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22. *Heavy Minerals in Metamorphosed Sediments from the Tsukuba District, Ibaraki Prefecture.**

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Introduction

The metamorphosed sediments assigned to the Upper Paleozoic are largely exposed on the hilly land of the Tsukuba district which extends sporadically from the northern corner of Tsukuba-gun to the southern half of Niihari-gun as well as to a part of Ishioka City, being characterized by the frequent occurrence of granitic rocks, abundance of various contact minerals, lit par lit injection of igneous materials, formation of hybrid rocks, etc. These metamorphosed sediments indicate a wide range of alteration from place to place. In this case, some of them were metamorphosed from sandstones, whereas the others were derived from conglomerates, shales and clayslates. They are all subjected to remarkable disturbances here and there. Such geological features have already been studied by H. Yamada,[1] F. Otsuki,[2] K. Jimbo,[3] S. Kōzu,[4] K. Iwasaki,[5] R. Kimura,[6] Y. Ōdaira,[7] H. Satō,[8] K. Sugi,[9] B. Yoshiki[10] and others.

The Tsukuba district is also a well-known area to the writer who was born there, and he was thus in a favorable position to promote his geological and mineralogical works on the metamorphosed sediments of this district. In the latter case, the writer had a special interest in

* Communicated by H. Tsuya.

1) H. YAMADA, *Geol. Map, Mito, 1:200,000 and Its Explanatory Text*, (1888).

2) F. ŌTSUKI, *Jour. Geol. Soc. Tokyo*, **8** (1901), 424–428; **9** (1902), 52–57, 115–131.

3) K. JIMBO, *Jour. Geol. Soc. Tokyo*, **12** (1905), 6, 35–42.

4) S. KŌZU, *Jour. Geol. Soc. Tokyo*, **12** (1905), 23–26, 91–94.

5) K. IWASAKI, *Jour. Geol. Soc. Tokyo*, **22** (1915), 372, 388–390.

6) R. KIMURA, *Jour. Geogr.*, **36** (1924), 391.

7) Y. ŌDAIRA, *M. S., Geol. Inst. Univ. Tokyo*, (1925).

8) H. SATŌ, *Geol. Map, Tsukuba, 1:75,000 and Its Explanatory Text*, (1927).

9) K. SUGI, *Jour. Geol. Soc. Tokyo*, **34** (1927); *Jour. Geol. Soc. Tokyo*, **35** (1928), 640–654; *Jap. Jour. Geol. & Geogr.*, **8** (1930), 29–112.

10) B. YOSHIKI, *Jour. Petrog. Min. & Ore Dep.*, **10** (1933), 4, 151–157.

Fig. 1. Map showing the location where the specimens of metamorphosed sediments were collected.

heavy mineral components almost free of those in original sediments except zircon crystals. Moreover, his attention was attracted to the presence or absence of some heavy minerals depending upon the distance from the granitic contact. To examine these heavy minerals, he collected abundant specimens from many localities during his field work. They were crushed and analysed mechanically by using heavy solutions. The isolated crystals extracted in this way were crystallographically and optically investigated, their mineralogical characters being furthermore confirmed by microscopical observations of thin sections of each specimen.

The results are summarized in the present paper.

General Features of Mother Rocks

The hilly land of the Tsukuba district (Fig. 1) is geologically a very complicated area, where various kinds of metamorphosed sediments assigned to the Upper Paleozoic are extensively exposed together with granitic rocks (Fig. 2). It extends from Ryūjin-yama to Hōjō westwards, including Negoyashinden, Kankyo-san, Fuji-yama, Sengen-zan, Aoyagi, Onogoe, Busshōji, Asahi-tōge, Tōjōji, Sawabe, Fudō-tōge, Hirasawa, Yamaguchi, Kowada, etc. The metamorphosed sediments here are the alteration products of clayslate, shale, sandstone and conglomerate due to the large intrusion of biotite granite and two-mica granite. In these cases, the grade of metamorphism is very changeable from place to place depending upon the distance from the granitic body and lit par lit injection of the granitic substances.

The Upper Paleozoic sediments of this district are thus affected weakly at the east, but strongly at the west, resulting in the formation of spotted biotite clayslate, hornfels, metamorphosed conglomerate and mica gneiss or schist. Among them, spotted biotite clayslate is widely distributed at the area extending over Ryūjin-yama, Namitsuki-iwa, Negoyashinden and Kankyo-san. This type of clayslate has a black color and is generally characterized by the abundance of biotite spots, 2 mm. in the maximum diameter. Commonly, the rock is composed of quartz, orthoclase, plagioclase, reddish brown biotite, hematite, zircon, apatite, muscovite, tourmaline and graphite. Moreover, some of it contains many andalusite or chiastolite crystals, 3 mm. or more in length, as is indicated by the specimens from the hill behind Tenma. It is frequently intercalated with hornfels derived from arenaceous rocks and has a strike of N40°–70°E and a dip of 50°–70°NW–NNW.

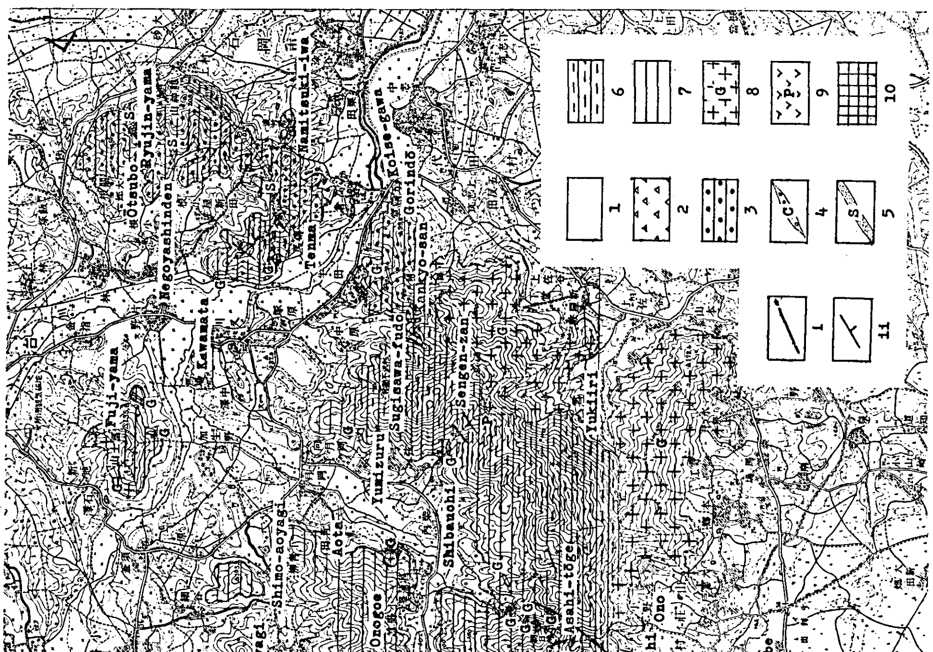

Fig. 2. Geological map showing the distribution of metamorphosed sediments in the Tsukuba district.

1. Recent fluviatile deposits and Pleistocene-Pliocene deposits, 2. Talus deposits, 3. Spotted biotite clayslate, 4. Metamorphosed conglomerate, 5. Hornfels derived from sandstone, 6. Hornfels derived from clayslate or shale, 7. Gneiss or schist, 8. Porphyritic biotite granite and two-mica granite, 9. Pegmatite, aplite and quartz vein, 10. Gabbro, gabbro pegmatite, anorthosite, and amphibolite, i. Fault, ii. Strike and dip.

By going westwards, however, hornfels and injection rock begin to crop out predominantly with the gradual transition and the frequent change of strike and dip. In the case of hornfels, there are several varieties altered respectively from argillaceous, arenaceous and calcareous sediments. They are represented by biotite hornfels, two-mica hornfels, hornblende diopside hornfels, diopside garnet hornblende hornfels, diopside biotite hornfels, andalusite or chiastolite hornfels and cordierite hornfels. The commonest type of these rocks is two-mica hornfels derived from clayslate or shale. Its exposures are traceable from Ryūjin-yama to Sawabe southwestwards, passing through Negoyashinden, Sugisawa-fudō, Sengen-zan and Tōjōji and intercalating other kinds of hornfels changed from arenaceous sediments as well as from rudaceous rocks. The occurrence of andalusite or chiastolite-bearing biotite or two-mica hornfels is known near Sengen-tōge and also on the ridge extending from here southwestwards, whereas cordierite hornfels is found at Sugisawa-fudō. Minerallogically speaking, biotite hornfels or two-mica hornfels consists of quartz, orthoclase, magnetite, apatite, zircon, tourmaline and graphite together with reddish brown biotite and muscovite. Such mineral components are quite similar even when phenoblastic andalusite, chiastolite and cordierite are present. The distribution of hornblende-bearing diopside hornfels and diopside garnet hornblende hornfels is restricted to a small extent as compared with other metamorphosed sediments. So far as is known at present, the former is to be seen on the hill just behind Kangōri, and the latter is found at the Hirasawa quarry. Besides these, quartzose diopside plagioclase hornfels is noticed by Sugi[11] on the hill near Sugisawa-fudō, Kami-aoyagi and Nakayama.

Hornblende-bearing diopside hornfels is highly quartzose, and the main part of this rock is composed of quartz, plagioclase, orthoclase and diopside with a subordinate amount of green hornblende, magnetite and zircon. Diopside garnet hornblende hornfels is a hard and compact rock with a light green or dark green color, being constructed by a granoblastic aggregate of quartz, orthoclase, plagioclase, titanite, magnetite, apatite zoisite, allanite and zircon as well as green hornblende, diopside and garnet. It is a xenolith in porphyritic biotite granite and grades into biotite-bearing variety at its marginal part.

Metamorphosed conglomerate is exposed in connection with spotted biotite clayslate, two-mica hornfels and injection mica gneiss. The most

11) K. SUGI, *op. cit.*, (1930), 75, 89–92.

remarkable one can be observed on the southern flank of a ridge rising up close to the truck road between Sawabe and Oda. Its exposure extends from north to south within the area of two-mica gneiss or schist.

The western half of this area is almost built up of injection mica gneiss characterized by a lit par lit injection of porphyritic biotite granite and other igneous materials. Frequently, it has a banded structure due to the repetition of mica-rich parts and quartzose laminae or lenses. In general, they are represented by intricate aggregates of quartz, orthoclase, plagioclase, biotite, muscovite, hematite, zircon, apatite, tourmaline and graphite, containing occasionally sillimanite, cordierite, garnet and andalusite or chiastolite. When biotite and muscovite are found together, the former is always more predominant than the latter, and some spotted structure is not infrequently formed by shimmer aggregates of these two minerals. In the specimens collected from near the exposures of granitic rocks, biotite flakes are sometimes associated closely with confused swarms of sillimanite needles. The occurrence of such sillimanite crystals seems to be restricted to the area which was subjected to the intense contact metamorphism, and it is well known at Hirasawa, Kowada and on Jō-yama as well as along the truck road of Fudō-tōge and in its vicinity where porphyritic biotite granite is repeatedly and complicatedly exposed.

Of these, the metamorphosed sediments of the Hirasawa quarry (Fig. 3) are biotite gneiss, biotite hornfels and diopside garnet hornblende hornfels. In this case, biotite gneiss is the most predominant rock, having thin layers of biotite or two-mica hornfels derived from sandstone. They are traversed and intercalated by porphyritic biotite granite, aplite, pegmatite and other igneous materials (Fig. 4). Such metamorphosed sediments are smoothly or intricately bordered against granitic rocks, and a sudden or gradual transition can be seen between them, being subjected to the complicated injection of igneous materials near the granitic contact (Figs. 5–6). Most of biotite gneiss here have a distinct banded structure and are remarkably folded close to the contact where biotite flakes are exceedingly increased and some aplitic or granitic veins are found together.

As to the chemical characters of metamorphosed sediments mentioned above, there are only few available data.[12] Some of them are shown in the following table (Table 1).

12) K. SUGI, *op. cit.*, (1930), 103.

Table 1.

	(1)	(2)	(3)
SiO_2	63.63	65.54	60.20
Al_2O_3	16.09	16.27	16.98
Fe_2O_3	0.55	1.10	5.89
FeO	5.00	3.54	3.80
MgO	2.28	2.15	2.98
CaO	1.24	2.00	1.57
Na_2O	2.09	2.99	0.83
K_2O	4.52	3.00	3.42
H_2O_+	1.02	1.42 }	4.14 (ig. loss.)
H_2O_-	0.17	0.40 }	
TiO_2	0.74	0.50	not det.
P_2O_5	0.08	0.56	not det.
MnO	0.10	0.07	not det.
C	2.00	not det	not det.
Total	99.53	99.54	99.81

(1) Sillimanite biotite gneiss from the Hirasawa quarry. Anal., S. Tanaka.
(2) Injection biotite gneiss from Fudō-tōge. Anal., T. Katō.
(3) Spotted biotite clayslate from Ryūjin-yama. Anal., Y. Ōdaira.

Mineralogical and Optical Characters of Heavy Minerals

The mineralogical and optical characters of heavy minerals can be well investigated by isolating them from their mother rocks. For this purpose, the writer crushed various types of metamorphosed sediments collected from many localities of the Tsukuba district (Fig. 1) and used Thoulet solution to extract them. In this operation, he could concentrate such heavy minerals as allanite, andalusite (chiastolite), apatite, biotite, garnet, hematite, magnetite, monazite, muscovite, sillimanite, titanite, tourmaline, zircon and zoisite. They are sometimes in high frequency, but are scarcely present, or absent in other cases.

Among them, biotite is the most remarkable heavy ingredient in all of metamorphosed sediments which include biotite gneiss (schist), two-mica gneiss (schist), biotite hornfels, two-mica hornfels and spotted biotite clayslate. The mineral is commonly scattered through the rock, but crowds together occassionally to form rounded spots here and there. It is strongly pleochroic from light brownish yellow (X) to reddish brown (Y, Z), having an index of refraction (γ) between 1.639 and 1.649. The crystal contains apatite, graphite and zircon.

Muscovite is less important than biotite. Both the minerals are frequently associated together, particularly at Hirasawa, Yamaguchi, Kowada and Oda as well as on Asahi-tōge and Fudō-tōge. It is often characterized by the presence of a worm-eaten structure and the abundance of enclosures represented mostly by graphite crystals.

The occurrence of andalusite (chiastolite) and sillimanite is restricted to a small extent. Andalusite takes a long prismatic habit, and its crystal is imperfectly terminated. Sometimes, the interior of this mineral is rich in the carbonaceous matter and passes into chiastolite. It alters to minute sericite scales when decomposed. The indices of refraction are as follows:

$$\alpha=1.613-1.627\ , \qquad \gamma=1.637-1.642$$

Sillimanite consists of transparent and colorless needles, 0.5 mm. in the maximum length. The crystal shows the highest frequency in biotite gneiss of the Hirasawa quarry (Fig. 9) and constructs confused aggregates which are distinguishable even with naked eyes. The indices of refraction are $\alpha=1.651$, $\beta=1.653$ and $\gamma=1.673$.

Diopside and hornblende (Fig. 7) are characteristic ingredients in hornfeles metamorphosed from sandstones rich in lime and magnesia. Both the minerals are found together, and some of them are associated with garnet, taking a subhedral or anhedral form in most specimens. In the case of hornblende, it has usually a poikilitic texture and is often intergrown with diopside in an intricate manner. The largest crystal is 1.52 mm. long and 0.72 mm. across. The mineral is distinctly pleochroic from light yellow or light brown (X) to greenish brown or brownish green (Y) and green or bluish green (Z). Moreover, its extinction angle, $c\wedge Z$, is 15°. When the crystal encloses zircon, the pleochroic halo is seen along the contact between them.

The amount of hornblende is more abundant than diopside in the specimens from the Hirasawa quarry, but is *vice versa* in those from Mukō-yama.

Diopside has a diameter of 0.3 mm. or thereabouts even in the largest crystal and contains zoisite crystals. Its extinction angle, $c\wedge Z$, is 40°.

The most remarkable accessory heavy mineral is tourmaline which is present in most specimens of biotite gneiss (schist), two-mica gneiss (schist), biotite hornfels, two-mica hornfels, spotted biotite clayslate, etc. It occurs as a stout or long prismatic crystal (Figs. 10–11), the former taking frequently a well-defined form as compared with the latter. They are composed of $m(10\bar{1}0)$, $a(11\bar{2}0)$ and $o(02\bar{2}1)$ as well as of $r(10\bar{1}1)$. So far as has been examined by the writer, the commonest form is represented by a combination of $(10\bar{1}0)$, $(11\bar{2}0)$ and $(10\bar{1}1)$. When the elongated crystal is truncated at the end, $(10\bar{1}1)$ is always absent as is indicated in the specimens of two-mica gneiss or schist from the area including Hōkyō-zan and Kowada. The size of such crystals shows a wide range. The largest one is 0.93 mm. long and 0.42 mm. across in the crystal with a stout prismatic habit, whereas it is 0.81 mm. long and 0.15 mm. across in the long prismatic variety. In this case, the refractive indices are as follows:

$$N_E = 1.622 - 1.628\ , \quad N_O = 1.648 - 1.655\ . \quad N_O - N_E = 0.026 - 0.027\ .$$

The mineral strongly pleochroic from light brownish yellow or light brown (N_E) to dark yellowish brown or dark brown (N_O). Some of it is faintly zoned and reveals a darker color at its inner part. The crystal has occasionally a clear appearance without any inclusion, but it is commonly rich in graphite and gas (?) inclusions. In the elongated crystal, they are exceedingly abundant and a dark core is formed by the high frequency of graphite inclusions.

The occurrence of zircon (Fig. 12) is not so remarkable as tourmaline, although this ingredient is contained in most of metamorphosed sediments. Its frequency seems to depend on the lithological characters of original sediments and has a tendency to be high in hornfelses derived from arenaceous sediments, but it lacks occasionally in gneisses and hornfelses altered from argillaceous rocks.

The mineral is found as colorless, purple and pink crystals with a short or long prismatic habit and well-rounded form (Fig. 12). In the writer's specimens, the frequency of the colorless zircon is much higher than that of the purple or pink variety, and sharp prismatic crystals are rarely found. It constructs the combinations of (100), (111); (110), (111) and (110), (100), (111), (311). Among them, the common type is composed of (100) and (111) or (110) and (111). In these cases, the colorless zircon is quite free of such a long and sharp prismatic form as found frequently in porphyritic biotite granite of the Hirasawa quarry and two-mica granite of Kankyo-san or elsewhere.

The purple zircon is contained in the specimens obtained from Ryūjin-yama, Negoya and Fudō-tōge, where the mother rock is two-mica hornfels changed from sandstone. It usually takes an ill-defined form and is sometimes worn to a spherical grain. In the specimens from Ryūjin-yama, the crystal has a bright purple color and is slightly pleochroic. The pink variety occurs only in two-mica hornfels exposed at the western side of Fudō-tōge. The original rock of hornfels here is also sandstone.

The length or diameter of various zircon crystals mentioned above ranges from 0.03 mm. to 0.22 mm., and their minute grains enclosed in biotite flakes afford a pleochroic halo along the contact between them.

Apatite is not so widely distributed as tourmaline and zircon in metamorphosed sediments. This mineral is almost or entirely absent in spotted biotite clayslate and associated hornfels of Ryūjin-yama and the adjacent area, but has a tendency to be increased in biotite gneiss (schist), two-mica gneiss (schist) and biotite or two-mica hornfels of Hirasawa, Kowada and others, where granitic rocks are exposed here and there. It is, therefore, always noticeable in the specimens obtained from the granitic contact of the Hirasawa quarry and also in their xenoliths captured by porphyritic biotite granite of the same place. Even in these cases, its frequency is not very high when compared with porphyritic biotite granite, particularly biotite-rich part of the contact which has already been described in the writer's previous paper.[13)]

Apatite has a stout prismatic habit or rounded form, the good crystal being a combination of prism, pyramid and base. It is mostly colorless and clear without any enclosure, but has rarely a dark grey core supposed to be a decomposed part. Such a crystal is occasionally associated with biotite flakes and sillimanite needles. The largest one is 0.14 mm. long and 0.09 mm. across.

The frequent occurrence of pink garnet is known in some specimens of biotite hornfels or two-mica hornfels collected from Mukō-yama, Hirasawa and the ridge between Busshōji and Rokusho, where they are believed to have been derived from various kinds of sandstone. Commonly, the mineral has a rounded form with the exception of beautiful rhombic dodecahedron formed in two-mica hornfels of Busshōji-Rokusho. At the Hirasawa quarry, garnet is complicatedly intermixed with green hornblende and diopside in the mother rock enclosed by porphyritic biotite granite. The round crystal mentioned above is 0.06 mm–1.12 mm. across and has an uneven surface, being characterized by the frequency of a mesh structure in thin sections (Fig. 8).

Monazite is a very rare ingredient in metamorphosed sediments of

13) T. ICHIMURA, *Bull. Earthq. Res. Inst.*, **33** (1955), 392.

this district, although it shows a high frequency in porphyritic biotite granite near its contact of the Hirasawa quarry. The writer separated out this mineral from biotite hornfels and two-mica hornfels which alternate with two-mica gneiss or schist at the western side of Fudō-tōge and are undoubtedly alteration products of arenaceous rocks. The crystal occurs as minute round grains, 0.07 mm.–0.17 mm. in diameter and is slightly pleochroic from light greenish yellow to light yellow or almost colorless. Moreover, it has a dark border due to the effect of refractive indices and is easily distinguishable from zircon or titanite.

The restricted occurrence of heavy minerals is also indicated by titanite and allanite which are present together only in the xenolith of diopside garnet hornblende hornfels found at the Hirasawa quarry. The former has an irregular or rounded form and is frequently associated with green hornblende or diopside, including occasionally ill-defined magnetite crystals. The latter is, on the other hand, very scarcely contained in the rock mentioned above. It is strongly pleochroic from light brown (X) to reddish brown (Y) or light yellow (X). The crystal is 1.07 mm. long and 0.3 mm. across.

In addition, there are some metallic minerals such as hematite, magnetite and pyrite, but they are negligible or absent in most specimens.

The heavy minerals in many specimens are summarized in Table 2.

Geological Considerations on the Occurrence of Heavy Minerals

As has already explained, metamorphosed sediments of the Tsukuba district contain various kinds of heavy minerals which change their frequency from place to place. In many specimens collected by the writer, biotite is the most predominant mineral. Even in the sediments affected slightly by contact metamorphism, this ingredient is always present with a high frequency. Its amount seems to depend on the grade of metamorphism and the lithological character of original sediments. It increases its frequency in metamorphosed sediments derived from clayslate and is especially abundant at or near the granitic contact.

The same may be said of muscovite which has a tendency to gradually increase in frequency in the area, where granitic rocks are sporadically exposed and some of them are still concealed under the present surface.

Sillimanite and andalusite (chiastolite) are, on the other hand,

Table 2. Heavy minerals in metamorphosed sediments

	1*	2*	3	4	5	6	7	8	9	10	11	12*	13*	14	15	16*	17*	18*	19*	20*	21	22	23
Allanite	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Andalusite (chiastolite)	—	—	×	—	—	—	—	—	×	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Apatite	—	—	—	—	—	—	×	—	—	—	×	—	×	—	×	—	—	—	×	×	—	×	—
Biotite	⊠	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗	×	⊗	⊗
Diopside	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Garnet	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Hematite	×	×	—	×	×	×	—	×	—	—	—	—	—	—	—	—	—	—	—	×	—	—	—
Hornblende	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Magnetite	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Monazite	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Muscovite	⊠	×	⊗	⊗	⊗	⊠	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗	—	⊗	⊗	×	⊠	⊗	⊗	⊗
Pyrite	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	×	—	—	—
Sillimanite	—	—	—	—	—	—	⊗	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	×
Titanite	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Tourmaline	⊠	×	⊠	⊠	⊠	×	⊠	⊠	×	×	×	×	⊠	×	×	×	—	—	×	×	×	×	×
Colorless zircon	⊠	×	×	×	⊠	×	×	×	×	×	×	⊠	×	×	×	⊠	×	×	×	×	×	×	×
Pink zircon	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Purple zircon	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Zoisite	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—

	24	25	26*	27*	28*	29	30	31	32	33*	34*	35	36*	37	38	39	40	41	42	43	44	45	46
Allanite	—	—	—	—	—	—	—	—	—	—	×	—	—	—	—	—	—	—	—	—	—	—	—
Andalusite (chiastolite)	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Apatite	—	—	—	—	—	×	—	×	⊠	×	×	×	×	×	×	—	⊠	⊠	×	×	—	×	—
Biotite	⊗	⊗	⊗	⊠	⊠	⊗	⊗	⊗	⊗	⊗	×	⊗	—	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗
Diopside	—	—	—	—	—	—	—	—	—	—	⊗	—	⊗	—	—	—	—	—	—	—	—	—	—
Garnet	—	—	⊠	—	—	—	—	—	—	—	⊗	—	—	⊠	—	—	—	—	—	—	—	—	—
Hematite	—	—	—	×	×	×	—	×	×	×	×	—	—	—	—	—	—	—	—	—	—	×	—
Hornblende	—	—	—	—	—	—	—	—	—	—	⊗	—	×	—	—	—	—	—	—	—	—	—	—
Magnetite	—	—	—	—	—	—	—	—	—	—	×	—	×	—	—	—	—	—	—	—	—	—	—
Monazite	—	—	—	×	×	—	—	—	×	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Muscovite	⊗	⊗	×	×	×	⊗	⊗	×	×	—	—	×	—	—	×	⊠	⊗	⊠	⊗	⊗	⊠	⊗	⊠
Pyrite	—	—	—	—	×	—	—	×	—	—	—	—	—	×	—	—	—	—	—	—	—	—	—
Sillimanite	—	—	×	—	—	—	×	⊗	⊗	—	—	⊗	—	—	⊠	×	×	—	×	×	×	—	—
Titanite	—	—	—	—	—	—	—	—	—	—	⊠	—	×	—	—	—	—	—	—	—	—	—	—
Tourmaline	⊠	×	⊠	×	—	×	×	×	⊗	—	—	×	—	×	⊠	×	—	⊠	×	⊠	⊠	⊠	—
Colorless zircon	×	×	×	⊠	⊠	⊠	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×
Pink zircon	—	—	—	—	×	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	×
Purple zircon	—	—	—	×	×	—	—	—	×	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Zoisite	—	—	—	—	—	—	—	—	—	—	×	—	×	—	—	—	—	—	—	—	—	—	—

⊗ Extremely abundant. ⊠ Fairly abundant. * Hornfels derived from sandstone.

Table 3. Localities of metamorphosed sediments in the preceeding table

	Village or town	District or city
(1) Ryūjin-yama (Two-mica hornfels)		Ishioka-shi .
(2) 〃 (〃)		〃 .
(3) Negoyashinden-Tenma (Andalusite spotted biotite clayslate)	Yasato-machi	Niihari-gun .
(4) Negoya-Tenma (Two-mica hornfels)	〃	〃 .
(5) 〃 (Two-mica gneiss)	〃	〃 .
(6) The summit of Sengen-zan (Two-mica hornfels)	Chiyoda-mura	〃 .
(7) Yumizuru (Two-mica hornfels)	Yasato-machi	〃 .
(8) 〃 (〃)	〃	〃 .
(9) 〃 (〃)	〃	〃 .
(10) Shibauchi (〃)	〃	〃 .
(11) Komachi (〃)	Niihari-mura	〃 .
(12) Tōjōji (〃)	〃	〃 .
(13) 〃 (〃)	〃	〃 .
(13) 〃 (〃)	〃	〃 .
(14) 〃 (〃)	〃	〃 .
(15) Tōjōji-Sawabe (〃)	〃	〃 .
(16) Sawabe (〃)	〃	〃 .
(17) 〃 (〃)	〃	〃 .
(18) 〃 (〃)	〃	〃 .
(19) 〃 (〃)	〃	〃 .
(20) 〃 (〃)	〃	〃 .
(21) Oda (〃)	Tsukuba-machi	Tsukuba-gun.
(22) Nakayama-Busshōji (Two-mica gneiss)	Yasato-machi	Niihari-gun .
(23) Busshōji (〃)	〃	〃 .
(24) 〃 (〃)	〃	〃 .
(25) Fudō-tōge (Two-mica schist)	Tsukuba-machi	Tsukuba-gun.
(26) Rokusho-Busshōji (Garnet two-mica hornfels)	〃	〃 .
(27) Yamaguchi (Two-mica hornfels)	〃	〃 .
(28) 〃 (〃)	〃	〃 .
(29) Hirasawa-yama (Two-mica schist)	〃	〃 .
(30) 〃 (Two-mica gneiss)	〃	〃 .
(31) 〃 (Sillimanite two-mica gneiss)	〃	〃 .
(32) Hirasawa (〃)	〃	〃 .
(33) 〃 (Biotite hornfels, xenolith)	〃	〃 .
(34) 〃 (Diospide garnet hornblende hornfels)	〃	〃 .
(35) Mukō-yama (Sillimanite two-mica gneiss)	〃	〃 .
(36) 〃 (Hornblende-bearing diopside hornfels)	〃	〃 .
(37) 〃 (Biotite hornfels)	〃	〃 .
(38) Jō-yama (Sillimanite two-mica gneiss)	〃	〃 .
(39) Yamaguchi (Two-mica gneiss)	〃	〃 .
(40) Kowada (Two-mica gneiss)	〃	〃 .
(41) 〃 (〃)	〃	〃 .
(42) 〃 (〃)	〃	〃 .
(43) 〃 (〃)	〃	〃 .
(44) 〃 (〃)	〃	〃 .
(45) Hōkyō-zan (Two-mica schist)	〃	〃 .
(46) Hōkyō-zan—Fudō-tōge (Two-mica gneiss)	〃	〃 .

restricted in distribution, both the minerals not being found together in the Tsukuba district. Generally speaking, the former occurs frequently in the area where metamorphosed sediments are closely associated with granitic rocks. In short, sillimanite is a stable mineral and is more abundant in biotite gneiss exposed close to the granitic contact, but it has some tendency to decrease its frequency with the increase of muscovite. Such a feature can be seen at the Hirasawa quarry and its adjacent area.

Andalusite is seen in metamorphosed sediments derived only from shale or clayslate which was less affected by the granitic intrusion. It is, therefore, contained in biotite hornfels or spotted biotite clayslate formed at the distance from the main granitic body.

Green hornblende and diopside are, however, noticed only in hornfels which were originally siliceous sediments rich in lime and magnesia. Geologically, they are not important minerals, since such kinds of mother rocks are scarcely distributed in this district.

One of the common heavy accessory minerals is tourmaline. Generally, it has a high frequency in gneisses and hornfelses derived from clayslate or shale, but is occasionally lacking even in these kinds of rock.

The similar tendency is also seen in hornfelses metamorphosed from sandstones and spotted biotite clayslate subjected to the least metamorphism, although the occurrence of this mineral is restricted to a smaller extent. These facts suggest that such a volatile component as boron was not uniformly circulated in the metamorphosed area, and the distribution of tourmaline crystals seems, therefore, independent of the distance from the granitic body, the lithological character of original sediments as well as of grade of metamorphism, spreading over all parts of the contact aureole. Its formation is supposed to have largely been facilitated by the sedimentary structure disturbed by the granitic intrusion.

Zircon is less frequently present than tourmaline, when both the minerals are found together in metamorphosed sediments. Commonly, it takes a rounded form and has some appearance of an ingredient in the original sediments, being almost free of such well-defined crystals as those of the Tsukuba type granite and Inada type granite.[14] These granites are characterized by coexistence of colorless and pink varieties

14) S. OKADA, N. SHIMODA & H. SHIBATA, *Stud. Geol. & Min. Inst. T.K.D.*, (1954), 217–307.

in which the former occurs as the beautiful crystal with a sharp outline. Among them, the pink zircon is generally contained in two different types of granite of the Tsukuba district, whereas the occurrence of the colorless one seems to be more remarkable in the Tsukuba type granite, particularly near its contact. It is, therefore, necessary to confirm whether zircon crystals of the granites were partly supplied from the Upper Paleozoic sediments exposed here or not.

So far as is known at present, the colorless zircon of metamorphosed sediments is, however, nearly wanting in well-defined crystals and reveals a quite different feature from that of granites. Accordingly, the ill-defined crystals of the colorless zircon derived from abovementioned sediments and enclosed in granites are impossible to get a sharp outline without the subsequent addition of zirconium. The sharp crystals of colorless zircon in granites, however, always have a clear appearance and lack a zonal structure. This evidence seems to suggest that there is no genetical connection between colorless zircon crystals of metamorphosed sediments and those of granites.

The same may be said of the pink zircon which has mostly a well-defined form in granites. In this case, it is supposed that the original zircon will lose its color by the thermal effect of the granitic magma.

The occurrence of apatite seems to depend on the distance from the granitic contact and the grade of metamorphism. Hence, it has a tendency to increase its frequency when approaching the granitic body. Such features are somewhat different from those of tourmaline which is found even at the periphery of the contact aureole and indicate an irregular distribution without any connection to the lithological characters of the original sediments. These facts may suggest that fluorine or chlorine acted only on the sediments adjacent to the granitic body. The frequency is, therefore, high at the contact, but decreases strikingly within a short distance from it.

Monazite is rarely contained in two-mica hornfels exposed at the western side of Fudō-tōge, where porphyritic biotite granite was intruded together with pegmatite. This mineral is, however, always absent in other metamorphosed sediments including those of the Hirasawa quarry. From these facts, it can be inferred that the formation of monazite was restricted to a small extent in the sediments subjected to metamorphism and took place largely within the granitic body in which it is a common accessory ingredient and increases its amount at the periphery.

Allanite, garnet, hematite, magnetite, pyrite, titanite and zoisite are also unimportant heavy accessory minerals, and their occurrence has no geological significance, since they are found in a negligible amount.

Among various heavy minerals mentioned above, zircon is specially noticed as an original ingredient of the Upper Paleozoic sediments. It was least affected by metamorphism and seems to have been preserved even when other minerals wholly disappeared by recrystallization. In the investigation of these heavy minerals, it is very desirable to examine those of the Upper Paleozoic sediments exposed on the Toriashi mountain land[15] which is situated farther north. The formation here is chiefly composed of sandstone and shale with occasional intercalations of limestone lenses and chert layers. It is, therefore, expected to contain many kinds of heavy minerals as in the case of the similar formation distributed largely in the Chichibu district.[16]

Summary

i) Various kinds of metamorphosed sediments assigned to the Upper Paleozoic are extensively exposed in the Tsukuba district which includes a part of Ishioka City, Niihari-gun and Tsukuba-gun. They are mostly the alteration products of argillaceous or arenaceous sediments due to the large intrusion of the Tsukuba type granite (porphyritic biotite granite and two-mica granite), being represented by biotite or two-mica gneiss (schist), several types of hornfels, metamorphosed conglomerate and spotted biotite clayslate.

ii) These metamorphosed sediments were crushed, and heavy minerals were extracted from them by using Thoulet solution. The heavy minerals thus obtained were examined under the microscope together with those in thin sections of the mother rocks. Besides biotite and muscovite, there are allanite, andalusite (chiastolite), apatite, diopside, garnet, hematite, hornblende, magnetite, monazite, sillimanite, titanite, tourmaline, zircon and zoisite.

iii) Among them, the commonest ingredient is biotite which is contained in almost all metamorphosed sediments. It seems to increase its amount in biotite or two-mica gneiss (schist) and biotite or two-mica hornfels derived from argillaceous sediments and is abundantly present at or near the granitic contact. The same tendency is also shown by muscovite which is more predominant when approaching the granitic body.

15) K. KAWADA, *Sc. Rept. T. B. D.*, (C), **2** (1953), 217-307.
16) T. ICHIMURA & H. MATSUBAYASHI, *Bull. Earthq. Res. Inst.*, **31** (1953), 159-164.

iv) Sillimanite and andalusite (chiastolite) are restricted in distribution, the former being found in biotite or two-mica gneiss (schist) close to the granitic mass, whereas the latter being contained in two-mica hornfels or spotted biotite clayslate less affected by the granitic intrusion. Hornblende and diopside occur only in hornfelses altered probably from sandstones rich in lime and magnesia.

v) Of accessory heavy minerals, most remarkable is tourmaline which has a wide distribution even in spotted biotite clayslate. Its formation seems to be independent of original sediments as well as of the grade of metamorphism, but reveals a close relationship to the sedimentary structure and disturbance due to the granitic intrusion.

vi) Zircon is the next important heavy accessory mineral. It is supposed to have been an ingredient of the original Upper Paleozoic sediments, since there is no evidence to suggest its formation due to the addition of zirconium from the granitic magma. In this case, the crystal seems to have been preserved without any striking alteration during metamorphism. Moreover, it may be said that Paleozoic sediments subjected to contamination were not the source of colorless zircon crystals coexisting with the pink variety in the Tsukuba type granite and Inada type granite.

vii) Apatite seems to increase its frequency in the neighbourhood of the granitic body. It is, therefore, abundant in biotite or two-mica gneiss (schist) near the granitic contact, but is almost absent in spotted biotite clayslate.

Allanite, hematite, magnetite, monazite, titanite and zoisite are negligible heavy accessory ingredients.

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22. 茨城県筑波地方産変質堆積岩の重鉱物

山形大学　市　村　毅

石岡市から新治郡及び筑波郡に跨る丘陵地域には上部古生層と見做される変質堆積岩が広く露出している．この岩石の原岩は頻繁に黒雲母花崗岩や複雲母花崗岩，或はこれ等に伴うペグマタイト，アプライトなどの貫入を受け，元来の岩石の内容，花崗岩からの距離，地層の構造その他の差により，様々なる変質岩を生ずるに至つた．黒雲母片麻岩又は片岩，複雲母片麻岩又は片岩．黒雲母ホルンフエルス，複雲母ホルンフエルス，点紋黒雲母粘板岩などはこれ等の代表的なるものであり，頁岩や粘板岩から変化した片麻岩，片岩，ホルンフエルスの中には紅柱石（空晶石），菫青石，珪線石を多く含む場合が知られている．若し堆積岩が石灰や苦土に富む場合には，透輝石，ザクロ石，緑色角閃石がしばし認められる．

黒雲母，白雲母，紅柱石，珪線石，ザクロ石，透輝石，角閃石の他に，重鉱物としては，電気石ジルコン，褐簾石，黝簾石，燐灰石，クサビ石，モナヅ石，赤鉄鉱，磁鉄鉱，黄鉄鉱などが存在する．それ等の中で最も多いのが黒雲母と白雲母とであり，大方の変質堆積岩に含まれる．又黒雲母や白雲母に次いで頻度が高いのは電気石，ジルコン，燐灰石であるが，珪線石とか紅柱石，透輝石，角閃石の如きは，時に多いことがあつても，その範囲が限られている．その他の重鉱物には重要視すべきものがない．

副成分重鉱物としては，電気石が最も著しく存在する．然もその分布は貫入火成岩からの距離とか岩質とかに関係なく，その原岩が原料の滲透に都合のよい構造を有する処に特に集中している様に思われるばかりでなく，場所によつては，これが結晶形に著しい変化が見られる．又ジルコンは大概円味を有し，その上無色透明なるものが大部分を占め，紫色種や淡紅色種は至つて少い．これ等は何れも原岩が変質する以前からその鉱物成分として存在したものであり，花崗岩漿からジルコニウムが特に供給されたために生じたものでない．又堆積岩を変質せしめたこの地方の花崗岩中に淡紅色ジルコンと共存する無色透明の美晶は，堆積岩からの捕獲晶が脱色し，ジルコニウムの供給により生長したと見做される証拠もなく，むしろ花崗岩の中で，結晶形や色を全然異にするジルコンの結晶が，岩漿的に且つ同時に生じたことを考える方が合理的である．ジルコンは一般に砂岩から生じた変質岩に多い様見受けられる．燐灰石は花崗岩との接触部にやや著しく集り，これを遠ざかると急劇に頻度の減少を見せている．

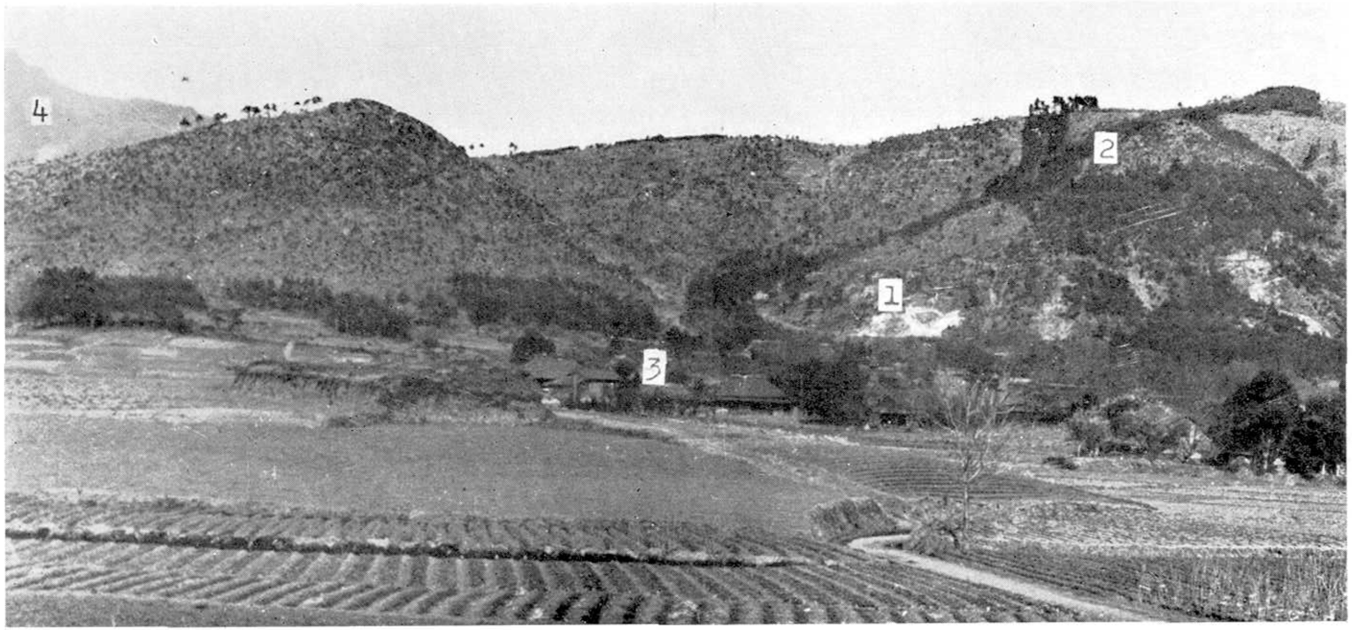

Fig. 3. The Hirasawa quarry viewed from near Hōjō. Various kinds of metamorphosed sediments and granitic rocks are well exposed at this quarry and on the hill in its background.

1=Hirasawa quarry, 2=Hirasawa-yama, 3=Hirasawa-mura, 4=Tsukuba-san.

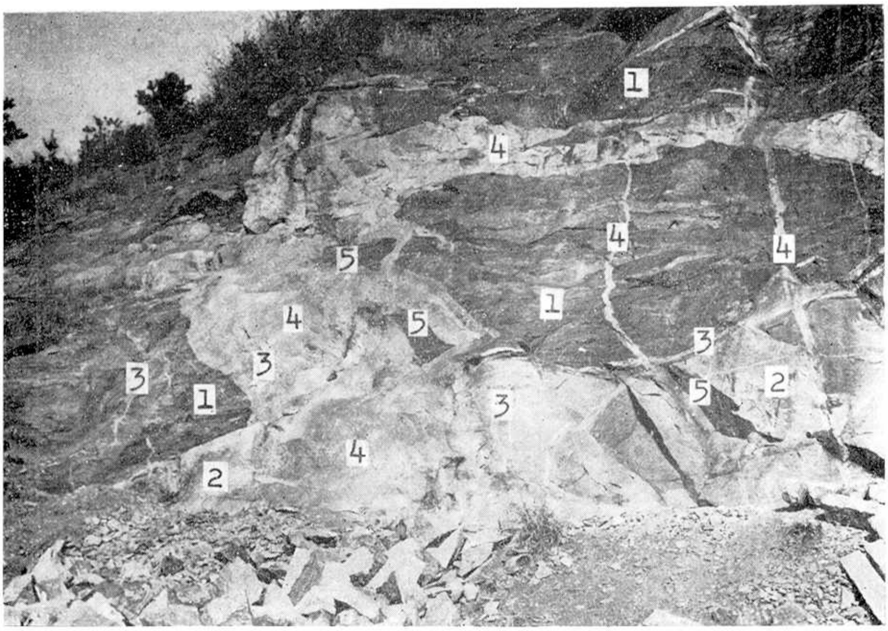

Fig. 4. Metamorphosed sediments and granitic rocks exposed at the Hirasawa quarry. Metamorphosed sediments here are intricately traversed by porphyritic biotite granite, pegmatite and aplite. In this case, the intrusion of biotite granite was succesively followed by those of pegmatite and aplite. 1=metamorphosed sediments, 2=Porphyritic biotite granite, 3=Pegmatite, 4=Aplite, 5=Xenolith.

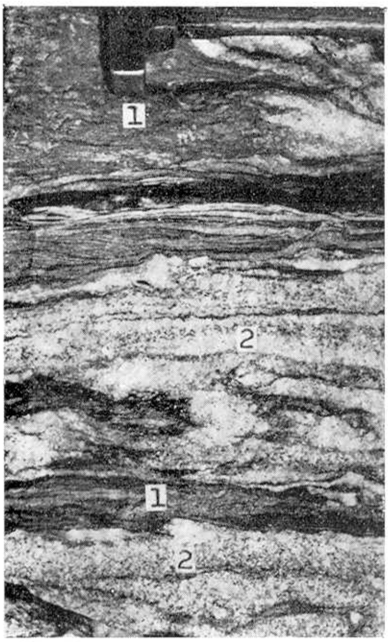

Fig. 5. Lit par lit injection of biotite granite. 1=Biotite gneiss, 2=Biotite porphyritic granite.
(Hirasawa quarry)

Fig. 6. Biotite gneiss contorted by the granitic intrusion. 1=Biotite gneiss, 2=Porphyritic biotite granite.
(Hirasawa quarry)

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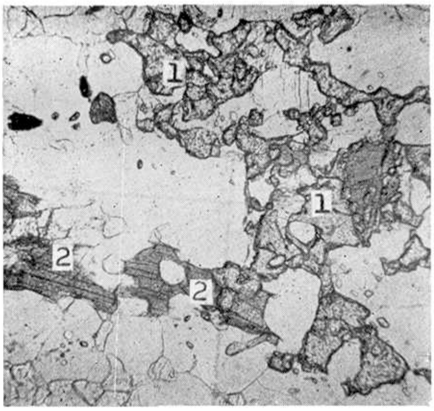

Fig. 7. Diopside and hornblende. 1= Diopside, 2=Green hornblende. (Diopside garnet hornblende hornfels, Hirasawa quarry). ×100.

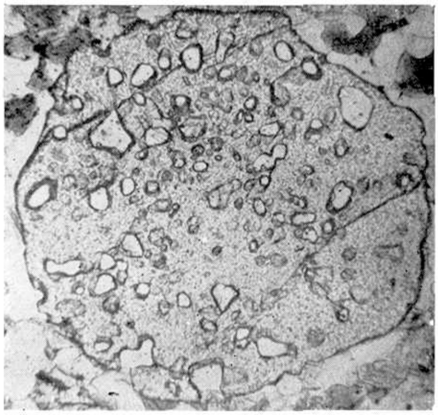

Fig. 8. Garnet crystals with a mesh structure. (Garnet two-mica hornfels, Roku-sho-Busshōji). ×100.

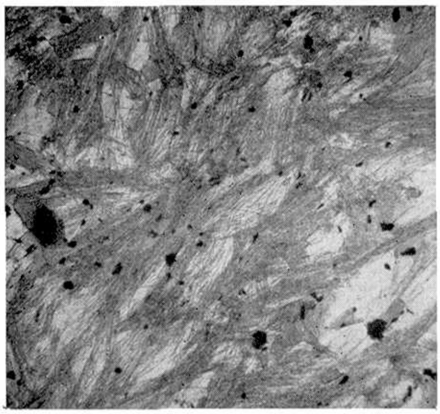

Fig. 9. Sillimanite needles. (Sil. two mica hornfels, Mukō-yama). ×100.

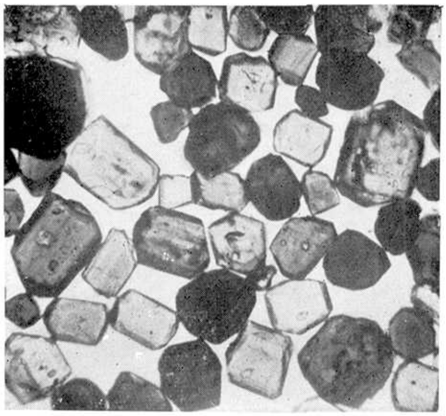

Fig. 10. Short prismatic crystals of tourmaline (Sil. two-mica gneiss, Hirasawa quarry). ×100.

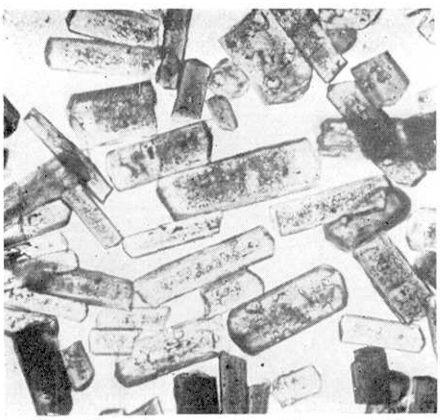

Fig. 11. Long prismatic crystals of tourmaline (Two-mica hornfels, Yumizuru). ×100.

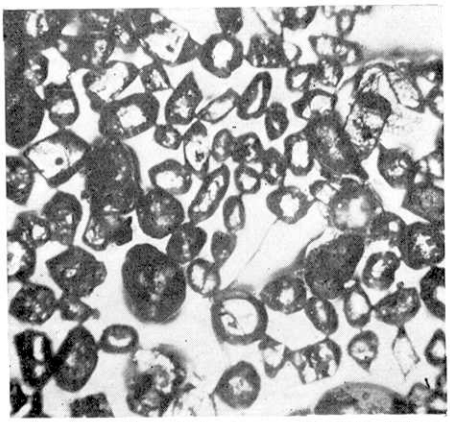

Fig. 12. Rounded zircon crystals (Two-mica hornfels, Sawabe). ×100.

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