PETROLOGICAL STUDY OF THE CRYSTALLINE SCHIST SYSTEM OF SHIKOKU, JAPAN

By

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[*With Plates I–IV.*]

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GEOLOGICAL INTRODUCTION

Shikoku is a large island which is especially well known on account of its interesting sedimentary and metamorphic formations. The island is situated in Southwestern Japan, lying between Kyûshû and the Kii Peninsula of Japan. Geologically the land space can be principally divided into six zones from north to south—(1) group of igneous rocks (mainly granite and andesite), (2) Izumi-sandstone Series (Cretaceous), (3) Crystalline Schist System, (4) Mikabu System, (5) Chichibu System and (6) Mesozoic System—which extend almost parallel to the long axis of the island. The zones of the Izumi-sandstone and the Crystalline Schist System are sharply divided by the so-called median dislocation line which runs through Japan proper, Shikoku and Kyûshû. The area to the south of this line is generally called the Outer Zone, while the northern area belongs to the Inner Zone in geological meaning. A general idea of the geology of Shikoku can be readily obtained from the following map (Fig. 1).

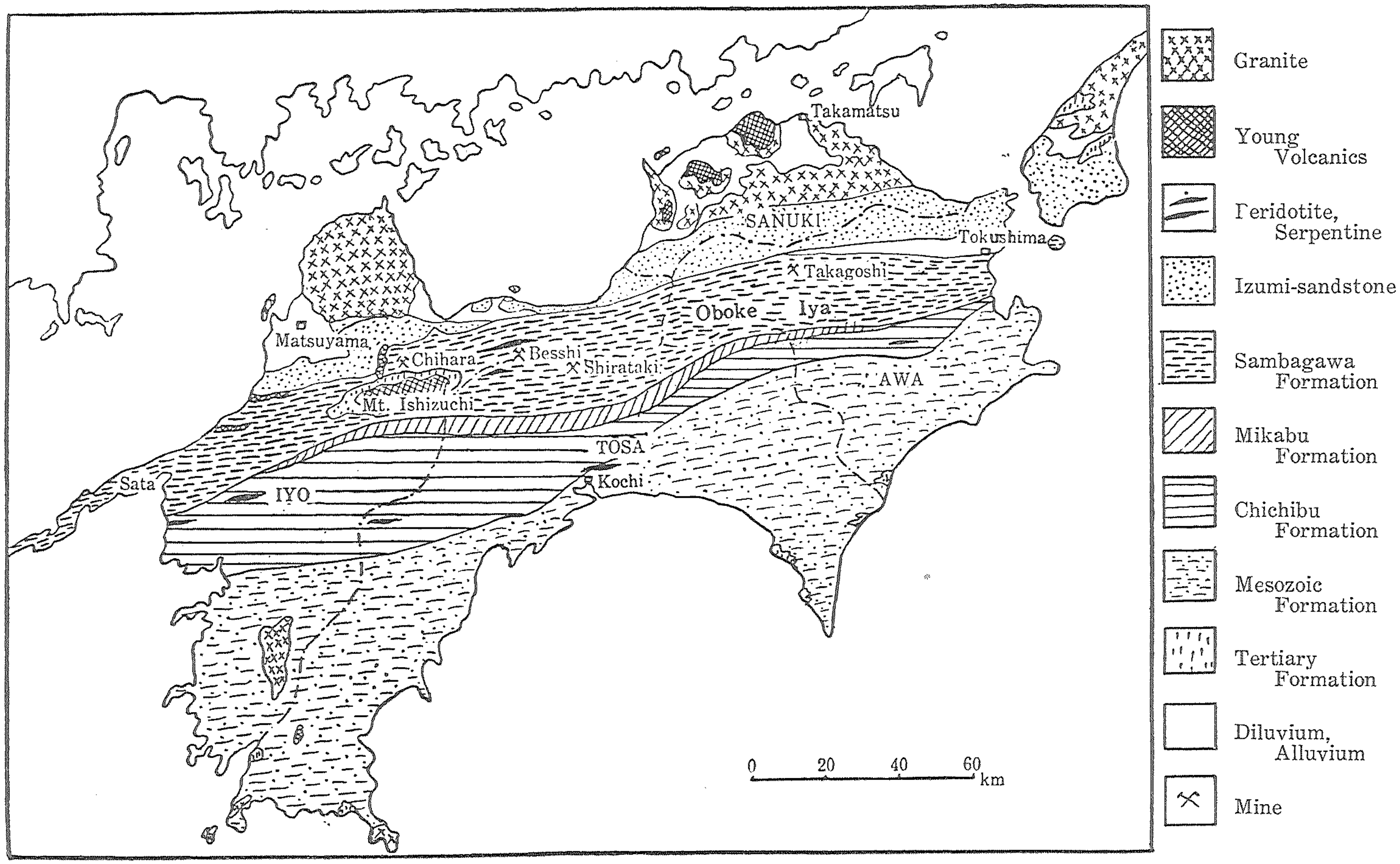

Fig. 1. Geological Map of Shikoku.

Though Shikoku is an isolated area, it shows an intimate relation, lithologically and geotectonically to the neighbouring lands on both sides and it will be easily recognized that they are all related to the same geological province.

The Crystalline Schist System which will now be described forms the foundation of the whole of Shikoku and extends over a large area in the central zone of the island, which stretches from Tokushima to the Sata Peninsula, as a narrow belt in a direction of approximately east to west. This crystalline complex comprises a great variety of metamorphic rocks differing largely in character. It is noticeable, that the detailed examination of these rocks has proved their similarity in every point to the original type of the so-called Sambagawa Formation of Kwantô of Japan proper, the formation of which had been fully studied by B. Koto.[1] Thus there is reason to believe that the Crystalline Schist System in Shikoku is closely connected with those of Kii, Chûbu and Kwantô of Japan proper and Kyûshû, and forms a particular formation in the so-called Outer zone of Japan. The distribution of the Crystalline Schist System (Sambagawa System) is shown in the accompanying map (Fig. 2).

The varied geological constitution of Shikoku has given rise to a corresponding topographical variety in the landscape for the protaxis of the Shikoku mountain ranges which are composed mostly of crystalline schists, trend in a direction parallel to the general foliation of the schists and the elongation of the island, showing that the relation of topographical features to geological nature is especially well illustrated. With the exception of the region of Ishizuchiyama which is composed of comparatively young volcanic rocks and some Tertiary sedimentary rocks, the crystalline schists have a predominant east to west strike and are

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(1) B. Koto: On the so-called Crystalline Schist of Chichibu. Jour. Coll. Sci. Imp. Univ. Tokyo, Vol. II, No. 1, 1883, p. 77.

From the typical occurrence in the Sambagawa valley of the Prov. Kozuke of Kwato, the crystalline Complex has been given the name "Sambagawa formation" by B. Koto.

highly folded. They usually form very steep ridges of a mature stage in the cycle of erosion. Some parts of the ridges are over 1500 m. above sea-level, and run nearly in a straight line. The central watershed of these ridges does not exactly correspond to the main axis of warping of the crystalline schist which indicates that the region has suffered by long denudation in the course of which peneplanation has probably taken place.

It is clear that the great orogenic movement which caused the metamorphism of the zone, finished before the deposition of the Carboniferous Formation, for we cannot find any dynamo-metamorphosed rocks in the carboniferous sedimentaries which are widely distributed in the neighbouring part of the zone.

Since the first survey of E. Naumann, the zone of the Crystalline Schist System of Shikoku has been the subject of repeated enquiry by geologists.(1) But from the summary of their conclusions, it may be

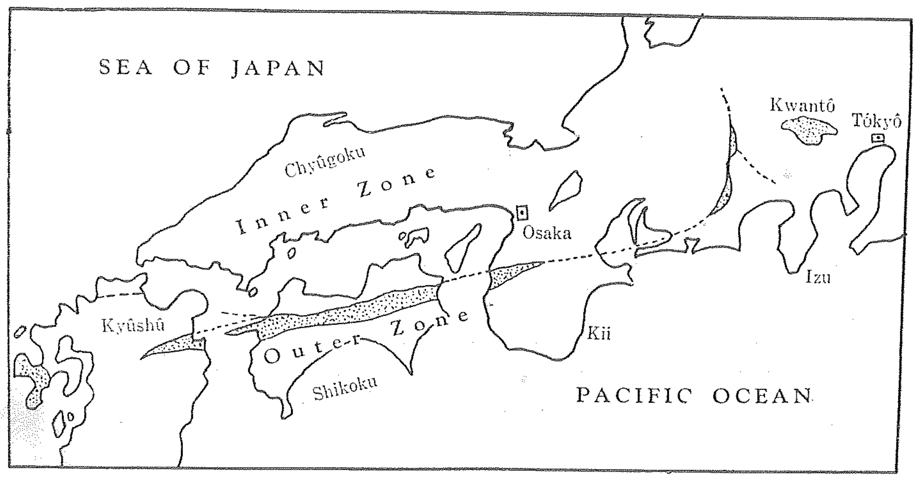

Fig. 2. Map, showing the distribution of the Crystalline Schist System of Japan.

(1) E. NAUMANN: Ueber den Bau und die Entstehung der japanischen Inseln. Berlin, 1885.
E. NAUMANN: Ueber die Geologie Japans. Compte Rendu, 3ème Session du Congrès Geol. Intern. Berlin, 1885.
E. NAUMANN: Neue Beiträge zur Geologie und Geographie Japans. Petermanns Mitteilungen, Ergänzungcheft No. 108, 1890.

inferred that it is difficult to study the stratigraphy of the System. For, as no organic remains have yet been found in any of the strata of the System, the subdivision of the System must be based on lithological grounds alone. It is also difficult to resist the impression that the stratification of the schists relates to an original banding, for the structure of the district is more obscure than the stratigraphy and it is clear that the folding and faulting have been extremely complex. Consequently, no definite attempt has been made to map them comprehensively, locally some localities excepted.

So far as the writer's observations are concerned, it seems that a rough two-fold division of the System into the *Besshi* and *Obokè* Series, as pointed out by T. Ogawa, is possible, stratigraphically and petrographically, though the exact order of succession of the subdivisional layers in these series is still uncertain. As the lateral extension of piedmontite schist and glaucophane schist in the Sambagawa System is very large in spite of their thinness, they have often been used as a keybed in studying the order of succession of the crystalline schists in the System. But recently some geologists noticed the fact that they occur in several different layers and expressed the opinion that they do not afford suffi-

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E. NAUMANN u. NEUMAYR: Zur Geologie und Palaeontologie von Japan. Denkschr. K. Akâd, Wien, Math. Naturw. Kl., Bd. LVIII., 1890.

T. HARADA: Die japanischen Inseln. Eine topographisch-geologische Uebersicht. 1890.

K. NAKAJIMA: Sulphide ore deposits in the Outer zone of the south part of Japan. Mem. Geol. Surv. Japan. No. 1. 1893.

T. SUZUKI: Tokushima sheet and its explanatory note, Imp. Geol. Surv. Japan, 1895.

M. YAMAGAMI: Marugame sheet and its explanatory note, Ibid. 1899.

T. OGAWA: Kôchi sheet and its explanatory note, Ibid. 1902.

K. INOUE: Uwashima sheet and its explanatory note, Ibid. 1903

S. KÔZU and S. NODA: Matsuyama sheet and its explanatory note, Ibid. 1910.

Y. OTSUKI: Hiwasa sheet and its explanatory note, Ibid. 1910.

E. SAGAWA: Resumé of a Report on the geology of the cupriferous pyrite deposits in the crystalline schist of the nothern part of Awa and the northwestern part of Iyo in Shikoku, Mem. Geol. Surv., No. 1, 1910.

K. ARAI: Besshi Mine, Jour. Min. Soc. Japan, 1911–1913.

S. KADOKURA: Preliminary note of the Saijo sheet, Rep. Geol. Surv. Japan, No. 83, 1920.

Y. OZAWA: Stratigraphical and structural studies of the Crystalline Schist System of Shikoku, Jour. Geol. Soc. Tokyo. XXXIII, 1926.

cient help for the exact correlation of distinct outcrops. It seems, however that these schists are restricted to the zone of green schists containing spotted schists and cupriferous pyrite deposits and in general they are not found in the so-called Oboké Series which is characterized by the presence of the so-called Oboké gneiss.

The most important point to be determined is the stratigraphical relation between the Besshi Series and Oboké Series. For in spite of the Besshi series resting directly on the Oboké Series, the rocks of the former always show a higher grade of dynamo-metamorphism than those of the latter series which is underlying it. According to the field evidence, the junction line of these series is apparently conformable and the schistosity in both series is usually parallel the one with the other. One of the best sections for studying the relations of these facts are always observed when the two series come into contact[1] (Fig. 3).

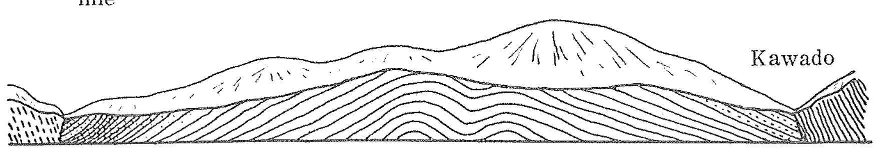

Fig. 3. Ideal section along the Oboké Valley.

The question of the relationship of these series has attracted the attention of many geologists[2] and has been carefully considered by

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(1) We can find many similar examples in other metamorphic provinces, in which the upper layer shows an apparently higher grade of dynamo-metamorphism than the lower layer. Such provinces are generally very complicated stratigraphically, tectonically or owing to igneous intrusions and the explanation of the geological relations of the districts has given rise to much discussion.
The districts of crystalline schists of the Southern Highlands of Scotland or Pensylvania and Maryland of America, are representative examples of this point.

(2) T. HARADA, T. OGAWA, E. SAGAWA, K. ARAKI, S. KOZU, S. NODA, Y. OZAWA, etc., loc. cit.

them. By some it is believed that the present positions of these series are due to folding or overthrusting and do not indicate the original relations. Others consider that the metamorphism depended on the intrusion of the gneissose granite mass of the Inner Zone, and increased in intensity in a upward sense. But summarizing from much geological and petrological evidence[1] it seems to be most probable that the stratigraphical sequence in the field corresponds to the original order.

It is also conceivable that the differences in metamorphic appearance between the Besshi Series and Oboké Series, might be caused by the effect of dynamometamorphism on a large scale which accompanied the extensive orogeny of pre-Carboniferous age and it is unnecessary to connect of metamorphism of these rocks with the local intrusion of igneous mass.

The crystalline Schist System has been generally attributed to the Archean, on the strength of its metamorphosed condition. In the Outer Zone of Japan, however, the oldest fossils known, those of the so-called Chichibu System, are Carboniferous; therefore, the age of the Crystalline Schist System and so-called Mikabu System, both older than the Chichibu System, is quite unknown. Accordingly, they are for the present simply considered to be pre-Carboniferous.

Concerning the relationship of the Crystalline Schist System, Mikabu System and Chichibu System in the central part of Shikoku it is as well to consider them as follows:

Permian-Carboniferous....Chichibu System

$$\text{Pre-Carboniferous}\cdots\begin{cases}\text{Mikabu System} \\ \text{Crystalline Schist System}\cdots\begin{cases}\text{Besshi Series}\\ \text{Oboké Series}\end{cases} \\ \quad\text{(Sambagawa System)}\end{cases}$$

(1) J. Suzuki: On the Oboké Gorge. Geographical Review (Tokyo) Vol. II., 1926. pp. 277–293.
J. Suzuki: On a conglomerate schist from Iya Valley in Shikoku. Proc. Imp. Acad. III. p. 675–678 and Journ. Geol. Soc. Tokyo. Vol. XXXV (1928) pp. 492–509.

I. PETROGRAPHICAL CHARACTERS OF THE SYSTEMS

The rocks of the Crystalline Schist System of the central part of Shikoku have undergone severe deformation by dynamo-metamorphism and they are, as a rule, distinctly schistose, being composed mostly of recrystallized minerals, though some of them contain the primary minerals or pebbles which have generally been elongated in certain direction, along the planes of foliation. These rocks have been usually folded and cleaved, showing a noticeable banded texture in the field.

The chief petrological type of the Besshi Series is green schist and next comes an abundance of siliceous schist. Calcareous schist is often intercalated in them, but compared with the green schists and siliceous schists, it is negligible in volume. The Obokė Series is composed essentially of so-called Oboké gneiss and graphite schist and a small quantity of green schist.

The following list shows the chief metamorphic rocks exclusive of the Crystalline Schist System which are to be found within the central part of Shikoku.

(A) Besshi Series.

a) Green schists.

1) Albite-epidote-chlorite schist
2) Amphibole chlorite schist
3) Amphibole schist or amphibolite
4) Garnet amphibolite and cyanite garnet amphibolite
5) Eclogite
6) Albite zoicite amphibolite
7) Actinolite schist
8) Serpentine
9) Epidote glaucophane schist
10) Glaucophanite and hornblende glaucophane schist
11) Sericite glaucophane schist.

b) Siliceous schists.
 1) Sericite quartz schist
 2) Glaucophane bearing sericite quartz schist
 3) Epidote quartz schist
 4) Piedmontite quartz schist
 5) Hematite quartz schist
 6) Graphite quartz schist.

c) Calcareous schists.
 1) Sericite calcite quartz schist
 2) Piedmontite sericite calcite-quartz schist
 3) Crystalline limestone.

(B) Oboké Series.
 1) So-called Oboké gneiss
 2) Graphite schist
 3) Green schist
 4) Conglomerate schist.

It is noticeable that the Crystalline Schist System contains a considerable quantity of cupriferous pyrite deposite which are not present being worked in numerous mines, such as, the Besshi, Shirataki, Higashigama, Takagoshi, Chihara, Minawa, etc. Beside this, the crystalline schists of the System have not infrequently been intruded or broken abruptly across their planes of foliation, by numerous veins each of which consists of several varieties of quartz, albite, calcite, epidote, chlorite, etc., together or in part-associations. It is important to study these are deposite and mineral veins in connection with the petrological investigation of the crystalline schists of the Sambagawa System.

A. Green Schists in the Besshi Series

a) Mode of Occurrence

The green schist forms the largest group in the Besshi Series and occupies a very extensive area in the central part of Shikoku, being conformably bedded with siliceous schists. Albite epidote chlorite schist and amphibole chlorite schist which are the conspicuous member of the Besshi Series, appear as thick belts associated essentially with amphibolite, graphite schist and piedmontite schist. The good exposures of these rocks are seen in the sections near Besshi, Shirataki, Chihara, Higashiyama, etc. Generally they extend in an almost east-west direction and dip north, at usually variable angles.

Various kinds of amphibole schist or amphibolite are also important members of the Besshi Series. They are exposed in lenticular form or as narrow belts in various parts of the central part of Shikoku. The best of these is developed in the environs of the Besshi Mine. It extends as a belt obout 40 km. in length running in a direction of nearly east to west. Though its width is variable in places, the finest expanse at Tonaru near the Besshi Mine reaches about 1000 m. in width.(1) From the field facts and petrological characters, it seems probable that the belt is the metamorphosed product of basic intrusive rock in sill-like form. The stratigraphical relations of the amphibolite belt and the neighbouring schists in the envirous of the Besshi Mine, can be readily interpreted from the accompany figure (Fig. 4).

In general, the amphibolite belt shows a sharp contact against the adjacent schists, but in some cases a gradual transition may be observed. There are a number of varieties in the belt depending on the kind of amphibole present and on the minerals associated with it, so that classification into various types, according to the predominant mineral composition, may be undertaken. The chief variations are as follows: amphibolite proper, albite zoisite amphibolite garnet amphibolite, eclogite, actinolite schist, serpentine, etc. through these types may graduate one into another.

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(1) S. KADOKURA (loc. cit.) and Y. OZAWA (loc. cit.) published the geological maps of the central part of Shikoku, including the amphibolite belt and its neighbouring schists, in which the boundaries of these rocks are mainly correct.

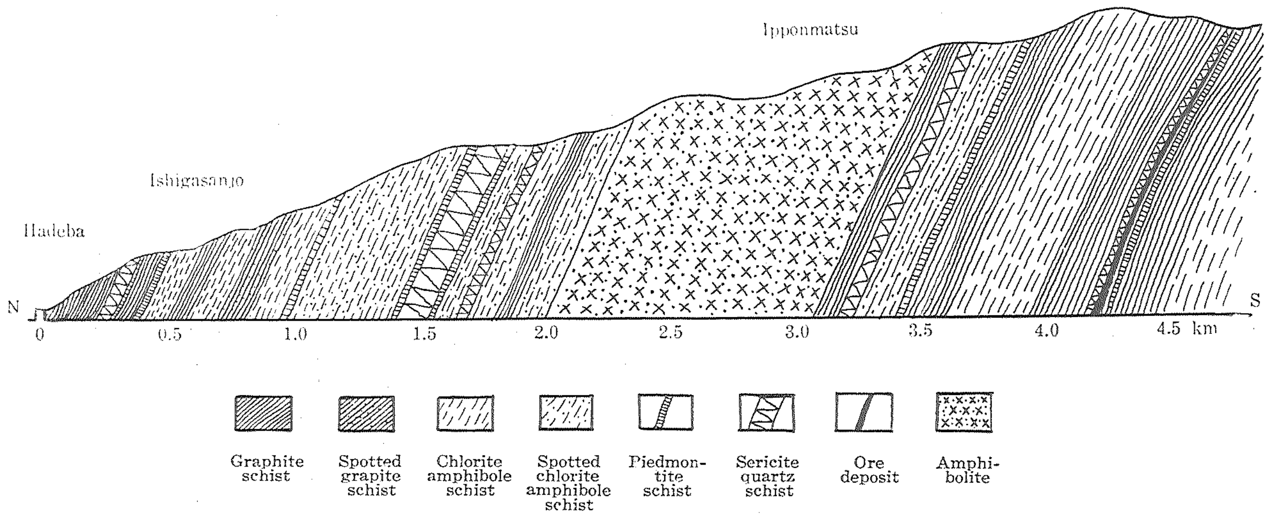

Fig. 4. Profile along the Fourth Tunnel of the Besshi Mine.

Garnet amphibolite generally occupies the upper margin of the proper amphibolite mass and albite zoisite amphibolite occurs as small patches or narrow layers in the mass.

Glaucophane schists are comparatively small in quantity, but are widely distributed in the System. They occur usually as thin layers associated with siliceous schists and various kinds of green schist, having locally the appearance of a distinct stratigraphical unit in the Besshi Series. One of the excellent exposures of the rock in the central part of Shikoku is found in the environs of Noji near the Shirakaki Mine. It is only several meters in average thickness but shows extensive development in lengths running EEW to WWS. It can be traced over five miles along the strike and forms the distinct index layer in the district. The other good outcrops of glaucophane schists are found in the envirous of the Chihara Mine and the Takakoshi Mine.

Serpentine rock and actinolite schist occur in lenticular form in various part of green schists. They are usually elongated and nearly parallel to the general foliation of the adjacent schists. Sometimes the serpentine rock is so massive that it may readily be mistaken for rocks which had been subjected to intrusion after the great folds in the district were completed. Serpentine shows occasionally gradual transition to the unaltered actinolite, and on the other hand is accompanied by a large quantity of secondary minerals, such as phlogophite, chlorite and talk. In general these different phases show zonal or concentric

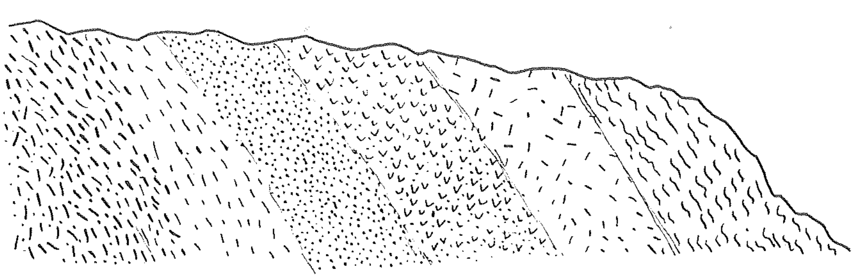

Fig. 5. Ideal section of the marginal part of the amphibolite mass.

arrangements, and proceeding outwards, one notes he gradual transitions of the rock. The typical exposure in the environs of the Besshi Mine is shown diagramatically in Fig. 5.

b) General Characters of the Green Schists

The rocks are characterized by an almost universal green colour, though the relative proportions of the essential mineral species vary markedly in the different layers. The term "green schist" will, therefore, be taken to various kinds of rocks, which are rich in ferromagnesian constituents and seem to be closely allied to the basic type. In general the green schist consists mainly of recrystallized minerals, produced by severe dynamo-metamorphism and always shows distinct schistose texture. But sometimes, there are, in addition, secondary products of alterations and pneumatolysis. The green schist may be classified into many types, from the standpoint of predominant mineral compositions.

The essential constituents of the main types of the green schists in the Besshi Series can be shown as follows:

Chlorite schist.	Chlorite, epidote, albite.
Chlorite amphibole schist.	Hornblende, chlorite, epidote, albite.
Amphibolite (proper).	Hornblende, epidote, albite (plagioclase).
Zoisite amphibolite.	Hornblende, zoisite, epidote, albite.
Garnet amphibolite.	Hornblende, garnet, albite (plagioclase, cyanite).
Eclogite.	Omphacite, garnet (glaucophane).
Glaucophane schist.	Glaucophane, epidote, albite.
Sericite glaucophane schist.	Glaucophane, sericite, albite.
Actinolite schist.	Actinolite, epidote, chlorite (calcite).
Serpentine.	Antigorite.

The general characters of the constituents of these types are dealt with below.

Chlorite is usually the principal constituent of the albite epidote chlorite schist and amphibole chlorite schist. It appears as greenish flaky plates of 0.3 mm. average diameter, showing parallel arrangement with the other minerals. Sometimes it is enclosed in the borders of albite or amphibole crystals. It is mostly of the usual type with small axial angle and positive optical character. It shows pale pleochroism, yellowish green to green. The double refraction is usually low, almost isotropic, but occasionally it shows well marked anomalous colours. Some falkes of chlorite occur closely associated with brownish iron ore and biotite.

Albite is an essential constituent of the chlorite schist or amphibolite. It fills the interspaces of the aggregation of the other components, but in some cases, it occurs as white phenoblasts. It is generally untwinned, and cleavage is often absent, but is one rare occasions zoned. A refractive index of the mineral in the green schist was determined in cleavage flakes[1] and is as follows:

n_1 (010) or (001)=1.531−1.534. $Ab_{94}An_6 - Ab_{86}An_{14}$. Phenoblastic albite in the so-called spotted green schist is about 1 mm. in average and the ratio of the greatest to the least diameter is 2 to 1. Sometimes it reaches locally 1 cm. or more; the best examples of this kind can be found in the amphibole chlorite schist of Hadeba near the Besshi Mine. The chemical analysis of a phenoblast is quoted by T. Harada[2] as follows: (The analysis is not good).

Albite from Besshi, Prov. Iyo.

SiO_2	66.92
Al_2O_3	20.58
CaO	0.80
Na_2O	7.39
Fe_2O_3	0.64
MgO	0.92
K_2O	tr.
H_2O	1.00
Total	98.25

(1) S. Tsuboi: A dispertion method of determing plagioclase in cleavage flakes. Mineralogical Magazine Vol. XX. p. 108.

(2) T. Harada: Die japanischen Inseln etc. 1890, p. 50.

The phenoblasts of albite are usually fresh and clean,[1] sometimes contain numerous inclusions, such as chlorite, hornblende, actinolite, epidote or garnet. These inclusion are, in some cases, arranged poikiloblastically across the borders of the albite individuals. It is clear that the porphyroblastic structure of these spotted schists was developed during dynamo-metamorphism and the phenoblastic albite is one of the last minerals which were crystallized in the schist.[2]

Epidote is a predominant constituent of the chlorite schist and of some kinds of amphibolite. In the former it occurs as minute prism, of 0.2 mm. average length and occupies in some cases 15% or more of the rock. It is usually light greenish yellow in colour, characterized by a high index of refraction and high double refraction, showing slight pleochroism. It is frequently almost colourless and shows similar properties as clinozoisite. Occasionally zonal structure may be developed. In such cases the outer zone is more ferriferous than the core. The secondary epidote which is closely associated with hornblende or albite, show quite the some optical properties as the recrystallized specimens. Sometimes elongated nodules or veinlets of epidote can be found in the green schist. The epidote in these is generally more yellowish than the two above mentioned types.

Hornblende is the predominant mineral of the amphibole chlorite schist or amphibolite; in the latter it amounts to 80–90% of the whole constituents. The average length of the mineral is about 3 mm., but occasionally it reaches 2 cm. or more. It always occurs as short prismatic crystals showing fine cleavage planes but the terminal part is usually broken up into numerous fibres. Pleochroism is comparatively strong and the absorption is as follows: X = yellowish green, Y = dark green, Z = bluish green and the absorption formular is $Z = Y > X$. This mineral often shows noticeable pleochroism, in pale, violet blue to indigo blue

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(1) It is noticeable that feldsper produced by recrystallization under metamorphism generally shows extremely fresh and clean appearance in comparison with that of igneous origin.

(2) J. Suzuki: On the origin of spots in metamorphic rocks, Jour. Geol. Soc. Tokyo, Vol. XXXIV, 1927. p. 275–303.

tints. This suggests that the isomorphous mixture of the mineral sometimes contains the glaucophane molecule. The hornblende in the amphibolite from Besshi shows a maximum extinction angle of 25° and the indeces of refraction on the cleavage pieces are n_1 (100) = 1.652. n_2 (110) = 1.661. In many sections, some hornblendes contain numerous microscopic flakes of chlorite or minute prisms of epidote which are distributed secondarily in planes parallel to the prismatic cleavage, showing a similar optical orientation as the original hornblende.

Glaucophane is the predominant ingredient of the glaucophane schists. Sometimes it occurs in amphibole chlorite schist and eclogite as accessory component. It shows a fine prismatic development with perfect cleavage parallel to the prism, but occasionally it occurs in a long needle like or fibrous form. The terminal part of the prism shows a tassel-like form. The mineral in the glaucophane schist is mostly 0.4 – 1 mm. in length and 0.05 – 0.1 mm. in width, but in places it reaches more than 2 cm. in langth and 0.3 cm. in width. The pleochroism is characteristic and the axial colours are as follows: X = blue, Y = violet blue, Z = greenish blue and the absorption formular is Z>Y>X. Glaucophane from Shirataki shows a maximum extinction angle of 12° and the indeces of refraction are $n_1(110)=1.648$ $n_2(1\bar{1}0)=1.658$.

A chemical analysis of glaucophane in glaucophane schist from Otakisan near Tokushima City, Shikoku, quoted by B. Koto[1] is given as follows:

Glaucophane from Otakisan, Prov. Awa.

SiO_2	56.71
Al_2O_3	14.14
Fe_2O_3	9.78
FeO	4.31
CaO	4.80
MgO	4.33
Na_2O	4.83
K_2O	0.25
Total	100.12

(1) B. Koto: A note on glaucophane, Jour. Geol. Sci. Tokyo Imp. Univ., Vol. I. 1887.

Actinolite occurs mainly in actinolite schist from Iratsuyama(1) near Besshi, and Shirataki, but small quantities of the mineral are usually contained in the green schists of the System. It show slight pleochroism, X=pale green, Y=Z=pale green with a yellowish tint, and the absorption formular is Z=Y>X. In some sections, it is faintly browned by an alteration product along the cleavage planes. The extinction angle(2) is almost 25° and the indeces of refraction of the mineral from Iratsuyama are as follows: $n_1\,(110)=1.639$, $n_2\,(1\bar{1}0)=1.654$.

The mineral is commonly altered into talc or phlogopite, often with the simultaneous formation of serpentine.

Pyroxene occurs only in eclogite from the environs of the Akaishi Mine, Prov. Iyo, Shikoku. It forms phenoblasts in the rock, showing short prisms with fine cleavage planes. It shows weak pleochroism, pale-green to yellowish green. The characters of the mineral and the chief zone are both positive and the maximum extinction angle is $c\hat{}Z=40°$. The index of refraction and double refraction are comparatively high. The optical properties indicate that the pyroxene may be belong to the diopsidic type, probably omphacite.

Garnet is one of the principal Constituents in the garnet amphibolite and eclogite. Usually it occurs as an accessory ingredient in the green schist in the Besshi Series, but never appears in the schists rich in the chlorite and epidote. Garnet in garnet amphibolite from Tonaru near Besshi is often idiomorphic showing the icositetrahedron, and is of various sizes between 0.5–5 cm. in diametre but it generally occurs in rounded forms composed of numerous granulated pieces. Most of the garnet is clear and homogeneous, though not entirely free from fine, dust-like inclusions. Garnet crystals are mostly of a slight pinkish colour and almost isotropic, showing no trace of optical anomalies. Garnet in garnet amphibolite from Tonaru near Besshi shows the following chemical composition. The analysis was made by Takayanagi, of the Geological Survey of Japan at the writers request.

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(1) D. SATO: On actinolite from Iratzuyama, Prov. Iyo. Jour. Geol. Soc. Tokyo, Vol. IX, 1902, p. 20.

(2) It is noticeable that the amphibole in the crystalline schists in the Sambagawa System usually shows a large extinction angle.

Garnet from Besshi, Prov. Iyo.

SiO_2	37.90
Al_2O_3	17.95
Fe_2O_3	25.54
MgO	4.63
CaO	9.35
TiO_2	1.11
MnO	3.02
Total	99.50

Cyanite occurs only in a special type of garnet amphibolite from Sekigawa-mura near Besshi. It is pale bluish white in colour and forms minute prisms though it may sometimes reach 1 cm. or more in length with marked cleavage. It shows a comparatively strong double refraction and a high index of refraction.

Quartz is not always a predominant constituent, but is usually present in varying quantities, associated with albite grains. There are sometimes small patches of fresh quartz grains mixed with minute crystals of epidote, garnet, etc. It occurs usually in xenomorphic form and shows undulatory extinction.

Sericite occurs as small flakes associated generally with chlorite and glaucophane, though it is less significant in quantity.

Biotite is usually absent in the normal green schists of the Besshi Series but it can be found in certain parts of the epidote chlorite schists and amphibole chlorite schists which are chiefly found in the immediate neighbourhood of the basic intrusive rocks. Good examples are observed in the vicinity of serpentine rock near the Shirataki and Besshi Mine. The mineral is practically uniaxial and is strongly pleochroic in pale greenish brown to dark greenish brown. The index of refraction is $\gamma=1.636$ indicating a composition with comparatively high percentage of iron.

Rutile is a constant feature in the green schists, though always present in very small amounts only. It occurs in rounded grains of high refraction, mingled with epidote, chlorite and amphibole. Sometimes it is locally abundant in the phenoblasts themselves, in some instances large brownish crystals reach 2 cm. or more, elongated along the c-axis and parallel to the schistosity of the rock. Some crystals are twined and show a good example of the sagenite web.

Titanite is a very important accessory mineral, usually found in minute wedge-shaped grains and irregular patches. It shows pleochroism in brownish green to browny tints.

Ilmenite and magnetite are uniformly distributed in the green schist though usually in small quantities. Both minerals occur in minute rounded grains and the former is now largely leucoxenized. Sometimes phenoblasts of magnetite can be found in the shlorite schist, the latter showing fine octahedral crystals reaching 0.5 cm. in diameter.

Tourmaline is a common accessory mineral of the rock. It occurs as minute needle-like prisms, penetrating most of the constituents, though some are included in albite crystals. It is green to brownish green in colour with strong pleochroism.

Very locally, pyrite and calcite are predominant constituents of the green schist. Very minute grains of basic plagioclase, containing appreciable amounts of anorthite, have also been observed in a few specimens of the rock.

c) Description of the Green Schists

1. Albite Epidote Chlorite Schist

The rock shows a moderately coarse grain and schistose texture. The constituent minerals are not readily apparent to the naked eye, though occasionally small phenoblasts of albite are noticeable. The general aspect of the rock is characterized by the light greenish colour which is due to the prominent constituents. The schist is composed essentially of chlorite, albite, epidote and quartz and some accessory minerals such as titanite, ilmenite, rutile, biotite, magnetite, tourmaline, (Pl. I, Fig. 1). A small quantity of glaucophane is locally associated with them. The schistose character of the rock is given entirely by a parallel orientation of chlorite flakes and epidote prisms. A feldspar free variety is often found in narrow belts in the normal chlorite schist. It consists mostly of fibrous chlorite, epidote and some oxide minerals.

A sample of the albite epidote chlorite schist from the Takakoshi District, Prov. Awa, was analyzed by Takayanagi of the Geological Survey of Japan, yielding the following result.(1)

Albite-epidote-chlorite-schist from Takakoshi, Prov. Awa
(Anal. K. Takayanagi)

	Wt. %	Mol. numb.
SiO_2	48.52	808.6
Al_2O_3	14.93	146
Fe_2O_3	3.82	24
FeO	9.53	132
MnO	0.43	6
MgO	5.35	134
CaO	10.57	189
Na_2O	2.65	42
K_2O	0.11	1
H_2O	—	—
TiO_2	0.93	12
P_2O_5	Tr.	—
Loss on ignition	2.95	—
Total	99.78	

2. Amphibole Chlorite Schist

The rock is almost identical in structure and occurrence with the albite-epidote-chlorite schist and shows similar development in Shikoku. It is essentially composed of chlorite, amphibole, epidote and albite, and iron ore and rutile are conspicuous among the accessory minerals

(1) Jour. Geogr. Soc. Tokyo, Vol. XXXIX. 1927.

(Pl. I, Fig. 2). In general, the crystals of chlorite and amphibole are orientated in parallel enclosing grains of epidote. The rock is generally darker than the chlorite schist which is free from amphibole, but sometimes it shows a light yellowish colour. The latter is found to be chiefly due to the rumerous bands of yellowish epidote. By an increase in the proportion of amphibole this type passes into amphibole schist or amphibolite: on the other hand, it often appears to pass insensibly into chlorite schist in which the green hornblende is wholly replaced by chlorite flakes. The chemical analysis of amphibole chlorite schist from Shirataki Prov. Tosa (I), and Sekizen Prov. Tosa (II), which were made by the author and Takayanagi of the Geological Survey, respectively are as follows:

I. Albite-epidote-hornblende-chlorite-schist from Shirataki, Prov. Tosa. (Anal. J. Suzuki)

II. Hornblende bearing epidote-chlorite-schist from Sekizen, Prov. Iyo. (Anal. K. Takayanagi)

	I		II	
	Wt. %	Mol. numb.	Wt. %	Mol. numb.
SiO_2	48.86	814	48.83	801
Al_2O_3	17.80	175	15.43	151
Fe_2O_3	4.87	31	4.56	28.5
FeO	7.39	103	6.65	92.5
MnO	—	—	0.54	8
MgO	3.87	96	6.11	153
CaO	10.50	188	8.48	152
Na_2O	2.32	37	3.14	51
K_2O	0.86	9	1.62	17
H_2O	1.27	—	—	—
TiO_2	1.05	13.5	1.09	14
P_2O_5	0.60	4	0.14	1
CO_2	0.65	—	—	—
Loss on ignition	—	—	3.66	—
Total	100.04		100.25	

It is noticeable that there are some special spotted green schists which contain numerous phenoblasts of albite, associated with the albite epidote chlorite schist or amphibole chlorite schist (Pl. I, Figs. 2 & 4).

Generally the mineral assemblage of these spotted schists in the same as that of the normal green schists discussed above. These special rocks are universal over the area of the green schist. In particular they show extensively in the environs of the Shirataki, Besshi and Chihara Mine. In these localities, they usually pass over into spot free varieties. As the spotted schists are distinctive members of the Besshi series, they have often been used as a characteristic zone in studying the general order of succession of the Series. But as these spots in the schist may be locally produced under the special condition of dynamometamorpohism,(1) it is questionable if we may consider them as a stratigraphical unit, till a more exact correlation is made.

3. Amphibolite (Proper)(2)

This type occurs in lenticular forms or narrow belts in the Besshi Series. It occupies a predominant part of the large amphibolite belt which developes near the Besshi Mine. The rock is dark green in colour and consists largely of glistening crystals of green hornblende, interspersed with smaller amounts of albite, epidote, quartz and some accessory minerals such as sericite, rutile, ilmenite, titamite, tourmaline, garnet, chlorite, glaucophane, biotite, etc. (Pl. I, Fig. 3) Sometimes it contains a number of albite phenoblasts, forming the so-called spotted amphibolite. The rock varies somewhat widely in coarseness of grain as way be easily recognized in the hand specimens. As a rule, a schistose texture is produced by the parallel orientation of the essential constituents, but in some places, a massive texture prevails in which the minerals are not orientated. The partial difference of texture probably originated from the different conditions of metamorphism. The rock contains in parts crowds of needless of dark greenish tourmaline which cross the schistosity of the rock. Occasionally large crystals,

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(1) J. Suzuki: On spots in metamorphic rocks, Jour. Geol. Soc. Tokyo, Vol. XXXIV, 1927, p. 278.

(2) J. Suzuki: On the origin of the amphibolite from the environ of the Besshi mine. Ibid. XXXIII. 1926.

about 3 cm. with terminal planes, are found in the crowds. There is thus clear evidence, that the growth of such large crystals may be due to the local concentration of volatile substances during metamorphism. In places, the amphibolite mass contains a notable quantity of minute crystals of calcite. The samples from the environs of Kamogawa and Senzokuyama in the Prov. Iyo, are typical examples of this kind, which were named "lime amphibolite" by T. Ogawa.[1] It seems that these calcite crystals must have arisen from the crystallization of circulating lime rich solutions which were locally concentrated in the amphibolite mass.

It is noticeable that the amphibolite locally contains a considerable amount of glaucophane. We can find a good example of the type in the amphibolite mass near the Sekizen. The chemical analysis of amphibolite proper from Tonaru near the Besshi Mine was made by Takayanagi of the Geological Survey of Japan, at the writer's request. The result is given in the following:

Albite-epidote-amphibolite from Tonaru, Prov. Iyo. (Anal. K. Takayanagi)

	Wt. %	Mol. numb.
SiO_2	46.38	773
Al_2O_3	16.35	160.5
Fe_2O_3	5.97	38
FeO	8.98	125
MnO	0.48	7
MgO	4.80	120
CaO	9.74	173.5
Na_2O	2.79	45
K_2O	0.70	7.4
TiO_2	1.09	14
P_2O_5	0.35	3.5
Loss on ignition	2.23	—
Total	99.86	

(1) Kochi sheet and its explanatory note. Imp. Geol. 1902.

4. Garnet Amphibolite and Cyanite Garnet Amphibolite

In certain places, the amphibolite proper assumes a peculiar appearance through the development of phenoblasts of garnet which spear across the schistosity plane of the rock. This garnet amphibolite is a very common rock in the vicinity of the Besshi Mine, next to amphibolite proper. It is remarkable that the garnet amphibolite occupies the upper margin of the proper amphibolite mass in the field. It seems probable that the part rich in garnet is neither a late intrusion nor an extremely altered one of the amphibolite proper produced during metamorphic movement, but a special phase of the original rock.

Parts of the garnet amphibolite are distinguished by an intimate bedding of rather dark green layers with light red ones. The former colour being due to amphibole and the latter to garnet.

The rock is composed essentially of amphibole, garnet, albite, quartz associated with a small amount of chlorite, rutile ilmenite, tourmaline. (Pl. I, Fig. 5 and Fig. 6) It is remarkable that the rock contains, in places, large amount of cyanite, reading to cyanite-garnet amphibolite. As a rule, epidote is abundant in the general green schist in the System, but they are practically absent in the typical garnet amphibolite or cyanite garet amphibolite. In general all the constituents mineral of these rocks are much coarser than in the specimens of amphibolite proper. In most cases the connection between garnet amphibolite and amphibolite proper is strikingly close; they appear to show gradual transition by means of increasing and decreasing garnet phenoblasts. The fact that the greater part of the garnet phenoblasts occurs in a granulated form, may be due to the mechanical deformation associated with orogenic movement which took place after the complete consolidation of the whole rock.

The chemical analysis of the typical garnet amphibolite from Tonaru which was made by Takayanagi of the Geological Survey of Japan at the writer's request, is as follows:

Garnet-amphibolite from Tonaru, Prov. Iyo. (Anal. K. Takayanagi)

	Wt. %	Mol. numb.
SiO_2	50.56	843
Al_2O_3	17.65	173.5
Fe_2O_3	4.95	31
FeO	6.72	93
MnO	0.68	10
MgO	2.30	58
CaO	3.13	145
Na_2O	3.32	53
K_2O	0.61	6.5
TiO_2	2.38	30
P_2O_5	0.15	1
Loss on ignition . . .	2.22	—
Total	99.67	

5. Eclogite

By certain geologists the garnet amphibolite has been reported as eclogite. However, it is clear that this name is an unsuitable one for they have never rocognized the presence of pyroxene in the rock. As far as the writer is aware, no account of the true eclogite of Shikoku has yet been bublished.

As the writer expected that eclogite might be present in the amphibolite belt of Shikoku, he gave himself much trouble to find traces of it, but was unfortunately unsuccessful. He has recently has the welcome opportunity of making the microscopical investigation of one section of eclogite from Shikoku, by the favour of Prof. T. Kato of the Imperial University of Tokyo. It is said that this section was sent by Mr. T. Otsu, geologist of the Meiji Mining Company, who collected the sample from the environs of the Akaishi Mine of the Province Iyo, Shikoku, some long time ago. Though the writer cannot yet give an account of the original locality of the rock, it may be inferred that it was found in the immediate neighbourhood of the garnet amphibolite mass.

Under the microscope, the rock consists essentially of garnet, pyroxene (omphacite), muscovite and quartz, associated with a small amount of glaucophane, plagioclase, rutile, chlorite and titanite. (Pl. II, Figs. 1 & 2). They show almost parallel arrangement, and the phenoblasts of garnet and pyroxene give a fine porphyroblastic structure to the rock. The rock differs from the garnet amphibolite chiefly in the presence of pyroxene and in the absolute absence of epidote. The writer will publish a more detailed account of the petrological nature and mode of occurrence of the eclogite of Shikoku on another occasion, when the true exposure of the rock has been found.

6. Albite Zoisite Amphibolite

The rock possesses an elongated lenticular habit and its longer axis is usually arranged almost parallel to the schistosity of the surrounding amphibolite mass. The exposures of the rock are not extensive but somewhat numerous. Generally these lenses are distinctly limited by sharp boundaries against the adjacent rocks. It is a comparatively whitish rock of usually leucocratic habit and shows a distinct foliated texture. As a rule, the rock is coarser than the amphibolite or garnet amphibolite.

The microscope reveals as the constituents green hornblende, albite, zoisite, quartz, biotite and some sericite with accessory grains of garnet ilmenite rutile and tourmaline. The white subparallel granulitic laminae of albite and quartz are separated by fibres of dark greenish hornblende. This rock is characterized by a comparatively large amount of biotite flakes, which have neither distinct crystal forms nor cleavage planes but show remarkable pleochroism. Hornblende prisms and biotite flakes are often bent and show undulated extinction, indicating that they received the mechanical deformation after their crystallization.

The rock from the Sekizen Mine was analyzed by Takayanagi of the Geological Survey of Japan, at the writer's request, and showed the following result.

Albite-zoisite-amphibolite from Sekizen, Prov. Iyo. (Anal. K. Takayanagi)

	Wt. %	Mol. numb.
SiO_2	50.25	837.5
Al_2O_3	18.15	177.5
Fe_2O_3	5.74	36
FeO	3.04	42
MnO	0.44	6
MgO	3.81	95.3
CaO	8.74	155
Na_2O	4.69	76
K_2O	0.20	2
TiO_2	1.19	15
P_2O_5	0.33	2.3
Loss on ignition	3.72	—
Total	100.30	

7. Actinolite Schist

It is interesting to note that the proper amphibolite mass is in places represented by an aggregation of actinolitic amphibole, generally mingled with chlorite, talc, biotite and quartz. The actinolite mass is coarse-grained and shows light greenish colour in contrast to the dark compact amphibolite, (Pl. II, Fig. 3). The most notable locality of the rock may be given as the vicinity of Iratsuyama, Prov. Iyo.(1)

No chemical analysls of the rock was made, but its mineral composition and mode of occurrence in most cases clearly indicate that it is derived from similar rocks as the other green schists such as chlorite schist, amphibolite, etc.

8. Antigorite Schist

The amphibolite may be secondarily changed into chloritic rock, but in another form of alteration may be turned into serpentine rock.

(1) D. Sato: Reported the large actinolite from Iratsuyama, 7 cm. in length and 3 cm. in diameter, with fine crystal faces (Jour. Geol. Tokyo, Vol. IX, 1902, p. 20.

We can find considerable masses of serpentine rock or serpentinized amphibolite in the amphibolite belts themselves or green schists of the Besshi Series. Sometimes it occurs as marginal phases of the actinolite schists.

The typical serpentine rock is mainly composed of serpentine, phlogopite and iron ores but occasinally it contains a considerable amount of unaltered hornblende, actinolite, epidote of the original rock. In certain places the rock contains a large amount of dark greenish tourmaline. Under the microscope, the serpentine is pale green in colour showing slight pleochroism. It is a laminated variety comparatively rich in iron. The axial angle is almost 0° and the mineral is optically negative. It often contains secondary iron ores besides primary chromite. It seems to be a serpentine approaching the character of antigorite.

It is noticeable that at numerous points the amphibolite belt and other crystalline schists of the System are intruded by serpentine rocks of younger age, namely Palaeozoic and Mesozoic.(1) The older serpentine rocks which are derived from the amphibolite mass, are often indistinguishable in the handspecimen from those of the younger age, but detailed examination of them proves that the younger serpentine rocks are characterized by the following particular points: (1) absence of antigoritic serpentine, (2) contents in partly fresh olivine relics, (3) absence of schistose texture, (4) the mode of occurence as a narrow belt which frequently crosses the foliation of surrounding schists, (5) the presence of sharp boundaries against the cystalline schist.

The serpentine rocks of the younger age always appear free from any appreciable deformations, so that, it seems likely that they intruded into the System after the cessation of most of the folding and shearing

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(1) Most of the serpentine rocks which develope in Mesozoic formation in the southern part of the Shikoku island, penetrate the lower cretaceouos giving some contact effects to the surrounding rocks (S. YEHARA: On the Monobegawa and Shimantogawa Series in Southern Shikoku. Jour. Geogr. Soc. Tokyo, Vol. XXXVIII, 1926, p. 11 and on the Trigonia-sandstone Group in the Katsuragawa Basin, etc. Japanese Jour. Geol. Geogr. Vol. III, 1925, p. 8.)

movements. An excellent example of young serpentine is to be found in the environ of the Akaishi Mountain, 5 miles westwards of the Besshi Mine. It covers a comparatively large area in the Besshi Series of the System.(1)

In some places, olivine bearing serpentine rocks appear to be conformable to the strike of the adjacent schists. The small lenses of this kind near the Besshi Mine have been called "Olivinschiefer," as a member of the Crystaline Schist System by E. Naumann,(2) but the writer's investigation shows that this name is not suitable and that it is probably to be regarded as younger.

I. Serpentine from Besshi, Prov. Iyo. (Anal. J. Suzuki)

II. Serpentine from Chichibu, Prov. Musashi. (Anal. T. Kondo)

	I		II	
	Wt. %	Mol. numb.	Wt. %	Mol. numb.
SiO_2	36.94	616	42.59	710
Al_2O_3	3.49	34	2.92	28
Fe_2O_3	2.83	30	0.65	4
FeO	4.83	67	6.11	85
MgO	38.40	952	33.56	839
CaO	0.96	17	2.26	41
Na_2O	0.09	1.4	—	—
K_2O	0.13	1.4	—	—
TiO_2	0.03	4	—	—
MnO	0.33	5	—	—
Loss on ignition	11.83	—	11.72	
Total	99.86		99.82	

(1) A full petrographical description of the rock was given by T. KATO in his discussion of the chronite ore deposits which are closely associated with the serpentine mass. He writes: It is also to be noted that the serpentine shows no sign of dynamometamorphism, notwithstanding that it occurs in the terrain of highly schistose rocks. It is thus suggested that the intrusion of the serpentine in question has taken place after the formation of the schistose structure of the surrounding rocks. (Note on the banded chromite ore from the Akaishi Mine in the Prov. of Iyo, Japan). Jour. Geol. Soc. Tokyo, Vol. XXVIII, 1921, p. 13-18.

(2) Ueber den Bau und die Entstehung der japanischen Inseln. 1885. p. 10.

The chemical analysis of the antigorite serpentine from the environ of the Besshi Mine, which was made by the writer, is given in the above table. The analysis of Palaeozoic serpentine from Obuchi in Chichibu of Kwanto, which was made by T. Kando,(1) is quated in parallel columns for comparison.

9. EPIDOTE GLAUCOPHANE SCHIST(2)

This rock is a normal type of the glaucophane schist and shows comparatively wide distribution in Shikoku. It is characterized by its yellowish blue colour which is due to the presence of a great quantity of glaucophane and epidote. The rock shows a moderately fine grained schistose texture and is essentially composed of glaucophane, epidote, albite and many kinds of accessory minerals such as sericite, quartz, garnet, rutile, calcite, titanite, ilmenite, specularite, magnetite chlorite and green hornblende. (Pl. II, Fig. 5)

In places it contains a small quantity of apatite zircon or tourmaline and in rare cases piedmontite. Sometimes it shows fine porphyroblastic structure in which the phenoblastic crystals are usually glaucophane, epidote, albite and rutile. The general character of whole rock closely resembles a normal green schist, though this rock contains comparatively little chlorite and green hornblende.

The typical localities of the rock are the environs of the Chihara mine and the Besshi mine. Some exposures of similar rock are known in the environs of the Iimori Mine in the Province of Kii and Norimoto of the Province of Mikawa in Japan proper. The chemical analysis of the rock from Shikoku has not been made, but that of the quite simillar type from Norimoto, Prov. Mikawa, which was made by H.S. Washington,(3) is given in following table:

(1) Jour. Geogr. Soc. Tokyo, Vol. XXXIX, 1927, p. 468.

(2) B. KOTO: A note on Glaucophane, Jour. Coll. Sci. Tokyo. Imp. Univ., Vol. I. 1887, pp. 85-90.

J. SUZUKI: On the glaucophane schists in Japan, Jour. Geol. Soc. Tokyo, Vol. XXXI, 1924, pp. 1-17.

(3) H. S. WASHINGTON: A chemical study of the glaucophane schist, Am. Jour. Sci., 4 Ser., Vol. XI., 1901, p. 35.

Epidote-glaucophane-schist from Norimoto, Prov. Mikawa.

(Anal. H.S. Washington)

	Wt. %	Mol. numb.
SiO_2	47.89	794
Al_2O_3	13.06	128
Fe_2O_3	6.77	43
FeO	5.36	75
MnO	0.09	1
MgO	4.10	102
CaO	11.65	207
Na_2O	3.35	53.5
K_2O	0.57	6
H_2O	1.51	—
TiO_2	2.14	27
CO_2	2.97	—
Total	99.46	

It is well known that some kinds of epidote glaucophane schist occur in the metamorphic region of Hokkaido. The rocks are fully described by K. Jimbo(1) and H. Yatani(2) and the chemical analysis of the rock from Kamuikotan was made by H. S. Washington,(3) is given in the following table. The chemical analysis of the glaucophane bearing epidote hornblende schist of the Mikabu Formation from Futamigaura, Prov. Ise, which was made by Takayanagi of the Geological Survey will be cited for comparison.

I. Epidote-glaucophane-schist from Kamuikotan, Hokkaido.
(Anal. H.S. Washington)

II. Glaucophane Bearing epidcte-hornblende-schist from Futamigaura Prov. Ise.
(Anal. K. Takayanagi)

	I		II	
	Wt. %	Mol. numb.	Wt. %	Mol. numb.
SiO_2	48.88	813	52.60	875
Al_2O_3	13.44	132	14.19	139
Fe_2O_3	5.32	33	6.64	42

(1) K. Jimbo: General geological sketch of Hokkaido, with special reference to the petrography. 1892.

(2) H. Yatani: Glaucophane rocks from Osirabetsu, Prov. Teshio, Hokkaido, Jour, Geol. Soc. Tokyo, Vol. IX, 1902, p.p. 98–104 and 147–148.

(3) H. S. Washington: loc. cit.

	I		II	
	Wt. %	Mol. numb.	Wt. %	Mol. numb.
FeO	8.96	125	5.36	75
MnO	Tr.	—	Tr.	—
MgO	4.21	105	4.05	100
CaO	5.80	104	8.43	150
Na_2O	3.73	60.5	3.26	53
K_2O	1.71	18	0.78	8
H_2O	3.73	—	—	—
TiO_2	3.90	49	1.77	22
Loss on ignition . .	—	—	2.26	—
Total	99.73		99.73	

10. Glaucophane Schist and Hornblende Glaucophane Schist

The former is a typical variety among the glaucophane bearing schists in Shikoku, though it is less widely distributed than those belonging to the other types. It is dark blue in colour and in texture varies from very coarse varieties to fine grained ones; it is usually schistose but in places massive. It is essentially composed of glaucophane crystals, associated with a small amount of quartz, albite, epidote and some other accessory minerals such as ilmenite, rutile, magnetite, garnet, etc. The best exposures of the type are found in the environs of Otakisan near Tokushima City, Prov. Awa, and in a part of the belt of sericite glaucophane schist of Noji near the Shirataki Mine. The glaucophane hornblende schist is a fine grained rock with bluish green colour in which glaucophane and hornblende are almost equally developed. It shows very distinct traces of schistosity and is as usual associated with the hornblende schist and amphibolite proper. Disregarding the exceptionally high percentage of glaucophane, this type shows petrologically many points of resemblance to the latter two types. In the vicinity of the Besshi Mine and the Chihara Mine, we can find many outcrops of this type.

11. Sericite Glaucophane Schist

The rock is an important member next to the epidote glaucophane schist in Shikoku. It is essentially composed of glaucophane and sericite and small amounts of albite, quartz, epidote, rutile, garnet, ilmenite, titanite, hematite, magnetite. The minute flakes of sericite are arranged more or less parallel to the orientated aggregations of the former. The rock is usually pale blue or bluish grey with silky luster, and it shows a distinct schistose texture with fine wavy folding. The rock differs very much in colour from the varieties of glaucophane schist, which is due to variation of the amount of sericite developed in the schist. A typical sample of the type can be collected from the exposures in the environs of Noji near the Shirataki Mine, Otoji near the Besshi Mine and the Takakoshi Mine.

The chemical analysis of the typical sericite glaucophane schist from the environs of Noji was made by the writter, showing the following result:

Sericite-garnet-glaucophane-schist from Nojo, Prov. Tosa. (Anal. J. Suzuki)

	Wt. %	Mol. numb.
SiO_2	53.90	899
Al_2O_3	17.66	174
Fe_2O_3	9.63	60
FeO	7.59	106
MnO	0.03	—
MgO	3.50	87
CaO	2.20	39
Na_2O	3.24	52
K_2O	0.66	70
H_2O (+)	0.72	—
H_2O (−)	0.23	—
TiO	0.24	3
CO_2	0.16	—
Total	99.76	

It is a remarkable thing, that the chemical analyses of all the types of glaucophane schists from the Besshi Series in Shikoku, show many pcints of resemblance to those of basic igneous rocks, as is also true in the cases of the chlorite schists and amphibolites.

B. Siliceous Schists in the Besshi Series

a) Mode of Occurrence

Siliceous schists are important members in the Besshi Series, next to the green schists, which are mentioned above. They are widely distributed and usually form thick layers which show a conformable relationship to those of green schists. Sericite quartz schist is the most remarkable rcck in the group and can be recognized in all parts of the area in which the Besshi Series is exposed, not only in the island of Shikoku but in other localities in Japan. In places, it appears as a very thick layer of 30 m. or more in the chlorite schist or chlorite amphibole schist.

Typical epidote quartz schist shows a comparatively limited distribution, occurring as a thin layer generally associated with normal sericite schist, though it grades into a sericite quartz schist of piedmontite quartz schist by gradual increase in the proportion of sericite or piedmontite.

Piedmontite quartz schists occurs as a thin bed, varying in thickness from one to ten meters, in various kinds of the crystalline schists, such as chlorite schist, hormblende schist, glaucophane schist, graphite schist and other siliceous schists. In spite of the thickness its lateral extension is comparatively large, often attaining 20 km. or more. The geographical distribution of the rock is very wide over the whole areas of the Crystalline Schist System of Japan: Shikoku, Kyûshû, Kii, Chubu, and Chichibu.

Hematite quartz schist has a very limited distribution occuring as a very thin layer, one to three meters in thickness. The rock is usually intercalated in other siliceous schists and in places it graduates to piedmontite hematite sericite quartz schist.

Graphite quartz schist is a predominant members of the Besshi Series and occurs as a thick layer generally arried by various green schists. In places it contains a thin layers of piedmontite schist or hematite schist and occasionally bedded deposits of cupriferous pyrite. It is remarkable that some graphite schist contains numerous nodules which prove to the albite phenoblasts, forming a socalled spotted graphite schist. The distribution of the type is extensive and may be traced everywhere in the area of the Besshi Series in the whole of Japan.

b) General Characters of the Siliceous Schists

The peculiarity of the siliceous schists is that they are predominantly composed of quartz and are usually deficient in ferromagnesian minerals, such as chlorite and amphibole. These schists are, as a rule, highly schistose rocks which are made up of an aggregation of recrystallized quartz grains and subparallel bands of accessory minerals. They are absolutely free from any relies of the parent rock or original texture. The siliceous schists in the Besshi Series in Shikoku may be divided into six main types, according to their predominant constituments, though some of them grade into one another. The mineral assemblage of these types will be shown as follows:

Sericite quartz schist.	Quartz, sericite, albite, (garnet)
Epidote quartz schist.	Quartz, epidote, albite
Piedmontite quartz schist.	Quartz, piedmontite, albite, (sericite)
Glaucophane bearing quartz schist.	Quartz, glaucophane
Hematite quartz schist.	Quartz, hematite, albite, (epidote)
Graphite quartz schist.	Quartz, albite, graphite, (sericite)

Quartz, the predominant constituent of all the varieties of these schists, occurs usually as minute elongated granules with a ratis of the greatest to the least diameter 2:1 to 3:1. The quartz granules show a microgranoblastic aggregation in which the greatest diameters run parallel to the rock flowage, though it does not seem that they show a uniform crystallographic arrangement. Most of them are very fresh and almost free from inclusions except some minute crystals of garnet and epidote, but in places they show severe undulatory extinction.

Sericite is found in a comparatively large amount, especially in the sericite quartz schist. It occurs as minute pale whitish flakes, with slight pleochroism and is usually arranged parallel with the large diameter of the quartz grains, giving the most frequent cause of the schistosity of the rock. Sometimes a folded sericite band can be observed in the granoblastic aggregation of quartz. The sericite shows high index of refraction and refringence and is characterized by its comparatively wide axial angle. The chemical analysis of sericite in the normal sericite quartz schist from Chichibu in Kwanto, which is cited in Koto's work, is given in the following table for reference. It was analyzed by Takayama of the Geological Survey of Japan:

Sericite from Chichibu, Prov. Musashi.

SiO_2	53.01
Al_2O_3	34.71
Fe_2O_3	Tr.
CaO	0.27
MgO	0.50
K_2O	6.05
Na_2O	1.01
H_2O	4.67
Total	100.21

Feldsper is a usual constituent varying in amount, though it is not always an essential ingredient of the siliceous schists. It occurs as more or less elongated grains, with irregular outlines, mingled with an aggregation of quartz grains. The former are a little larger than the latter. It is, as a rule colourless and sometimes contains minute

(1) B. KOTO: On the so-called Crystalline Schist of Chichibu, Jour. Coll. Sci. Imp. Univ. Tokyo, Vol. II, No. 1, 1888. p. 89.

crystals of epidote, magnetite and quartz. Cleavages are usually well developed and a simple twin can occasionally be observed, but zonal structure and polysynthetic lamellae are almost absent. The index of refraction of the feldspers is n (010) or (001) = 1.530 – 1.534, indicating that they belong to the albitic feldspers with chemical composition of $Ab_{95}An_5$ to $Ab_{85}An_{15}$. Occasionally albite occurs as phenoblastic crystals in the so-called spotted graphite schist. The spots are somewhat thick lenticular forms, 0.3 to 0.5 cm. in length and of a blackish colour. The blackness of the spots is caused by an enormous accumulation of carbonaceous inclusions which are associated with minute crystals of some of the following minerals: rutile, tourmaline, garnet, actinolite and magnetite. Sometimes a zonal band of minute particles of graphite can be observed in the spots. It is clear that the phenoblasts of albite were developed in the last stage of dynamo-metamorphism and have a quite similar nature to those of the so-called spotted green schist.

Epidote is not always a predominant constituent of the siliceous schist but is a characteristic member of the epidote quartz schist. It occurs in a short prismatic form, generally associated with quartz and shows an orientated arrangement as regards the plane of schistosity and a slight pleochroism, yellowish brown to yellowish green. It has a high refractive index and strong double refraction. The prisms range from 0.05 to 0.1 mm. in length, but occasionally reach 0.5 cm. or more. The writer found a good example in a sample from the Chihara Mine. Sometimes, the epidote prisms contain a number of minute grains of rutile, magnetite and hematite, while epidote itself is bound as inclusions in quartz, albite or garnet crystals. Some crystals of epidote in the epidote quartz schist and piedmontite quartz schist show a special pleochroism, light yellow to light pink and in other cases some are characterized by the inclusion of rosy pigments which are concentrated at the centre, so as to form a distinct zone.[1] The same points can be observed in the samples of piedmontite quartz schist.

(1) B. KOTO explains that the rosy pigment is certainly due to the presence of a manganese oxide and the mineral forms an intermediate link between common epidote and piedmontite (Q. J. G. S. 1888, p. 479).

Piedmontite[1] is a predominant member of the piedmontite quartz schists and hematite piedmontite quartz schists. It occurs in idioblastic form like epidote, arranged more or less parallel to the plane of schistosity. It is sometimes comparatively large, nearly 3 cm. in length, as in the case of a specimen from the Ikodazu Mine, Prov. Iyo, though it is generally small, ranging from 0.1 mm. to 0.3 mm. The determinable faces are (001), (100), (101), (111) and (102). Cleavages parallel to the base and orthopinacoid are sometimes observed. Occasionally the crystal is traversed by characteristic cracks nearly perpendicular to b-axis and is separated into numerous fragments. The extinction angle $\hat{cX}$ is nearly 3° and the character of the mineral is always negative. The pleochroism is characteristic and the axial colours are as follows: X = yellow, Y = violet, Z = carmine. The absorption is Z > Y > X[2]. A chemical analysis of piedmonitite from Otakisan near Tokushima city, cited by B. Koto, is given in the following table:

Piedmontite from Otakisan, Prov. Awa.

SiO_2	36.16
Al_2O_3	22.52
Mn_2O_3	6.43
Fe_2O_3	9.33
CaO	22.05
MgO	0.40
Na_2O	0.44
H_2O	3.20
Total	100.53

(1) B. Koto: Some occurrence of piedmontite in Japan. Jour. Coll. Sci. Imp. Univ. Tokyo, Vol. I. 1887, pp. 303-312.
B. Koto: On the occurrences of piedmontite schist in Japan. (Q. J. G. S. 1887, pp. 474-480.)
J. Suzuki: On the piedmontite schist of Japan, Japanese Jour. Geol. Geogr., Vol. III, 1924. pp. 135-149.
F. Ogawa: Genesis of the piedmontite schist of Japan. Chikyu—The Globe. Vol. III., No. 5, 1925, p. 502.

(2) It is said that the colour of piedmontite in some thin sections has gradually faded during the course of a long period of time, and the mineral has finally become almost colourless (Jour. Geol. Sci. Tokyo, Vol. V., 1897 p. 308).

Garnet is less conspicuous in quantity in the siliceous schist and in special parts is almost lacking. It is of a pale greenish variety and generally forms rhombic dodecahedra. The crystals are usually 0.1 to 1 mm. in diameter, but, occasionally reach 3 mm. or more. They are almost irotropic and fresh but some contain minute crystals of rutile, epidote, and magnetite. Sometimes the grains of garnet form fine narrow bands which run parallel with the greatest diameter of granoblastic quartz and feldsper.

Hematite occurs in a minute scaly form, showing parallel arrangement to the schistosity plane of the rocks. The flakes generally have an irregular outline, but occasionally occur as thin hexagonal plates. It is, as usual, clear reddish brown in the marginal zone of individual crystals becoming absolutely opaque towards the centre. In special cases, minute flakes of hematite occur as an inclusion in feldsper and epidote.

Graphite occurs in minute individuals and cannot be found in definite crystal form in any thin section of the rocks. It is commonly contained in the sericite quartz schist and epidote quartz schist, as well as in the actual graphite quartz schist.

Calcite is not always an essential constituent of the siliceous rocks but it is usually present in a varying amount, filling up the interstices of the other ingredients. In special cases it occurs predominantly as a mosaic aggregate in the sericite quartz schist and piedmontite quartz schist.

Actinolite is uniformly distributed in the various kinds of the siliceous schists though usually in small quantities. It occurs as fine prisms and shows pale greenish colour.

Cyanite is rarely found in the schists, especially in the sericite quartz schist and piedmontite quartz schist. It occurs as fine needles or minute rounded grains showing high relief on account of its high refractive indices. It is almost colourless or pale blue with weak pleochroism. Extinction angle on the macropinacoid is about 34°.

Rutile is a rare ingredient of the schists and usually occurs as an inclusions in garnet and epidote, indicating that the crystallization of the mineral may have taken place in an earlier stage of metamorphism. It is of a brownisch yellow colour and forms short prisms, 0.01 to 0.1 mm. in length with occasional knee-shaped twins.

Titanite and ilmenite occur as irregular grains and are uniformly distributed in various kinds of rocks but only in small quantity. They are usually accompanied by rutile or magnetite grains.

Magnetite is also less significant in quantity, though it is usually present in all the varieties of the siliceous schists. It occurs as irregular grains or fine octahedral crystals.

Tourmaline is found less commonly in the rocks. It shows minute subidiomorphic forms, green to dark green in colour with strong pleochroism. Occasionally it occurs in albite crystals as an inclusion.

c) Description of Siliceous Schists

1. Sericite Quartz Schist[1]

The rock is grey in colour and shows a distinctly schistose texture. It is chiefly composed of an aggregation of somewhat elongated grains of quartz and albite with subparallel bands of sericite, garnet, rutile, calcite, epidote magnetite, graphite, hematite, tourmaline and titanite. (Pl. III, Fig. 1). By the gradual increase in the proportion of epidote or piedmontite, it grades into a sericite epidote quartz schist or sericite piedmontite quartz schist, while if sericite decreases and ultimately disappears it passes into typical quartz schist, though this latter case is rare. Generally no definite relationship between these rock boundaries can be distinguished in the field, and it is difficult to trace zones of definite composition over an extensive area.

(1) Similar rock from the Sambagawa valley of Kwanto has been fully described by B. Koto under the name of "Normal sericite schist." (Jour. Coll. Sci. Tokyo, Vol. II, No. 1, 1888, p. 85.)

The chemical analysis of the sericite quartz schist from the Takakoshi Mine[1] was made by K. Takayanagi of the Geological Survey of Japan, and gives the result quoted below:

Sericite-quartz-schist from Takakoshi, Prov. Awa. (Anal. K. Takayanagi)

	Wt. %	Mol. nnmb.
SiO_2	84.68	1410
Al_2O_3	5.10	50
Fe_2O_3	2.71	17
FeO	0.79	11
MnO	0.59	8
MgO	1.35	36.6
CaO	0.86	15.4
Na_2O	0.47	7.6
K_2O	1.53	16
TiO	0.17	2
P_2O_5	Tr.	—
Loss on ignition. . . .	1.57	—
Total.	99.82	

2. Glaucophane-bearing Sericite Quartz Schist

The rock usually occurs as a thin belt in the normal sericite quartz schist layer nd occasionally shows a gradual transition to the latter. The best exposures of the type can be found in the environs of the Chihara Mine, Prov. Iyo and the Takakoshi Mine, Prov. Awa. It is of slightly bluish rock and shows a highly schistose texture (Pl. III, Fig. 6.) The general characters of the rock are almost identical to those of the above mentioned normal sericite quartz schist but it is characterized by the comparatively high amount of garnet and glaucophane.[2] The

(1) Jour. Geogr Tokyo, Vol. XXXIX, 1927.

(2) Recently Y. Ozawa (Jour. Geol. Soc. Tokyo, Vol. XXXIII. 1926, p. 314) reported a similar rock in the Mikabu Formation in the envirous of the Jizo River, a tributary of the Yoshino River. It is a greenish quartz rock which contains a large amount of glaucophane fibres. According to the observation of H. S. Washington (Am. Jour. Sci., 4 ser. Vol. XI. 1901) glaucophane schist may be divided into three main types from the standpoint of chemical composition: (1) basic type, (2) intermediate type and (3) acidic type. Most of the Japan correspond to the first type but the siliceous rocks from Chihara Takakoshi and the Jizogawa district which are now described, may belong to the third type.

latter occurs as fine fibres and usually shows peculiar pleochroic colours such as X = light yellowish green, Y = light purple, Z = light blue. In general the mineral is lighter in colour than of normal glaucophane, indicating low content of iron. The fibers usually show an orientational arrangement along the schistosity of the rock.

The chemical analysis of the rock from the Chihara Mine was made by Takezo Kato of the First Higher School at the writer's request, giving the result as follows:

Glaucophane-bearing sericite-quartz schist from Chihara, Prov. Iyo.

(Anal. Tz. Kato)

	Wt. %	Mol. numb.
SiO_2	72.30	1205
Al_2O_3	12.80	125
Fe_2O_3	4.35	27
FeO	3.25	45
MnO	—	—
MgO	1.85	46
CaO	1.37	24
Na_2O	2.59	42
K_2O	1.53	16
H_2O	0.56	—
TiO_2	0.10	1
Total	100.70	

3. Epidote Quartz Schist

The rock is grey or yellowish white and shows highly schistose texture. It is essentially composed of quartz epidote albite and accessory minerals such as sericite, rutile, titanite, magnetite, garnet, hematite and graphite. Good exposures of the rock are found in the environs of the Chihara Mine, Prov. Iyo. It shows many points of resemblance to the normal sericite quartz schist excepting that epidote is an essential constituent of the rock. The chemical composition has not yet been determined.

4. Piedmontite Quartz Schist

The piedmontite quartz schist is an interesting member of the Besshi Series and for a long time has been attracting the attention of geologists on account of its peculiar colour which is due to the presence of the violet mineral, piedmontite.

The rock is usually of fine schistose texture and megascopically light violet or pink in colour, but it varies considerably in appearance on account of differences in the relative quantities of the mineral constituents. The rock is generally composed of a hetrogenous aggregation of quartz, albite, piedmontite, sericite, epidote, calcite, hematite and accessory minerals, such as magnetite, garnet, cyanite, tourmaline, rutile and titanite. (Pl. III, Fig. 3). The rock may be classified into three main types from the standpoint of predominant mineral composition, though these types are not distinctly, separated from one another, viz. piedmontite sericite quartz schist, piedmontite hematite sericite-quartz schist and piedmontite sericite calcite quartz schist.

The petrographical studies of the piedmontite schist in Japan have been published in the papers of B. Koto,(1) T. Ogawa(2) and the writer,(3) so that the general description of the rock will be omitted here.

Piedmontite-sericite-quartz-schist from Shirataki, Prov. Tosa.
(Anal. J. Suzuki)

	Wt. %	Mol. numb.
SiO_2	73.94	1232
Al_2O_3	7.41	73
Fe_2O_3	3.50	22
FeO	1.58	22
MnO	0.60	8

(1) B. Koto: Some occurrence of piedmontite in Japan. Jour. Coll. Sci. Imp. Univ. Tokyo, Vol. I, 1887, pp. 303–312 and on the occurrences of piedmontite schist in Japan. Q. J. G. S. 1887, pp. 474–430.

(2) T. Ogawa: Genesis of the piedmontite schist of Japan. Chikyu—The Globe. Vol. III., No. 5, 1925, p. 503–510.

(3) J. Suzuki: On the piedmontite schists of Japan. Jap. Jour. Geog. Geol. Vol. III. 1924, pp. 135–149.

	Wt. %	Mol. numb.
MgO	2.63	66
CaO	2.88	25
NaO	3.26	52
K_2O	1.64	17
H_2O (+)	1.18	—
H_2O (−)	0.22	—
TiO_2	0.64	8
Total	99.48	

The chemical analysis of the typical piedmontite sericite quartz schist from Noji near the Shirataki Mine, Prov. Iyo, which was made by the writer, is given above.

5. Hematite Quartz Schist

The rock is characterized by a universal reddish or brownish colour and occasionally it has, megascopically, a good resemblance to some piedmontite quartz schists. The constituent minerals of the rock are quartz, albite, hematite, epidote, sericite and accessory minerals such as rutile, titanite, garnet and toumaline. (Pl. III, Fig. 2). Some bands of the schist are rich in garnet (Pl. II, Fig. 4). In places the rock contains comparatively large amounts of piedmontite mingled with epidote and sericite and graduates to piedmontite hematite sericite quartz schist. Among many good exposures of typical hematite quartz schist we may especially call the attention to those in the environs of the Asatani Valley and the Takakoshi Mine.

It is noteworthy that there occurs another peculiar specularite quartz schist which is found in the neighbourhood of the cupriferous pyrite deposits. It is dark grey with metallic luster and sometimes in general appearance closely resembles the graphite quartz schist. In spite of the handspacimens of the rock being very dark in colour, the thin section, which is chiefly composed of colourless grains of quartz and feldsper and minute amounts of black scales of specularite, shows a light appearance under the microscope. A probable explanation of this fact may be that all grains of quartz and feldsper in the hand-specimen are covered with a thin black film of specularite. In reflected light the flakes of specularite appear with a steel grey luster like that of magnetite, though the weathered surface is commonly stained with reddish brown oxide of iron. Judging from the mode of occurrence, the origin of the rock may be closely related to the formation of the cupriferous pyrite deposits, and there is no genetical relationship between blood coloured hematite and black specularite.

6. Graphite Quartz Schist

The rock is like the normal sericite quartz schist in composition, except for the greater abundance of graphite and smaller amount of sericite. It shows megascopically a dark grey colour and distinct schistose texture. It consists mainly of quartz, feldsper, graphite, sericite, hematite associated with rutile, garnet, actinolite, magnetite, calcite and tourmaline as accessory minerals. Under the microscope dusty graphite is scattered about in the granoblastic aggregation of quartz and feldsper though occasionally it shows a banded arrangement in the direction of the greatest diameter of the elongated grains of the above mentioned two minerals. As already mentioned, parts of the rock contain numerous nodules of a blackish coloured albite. (Pl. III, Fig. 6)

No chemical analysis was made of the typical graphite quartz schist, but from its mineral constituents it is probable that it may have similar composition to the sericite quartz schist.

C. Calcareous Schists in the Besshi Series

a) Mode of Occurrence and General Characters of the Rocks

The Besshi Series is principally characterized by the multiple alternation of various kinds of the green schists and siliceous schists, but in some cases it contains thin layers of calcareous schists. Representative calcareous types are as follows: 1. sericite-calcite-quartz schist, 2. piedmontite-sericite-calcite-quartz schist and 3. crystalline limestone. These rocks show comparatively numerous expcsures, but usually occur as thin layers or small patches, which are conformably intercalated in the adjacent schistose rocks. The sericite-calcite quartz schist is of a very limited distribution occurring as a local phase of normal sericite quartz schist. Good expcsures of the rock, though they are less significant in quantity, can be found near the Shirataki Mine and the Takakoshi Mine. The piedmontite-sericite-calcite-quartz schist shows an almost similar mcde of occurrence with normal piedmontite quartz schist. Sometimes they occur together in one layer. The typical localities of the calcareous piedmontite schist are Hadeba near the northern entrance of the lowest tunnel of the Besshi Mine. Similar rock can be found in Kayamura, Prov. Iyo in Shikoku and Sueno, Prov. Musashi in Kwanto.

The crystalline limestone layers which are intercalated between the green schists in the Besshi Series can be divided into two varieties according to their nature. One type is associated with other crystalline schists except amphibolite, and forms a long thin schistose layer and the other type usually occurs in a thin lenticular form in the amphibole mass. Judging from their nature, they seem to differ genetically from one another; thus the first type is a member of the Besshi Series and originated under severe metamorphism with other crystalline schists while the origin of the second type seems to be the secondary precipition of lime from circulating solutions, along the foliation planes of the amphibolite. It is characteristic that the limestone of both types shows a sharp contact with the adjacent schists, while gradual transitions between then never cccur. The general characters of the constituent minerals of the calcareous schists are usually the same to those of siliceous schists.

b. Description of the Calcareous Schists

1. Sericite Calcite Quartz Schist

The nature of the rock is quite similar to the normal sericite quartz schist excepting the large amount of calcite as one of the essential components. Calcite in the rock forms a mosaic aggregation filling up the interspaces of granoblastic grains of quartz and albite. Each calcite crystal occurs a small particle, 1 mm. or more in diamter, with an irregular outline usually showing multiple twinning. As a rule it is whitish in colour, but it sometimes contains various kinds of inclusions such as epidote, biotite, etc. Some of the calcite crystals are bent occasionally into a considerable arc along gliding planes, indicating that they have received a severe mechanical deformation by orogenitic movement after their formation.

2. Piedmontite Sericite Calcite Quartz Schist

The rock shows an almost similar mode of occurrence as normal piedmontite quartz schist, but the principal characteristic of the type is the presence of calcite as a percentage of lime in the chemical composition. In this rock, calcite occurs in comparatively large phenoblasts among the granoblastic quartz grains and nearly always encloses minute grains of piedmontite, albite, sericite, quartz, garnet, magnetite and hematite. (Pl. III, Fig. 4). The rock from Kayamura, Prov. Iyo, was reported by S. Kozu and S. Noda[1] who compared the rock with cipolin.

The chemical analysis of typical sample of piedmontite sericite calcite quartz schist from Hadeba, Prov. Iyo, which was made by the writer,[2] is given in the following table :

(1) Matsuyama sheet. Imp. Geol. Surv. Japan. 1910.
(2) Japanese Jour. Geol. Geogr. Vol. III. 1924, p. 145.

Piedmontite-calcite-quartz-schist from Hadeba, Prov. Iyo. (Anal. J. Suzuki)

	Wt. %	Mol. numb.
SiO_2	50.51	852
Al_2O_3	3.31	32
Fe_2O_3	3.19	20
FeO	3.93	54
MnO	0.43	6
MgO	1.28	30
CaO	22.47	401
Na_2O	0.83	13.4
K_2O	0.35	4.8
H_2O (+)	0.94	—
H_2O (−)	0.07	—
TiO_2	0.72	9
CO_2	12.72	289
Total	100.72	

It is worthy of note that biotite quartz schist is never found in the area of the Besshi Series in Shikoku, though it is well exposed along the Arakawa Valley (Nagatoro), Chichibu, forming a intercalated layer in chlorite schist. It has the habit and appearance of the sericite calcite quartz schist or piedmontite-sericite calcite quartz schist, but it is characterized by a great abundance of biotite. A chemical analysis of the rock which was made by Tz. Kato of the First Higher School is given for reference and is as follows:

Biotite-calcite-quartz-schist from Nagataro, Prov. Musashi. (Anal. Tz. Kato)

	Wt. %	Mol. numb.
SiO_2	57.23	955
Al_2O_3	7.40	72
Fe_2O_3	3.16	20
FeO	3.40	47
MnO	0.71	10
MgO	4.04	100
CaO	14.25	254
Na_2O	1.15	19
K_2O	1.73	18
H_2O	0.45	—
CO_2	6.57	149
Total	100.51	

3. Crystalline Limestone

As already described, the crystalline limestone in the Besshi Series can be classified into two types according to its nature.

One type which occurs in the siliceous schists or chlorite schist as thin layers, is usually grey in colour and shows fine schistose texture. It is essentially compsed of an aggregation of elongated calcite grains, accompanied by a small quantity of green hornblende, diopside, chlorite, biotite, epidote, titanite, and magnetite. The other type which is associated with the amphibolite belt and occurs in a lenticular form, is commonly whitish or pinkish white in colour. It varies from fine to coarse grain and in part shows saccharoidal structure. It is principally composed of mosaic grains of calcite and a negligible amount of dusty substance.

As previously mentioned, these two types of crystalline limestone differ genetically from one another.

D. Crystalline Schists in the Oboké Series

a.) Mode of Occurrence and General Characters of the Rocks

The Oboké Series which underlies the Besshi Series, is composed of a metamorphic group containing beds of so-called Oboké gneiss and graphite schist associated with a small quantity of green schist and conglomerate schist. The series is widely distributed in Shikoku, but it does not seem to show such extensive exposures in the other localities of the crystalline schists in Japan as the Besshi Series. The metamorphics of the Oboké Series are very well developed along the Oboké Valley of the River Yoshino in Shikoku, forming the great anticlinal folding which runs in a direction from east to west crossing the valley. On the northern side of the anticlinal axis, the layers of these metamorphics dip towards the north associating with the metamorphic layers of the Besshi Series. The field evidence clearly indicates that the Oboké Series conformably underlies the Besshi Series.

The so-called Oboké gneiss is the lowest layer recognized in the area and forms the core of the anticlinal folding. It is the commonest rock in the Oboké Series in Shikoku and there occupies a very wide area, intermingling with bands of graphite quartz schist and conglomerate schist.

Graphite quartz schist shows a comparatively wide distribution, and is next to the Oboké gneiss in quantity in the Oboké Series. Usually it occurs us a very thick layer overlying and intercalating conformably with the layer of Oboké gneiss.

Green schist in the Oboké Series usually occurs as a thin layer which is intercalated in the graphite quartz schist.

Conglomerate schist occurs as an interstratified layer, 30 m. or more in thickness in the Oboké gneiss, usually showing well foliated planes of stratification. It is well exposed along the eastern bank of the Iya Valley, 1 km. north of Itchu on the south wing of the so-called Oboké anticlinal axis.

The crystalline schists of the Oboké Series can be divided into four main types, according to their predominant constituents, viz: 1. so-called Oboké gneiss, 2. graphite quartz schist, 3. green schist and 4. conglomerate schist. Excepting the green schist, they belong mostly to the siliceous type.

Quartz and feldsper are essential constituents of the Oboké gneiss and graphite quartz schist; usually quartz predominants over feldsper in quantity. They occur as minute elongated granules, showing a microgranoblastic aggregation. It is noticeable that with these granules is mingled a considerable amount of clastic grains of original quartz and feldsper. Occasionally the clastic grains show a fine phenoclastic or Augen-form which is normally broken up into mosaic fragments along the peripheral zone. The phenoclasts of the minerals reach 1 cm. or more in greatest diameter. The eyes of feldsper are oligoclase which is partly zoned and twinned on the albite low. The crushed grains of original quartz and feldsper ara usually cloudy compared with the recrystallized products. The general characters of the coloured minerals in the rocks of the Oboké Series are usually similar to those of the Besshi Series.

b) Description of the Rocks

1. So-called Oboké Gneiss[1]

The rock varies much in character ranging from a hard compact rock to a comparatively fine schistose rock and in colour it passes from light greenish grey to dark grey. The principal constituents of the rock are quartz, feldsper and in some parts, sericite, actinolite, chlorite, graphite, hematite, may be important ingredients. Accessorily developed are epidote, allanite, rutile, titanite, apatite, zircon, tourmaline, iron ore and ilmenite. Sometimes the rock contains a considerable amount of crushed grains of quartz and feldsper, which show highly undulose extinction (Pl. IV, Fig. 1). It seems that an advanced stage in the granulation of quartz was usually reached before the feldsper began to show signs of pressure.

The chemical analysis of the typical Oboké gneiss, collected from the anticlinal core, was made at the author's request by S. Tanaka of the Earthquake Research Institute in the Tokyo Imperial University and shows the following result: [2]

Oboké gneiss from Oboké, Prov. Awa. (Anal. S. Tanaka)

	Wt. %	Mol. numb.
SiO_2	75.92	1265
Al_2O_3	12.38	123.5
Fe_2O_3	0.13	1.3

(1) The name Oboké gneiss was applied by T. Ogawa to particular siliceous schistose rocks of the System, on accotnt of the well developed character and good exposures of the formation in the Oboké Valley along the River Yoshino in Shikoku. (Kochi, Sheet. Imp. Geol. Surv. Japan 1902)

(2) J. Suzuki: On a conglomerate schist from Iya Valley in Shikoku, Proc. Imp. Acad. Vol. III. 1927, pp. 675-678 and Jour. Geol. Soc. Tokyo. Vol.

	Wt %	Mol. numb.
FeO	2.13	29.6
MgO	0.62	15.5
CaO	1.04	18
Na_2O	3.08	50
K_2O	3.08	31.5
H_2O (+)	1.23	—
H_2O (−)	0.02	—
TiO_2	0.28	4
P_2O_5	0.04	—
MnO	0.03	3
Total	100.06	

As has been noted, from its mineral components, chemical composition and the texture, Oboké gneiss may be regarded as a metamorphosed form of a complex of acidic lavas and their tuffs, produced by a moderate pressure at a certain depth. It is noticeable that the gneiss is identical petrographically with the pebbles of A and B types in the conglomerate schist. For the natures of these pebbles clearly show that they have been derived from an acidic volcanic rock with a porphyritic structure.

If the above consideration be correct, the Oboké gneiss is not equivalent of greywacke sandstone, as it has been believed by many geologists, and indicates an important fact that a notable igneous activity of acidic rocks took place before the Carboniferous age in Japan.

2. Graphite Schist

The rock is, as a rule, a fairly fine grained granulitic type showing little trace of cataclastic structure, and is principally composed of grains of quartz and feldsper and minute flakes of graphitoid material, associated with a small amount of epidote sericite, hematite. The remarkable difference of the rock from the graphite schist in the Besshi Series is that the former completely lacks any eye formed phenoclasts of feldsper and crushed grains of original quartz and feldsper.

3. Conglomerate Schist

The rock from Iya Valley, Shikoku, consists of numerous pebbles of lenticular form, regularly arranged in the plane of schistosity and imbedded in a matrix of remarkable schistose texture. Average lengths of the major and minor diamters of the pebbles are 10 cm. and 2 cm. respectively (Pl. IV, Fig. 3). The surface of the pebbles is usually smooth and round, giving evidence that they were perfectly waterworned (Fig. 6). These pebbles may be petrographically classified into

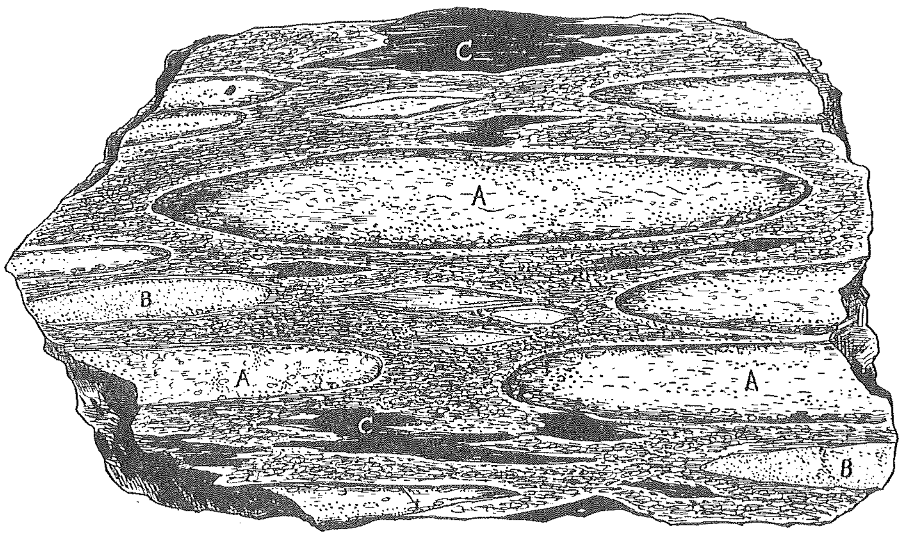

Fig. 6. Conglomerate schist from the Iya Valley in Shikoku 1/3 nat. size.

three types, viz., Type A. prophyroid rock with phenocrysts of quartz and feldsper (Pl. IV, Fig. 2). Type B compact rock with phenocrysts of feldsper and Type C black schistose rock. The petrographical studies of these pebbles and matrix have been publised in a former paper of the writer,(1) so that the general description is omitted here; the chemical analysis of the pebbles (type A) will be given again for comparison with that of the Oboké gneiss. The analysis was made by Takezo Kato of the First Higher School at the writer's request.

(1) J. Suzuki: On a conglomerate schist from Iya Valley in Shikoku, Proc. Imp. Acad. Vol. III. 1927, pp. 675–678.

Porphyrold pebble in conglomerate schist from Iya, Prov. Awa.
(Anal. Tz. Kato)

	Wt. %	Mol. numb.
SiO	76.12	1260
Al_2O_3	14.16	138.6
Fe_2O_3	0.62	3.8
FeO	1.12	15.6
MgO	1.04	25
CaO	1.32	23.6
Na_2O	2.23	35
K_2O	3.17	34
Total	99.79	

The mineral components, chemical composition and the texture of the pebbles clearly show that they have been derived from an acidic rock of porphyritic character.

4. Green Schist

The rock is chiefly composed of chlorite, albite and epidote associated with a small quantity of titanite, rutile, magnetite and tourmaline. It shows a comparatively fine schistose texture. Though the chemical composition is still undetermined, the lithological characters are quite similar to those of the albite epidote chlorite schist of the Besshi Series.

E. Ore Deposit in the Crystalline Schist System

It is noticeable that the crystalline schists locally present numerous intercalate beds of cupriferous pyrite deposits. These deposits of Besshi, Shirataki, Chihara, Higashiyama, Takakoshi, etc. are the representative types of this kinds in Shikoku; the Besshi deposit ranks among the largest examples in the world.

The deposits occurs usually in lenticular or thin bedded form and consist mostly of massive cupriferous pyrite and pure calcopyrite veinlet.

The genesis of these deposits has long been discussed by many geologists and has given rise to much opinions. But the deposits are considered, as is stated by T. Kato,[1] to be metasomatic replacement product of ascended mineralizing solution from basic igenous intrusions, which are believed to be closely connected with the great crustal movement. It is clear that the deposits had received a severe deformation together with the adjacent rocks during the dynamo-metamorphism. The direct relationship between the bedded deposit and any igneous rock in this district is still uncertain, but the serpentinized small patches of amphibolite of the Sekizen Mine near Besshi contain a considerable amount of cupriferous pyrite in an irregular form. The nature of the Sekizen deposit bears many points of resemblance to those of the Seki and Shibuki Mine, which were lately reported by T. Kato[2] and affords instructive data for studying the origin of the cupriferous pyrite deposit in the Crystallin Schist System of Japan.

A more detailed account of the nature of the cupriferous pyrite deposit in the Crystalline Schist System will be stated on another occasion.

II. CHEMICAL ASPECTS OF THE CRYSTALLINE SCHISTS OF THE SAMBAGAWA SYSTEM

We shall now proceed to discuss the chemical aspects of the crystalline schists under investigation and for comparison have tabulated the chemical analyses, which were quoted in the descriptive part. The majority of these was specially made for this investigation : some, however, have their source in the literature.[3] Beside the analyses of

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(1) T. Kato : The problem of the cupriferous pyritic deposits, Econ. Geol. Vol. XX, No. 1. 1925, p. 97–100.

(2) T. Kato : The cupriferous pyritic ore deposits of the Shibuki and Seki Mines in the Province of Bungo, Japan. Jour. Fac. Sci. Imp. Univ. Tokyo. (II). Vol. I., Part. 2, 1925. pp. 65–76.

(3) A few chemical analyses of rocks from the younger formations, namely of the green schists of the Mikabu and Chichibu Formations, are added to in order to give an idea of the general chemical characteristics of the old basic metamorphic rocks in Japan.

rocks such of the chief constituent minerals are also given in the Tables. The material for the latter was mostly taken from the rocks in question. These Tables of mineral analyses are supplemented by some mineral analyses of other localities. In these cases care was taken to select data entirely to minerals which derive from rocks similar in their petrographic characters to those under consideration. This was necessary, as we shall see later, to illustrate the close relationship between the chemical composition of the metamorphic rocks and that of their mineral constituents.

In the systematic treatment of the rock and mineral analyses, the methods of P. Niggli have been followed which are well adapted for the interpretation of the products of metamorphism, and especially derivatives from dynamothermal metamorphism. The rocks under consideration belong to the latter group and it may be assumed that the chemical composition of the original rocks plays the main role, having remained practically unchanged throughout the process of metamorphism which in their case (diverse on the products may seem) means no more than the reestablishment of equilibrium disturbedly changes of temperature and pressure.

In the following Tables the molecular values according to P. Niggli[1] are given with the analyses of both to minerals and rocks.

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(1) The methods of Niggli are nowadays so widely used by continental petrographers that an explanation is scarcely called for. It will, however, be convenient to note the following points.

al means molecular number of $Al_2O_3+Cr_2O_3$ etc.
fm means molecular number of (Fe, Mn) $O+MgO+NiO$ etc.
c means molecular number of $CaO+(BaO+SrO)$
alk means molecular number of Na_2O+K_2O etc.

is being assumed that al+fm+c+alk=100.

si means $\frac{\text{molecular number of } SiO_2}{\text{molecular number of } Al_2O_3} \cdot \text{al}$

h means $\frac{\text{molecular number of } H_2O}{\text{molecular number of } Al_2O_3} \cdot \text{al}$

co_2 means $\frac{\text{molecular number of } CO_2}{\text{molecular number of } Al_2O_3} \cdot \text{al}$

k means $\frac{K_2O}{K_2O+Na_2O+Li_2O}$

mg means $\frac{MgO}{FeO+MnO+MgO}$

where K_2O, Na_3O, MgO are expressed as molecular numbers.

TABLE I. (Rocks)

	1	2	3	4	5
SiO_2	48.86	48.52	46.38	48.83	50.25
Al_2O_3	17.80	14.93	16.35	15.43	18.15
Fe_2O_3	4.87	3.82	5.97	4.56	5.78
FeO	7.39	9.53	8.98	6.65	3.04
MnO	—	0.43	0.48	0.54	0.44
MgO	3.87	5.35	4.80	6.11	3.81
CaO	10.50	10.57	9.74	8.48	8.74
Na_2O	2.32	2.65	2.79	3.14	4.69
K_2O	0.86	0.11	0.70	1.62	0.20
H_2O	1.29	—	—	—	—
TiO_2	1.05	0.93	1.09	1.09	1.19
P_2O_5	0.60	Tr	0.35	0.14	0.33
CO_2	0.65	—	—	—	—
Loss on ignition	—	2.95	2.23	3.66	3.72
Total	100.04	99.78	99.86	100.25	100.30
si	121	116	111	116	147.5
al	26	21	23	22	29
fm	39	46	46	46	32
c	28	27	24	22	26
alk	7	6	7	10	13
k	0.19	0.03	0.14	0.25	0.03
mg	0.37	0.42	0.37	0.49	0.44
co_2	0.24	—	—	—	—
c/fm	0.72	0.59	0.52	0.53	0.81

* 1. Albite epidote hornblende chlorite schist from Shirataki, Prov. Tosa. (Anal. J. Suzuki).

** 2. Albite epidote chlorite schist from Takakoshi, Prov. Awa. (Anal. K. Takayanagi).

* 3. Albeit epidote amphibolite from Tonaru, Prov. Iyo. (Anal. K. Takayanagi).

* 4. Hornblende bearing epidote chlorite schist from Sekizen, Prov. Iyo. (Anal. K. Takayanagi).

* 5. Albite zoisite amphibolite from Sekizen, Prov. Iyo. (Anal. K. Takayanagi).

* Indicates new analysis.

** Indicates analysis which is reported in article written in Japanese.

TABLE II. (Rocks)

	6	7	8	9	10
SiO_2	50.56	53.90	47.89	52.60	48.88
Al_2O_3	17.65	17.66	13.06	14.19	13.44
Fe_2O_3	4.95	9.63	6.77	6.64	5.32
FeO	6.72	7.59	5.36	5.36	8.96
MnO	0.68	0.03	0.09	Tr	Tr
MgO	2.30	3.50	4.10	4.05	4.21
CaO	8.13	2.20	11.65	8.43	5.80
Na_2O	3.32	3.24	3.35	3.26	3.73
K_2O	0.61	0.66	0.57	0.78	1.71
H_2O	—	0.95	1.51	—	3.73
TiO_2	2.38	0.24	2.14	1.77	3.90
P_2O_5	0.15	Tr	—	—	—
CO_2	—	0.16	2.97	—	—
Loss on ignition	2.22	—	—	2.65	—
Total	99.67	99.76	99.46	99.73	99.73
si	141	156	125	140	129.5
al	29	30	20	22.5	21
fm	37	53	39	42.5	48
c	24	7	32	25	18
alk	10	10	9	10	13
k	0.11	0.13	0.11	0.13	0.23
mg	0.26	0.27	0.39	0.39	0.36
co_2	—	0.7	10.6	—	—
c/fm	0.65	0.13	0.82	0.59	0.37

* 6. Garnet amphibolite from Tonaru, Prov. Iyo. (Anal. K. Takayanagi).

** 7. Sericite garnet glaucophane schist from Noji, Prov. Tosa. (Anal. J. Suzuki).

8. Epidote glaucophane schist from Norimoto, Prov. Mikawa. (Anal. H. S. Washington).

* 8. Glaucophane bearing epidote hornblende schist from Futamigaura, Prov. Ise. (Anal. K. Takayanagi).

10. Epidote glaucophane schist from Kamuikotan, Hokkaido. (Anal. H. S. Washington).

TABLE III. (Rocks)

	11	12	13	14	15
SiO_2	36.94	42.59	48.95	72.30	57.23
Al_2O_3	3.49	2.92	17.11	12.80	7.40
Fe_2O_3	2.83	0.65	5.22	4.35	3.16
FeO	4.83	6.11	7.44	3.25	3.40
MnO	0.33	—	0.50	—	0.71
MgO	38.40	33.56	3.74	1.85	4.04
CaO	0.96	2.26	9.83	1.37	14.25
Na_2O	0.09	—	2.83	2.59	1.15
K_2O	0.13	—	0.53	1.53	1.73
H_2O	—	—	—	0.56	0.45
TiO_2	0.03	—	1.53	0.10	—
P_2O_5	—	—	0.32	—	—
CO_2	—	—	—	—	6.57
Loss on ignition	11.82	11.72	2.13	—	—
Total	99.86	99.82	100.11	100.70	100.51
si	58	76	120.5	435	174
al	3	3	25	35.5	14
fm	95	93	41	41	34
c	1.5	4	26	7	46
alk	0.5	0	8	16.5	6
k	0.5	0	0.12	0.28	0.5
mg	0.9	0.9	0.35	0.32	0.54
co_2	—	—	—	—	33
c/fm	0.02	0.04	0.65	0.17	1.35

* 11. Serpentine from Besshi, Prov. Iyo. (Anal. J. Suzuki).

** 12. Serpentine from Chichibu, Prov. Musashi. (Anal. T. Kondo).

* 13. Epidote albite hornblende schist (Mikabu System) from Sugi, Prov. Tosa. (Anal. J. Suzuki).

* 14. Glaucophane bearing Sericite quartz schist from Chihara, Prov. Iyo. (Anal. Tz. Kato).

* 15. Biotite calcite quartz schist from Nagatoro, Prov. Musashi. (Anal. Tz. Kato).

TABLE IV. (Rocks)

	16	17	18	19	20
SiO_2	84.68	75.92	76.12	73.94	50.51
Al_2O_3	5.10	12.38	4.16	7.41	3.31
Fe_2O_3	2.71	0.13	0.62	3.50	3.19
FeO	0.79	2.13	1.12	.58	3.93
MnO	0.59	0.03	—	0.60	0.43
MgO	1.35	0.62	1.04	2.63	1.28
CaO	0.86	1.04	1.32	2.88	22.47
Na_2O	0.47	3.08	2.23	3.26	0.83
K_2O	1.53	3.08	3.17	1.64	0.35
H_2O	—	1.25	—	1.40	1.01
TiO_2	0.17	0.28	—	0.64	0.72
P_2O_5	Tr	0.04	—	—	—
CO_2	—	—	—	—	12.72
Loss on ignition	1.57	—	—	—	—
Total	99.82	100.06	99.79	99.48	100.75
si	818	450	455	395	147
al	29	46	50	23	5.5
fm	48	17	17	42	23
c	9	7	8	15	68
alk	14	30	25	21	3.5
k	0.68	0.38	0.49	0.24	0.27
mg	0.45	0.33	0.52	0.47	0.22
co_2	—	—	—	—	50
c/fm	0.19	0.41	0.47	0.37	2.9

** 16. Sericite quartz schist from Takakoshi, Prov. Awa. (Anal. K. Takayanagi).

17. Oboké gneiss from Oboké, Prov. Awa. (Anal. S. Tanaka).

18. Porphyrold Pebble in conglomerate schist from Iyo, Prov. Awa. (Anal. Tz. Kato).

19. Piedmontite sericite quartz schist from Shirataki, Prov. Tosa. (Anal. J. Suzuki).

20. Piedmontite calcite quartz schist from Hadeba, Prov. Iyo. (Anal. J. Suzuki).

TABLE V. (Minerals)

	A	B	C	D	E	F
SiO_2	64.81	37.83	42.35	36.16	33.64	42.73
Al_2O_3	20.13	22.63	28.30	22.52	10.64	1.33
Fe_2O_3	0.21	15.02	3.08	9.33	—	—
FeO	—	0.93	—	—	8.83	7.20
MgO	0.45	Tr	0.56	0.40	34.95	36.51
Mn_2O_3	—	Tr	—	6.43	—	—
CaO	1.29	23.27	21.60	22.05	—	—
Na_2O	11.62	—	0.91	0.44	—	—
K_2O	0.68	—		—	—	—
H_2O	—	2.05	3.18	3.20	12.40	11.66
TiO_2	—	—	—	—	—	—
Total	99.22	100.73	99.98	100.53	100.46	99.49
si	252	75	96	76	51	69
al	46	26.5	38	28	9.5	1.5
fm	3	24	8	21	90.5	98.5
c	5.5	49.5	52.5	50	0	0
alk	45.5	0	1.5	1	0	0
k	0.04	0	—	0	0	0
mg	0.79	0	0.25	0.09	0.88	0.89
h	—	13.5	24	26	63	63

A. Albite from Val de l'Erançon Piedmont.
B. Epidote from Sulzbachtal, Tirol.
C. Zoisite from Saastal, Wallis.
D. Piedmontite from Otakisan, Prov. Awa.
E. Pennine from Zermatt, Wallis.
F. Antigorite from Zermatt, Wallis.

TABLE VI. (Minerals)

	G	H	I	J	K	L
SiO_2	44.53	56.71	56.25	37.90	53.01	36.98
Al_2O_3	11.11	15.14	1.24	17.95	34.71	17.11
Fe_2O_3	5.03	9.78	0.78	25.54	Tr	2.79
FeO	3.83	4.31	5.50	—	—	16.87
MgO	18.78	4.33	21.19	4.63	0.50	10.88
MnO	—	—	0.48	3.02	—	0.24
CaO	11.26	4.80	12.08	9.35	0.27	—
Na_2O	1.75	4.88	0.19	—	1.01	0.60
K_2O	0.87	0.25	0.28	—	6.05	10.82
H_2O	0.14	—	1.81	—	4.67	1.98
TiO_2	1.45	—	—	1.11	—	1.71
Loss on ignition	1.10	—	—	—	—	—
Total	99.85	100.15	99.84	99.50	100.21	99.98
si	79.5	163	156	73	197	73
al	11.5	24	2	21.5	77	20
fm	63	49	72	58	3	65
c	21.5	14	25	20.5	1	0
alk	4	13	1	0	19	15
k	0.24	0.03	0.45	0	0.84	0.92
mg	0.80	0.38	0.86	0.24	1.0	0.50
h	—	—	—	—	—	—

G. Hornblende from Clemgia Unterengadin.
H. Glaucophane from Otakisan, Prov. Awa.
I. Actinolite from Greiner, Tirol.
*J. Garnet from Besshi, Prov. Iyo.
K. Sericite from Chichibu, Prov. Musashi.
L. Biotite from St. Gotthard.

As already shown in the descriptive part, the crystalline schists of the Crystalline System can be petrographically divided into two groups: 1. green schists and 2. siliceous schists including calco-siliceous rocks. As can be seen from the Tables this classification can also be decuced from the chemical data. While most of the green

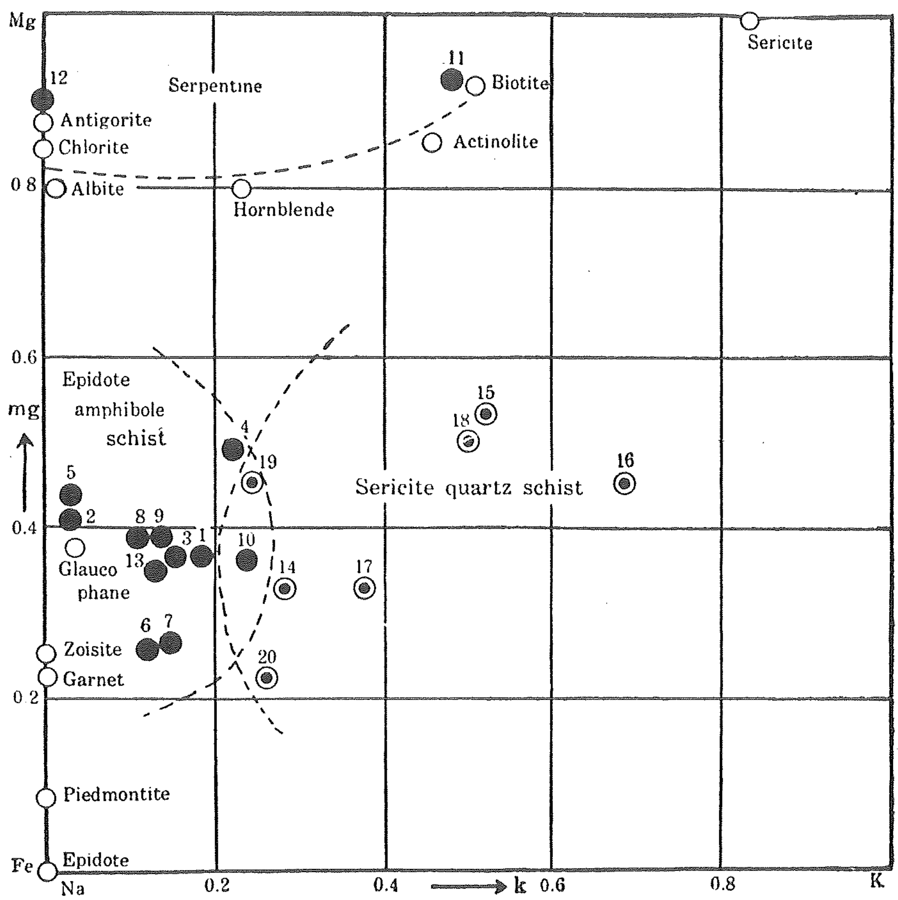


Fig. 7. mg.-k-Diagram.

schists show mg and k values ranging from 0.2–0.5 and from 0.0–0.25 respectively, the corresponding values for the siliceous schists are 0.2–0.5 and 0.25–0.7 respectively (see Fig. 7) thus, though the mg values show no marked difference in the two cases the k values are on an average much higher in the latter group. That these rocks also have much higher si values is obvious. The following figures clearly indicate the essential difference in composition between groups 1 and 2:

	si	si (average)	k	k (average)
Siliceous schists	147–818	376	0.24–0.68	0.41
Green schists	58–163	134	0–0.41	0.13

It is generally accepted that the green schists of dynamothermally metamorphosed region are derived from basic igneous rocks. In the present case, also, the chemical composition of the green schists is similar to that of rocks of this type,(1) a fact which becomes especially conspicuous if the projection methods of P. Niggli be used in connection with the analytical data.

In Fig. 8 we plotted the calculated values of the green schists in question, together with those of a number of the average composition of basic igneous rocks as given by P. Niggli. It is obvious that the loci of the green schists of the Crystalline Schist System not only fall into the eruptive fields on Sections II, III, IV, and V, but also practically coincide with those of gabbroid rocks. From this facts it may safely be inferred that the green schists are metamorphosed basic igneous rocks.(2)

(1) The previously mentioned molecular numbers are platted in a tetrahedron, then corners which represent 100% al, fm, c, alk respectively. It is thus possible to assign a specific position to any igneous rock. A simple method of ascertaining the relative positions occupied by a series of rocks thus projected, consists in laying a series of sections through the tetrahedron. Each section in mode to pass through the al-alk edge of the tetrahedron and a point of its c-fm edge, a number of ternary diagrams al-alk-c/fm (with a difinite value of c/fm in each case) being thus obtained. Niggli has shown the ten sections (I–X) in which the area occupied by igneous rock analyses—the so-called "eruptive field"—is indicated by the shaded facts.

(2) Concerning the green schists from the Crystalline Schist System of Chichibu, B. Koto already saw fit to regard them as an altered series of basic igneous rocks allied to the diabases in composition and possibly consisting in part of altered tuff. (Jour. Coll. Sci. Tokyo Imp. Univ. Vol. II, 1888, p. 130.)

L. Milch also quoted the two analyses of glaucophane schists from Norimoto, Prov. Mikawa and Kamuikotan, Hokkaido, in his paper and compared the former to hypersthene gabbro from Sulphurbanck in California and the latter to nepheline basalt from Steinsberg in Oldenwald. (Ueber Glaukophan und Glaukophan-Gestein von Elek Dagh, Nördliches Kleinasien. Neues Jahrbuch, Festband, 1907, p. 348.)

It is also noteworthy that in the mg-k-Diagram the projections of the green schist analyses concentrate in the field of k (0– 0.25) and mg

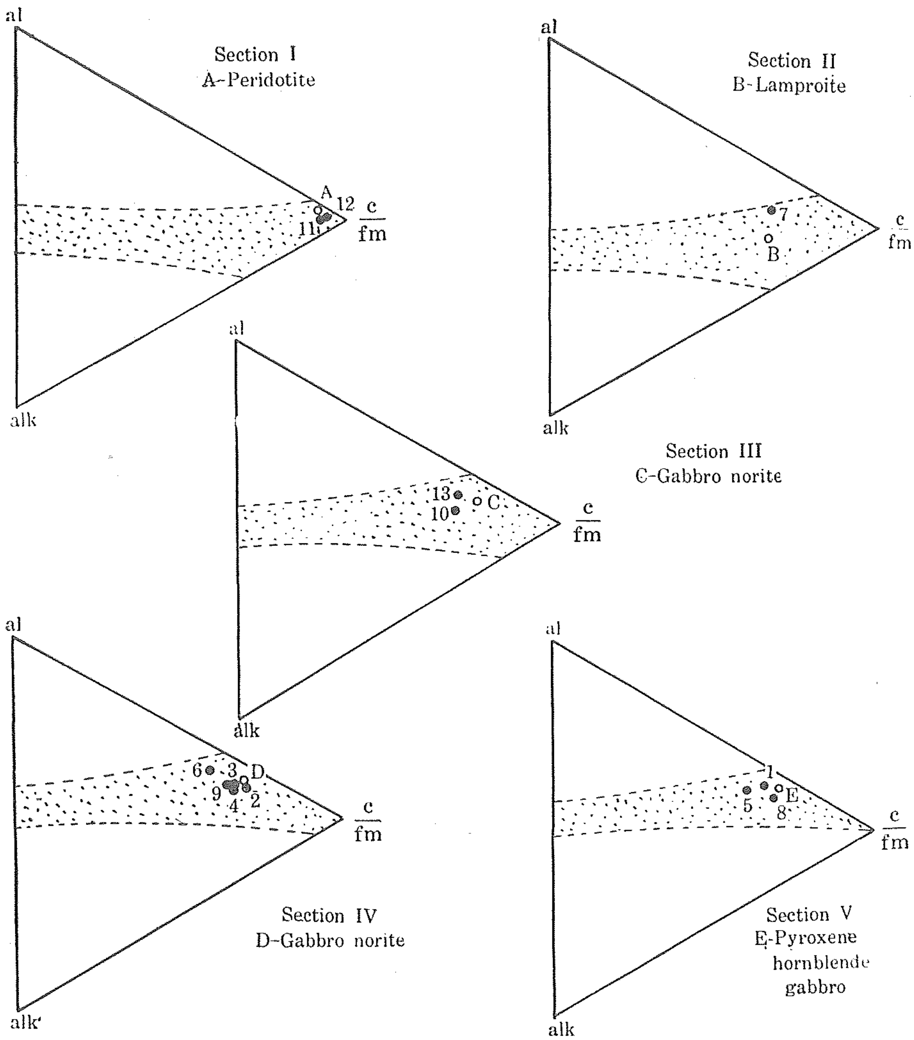


Fig. 8. al, alk, c/fm-Diagram.

(0.2–0.5), showing that they belong to the field of the so-called Calc-alkali Series.[1]

(1) P. NIGGLI: Gesteins-und Mineral-Provinzen. Band I, 1923, p 96.

Notwithstanding the diversity of constituent minerals found in the green schists, the chemical analyses of the rocks themselves show an apparently small variation. A closer inspection of the values obtained indicates, however, that there are in fact certain distinct differences which may be parallelized with the presence or absence of certain minerals. This becomes particularly clear, if we use the projection

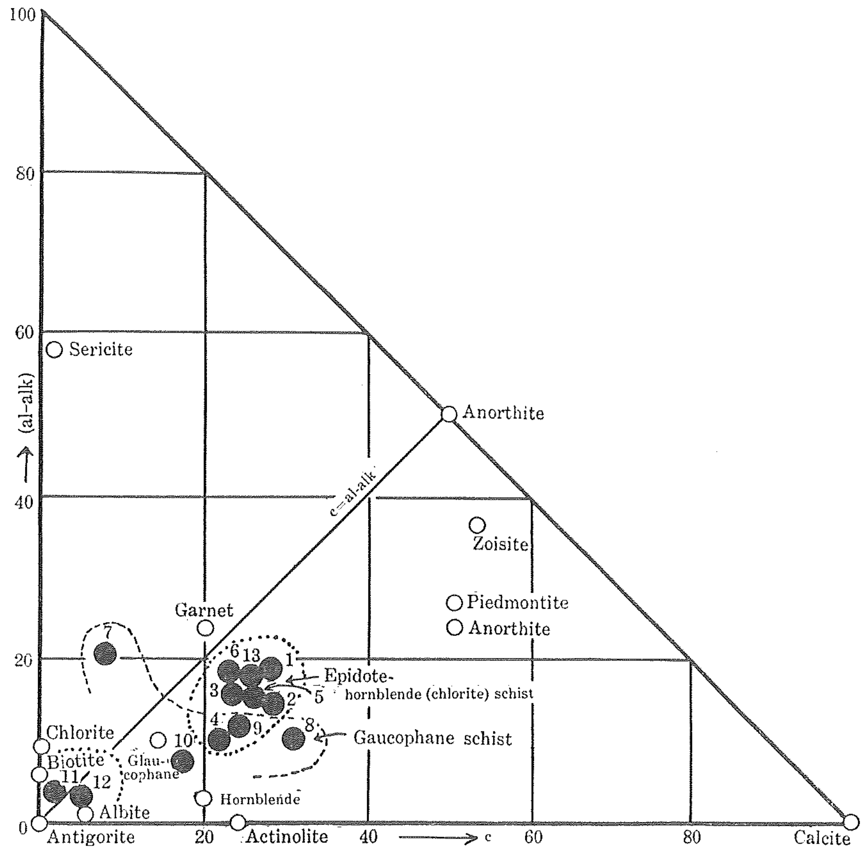


Fig. 9. (al-alk), c-Diagram (green schists).

diagram (Figs. 9 and 10) also after P. Niggli, in which c is taken as absissa and the difference (al-alk) as ordinate. If the molecular values of the rocks and their constituent minerals be included in the same diagram, the facts are revealed that there are certain distinct regularities in the distribution of each.

Thus, the glaucophane bearing rocks gather together in the lower part of the diagram which is also the area in which the glaucophane analysis falls. Directly above lies the area of chlorite and hornblende schists. The loci of garnet bearing schist lie in the upper part of the figure but always under the line c=(al-alk). Beyond this line and in its immediate neighbourhood is situated the zone of the mineral garnet.

The zones representing the composition of zoisite-epidote and hornblende respectively, limit the area occupied by the rocks. This shows

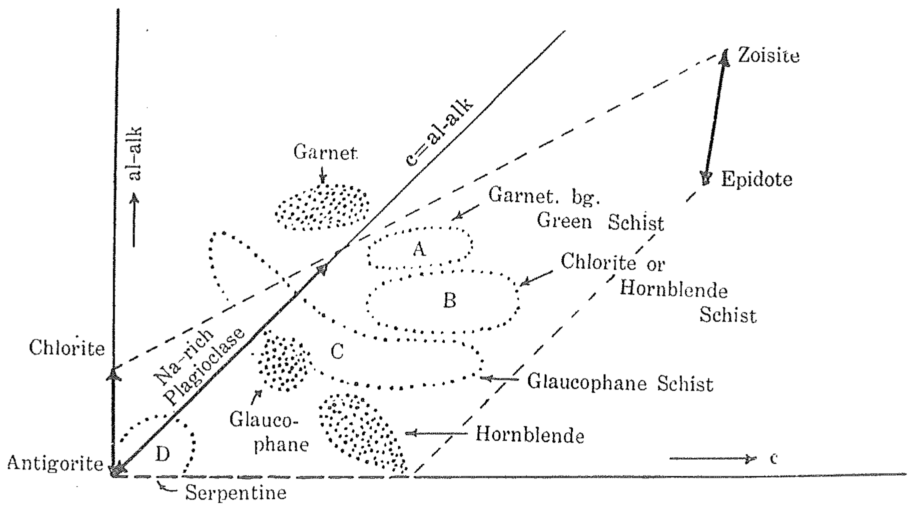


Fig. 10. (al-alk), c-Diagram (green schists).

convincingly that there is a certain restricted area in which a given rock type (or mineral assemblage) can persist. In other wards differences in chemical composition are responsible for the precence of the different minerals in the green schists.

A ternary diagram FM-AL-C(1) gives also another good illustration of this point (Fig. 11).

In short, a general summary of the chemical characteristics of the green schists may be given as follows:

---

(1) In this case, $FM+Al+C=(FeO+MgO)+Al_2O_3+CaO=100$.

1. The relatively high values of alk and fm and the comparatively low figures for al and mg distinguish the glaucophane-bearing rocks from chlorite or hornblende rocks.

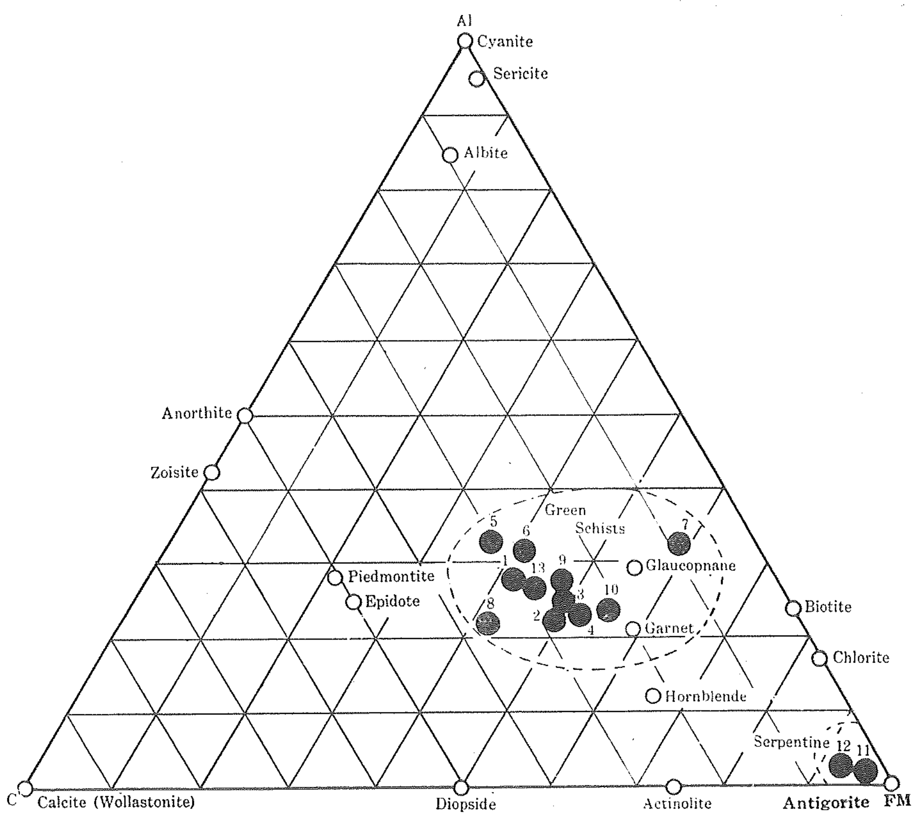


Fig. 11. AL-FM-C-Diagram (green schists).

2. Sometimes hornblende schist is considered to be derived from chlorite schist by continued metamorphism, but in this case, the difference between these rocks may be considered as a result of primary chemical differences in the original rocks. For the chlorite schist in the system usually shows a higher amount of magnesia and lower amount of iron and alumina than the hornblende schist.

3. Epidote occurs in the green schist as an essential constituent, but mica is usually poor in them. This facts indicate that the rocks are relatively high values of c and relatively low values of k.

4. Garnet always exists in rocks relatively rich in iron and alumina. The garnet bearing green schist is occasionally considered to be

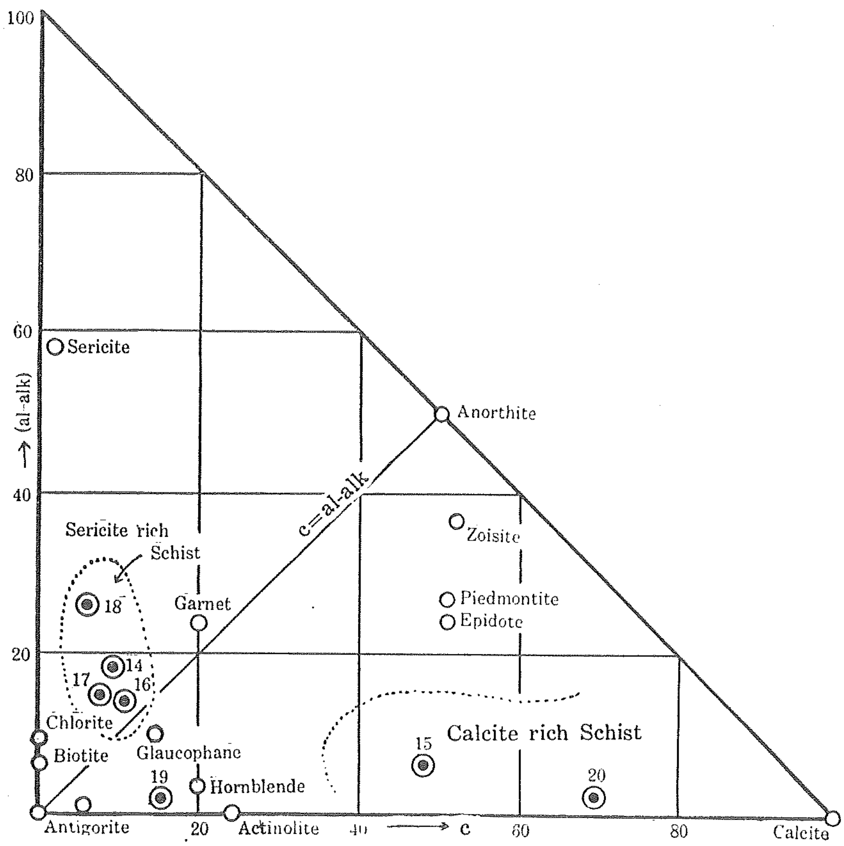


Fig. 12. al, alk-Diagram (siliceous and calcareous schists).

the products under the higher grade of metamorphism, than the common green schist, but in the present case, it is also possible to explain its origination from the chemical side.

5. Zoisite-rich rocks show lower values of fm than epidote bearing ones.

6. Antigorite schists and serpentine are always characterized by the low values of al, si, c and al and by the high values alternatively fm and the molecular ratio of FeO : MgO which may rise as high as 1 : 9. Taking these facts into account, the green schists in question can be classified into two main types : one has mg<0.4, the other mg>0.4.

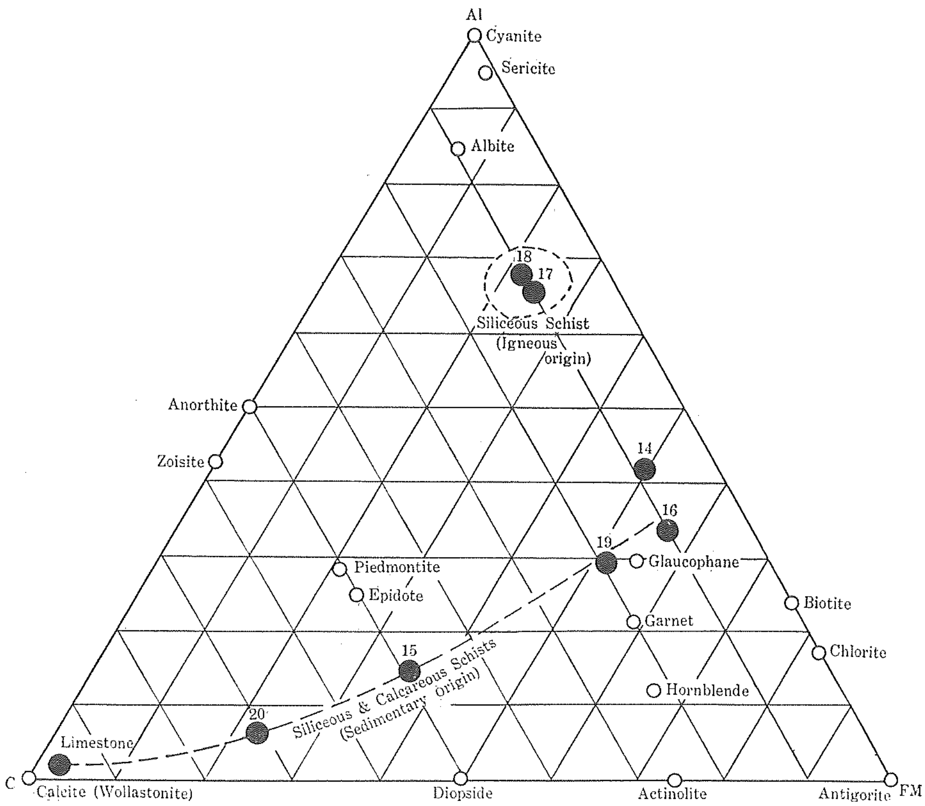
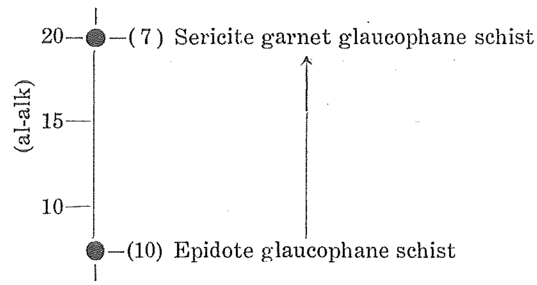


Fig. 13. AL-FM-C-Diagram (siliceous and calcareous schists).

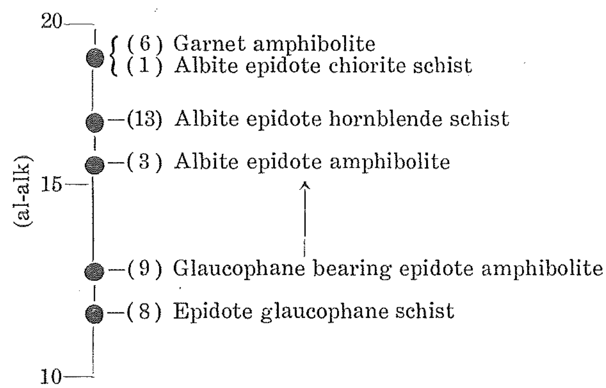
In each type two subtypes may be distinguished according to whether c<20 or c>20. Within each subtype the expression al-alk assumes characteristic values for each rock type, containing definite mineral constituents as described in Part I. The result may be shown diagramatically as follows :

(1) mg <0.4

(a) $c<20$

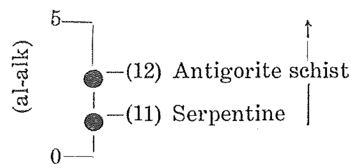


(b) $c>20$

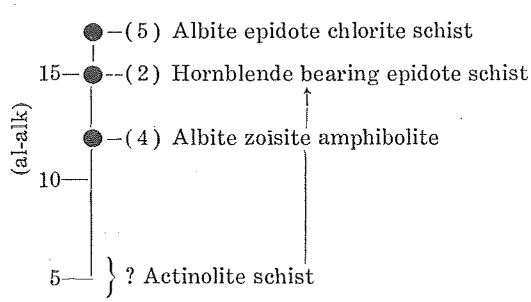


(2) mg >0.4

(a) $c<20$



(b) $c>20$



We proceed to the projection of the calculated molecular values of the siliceous schist in the concentration diagram. The same procedure as was applied to the green schists permits us to conclude that we have here to do with the derivatives of both igneous and sedimentary rocks. (Fig. 12 and Fig. 13).

An inspection of these diagrams and Tables indicates that the chemical characteristics of the siliceous rocks may by summarised as follows :

1. The siliceous and calco-siliceous schists of the Besshi Series are represented in the diagram by a nearly straight line from the corner C. That means that the ratio fm : al remains almost constant in these rocks. It is noteworthy that they show a close relationship between their chemical character indicating that they might have been derived from the continuous series of siliceous and calcareous sedimentary layer.(1)

2. At the one end of the line in diagram, we find the glaucophane-bearing sericite quartz schist and at the other the limestone. In other words, glaucophane appears in rocks poor in c.

3. It is to be noticed that in the siliceous schists glaucophane always appears with sericite, whereas in the green schists it is usually associated with epidote. Chemically the difference between the two types lies in the higher value of k and the lower value of c in rocks of the first type.

4. The piedmontite-bearing rock is characterized by its content of MnO, while the biotite rock shows a high content of MgO.

5. The projection points of some siliceous rocks in the Oboké Series lie in the top part of the diagram (Fig. 13) and show no relation

(1) On the origin of the siliceous schist of the Crystalline Schist System of Chichibu, B. Koto has concluded that the normal sericite schist may have resulted from a coarse graywacke sandstone or volcanic tuff, while the epidote sericite gneiss may have been changed from a fine variety, and the graphite sericite schist may have had its origin in a carbonaceous schale (loc. cit. p. 130.)

to the types just discussed. The former show an extremely high content of al and alk and a low content of fm and fall into the eruptive field on Section III.

From these facts the following classification of siliceous schists including calo-siliceous rocks is now proposed :

1. Sedimentary origin.
   Glaucophane-bearing sericite quartz schist.
   Sericite quartz schist.
   Piedmontite quartz schist.
   Biotite calcite quartz schist.
   Piedmontite calcite quartz schist.
   Diopside-bearing crystalline limestone.
   Crystalline limestone.
2. Igneous origin.
   Siliceous gneiss (so-called Oboké gneiss).
   Porphyroid schist.

These results show very clearly the close relationship existing between the mineral assemblage and the chemical composition thus indicating the role played in connection with the metamorphism by the chemical factor. A rock type with a given mineral assemblage has a chemical character specifically its own and differing sharply from that of other types. It may safely be asserted that the chemical composition of the original rocks stands in close causal relationship with the mineral constituents of the metamorphosed rocks of the Sambagawa System.

III. NATURE OF THE METAMORPHISM

A discussion of the nature of the metamorphism, which took place in a certain region is often liable to become speculative. So long as we have no decisive evidence on which to argue it is not only useless but also fatal to the progress of science to say for example, that a certain mineral is the metamorphosed product of certain other mineral or to infer that a certain rock has undergone a high or low grade of metamorphism because it contains a certain mineral or a certain group of minerals. In view of the fact that different minerals may be found and continue to exist under different physico-chemical conditions, and having regard for the different physical-chemical conditions, which may have prevailed in a petrographic region, the utmost care should be exercised before any conclusions are drawn on these lines during the study of a limited geological unit. We must in the first place seek after evidence on which safe inferences may be based. If a rock is found to contain unaltered fragments or shows a more or less distinct palimpsest texture, it is not generally difficult to decide the nature of the premetamorphic rock. In the present case, however, the metamorphic process is so complete that the rocks are entirely composed of metamorphic minerals. There are no traces and no relies of originals and nothing can be said about the metamorphic transitions from mineral to mineral, which may have taken place in these rocks.(1) There is also no positive evidence to the effect the different physico-chemical conditions existed in the different parts of the formations in question. We have at our disposal the following criteria only:

1. The fact that the studied area forms a geological unit.

2. The definite chemical differences which have been shown to exist between the various types of rocks and which have been fully discussed in the previous part. The results may now be stated in another form as follows:

---

(1) Amphibolite or allied rocks from the other metamorphic districts in Japan, not infrequently, contains a certain content of primary pyroxene crystals, as an unstable relics thought the border of the latter may be more or less amphibolized as a result of stress. For example, B. KOTO describes three kinds of amphibolite, one from Nakakubo, Prov. Kozuke, containing brown pyroxene with uralitized border and the other two from the Tsuitate Pass, Prov. Tosa, and Izushi, Prov. Musashi containing diallage with glaucophanized borders. T. KATO also reported on the diallage with actinolitized margin in the basi metamorphic rock from the environs of the Shibuki Mine and the Seki Mine in the Prov. Bungo (see B. KOTO: Jour. Coll. Sci. Tokyo. Vol. I. 1887 and T. Kato: Jour. Fac. Sci. Tokyo. Vol. I. 1926.)

for the green schists,

SiO_2	high MgO ↑ low MgO	low FeO ↓ high FeO	low Al_2O_3 ↓ high Al_2O_3	CaO	Na_2O + K_2O	Antigorite schist Chlorite schist Actinolite schist Hornblende schist Zoisite hornblende schist Epidote hornblende schist Garnet hornblende schist

for the amphibole schists,

SiO_2	high MgO ↑ low MgO	low FeO ↓ high FeO	high Al_2O_3 ↑ low Al_2O_3	CaO	low Na_2O+K_2O ↓ high Na_2O+K_2O	Hornblende schist Glaucophane schist

for the siliceous and calcareous schists,

high SiO_2 ↑ low SiO_2	high $FeO+MgO+MnO$ ↑ low $FeO+MgO+MnO$	high Al_2O_3 ↑ low Al_2O_3	low CaO ↓ high CaO	high Na_2O+K_2O ↑ low Na_2O+K_2O	Glaucophane-bearing quart schist Sericite quartz schist Piedmontite sericite quartz schist Biotite calcite quartz schist Piedmontite calcite quartz schist Diopside bearing crystalline limestone Crystalline limestone

The tables show that every rock received a difinite position in the classification according to its chemical composition.

3. The character of the mineral assemblage of the System as a whole and of the texture and structure of the rocks in question. It

seems probable that the System has undergone a more or less uniform and not severe dynamo-metamorphism.(1) On the strength of field evidence it is almost impossible to divide the System into zones either according to the mineral assemblage or the textural or structural character of the rocks.

In as far as we may judge from these points, the conclusion seems justified that the metamorphic character of the System is mainly due to the diversity in chemical composition of the original rocks and that the process of metamorphism has taken place under more or less uniform phyisco-chemical conditions throughout the entire System. In other words the metamorphic rocks in question are isophysical rocks but not isochemical ones in every respect. The re-establishment of equilibrium is to be regarded as complete, because, on the one hand, the rocks in question are made up entirely of recrystallized minerals and on the other the chemical composition of each rock is characteristic for its mineral assemblage. There is no case, in which the classification based on chemical composition stands in contradiction to that based upon mineral assemblage.

As has been shown, the green schists of the Besshi Series must from their chemical composition be considered to be the equivalent of basic igneous rocks. But it is by no means certain whether they were derived from intrusive masses, lavas, sills or tuffs of ancient eruptive series. As regards their modes of occurrence, the normal chlorite schist and the chlorite hornblende schist generally appear as very thick layers with uniform composition and are extensively dis-

(1) From the mineral assemblage, the rocks may be considered as the products under comparatively low grade of dynamometamorphism coincided approximately with the intermediate position of epizone and mesozone. (see U. GRUBENMANN u. P. NIGGLI: Die Gesteinsmetamorphose I. 1924. p. 374). The green schist which mainly shows an assemblage of four minerals: chlorite, amphibole, epidote and albite, is widely distributed not only in Shikoku but in other parts of Japan and these four essential minerals are generally developed in a stable state. These facts suggest that there exists a certain prodominant facies in a metamorphose basic rock. Similar point has already been discussed by Becke, Tilley and Eskola (see F. BECKE: Zur Facies-Klassification der Metamorphosen Gestein. T. M. P. M., 35. 1921, p. 224. C. E. TILLEY: The facies classification of metamorphic rocks, Geol. Mag. Vol. LXI, 1924 p. 170 and P. ESKOLA: On the petrology of Eastern Fennoscandia, etc. Fennia 45. No. 19. 1925.)

tributed in direction of the strike in the terrains of the Sambagawa System not only in Shikoku but in Japan proper and Kyûshû. The possibility must, however, also be considered that they are derived from tufaceous sedimentaries of basic composition. The sedimentary origin of these schists that this is in fact the case, has been established satisfactorily by their field relationship to the siliceous or calcareous schist, which occur as intercalated layers in the green schists themselves.

The amphibolite, antigorite schist and some kinds of glaucophane schist generally occur as narrow lenticular belt extending over a comparatively small area and show a sharp boundary against the surrounding country rock. It may be supposed that they were produced from sill-like basic intrusives, which were connected with the adjacent basic rock. The antigorite schist is considered to be the recrystallized product of the serpentinized part of the original basic sills. Strictly speaking, the present rock is due to dynamometamorphic action, but serpentinization of rock was completed a comparatively short time after the intrusion of the original rock, the water which was the main source of serpentinization may have issued from the basic magma itself during the last stage of its consolidation.

In short from the modes of occurrence it seems probable that the original intrusive rocks were of great fluidity at the time of their intrusion and it is probable that the intrusion took place during great tectonic movements and the consolidation under severe stress. It is not unusual that the intrusion of igneous rocks is found to be somewhat intimately connected with the orogenic movement.

SUMMARY

The result of the present investigation can be summarized as follows :

1. The crystalline schists of the Crystalline Schist System of central Shikoku, Japan, can be stratigraphically classified into two main series, the Besshi Series and Oboké Series.

2. Petrographically they may be divided into two main groups of which the first includes the green schists, siliceous and calc-siliceous schists, the second the siliceous gneiss. The latter belongs to the Oboké Series and the former to the Besshi Series.

3. On account of their chemical composition the green schists can be regarded as the equivalent of basic igneous rocks and tuffs.

In the green schists are included :
chlorite schist,
chlorite hornblende schist,
amphibolite,
garnet amphibolite,
eclogite,
glaucophane schist,
antigorite schist, etc.

It is probable that the chlorite schist and chlorite hornblende schist were mostly derived from tufaceous sediments of basic composition. The mode of occurrence of the amphibolite, glaucophane schist and antigorite schist indicates that they originally intruded as basic intrusive sills.

4. The siliceous schists and calc-siliceous schists can for chemical reasons be traced back to sediments rich in sand and lime.

In this type are included :
sericite quartz schist,
epidote quartz schist,
piedmontite quartz schist,
glaucophane quartz schist,
graphite quartz schist, etc. all poor in lime,
and sericite calcite quartz schist,
piedmontite calcite quartz schist,
diopside bearing crystalline limestone,
crystalline limestone, etc. rich in lime.

5. Glaucophane exists both in the green schists and siliceous schists. In other words it exists both in rocks of igneous and sedimentary origin. In the former it is usually accompanied by epidote and in the latter by sericite. Marked differences in chemical composition exist between the two groups.

6. The siliceous gneiss of the Oboké Series may be considered as derivatives of acidic volcanic rocks. Its mineral constituent, chemical composition and texture support this suggestion.

7. Little can be said on the nature of the metamorphism except from the chemical point of view. The chemical composition of the original rocks seems to be solely responsible for the differences now existing between the various types. The mineral assemblage of the System as a whole suggests that the latter has undergone a more or less uniform metamorphism, which continued until equilibrium was reestablished and the rocks totally recrystallized. The rocks of the System are isophysical but not isochemical.

8. With regard to age it can be said that the metamorphism of the System had practically ended before the deposition of the Carboniferous Formation, represented by the Chichibu System, took place. In the latter the rocks show a markedly different metamorphic character.

9. The great thickness and persistence of the green schists throughout the area under investigation indicate that an extensive igneous activity producing basic rocks took place in Japan before the Carboniferous age. It is noteworthy that these rocks bear close resemblance to the volcanic rocks of the post-Mesozoic in Japan, especially in their chemical character.

10. The siliseous gneiss of the Oboké Series, assumed to be derived from some acidic igneous rocks, gives reason to suppose that igneous activity producing acidic magmas took place in the pre-Carboniferous of Japan.

In conclusion, the writer wishes to express his sincere thanks to Emeritus Prof. B. Koto, Prof. T. Kato and Prof. S. Tsuboi in Tokyo for their valuable criticism and suggestion during this investigation. His thanks are also due to Prof. P. Niggli for much help during his stay in Zürich in 1928—1929 and to whom he is indebted for the new chemical points of view in the investigation of metamorphic rocks. The writer is also indebted to the Geological Survey and Imperial Academy of Japan, the former afforded the facilities for the chemical analyses of the rocks and the latter supported him during his geological observation.

February 11, 1929.

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Plate I

Explanation of Plate I

Fig. 1. Albite-epidote-chlorite schist from Chihara Prov. Iyo. Ordinary light. Magnified 40 diameters, A, albite ; C. chlorite ; E, epidote.

Fig. 2. Spotted hornblende chlorite schist from Shirataki, Prov. Tosa. Ordinary light. Magnified 40 diameters, A, albit.

Fig. 3. Amphibolite (proper) from Tonaru near Besshi, Prov. Iyo. Ordinary light. Magnified 40 diameters, E, epidote ; H. hornblende.

Fig. 4. Spotted amphibolite from Ipponmatsu near Besshi. Ordinary light. Magnified 40 diameters, A, albit.

Fig. 5. Garnet amphibolite from Tonaru near Besshi, Prov. Iyo. Ordinary light. Magnified 40 diameters, G, garnet ; H, hornblende.

Fig. 6. Garnet amphibolite from Tonaru near Besshi, Prov. Iyo. Ordinary light. Magnified 40 diameters, G, garnet ; H, hornblende.

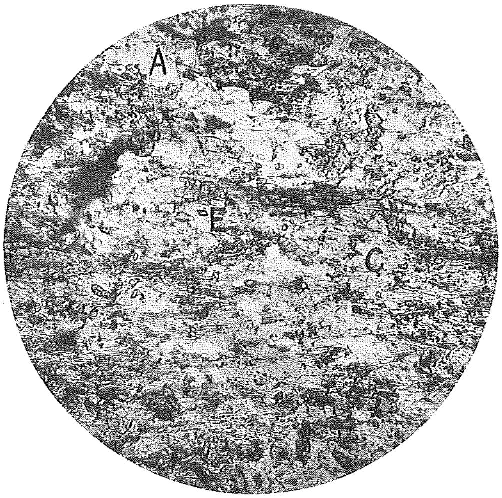


Fig. 1

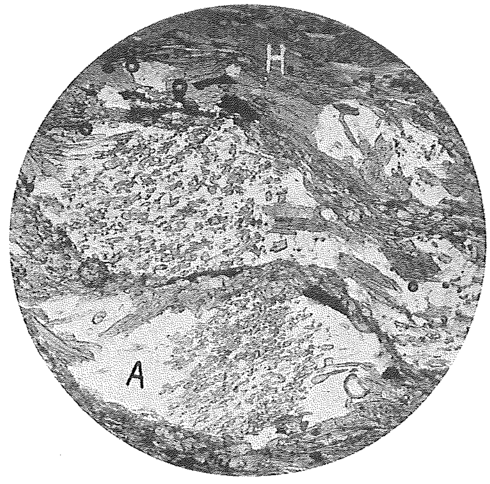
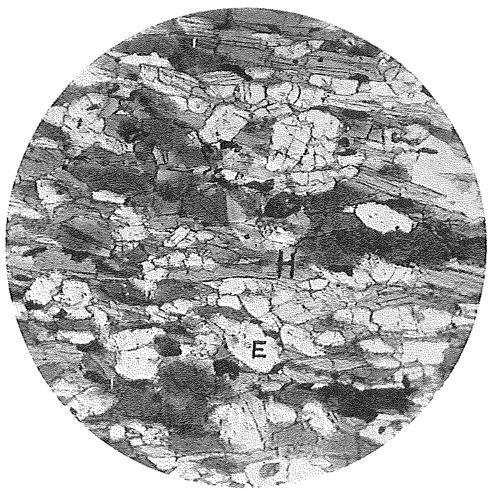


Fig. 2



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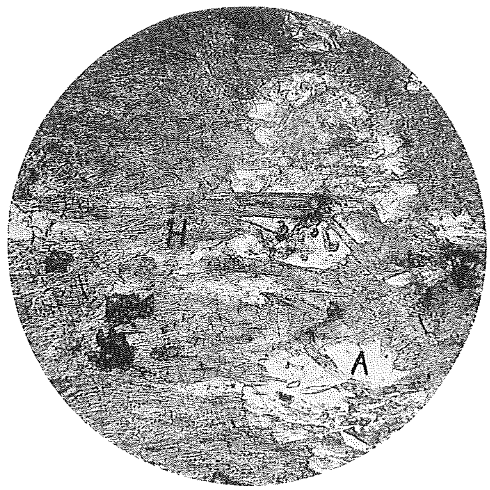

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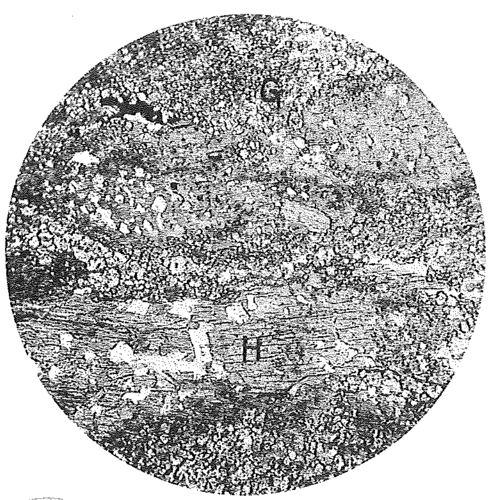

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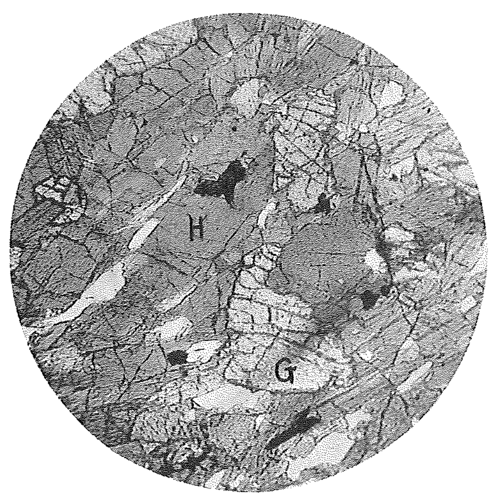


Fig. 6

J. Suzuki: Crystalline Schist of Shikoku.

Plate II

Explanation of Plate II

Fig. 1. Eclogite from Akaishi, Prov. Iyo. Ordinary light. Magnified 40 diameters, O, omphacite; G, garnet; Gl, glaucophane.

Fig. 2. Eclogit from Akaishi, Prov. Iyo. Ordinary light. Magnified 40 diameters, O, omphacite; G, garnet.

Fig. 3. Actinolite schist from Besshi, Prov. Iyo. Ordinary light. Magnified 40, A, actinolite, P, phlogopite.

Fig. 4. Garnet-henatite-schist from Takakoshi Prov. Awa. Ordinary light. Magnified 40 diameters, G, garnet; H. hematite.

Fig. 5. Albit epidote, glaucophane schist from Shirataki, Prof. Tosa. Ordinary light. Magnified 35 diameters, Gl, glaucophane; A, albit; E, epidote; H, hematite.

Fig. 6. Glaucophane bearing sericite quartz schist from Chihara, Prov. Iyo. Ordinary light. Magnified 35 diameters, Gl, glaucophane, Q, quartz.

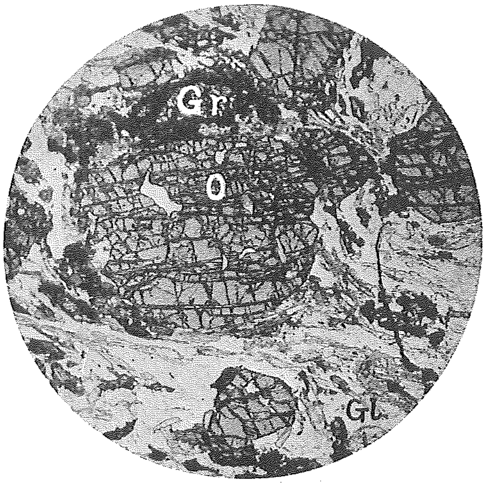


Fig. 1

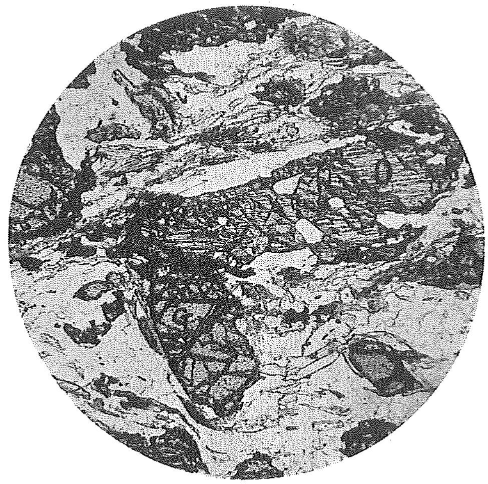


Fig. 2

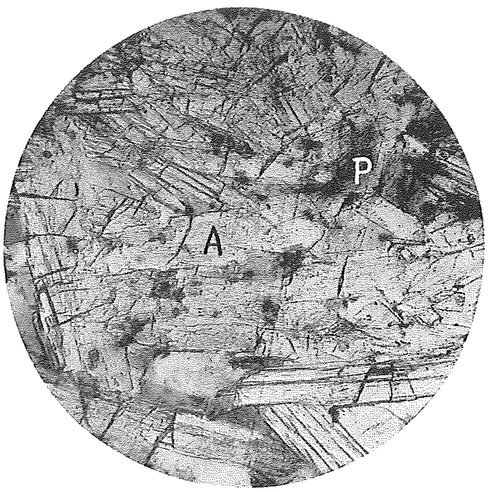
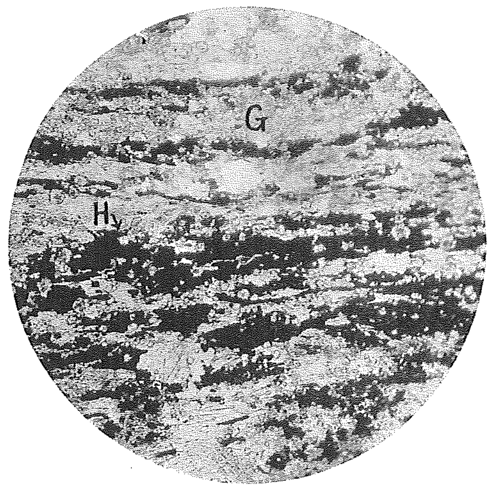


Fig. 3



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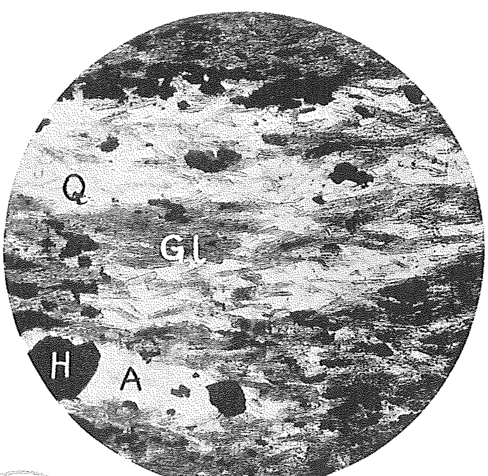

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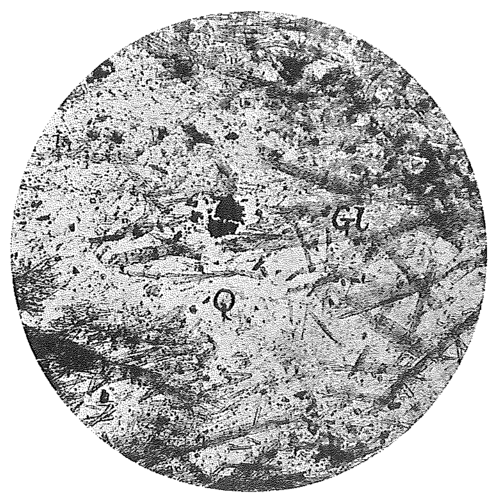


Fig. 6

J. Suzuki: Crystalline Schist of Shikoku.

Plate III

Explanation of Plate III

Fig. 1. Sericite albite quartz schist from Shirataki, Prov. Tosa. Ordinary light. Magnified 35 diameters, S, sericite; Q, quartz, A, albite.

Fig. 2. Hematite quartz schist from Chihara, Prov. Iyo. Ordinary light. Magnified 40 diameters. H, hematite.

Fig. 3. Piedmontite-sericite-quartz-schist, Noji near Shirataki. Prov. Tosa. Ordinary light. Magnified 60 diameters, P, piedmontite; Q, quartz; S, sericite, G, garnet; H, hematite.

Fig. 4. Piedmontite-calcite-quartz schist from Hadeba near Besshi, Prov. Iyo. Ordinary light. Magnified 60 diameters, P, piedmontite; pE, epidote; C, calcite, Q, quartz; M, magnetite.

Fig. 5. Garnet quartz schist from Shirataki, Prov. Tosa. Ordinary light. Magnified 40 diameters, G, garnet; Q, quartz.

Fig. 6. Graphite sericite quartz schist from Besshi, Prov. Iyo. Ordinary light. Magnified 40 diameters, Gr, graphite; S, sericite; Q, quartz.

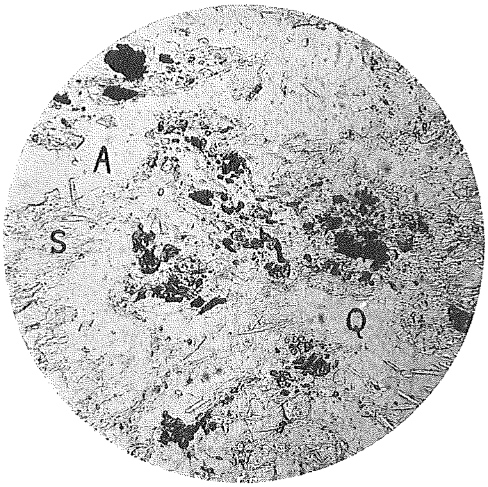
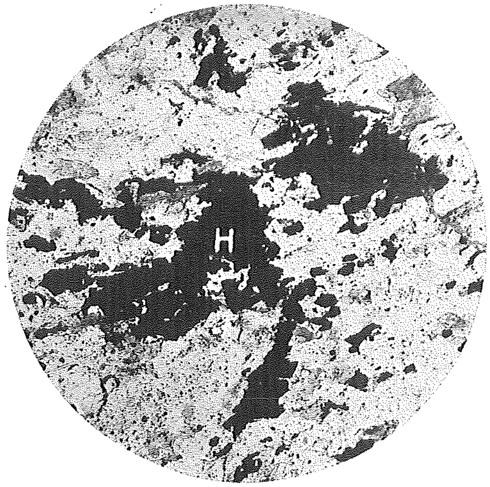


Fig. 1



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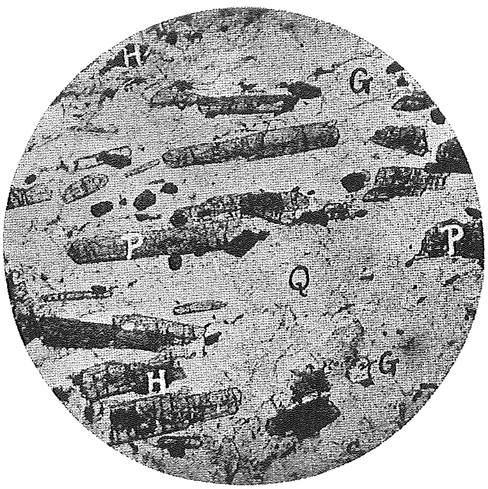


Fig. 3

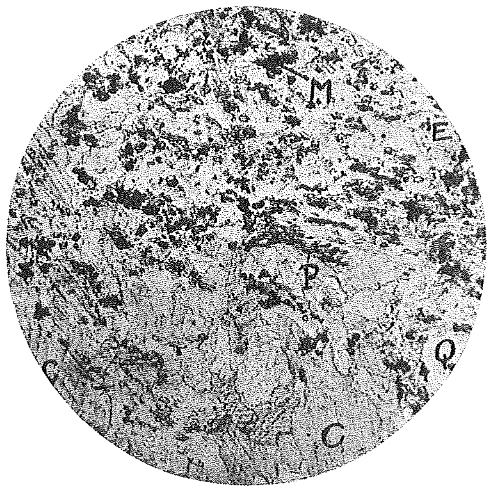


Fig. 4

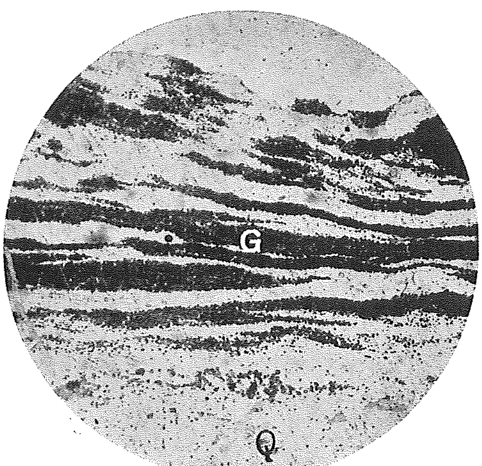


Fig. 5

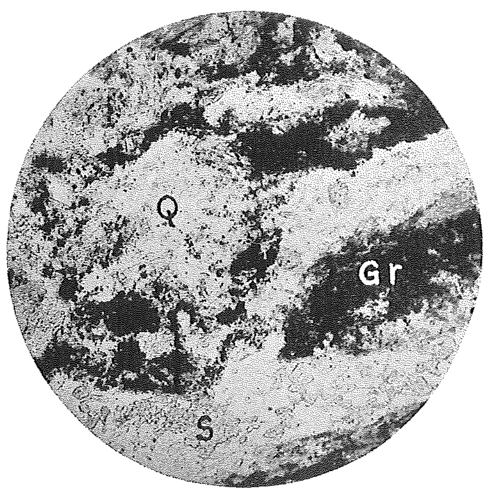


Fig. 6

J. Suzuki: Crystalline Schist of Shikoku.

Plate IV

Explanation of Plate IV

Fig. 1. So-called Oboké gneiss from Oboké, Prov. Awa. Crossed Nicols. Magnified 60 diameters, Q, quartz.

Fig. 2. Porphyroid rock (Pebble A type) in the conglomerate schist from the Iyo valley, Prov. Awa. Crossed Nicols. Magnified 60 diameters, Q, quartz.

Fig. 3. Conglomerate schist from the Iyo Valley Prov. Awa. 1/3 natural size, A, Pebble of porphyroid rock; B, Pebble of black schist.

Fig. 4. Serpentine (Palaeozoic) from Besshi. Ordinary light. Magnified 60 diameters, O, olivine.

Fig. 5. Green schist in the Mikabu System from Sugi, Prov. Tosa. Ordinary light. Magnified 60 diameters, H, hornblende, P, pyroxene (relics).

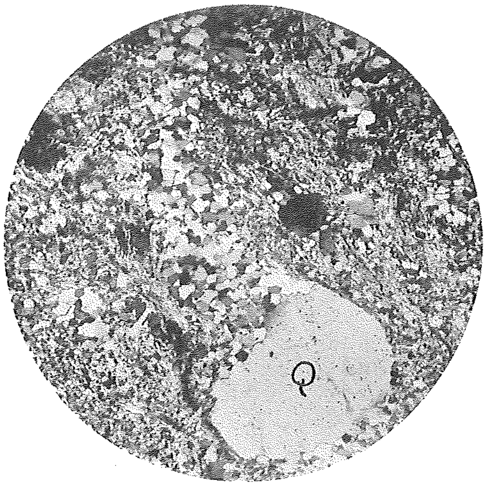
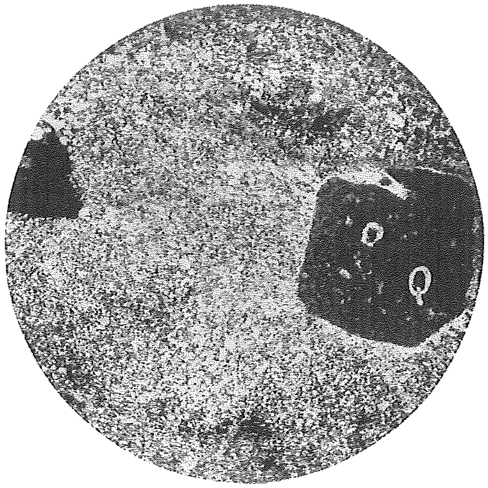


Fig. 1



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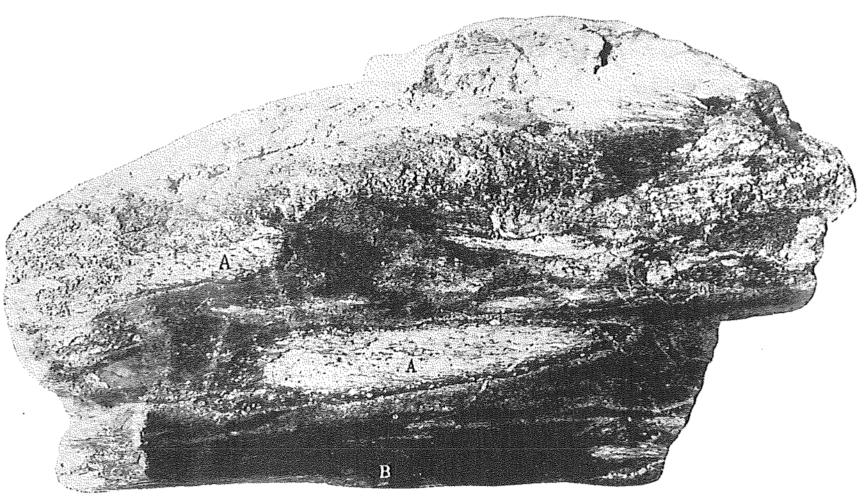

Fig. 3

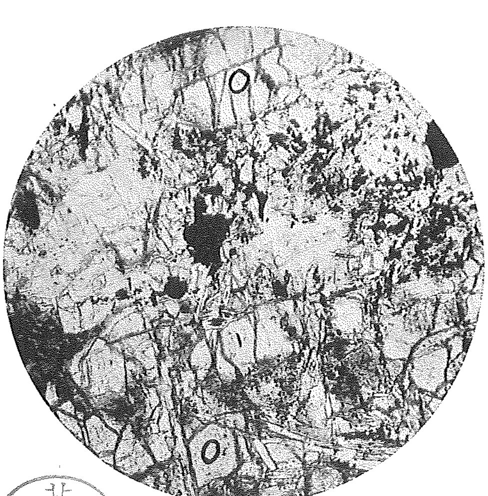

Fig. 4

Fig. 5

J. Suzuki: Crystalline Schist of Shikoku.