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Finding of Axinite-schist in the Sangun Metamorphic Zone at Mitaké, Yamaguchi Prefecture, Southwest Japan

by

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with 5 Text-figures, 3 Tables, and 2 Plates

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ABSTRACT: Axinite, in association with epidote, stilpnomelane and chlorite, was newly found from greenschist in the Sangun metamorphic zone. Complete chemical analysis of axinite has not been successful, because most grains of the axinite include a number of minute grains of quartz and perhaps of sphene. The axinite may be manganoan one, and has optical properties such as followings: $\alpha=1.674$, $\beta=1.680$, $\gamma=1.683$, optically negative, $2V=70°$. The X-ray diffraction patterns show noted similarity to the patterns recorded for axinite from Dauphine, France. The refractive indices for the axinite are unexpectedly lower than those for the manganoan axinite so far reported by many authors.

The axinite was recognized as one of metamorphic minerals which were stably crystallized under the condition of the quartz-albite-muscovite-chlorite subfacies of TURNER and VERHOOGEN (1960).

CONTENTS

I. Introduction
II. Modes of occurrence of axinite-schists
III. Descriptions of the axinite-schist at Mitaké
IV. Physical and chemical properties of the axinite at Mitaké
V. Discussion

I. INTRODUCTION

In his work now in progress on the crystalline schists of the Sangun metamorphic zone, the author noticed rather common occurrence of axinite-schist in association with the normal greenschists in a limited area. Axinite-schist is not so rare in greenschists of the Sambagawa metamorphic zone in the Kantô Mountainland as well as in the Yoshinogawa district in Shikoku. Axinite from the Kantô Mountainland is in association with stilpnomelane (KOJIMA, 1944). From the Sangun metamorphic zone, however, no axinite has been reported by any author.

An examination of the recorded occurrences of axinite may show, as pointed out by MASON (1959), that it is usually found in one of three; (1) contact-metamorphic rocks, often close to granite intrusions, (2) cavities in granites and (3) hydrothermal veins. Many authors have believed that axinite can be formed under relatively high temperature and/or under conditions of boron metasomatism. To the author's knowledge, MASON was the first to point out that axinite may be formed under relatively lower temperature, i.e., a little higher than that of the chlorite 2 subzone in New Zealand, correlatable with the quartz-albite-muscovite-chlorite subfacies, though in his case axinite was found only in quartz-veins.

Axinite now the present author concerned has been found not only in quartz-albite-veins but also in bands especially rich in axinite and stilpnomelane, which are surrounded by the greenschists of low grade.

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II. MODES OF OCCURRENCE OF AXINTE-SCHISTS

Three localities have been found in the district near Mitaké. They are shown in the figure 1 by Arabic numerals, *1*, *2* and *3*. The locality *1* is the most extensive exposure among them, and will be only concerned in detail in the present paper.

The locality *1* at Mitaké is situated on an exposure about 2.5 km to the east along a road running from Suma to Kano-chô. At the exposure, axinite-schist can be found within a scope about 4 to 5 meters on the road cutting, and the surrounding greenschists change suddenly, but with no sharp boundary, from green to black in colour, because of appearance of greenschist abundant in stilpnomelane. There are two varieties of greenschists abundant in stilpnomelane, the one being axinite-schist and the other epidote-stilpnomelane-schist. Thus, the greenschists abundant in stilpnomlane may form as a whole a large lense-like mass, whose axis of elongation appears to be nearly parallel with the regional trend of the axis of fold in the surrounding greenschists. The road cuts the regional trend of the axis of fold at an angle nearly normal, and any exposure other than that at the road cutting is lacking, so that it is difficult to decide how long the lense-like mass is laterally elongated. The surrounding greenschists contain very often spheroidal clots mainly composed of epidote, which show rather irregular froms with no symmetry and attain in some cases to thirty cm. in diagonal diameter.

The Plate 15-A is a photograph showing the mode of occurrence of axinite-schist at the locality *1*. As shown in the photograph, the axinite-schist characterized by abundant spots of axinite is alternated with the axinite-schist containing spots of axinite only sparsely. They are sometimes alternated with epidote-stilpnomelane-schist and/or thin layers of greenschist rich in epidote and chlorite but not in stilpnomelane. The axinite-schist occurs as layers or bands which are concordant with the schistosity. Each of these layers is generally traceable within a limit 1 m or less along the schistosity, and 4 cm or less in apparent width.

Spots of axinite in the axinite-schist sometimes attain to 2.5 mm in diagonal diameter, but commonly to more or less 1 mm. The axinite is milky-white to pale pink in colour. Epidote in the epidote-stilpnomelane-schist is noticed also as small spots by the

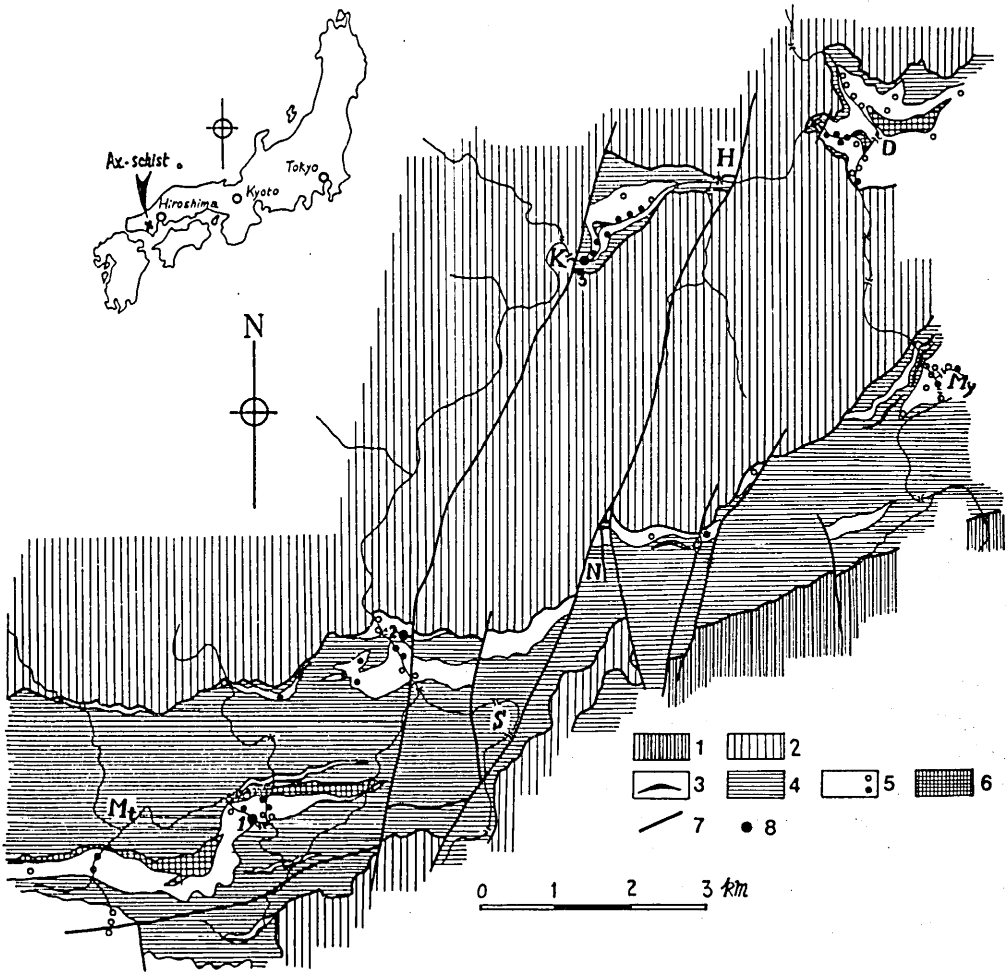

Fig. 1. Schematic geological map of the area between Miyanokushi and Mitaké, Northeastern part of Yamaguchi Prefecture. 1: Kuga group (Palaeozoic, marginal part of the Ryôké metamorphic zone) 2: Nishiki group (Palaeozic, metamorphics of the prehnite-pumpellyite-metagraywacke facies). 3-6: Tsuno group (Palaeozoic, Sangun metamorphics of the greenschist facies; 3 Crystalline limestone 4 Crystalline schists of pelitic and psammitic rock origin 5 Greenschists of volcanic rock origin, open circles showing localities of glaucophane and solid circles those of greenschist rich in epidote 6 Ultramafics) 7 Faults and slides 8 Localities of axinite-schists, numbered from 1 to 3.

D: Deai H: Hirosé K: Kitanibara Mt: Mitaké My: Miyanokushi N: Nagatani S: Suma naked eye, these spots resembling closely those of the axinite not only in mode of occurrence but also in colour. It is very difficult or rather impossible to discriminate between spots of the axinite and those of the epidote by unaided eyes.

At the locality *3*, axinite-schist occurs also as a lense-like body that is very small in extension, 30 cm × 100 cm, and is surrounded by greenschist with abundant clots of epidote. The axinite-schist here, however, is accompanied by less abundant stilpnomelane but by abundant chlorite. The position of the locality *2* on the figure 1 may not show strictly that of an actual exposure but of blocks of an axinite-schist, the mode of occurrence of the rock is yet unknown. The axinite-schist at the locality *2* may be siliceous rock in origin.

III. DESCRIPTIONS OF THE AXINITE-SCHIST AT MITAKÉ

In this chapter axinite-schist at the locality *1* will be treated only.

Mineral assemblages of greenschists near and at the locality *1* are;

a) epidote-actinolite-chlorite-muscovite-albite-quartz,
b) epidote-actinolite-glaucophane-chlorite-muscovite-albite-quartz,
c) epidote-actinolite-glaucophane-stilpnomelane-chlorite-albite-quartz,
d) epidote-stilpnomelane-chlorite-albite-quartz,
e) epidote-stilpnomelane-axinite-chlorite-albite-quartz,
f) epidote-stilpnomelane-axinite-chlorite-muscovite-albite-quartz,
with titanite, (calcite) and iron ores as accessories.

Glaucophane is a sub-glaucophane in optical properties, and ubiquitous in the surrounding greenschists. In the whole area shown in the figure 1, greenschist with no glaucophane is often alternated unsystematically with greenschist accompanied by glaucophane ("glaucophane-schist" of some authors). *d*), *e*) and *f*) are rocks abundant in stilpnomelane at the locality *1*, the first being called now under the name epidote-stilpnomelane-schist and the latter two axinite-schist. The axinite-schist and the epidote-stilpnomelane-schist are not accompanied by glaucophane.

The Plates 15–B and 16–B are microphotographs of the axinite-schist, and the Plate 16–A is also one but with a quartz-albite-vein that cuts the schistosity of the axinite-schist at an angle nearly normal. The mode of occurrence of epidote in the epidote-stilpnomelane-schist is apparent in the Plate 16–C, it being rather similar to that of axinite in the axinite-schist.

As shown in these plates, axinite appears to be porphyroblastic in petrographic character. The porphyroblasts of axinite, which occur often as wedg-shaped but mostly as irregular grains, are crowded within bands of generally a few centimeters in apparent width. Diagonals of them show no preferred orientation but random. The bands crowded with the porphyroblasts of axinite appear to be cut by quartz-albite-vein by unaided eyes, but, under the microscope, they actually continue through the latter. Axinite is also porphyroblastic in the quartz-albite-vein, and is crowded in layers which are the direct extension of the bands crowded with axinite in the axinite-schist. Some porphyroblasts cross the boundary between the host rock and the quartz-albite-vein (Plate 16–A), they becoming however more irregularly outlined in the latter. The longest dimensions of the porphyroblasts in the quartz-albite-vein are parallel to those of quartz grains which do generally not parallel but make an angle to the schistosity surface of the axinite-schist (Plate 16–A and Fig. 3).

The porphyroblasts of axinite are often accompanied by calcite (Plate 15–B). Needles of stilpnomelane rarely break through the outer margin of the porphyroblasts. Inclusions of quartz, sphene and others are generally found from the central part of each porphyroblast, and the marginal part is remained clear. Of interest is that, though these inclusions are abundant in nearly every grains of axinite, they become inferior in amount or absent in axinite crystallized in the quartz-albite-vein (Plate 16–A).

These evidences mentioned above may suggest that the quartz-albite-vein is not one derived from such external sources as, for example, a late magmatic source, but one of segregated from the host rock, and that materials have been shifted laterally during time of formation of the segregated vein.

The figure 2 is an orientation diagram for the optic elasticity axes of axinite, data of which are mainly collected from the axinite-schist but some from the quartz-albite-vein. S and L in the diagram correspond to the general trend of schistosity surface and lineation in rocks respectively. No preferred orientation of each optic elasticity axis has been detectable in the diagram. The figure 3 is also an orientation diagram for quartz c-axes. S and L mean the same general trends as in the figure 2. V and G in the figure 3 correspond to the trend of walls of the quartz-albite-vein and that of the longest dimensions for quartz grains measured on the thin-section. As evident

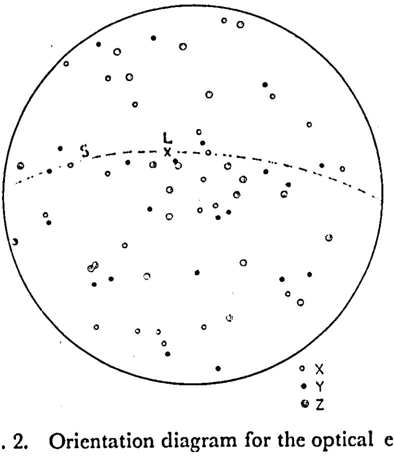

FIG. 2. Orientation diagram for the optical elasticity axes, X, Y and Z, of axinite in axinite-schist at Mitaké (locality *1*). S crresponds to schistosity surface, and L to lineation axis, parallel with the regional trend.

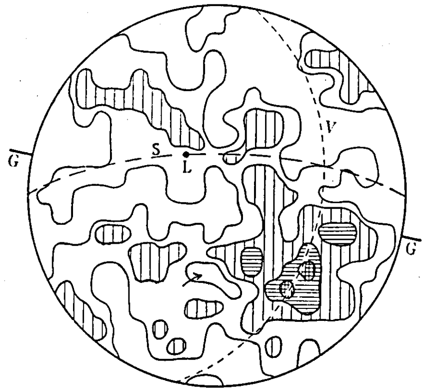

FIG. 3. Orientation diagram for c-axes of quartz in a quartz-albite-vein. S and L are synonymous with those in FIG. 2. V corresponds to the trend of walls of the vein, and G to the mean trend of the longest dimensions for quartz-grains. Contours: 4–3–2–1%.

in the Plate 16-A as well as in the figure 3, preferred orientation of the longest dimensions for quartz grains is nearly normal to the walls of the vein.

The figure 3 has one maximum area which lies on the walls of the vein, and is inclined to the schistosity surface of the host rock at an angle about 45°. There is no other maximum area in the diagram. A complete explanation of mechanical meanings of the maximum can not be possible in this only one diagram, but it is evident that c-axes of quartz have been preferably oriented either during or after the time of primary crystallization of quartz in the vein. In the present case, there seems no evidence that suggests later deformation of the vein-forming minerals, including axinite. The preferred orientations of c-axes and of the longest dimensions of grains of quartz are probably completed during the primary crystallization of the vein-forming minerals. Formation of the quartz-albite-vein is to be late- (or post-) kinematic. Judging from various petrographical characters of the axinite, it will be reasonable to consider that the crystallization of axinite appears to happen at the same time as the primary crystallization of quartz and albite in the quartz-albite-vein. This interpretation for axinite seems to be favourable to the case of epidote-porphyroblasts in the epidote-stilpnomelane-schist.

Stilpnomelane occurs in association with axinite in the quartz-albite-vein. Crystallization of stilpnomelane seems unexpectedly prolonged, i. e., it might begin prior to the time during which the porphyroblasts of axinite and epidote were formed, but evidently it is prolonged later than that time.

Five samples have been chemically analysed, mineral assemblages of them being listed bellow (Arabic numerals corresponding to those of columns in the table 2):

1) Greenschist (surrounding); epidote-actinolite-chlorite-muscovite-albite-quartz, without glaucophane,

2) Greenschist (epidote-stilpno.-schist); epidote-stilpnomelane-chlorite-albite-quartz, with abundant porphyroblasts of epidote,

3) Greenschist (axinite-schist); axinite-stilpnomelane-chlorite-epidote-albite-quartz, with less abundant porphyroblasts of axinite.

4) Greenschist (axinite-schist); axinite-stilpnomelane-chlorite-epidote-muscovite-albite-quartz, with abundant porphyroblasts of axinite.

5) Axinite (impure, because of much amount of impurities); separated from 4).

Calcite, sphene and opaques such as iron ore are very variable in amount in each greenschist. Axinite in the axinite-schist is generally accompanied by epidote that is, however, commonly very scarce.

The optical properties of the main rock-forming minerals and the chemical compositions of the greenschists listed above are shown in the tables 1 and 2 respectively. Refractive indices of minerals were measured by immersion method, and optic angle 2V was measured by the universal stage.

Two varieties of stilpnomelane, one being the greenish brown variety and the other the brown, sometimes reddish brown, variety, are found only in the epidote-stilpnomelane-schist *2)*. The γ-index of the brown variety varies from 1.656 to 1.680, and seems higher in the axinite-schist than in the epidote-stilpnomelane-schist. Plotting the γ-indices of stilpnomelane in the greenschists on the curve given by DEER et al.

TABLE 1. OPTICAL PROPERTIES OF STILPNOMELANE, EPIDOTE, AXINITE AND ALBITE FROM ROCKS CHEMICALLY ANALYSED:

		1**	2	3	4
stilpnomelane (a)*	γ		1.604 ± 0.003		
stilpnomelane (b)	γ		$1.656-1.671$ ± 0.002	1.657 ± 0.001	$1.674-1.680$ ± 0.001
epidote	2Vx	72°–73°	78°–84°	77°–88°	80°–86°
	$\widehat{aZ}$	22°–24°	22°–25°	24°–25°	23°–24°
	α		1.718 ± 0.002		
	β		1.727 ± 0.002		
	γ		1.737 ± 0.002		
	$\gamma-\alpha$		0.019		
	X	colourless	colourless	colourless	colourless
	Y=Z	pale greenish yellow	pale greenish yellow	pale greenish yellow	pale greenish yellow
axinite	2Vx				70° ± 1°
	α				1.674 ± 0.001
	β				1.680 ± 0.002
	γ				1.683 ± 0.002
	$\gamma-\alpha$				0.009
	X, Y, Z				with no axial colour
albite	2Vz	76°–80°	76°–80°	78°–80°	77°–81°

* Stilpnomelane (a): greenish brown variety
Stilpnomelane (b): brown (sometimes reddish brown) variety

** Numbers of columns are correlatable with those in the text (p. 246).

(1962), the atomic percent $Fe^{+3}+Al/Fe^{+2}+Mn+Mg+Fe^{+3}+Al$ of the greenish variety may be defined within 25-35%, and that of the brown variety within 50-60%.

Epidote in every samples shows no visible zoning structure. Epidote in the surrounding greenschist *1)* appears fairly richer in $Ca_2Fe_3^{+3}Si_3O_{12}(OH)$ molecule than that in the epidote-stilpnomelane-schist as well as the axinite-schist. In the latter two schists, 2V over X varies nearly within 10 degrees, the variation being also the case of one sample *3)*. By the X-ray diffraction patterns of epidote in the epidote-stilpnomelane-schist, $d_{(020)}$ being 2.185 Å, the molecular percent of $Ca_2Fe_3^{+3}Si_3O_{12}(OH)$ in the epidote may be defined within 22-27 (MYER, 1966).

Albite may be An_5 or lower in An molecular percent in the epidote-stilpnomelane-schist as well as in the axinite-schist, though it was decided only by 2V.

The figure 4 is an A-C-F diagram showing the mineral assemblages of the greenschists found near and at the exposure of the axinite-schist. Judging from the descriptions mentioned above, all of the greenschists now the present author concerned, in-

TABLE 2. CHEMICAL COMPOSITIONS OF GREENSCHISTS AND IMPURE AXINITE

	Wt %				
	1	2	3	4	5
SiO_2	48.73	45.95	62.91	76.31	
TiO_2	1.49	1.98	0.92	0.97	1.65
Al_2O_3	13.53	15.69	13.38	8.40	14.32
Fe_2O_3	5.77	5.46	5.73	3.28	0.67
FeO	5.28	9.20	2.40	1.63	2.47
MnO	0.33	0.61	0.16	1.06	8.61
MgO	6.51	3.40	2.16	1.47	0.71
CaO	12.01	5.67	1.38	1.17	13.16
Na_2O	2.40	3.55	5.87	2.52	0.37
K_2O	0.35	1.03	0.85	1.11	0.56
P_2O_5	0.11	0.04	0.11	0.11	
H_2O^-	0.33	1.62	0.94	0.28	
ig. loss	2.72	5.20	2.74	2.02	
total	99.56	99.40	99.55	100.33	
B_2O_3	0.014	0.008	n. d.	0.216	

1: analyst, Y. NISHIMURA
2, 3, 4, 5: analyst, T. NUREKI
Analyses of boron were carried out by K. WATANABE (1 and 2) and by A. ISHIZUKA (4).

cluding axinite-schist as well as epidote-stilpnomelane-schist, are correlatable with the quartz-albite-muscovite-chlorite subfacies (TURNER & VERHOOGEN, 1960), though they are often alternated unsystematically with "glaucophane-schist."

Chemical compositions of the axinite-schist, *3)* and *4)*, differ significantly from those of the surrounding greenschist *1)* and of the epidote-stilpnomelane-schist *2)*, the former two being richer in SiO_2 and B_2O_3 and poorer in CaO, FeO and MgO than the latter two. *1)* and *2)* are basaltic in composition, the latter being somewhat alkalic. The main difference in the chemical compositions between *1)* and *2)* may be noticed on FeO, MgO, CaO and Na_2O. Comparing *3)* with *4)*, the former is richer in Al_2O_3, Fe_2O_3 and Na_2O and poorer in SiO_2, MnO (and B_2O_3.) The axinite-schist *4)* cotains much SiO_2, but alkalies especially K_2O are much poorer than common acid igneous rocks.

All of the above greenschists contain much higher content of boron than the nomal greenschists.

In the figure 4, the chemical compositions of the analysed rocks are also plotted. As shown in the figure, the epidote-stilpnomelane-schist and the axinite-schist are plotted in a triangle joining brownish stilpnomelane-epidote-chlorite (and stilpnomelane). The position of the axinite-schist *3)* in the figure is found near the epidote-brownish stilpnomelane-join and/or the axinite-brownish stilpnomelane-join, while, the position of *4)* seems unsuitable for axinite-schist mainly composed of axinite, epidote and stilpnomelane. It is perhaps due to abundance of boron in the rock.

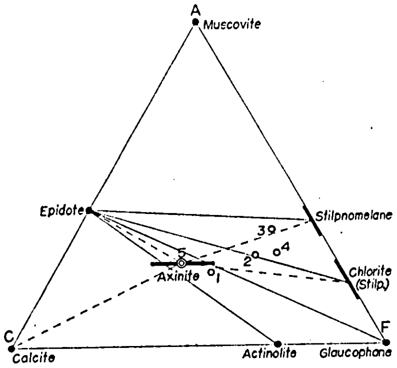

FIG. 4. A C F diagram for greenschists at Mitaké. Open and double open circles, numbered 1 to 5, are correlatable with those in the table 1 or table 2 respectively. 1 is analysed greenschist surrounding the axinite-schist; 2 is analysed epidote-stilpnomelane-schist; 3 and 4 are analysed axinite-schist; 5 shows approximate position for the axinite at Mitaké. Quartz and albite are additional phases.

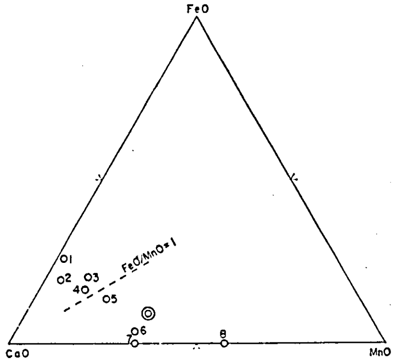

FIG. 5. FeO-CaO-MnO diagram for axinite. Numbers 1 to 8 correspond to those given by DEER et al. (1962, pp. 322–323). Double open circle is for axinite at Mitaké. The axinite at Mitaké may be called manganoan axinite.

IV. PHYSICAL AND CHEMICAL PROPERTIES OF THE AXINITE AT MITAKÉ

In hand specimen axinite now concerned is milky white to pale pink in colour. Under the microscope, it shows no axial colour and really porphyroblastic in petrographic character as already mentioned above. No well-developed cleavage has been found in each grain of the axinite.

Axinite was separated from the axinite-schist *4*) by using heavy liquids. Separation of the axinite from the other constituent minerals was relatively easy, but impurities in the axinite could not be picked out by any mean. The 2Θ values for the X-ray diffraction patterns were calibrated by the diffraction of silicon standard.

The optical properties and the X-ray powder patterns of the axinite at Mitaké are shown in the tables 1 and 3 respectively. Optical properties of axinite so far reported by many authors are fairly variable and do not show good correlation with chemistry of axinite. The X-ray powder patterns of axinite, on the other hand, do not show any discernible difference between common axinite and manganoan axinite (MILTON et al., 1953).

The chemical composition of the axinite at Mitaké is shown in the No. 5 column in the table 2, tough complete chemical analysis has not been carried out because separation of pure axinite was not possible. Approximate chemistry of the axinite, however, will be possible to infer from results of the chemical analysis.

The axinite is rich in MnO and poor in FeO and MgO. Magnesium can not be regarded as a main component in chemistry of the axinite at Mitaké. Relatively

TABLE 3. X-RAY DIFFRACTION DATA FOR AXINITE (Cu K_α)

Axinite 1)		Axinite 2)		Manganoan axinite 3)		Axinite 1)		Axinite 2)		Manganoan axinite 3)	
d Å	I/I_1	d Å	I/I_1	d Å	I	d Å	I/I_1	d Å	I/I_1	d Å	I
				8.83	3			2.206	30		
6.31	50	6.30	70	6.30	7	2.190	20	2.190	60		
		5.87	5	5.90	2			2.179	20	2.179	4
		5.15	5	5.12	2	2.160	40	2.163	70		
		4.99	10	4.94	2					2.152	7
4.84	20	4.80	20	4.78	3			2.134	30B		
4.53	20	4.53	30	4.55	3					2.126	2
3.99	10	3.99	20	3.96	3	2.059	20	2.060	50	2.060	4
				3.87	1			2.040	50		
		3.80	30							2.033	
3.68	30	3.68	60	3.66	3			2.014	30B		
3.46	80	3.46	80	3.46	8					2.008	7B
3.43	20B	3.42	5	3.42	4	1.997	20	1.998	30B		
		3.39	5			1.988	30	1.989	50	1.990	2
3.28	30	3.28	60	3.28	6			1.973	5		
		3.23	5							1.967	3
		3.19	5			1.955	20	1.955	40		
3.15	100	3.16	90	3.14	7					1.940	2
3.08	20	3.08	40B	3.06	4			1.926	50		
3.02	40	3.02	50	3.01	5					1.923	3B
2.992	40	2.998	60	2.975	7			1.895	10B		
2.965	30	2.968	50							1.870	2B
		2.931	30							1.818	2
				2.881	6			1.808	20		
2.873	20	2.874	30			1.785	20	1.788	40	1.791	4B
2.833	20	2.839	40			1.745	20	1.744	10		
2.808	90	2.812	100	2.812	10			1.732	30	1.732	2
2.788	30	2.792	40					1.721	30		
				2.766	2			1.704	20	1.706	2
2.753	20	2.760	40			1.692	20	1.691	10	1.693	2
				2.734	2			1.680	10		
2.666	20	2.667	40					1.668	40	1.668	2
				2.661	3			1.652	40	1.650	2
2.647	20	2.643	40B			1.632	20	1.636	50		
				2.620	2					1.630	4
2.577	30	2.575	50					1.623	30		
		2.564	60							1.617	3
2.556	30			2.553	6B			1.608	20		
		2.526	30					1.597	30	1.597	3
		2.489	20					1.580	40		
		2.474	20	2.474	3	1.575	20	1.570	20	1.570	3
		2.444	50					1.538	30		
2.419	20	2.424	50	2.424	3					1.526	2B
				2.400	3			1.516	20B		
		2.396	10							1.505	1
				2.368	3			1.495	30		
2.363	30	2.363	50							1.490	2
				2.323	2			1.478	20		
		2.318	5							1.463	2B
		2.292	10			1.456	20	1.460	40B		
		2.271	30							1.449	2B
				2.254	1			1.442	10		
		2.250	30					1.435	10		
		2.226	10							1.430	2
				2.210	1			1.426	30		

1) Axinite from Mitaké, Yamaguchi Prefecture, Japan.

2) Axinite from Bourg d'Oisans, Dauphine, France (U.S.N.M C-3141) (film 7051).

3) Manganoan axinite=Tinzenite from Tinzens, Switzerland (U.S.N.M. R-6433) (film 6987).

high weight percent of TiO_2 seems due to abundance of inclusions of sphene, it being trace or up to 0.2 in weight percent in common axinite after the data given by DEER et al. (1962). The figure 5 is a FeO-CaO-MnO diagram for molecular proportions in axinite. MgO was neglected from this diagram, because it is more or less 1 in weight percent in common axinite and is only subsidiary component in most cases. The axinite of number 8 was originally called manganoan axinite by MILTON et al., but axinite of numbers 5 to 7 may be called maganoan axinite (DEER et al., 1962). Double open circle in the diagram shows approximate composition of the axinite at Mitaké. In this case, the molecular percent of CaO that expected forming the molecules of sphene was subtracted from the total molecular percent of CaO. The axinite at Mitaké is regarded as manganoan axinite. It was also plotted as double open circle (number 5) in the figure 4.

MILTON et al. are of opinion that the ideal molecular formula of axinite is to be $(Ca, Fe^{+2}, Mn)_3 Al_2 BSi_4 O_{15} (OH)$, that has been supported by many mineralogists. After the opinion of MILTON et al., Mn^{+2} can probably substitute for Ca in manganoan axinite. Atomic ratio $Ca : Fe^{+2}+Mn^{+2}$ in manganoan axinite is actually variable, it being 1.3 : 1.7 in the manganoan axinite, originally called tinzenite, reported from Tinzens, Switzerland. In the axinite at Mitaké the ratio $Ca : Fe^{+2}+Mn^{+2}$ may be more or less 1.7 : 1.3.

The fact that the axinite-schist *4*) is richer in MnO than the others can be well explained by abundance of the manganoan axinite in the former. The refractive indices of the axinite at Mitaké are unexpectedly lower than those of ordinary manganoan axinite so far reported from various areas in the world. The optical properties of the axinite at Mitaké is, however, similar to those given by MASON (1959) for the Perth River axinite, they being as follows after MASON: $\alpha=1.674$, $\beta=1.681$, $\gamma=1.684$, optically negative, $2V=70°$. MASON is of opinion that the low refractive indices of his axinite may be due to "a considerable amount of replacement of (Mn+Fe) by Mg (p.138)". Unfortunately he gives no chemical composition of his axinite. In case of the axinite at Mitaké, such replacement as deduced by MASON will be negligible.

V. DISCUSSION

Referring to the petrographical data of the axinite, axinite-schist and surrounding greenschists at Mitaké described above, the following two points will be discussed here; the one concerns with paragenesis of the axinite in association with the other metamorphic minerals, and the other with the geological background of the axinite-schist.

Axinite is a commonest boron-bearing calc-aluminous silicate that occurs as a mineral of contact metamorphism and metasomatism. Some axinite has been found in areas of regional metamorphism. Even in such cases axinite commonly occurs in veins, whose materials are deduced to be derived from acid magmas (RASSMANN & LUITHLEN, 1952; SIMONEN & WIIK, 1952), excepting one case reported by MASON (1959). SERDYUCHENKO (1956) has an unique opinion about boron-bearing metamorphic assemblages that the boron-bearing material was of primary sedimentary deposition and subsequently recrystallized to form axinite on metamorphism. Such being the case, knowledge of boron-bearing metamorphic assemblages is insufficient as far as the present author knows.

In the present case of the author, axinite is probably one of metamorphic minerals in the axinite-schist (axinite-bearing greenschist). The axinite is in stable association with epidote, chlorite, stilpnomelane, calcite, albite and quartz. Modes of occurrence of axinite and epidote in the axinite-schist show close similarity with each other. Both generally occur as porphyroblasts or spots, and are often accompanied by calcite. Needles of stilpnomelane rarely break through the outer margin of porphyroblasts of axinte and epidote.

Axinite is much abundant in the axinite-schist, and epidote is scarce. In the epidote-stilpnomelane-schist (greenschist, especially rich in epidote and stilpnomelane), on the contrary, epidote is much abundant and axinite is scarce or absent. No greenschist containing nearly equal amount of axinite and epidote has been found. These may mean that it probably depends on differences in chemical compositions of rocks, perhaps mainly on B_2O_3 content, whether a rock will become rich in axinite or rich in epidote. Chemical composition of the axinite-schist seems to be appropriate for greenschists of epidote-stilpnomelane-chlorite assemblage (Fig. 4). The crystallization of axinite appears more preferable than that of epidote under the physical conditions of the quartz-albite-muscovite-chlorite subfacies, provided that the chemical potential of boron is moderate or high and P_{CO_2} is also moderate. To know the stability range of epidote in association with axinite is the best way to deduce a condition under which the axinite was crystallized.

Epidote in the epidote-stilpnomelane-schist and in the axinite-schist shows no visible zonal structure, and has probably an uniform chemical composition that is estimated as 25±2% in molecular proportion of $Ca_2Fe_3^{+3}Si_3O_{12}$ (OH), using the X-ray powder patterns. Exact chemistry of epidote can be, at the present state of knowledge, best estimated by $d_{(020)}$Å as proposed by Myer, but optical data seem inadequate to derive an exact composition of epidote. Epidote in the surrounding greenschist still appears to be a little higher in $Ca_2Fe_3^{+3}Si_3O_{12}(OH)$ component than that in the axinite-schist as well as in the epidote-stilpnomelane-schist.

Stability relations of the clinozoisite-epidote series are now of much interest among many petrologists such as Strens (1964, 1965), and in near future the stability range of epidote series will be clarified.

At the second, the geological background of the axinite-schist will be discussed. As mentioned in the other chapter and as shown in the figure 1, the localities from which the axinite-schist has been found are enclosed by greenschists of various compositions as well as various mineral assemblages which are shown in Chapter III. Chemical compositions of these miscellaneous greenschists are expected to be significantly variable through the whole mapped area. They are really variable as shown in the table 2, that is only an example. These greenschists are often accompanied by ultramafic bodies composed mainly of serpentine and olivine, and appear to have a stratigraphic horizon as a whole.

The upper formation of the Tsuno group, now being regionally metamorphosed, is characterized by prevalence of basic volcanic rocks and less prominent pelitic rocks (KOJIMA, 1953; NISHIMURA & NUREKI, 1966). In the upper formation, there is a stratigraphic horizon characterized by crystalline limestone that occurs generally as lense-like bodies inserted within the crystalline schist of pelitic rock origin. The greenschists accompanied by the axinite-schist are commonly lain just under the stratigraphic horizon of the crystalline limestone. Original rocks of the greenschists are perhaps of miscellaneous volcanic rocks, some being lava-flows and others intrusives. The rocks rich in boron and in silica would be originally accompanied with some of the volcanic rocks, and later developed to the axinite-schist during the Sungun regional metamorphism.

The author expects the analogous genesis on axinite and axinite-schist will be favorable in the case of the Sambagawa metamorphic rocks.

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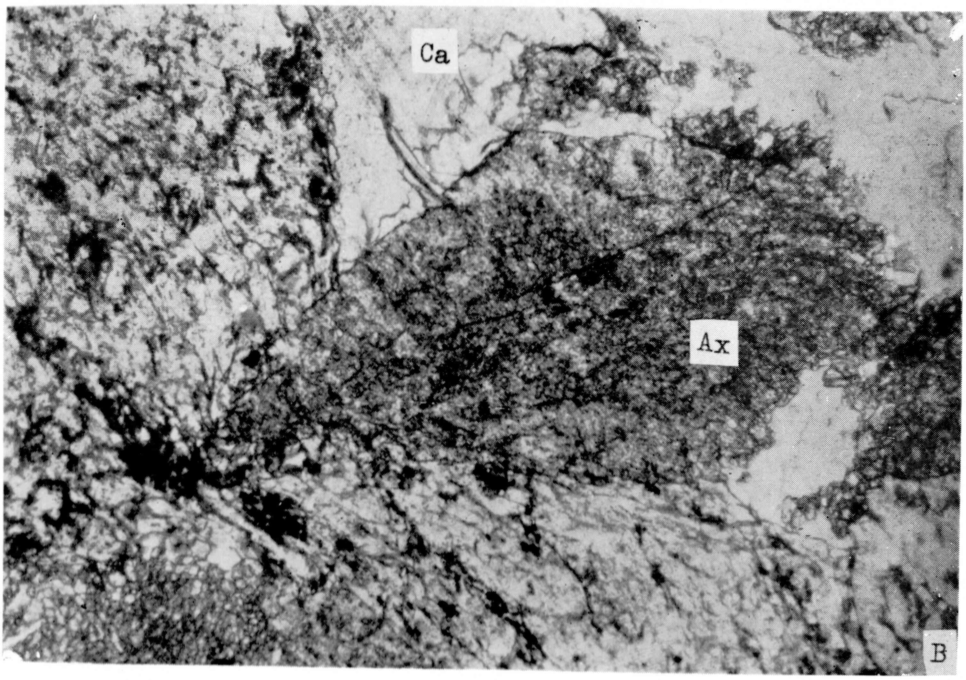
EXPLANATION OF PLATE XV

A: Photograph showing the mode of occurrence of axinite at Mitaké. Most of the white spots are of the axinite, but spots of epidote are also abundant. The spots of axinite and epidote can not be discerned by unaided eyes. Thin white veins composed mainly of quartz and albite cut the schistosity surface of the axinite-schist at an angle nearly normal.

B: Microphotograph of an axinite in the axinite-schist at Mitaké. Nearly all of grains of the axinite contain much amount of impurities. Calcite occurs often around the axinite. Open nicol. Ax: axinite Ca: calcite. ×40.


A

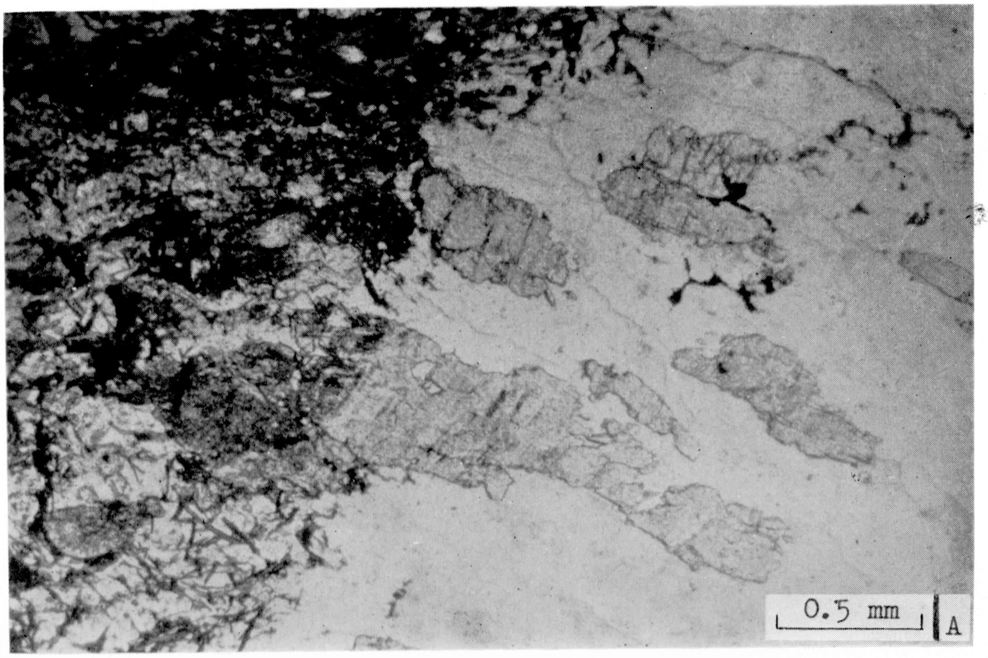

Ca
Ax
B

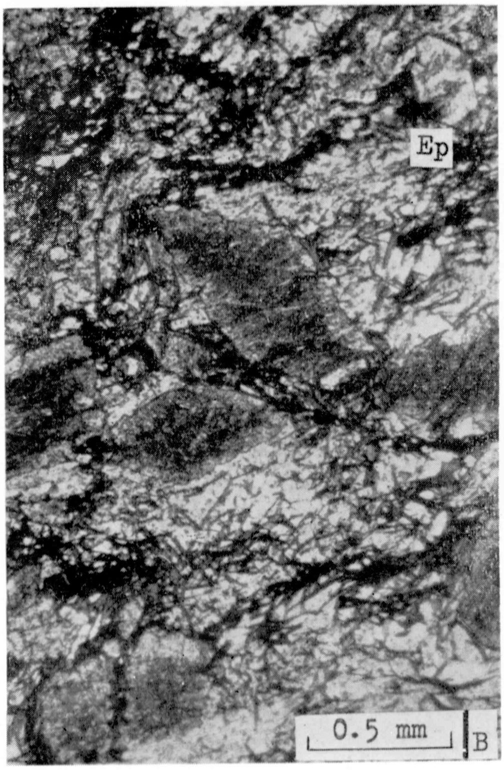
EXPLANATION OF PLATE XVI

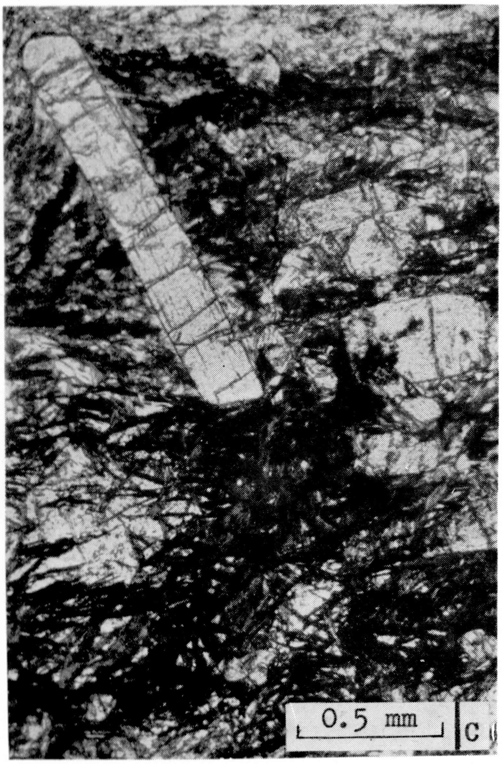
A: Microphotograph showing porphyroblasts of axinite at Mitaké. The left-half is of the axinite-schist and the right-half the quartz-albite vein. One porphyroblast crosses the boundary between them. The grains of axinite crystallized in the vein contain lesser amount of impurities and become more irregularly formed than those in the axinite-schist. The longest dimensions for quartz-grains as well as axinite-grains are preferably oriented at right angle to the wall of the vein. Open nicol.

B: Axinite-schist at Mitaké. Some porphyroblasts of the axinite show well-developed crystal habit, but most are irregularly shaped. Stilpnomelane is much more prominent than chlorite in amount. One grain of epidote (Ep) can be found at the right-upper corner. Open nicol.

C: Microphotograph showing porphyroblastic development of epidote in the epidote-stilpnomelane-schist that is also abundant in stilpnomelane. Open nicol.


0.5 mm
A


Ep
0.5 mm
B


0.5 mm
C