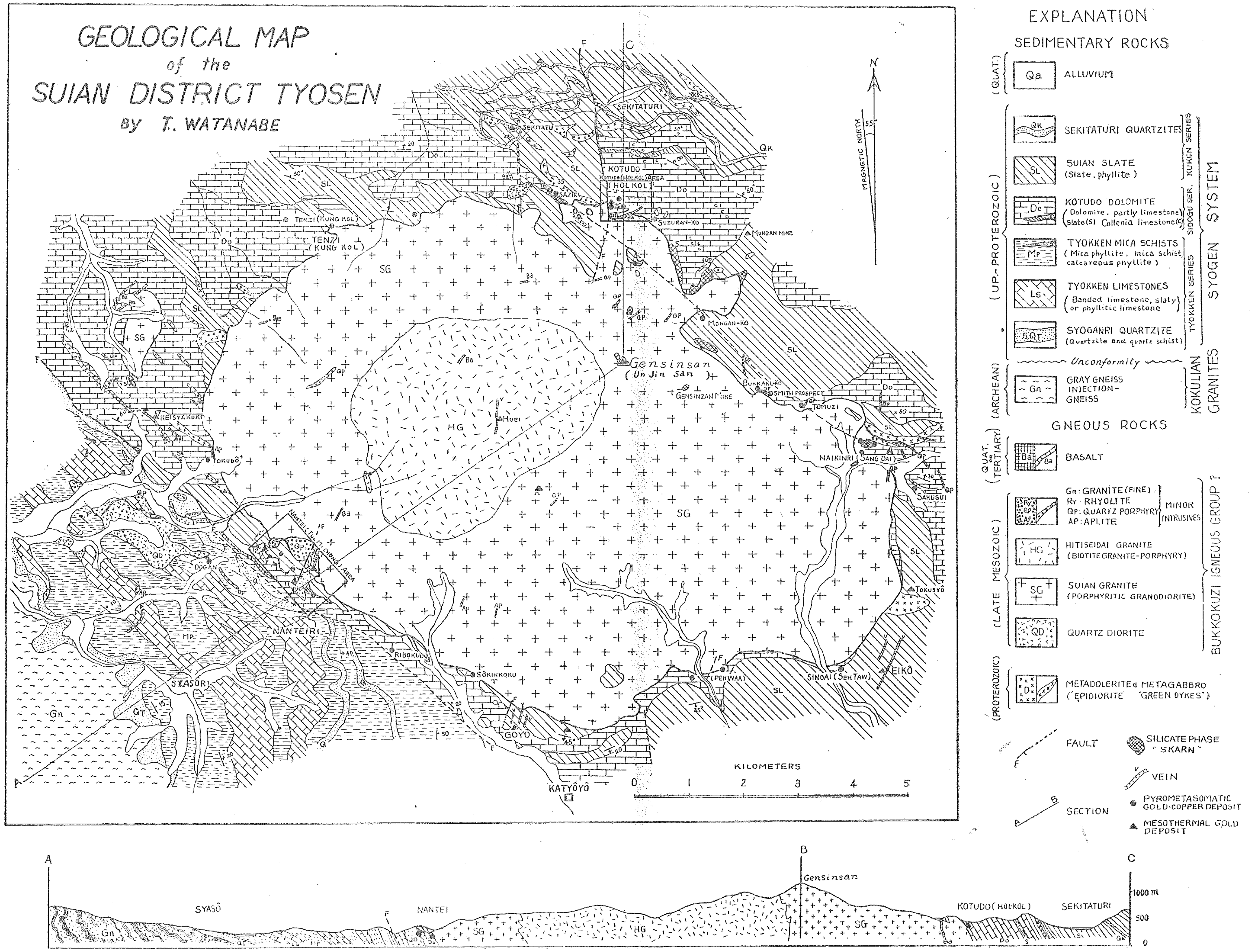

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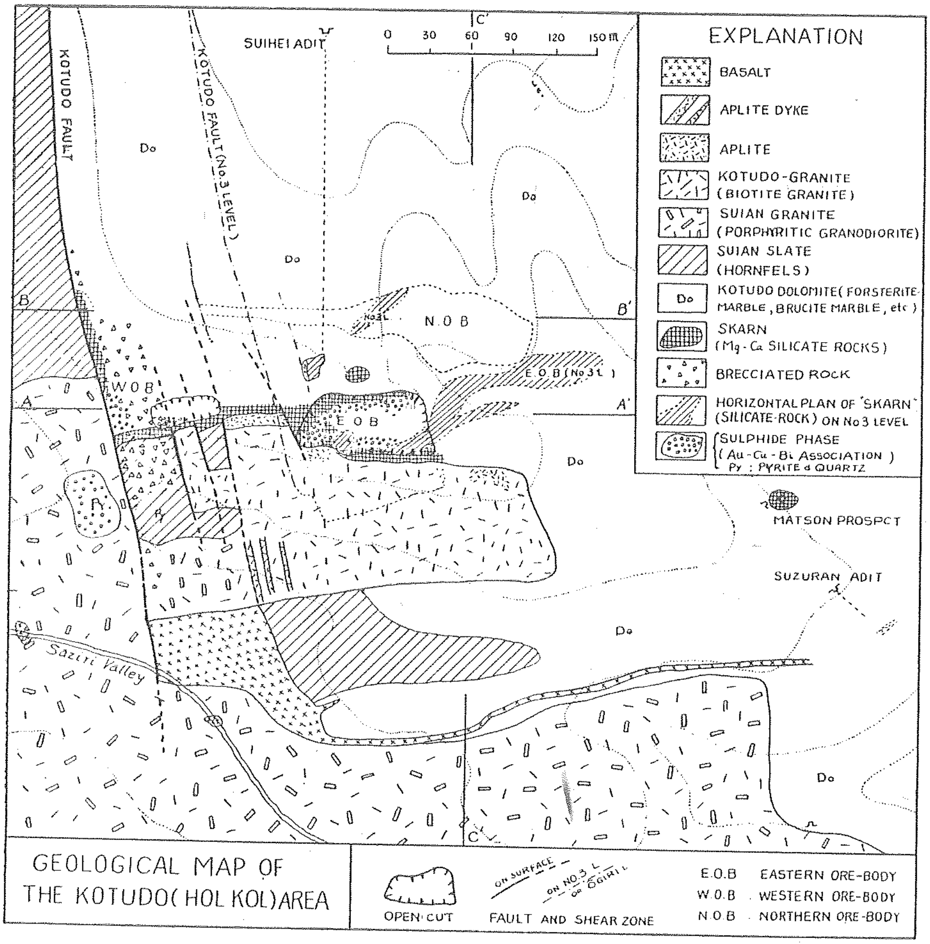
Plate XLVII (II)

Plate XLVII (II)

The geological sketch map of the Kotudô mine. Cross sections along lines, A–A′ and B–B′ are shown Text-fig. 11 and cross section along line C–C′ is shown Text-fig. 12.



GEOLOGICAL MAP OF THE KOTUDO(HOL KOL)AREA

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Plate XLVIII (III)

Plate XLVIII (III)

The geological map of the Nantei mine. Cross sections of the isometric block diagrams (Plate XLIX (IV)) are indicated by lines:
A–A′, B–B′, C–C′, D–D′, E–F, F–F′.

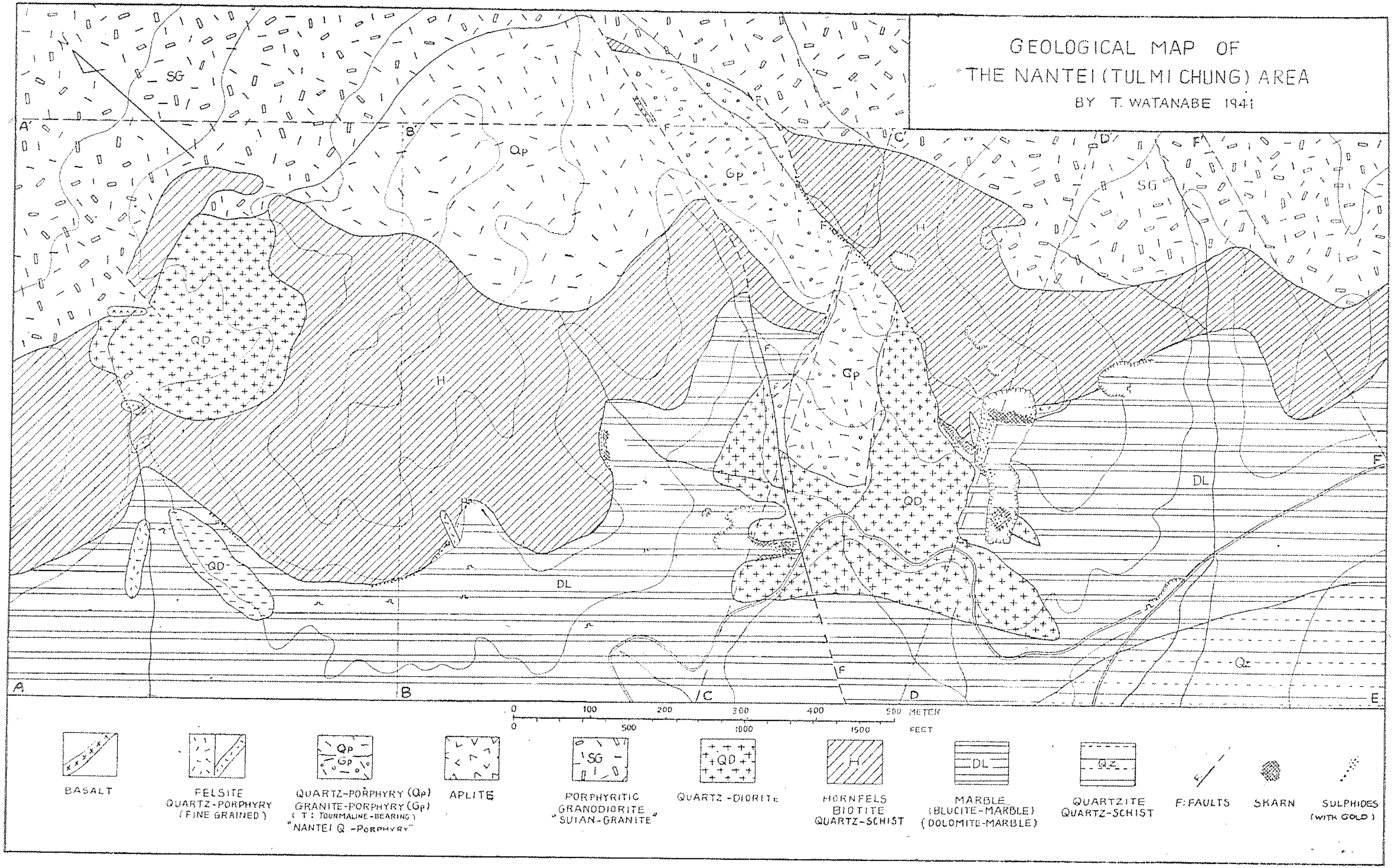

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Plate XLIX (IV)

Plate XLIX (IV)

Isometric block diagram of the Nantei mine. Suian, Tyôsen (Korea).
The surface geology is shown on Plate XLVIII (III).

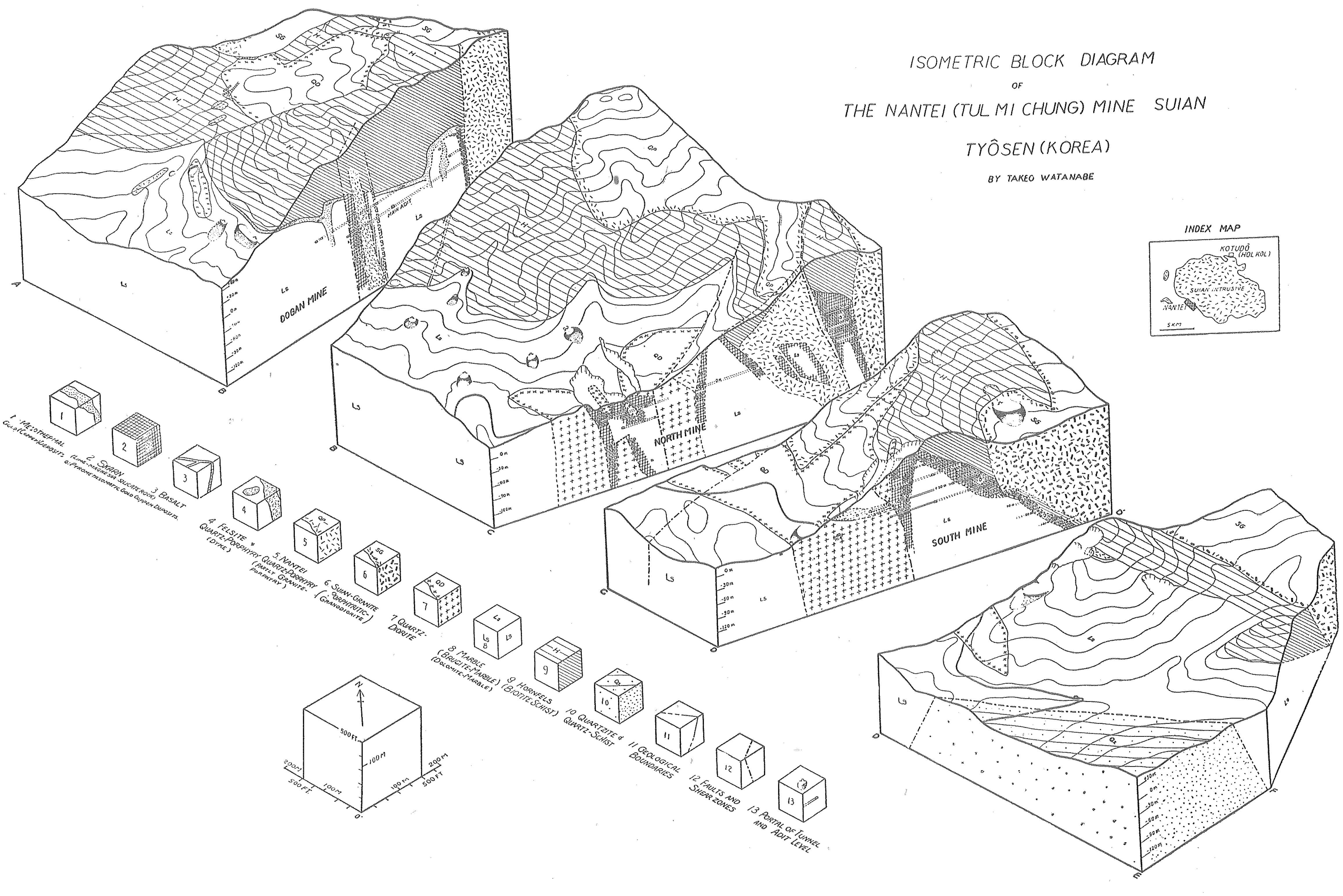

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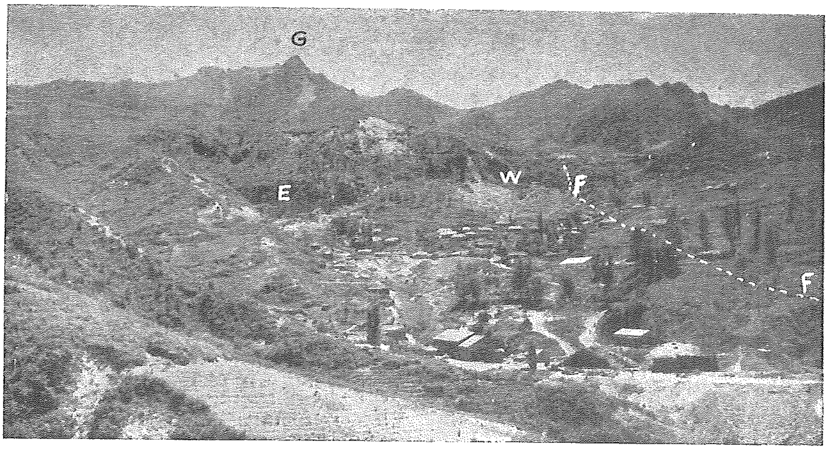
Plate L (V)

Plate L (V)

Fig. 1. View looking south up the Kotudô valley towards the summit (G) of the Gensin-San. E: Eastern open-cut, W: Western open-cut, F: Kotudô fault.

Fig. 2. Outcrop of the contact-metamorphosed Kotudô dolomite showing the characteristic banded structure. Loc. East of Tenzi.

Fig. 3. Minor foldings of the siliceous Suian slate near Sekitaturi.



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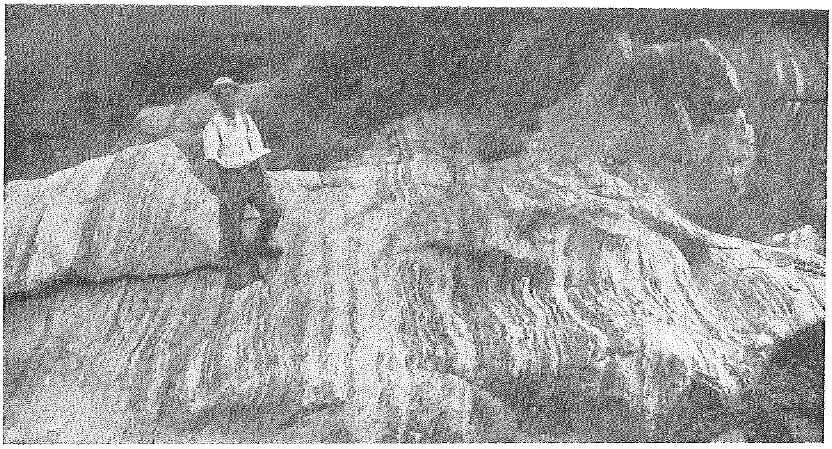

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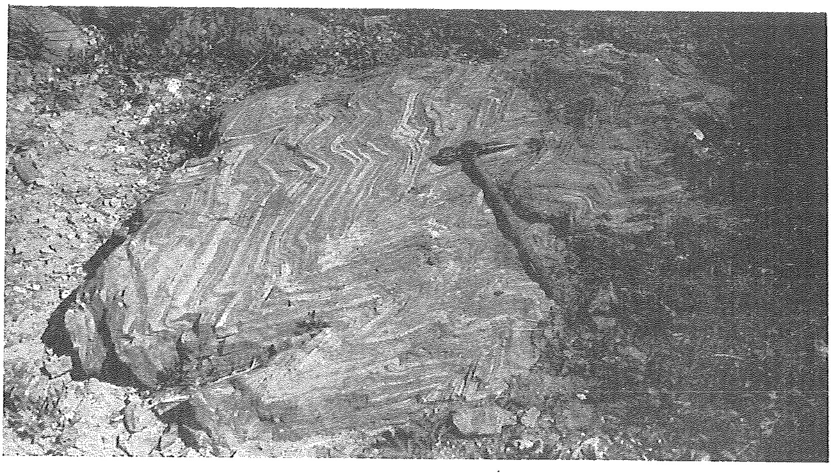

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Plate LI (VI)

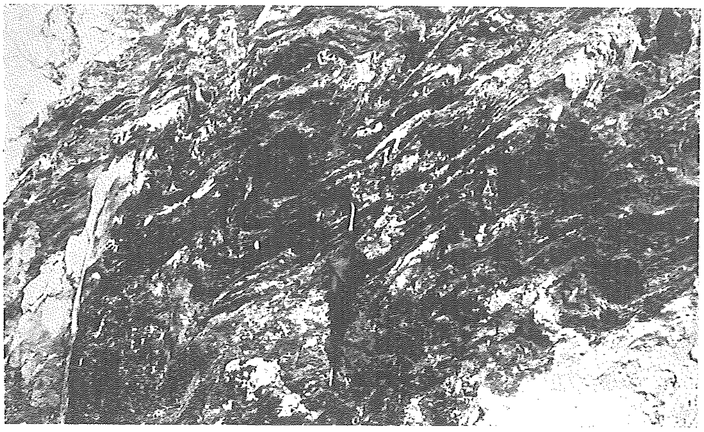
Plate LI (VI)

Fig. 1. Cliff-face of the Tyokken limestone, showing the characteristics minor folding developed by selective weathering. The layers of siliceous parts stand in relief above the calcareous bands. Near Nantei mill.

Fig. 2. The Tyokken mica-schist, showing the characteristic intercalation of quartzose layers. Near Syasô-ri.

Fig. 3. *Collenia* limestone of Sidôgu series on the eastern ridge of the Kotudô valley.

Fig. 4. Biotite-hornfels (black) cut by the Nantei quartz-porphyry. On the surface of the Nantei mine.



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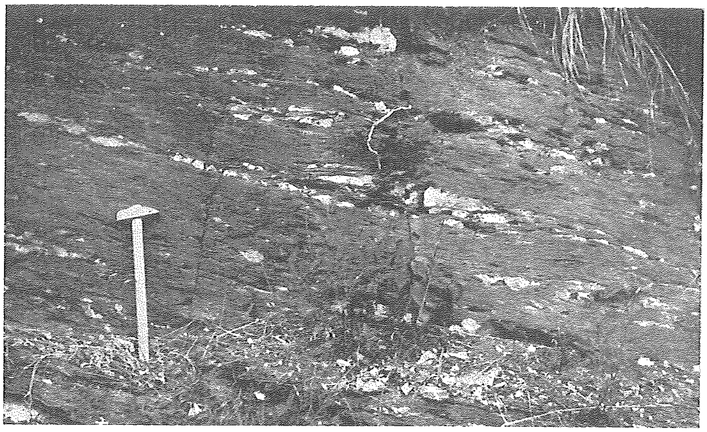

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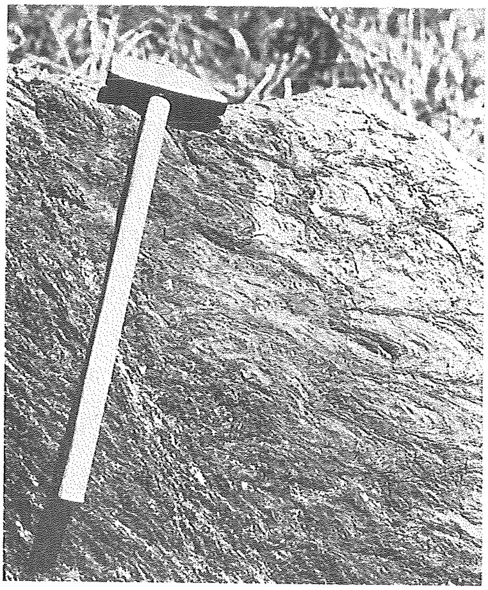

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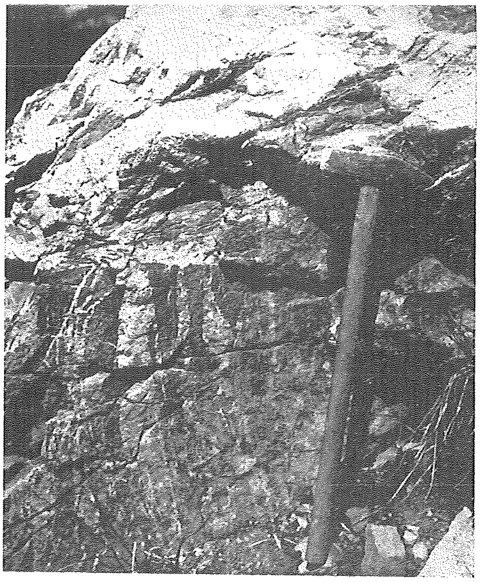

4

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Plate LII (VII)

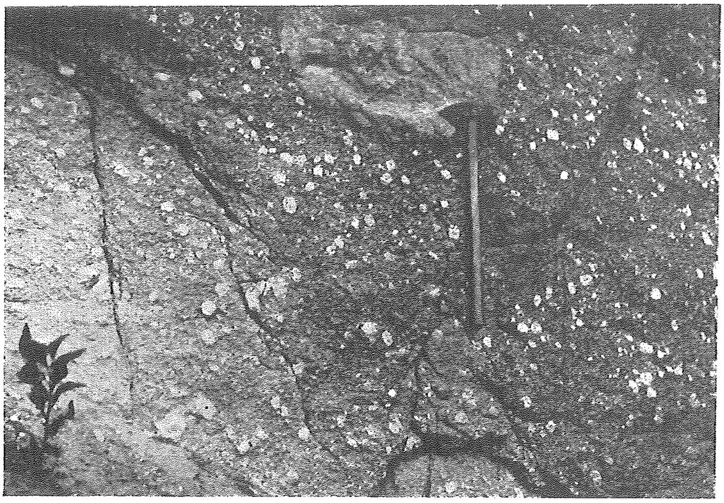
Plate LII (VII)

Fig. 1. Weathered surface of the Suian granite having large unmantled ovoids of microperthitic orthoclase, which project in relief above the matrix. Note the occurrence of rounded basic inclusions. Near the Nantei mine.

Fig. 2. Photomicrograph of thin section of the Suian granite No. S. 119). Euhedral or corroded quartz (q) is cemented by anhedral orthoclas (Or) One nicol. ×7.

Fig. 3. Ditto, showing subhedral plagioclase (pl) with fine zonal structure. Crossed nicols. ×7.

Fig. 4. Photomicrograph of polished section of the Suian granite, showing the occurrence of euhedral magnetite (mg) and anhedral ilmenite (il). Note the beginning of martitization in magnetite. Oil-immersion. ×230.



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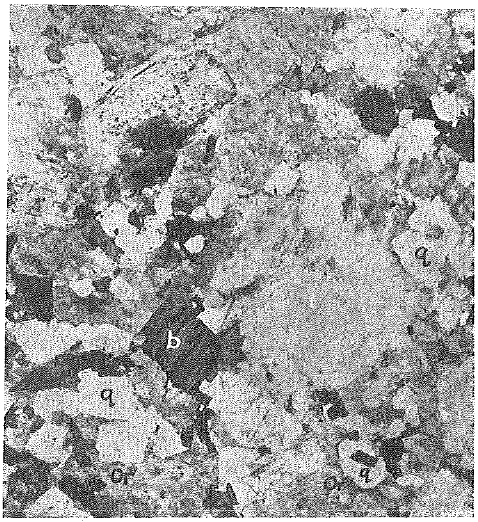

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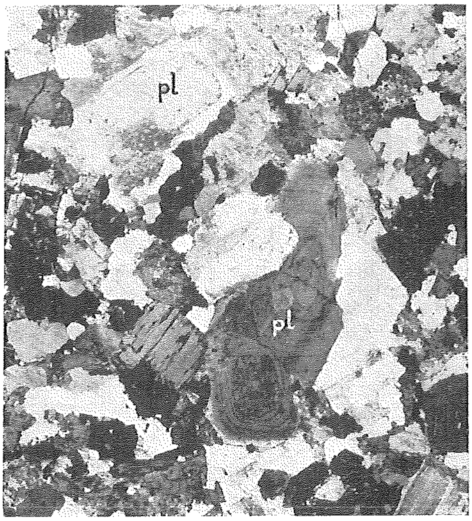

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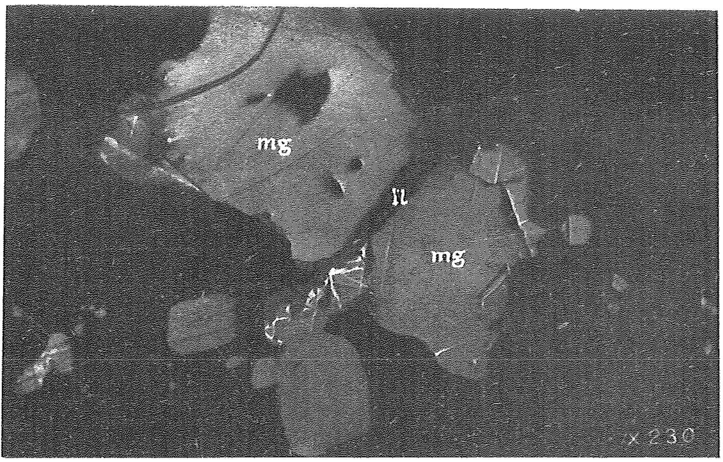

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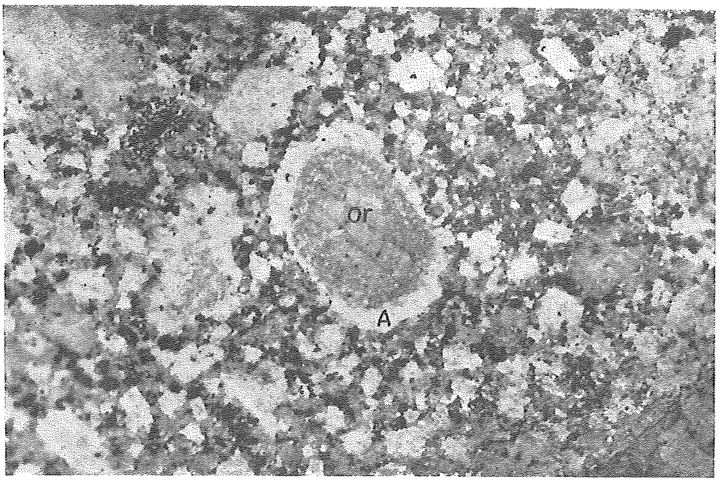
T. Watanabe: Geology and Mineralization of the Suian District.

Plate LIII (VIII)

Plate LIII (VIII)

Fig. 1. Polished specimen of the Suian granite showing the typical "Rapakivi" texture. Mantled ovoid of microperthite (Or) includes poikilitic crystals of quartz, plagioclase and mafic minerals. Rapakivi mantle (A) consists essentially of plagioclase (oligoclase). Natural size. Loc. Gensinsan.

Fig. 2. Photomicrograph of mantled ovoid of orthoclase (microperthite), showing the details of mantling zone. Microperthite (Or) is encroached by resorption and margined by a zone of slightly zoned oligoclase-prisms (Pl) in parallel to sub-parallel orientation. The crystals of oligoclase are usually euhedral against matrix. The mantled ovoid (Or) also contains idiomorphic or rounded quartz grains together with the characteristic grains of "aussenkonkaver" quartz (qc) grains as described by Popoff). Pl, plagioclase; q, quartz; Or, microperthite. Crossed nicols. ×8. Loc. Ditto.



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T. Watanabe: Geology and Mineralization of the Suian District.

Plate LIV (IX)

Plate LIV (IX)

Fig. 1. Surface of the Hitiseidai granite (HG) with schlieren-like inclusions of coarse grained granitic rock (SG) which belongs probably to the Suian granite. Loc. Northeast of the Nantei mine.

Fig. 2. Polished specimen showing the contact relation of the fine-grained granite (Hitiseidai granite) to the coarse-grained Suian granite. Natural size. Loc. Ditto.

Fig. 3. Photomicrograph of thin section showing the texture of contact part of the Hitiseidai granite (left) and the Suian granite (right) Crossed nicols. ×75.

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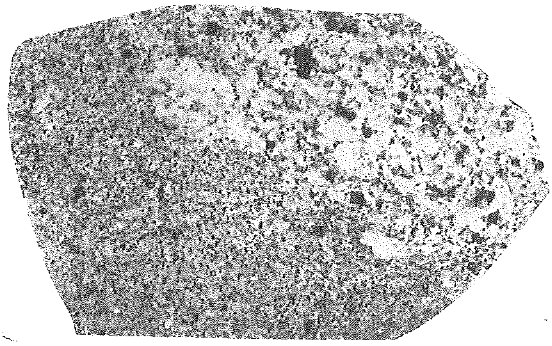

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Plate LV (X)

Plate LV (X)

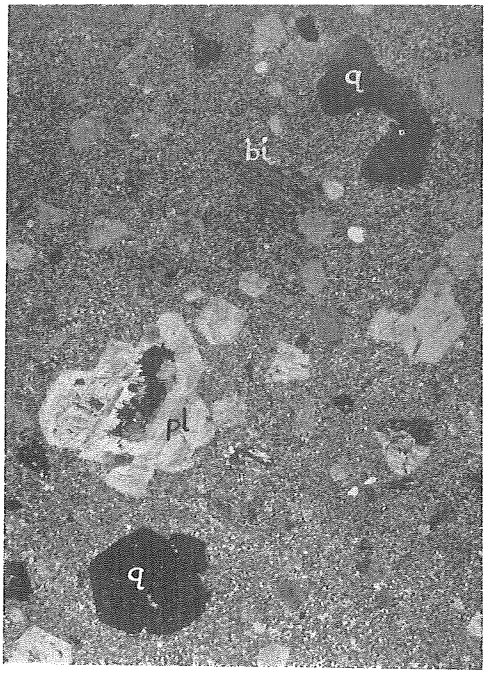
(Photomicrographs of thin sections)

Fig. 1. Quartz-porphyry near the Rakken village . q, quartz; pl, plagioclase; bi, biotite. Crossed nicols. ×9.

Fig. 2. Granite-porphyry, near the Rakken village. or, orthoclase; pl. plagioclase; q, quartz. Crossed nicols. ×10.5.

Fig. 3. Nantei quartz-porphyry with large phenocrysts of quartz (q) and plagioclase (pl). Crossed nicols. ×7.

Fig. 4. Quartz-porphyry of the Saziri-type. Note that biotite has became chlorite. q, quartz; ch, chlorite. One nicol. ×64.



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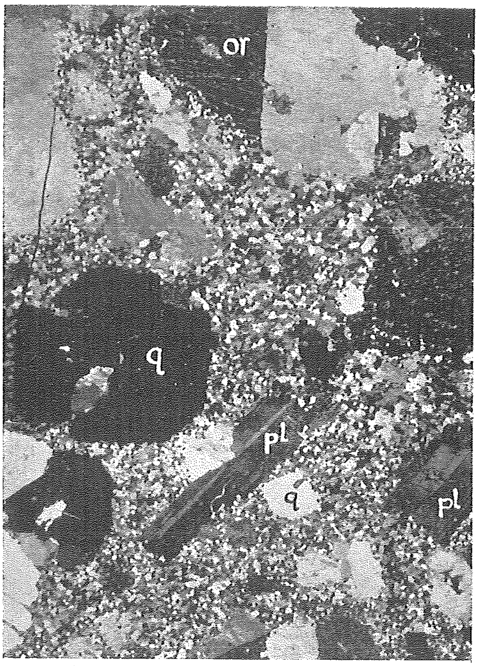

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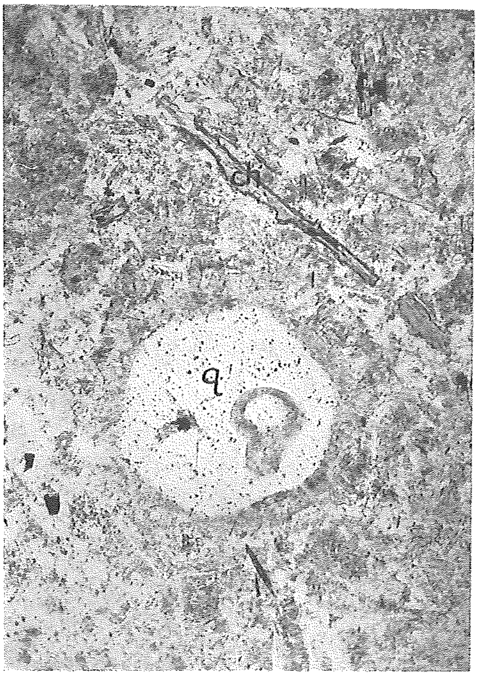

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T. Watanabe: Geology and Mineralization of the Suian District.

Plate LVI (XI)

Plate LVI (XI)

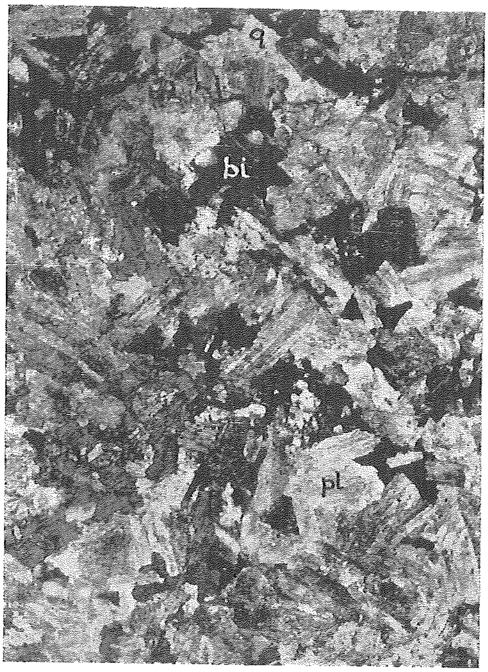
(Photomicrographs of thin sections)

Fig. 1. Nantei quartz-diorite, surface of the Minami-kô (the South mine), Nantei. q, quartz; pl. plagioclase; bi, biotite. Crossed nicols. ×8.

Fig. 2. Diopside bearing quartz-diorite, a dyke near the Dôgan village. di, diopside; white part, plagioclase and quartz. One nicol. ×64.

Fig. 3. Felsite, west of the Saziri valley. Note the occurrence of a corroded quartz (q) in a very fine-grained felsitic groundmass. Crossed nicols. ×70.

Fig. 4. Olivine-basalt, Saziri valley. In the figure euhedral phenocrysts of olivine (upper) and titanaugite (lower) are seen. The groundmass consists of lath-shaped plagioclase, titaniferous augite and magnetite. One nicol. ×64.



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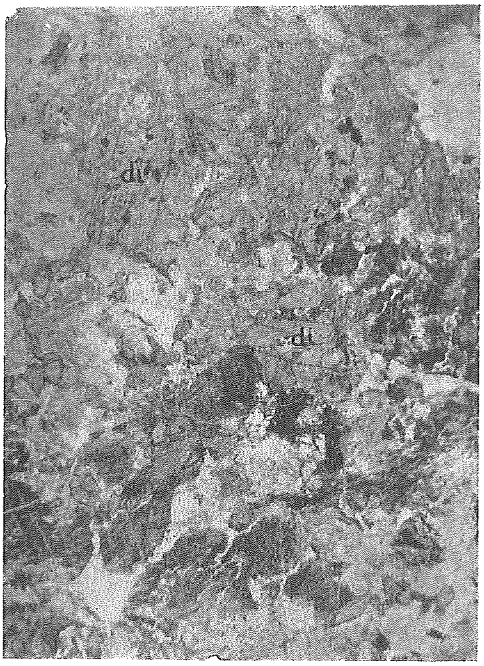

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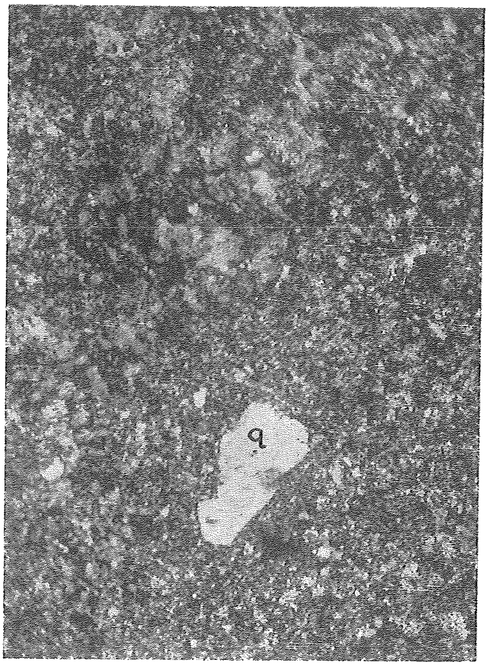

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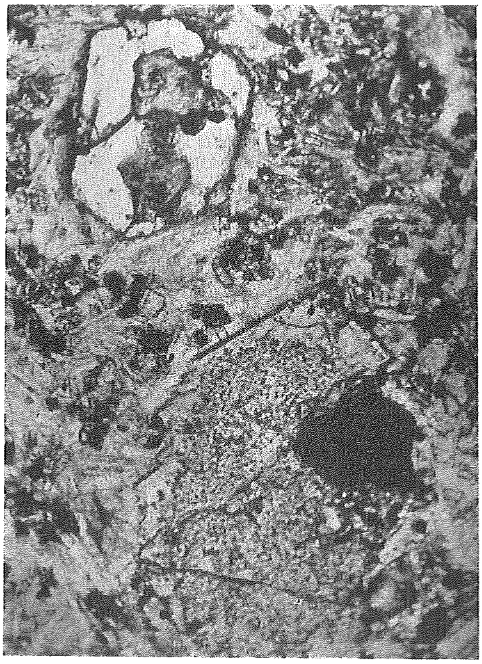

4

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Plate LVII (XII)

Plate LVII (XII)

Fig. 1. Photomicrograph of metadolerite. Note the development of uralitic amphibole throughout the rock. The matrix consists essentially of sodic plagioclase (albite). Crossed nicols. ×17.

Fig. 2. Photomicrograph of contact-metamorphosed metadolerite. Near the Keisyakoku prospect. The uralitic amphibole and albite disappeared and diopsidic pyroxene (di), biotite (bi) and basic plagioclase (labradorite, pl) took their place. Compare its texture with that of fig. 1. One nicol. ×33.

Fig. 3. Polished specimen showing the contact of the Suian granite with hornfels. On the surface of the Nantei mine. Lit-par-lit injection of the granitic material into the hornfels is shown. Natural size.

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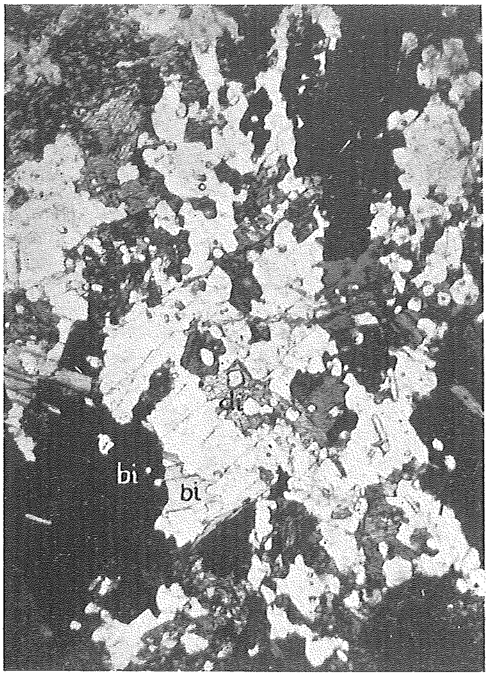

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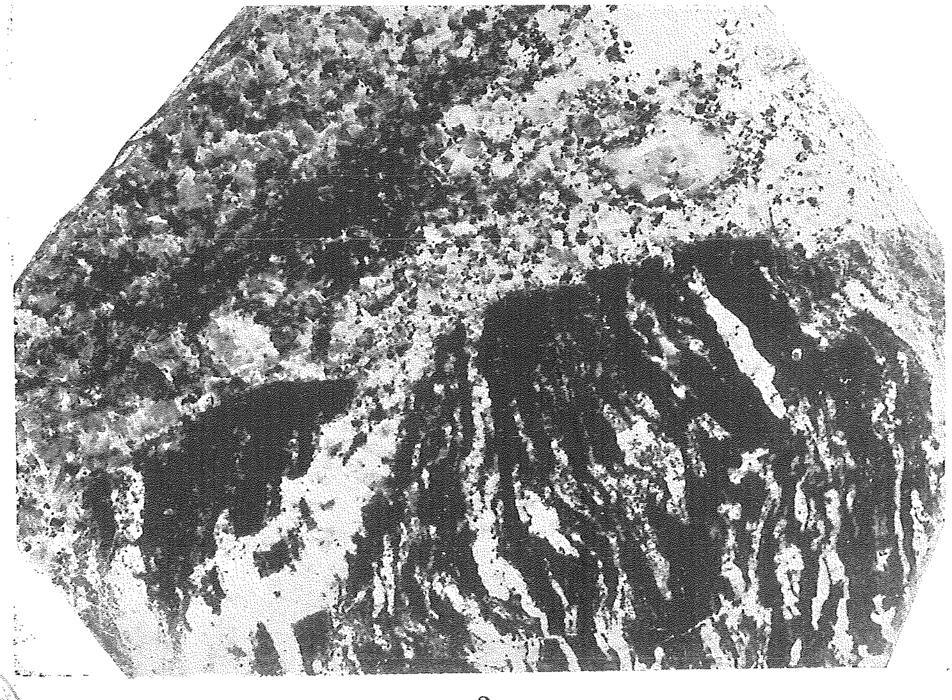

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T. Watanabe: Geology and Mineralization of the Suian District.

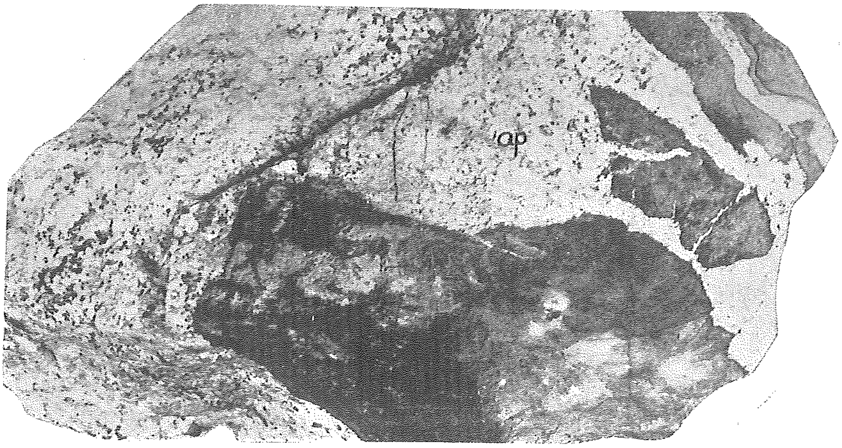
Plate LVIII (XIII)

Plate LVIII (XIII)

Fig. 1. Specimen from the Nantei mine, showing that angular salite-skarn masses (Sk) are intruded by aplitic granite. Natural size.

Fig. 2. Polished slab of the Suian granite with abundant angular xenoliths of diopside skarn (di). Light-colored diopside skarn surrounded by a narrow zone of dark iron-rich diopside. Loc.—30 m Level, South mine, Nantei. Natural size.

Fig. 3. Photomicrograph of thin section of the contact of the Suian granite (right) with the xenolithic skarn (left). Micrographic intergrowth of quartz and orthoclase is well shown. di, diopside; or, orthoclase; and q, quartz. Crossed nicols. ×8.



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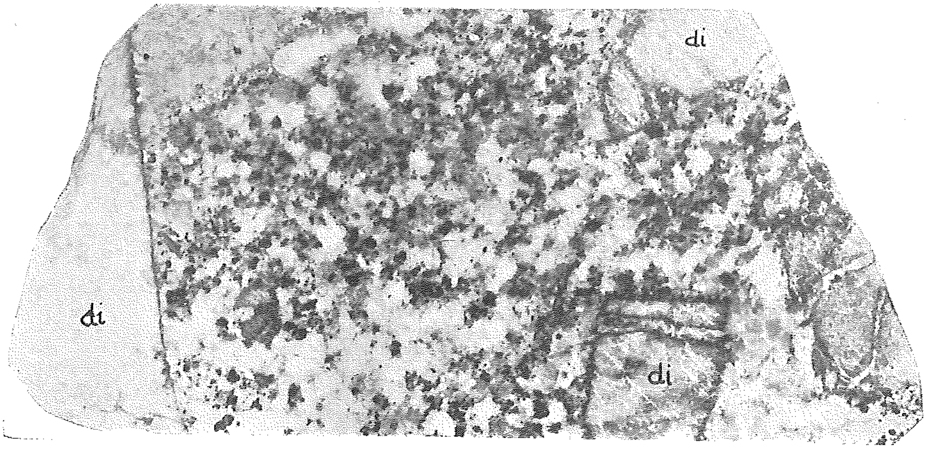

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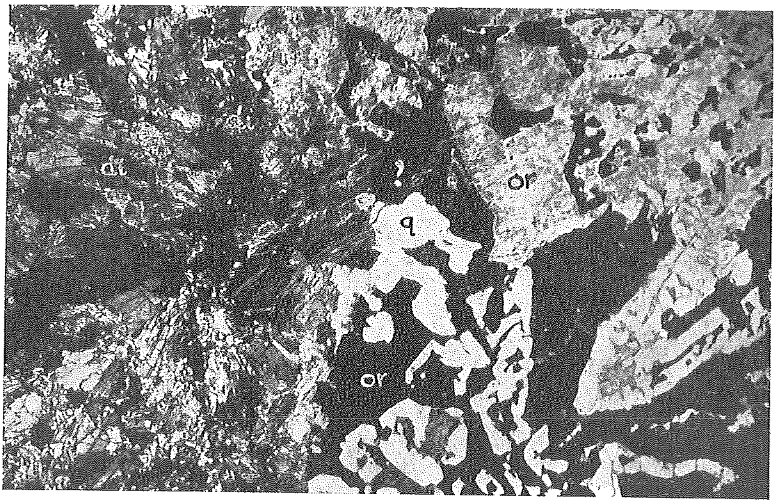

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T. Watanabe: Geology and Mineralization of the Suian District.

Plate LIX (XIV)

Plate LIX (XIV)

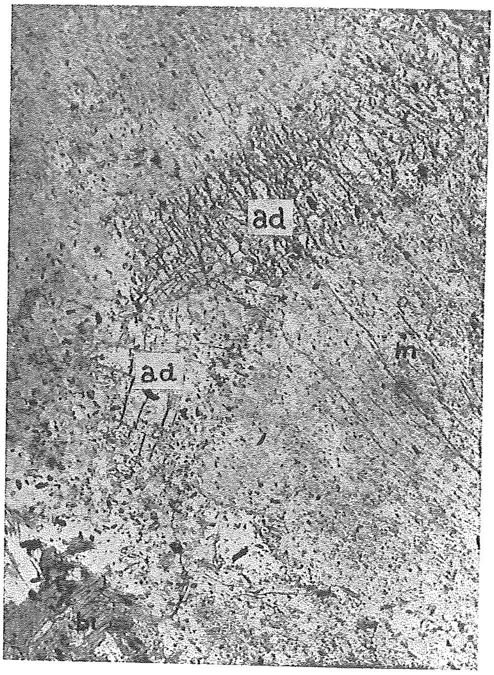
(Photomicrographs of thin sections)

Fig. 1. Andalusite-mica-schist from the Goyô mine. ad, andalusite cut nearly perpendicular to c-axis; m, muscovite; bi, biotite. One nicol. ×64.

Fig. 2. Andalusite-hornfels from the Nantei mine. ad, andalusite; q, quartz; mg, magnetite. One nicol. ×70.

Fig. 3. Corundum-spinel-biotite hornfels (xenolith) from the Nantei mine. c, corundum; sp. spinel; bi, biotite. White part, orthoclase. One nicol. ×70.

Fig. 4. Corundum-spinel-magnetite-andalusite-hornfels from the Nantei mine. c, corundum; sp. spinel (hercynite); m, magnetite; ad, andalusite; q, orthoclase. One nicol. ×64.



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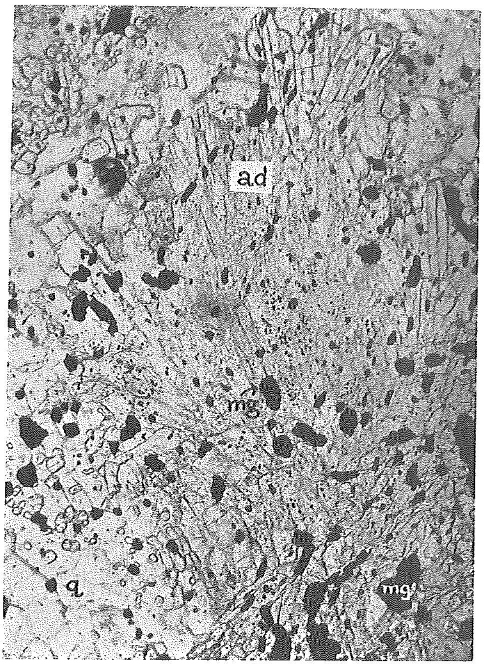

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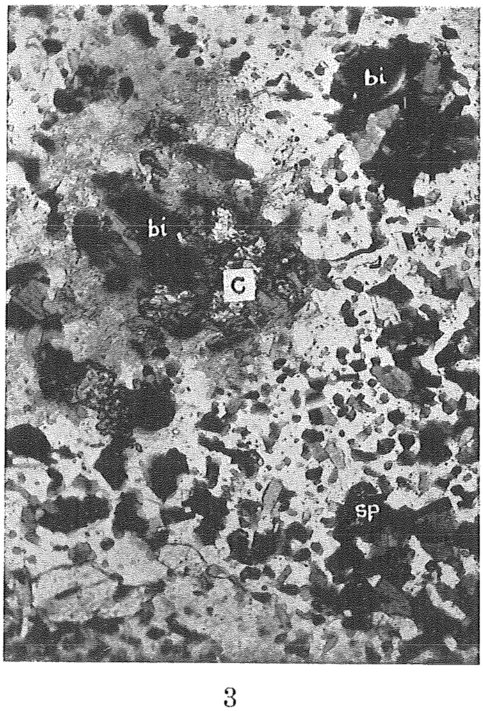

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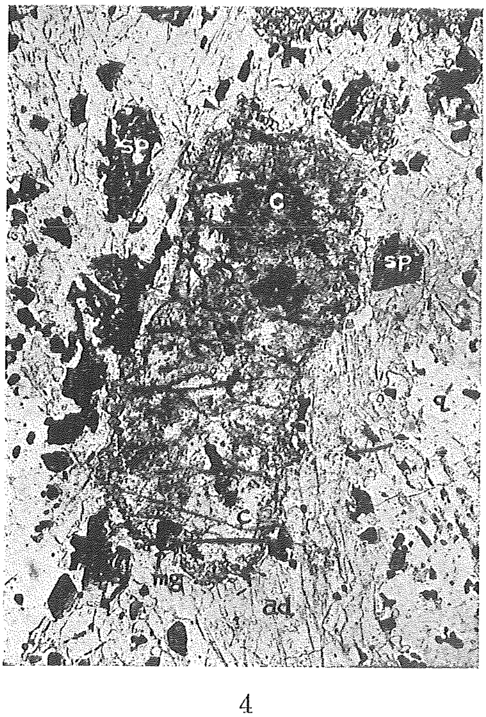

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T. Watanabe: Geology and Mineralization of the Suian District.

Plate LX (XV)

Plate LX (XV)

(Photomicrographs of thin sections)

Fig. 1. Spotted biotite-hornfels from the Goyô mine. Section cut nearly parallel to the bedding plane. One nicol. ×3.

Fig. 2. Diopside-plagioclase-hornfels (lime-silicate rock) from the northern contact zone, east of Tenzi. g, garnet; di, diopside; pl, plagioclase. One nicol. ×64.

Fig. 3. Tourmaline-quartz-vein cutting quartzose biotite-hornfels. Note the mode of distribution of tourmaline crystals in contact zone. t, tourmaline; q, quartz. One nicol. ×9.

Fig. 4. Diopside-forsterite layers (fo-di) intercalating with pure dolomite-layers (do). Loc. Eastern ridge of the Kotudô valley. Crossed nicols. ×7.

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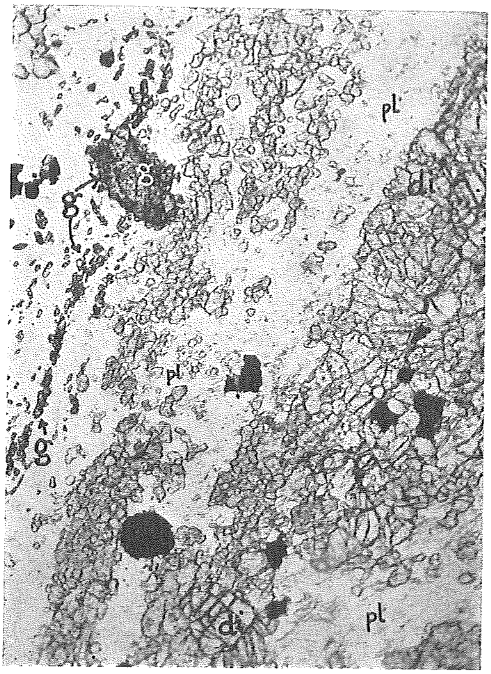

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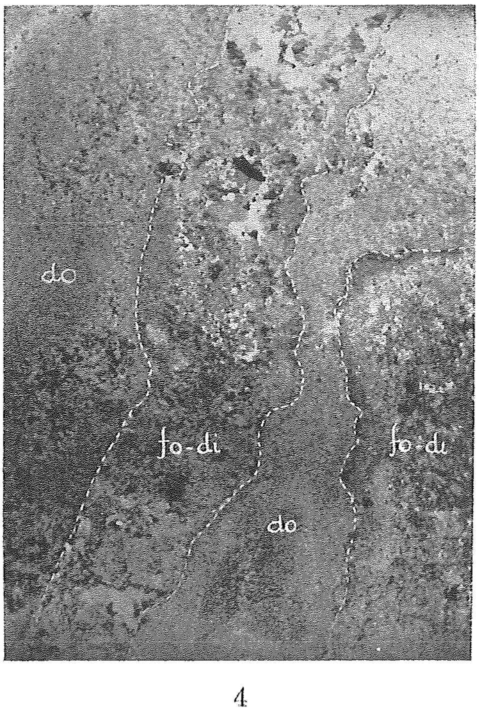

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T. Watanabe: Geology and Mineralization of the Suian District.

Plate LXI (XVI)

Plate LXI (XVI)

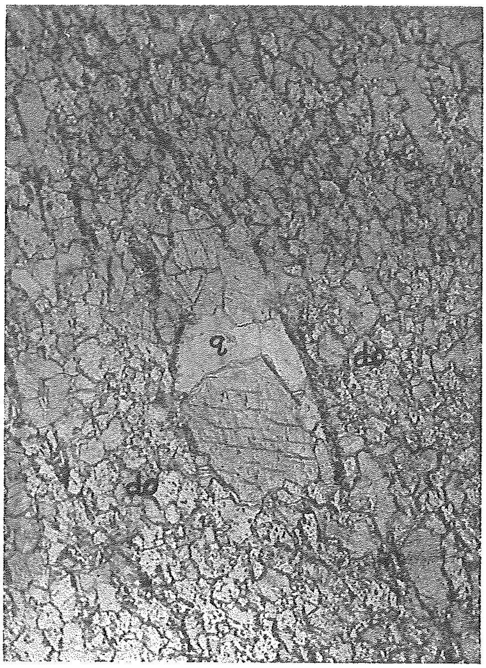
(Photomicrographs of thin sections)

Fig. 1. Siliceous dolomite from the first zone shown in Text-fig. 6, showing the dolomite-quartz assemblage. Note the direct contact of dolomite (d) with quartz (q). One nicol. ×74.

Fig. 2. Tremolite-bearing dolomite from the second zone shown in Text-fig. 6, showing the dolomite-tremolite-calcite assemblage. tr, tremolite; d, dolomite; c, calcite. One nicol. ×64.

Fig. 3. Forsterite-dolomite-marble from the third zone shown in Text-fig. 6, showing the relation of forsterite (fo) to the newly formed clacite (c). The former is usually surrounded by an aureole of the latter. do, dolomite. One nicol. ×72.

Fig. 4. Dolomite-marble from the fourth zone. The thin section was stained by the Lemberg's solution. The rock consists essentially of dolomite (d) with a very small amount of calcite grains (c) having became dark by staining. One nicol. ×33.



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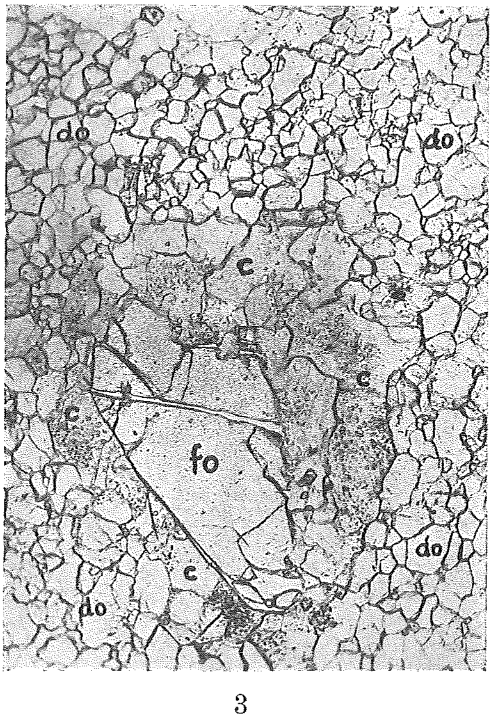

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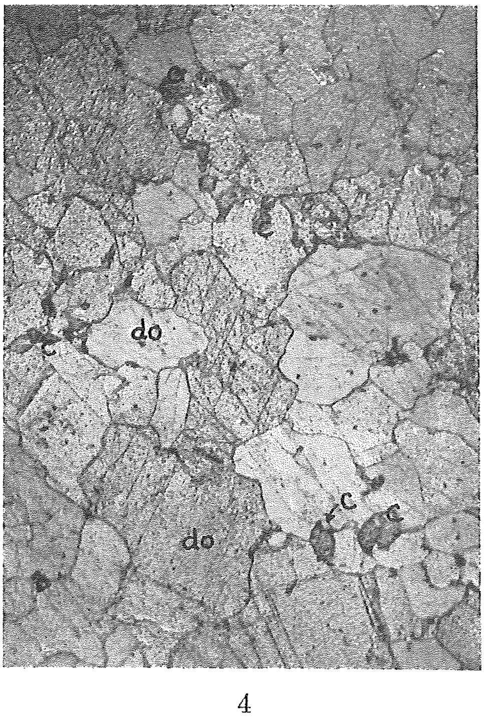

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Plate LXII (XVII)

Plate LXII (XVII)

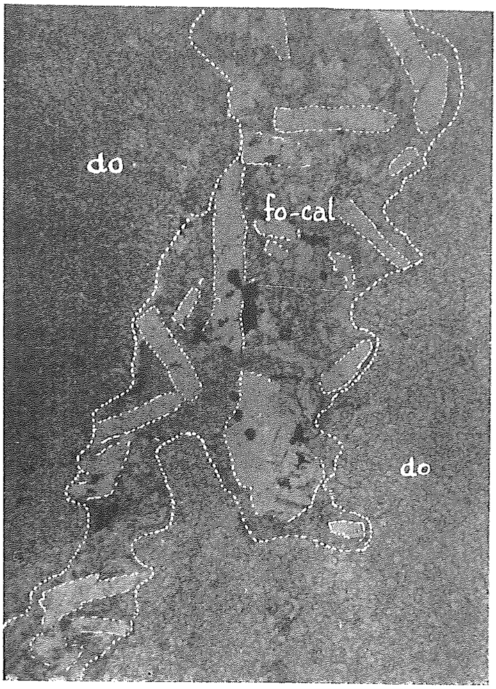
(Photomicrographs of thin sections)

Fig. 1. Forsterite-dolomite-marble of the third zone shown in Text-fig. 6, showing forsterite-calcite band (fo-cal) in dolomite-matrix (do). One nicol. ×11.

Fig. 2. Forsterite-dolomite-marble of the third zone of Text-fig. 6, showing crystals of tabular forsterite (fo) with thin rim of newly formed calcite (c), which are embedded in dolomite (do). Loc. East ridge of the Kotudô Valley. One nicol. ×33.

Fig. 3. Forsterite-marble of the fourth zone shown in Text-fig. 6, showing the intergrowth of forsterite (fo) with clinohumite (cl). Traces of cleavage plane (010) of forsterite are parallel to trace of twinning plane (001) of clinohumite. Crossed nicols. ×64.

Fig. 4. Brucite-marble from the Kotudô mine. Note the form of pseudomorphic brucite (br) indicating the original cubic outline of periclase. Forsterite, in the center, altered to serpentine (sp). c, calcite. One nicol. ×71.



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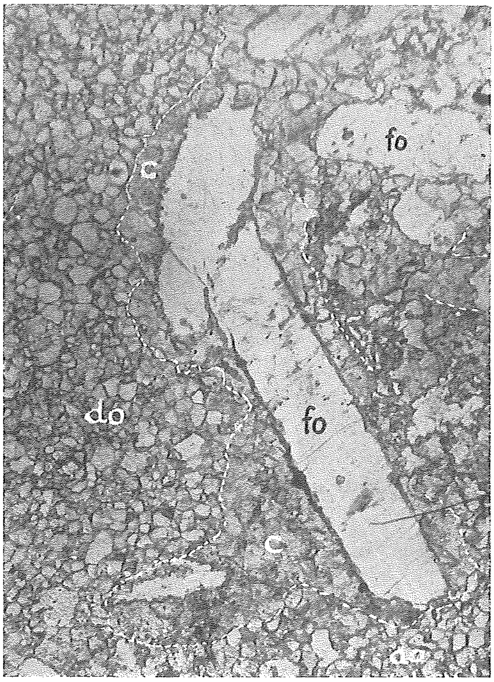

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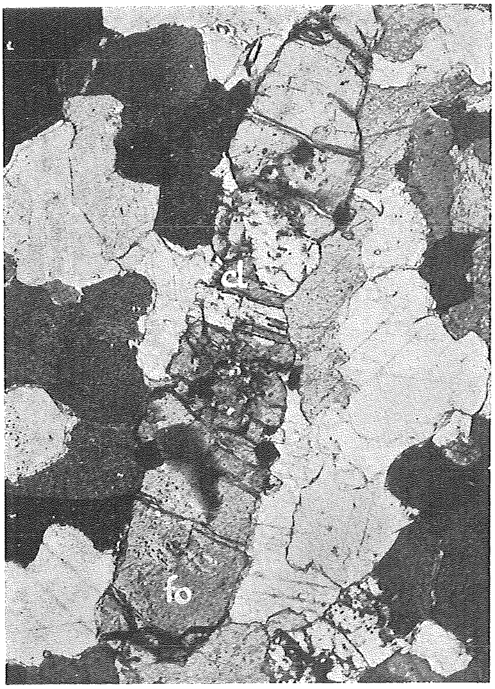

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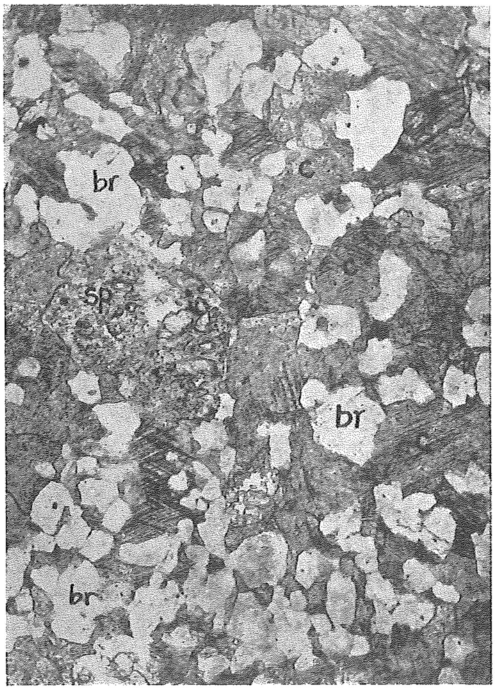

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T. Watanabe: Geology and Mineralization of the Suian District.

Plate LXIII (XVIII)

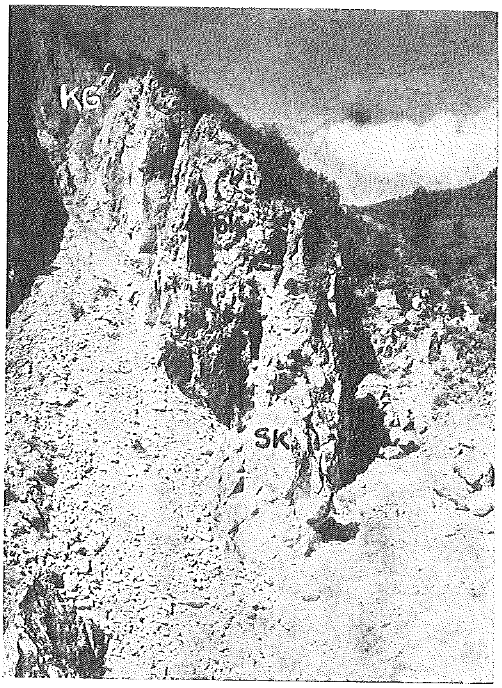
Plate LXIII (XVIII)

Fig. 1. View of the eastern open-cut of the Kotudô mine, showing the relation of the Kotudô granite (KG) to the garnet-scapolite-skarn (SK).

Fig. 2. Surface of the garnet-scapolite skarn, showing the mode of occurrence of very large radiated crystals of scapolite (Sc). Loc. Eastern open-cut, the Kotudô mine.

Fig. 3. Skarn vein (Sk) consisting mainly of salite, epidote and scapolite, cutting the Suian granite (SG) along its joints, near the Saziri village.

Fig. 4. Skarn vein (Sk) cutting the Suian granite (porphyritic granodiorite), showing the symmetrical banding of the conststituent minerals. Scapolite. (Sc) occupies the center of the vein. The width of the vein is about 30 cm. Saziri valley.



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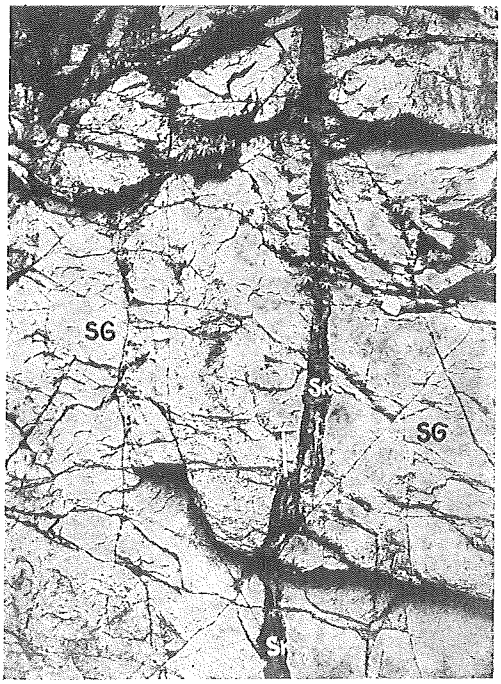

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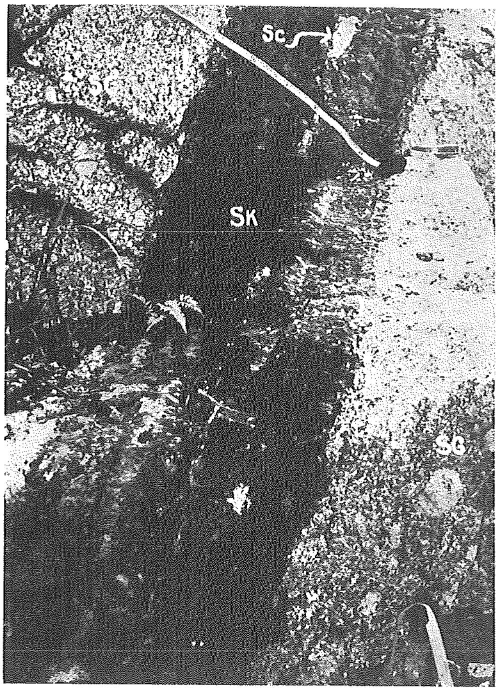

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Plate LXIV (XIX)

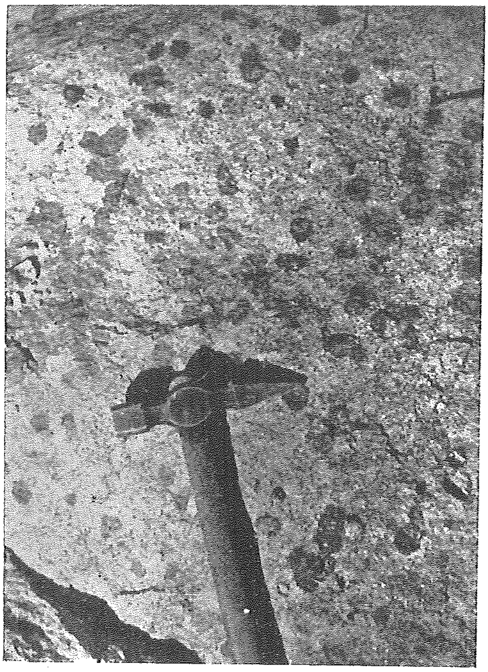
Plate LXIV (XIX)

Fig. 1. The Kotudô granite (an aplitic granite) containing abundant rounded xenoliths (skarn balls) consisting of garnet, epidote and calcite. On the eastern open-cut of the Kotudô mine.

Fig. 2. Photomicrograph of thin section of the skarn-ball (Fig. 1), showing the detail of the boundary between the ball and the surrounding rock. Sk, garnet-epidote-skarn; g, granite. One nicol. ×6.

Fig. 3. Photomicrograph of thin section of garnet-scapolite-skarn from the Kotudô mine. sc, scapolite; g, garnet. One nicol. ×9.

Fig. 4. Photomicrograph of garnet-diopside-skarn from the Kotudô mine, showing zonal structure of the garnet. g, garnet; di, diopside; c, calcite. Crossed nicols. ×8.



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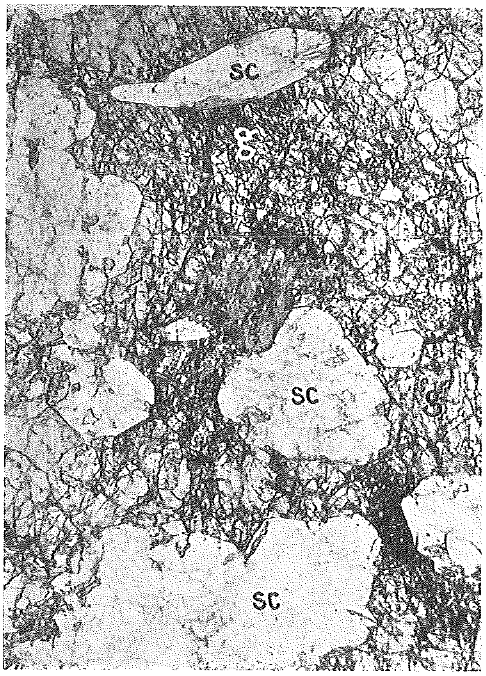

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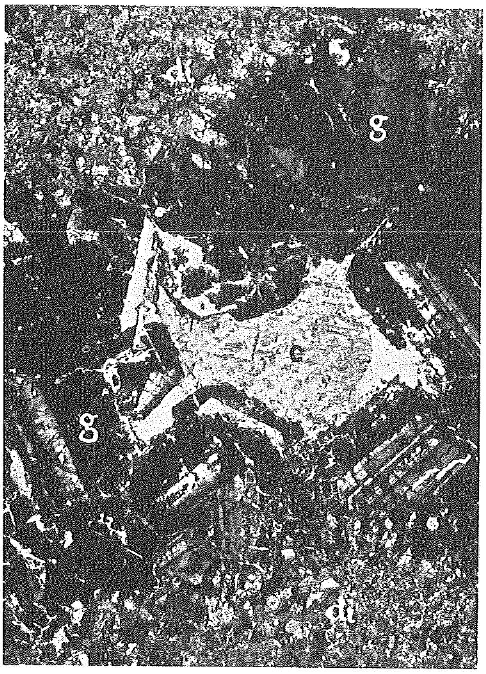

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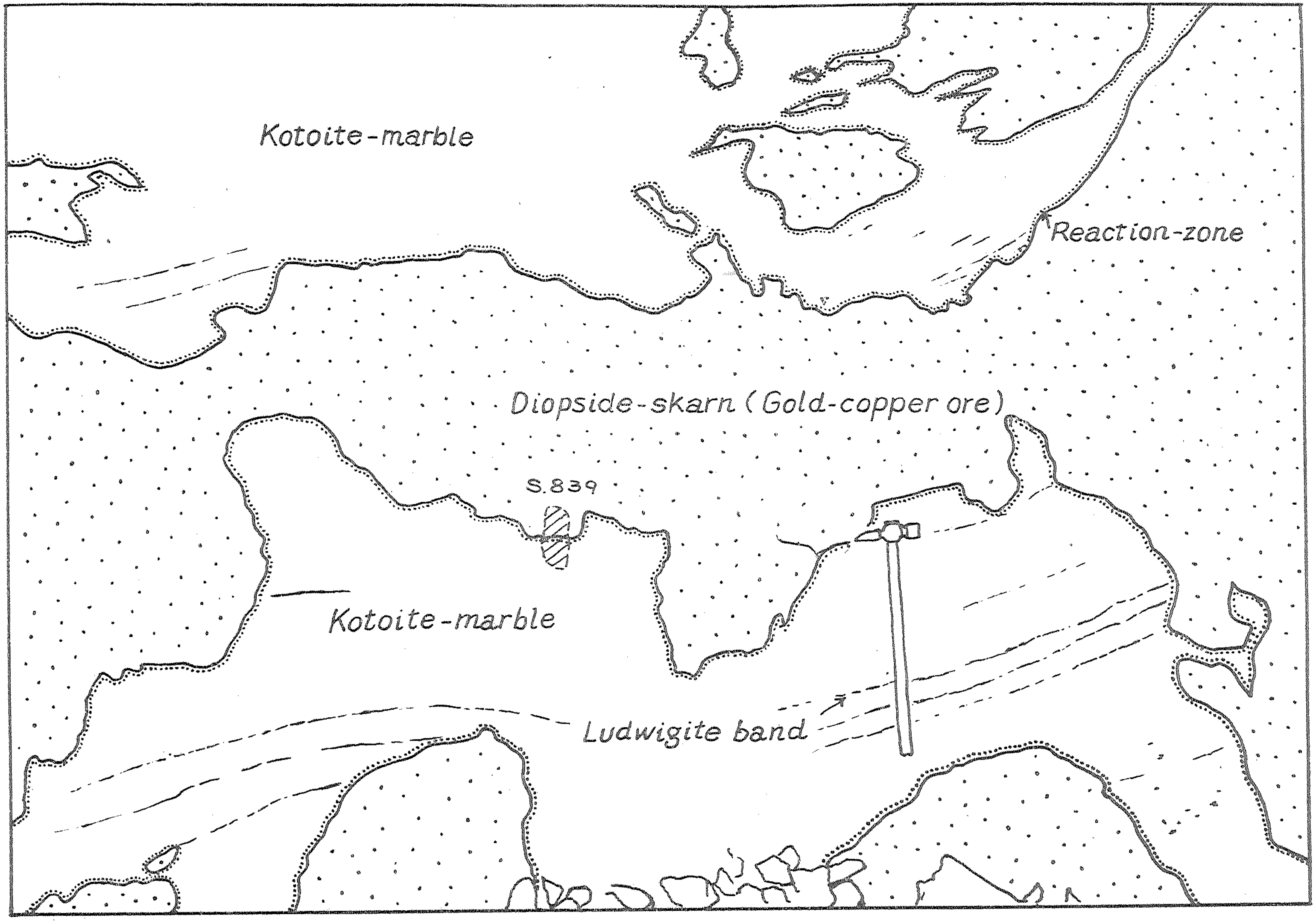
Plate LXV (XX)

Plate LXV (XX)

Underground photograph of the stope-face of the Northern ore-body (N.O.B.) of the Kotudô mine, showing the relation of gold-copper-bismuth-ore (diopside-clinohumite-phlogopite-skarn) to kotoite-marble. Plane of stratification of the original rock is well preserved by the black bands of ludwigite. Note the development of reaction zone surrounding the diopside-skarn, in which fluoborite, szaibelyite, and clinohumite are found. Shaded area (S839) indicating the locality of the polished specimen shown in Plate LXVII(XXII).


Kotoite-marble
Reaction-zone
Diopside-skarn (Gold-copper ore)
S.839
Kotoite-marble
Ludwigite band

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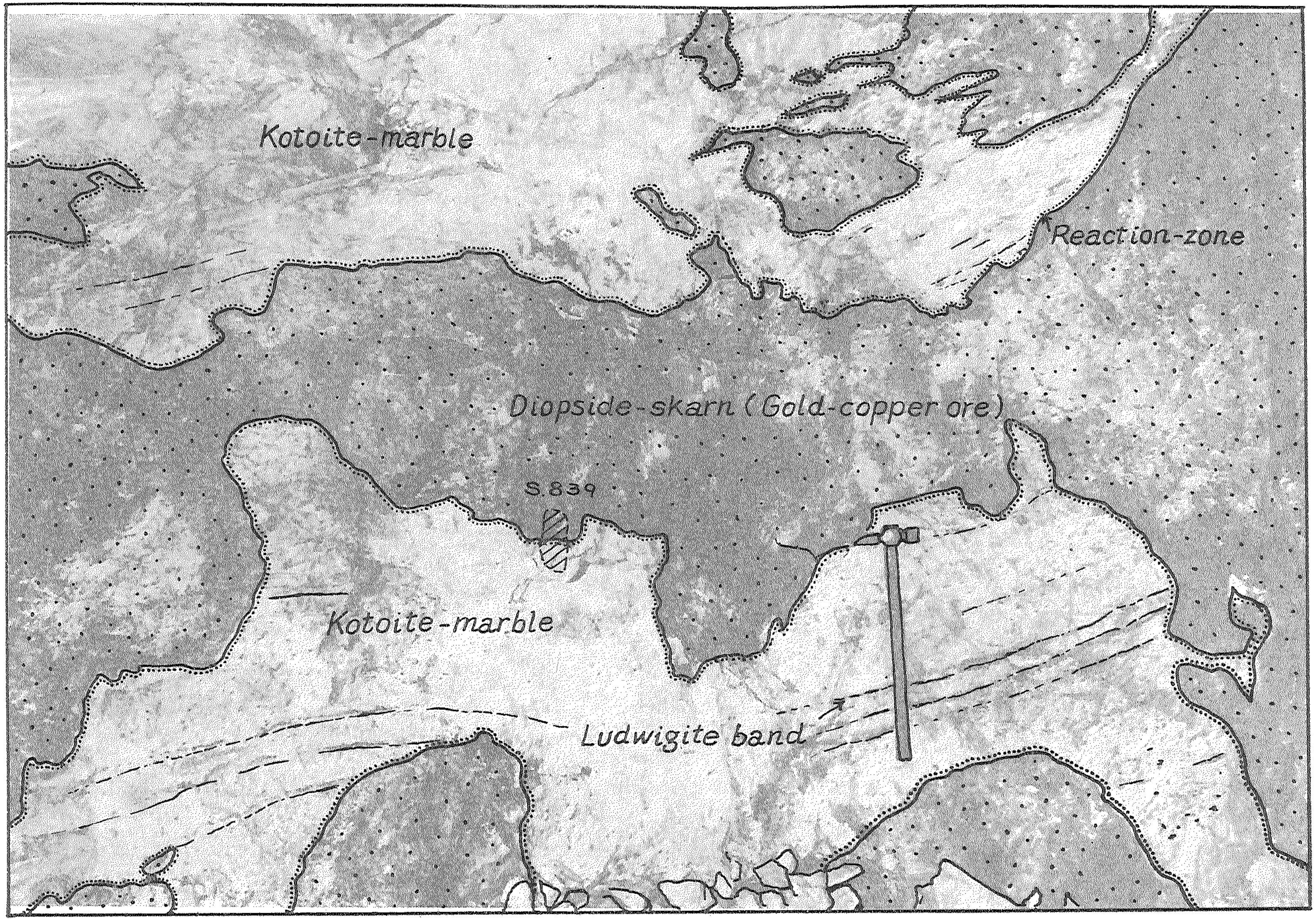

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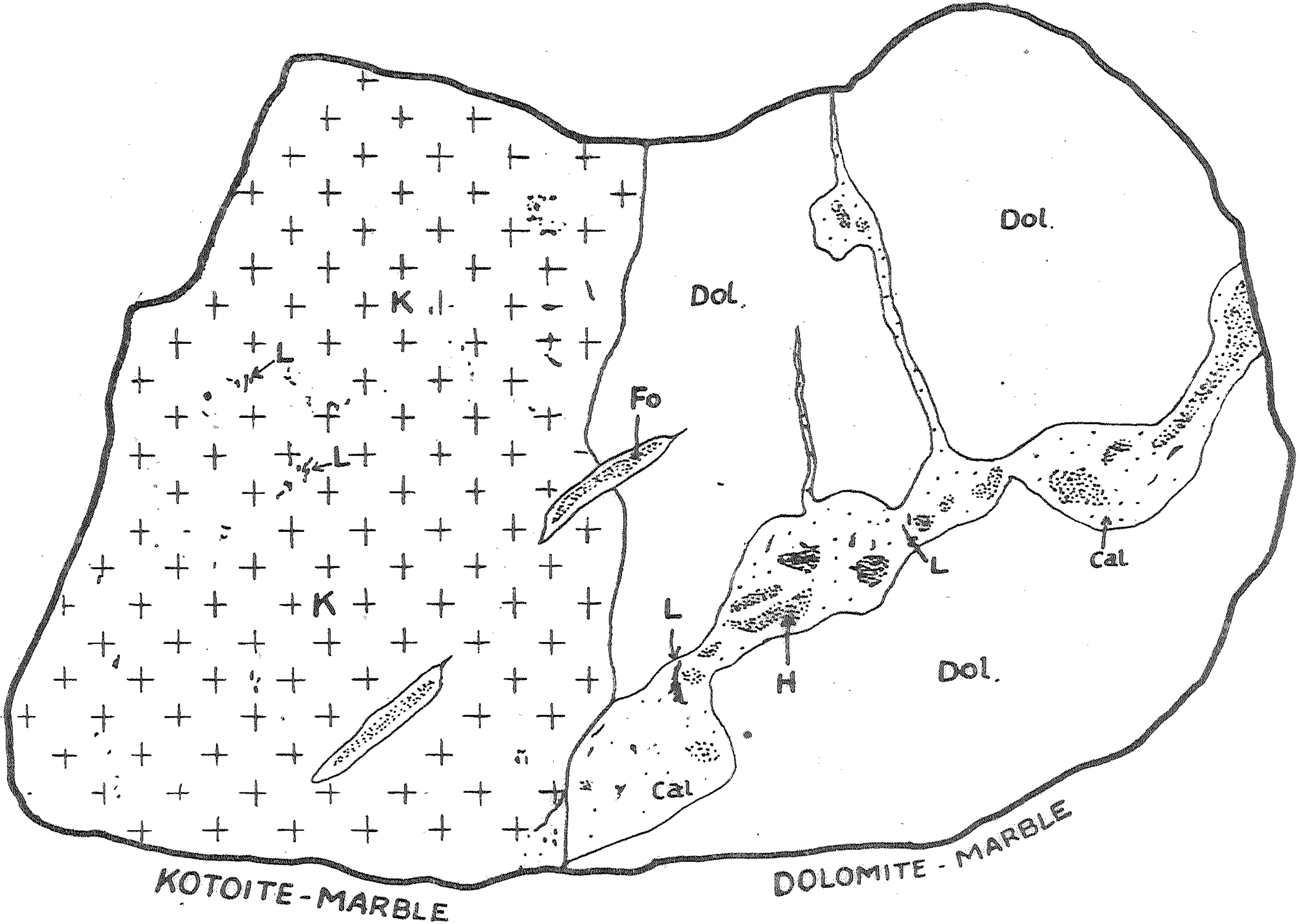
Plate LXVI (XXI)

Plate LXVI (XXI)

(Colour plate reproduced from JAPANESE MINERALS IN PICTURE (Vol. IV) by courtesy of Prof. T. Ito.)

Polished specimen (No. S. 1012) from the Northern ore-body (N.O.B.), Kotudô mine, showing the relation of kotoite-marble (k) to dolomite-marble (Dol.). Note the sharp boundary between the two rocks. The kotoite-marble contains sparsely minute needles of ludwigite and undetermined brown minerals. The dolomite-marble is penetrated by veinlets consisting of ludwigite (L), clinohumite (H), and calcite (cal).


K
L
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Fo
Dol.
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Cal
KOTOITE-MARBLE
DOLOMITE-MARBLE

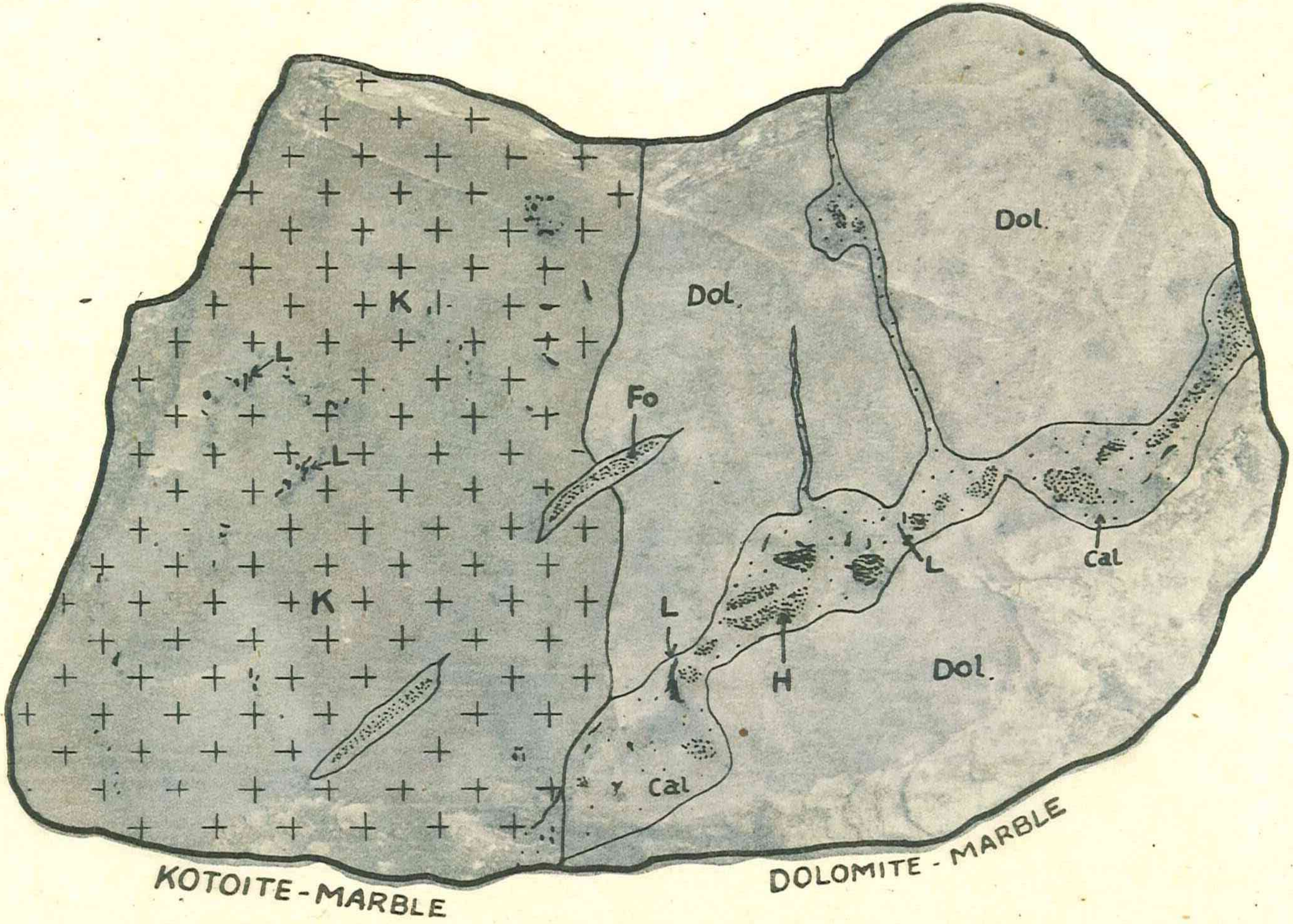

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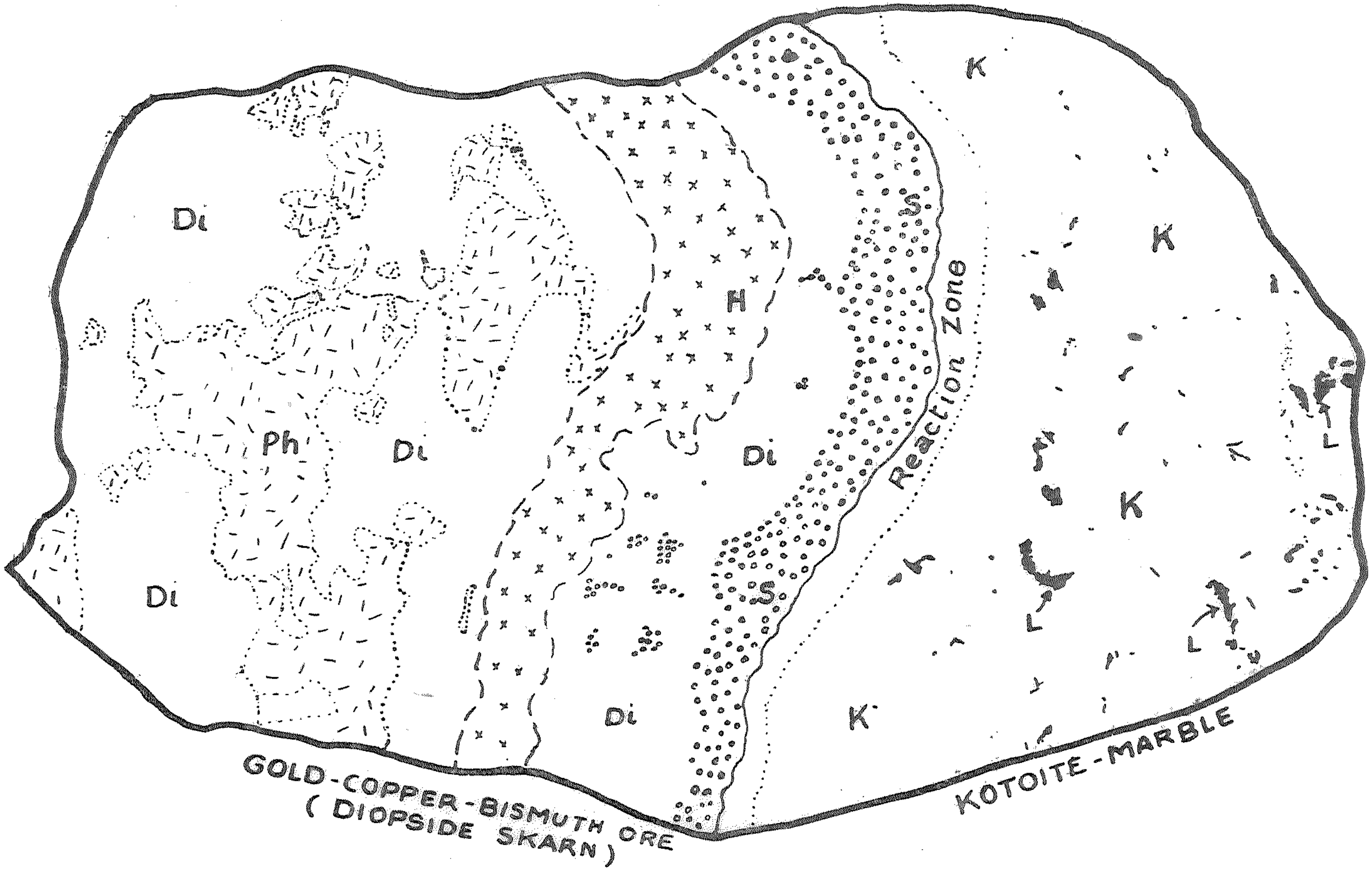
Plate LXVII (XXII)

Plate LXVII (XXII)

(Colour plate reproduced from JAPANESE MINERALS IN PICTURE (Vol. IV) by courtesy of Prof. T. Ito.)

Polished specimen (No. S. 839) from the Northern ore-body, Kotudô mine, showing the contact relation of the skarn to the kotoite-marble. Note the zonal arrangement of the constituent minerals of the skarn. The occurrence of fluoborite is usually confined to the reaction zone between the skarn and the kotoite-marble. The kotoite-marble (K) contains specks of ludwigite (L). s, metallic minerals consisting of gold, bismuth, chalcopyrite, pyrrhotite, cubanite, etc.; Di, diopside; H, minerals of humite-group, usually clinohumite; Ph, phlogopite. Natural size.


Di
Ph
Di
Di
H
Di
S
S
Di
Reaction Zone
K
K
K
K
L
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L
GOLD-COPPER-BISMUTH ORE
(DIOPSIDE SKARN)
KOTOITE-MARBLE

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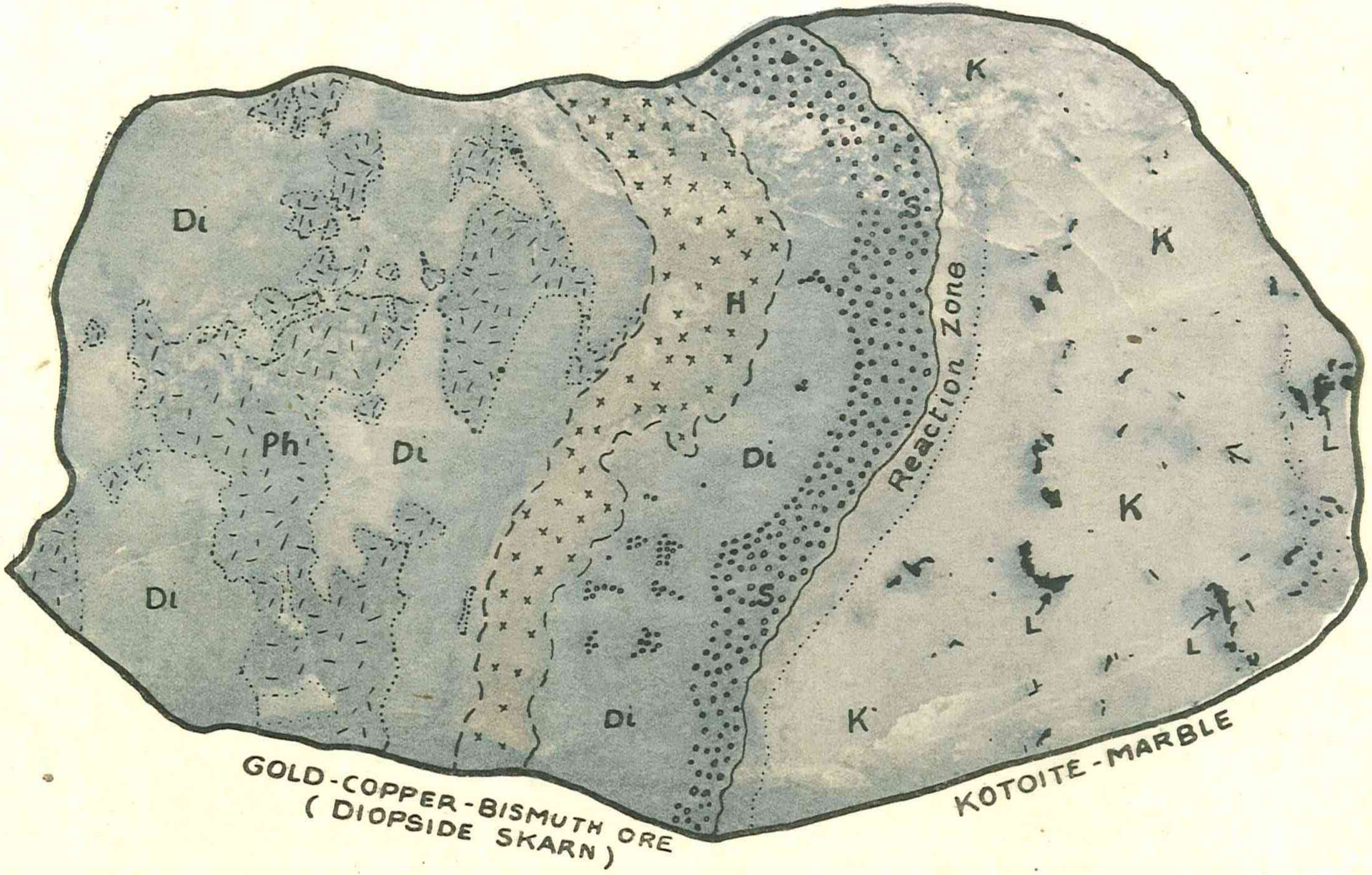


T. Watanabe: *Geology and Mineralization of the Suian District.*

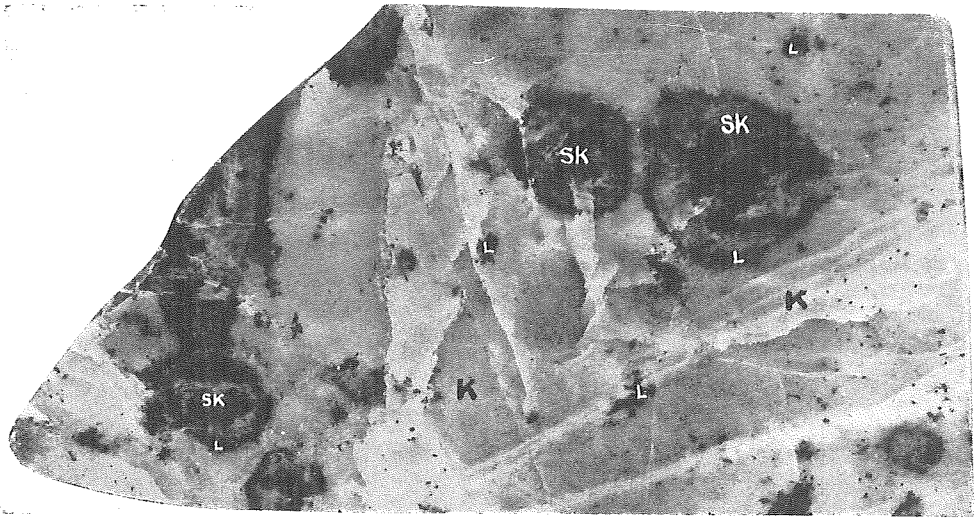
Plate LXVIII (XXIII)

Plate LXVIII (XXIII)

Fig. 1. Polished specimen of kotoite-marble (k) containing the nodular masses of diopside-skarn (sk). The skarn masses are usually surrounded by black reaction-zone consisting principally of ludwigite (L). Radiated or prismatic crystals of ludwigite are sparsely found in the kotoite-marble. Loc. 700 syaku-level, Northern ore-body (N.O.B.), Kotudô mine. Natural size.

Fig. 2. Photomicrograph of a portion of the reaction zone of fig. 1. k, kotoite-marble; L, ludwigite-zone; di, diopside-skarn. One nicol. ×8.

Fig. 3. Photomicrograph of thin section, same as fig. 2 but with crossed nicols. ×8.



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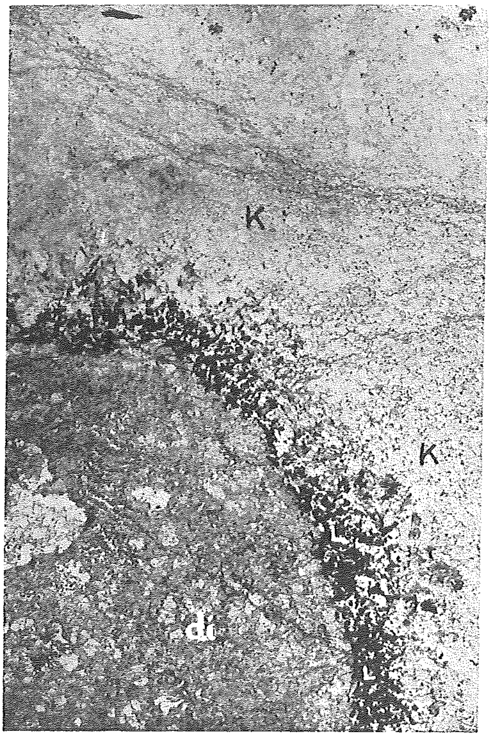

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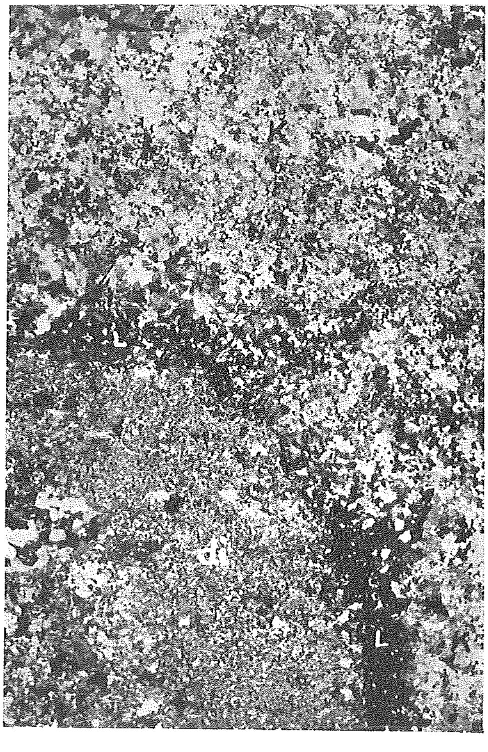

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Plate LXIX (XXIV)

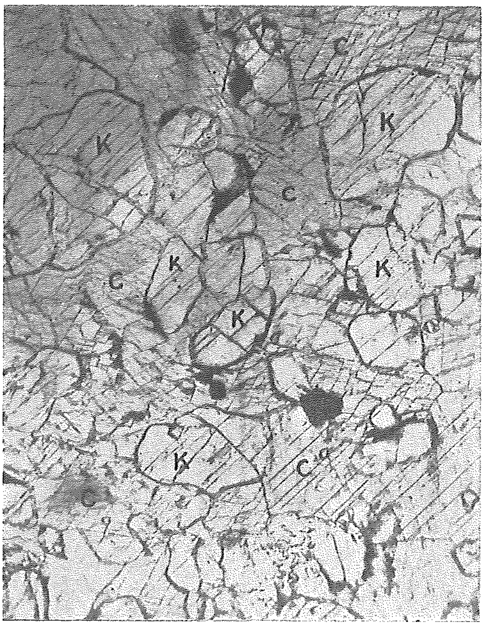
Plate LXIX (XXIV)

(Photomicrographs of thin sections.)

Fig. 1. Kotoite-marble from the Kotudô mine. Detached subhedral grains of kotoite (k) oriented in the same direction and embedded in a groundmass of calcite (c). Kotoite shows traces of prismatic cleavage. One nicol. ×100.

Fig. 2. Kotoite-marble same as Fig. 1 but crossed nicols. k, kotoite; c, calcite. ×100.

Fig. 3. Kotoite-marble showing that a large number of granular crystals of kotoite are in crystallographic parallelism. Kotudô mine, Suian. k, kotoite; l, ludwigite; c, calcite. Crossed nicols. ×70.



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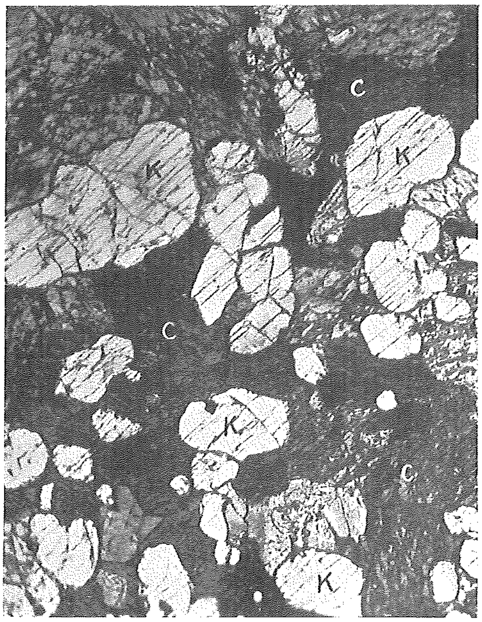

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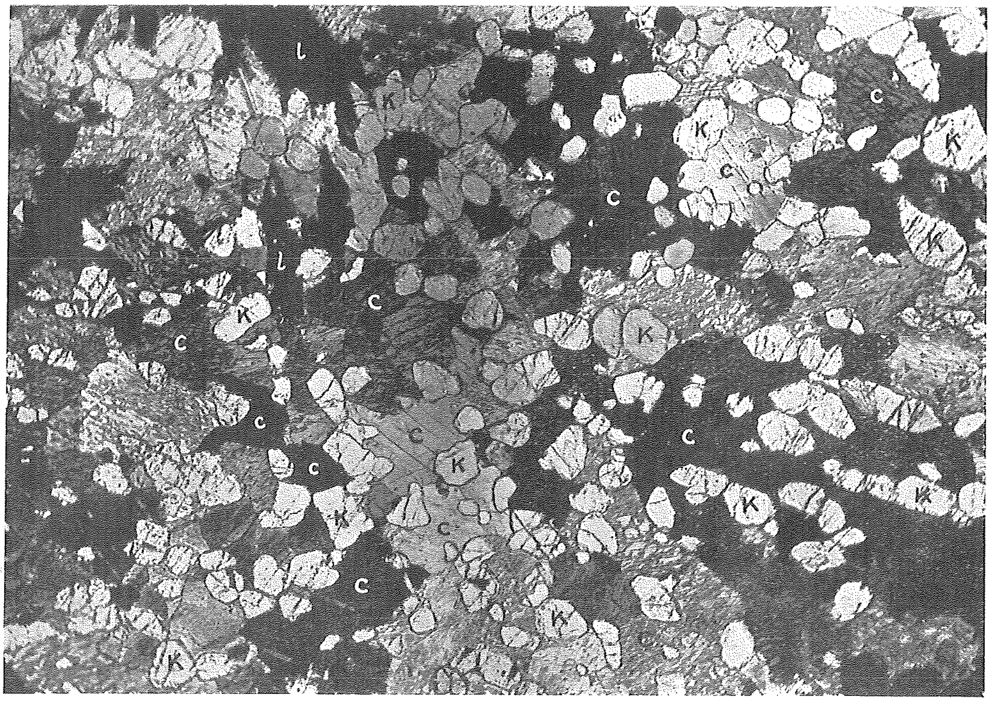

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Plate LXX (XXV)

Plate LXX (XXV)

(Photomicrographs of thin sections.)

Fig. 1. A portion of thin section showing the sharp boundary between dolomite-marble (upper) and kotoite-marble (lower). Loc., the Kotudô mine. One nicol. ×24.

Fig. 2. Alteration of kotoite-marble along a crack (center), shown by decomposition of small clear grains of kotoite into dull aggregates of a hydrous borate. Kotudô mine. One nicol. ×17.

Fig. 3. A portion of thin section of the reaction zone. Szaibelyite-needles (sz) and ludwigite crystals (L), scattering through the reaction zone, which surrounds the diopside-skarn in kotoite-marble as shown in Plate LXVII (XXII). c, calcite. One nicol. ×64.

Fig. 4. Fluoborite (fb) associated with spinel (sp) and szaibelyite (sz) are embedded in calcite (c) of the reaction-zone between the diopside-skarn and the kotoite-marble. Note the hexagonal cross section of fluoborite. One nicol. ×61.

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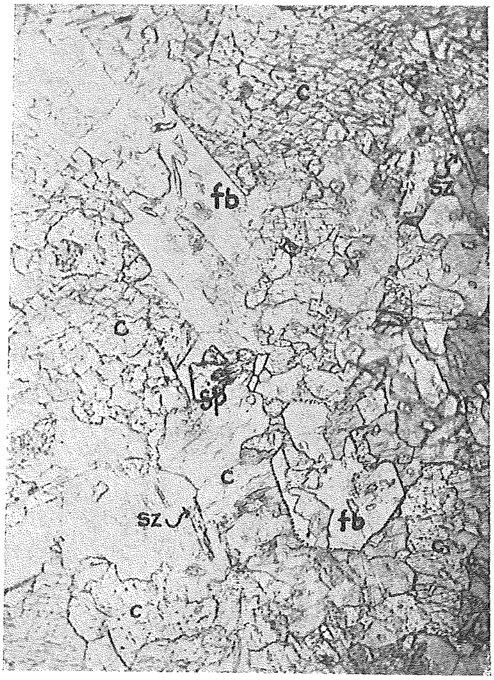

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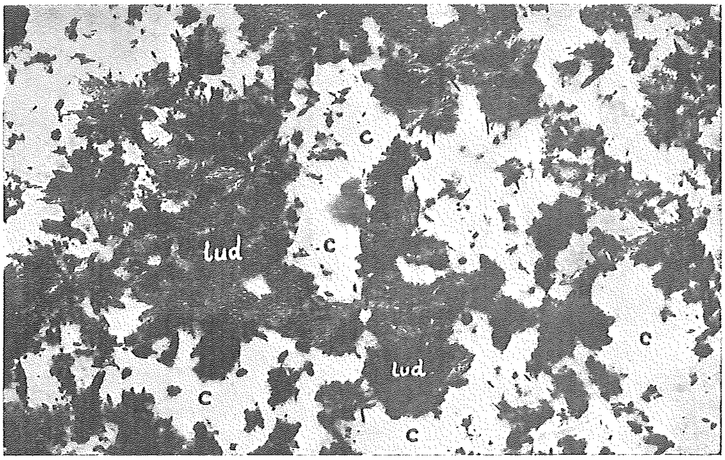
Plate LXXI (XXVI)

Plate LXXI (XXVI)

Fig. 1. Polished specimen of ludwigite-bearing rock from the Kotudô mine. Lud, ludwigite; cl, clinohumite; c, calcite. Natural size.

Fig. 2. Photomicrograph of thin section of ludwigite in the kotoite-marble from the Kotudô mine. Slender crystals of ludwigite (lud) are surrounded by mozaic grains of calcite, while granular crystals of kotoite (k) are embedded in calcite (c). Kotoite has never been observed as inclusion in ludwigite. One nicol. ×66.

Fig. 3. Photomicrograph of polished section of ludwigite (lud) from the Kotudô mine, showing strong reflection-pleochroism. The associated metallic minerals are magnetite (mg) and hematite (ht). c, calcite. Reflected light, one nicol. Oil-immersion. ×150.



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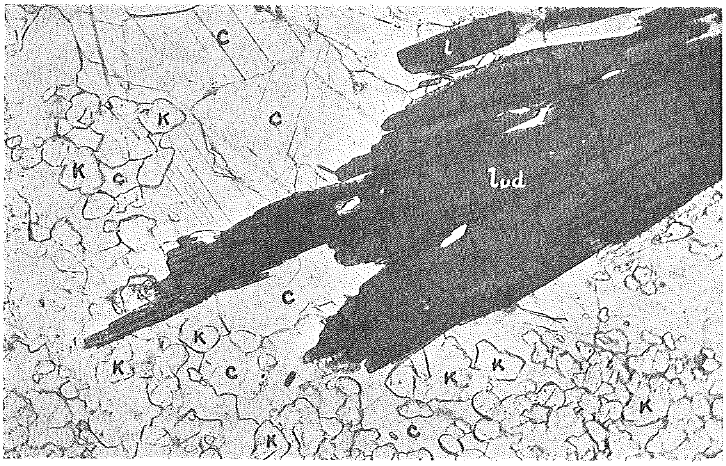

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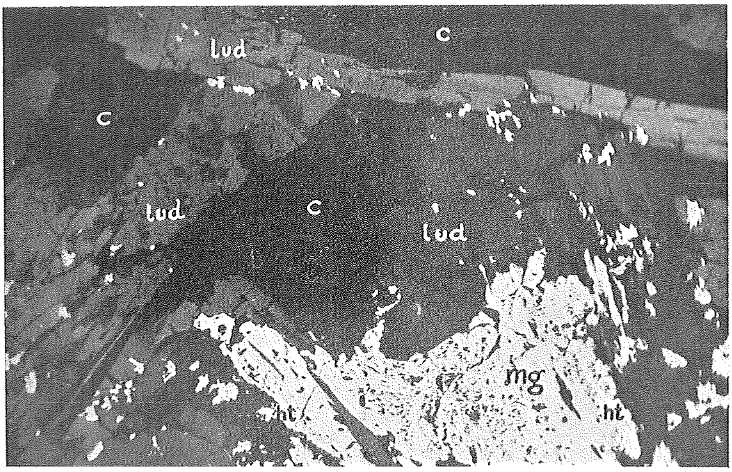

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Plate LXXII (XXVII)

Plate LXXII (XXVII)

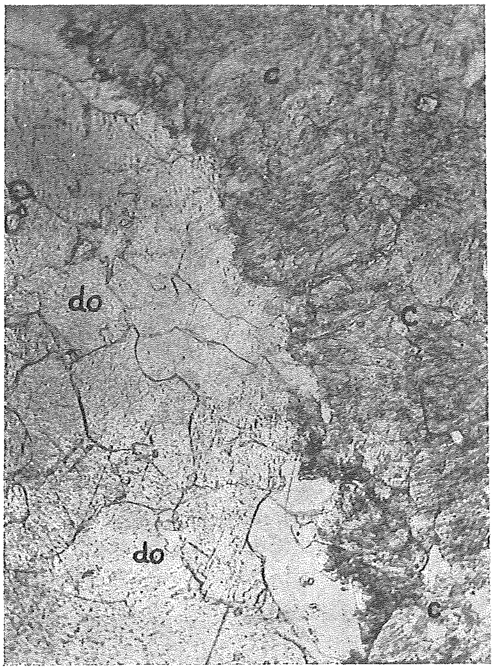
(Photomicrographs of thin sections of ores)

Fig. 1. Specimen showing the contact between the wall rock (do, dolomite-marble) and the calcite-zone (c) surrounding the skarn-ore of the Eastern ore-body, Kotudô mine. One nicol. ×64.

Fig. 2. Chondrodite from the skarn-ore of the Eastern ore-body, showing polysynthetic twinning after (001). Crossed nicol. ×100.

Fig. 3. Diopside-chondrodite skarn from the Eastern ore-body, the Kotudô mine. di, diopside; ch, chondrodite; c, calcite; s, sulphides. Crossed nicols. ×14.

Fig. 4. Thin section of gold-copper-ore, showing sulphides (s) replacing tremolite (tr) and diopside (di), Kotudô, Tyôsen. One nicol ×14.



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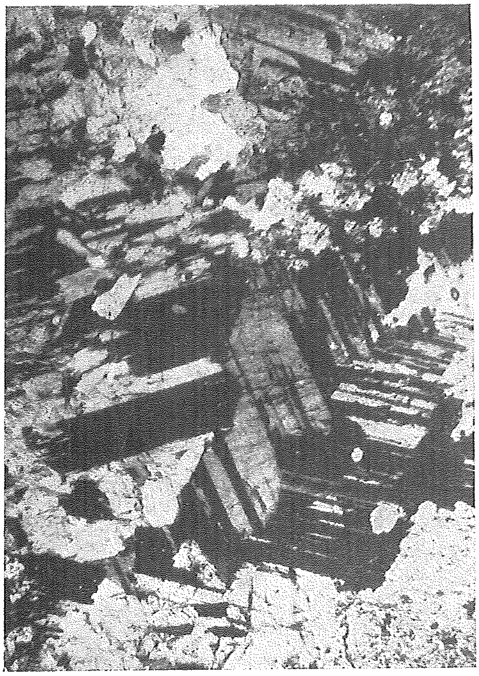

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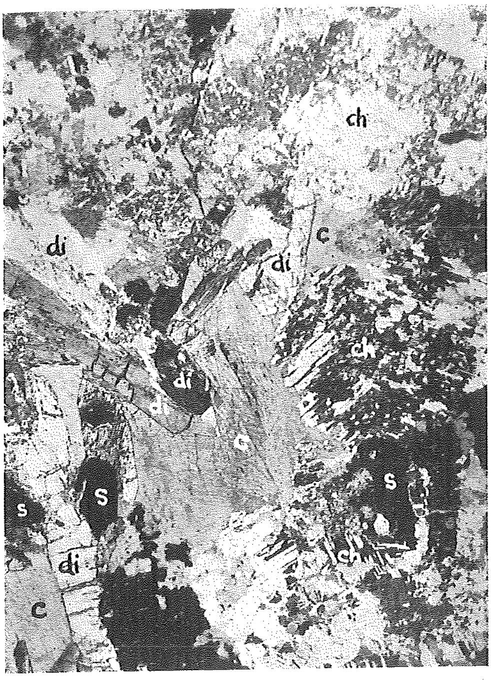

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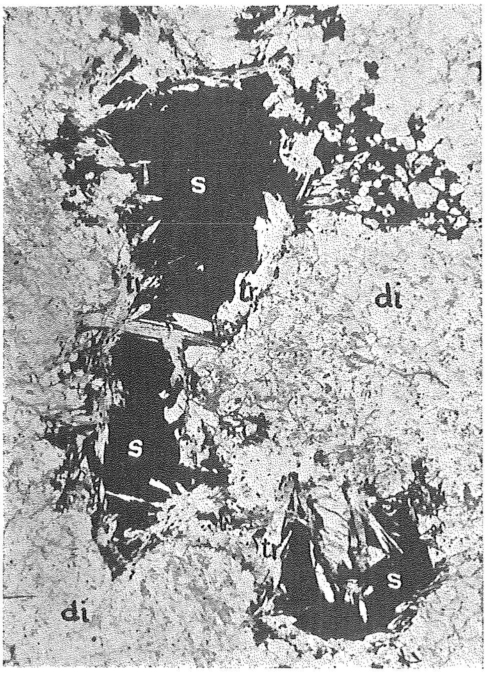

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Plate LXXIII (XXVIII)

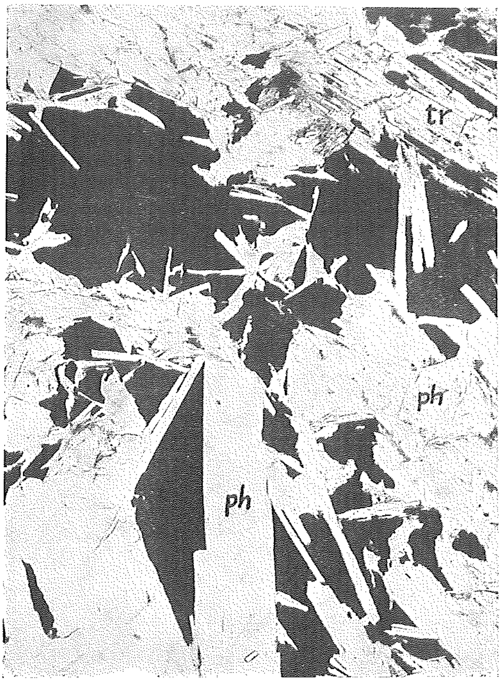
Plate LXXIII (XXVIII)

(Photomicrographs of thin sections of ores)

Fig. 1. Ore minerals (black) replacing phlogopite (ph) and tremolite (tr). Kotudô mine. One nicol. ×70.

Fig. 2. Specimen from the Western ore-body of the Kotudô mine, showing replacement of garnet (g) and calcite by sulphides (s). One nicol. ×64.

Fig. 3. Specimen of diopside-tremolite-skarn from the Kotudô mine, showing the relation of ore minerals to gangue minerals. The silicate minerals (di, diopside; tr, tremolite) are partially replaced by the sulphides (s). One nicol. ×76.



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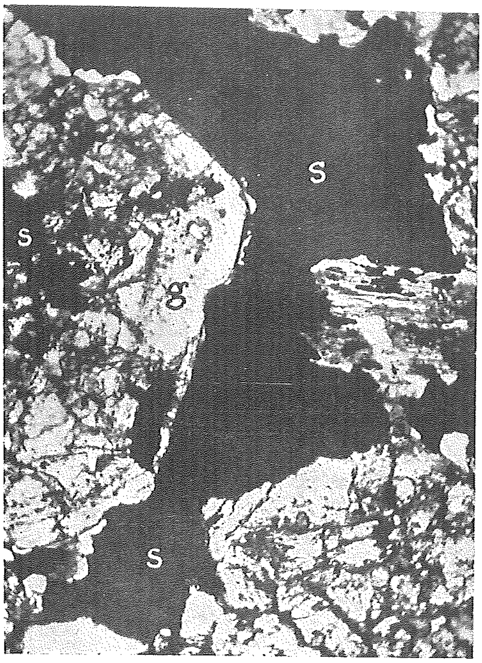

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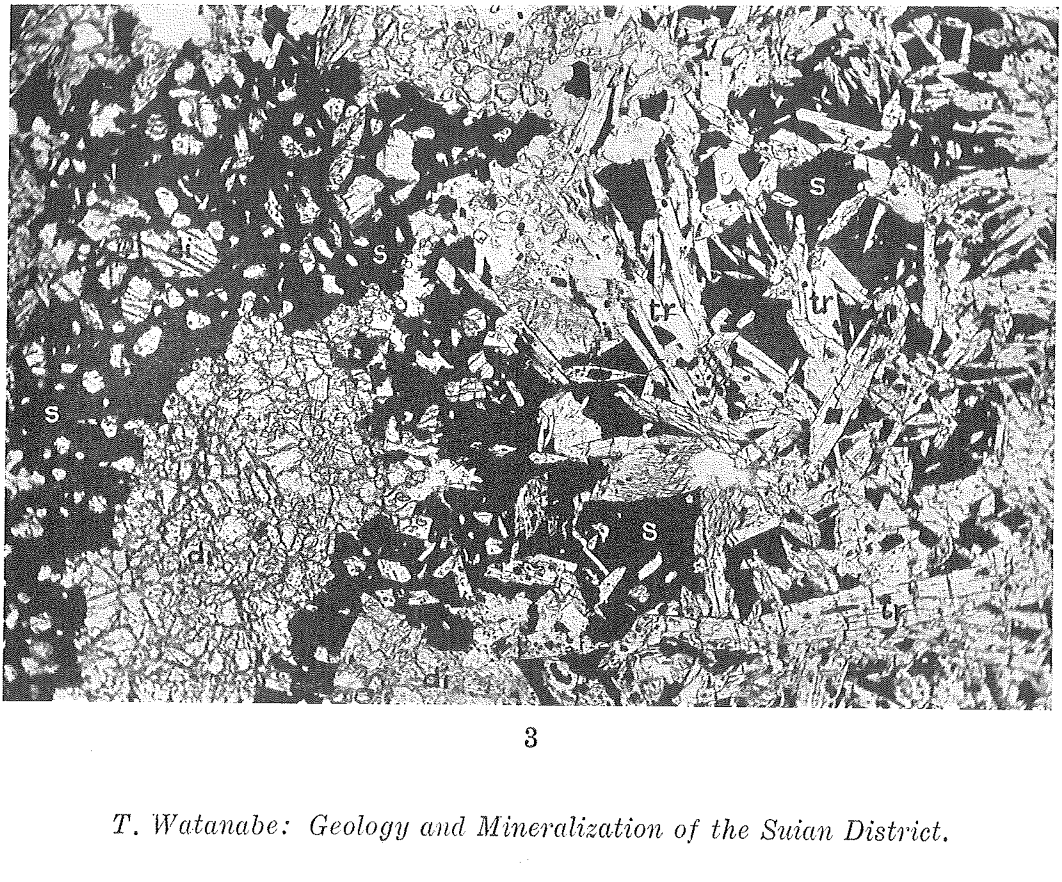

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Plate LXXIV (XXIX)

Plate LXXIV (XXIX)

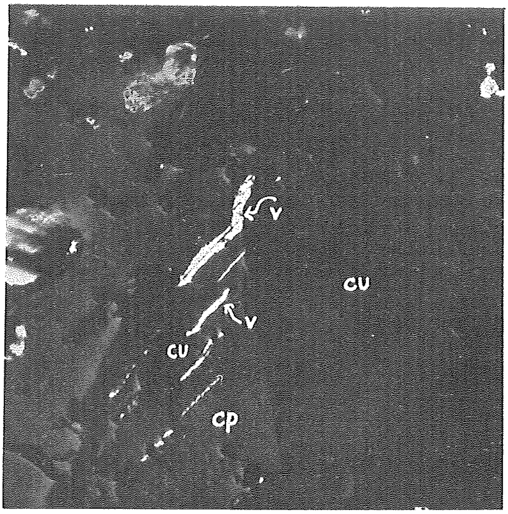
(Photomicrographs of polished sections)

Fig. 1. Lamellar valleriite (v) along (100) or (001) in chalcopyrite (cp) showing its strong anisotropism in diagonal position. Note that cubanite (cu) is free from valleriite-lamellae. Northern ore-body, Kotudô mine. Oil-immersion. ×200.

Fig. 2. Flame-like valleriite (v) along (100) and (001) in chalcopyrite (cp) twinned polysynthetically after (111). The Northern ore-body, Kotudô mine. Crossed nicols. Oil-immersion. ×200.

Fig. 3. Crystallographic intergrowth of cubanite (cu) and chalcopyrite (cp) in an ore from the Northern ore-body, Kotudô mine. Flame-like valleriite (v) projecting from a crack into chalcopyrite, has never been found in cubanite (cu) area. One nicol. Oil-immersion. ×200.

Fig. 4. Pyrrhotite (po) replaced by cubanite (cu) and chalcopyrite (cp). Black portions are gangue minerals (tr, tremolite). One nicol. Oil-immersion. ×150.



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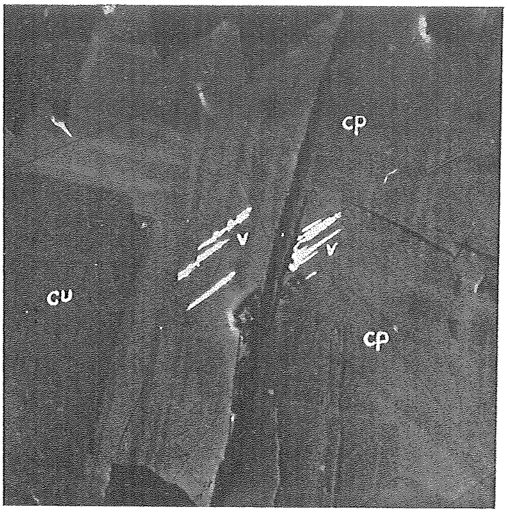

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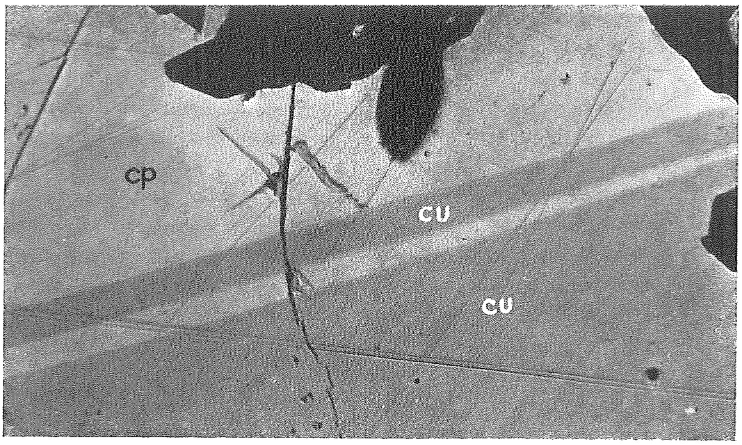

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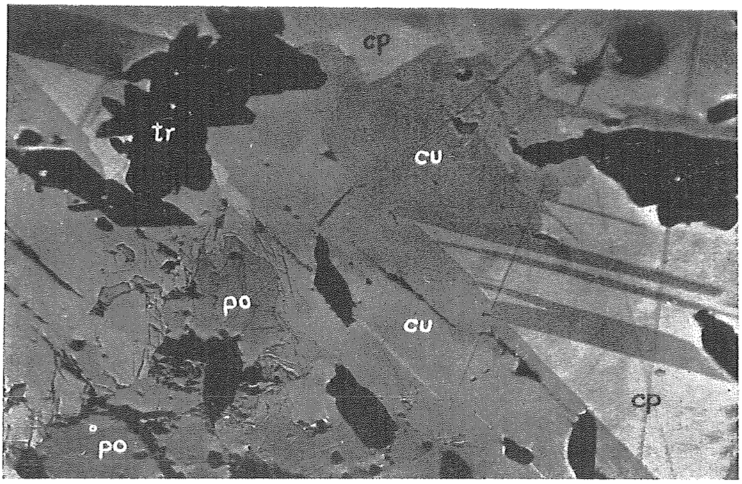

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T. Watanabe: Geology and Mineralization of the Suian District.

Plate LXXV (XXX)

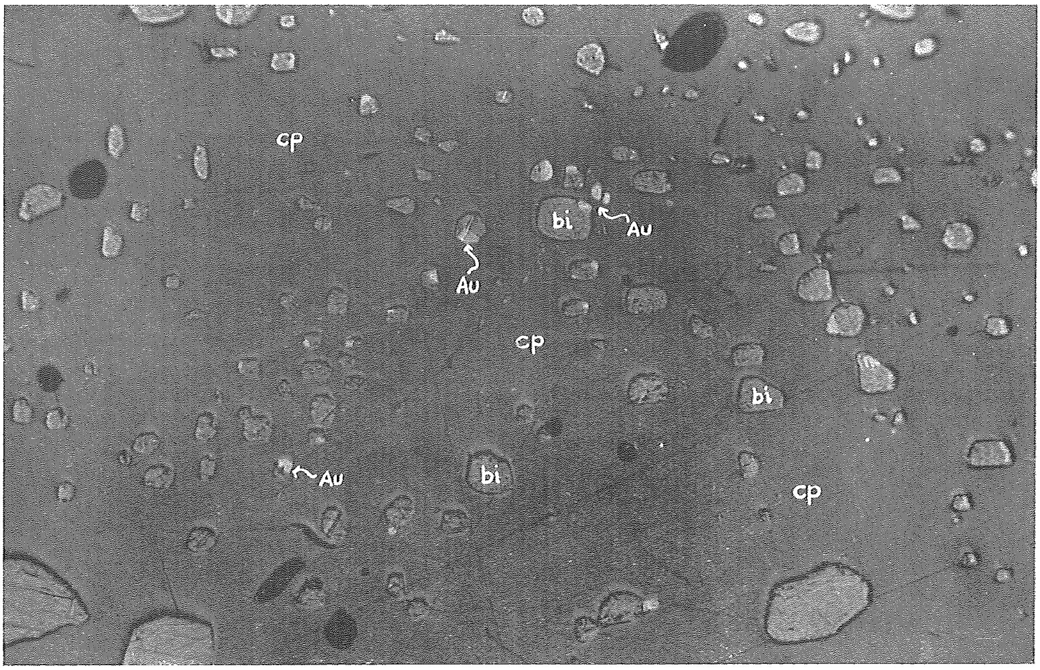
Plate LXXV (XXX)

(Photomicrographs of polished sections)

Fig. 1. Drop-like bismuth (bi) with gold (Au) enclosed in chalcopyrite (cp). One nicol. Oil-immersion. ×350.

Fig. 2. Native bismuth (bi) in chalcopyrite (cp). One nicol. Oil-immersion. ×150.

Fig. 3. Figure same as fig. 2 but crossed nicols. Showing the polysynthetic secondary twinning of native bismuth. Oil immersion. ×150.



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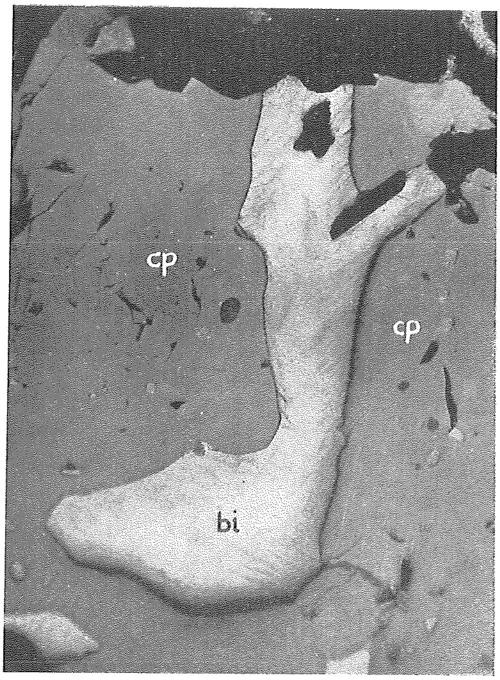

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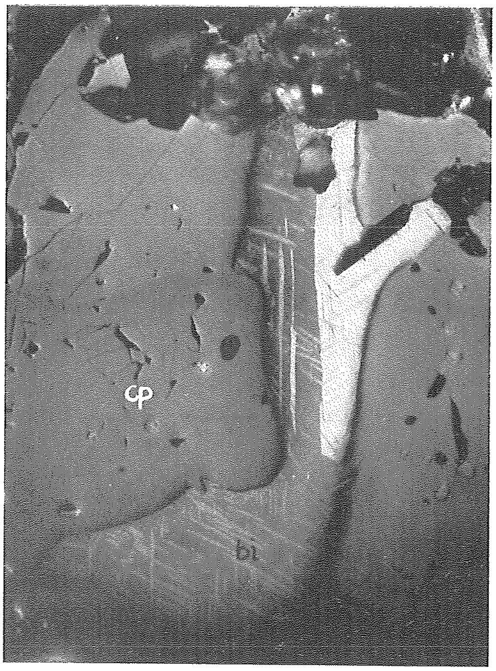

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T. Watanabe: Geology and Mineralization of the Suian District.

Plate LXXVI (XXXI)

Plate LXXVI (XXXI)

Fig. 1 and 2. Specimen of the bornite-ore from the Northern ore-body, Kotudô mine, showing the occurrence of two types of chalcopyrite in bornite. Massive chalcopyrite (cp. 1) usually contains minute drops of bismuth (bi). Lamellar chalcopyrite (cp. 2) is in three directions parallel to (100) in bornite (B). Veinlets composed of bismuth and bismuth-copper-sulphosalts (klaprothite and wittichenite) cutting bornite (B) fig. 1. One nicol. Oil-immersion. ×130; fig. 2, tracing of the photograph of fig. 1.

Fig. 3. Photomicrograph of polished section of ore from the Kotudô mine, showing swarm of drop-like native bismuth (bi) in chalcopyrite (cp) and also in bornite (B). One nicol. Oil-immersion. ×130.

Fig. 4. Tracing of the photograph, fig. 1, with additional sketching under the polarizing ore-microscope, showing polysynthetic twinning in chalcopyrite (cp), bornite and bismuth. ×130.

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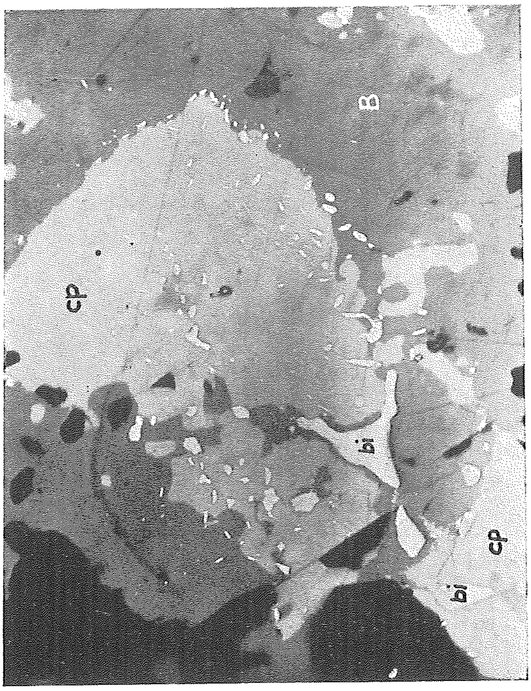

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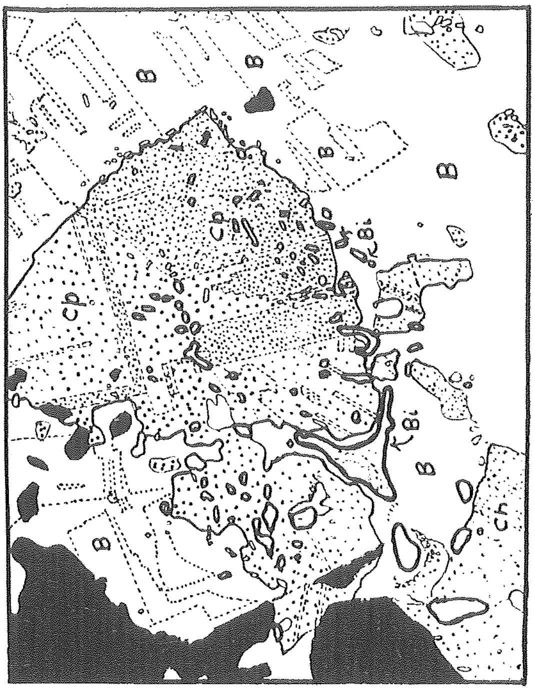

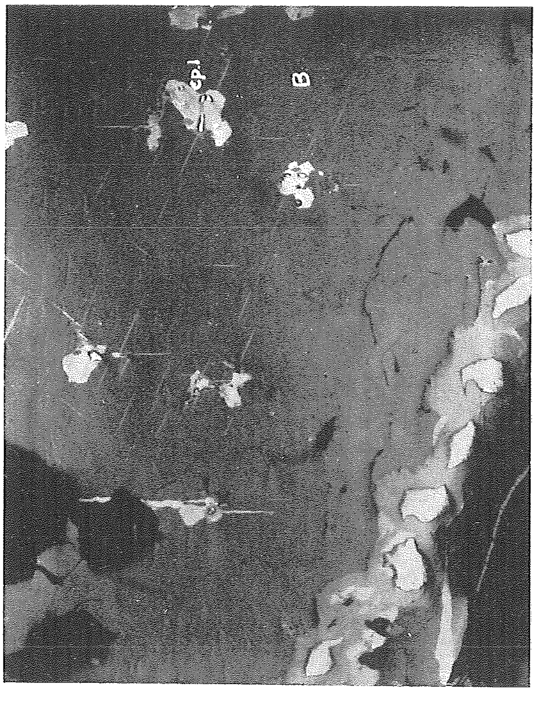

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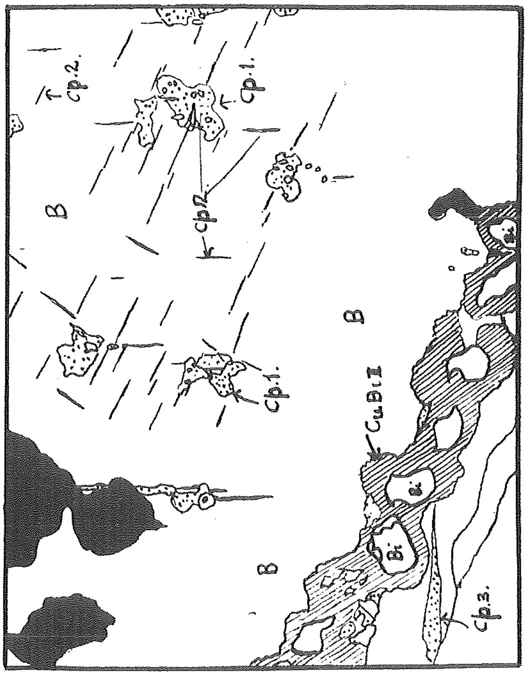

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Plate LXXVII (XXXII)

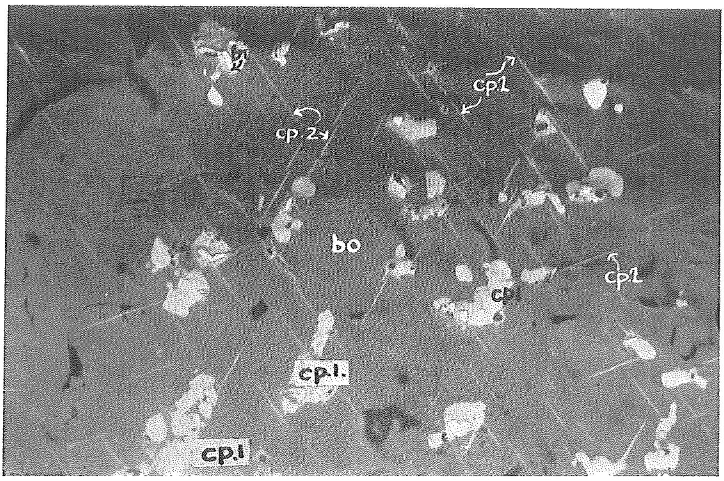
Plate LXXVII (XXXII)

(Photomicrographs of polished sections)

Fig. 1. Lamellar chalcopyrite (cp. 2) in three direction in bornite (bo). Massive chalcopyrite (cp. 1) containing generally small grains of bismuth (bi). One nicol. Oil-immersion. ×200.

Fig. 2. Enlargement of a similar portion to Fig. 1, showing details of the relation of two types of chalcopyrite to bornite. Native bismuth (bi) is partly surrounded by narrow rim of klaprothite (k). One nicol. Oil-immersion. ×470.

Fig. 3. Portion of veins consisting of bismuth minerals, penetrating bornite (bo). Native bismuth (bi) having characteristic twinning lamella, are surrounded by two kinds of Cu-Bi-minerals. (w, wittichenite (darker); k, klaprothite (lighter)). One nicol. ×110.



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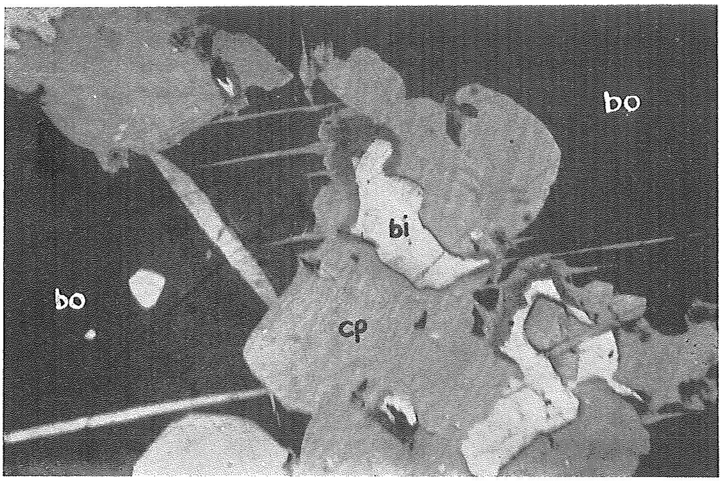

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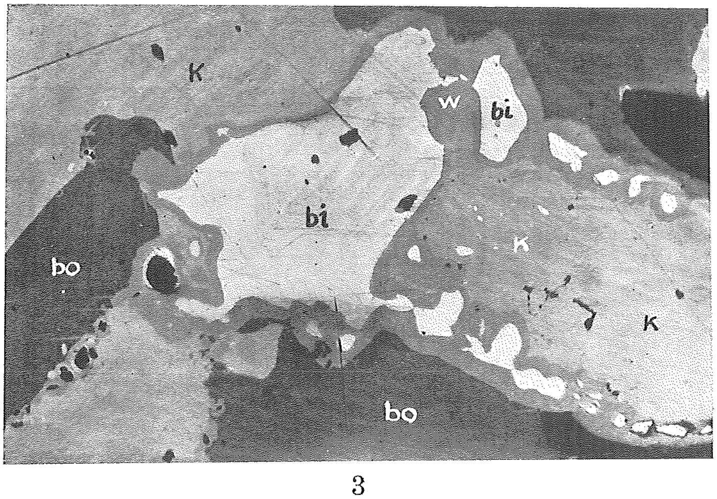

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Plate LXXVIII (XXXIII)

Plate LXXVIII (XXXIII)

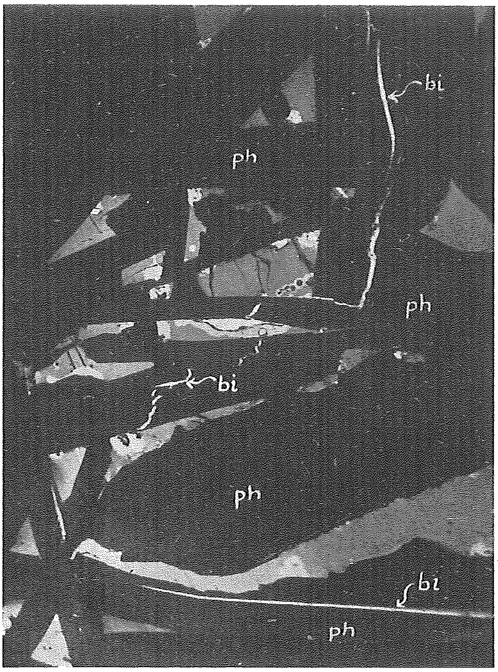
(Photomicrographs of polished sections of ores from the Kotudô mine).

Fig. 1. Native bismuth (bi) cutting phlogopite (ph) along its basal cleavage. Note the bending of flaky phlogopite. Intersticial spaces of phlogopite are filled by bornite and bismuth-mineral of a later stage. One nicol. ×100.

Fig. 2. Small needles and dots of bismuth (white) oriented along crystallographic directions in sphalerite (grey), probably along cleavage planes. One nicol. Oil immersion. ×370.

Fig. 3. Pseudoeutectic intergrowth of bornite (bo) and supergene chalcocite (cc). One nicol. Oil immersion. ×200.

Fig. 4. Small blebs and rods of klaprothite showing an irregular distribution in bornite. One nicol. Oil-immersion. ×200.



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T. Watanabe: Geology and Mineralization of the Suian District.

Plate LXXIX (XXXIV)

Plate LXXIX (XXXIV)

(Photomicrographs of polished sections of ores from the Kotudô mine).

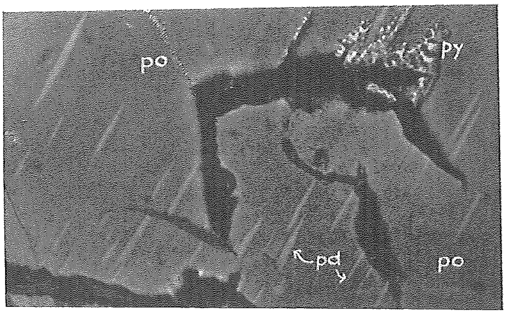
Fig. 1. Parallel blades of pentlandite oriented crystallographically in pyrrhotite (po). Note that flame-form secondary pyrite after pentlandite and some blades of pentlandite project from cracks. One nicol. Oil-immersion. ×620.

Fig. 2. Pentlandite (pd) embedded in pyrrhotite (po). One nicol. Oil-immersion. ×360.

Fig. 3. Pentlandite (pd) penetrated and partly replaced by gold (Au) and chalcopyrite (cp) along octahedral cleavages. One nicol. ×110.

Fig. 4. Section of Fig. 3 at higher magnification, showing the relation of the later gold (Au) and chalcopyrite to the earlier pentlandite (pd). One nicol. Oil-immersion. ×350.

Fig. 5. Pentlandite (pd) partly replaced by chalcopyrite (cp) and klaprothite (k) with millerite (m) along cleavages parallel to (111). Note the traces of cleavages of pentlandite in four directions. One nicol. Oil-immersion. ×350.



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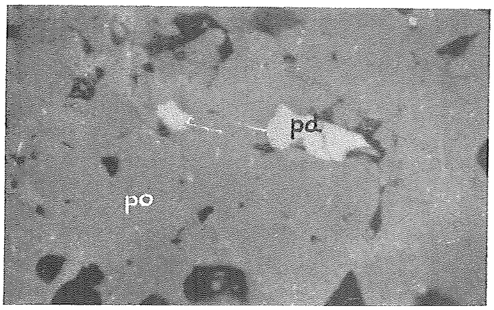

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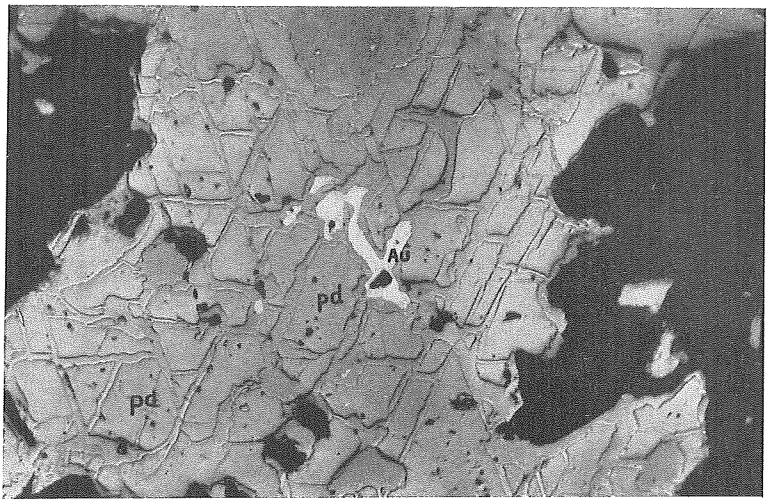

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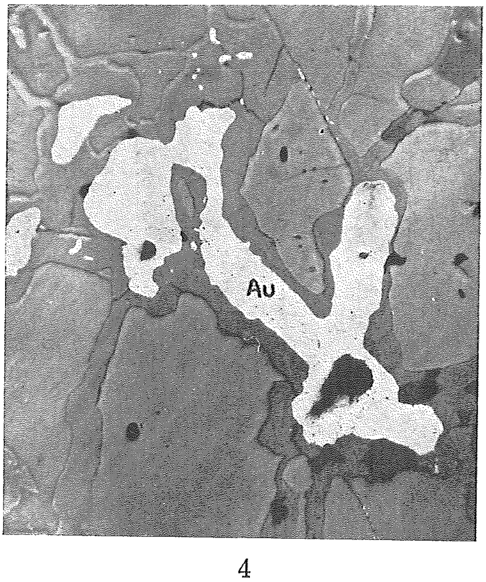

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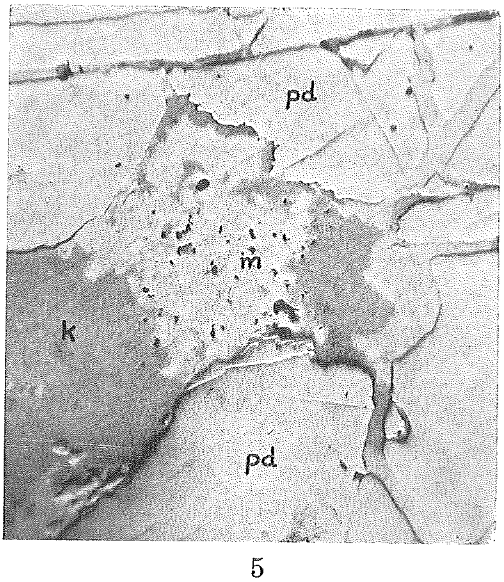

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T. Watanabe: Geology and Mineralization of the Suian District.

Plate LXXX (XXXV)

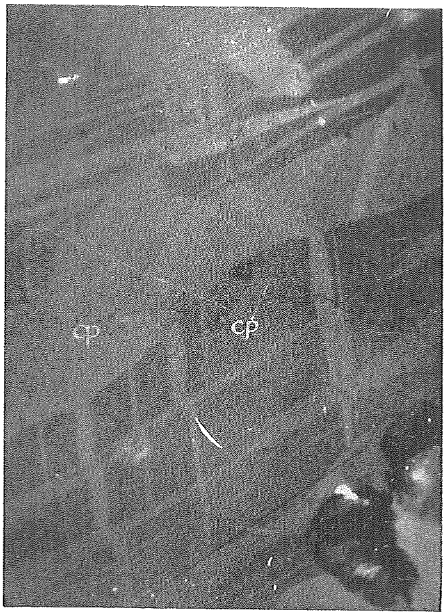
Plate LXXX (XXXV)

(Photomicrographs of polished sections)

Fig. 1 and 2. Lamellar twinning of chalcopyrite (cp) from the Kotudô mine. Note the occurrence of string-like pyrrhotite (po) and sphalerite (s) between crystal boundaries of chalcopyrite. Nicols nearly crossed. Oil-immersion. ×70.

Fig. 3. Dots of chalcopyrite in sphalerite formed as a result of unmixing of a solid solution. The sphalerite (sp) has been replaced by chalcopyrite (cp) and bornite (b). Oil-immersion. ×150.

Fig. 4. Pyrrhotite (po) replaced by chalcopyrite (cp) and penetrated by newly formed magnetite (mg). One nicol. Oil-immersion. ×150.



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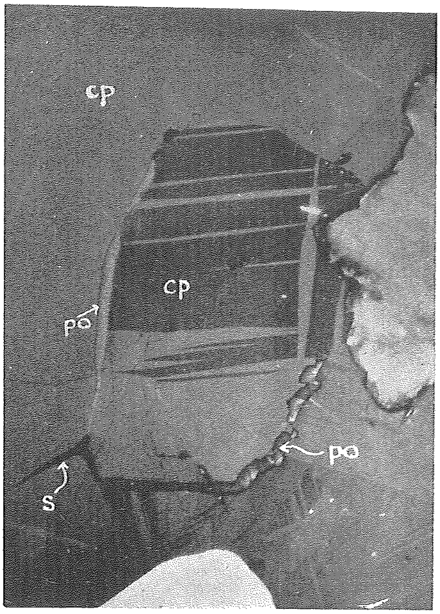

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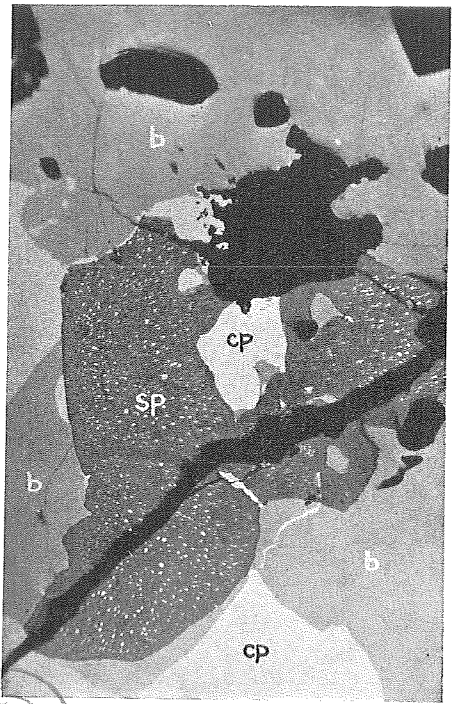

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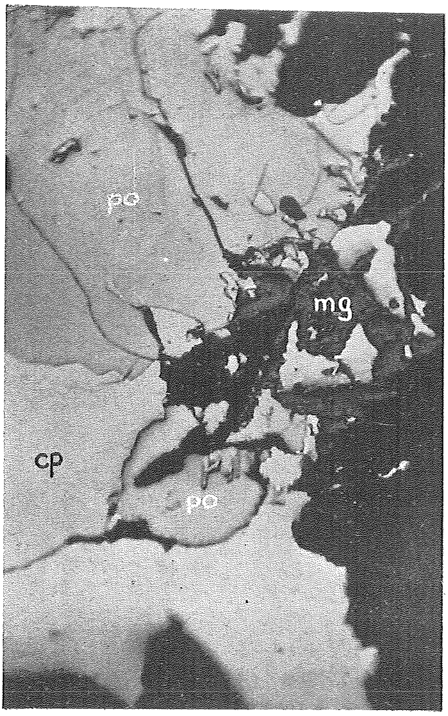

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T. Watanabe: Geology and Mineralization of the Suian District.

Plate LXXXI (XXXVI)

Plate LXXXI (XXXVI)

(Photomicrographs of polished sections of specimens from the Kotudô mine)

Fig. 1. Complex skelton-crystals of sphalerite (sp) in chalcopyrite (cp). One nicol. ×110.

Fig. 2. Skelton-crystals of sphalerite (sp) (so-called zincblende-star or "Zinkblende-sternchen") in chalcopyrite (cp), in common orientation. One nicol. ×110.

Fig. 3. Worm-like sphalerite included in pyrrhotite which has been replaced around border by chalcopyrite (cp). One nicol. Oil-immersion. ×415.

Fig. 4. Sphalerite (sp) with chalcopyrite-inclusions, replaced by pyrrhotite (po). Small grains of gold (Au) occur between the sphalerite and the pyrrhotite. One nicol. Oil-immersion. ×200.

Fig. 5. Vein-like masses of pyrrhotite (po) occurring along the grain boundaries of chalcopyrite (cp). Note that very small rods of sphalerite (sp) oriented in crystallographic direction of chalcopyrite by the unmixing of a solid solution. One nicol. Oil-immersion. ×415.

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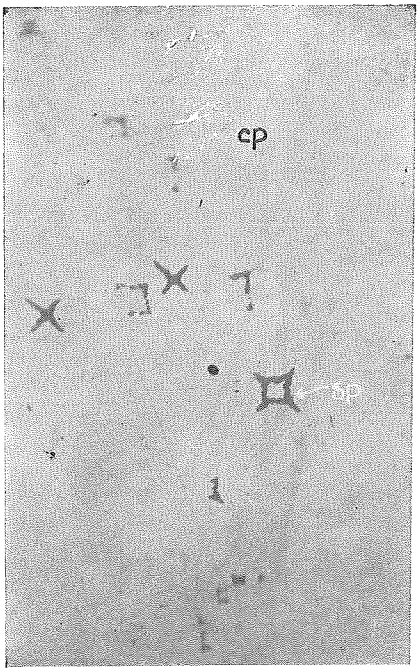

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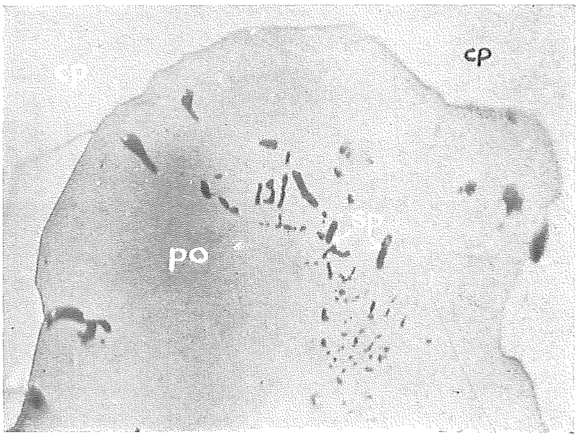

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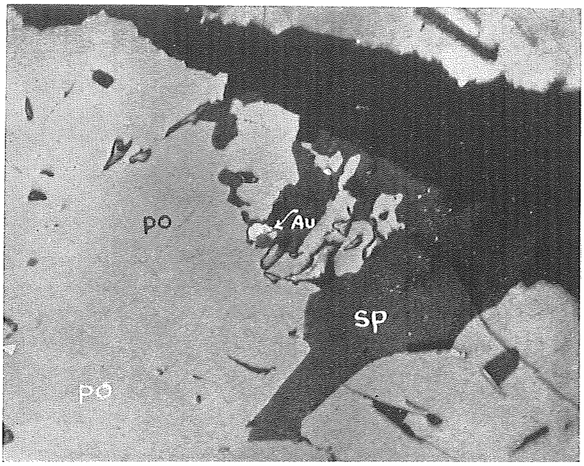

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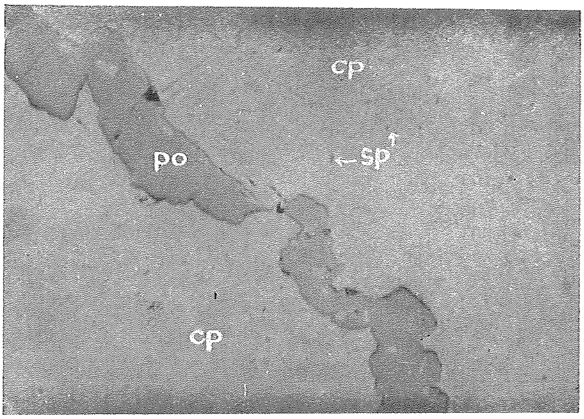

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Plate LXXXII (XXXVII)

Plate LXXXII (XXXVII)

(Photomicrographs of polished sections of gold-ores)

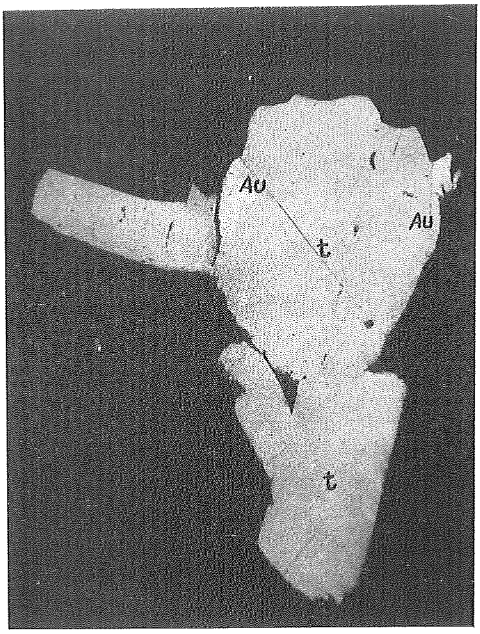
Fig. 1. Crystals of tetradymite (t) embedded in a matrix of calcite. Gold (Au) occurs in boundary-zone. Loc. Kotudô mine. One nicol. ×100.

Fig. 2. Klaprothite (k) replaced by chalcopyrite (cp) and gold (Au). Darker part is bornite (b). Loc. Kotudô mine. One nicol. Oil-immersion. ×200.

Fig. 3. Gold (Au) included in pyrrhotite (pyrr). Pyrrhotite replaced by chalcopyrite (cp). Loc., E. O. B., Kotudô mine. One nicol. ×450.

Fig. 4. A large grain of gold (Au) occurring between chalcopyrite (cp) and gangue (black part). Loc., E. O. B., Kotudô mine. One nicol. ×100.

Fig. 5. Intimate association of gold (Au) with tetradymite (t). Basal cleavage of tetradymite crystals are shown. Loc., Sakusui mine. One nicol. ×410.



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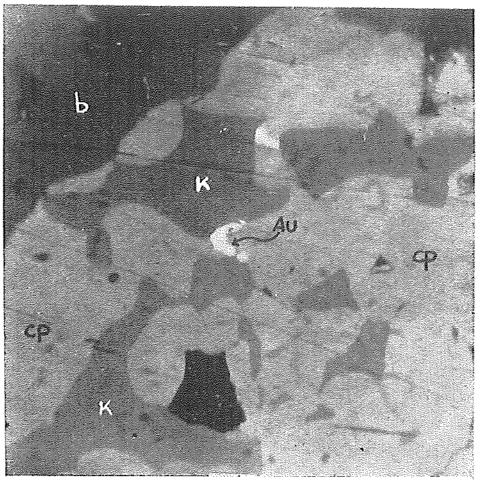

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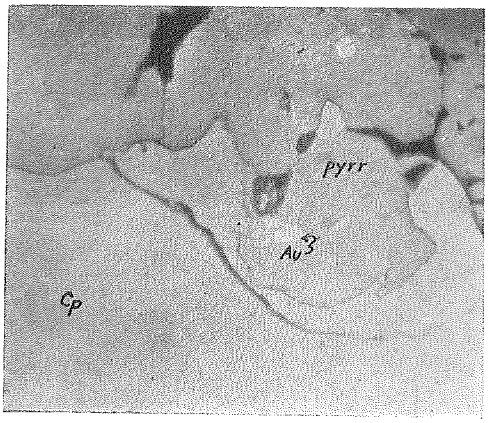

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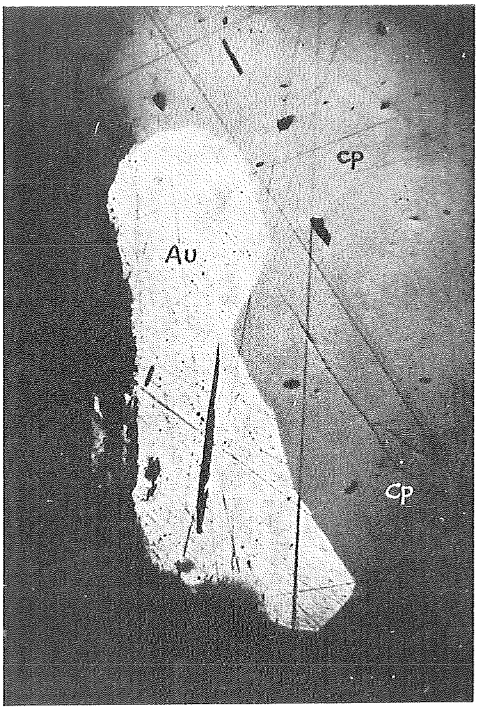

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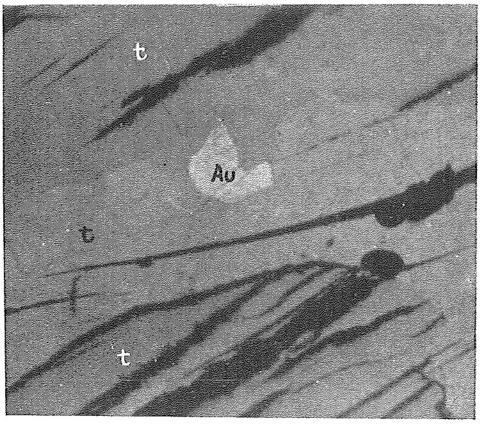

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Plate LXXXIII (XXXVIII)

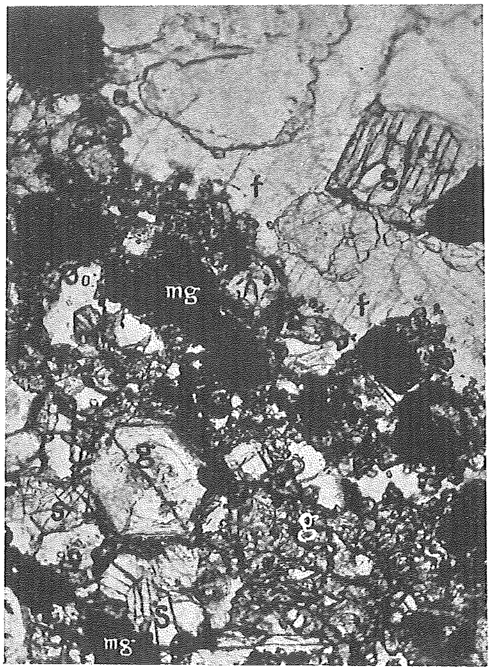
Plate LXXXIII (XXXVIII)

Fig. 1. Photomicrograph of thin section of garnet-salite-skarn from the Nantei mine. g, garnet; s, salite; fl, fluorite; m, magnetite. One nicol. ×64.

Fig. 2. Photomicrographs of thin section of salite-skarn from the Nantei mine. Note that ore-minerals (black) have replaced silicate minerals. One nicol. ×17.

Fig. 3. Photomicrographs of polished section of a mesothermal ore from the Dôgan mine, Nantei. Tetrahedrite (te) replacing chalcopyrite (cp). One nicol. ×100.

Fig. 4. Photomicrographs of thin section of iron-rich amphibole in garnet skarn, showing its strong pleochroism. One nicol. ×34.



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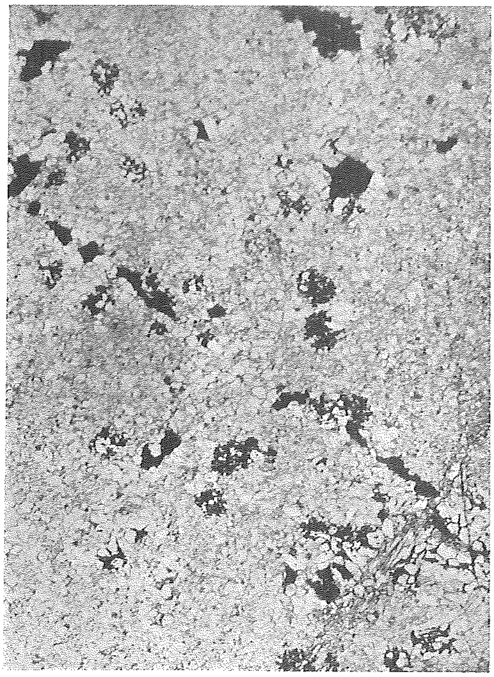

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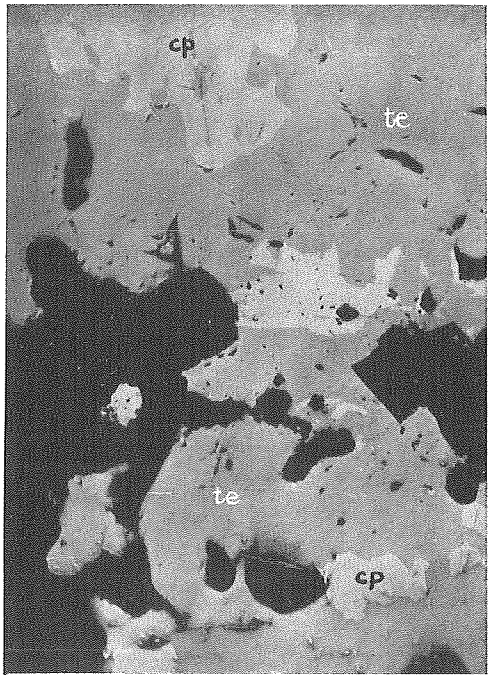

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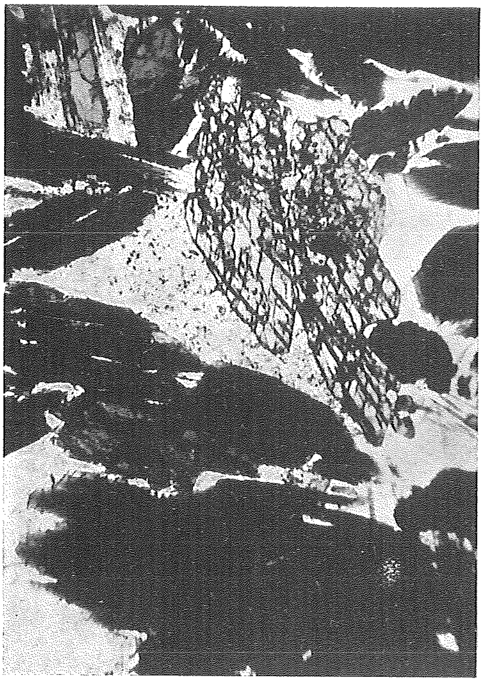

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Plate LXXXIV (XXXIX)

Plate LXXXIV (XXXIX)

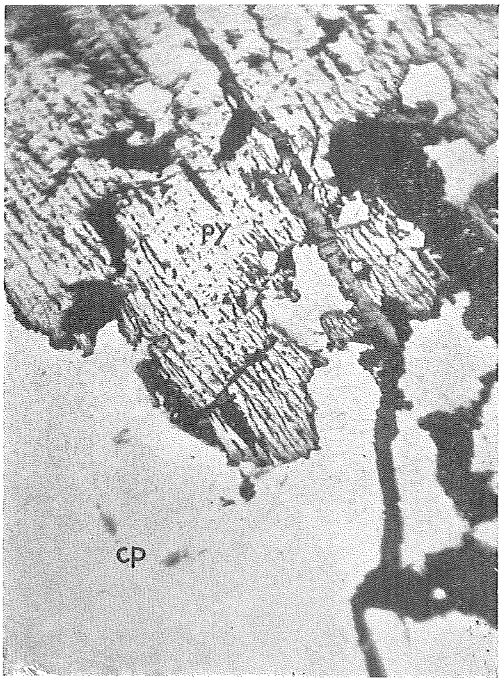
(Photomicrographs of polished sections of ores from
the Nantei mine)

Fig. 1. Pyrite (py) forming a pseudomorph after pyrrhotite and showing the original basal cleavages of pyrrhotite. The original pyrrhotite being replaced by chalcopyrite (cp). One nicol. Oil-immersion. ×200.

Fig. 2. Bent molybdenite (mo) embedded in a matrix of calcite. One nicol. ×89.

Fig. 3. Pyrite (py) and hematite (ht) after pyrrhotite (lower part). Upper isolated patch in gangue consists of gold (Au) and tetradymite (te). One nicol. Oil-immersions. ×200.

Fig. 4. Specimen of high grade gold-ore indicating close association of gold (Au), tetradymite (t) and bismuthinite (Bi_2S_3). Euhedral löllingite (lo) is surrounded by these minerals. One nicol. Oil-immersion. ×300.



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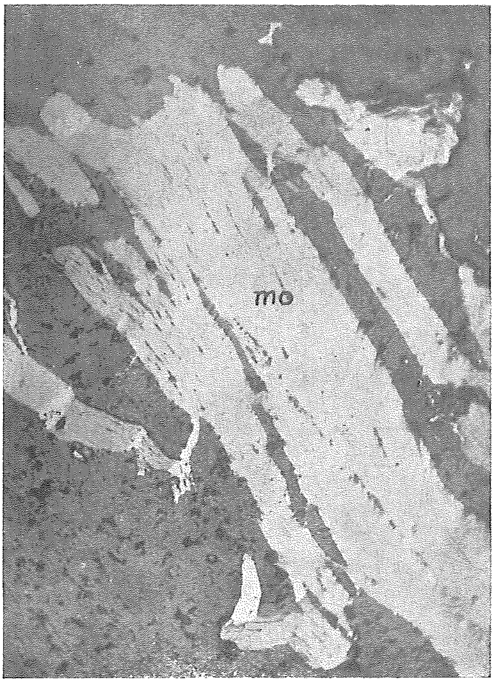

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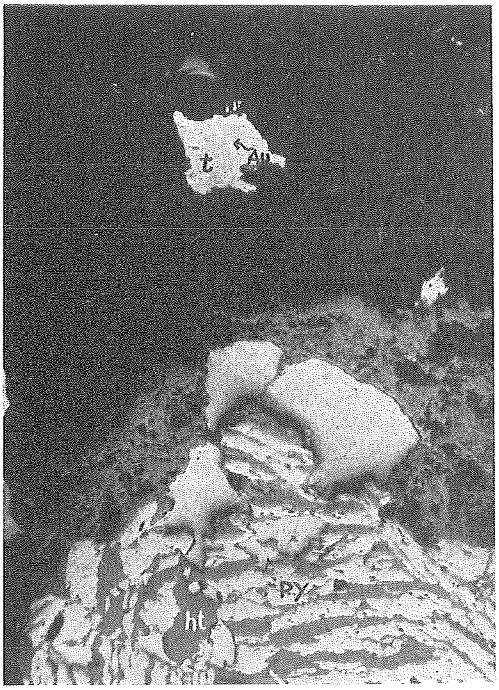

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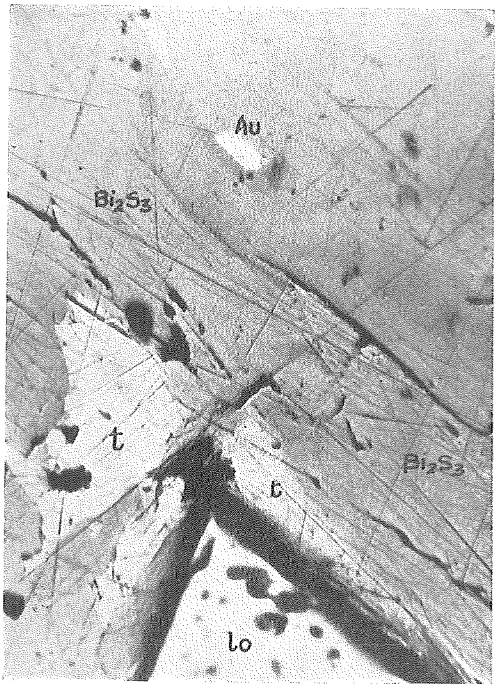

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T. Watanabe: Geology and Mineralization of the Suian District.

Plate LXXXV (XL)

Plate LXXXV (XL)

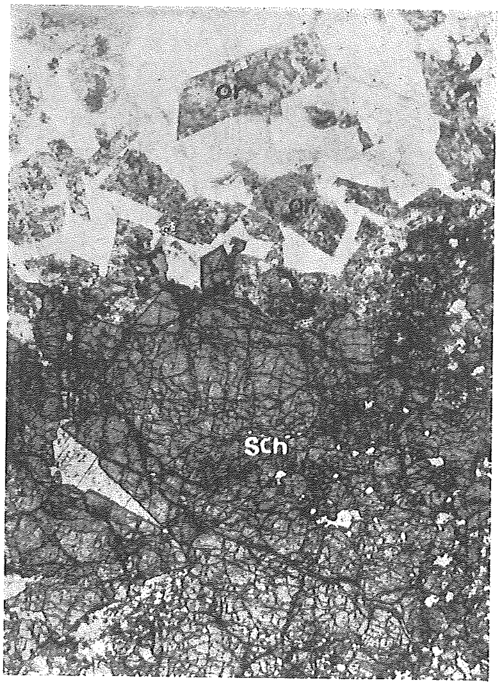
(Photomicrographs of thin and polished sections)

Fig. 1. Thin section of scheelite (sch), Tenzi prospect. Note the occurrence of orthoclase (or) showing adularia habit. White area is quartz. One nicol. ×14.

Fig. 2. Thin section of scheelite ore, Sekitaturi prospect. Sch, scheelite; q, quartz. One nicol. ×14.

Fig. 3. Thin section of sericitized hornfels, a country rock of the Goyô gold-quartz vein. One nicol. ×70.

Fig. 4. Polished section of ore from the Goyô mine, showing the relation of chalcopyrite (cp) to pyrrhotite (po) Sphalerite-stars (sp) are enclosed in chalcopyrite. One nicol. ×100.



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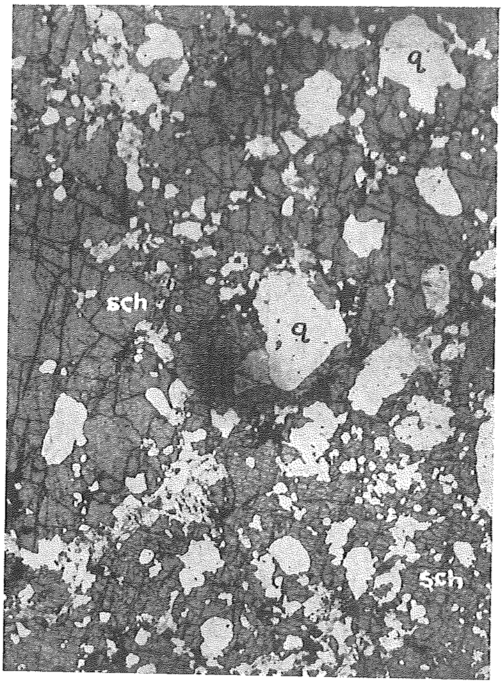

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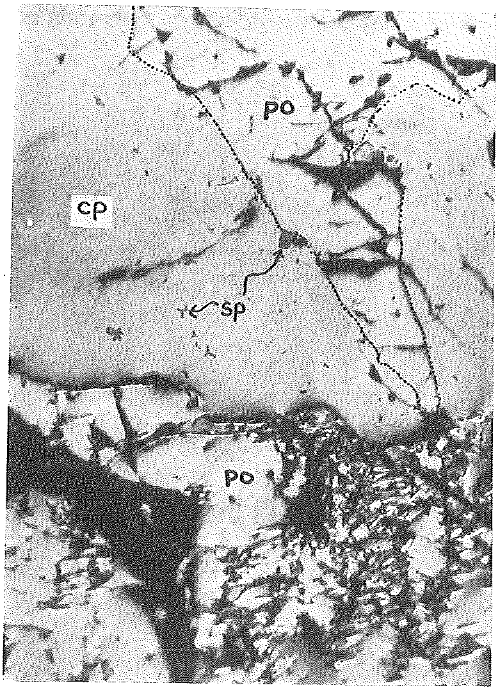

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Plate LXXXVI (XLI)

Plate LXXXVI (XLI)

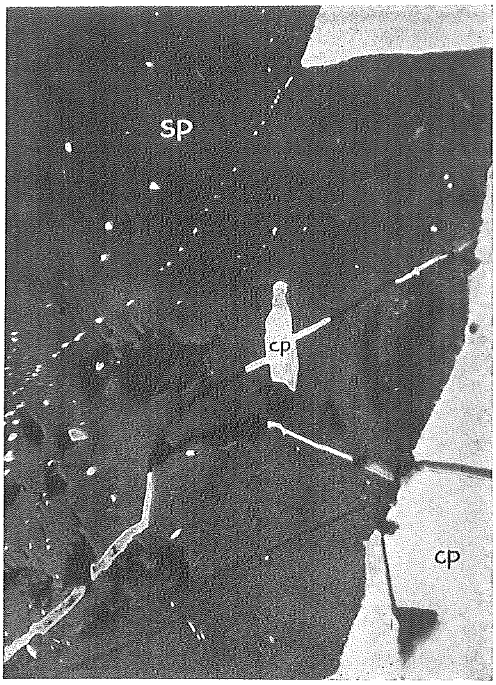
(Photomicrographs of polished sections of ores from
the Goyô mine)

Fig. 1. Sphalerite (sp) cut and replaced by chalcopyrite (cp). Linear arrangement of chalcophyrite-spots in sphalerite suggesting that the former has been formed later than the latter. One nicol. Oil-immersion. ×200.

Fig. 2. Gold (Au) in galena (ga) replacing pyrite (py). sp, sphalerite; py, pyrite. One nicol. Oil-immersion. ×300.

Fig. 3. Galena (ga) replacing pyrite (py) and sphalerite (sp). One nicol. ×145.

Fig. 4. Development of crystals of arsenopyrite (as) on sphalerite (sp). Both minerals are surrounded by chalcopyrite of a later stage (cp). One nicol. ×100.



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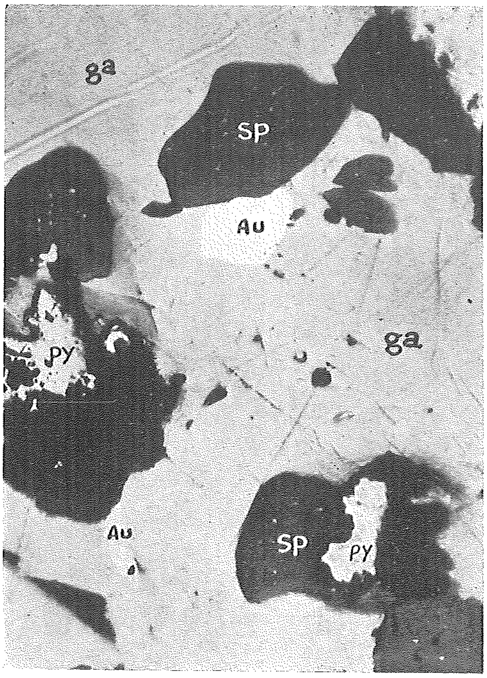

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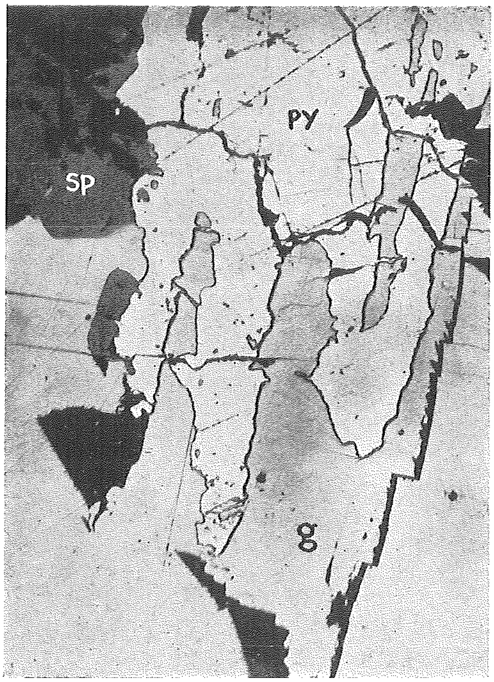

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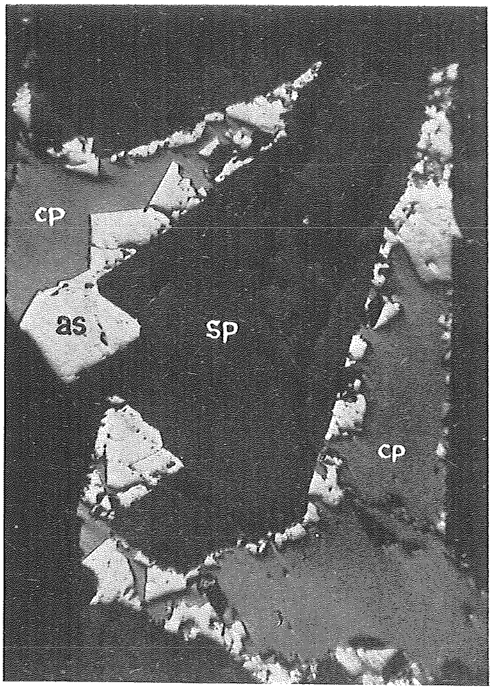

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