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NICKELIFEROUS PYRRHOTITE DEPOSITS AND ORES FROM THE OSHIRABETSU MINE, TOKACHI PROVINCE, HOKKAIDO

by

Takeo Bamba

(with 6 text-figures and 7 tables)

Abstract

Nickeliferous pyrrhotites are found concentrated in various grade in the Oshirabetsu gabbro mass which occupies the southeastern piedmont of the Hidaka mountains, Central Axial Zone of Hokkaido. One of the most characteristic features is that the pyrrhotite is generally accompanied by graphite.

The Oshirabetsu gabbro, host rock of the preceding nickel sulfide ores can be classified into several rock facies: a) olivine gabbro, b) norite, c) hornblende gabbro, d) diorite. The nickeliferous pyrrhotite ores are closely related to the former three rock facies. On the other hand, the nickel sulfide ore is classified into four types: 1) fine-disseminated, 2) coarse-disseminated, 3) semi-massive, 4) massive. The latter two types are structurally controled by fracture or shear zones where abundant quartz, chlorite are generally present and scant garnet and tourmaline are rarely associated.

Pyrrhotites and pentlandites from the above-classified sulfide ores were chemically as well as mineralogically investigated, and the following interesting results have been obtained: Almost all pyrrhotite belongs to hexagonal and peak type thermomagnetically. From the microscopic mode of occurrence, the pyrrhotite was classified into lamella type, granular type and spindle type. The value of (1+x) in chemical formula, FeS_{1+x} of Oshirabetsu pyrrhotite has been shown to be 1.09 in average, ranging from 1.04 to 1.14. Nickel contents in Oshirabetsu pyrrhotite range from 0.02 to 1.19, and it has been found that pentlandite is apt to appear in the pyrrhotite which contains around 1% Ni. On the other hand, Co contents in pentlandite are rather abundant (9.99–12.31) in semi-massive sulfide ores.

Judging from these results, the formation stage of sulfide ores in the Oshirabetsu gabbro can be classified from orthomagmatic to pneumatolytic-hydrothermal phases.

Introduction

Gabbro in which nickeliferous pyrrhotite deposits are present is found at the Oshirabetsu district, southeastern piedmont of the Hidaka mountains, Central Axial Zone of Hokkaido. The most characteristic feature of the ore deposits is the appearance of accessory graphite. The gabbro and the associated ore deposits were studied from the geologic, petrographic and mining aspects by Akaoka et al (1941), Hashimoto (1941, 1949, 1950), Murayama (1946), Koseki (1949), Shiboi et al (1956), Satoh (1953), Bamba et al (1955, 1980), Ishibashi et al (1953, 1956), Kim (1966) and Takahashi (1979).

The following information has been accumulated from the above-mentioned projects.

The mineralized area is located at the eastern part of the Oshirabetsu gabbro mass. The gabbro is considered to be partly metasomatised, and is complicated being composed of various kinds of rock facies as a) olivine gabbro, b) norite, c) hornblende gabbro and d) diorite. Nickeliferous pyrrhotite deposits occur restrictedly in olivine gabbro, norite and in hornblende gabbro facies. Ore is classified into the following four types from the mode of occurrence of pyrrhotite: 1) fine-disseminated, 2) coarse-disseminated and 3) semi-massive

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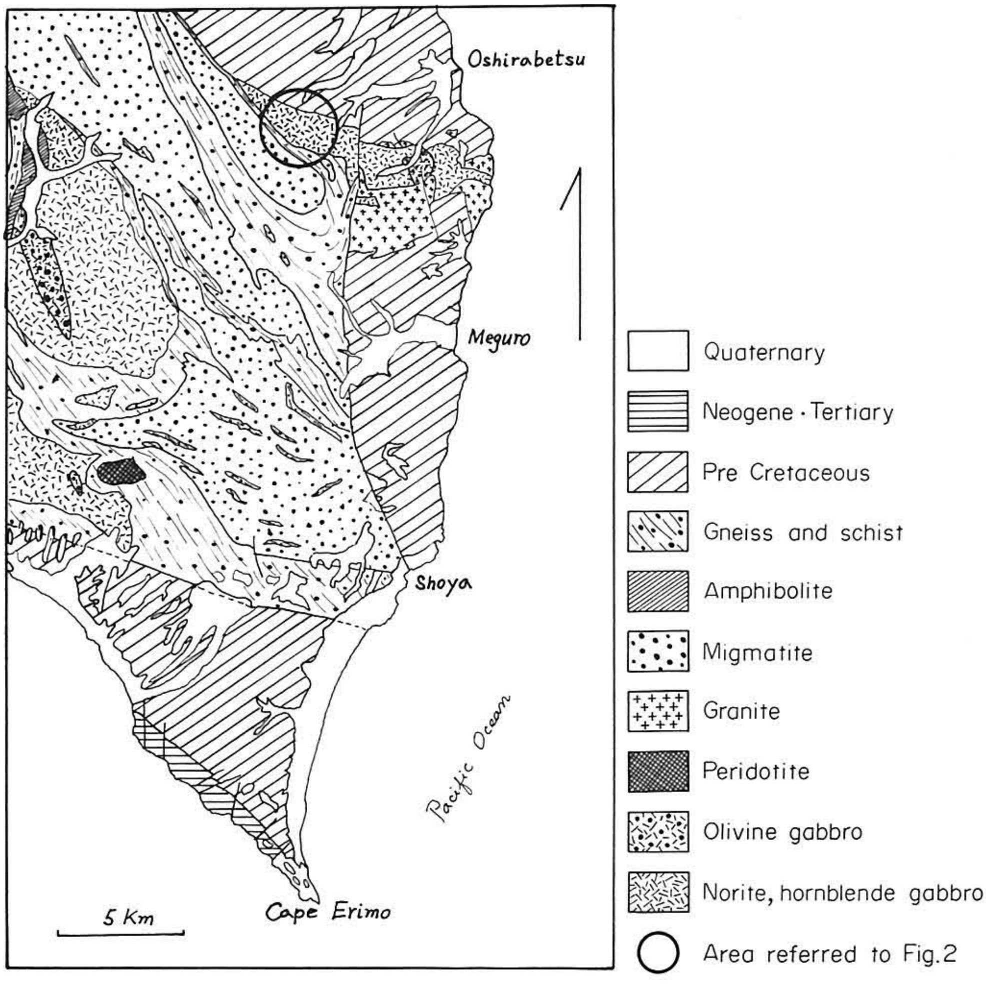
or massive. The fine-disseminated sulfides appear in olivine gabbro, norite and hornblende gabbro facies, and the coarse-disseminated sulfides occur in norite and in hornblende gabbro facies, while the massive and semi-massive ores are independent from the rock facies. This type of ore is structurally controled by fracture or shear developed within the gabbro mass.

Graphite ore is classified into the following four types: a) disseminated, b) pisolite textured, c) massive, d) vein-form. The former two are closely related to pyrrhotite, whereas the third and fourth ones are independent from the pyrrhotite.

Although the ore deposit is considered to be mostly orthomagmatic origin, some are



Text-fig. 1 Geological map of the southern end of the Hidaka mountains indicating the position of the Oshirabetsu gabbro mass.

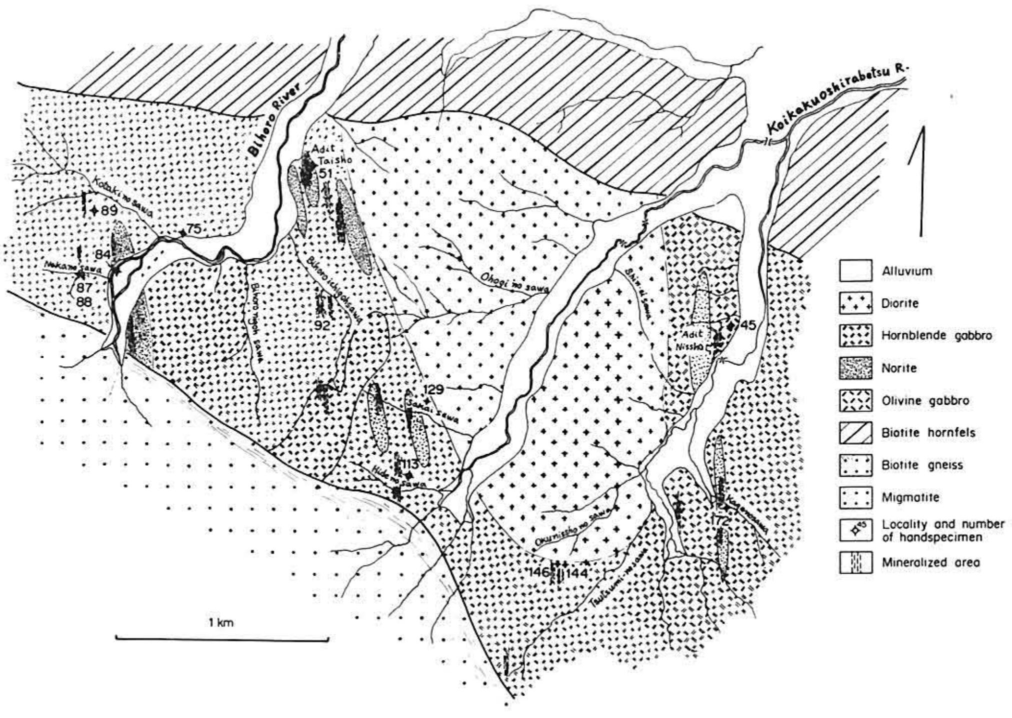
known to be hydrothermal. Mineralogic studies to establish the genetic relationship between pyrrhotite and graphite has not yet been carried out in connection with the study.

The author has been working on the relationship between the sulfide minerals present in the various rock types in question. This study is to show the grade and concentration variation of pyrrhotite and pentlandite in the gabbroic rocks of various types, especially to show the concentration variation of Ni and Co in the nickel sulfide minerals.

Vaughan and Craig (1978) reported to identify hexagonal pyrrhotite in X-ray diffraction method. It is known that Shibuya (1966) made some thermomagnetic studies on pyrrhotites and discussed the implications of his findings. The present work to know the characteristics of the Oshirabetsu pyrrhotite is much indebted to the preceding works.

Outline of Geology

The geology of the mining district was investigated by Hashimoto (1941, 1950). The so-called Hidaka Super Group consisting of a thick Triassic to Jurassic pile of geosynclinal sediments of clastic materials is the basement in this area. At the mining area, biotite hornfels, lower grade metamorphic rock, occurs at the northeastern contact of the gabbro, while higher grade metamorphics, biotite gneiss and migmatite appear at the southwestern contact of the gabbro. In other words, the gabbro in question occupies the boundary of



Text-fig. 2 Map showing the distribution of classified rock facies and mineralized area in the Oshirabetsu gabbro mass.

biotite hornfels and biotite gneiss showing as EW to NW-SE trend (Text-fig.2). This gabbro mass is intruded by tonalitic granite which is believed to be the latest magmatic activity in the Hidaka metamorphic belt.

Various kinds of rock facies, especially hornblende gabbro facies are present near the southwestern contact of the mass. This has been interpreted as meaning that the variation of rock facies of gabbro might have been caused not only by the magmatic differentiation but by the affect of migmatitization.

Though flow structure is obscure, a well developed joint system is observable in the gabbro as shown in Text-fig.3. Dominant joint trend is NW-SE, dipping towards diorite. If a dome structure model is accepted for the diorite intrusion, the joint trend given here could be explained as "cross joint" (Steilen Querklüften) as defined by Cloose (1963).

Classification of Rock Facies of the Oshirabetsu Gabbro

The gabbro is massive in appearance but flow structure and cumulate texture are obscured. A change of rock types based on the mineral assemblage in the mass is quite noticeable. Hashimoto (1950) distinguished the following rock facies based on the mineral assemblage: 1) olivine gabbro, 2) norite, 3) hornblende gabbro and 4) diorite.

The boundaries of above-stated rock facies are generally irregular and gradational. This feature makes the expression of geology on the map difficult. Besides, fine-grained rock facies as well as coarse-graind rock facies, and sometimes pegmetites are present in the gabbro mass, so the classification of rock facies dealt with in this paper has only been given as in Text-fig.2. There is a tendency that diorite facies occupies the central part of the mass and hornblende gabbro facies in which norite facies occluded surrounds the former.

Description of Gabbro

The Oshirabetsu gabbro mass is mainly composed of a) olivine gabbro, b) norite, c) hornblende gabbro and d) diorite. The relationship between the above-stated rock facies in the field is complicated, the boundary between different rock facies is generally gradational. Only olivine gabbro shows a contrast with neighbouring norite in field occurrence, but others resemble to each other, so it is hard to distinguish one from another in the field. Therefore, microscopic studies help to determine different rock facies.

Diorite facies is characterized by the presence of a considerable amount of biotite and quartz. The lack of sulfide minerals in diorite facies is one of the most fundamental features of the Oshirabetsu gabbro mass, whereas olivine gabbro, norite and hornblende gabbro rocks in the same mass are the host rocks for the nickeliferous pyrrhotite. That is to say the occurrence of sulfide mineralization is restricted to those three preceding rock facies. Descriptions of typical olivine gabbro, norite, hornblende gabbro and diorite are below.

Olivine gabbro

This is comparatively coarse-grained and melanocratic consisting mainly of olivine, rhombic pyroxene and plagioclase. Olivine shows mesh structure caused by the replacement of serpentine minerals in which magnetite dust is abundant. The serpentine area is partly composed of blue coloured chlorite that indicates the presence of Ni. Plagioclase ranges from

	(b)	(c)	(c)	(d)
SiO_2	51.90	53.80	57.16	58.27
TiO_2	1.64	0.64	1.01	1.15
Al_2O_3	17.00	15.00	17.18	15.28
Fe_2O_3	5.02	4.95	3.36	4.19
FeO	7.34	7.41	4.75	5.62
MgO	4.07	6.42	4.01	4.19
CaO	10.26	10.97	7.04	6.11
Na_2O	2.32	3.51	2.45	3.51
K_2O	0.42	0.69	0.76	1.43
H_2O (+)	0.07	0.80	1.09	0.89
H_2O (−)	0.01	0.68	−	−
Total	100.05	99.87	99.13	100.64

Analyst: Seiji Hashimoto

(b): norite (c): hornblende gabbro (d): diorite

Table 1 Chemical composition of the classified rock facies of the Oshirabetsu gabbro, Central Axial Zone of Hokkaido

An_{60} to An_{80}. Scattering sulfide mineral is fine-grained and scant. The sulfide minerals occur along the boundaries between silicate minerals or along the cleavage of silicate mineral showing intersertal texture. Pyrrhotite, pentlandite and chalcopyrite are major constituents of the sulfide clots. Chemical composition of this rock facies has not yet been examined.

Norite

The essential minerals are plagioclase and orthopyroxene. Clinopyroxene, biotite, hornblende, pyrrhotite and quartz are observed as accessory minerals. Their ratios are estimated as follows: plagioclase 50% orthopyroxene 20% hornblende 15% clinopyroxene 5% others in total 10%

The grain size of each mineral is 1–2mm on average. Plagioclase from this rock facies has been optically measured on many crystals by Kim (1966), and it has been concluded that there are two peaks of concentration around An_{40} and An_{57}.

Orthopyroxene is prismatic, pale brownish green in colour, occasionally they have a rim of brown hornblende. Fine-grained biotite is seen along the cleavage of the orthopyroxene. On the other hand, small amount of platy biotite showing 0.5–1.0mm of diameter is frequently present in norite. Pyrrhotite in which chalcopyrite and pentlandite are present is intersertal with silicate minerals, especially the pyrrhotite is frequently accompanied by this platy biotite. The chemical composition of this rock has been studied by Hashimoto (1957) as given in Table 1.

Hornblende gabbro

Plagioclase, hornblende, biotite, quartz, pyrrhotite and pyroxenes are essential constituent minerals of hornblende gabbro. Grain size of above-stated minerals is 2–3mm on average, rather coarse compared with those of norite.

Plagioclase is tabular, sometimes takes lath-shape in thin section. Both of them show well developed albite twinning. The tabular shaped one was considered as a kind of porphyroblast by Kim (1966), and it has been shown that An molecular percent value concentrates around An_{57}. Strictly speaking, when zoning is observed, the core of plagioclase shows An_{60} and the rim An_{48} on average. On the other hand, An molecular percent of lath-shaped plagioclase is estimated around An_{45} measured through the maximum symmetrical distinction angle method.

Hornblende is 1.5x3.0mm in size. It is pale brown in colour and pleochroism is X=Y=colourless Z=pale brown. Small flaky biotite appears along the cleavage of hornblende. Besides, idiomorphic biotite of 0.6mm in size is also observed. A considerable amount of intergranular quartz is present in which small amount of apatite is associated. Scattering of fine-grained pyrrhotite showing various grades of concentration is intersertal with silicate minerals. This is the characteristic feature of this hornblende gabbro. Chemical composition of this rock is given in Table 1.

Diorite

Diorite defined in this paper is gradational to the preceding hornblende gabbro in field occurrence and in rock properties, i.e. the abundance of hornblende and pyrrhotite decreases in the diorite in question compared with those of hornblende gabbro. In the rock, the amount of hornblende decreases with the increase of biotite and quartz. Silica content reaching percent is 58.27 as given in Table 1. On the basis of mineral association and of chemical composition, the present author has used the term "diorite" for the above-noted rock.

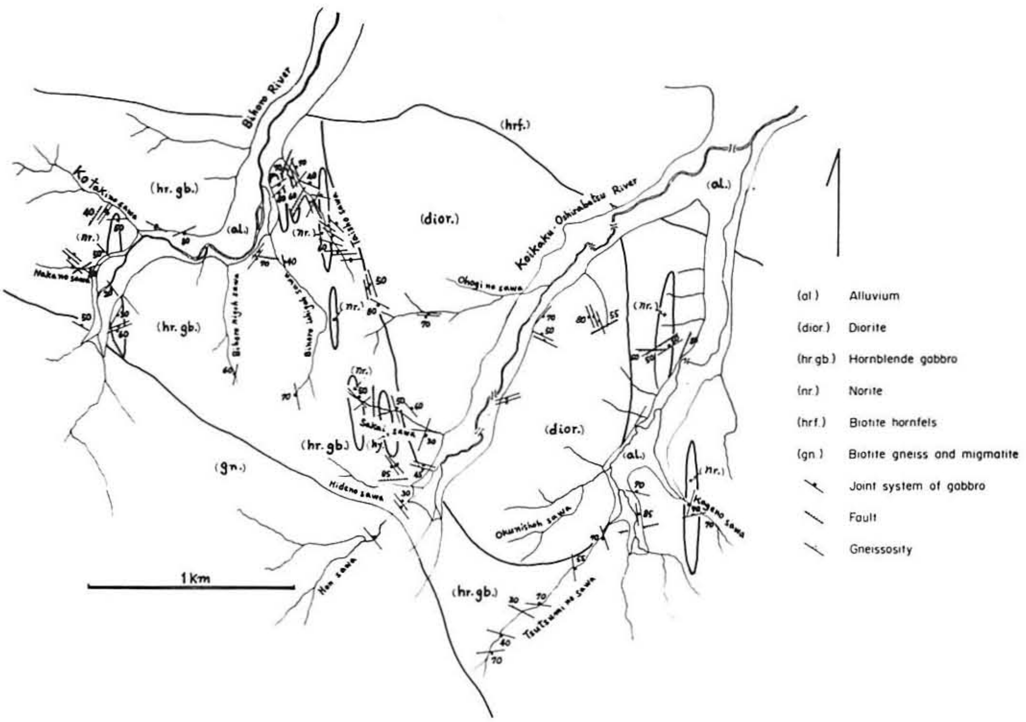
Mode of Occurrence of Nickeliferous Pyrrhotite

Mineralization characterized by the presence of nickeliferous pyrrhotite is localized in the western part of the Oshirabetsu gabbro mass. The pyrrhotite is restrictedly found in olivine gabbro, norite and in hornblende gabbro, nevertheless, in the diorite, sulfide mineral is unobserved. The most highly concentrated sulfide ore body which was exploited until 1955 is in the Taisho gallery (Text. fig.4) along the down stream section of the Bihoro river.

Mineralized zones recognized on the surface are shown in Text-fig.2. The mineralized zones are distributed in the western and eastern parts of the mapped Oshirabetsu gabbro mass. This means that the formation of sulfide ore is closely related to the peculiar rock facies as the hornblende gabbro and the norite facies.

The structural pattern of the gabbro mass is given in Text-fig.3. As shwn in the map, flow structure is obscure, whereas, joint systems are well developed. Two joint systems are distinguished. One of joint systems shows a radial pattern trending towards the center of the diorite. On the other hand, another joint system appears to be parallel to the boundary between diorite and surrounded hornblende gabbro. The former should belong to the cross joint and the latter to the longitudinal joint systems. Judging from the above-stated features, it is estimated that there exists a kind of dome structure with diorite as its center.

A shear zone where massive pyrrhotite is present is observed at the lower stream of



Text-fig. 3 Map showing the distribution of joint system in the Oshirabetsu gabbro mass.

Bihoro river along the boundaries between different rock units such as norite and hornblende gabbro. Concentration of pyrrhotite is known to be showing N-S trend as given in Text-fig.4. Thus the structural control of the Oshirabetsu pyrrhotite is distinct as stated by Shiboi et al (1956).

Classification of Sulfide Ore

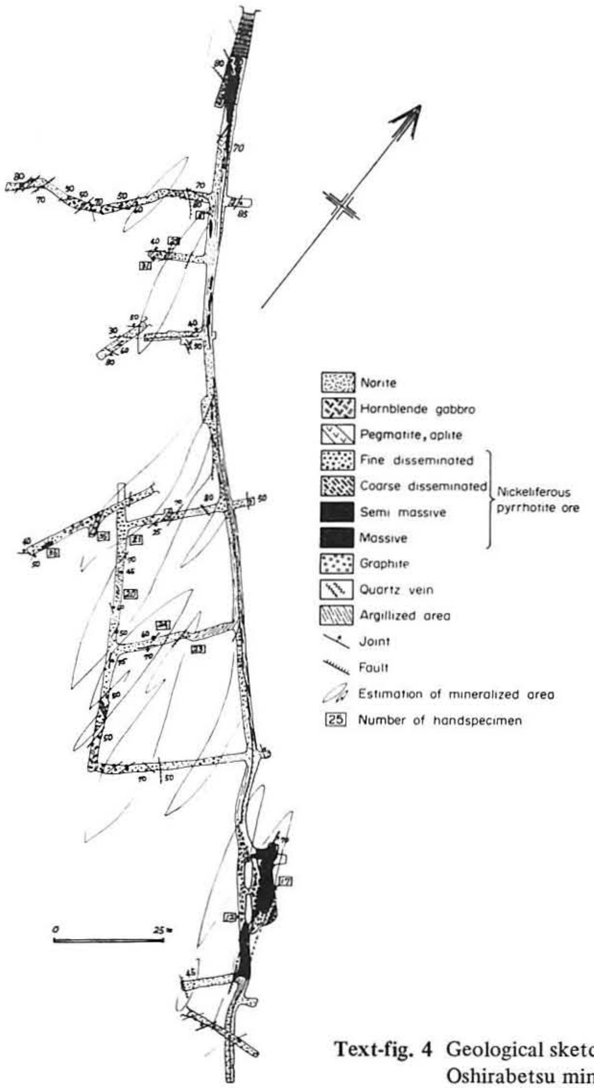
Nickeliferous pyrrhotite ore from the Oshirabetsu mine is tentatively classified as given in Table 2.

More or less one hundred handspecimens of sulfide ore were collected by the present author from the Oshirabetsu mine. Chemical analyses, X-ray diffraction and microscopic studies of the samples collected have been carried out. On some of the pyrrhotites (30 specimens listed in Table 2), etching test, reflectivity and VHN measurements and thermomagnetic studies have also been made. The results obtained are given in Table 3*. Pyrrhotite and pentlandite in each rock facies are described here in this paper.

a) Fine-disseminated ore in olivine gabbro

Handspecimen, number 1 belongs to this type of ore. Small aggregation of pyrrhotite, pentlandite and chalcopyrite form the sulfide clot scattered. The size of the clot is 1–2mm.

* Niccolite (Ishibashi *et al,* 1956) and cubanite (Ishibashi *et al,* 1953) have been reported from the Oshirabetsu mine. These minerals seem to be rare, and these are omitted from the list.



Text-fig. 4 Geological sketch of the Taisho gallery, Oshirabetsu mine.

Pyrrhotite is major constituent of the sulfide clot and this mineral shows spindle texture microscopically. The pyrrhotite has been chemically analysed by EPMA. The value of (1+x) in FeS_{1+x} shows wide variation ranging from 1.04 to 1.116. The higher value has been obtained at the spindle of the pyrrhotite. 0.23% Ni was detected from the pyrrhotite. Etching test by the saturated solution of CrO_3 was applied, reaction was negative during 7 minutes period. This pyrrhotite was clarified to be hexagonal through the X-ray diffraction.

Pentlandite and chalcopyrite are commonly found at the margin of pyrrhotite. The pentlandite contains 3.08% Co and 32.32% Ni. Consequently Co/Ni=0.09.

Table 2 Classification of nickeliferous pyrrhotite ore from the Oshirabetsu Mine, Hokkaido

a)	fine-disseminated in olivine gabbro	1*
b_1)	fine-disseminated in norite	21* 23 24 43 75 100 129
b_2)	coarse-disseminated in norite	5 20 29* 31 35
b_3)	semi-massive in norite	16 36*
c_1)	fine-disseminated in hornblende gabbro	45* 87 88 89* 92 94* 172
c_2)	coarse-disseminated in hornblende gabbro	17 55* 84 113 114* 146
c_3)	semi-massive in hornblende gabbro	12*
d)	semi-massive in graphite ore	44*
e)	massive	51*

Specimen numbers given on the right correspond with the classified ore.
* Specimen chemically analysed.

b_1) Fine-disseminated ore in norite

Handspecimens, sample number 21, 23, 24, 43, 75, 100 and 129 belong to the fine-disseminated ore in norite. Sulfide mineral association of pyrrhotite-chalcopyrite-pentlandite is common. Sometimes violarite formed along the cracks of pentlandite is observed microscopically. In two of the handspecimens, ilmenite and graphite are associated. Pyrrhotite is distinguished that there exist lamella type, spindle type and granular-bleb type from its allotropism as given in Plate 5. Thermomagnetic examination of pyrrhotite shows that almost of these belong to peak type. To distinguish monoclinic and hexagonal pyrrhotite, etching test with saturated solution of CrO_3 in water was applied, reaction was in general negative during the 10 minutes period. X-ray diffraction analyses, thermomagnetic examination and etching studies have determined that these pyrrhotites belong to hexagonal phase. The value of 1+x in FeS_{1+x} of the pyrrhotite of this phase is calculated as 1.089.

Cobalt is not detected in the pyrrhotite but about 1% of nickel is detected. Pentlandite occurs as a fine-grained xenomorphic crystal. Flame-like bodies of pentlandite are observed in the lamella type pyrrhotite, especially along the boundaries of lamella twinning (Plate 5-5). The value of Co/Ni in pentlandite is small, e.g. pentlandite contains 2.24% Co and 34.20% Ni, consequently Co/Ni=0.065.

b_2) Coarse-disseminated ore in norite

Five handspecimens (5, 20, 29, 31, 35) are examined. Sulfide mineral association of pyrrhotite-chalcopyrite-pentlandite is common, but some of them contain violarite along the cracks of pentlandite. Pyrrhotites from three handspecimens (5, 20, 31) belong to lamella-spindle type, and the other two are of granular type. Thermomagnetic examination for these pyrrhotite shows that these are peak type. Based on a chemical analysis of pyrrhotite, chemical formula of the pyrrhotite from b_2 phase can be given as $FeS_{1.096}$. Nickel content of the pyrrhotite is more or less 1%, and 0.05% cobalt is detected (Table 3).

A pentlandite from this group of ore was chemically analysed by EPMA. The results

Table 3 Mineral association of nickeliferous pyrrhotite ore and some other characteristics of pyrrhotite from the Oshirabetsu mine, Tokachi Province, Hokkaido

specimen	number	ore mineral association	allotropism of pyrrhotite	thermomagnetic type of pyrrhotite
(a)	1	po-cp-pe	spindle	.
(b_1)	21	po-cp-pe-vio	granular	
	23	po-cp-pe	lamella	
	24	po-cp-pe	lamella	peak
	43	po-pe-gph	granular	
	75	po-il-gph	granular	
	100	po-cp-il	granular	
	129	po-cp-pe-il	lamella & granular	peak
(b_2)	5	po-cp-pe-vio	lamella	
	20	po-cp-gph	spindle	
	29	po-cp-pe-vio-gph	granular	peak
	31	po-cp-pe-gph	lamella	
	35	po-cp-pe-il	granular	peak
(b_3)	16	po-cp-pe-il	lamella & granular	peak
	36	po-pe	granular	peak
(c_1)	45	po-cp-pe	granular	weiss
	87	po-cp-py-il	granular	
	88	po-cp-pe	granular	
	89	po-cp-pe	spindle	peak
	92	po-cp-pe-il	lamella & granular	
	94	po-cp-pe	granular	intermediate
	172	po-cp-pe	granular	peak
(c_2)	17	po-cp-mt	lamella	
	55	po-cp-pe-gph	lamella	
	84	po-pe-gph	granular	
	113	po-cp-pe	granular	
	114	po-cp-pe-mt	granular	peak
	146	po-cp-pe	lamella & granular	peak
(c_3)	12	po-cp-pe	lamella	
(d)	44	po-cp	lamella	peak
(e)	51	po-py-il	lamella & granular	peak

(a) : fine-disseminated in olivine gabbro
(b_1) : fine-disseminated in norite
(b_2) : coarse-disseminated in norite
(b_3) : semi-massive in norite
(c_1) : fine-disseminated in hornblende gabbro
(c_2) : coarse-disseminated in hornblende gabbro
(c_3) : semi-massive in hornblende gabbro
(d) : semi-massive in graphite ore
(e) : massive

po : pyrrhotite
cp : chalcopyrite
pe : pentlandite
vio : violarite
gph : graphite
il : ilmenite
mt : magnetite
py : pyrite

obtained are given in Table 5. It shows that pentlandite contains 5–6% cobalt and 33% nickel. The values of Co/Ni in pyrrhotite and in pentlandite from this group of ore are as follows:

pyrrhotite Co/Ni=0.05–0.06
pentlandite Co/Ni=0.14–0.21

The value of Co/Ni in pentlandite is three times higher than that in pyrrhotite.

b_3) Semi-massive ore in norite

Handspecimens of samples 16, 36 belong to this phase. Concentration grade of sulfide minerals in the ore amounts to more than 50%. Major constituent of sulfide minerals are generally made up of pyrrhotite, pentlandite and chalcopyrite. In specimen of no.16, ilmenite is also observed. It is the characteristic feature of the ore of this group that no graphite is found associated. Pyrrhotite of this phase is microscopically granular textured type, and thermomagnetically it belongs to peak type. Etching test with saturated solution of CrO_3 applied tarnishes some areas of polished pyrrhotite in four minutes. Both of pyrrhotite, tarnished and non-tarnished, are however determined as hexagonal phase by X-ray diffraction studies. The chemical formula of the pyrrhotite is calculated as $FeS_{1.094}$ containing 0.02% Co and 0.47% Ni.

Pentlandite accompanied by the pyrrhotite was chemically analysed by EPMA. Results obtained are given in Table 5. The values of Co/Ni in pyrrhotite and in pentlandite from this ore are respectively calculated as follows:

pyrrhotite Co/Ni=0.04
pentlandite Co/Ni=0.33

c_1) Fine-disseminated ore in hornblende gabbro

Handspecimens of samples 45, 87, 88, 89, 92, 94 and 172 belong to this phase. Sulfide minerals present are in general pyrrhotite, chalcopyrite and pentlandite. Specimen no.87 contains a small amount of pyrite. Graphite is scant or absent in this phase. Microscopic texture of pyrrhotite belongs wholly to granular type as shown in Plate 5-1. From thermomagnetic analysis of the pyrrhotite, peak type, weiss type and intermediate type were recognized.

Structural etching for three handspecimens with a saturated solution of CrO_3 gave interesting results two of them are negative but one of them (no.89) is positive. i.e. CrO_3 liquid stains the polished surface of pyrrhotite except spindle area, so the spindle texture of pyrrhotite becomes much more clear. It is interesting that chemistry of the tarnished area of pyrrhotite and of untarnished spindle of pyrrhotite examined by EPMA are almost the same, furthermore, these two pyrrhotites are indistinguishable from the X-ray diffraction analysis, as these two show the diffraction pattern indicating hexagonal phase.

Pyrrhotites from three handspecimens (45, 89, 94) of this phase were chemically analysed by EPMA as given in Table 4. From the chemical composition, the chemical formula of the pyrrhotite is estimated to show a variation between $FeS_{1.095}$–$FeS_{1.140}$ (Table 6). Cobalt and nickel contents of the pyrrhotites of this phase are given in Table 4. Pentlandite associated with the pyrrhotite of this phase was also analysed by EPMA. It has been shown that pentlandites of this phase contain 6.9–4.7% cobalt and 33–31% nickel, therefore Co/Ni is calculated as 0.2–0.15.

Table 4 Chemical composition of pyrrhotite from the Oshirabetsu Mine, Hokkaido

wt %

	S	Fe	Co	Ni	Total
1 (a)	38.90	60.39	–	0.39	99.96
21 (b_1)	38.53	60.27	–	1.10	99,90
29 (b_2)	38.51	60.25	0.05	0.95	99.76
36 (b_3)	38.52	60.83	0.02	0.47	99.84
45 (c_1)	39.19	58.78	0.10	1.09	99.16
89 (c_1)	38.23	59.88	0.06	1.08	99.25
94 (c_1)	37.76	61.51	–	0.37	99.64
55 (c_2)	38.70	60.19	0.02	0.79	99.70
144 (c_2)	38.30	60.14	–	0.74	99.18
12 (c_3)	38.60	61.63	0.06	0.51	100.80
44 (d)	38.61	61.57	0.04	0.02	100.24
51 (e)	37.88	61.74	0.10	0.52	100.24

Analyst: Eijun Ohta

Table 5 Chemical composition of pentlandite from the Oshirabetsu Mine, Hokkaido

wt %

	S	Fe	Co	Ni	Cu	Total
1 (a)	33.16	30.76	3.08	32.32	–	99.32
21 (b_1)	33.82	28.84	2.24	34.20	0.17	99.27
29 (b_2)	33.34	28.18	5.13	33.38	–	100.03
36 (b_3)	33.76	26.83	9.99	29.67	–	100.25
89 (c_1)	33.62	26.57	6.99	33.23	–	100.41
94 (c_1)	33.62	29.66	4.76	31.06	–	99.10
55 (c_2)	33.77	26.51	6.86	32.78	–	99.92
144 (c_2)	33.34	30.39	1.80	34.21	–	99.74
12 (c_3)	33.83	25.30	12.31	28.36	–	99.80

Analyst: Eijun Ohta

c_2) Coarse-disseminated ore in hornblende gabbro

Handspecimens 17, 55, 84, 113, 144 and 146 belong to this phase. Essential sulfide minerals of these ores are pyrrhotite, chalcopyrite and pentlandite. Two of these, nos.17 and 144 are associated with magnetite. Another two of them, nos.55 and 84, are accompanied by graphite. Pyrrhotite can be separated into granular and lamella types from microscopic texture, while both gave negative results in the chemical etching test by saturated solution of CrO_3. Pyrrhotites from the above-stated six handspecimens thermomagnetically belong to the peak type.

Pyrrhotites from handspecimens (55, 144) were chemically analysed. On the basis of chemical composition of pyrrhotite, the chemical formula of this mineral is calculated as $FeS_{1.101}$-$FeS_{1.102}$. Nickel content of the pyrrhotite is 0.74–0.79% and cobalt was determined as 0.02–0.06%. Pentlandite associated with the pyrrhotite contains 6.86–1.80% cobalt and 32.78–34.21% nickel.

c_3) Semi-massive ore in hornblende gabbro

Handspecimen no.12 belongs to this kind of ore. Pyrrhotite, chalcopyrite and pentlandite are major costituents. Pyrrhotite shows lamella twinning. The pyrrhotite was shown by X-ray diffraction studies to be of hexagonal phase and is negative in structural etching test by saturated solution of CrO_3. The pyrrhotite belongs to the peak type thermomagnetically. One of the most characteristic features of the ore is the presence of peculiar milmekite texture shown by quartz and albite. This texture indicates that the formative condition of the ore seems to belong to the final phase of solidification of magma.

On the basis of chemical analysis, the chemical formula of pyrrhotite is given as $FeS_{1.081}$, and EPMA analysis shows that it contains 0.06% cobalt and 0.51% nickel, therefore Co/Ni is calculated as 0.14. Pentlandite from this ore has been analysed by EPMA and 12.31% cobalt has been detected. It is notable that this is the highest percentage of cobalt in pentlandite form the Oshirabetsu ore. Nickel content of this pentlandite is 28.36%, consequently Co/Ni value is calculated as 0.43.

d) Semi-massive ore occluded in massive graphite ore

Handspecimen no.44 belongs to this type of ore. This occurs at the Taisho gallery. Sulfide mineral assemblage is made up of abundant pyrrhotite and scanty chalcopyrite. The texture of pyrrhotite is granular type as given in Plate 5-1. Fine-grained bleb-form pyrrhotite of 0.3–0.5 mm concentrates irregularly and form semi-massive ore. Silicate minerals, diopside, garnet, tourmaline, chlorite and quartz are present as gangue minerals. From the above-stated mineral association as well as the texture, this rock facies seems to be formed in a skarn zone. The garnet hexagons commonly co-axial intergrowth in thin section. The manner of intergrowth is easily recognized by the peculiar anisotropism of garnet.

From the thermomagnetic studies of this type of pyrrhotite, it is shown that the mineral is of the peak type. An etching test made by applying a saturated CrO_3 solution produced a negative result. X-ray diffraction studies of this mineral have also indicated that pyrrhotite is hexagonal phase. From the above-noted mineral assemblage, the formation processes of this ore are considered to be related with the pneumatolytic-high temperature hydrothermal phase. Pyrrhotite has been chemically analysed by EPMA and the chemical formula has been calculated as $FeS_{1.090}$ containing 0.04% cobalt and 0.02% nickel.

e) Massive ore

Handspecimen sample number 51 represents this type of ore. Highly concentrated massive pyrrhotite ore is restrictedly found only in the Taisho gallery as shown in Text-fig.4. The ore is composed of pyrrhotite and accessory pyrite. Pyrrhotite is generally granular but some are of spindle type. Both of these gave negative result in structural etching test made

Table 6 The value of (1+x) in FeS_{1+x} (pyrrhotite) from the Oshrabetsu mine, Hokkaido

	(1+x) in FeS_{1+x}
1 (a)	1.116-1.046
21 (b_1)	1.089
29 (b_2)	1.096
36 (b_3)	1.094
45 (c_1)	1.140
89 (c_1)	1.095
94 (c_1)	1.103
55 (c_2)	1.102
144 (c_2)	1.101
12 (c_3)	1.081
44 (d)	1.090
51 (e)	1.060

Table 7 Reflectivity and hardness (VHN) of pyrrhotites

phase	$R_{(o)}$	$R_{(e)}$	VHN
	(547nm)	(547nm)	(100g)
(b_2) fine-disseminated in norite	34.5-36.8%	35.0-36.5%	258-294
(b_3) semi-massive in norite	36.0-37.2%	37.5-37.7%	236-254
(c_1) fine-disseminated in ho-gabbro	33.2-33.5%	33.5-35.5%	236

by a saturated CrO_3 solution. X-ray diffraction studies show that it is of hexagonal phase. Thermomagnetic analysis indicates that pyrrhotite is of peak type. Pyrite occurs in the vein form along the cleavage or cracks of the pyrrhotite. From the mode of occurrence, it is easily seen that of pyrite is formed subsequent to the pyrrhotite phase. EPMA analysis of pyrrhotite was carried out and the chemical formula has been given as $FeS_{1.060}$ which contains 0.10% Co and 0.52% Ni.

Reflectivity and VHN of Oshirabetsu pyrrhotites

Measurements of reflectivity and VHN of pyrrhotites from b_2, b_3 and c_1 phases were carried out and the results obtained are given in Table 7. The reflectivity of Oshirabetsu pyrrhotite shows a rather low value compared with the pyrrhotite of Uytenbogaardt and Burke (1971)'s average of R(o) 34.0%, R(e) 39.2% in 546 nm. The VHN of Oshirabetsu pyrrhotite is lower compared with the maximum VHN of pyrrhotite which was measured by Uytenbogaardt and Burke (1971). Oshirabetsu pentlandites are unfortunately unmeasurable for the reflectivity and VHN, as the individual grains are too small in size.

Explanation of Plate 1

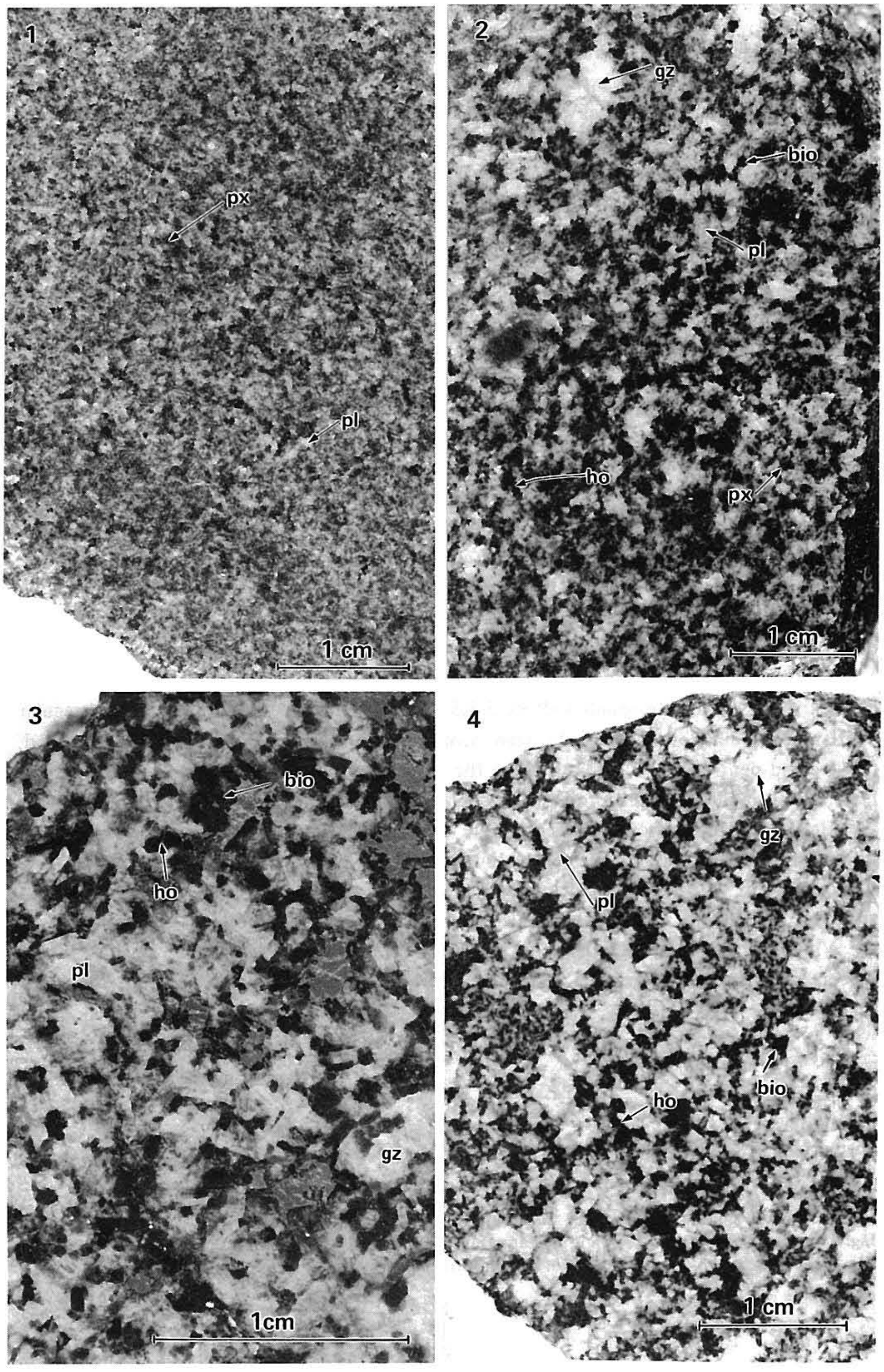
Photographs of slabs of some rock facies consisting of the Oshirabetsu gabbro mass.

Fig. 1 Norite. px: orthopyroxene, pl: plagioclase

Fig. 2 Hornblende gabbro (fine-grained). px: orthopyroxene, ho: hornblende, bió: biotite, pl: plagioclase, qz: quartz

Fig. 3 Hornblende gabbro (coarse-grained). ho: hornblende, bio: biotite, pl: plagioclase, qz: quartz

Fig. 4 Diorite (coarse-grained). ho: hornblende, bio: biotite, pl: plagioclase, qz: quartz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Conclusion

Table 2 shows that fine-disseminated and coarse-disseminated pyrrhotites are common but semi-massive pyrrhotite is rare in norite. Table 3 shows that pyrrhotite in norite belongs to peak type thermomagnetically in spite of the difference of allotropism being lamella type and granular type.

The pyrrhotites in hornblende gabbro facies commonly form fine-disseminated and coarse-disseminated ores, but semi-massive ore is less. It is noteworthy that fine-disseminated pyrrhotite in hornblende gabbro facies shows variations thermomagnetically, i.e. weiss type, intermediate type and peak type are distinguishable thermomagnetically (Table 3). Fine-disseminated pyrrhotite in norite is wholly of peak type, on the oter hand, the coarse-disseminated pyrrhotite in hornblende gabbro facies is also wholly of peak type and is similar to these in norite.

Semi-massive pyrrhotite in norite is thermomagnetically similar with that in hornblende gabbro facies, i.e. both belong to peak type.

Massive pyrrhotite is peculiar in mineral assemblage. Pyrite is restrictedly present in this phase. The mode of occurrence and the mineral association of the ore indicates that the ore may belong to the final mineralization stage in the formation of Oshirabetsu ores.

Pentlandite is abundant in handspecimen of the samples 12(c_3), 29(b_2), 36(b_3), 45(c_1), 84(c_2), 89(c_1) and 92(c_1). Pentlandite is found in the form of irregular grains of length not exceeding 0.5 mm. At the boundaries between pyrrhotite and chalcopyrite, pentlandite appears frequently. Otherwise, pentlandite is present in pyrrhotite. In the latter case, mode of occurrence of pentlandite seems to be controled by the microtexture of pyrrhotite, i.e. in a spindle textured pyrrhotite, pentlandite appears interspersed in feather like forms at the boundaries of pyrrhotite spindles (Plate 5-4,5). In the granular textured pyrrhotite, irregular pentlandite grains are commonly seen around pyrrhotite grains. On the other hand, fine-grained pentlandites are found along the lamella in the pyrrhotite with lamella texture. Isolated pentlandite in silicate minerals has never been found in Oshirabetsu ore.

Under the ore-microscope, pentlandite appears gray white in colour and violarite is frequently observed along the cleavages in pentlandite. Violarite is easily distinguished from the pentlandite due to its peculiar blueish tint. Judging from the mode of occurrence of violarite, this mineral is thought to have developed as a secondary mineral after pentlandite.

Violarite bearing ores in Oshirabetsu mine were restrictedly obtained from the gallery, especially around the pegmatite veins. Therefore, the formation process of this mineral is

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Explanation of Plate 2

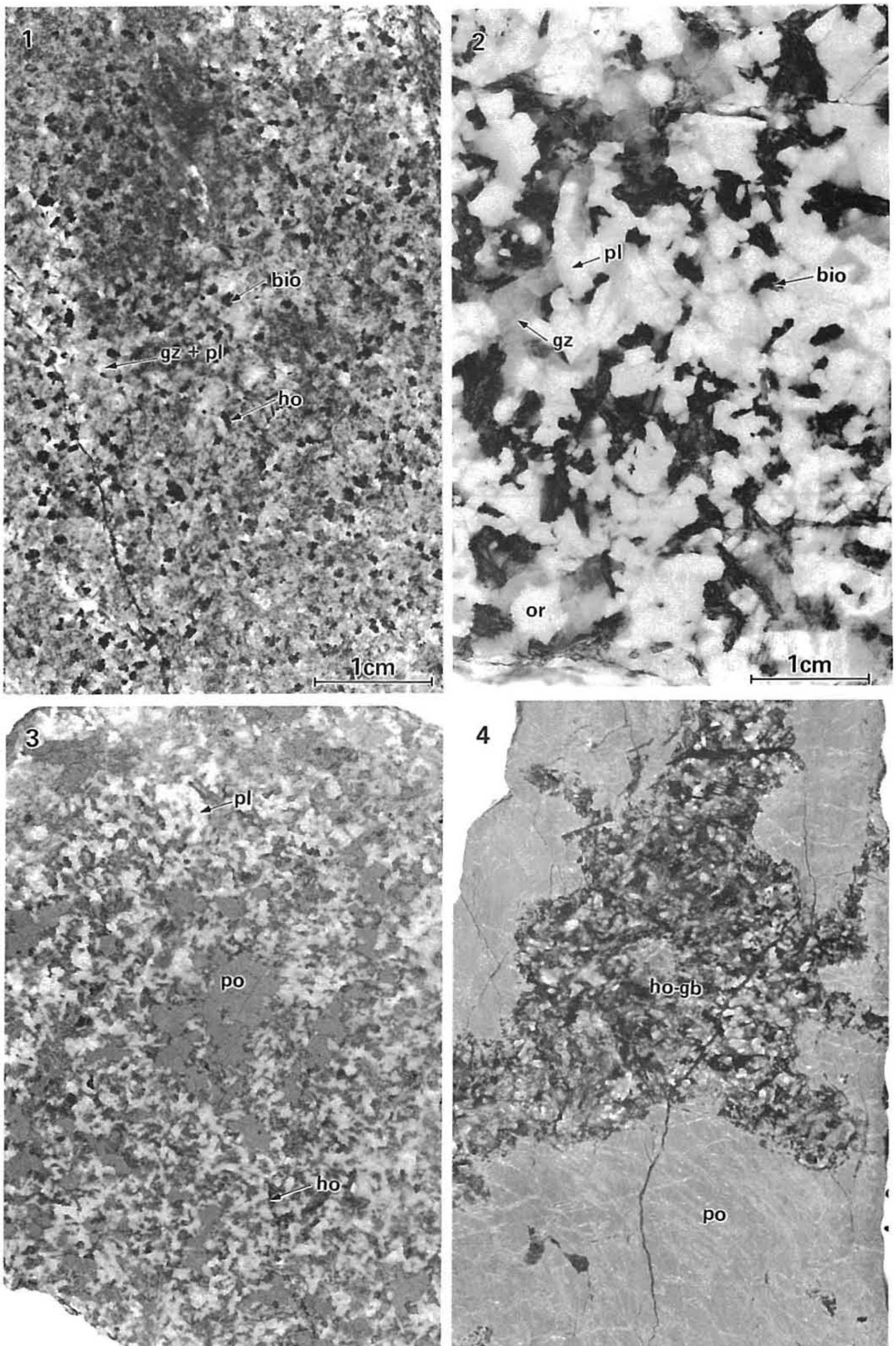
Photographs of slabs illustrating the classified rock facies of the Oshirabetsu gabbro mass and nickeliferous pyrrhotite ores.

Fig. 1 Diorite (fine-grained). ho: hornblende, bio: biotite, pl: plagioclase, qz: quartz

Fig. 2 Gabbro pegmatite. bio: biotite, pl: plagioclase, qz: quartz

Fig. 3 Coarse-disseminated ore in hornblende gabbro. ho: hornblende, pl: plagioclase, po: pyrrhotite

Fig. 4 Massive ore in hornblende gabbro. ho-gb: hornblende gabbro, po: pyrrhotite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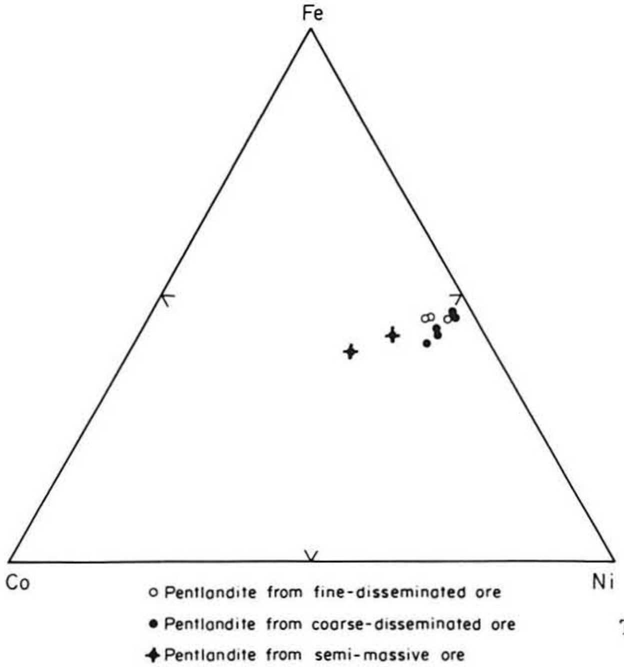

Text-fig. 5 Fe-Co-Ni diagram of pentlandites from the Oshirabetsu mine.

considered to be closely related to the intrusion of pegmatite, though the formation conditions have recently been discussed by Imai (1978) as an endothermal product of pentlandite.

In preceding chapters, the Ni and Co contents in pentlandite and pyrrhotite from the Oshirabetsu mine were described. The results obtained are summarized here.

Handspecimens 29, 45, 84 and 89 are abundant in pentlandite. The pyrrhotites in preceding numbers of ore contain considerable amount of Ni, e.g. pyrrhotite no.29 contains 0.95–1.15% Ni, that of no.89 contains 1.08% Ni, On the contrary, pyrrhotites unaccompanied by pentlandite are poor in Ni content, e.g. handspecimen no.44 contains only 0.02% Ni, and no.51 contains 0.38% and 0.52% Ni. Judging from the above-stated features, it is condidered that Oshirabetsu pyrrhotite has a limit of 1% Ni content, and excess of 1% Ni may form pentlandite showing a closed relation with the pyrrhotite.

The value of Co/Ni in disseminated pyrrhotite is 0.04 in average. This indicates that Ni content of pyrrhotite is far more abundant compared with Co content, while the value of

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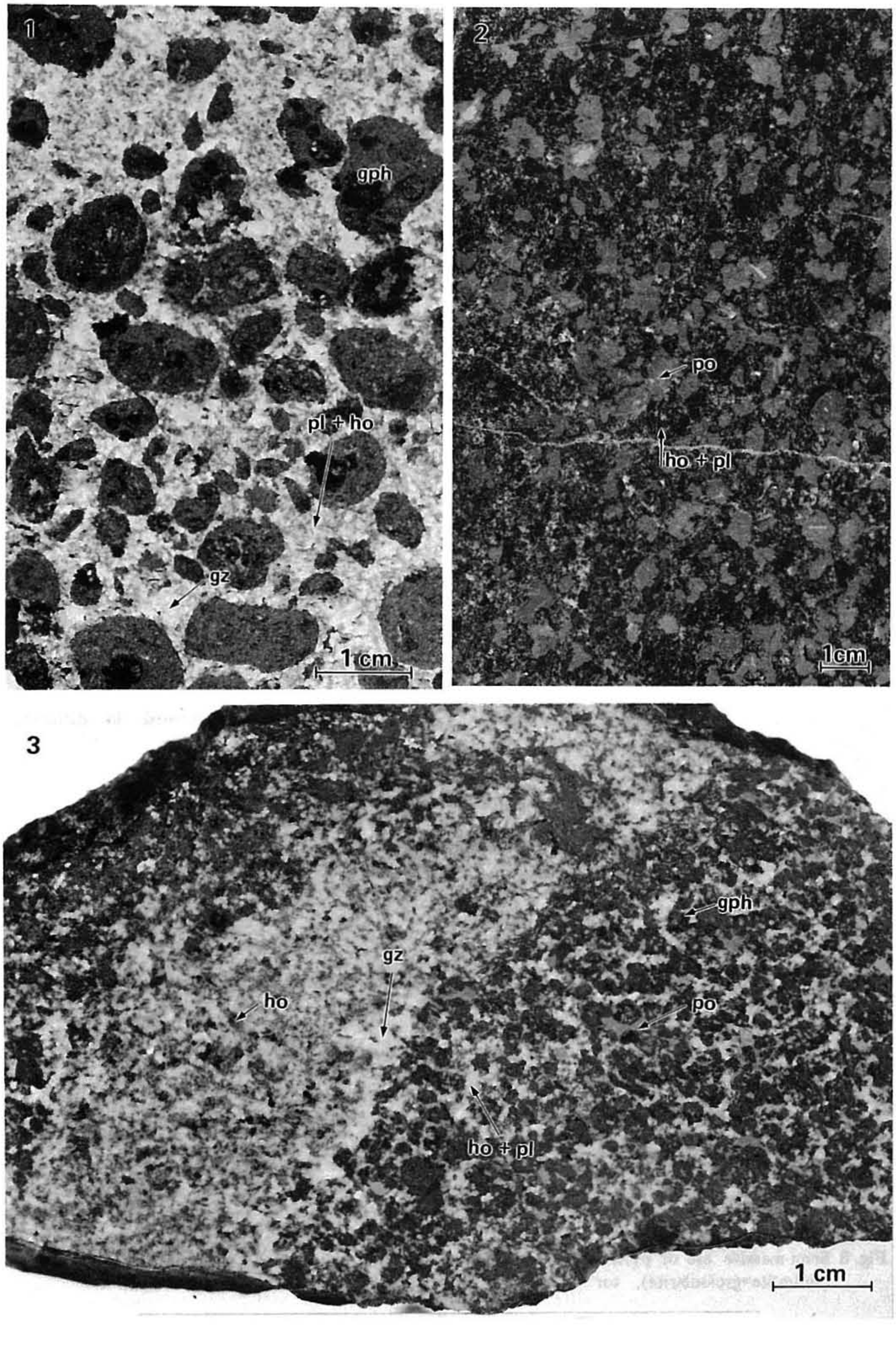
Explanation of Plate 3

Photographs of slabs of graphite ore and nickeliferous pyrrhotite ore.

Fig. 1 Graphite of pisolitic type in hornblende gabbro from Nissho gallery. gph: graphite, pl: plagioclase, ho: hornblende, qz: quartz

Fig. 2 Coarse-disseminated ore in hornblende gabbro. po: pyrrhotite, ho: hornblende, pl: plagioclase

Fig. 3 Fine-disseminated ore in norite. ho: hornblende, pl: plagioclase, po: pyrrhotite, gph: graphite, qz: quartz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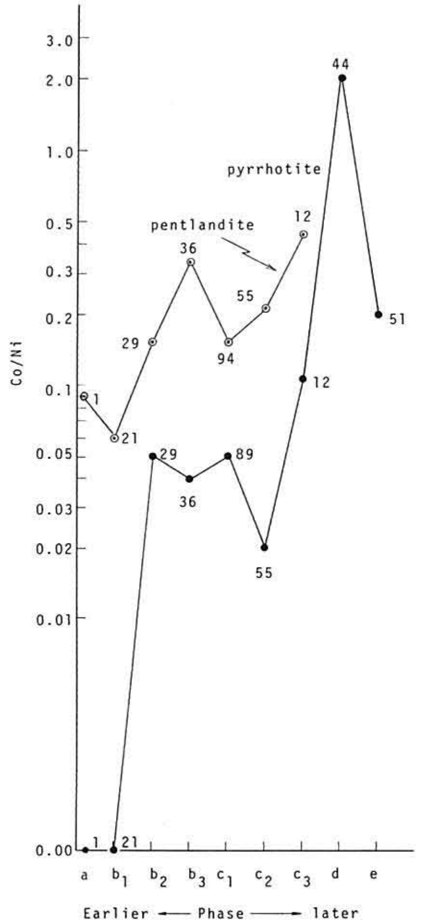


Text-fig. 6 Semi-logalithmic plots of Co/Ni variations of pyrrhotites and pentlandites formed in different phases.

Co/Ni of semi-massive pyrrhotite gives 2.0. It is concluded that Co/Ni ratio increases with the increase of the concentration of Co, Ni in the sulfides as shown in Text-fig. 6.

Explanation of Plate 4

Photomicrographs illustrating the classified some rock facies of the Oshirabetsu gabbro mass and paragenetic relations of nickeliferous pyrrhotite.

Fig. 1 Norite. po: pyrrhotite, opx: orthopyroxene, pl: plagioclase (parallel nicols)

Fig. 2 Norite. po: pyrrhotite, opx: orthopyroxene, pl: plagioclase (crossed nicols)

Fig. 3 Hornblende gabbro. ho: hornblende, pl: plagioclase, bio: biotite

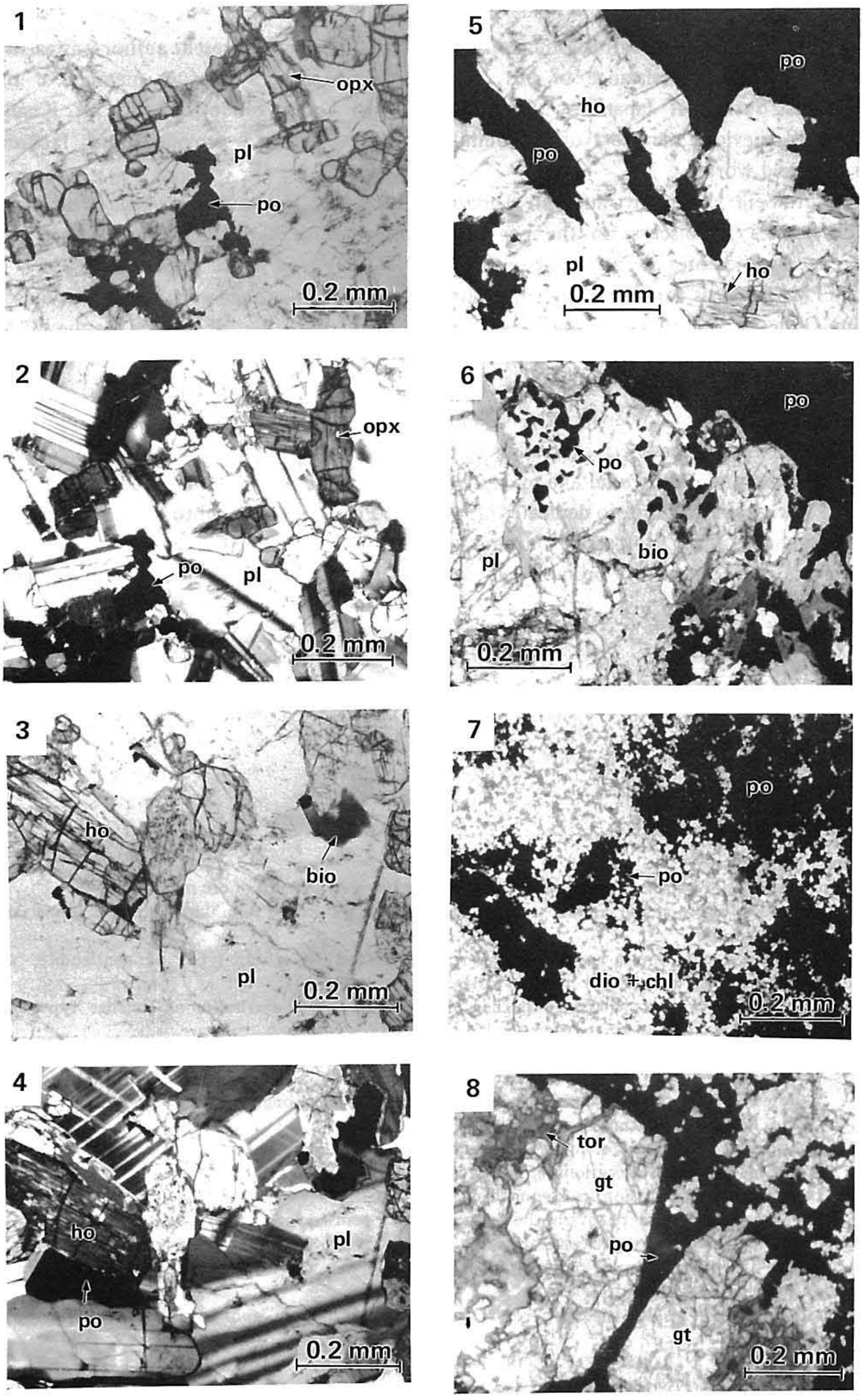
Fig. 4 Hornblende gabbro. ho: hornblende, pl: plagioclase, bio: biotite (crossed nicols)

Fig. 5 Corse-disseminated ore in hornblende gabbro. po: pyrrhotite, ho: hornblende, pl: plagioclase (parallel nicols)

Fig. 6 Contact between semi-massive ore and hornblende gabbro. po: pyrrhotite, bio: biotite, pl: plagioclase

Fig. 7 Semi-massive ore of pyrrhotite in the graphite ore. po: pyrrhotite, chl: chlorite, dio: diopside (parallel nicols)

Fig. 8 Semi-massive ore of pyrrhotite in the graphite ore (parallel nicols). po: pyrrhotite, gt: garnet (andralite=grossularite), tor: tourmaline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The present author would like to express his sincere thanks to above-stated persons.

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Explanation of Plate 5

Photomicrographs of polished sections illustrating the mode of occurrence of ore minerals.

Fig. 1 Semi-massive ore at the contact with graphite ore po: pyrrhotite of granular type (oil immersion, crossed nicols)

Fig. 2 Fine-disseminated ore in hornblende gabbro. po: pyrrhotite of spindle type, pe: pentlandite, cp: chalcopyrite (oil immersion, crossed nicols)

Fig. 3 Semi-massive ore of pyrrhotite in hornblende gabbro. po: pyrrhotite of lamellae type, pl: plagioclase (oil immersion, crossed nicols)

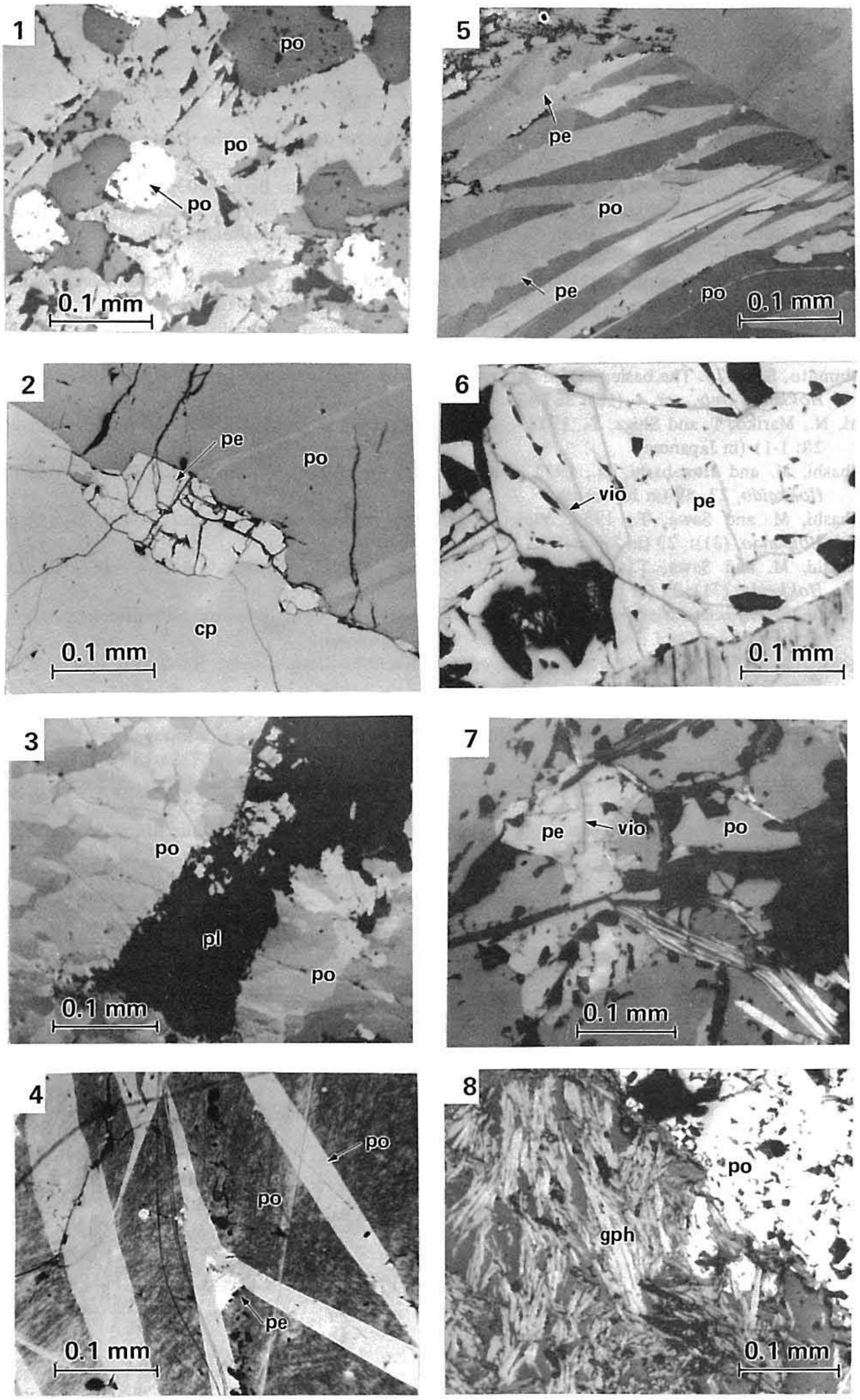
Fig. 4 Fine-disseminated ore of pyrrhotite in hornblende gabbro. po: pyrrhotite of spindle type, pe: pentlandite. Polished surface was structurally etched by saturated solution of CrO_3 for five minutes. Pyrrhotite stains differentially. Dark area is more strongly turnished to be brown, while both is hexagonal. (oil immersion, parallel nicols)

Fig. 5 Coarse-disseminated ore of pyrrhotite in norite. po: pyrrhotite of lamellae type, pe: pentlandite Flame-feather like segregations of pentlandite is observed along the lamellae twinning planes of pyrrhotite. (oil immersion, crossed nicols)

Fig. 6 fine-disseminated ore of pyrrhotite in norite. pe: pentlandite, vio: violarite, po: pyrrhotite Violarite occurs showing streak along some cleavages of pentlandite. (parallel nicols)

Fig. 7 Coarse-disseminated ore of pyrrhotite in norite. po: pyrrhotite, pe: pentlandite, vio: violarite, gph: graphite (crossed nicols)

Fig. 8 Graphite ore of pisolite type from Nissho-gallery. po: pyrrhotite, gph: graphite (crossed nicols)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