Clay Veins and Clay Minerals in the Granitic Rocks in Hiroshima and Shimane Prefectures, Southwest Japan

—— Effect of the hydrothermal activities on the decomposition of the granitic rocks ——

By

Ryuji KITAGAWA

---

with 8 Tables, 38 Text-figures and 9 Plates

To be published in Journal of Science of the
Hiroshima University, Series C, Vol.9, No.1
(1986)

ABSTRACT: This paper deals with the clay minerals found in the granitic rocks distributed in Hiroshima and Shimane Prefectures with special reference to the effects of hydrothermal activities on the decomposition process of the granitic rocks. Many clay veins and hydrothermal clay deposits are commonly developed in the granitic rocks and their mode of occurrences were investigated in detail. The preferred orientations of the clay veins and microcracks found in the constituent minerals of granitic rocks were examined. The constituent clay minerals and their mineralogical characteristics of clay veins, clay deposits and alteration products of plagioclase in granitic rocks were investigated by means of X-ray diffraction, optical microscope, electron microscope(TEM and SEM), hydrogen isotope ratio and so on. The major results obtained are as follows.

1) The preferred orientations of microcracks within granitic rocks are very similar to those of clay veins which have been formed under the regional compression stress field.

2) The constituent clay minerals of clay veins, clay deposits and alteration products from plagioclase and their mineralogical characteristics are almost identical with each other.

3) Mineral sequence found in the vertical direction of a clay vein and altered granitic rocks resemble to that observed in some present geothermal areas.

4) Mineralogical characteristics of the clay minerals indicate that the clay minerals were formed by hydrothermal solution subsequent to the post granitic activity. The temperature of hydrothermal solution ranges about 50° - 300° C and originated from meteoric water. Some clay minerals seem to be directly precipitated from the hydrothemal solution.

Based on the results mentioned above, it is considered that granitic rocks distributed in the investigated areas have been strongly fractured and characterized by remarkable alteration to clay minerals at hydrothermal stage before the weathering stage.

CONTENTS

I. INTRODUCTION

Studies of decomposed rocks are important to prevent the disasters such as the landslide and the avalanche of earth and rocks. Therefore, the decomposition of granitic rocks has been studied in various field such as pedology, geomorphology and civil engineering as well as in the fields of geological sciences. Nevertheless, the mechanism or process of the decomposition of granitic rocks have not been systematically explained yet.

In the inner zone of southwest Japan, granitic rocks of Cretaceous to Palaeogene age are distributed widely and the rocks are characterized, in general, by common development of fractures and extensive alteration. The decomposition extends usually to the depth of ten to twenty meters and in some places the depth reaches more than hundred meters. while conducting the mineralogical study on the alteration mechanism of plagioclase in the granitic rocks, the author has found that clay veins or veinlets are commonly observed in the rocks (Kitagawa and Kakitani, 1977a). These clay veins seem to have been formed by filling fissures and/or fractures developed in granitic rocks. Subsequent studies on the mode of occurrence, detailed constituent clay minerals and distribution of these clay minerals have revealed that clay veins are intimately associated with the post-magmatic activities, i.e., hydrothermal activities (Kitagawa and Kakitani, 1977b; 1978a, b, c and 1981). Clay deposits developed in the granitic rocks have also been proved to be related to the hydrothermal activities

(Kitagawa and Kakitani, 1979b; Ishihara et al. , 1980 and Kitagawa et al., 1982).

The constituent minerals of the host granitic rocks are, more or less, altered to clay minerals. It is to be noted is that some clay minerals of the alteration products are similar to those of the clay veins in the mineralogical characteristics such as mineral species and their paragenesis (Kitagawa et al., 1984; Kitagawa, 1985). These facts described above suggest that the hydrothermal activities may play an important role on the decomposition. In addition, preferred orientations of fractures were recognized at many localities suggesting that the fracture patterns were formed under the regional stress field (Kitagawa and Okuno, 1984).

Based on the mineralogical and geochemical studies of the clay veins, clay deposits and clay minerals altered from plagioclase and geometrical analysis of the fractures developed in the granitic rocks of Chugoku district, a systematic explanation for the effect of the hydrothermal activity on decomposition process of granitic rocks, will be described in the present paper.

ACKNOWLEDGEMENTS: The author wishes to express his sincerest gratitude to Professor Satoru KAKITANI of the Hiroshima University for his constant and invaluable advices rendered durning the course of the work as well as for his critical reading of the manuscript. He is also indebted to Professors Akira HASE, Akira SOEDA, Ikuo HARA and Assistant Professor of Yuji OKIMURA of the same University for their guidance and critical advices. He also gratefully acknowledges Assistant Professor Setsuo TAKENO of the same University for his continuing guidance and discussions and for critical reading of the manuscript. Thanks are also du to Dr. M. SUZUKI, Dr. T. SHIMAMOTO, Dr. A. WATANABE and Dr. T. MIYAMOTO for their helpful advice and encouragement. He also grateful to Mr. A. MINAMI of the Hiroshima University for his kind help with the techniques in the laboratory, and Mr. H. TAKAHASHI and Mr. A. MAGAI for preparing thin sections. He is also due to Mr. A. Funaki, Mr. Y.NISHIDA, Mr.H. KAMEOKA, Mr. Y. HABU, Mr.T. OZAWA, Mr.T.OKUNO, Mr.N. HIROSAWA, Mr.K.NAGAI, Mr.T. NOBUSHITA, Mr.K. ABE, Mr.M. TAKEMOTO, Mr.T. BABA, Mr.H. MITANI, Mr.J. HIGASIO for capable assistance in the field. Special thanks go to Prof. H. TAKAHASHI of Hiroshima University who read the manuscript and gave helpful comments on the final manuscript. He would like to thank to Miss. S. KODAMA for her kind assistance durning the preparation of the manuscript.

II. CLASSIFICATION AND DISTRIBUTION OF CLAY VEINS AND CLAY DEPOSITS

Clay veins are observed commonly in the granitic rocks, especially in the decomposed parts as mentioned below. The width of veins varies from one millimeter to one meter. In addition to the clay veins which have been formed filling fractures by clay minerals, aggregates of clay minerals of replacement origin which are aligned in certain directions resulting vein-like appearance will be also discussed. The mode of occurrences of clay deposits are similar to that of clay veins and/or vein-like replacement products.

A. CLASSIFICATION

As will be described later, the vein-like replacement products were caused by the hydrothermal activities by which the clay veins were formed. Therefore, the vein-like replacement products will be included in the clay veins in this paper. In the following, these clay veins and vein-like replacement products will be classified into five types based mainly on their mode of occurrence such as the characters of fractures and/or cracks (Fig. 1).

Type 1: Clay veins formed along the interstices of both sides of a dike rock such as granite porphyry, quartz porphyry and porphyrite (Plate 1). The scale of the veins varies from one centimeter to one meter.

Type 2: Clay veins formed by filling nearly vertical fissures or cracks (Plate 1). This type occurs most frequently and can be further divided into three types (Types

2-A, 2-B and 2-C) on the basis of the character of the fractures. Type 2-A is formed along faults and corresponds to the fault clay or gouge with relatively large width than those of the other types. Both types 2-B and 2-C are formed along sheared and/or open fractures.

Type 3: Clay veins formed along vertical or horizontal joints corresponding to the so-called joint-clay (Miura and Hata, 1970).

Type 4: Clay veins formed along small fissures of 1mm to 10mm in width. Network development of this type is observed in some places (Plate 1).

Type 5: Aggregates of clay minerals of replacement products alignes certain directions (Plate 1). Veins of this type are formed along many microfractures extending in certain directions.

Although the color of these veins varies complicatedly, all of the veins were roughly divided into two colors such as green and white. Veins of types 1, 2 and 5 belong mainly to the green type, whereas those of types 3 and 4 to the white type. As was reported in the previous paper, the color of the veins reflects their constituent clay minerals, i.e., the veins of white type are composed mainly of kaolin minerals and green type, smectite and mica clay minerals (Kitagawa et al., 1977b, 1978a).

Suitable outcrops for such observation and for measurement of the orientations (strike and dip) of the veins can be often found at the construction places of tunnel, cave of dam-site, housing and so on.

A continuous development of veins of types 1,2 and 5 can be pursued more than several kilometers in the Kamo district between Nishitakaya and Shiraichi as shown in Fig. 2. During the construction of a dam, detailed observations of the development of clay veins, mainly those of type 2 could be performed at Nukui, Kake-cho, Hiroshima Prefecture (Fig. 3). These veins can be pursued more than two hundred meters in the lateral direction and more than hundered meters in the vertical direction. As is seen in Fig. 3, the distribution pattern of the veins of type 2 is almost similar to that of type 4. The only difference between the two types is the scale. Veins of types 3 and 4 are found near the ground surface, whereas those of types 1, 2 and 5 occur not only near the surface but also under the ground of more than 100m in depth.

The degree of the decomposition were roughly measured by the alteration degree of plagioclase in the granitic rocks. As seen in Figs. 4, 5 and 6, all types of clay veins develop considerably at the relatively more decomposed parts of the respective granitic rocks.

B. MODE OF OCCURRENCE OF CLAY DEPOSITS

A number of hydrothermal clay deposits are found mainly in granitic rocks distributed in relatively restricted areas of Hiroshima and Shimane Prefectures (Fig. 7). Considering the main constituent clay minerals, two kinds of ore deposits are distingishable in these districts: one is

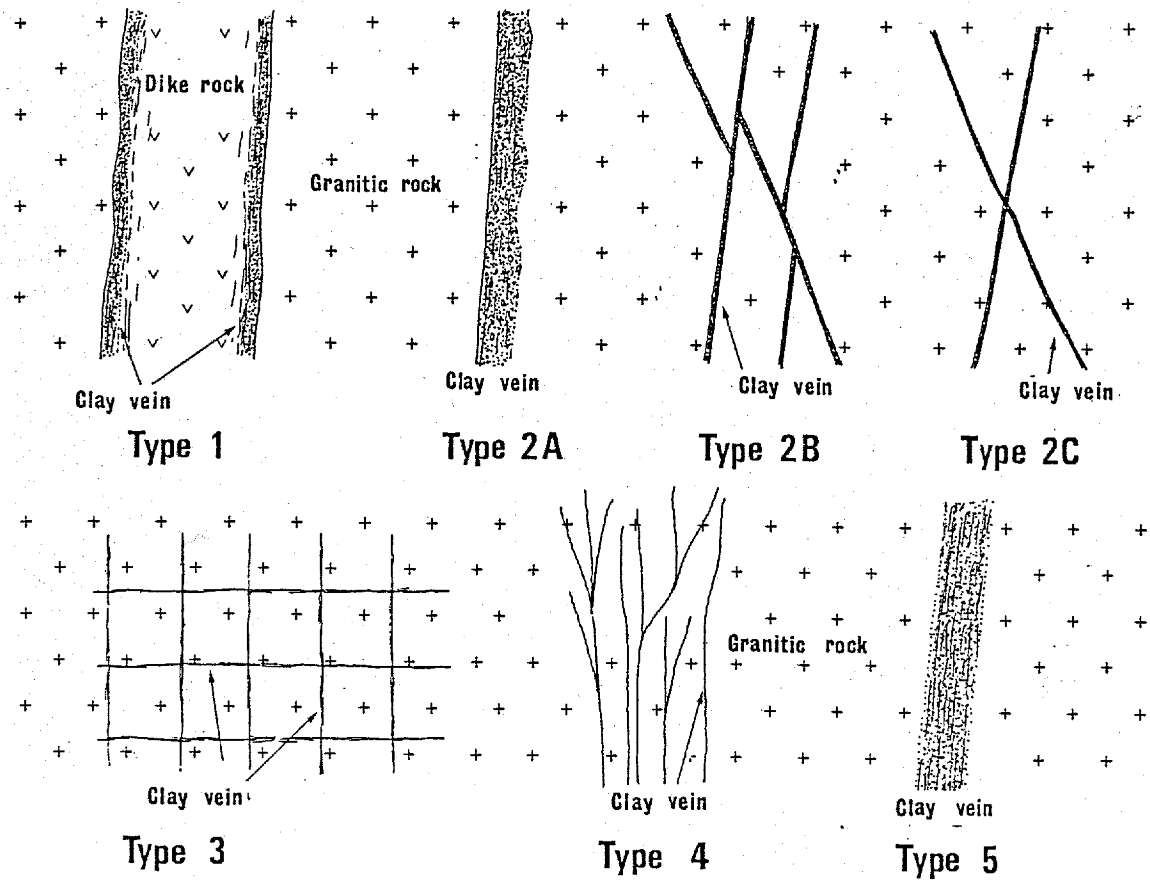


Fig. 1. Schematic diagrams of clay veins of five types classified based on the characteristics of fractures.

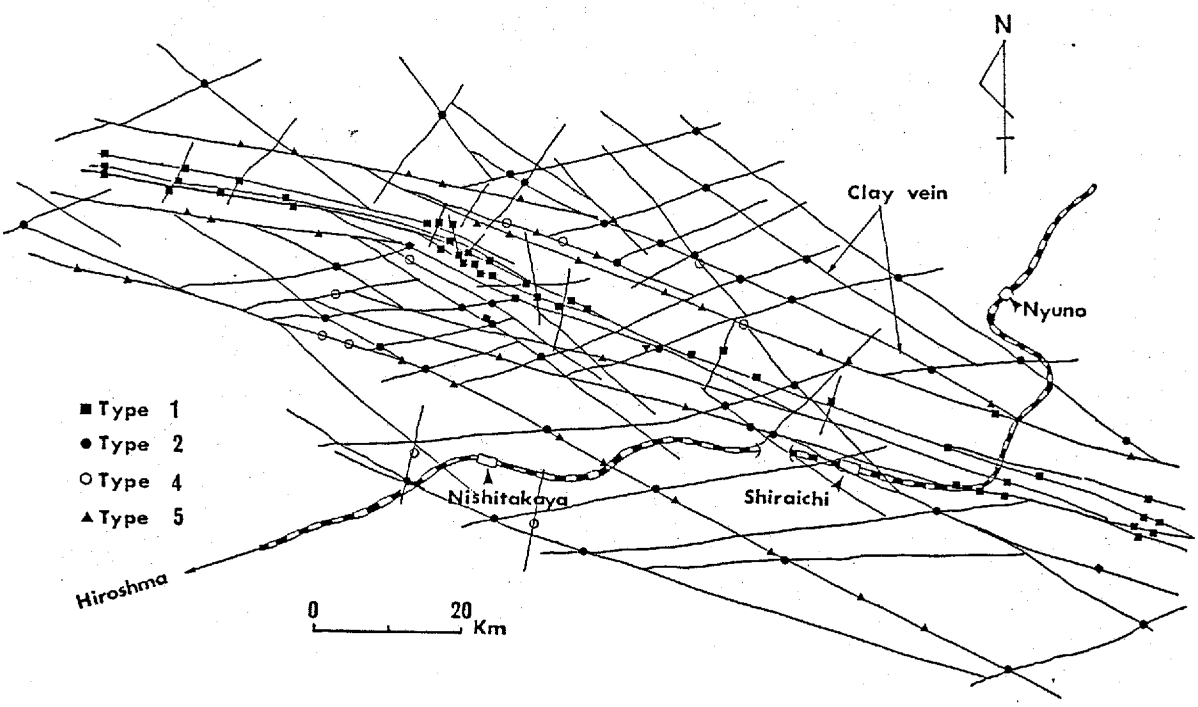
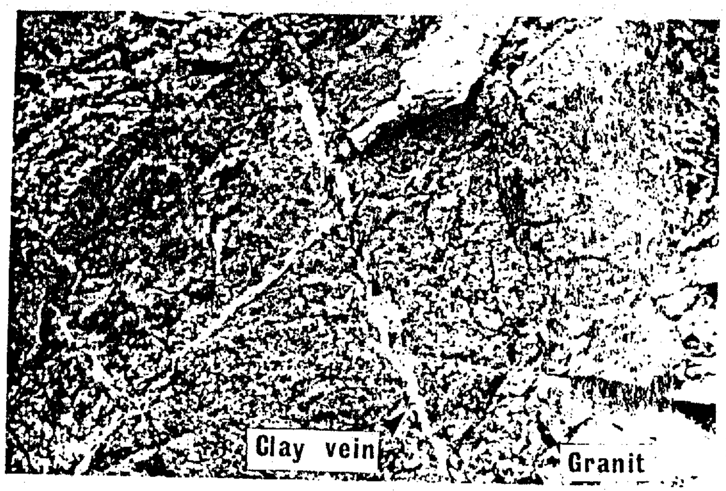
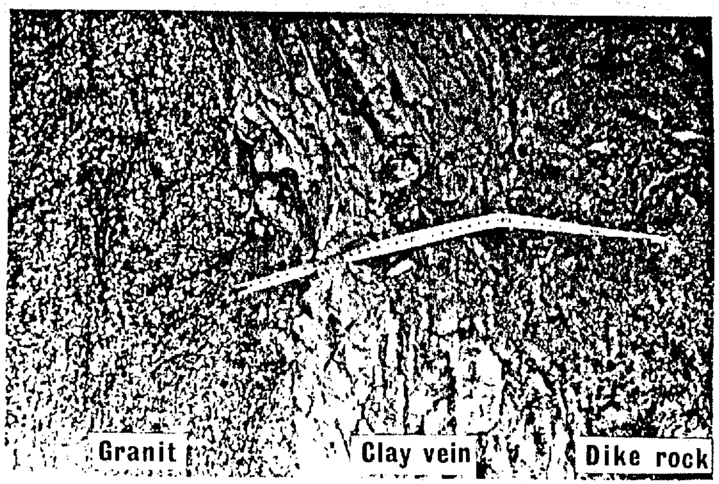


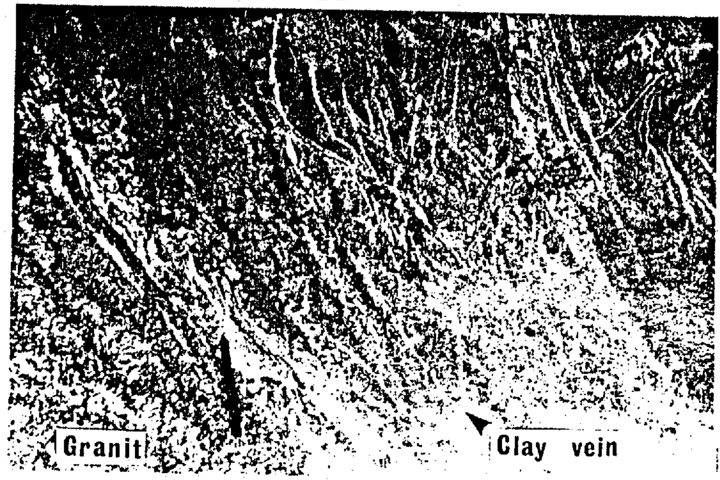
Fig. 2. Developments of clay veins of Types 1,2,4 and 5 in Kamo district, Hiroshima Prefecture.



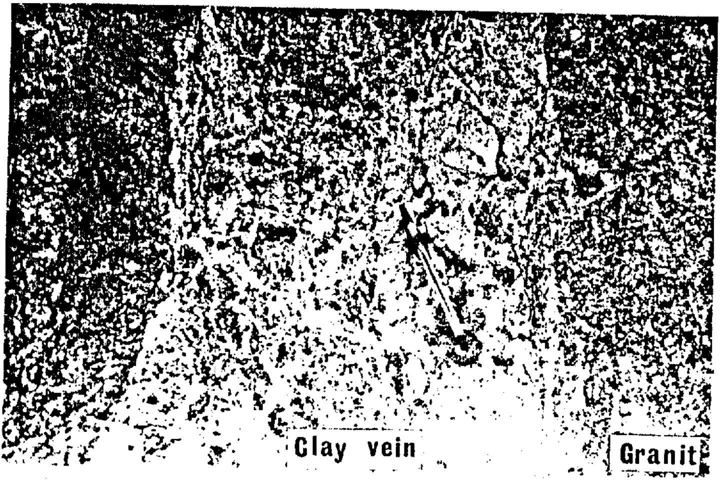
Type 2



Type 1



Type 4



Type 5

Plate 1. Mode of occurrence of clay veins.

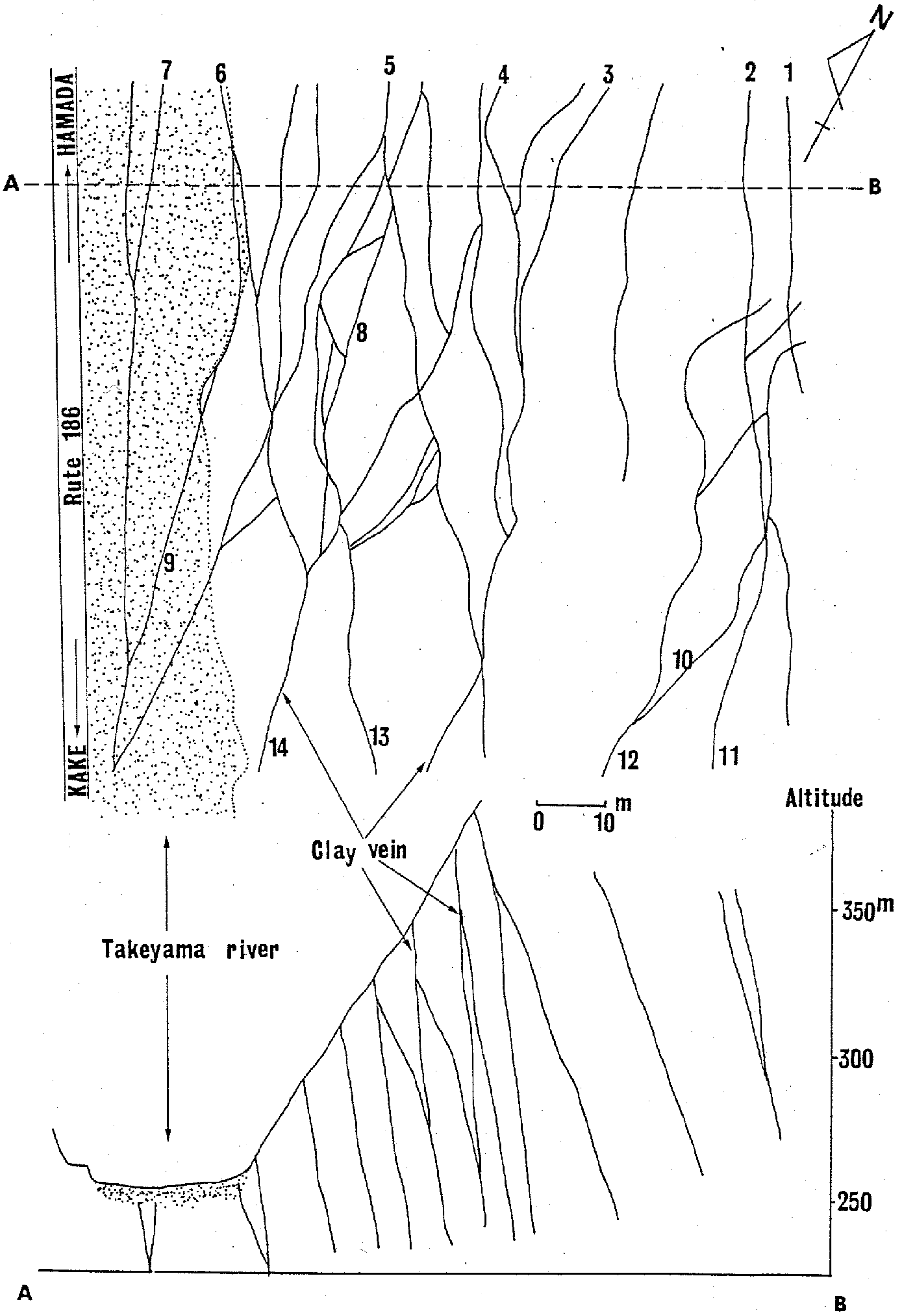


Fig. 3. Developments of clay veins at Nukui, Kake-cho, Hiroshima Prefecture.

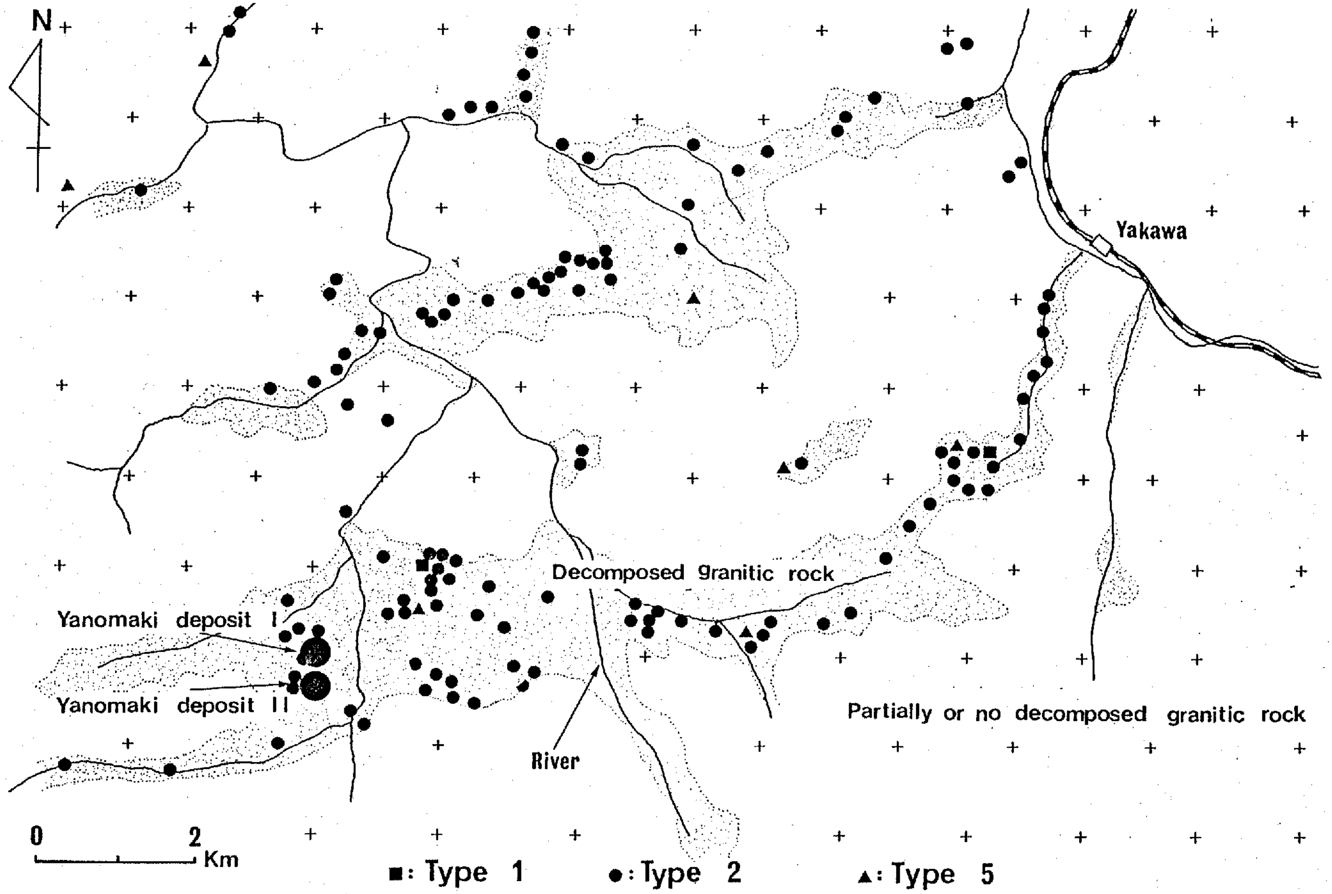


Fig. 4. Distribution of clay veins in granitic rocks in Yokota district, Shimane Prefecture.

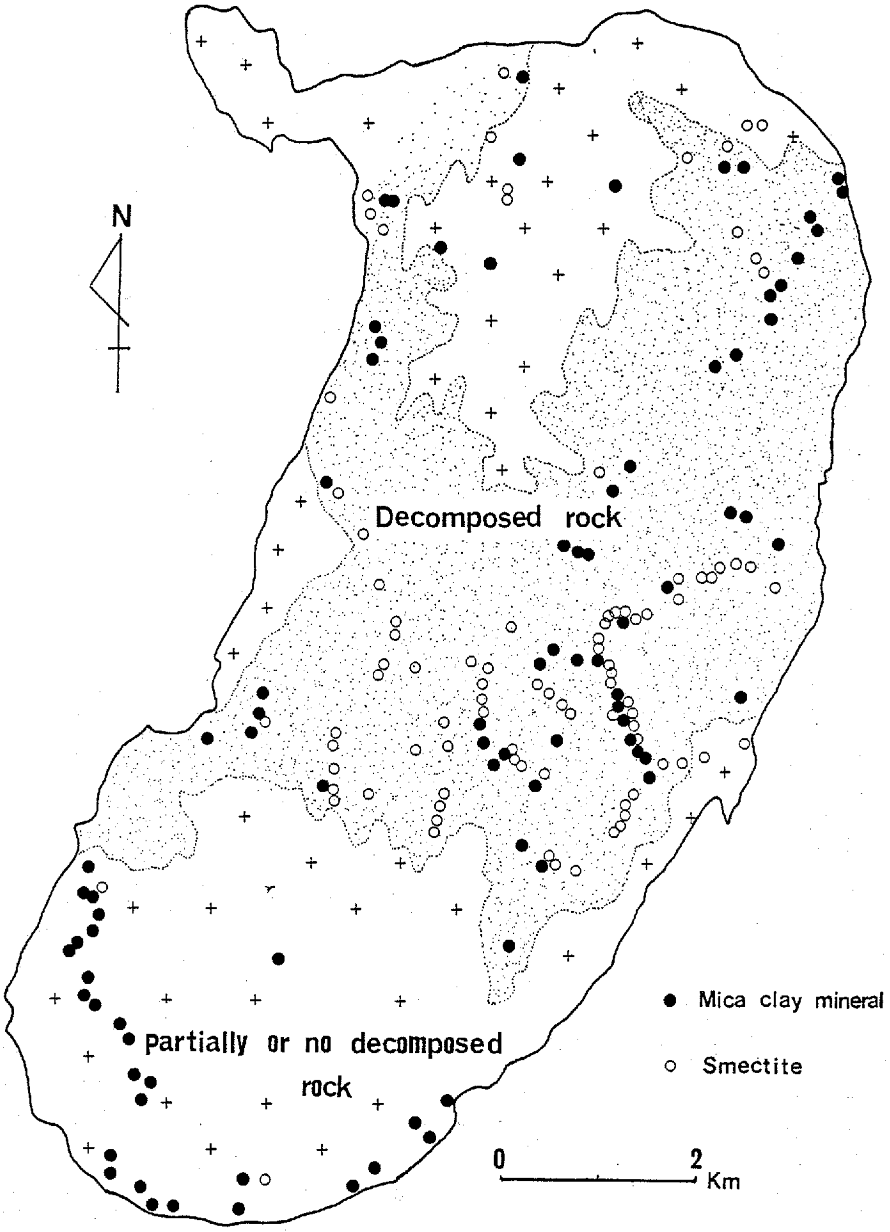


Fig. 5. Distribution of clay veins (mica clay mineral and kaolin mineral) in the Kumogi granite mass in Kanagi district, Shimane Prefecture.

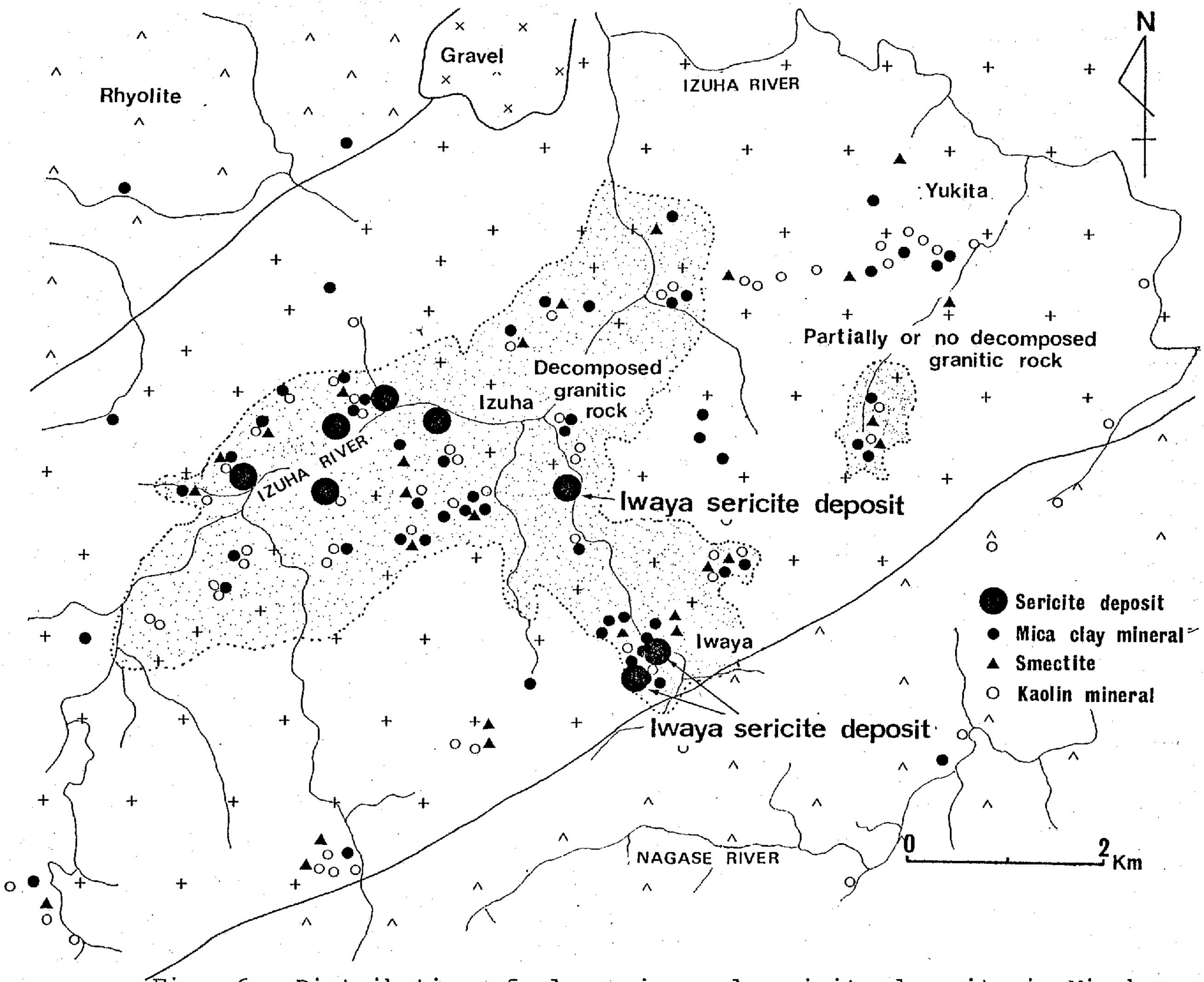


Fig. 6. Distribution of clay veins and sericite deposits in Mizuho district, Shimane Prefecture.

kaolin mineral and the other is mica clay mineral (sericite). All of these clay deposits were formed by hydrothermal conditions (Minato and Takano, 1952 ; Iwao, 1953; Matsumoto, 1965; Minato, 1969; Kitagawa and Kakitani, 1979b; Kitagawa et al., 1982; Kitagawa and Kameoka, in press).

Sericite deposit:

There occur sericite deposits which have been worked by underground mining in the Mitoya and Mizuho districts, Shimane Prefecture. As shown in Fig. 8, many small sericite deposits are concentrated in an area of the Mitoya district (about 4 x 8km). These deposits occur as lenticular mass of several meters in width and less than 100m in length, and as fissure-filling within the Palaeogene granitic rocks. These deposits are arranged along certain directions which are similar to those of clay veins (mainly types 2 and 5) developed in the district, as are seen in Fig. 8.

The deposits in the Mizuho district, on the other hand, occur as fissure fillings of nearly perpendicular fissures of about 1 to 2m width (Fig. 9). The orientation of clay veins developed in this district are almost similar to those of clay deposits.

There are two halloysite deposits which are sharply bordered from the host rocks, working by open pit mining in the Yokota district, Shimane Prefecture (Yanomaki or Komaki halloysite deposit). The two ore deposits are about 60m x 30m and 100m x 40m lenticular form, respectively. Both deposits occur as replacement products of fractured felcitic rocks in granitic rocks. The ores consist mainly of halloysite and kaolinite associated with sericite and smectite. Many clay veins (Type 2) of 1-50mm width are found within the both ore deposits (Plate 2-A). A number of clay veins of types 2 and 5 occur in the surrounding granitic rocks of the deposits.

In Khodachi district, Hiroshima Prefecture, the Khodachi kaolin deposit with lenticular form occurs in biotite granite. The deposit occurs as replacement products of the granitic rock. The ore body is about 250m in length and 100m in width, extending toward northeast. The ore consists mainly of kaolinite and halloysite.

The mode of occurrence of these clay deposits are very similar to that of clay veins, e.g., Types 2 and 5 veins. The only difference between them is the scale.

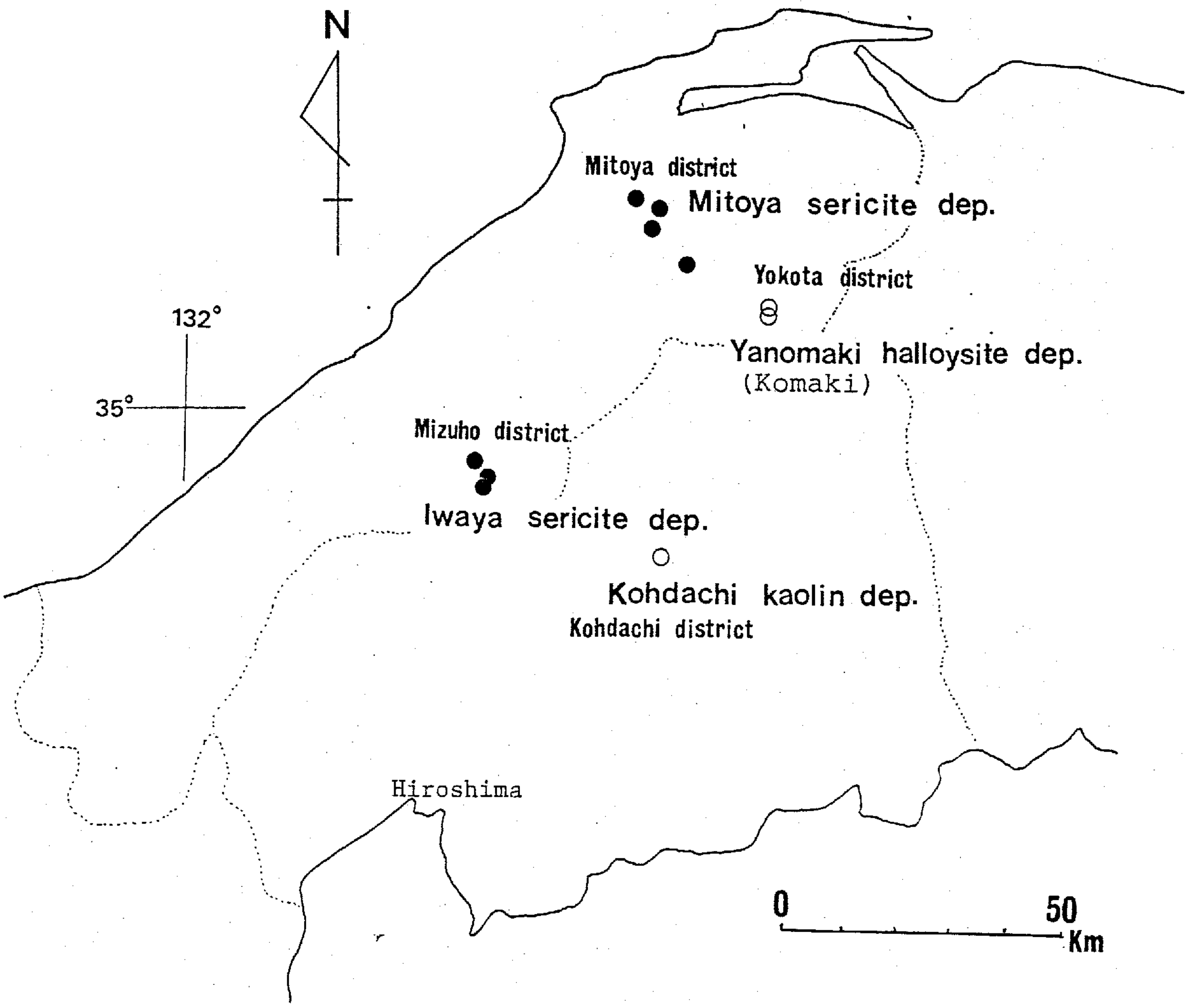


Fig. 7. Hydrothermal clay deposits in granitic rocks in Hiroshima and Shimane Prefectures.

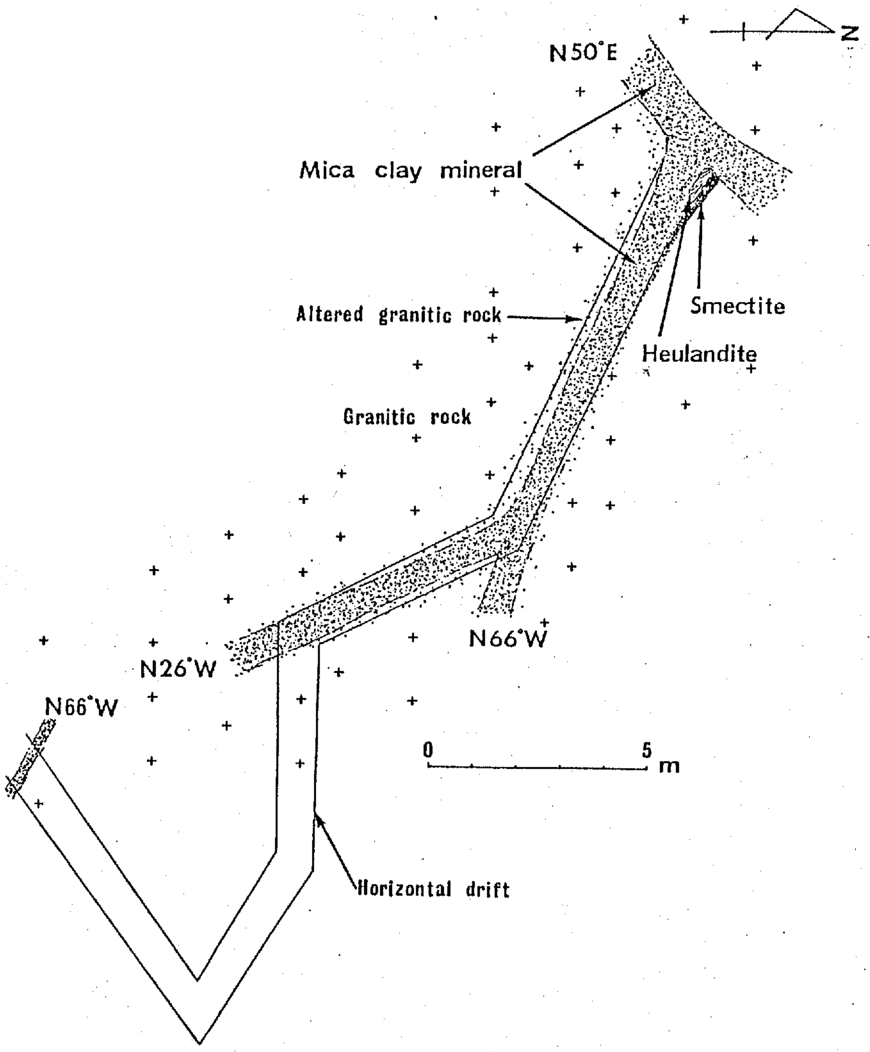


Fig. 9. Mode of occurrence of sericite deposit at Iwaya, Mizuho district, Shimane Prefecture.

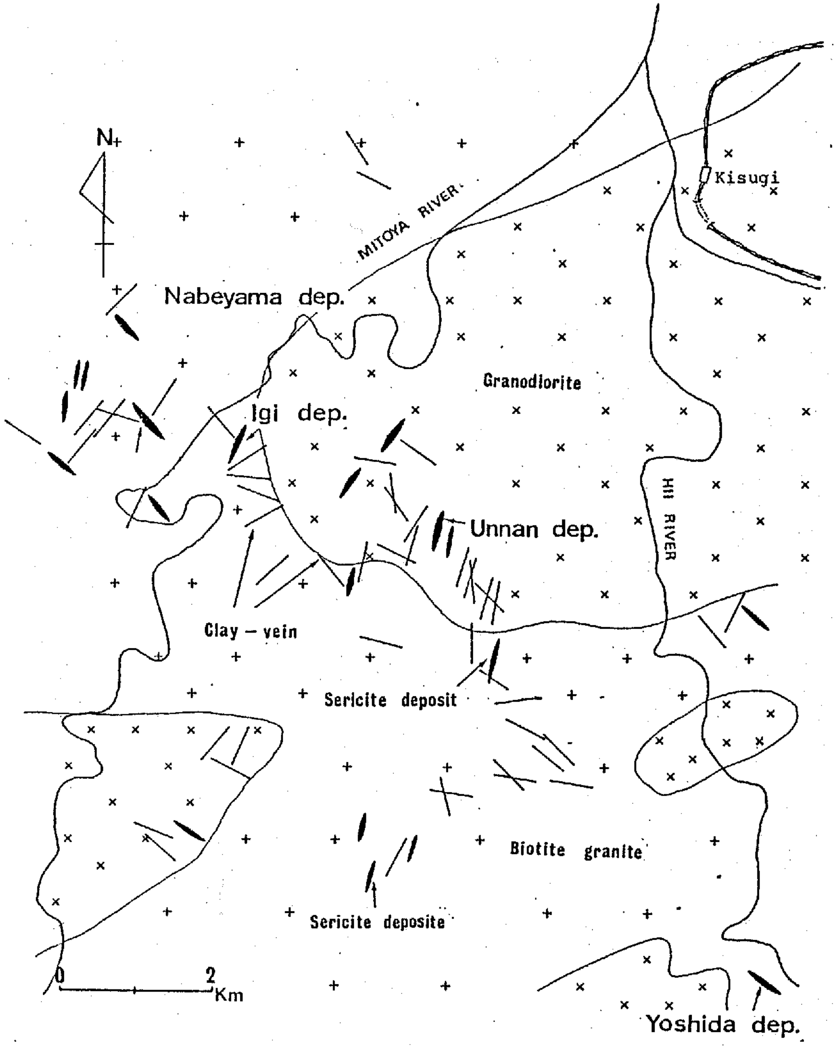


Fig. 8. Distribution and variation of strike of sericite ore bodies and clay veins in Mitoya district, Shimane Prefecture.

III. FRACTURES DEVELOPED IN GRANITIC ROCKS

Common developments of the clay veins in the granitic rocks may suggest that these fractures were formed in relation to the stress fields during the geological age as well as the cooling process of the granitic rocks. In order to confirm such possibilities, the orientation of the fractures (strike and dip) found in the granitic rocks and in and around the clay deposits were examined. In addition to these fractures, microcracks observed in the constituent minerals of the host granitic rocks under the microscope will be also examined from the same view points.

A. CLAY VEINS

Orientation of the fractures (Clay veins) show in general certain preferred directions if the area is limited. Based on the preliminary measurements of the strikes of the clay veins, the whole district of the granitic rocks are divided into 10 districts and the preferred orientations of the fractures of each district are shown in Fig. 10 and the results are summarized in Table 1. As is shown in the figure and the table, each district is characterized by two or three preferred orientations of the fractures. Concerning the significance of these, preferred orientations will be discussed later.

B. CLAY DEPOSITS

The relation between the distribution pattern of the clay deposits and preferred direction of the fractures were examined concerning several districts. First, clay

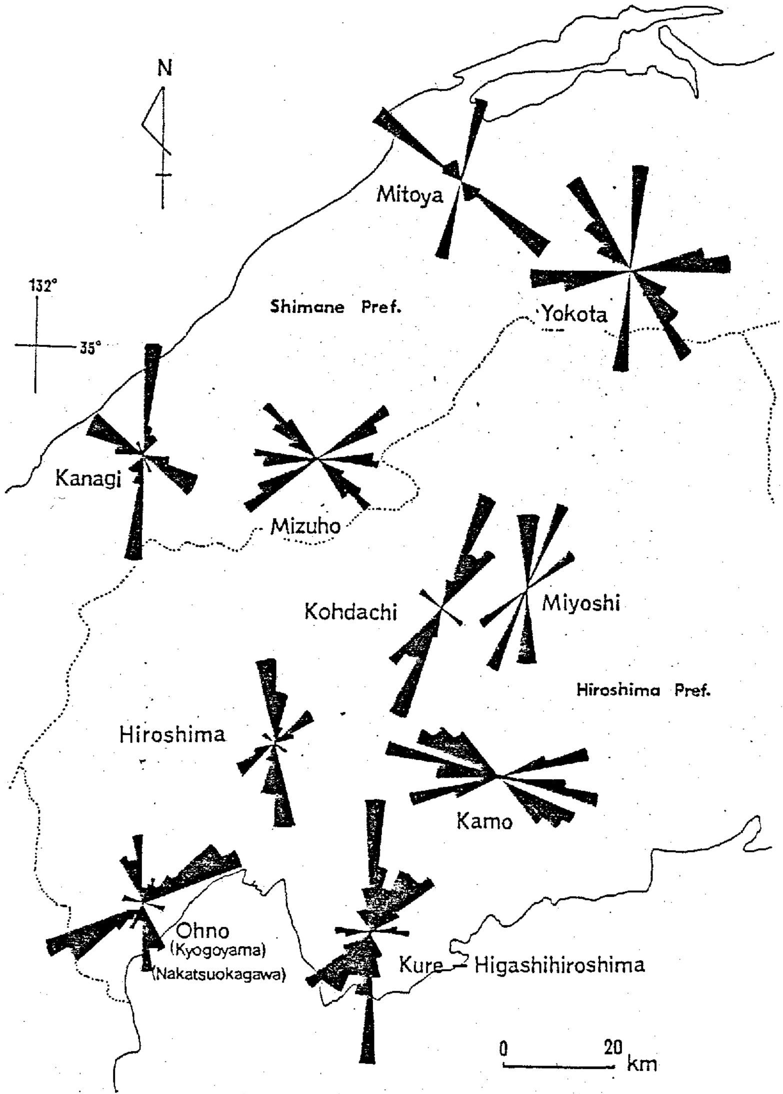


Fig. 10. Histgram of strike of clay veins distributed in Hiroshima and Shimane Prefectures.

District	Type	Strike	Dip
Kure-Higashihiroshima	2	N0°-20°E, E-W, N40°-70°E	70°-90°
Ohno	2	N0°-30°W, N40°-70°E	60°-90°
Hiroshima	2	N0°-10°E, N60°-80°E	60°-90°
Kamo	1, 5	N60°-90°W	70°-90°
	2	N50°-90°E, N40°-80°W	70°-90°
	3, 4	N50°-90°E, N40°-80°W	70°-90°
Kohdachi	5	N20°-60°E	70°-90°
Miyoshi	2, 3, 5	N-S, N20°-30°E, N50°-60°E	70°-90°
Mizuho	1	N40°-60°W, E-W	60°-90°
	2	N40°-70°E, N30°-70°W	60°-90°
	5	E-W	60°-90°
Kanagi	2, 4, 5	N0°-20°E, N50°-80°W	70°-90°
Yokota	2, 5	N30°-60°W, N0°-20°E, N80°-90°E	60°-90°
Mitoya	2, 5	N10°-20°E, N50°-60°W	70°-90°

Table 1. Strike and dip of clay veins in the respective districts.

deposits found in the Mitoya district develop along the two distinct directions, i.e., N50° - 60° W and N10° - 20° E as is seen in Fig. 8. It should be noted in the figure that the two directions coincide well with the dominant directions of the fractures (clay veins). In the Iwaya deposit (Mizuho district), the two preferred directions are also recognized, i.e., one is N10° - 70° W and the other is N50° - 70°E (Fig. 9). As is seen in Fig. 11, the two deposits of the Yanomaki(Komaki) mine located in the Yokota district are extended in the two directions, N20°E and N30°W. Clay veins found in both ore deposits and the district are developed in three directions, N0°- 20° E, N30 ° - 60°W and N80° - 90 °E. Clay veins developed in the district are also aligned on the three directions (Fig. 12). Kaolin deposit in the Khodachi district is elongated slightly in the direction of N50°E. The orientation of the fractures in the ore body is rather concentrated in the same direction. Almost all the fractures described above are nearly vertical and the preferred orientation of the veins is almost similar to those of clay deposits in the respective direction.

C. MICROCRACKS

Microscopic-microcracks developed in the constituent minerals of the host granitic rocks (mainly in quartz) were measured on the orientated thin sections of parallel and perpendicular to the ground surface using an universal stage attached to the microscope. The microscopic-microcracks are illustrated in Fig. 13 and some photographs of the

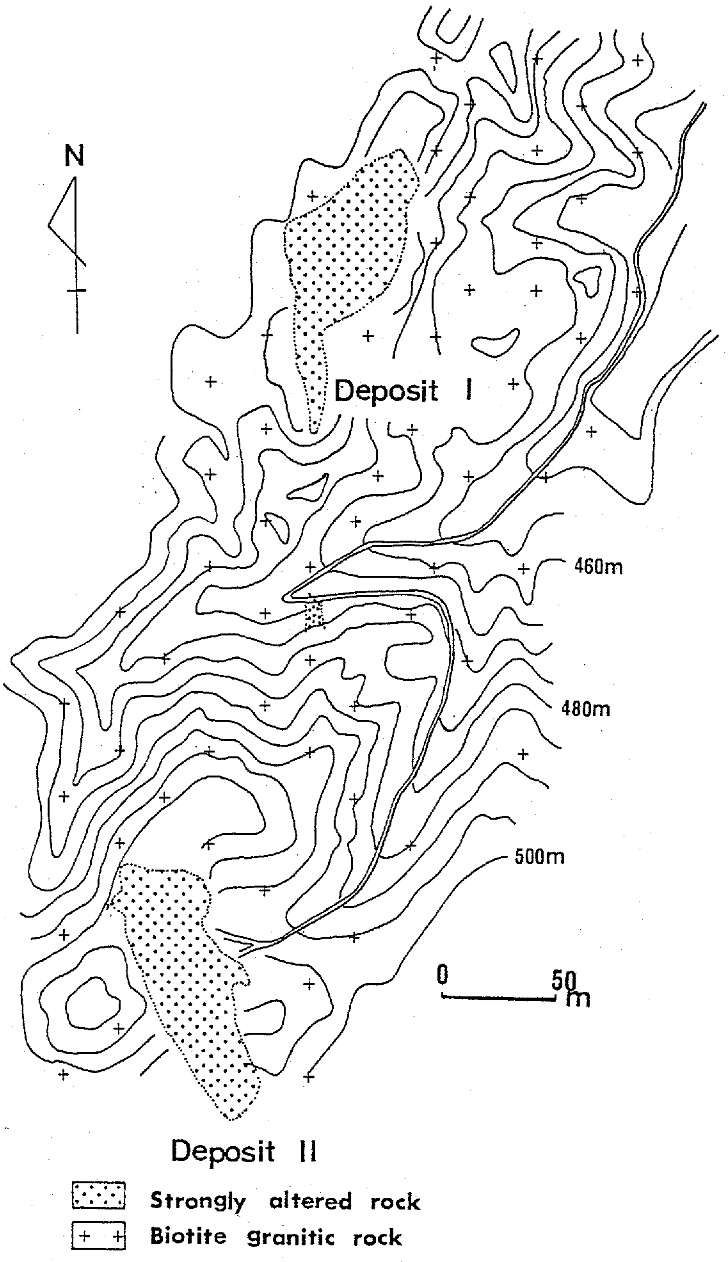
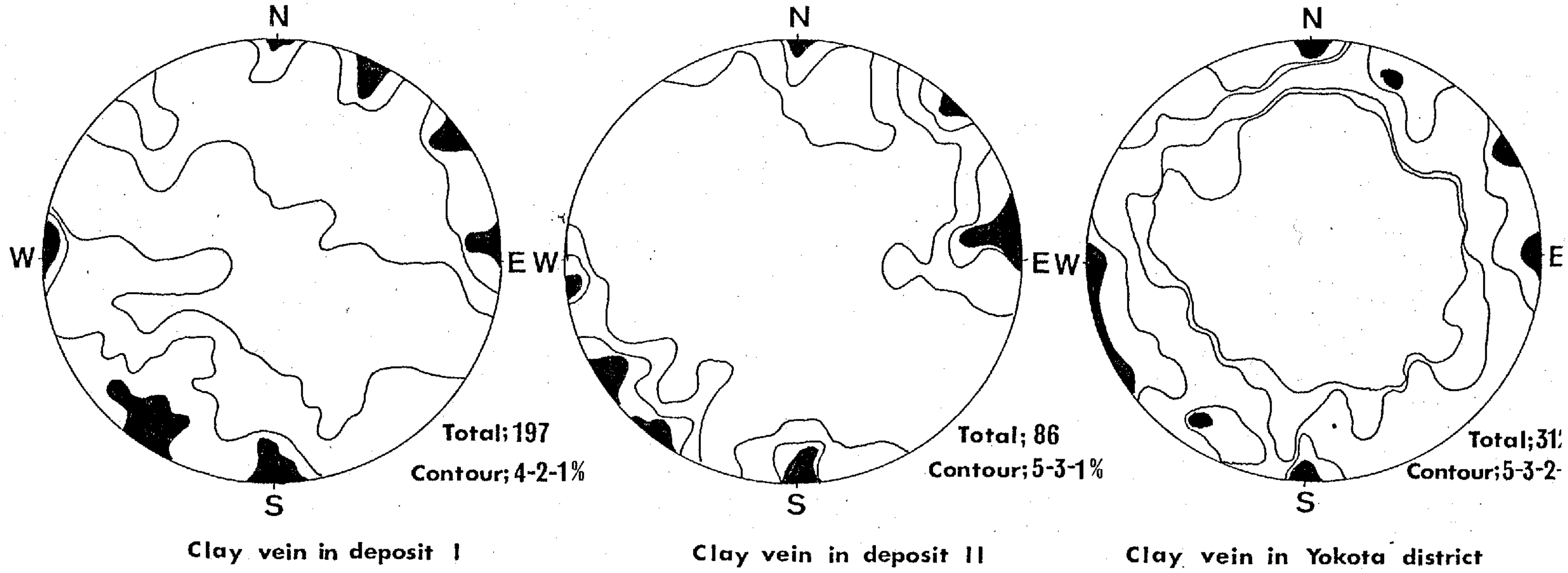


Fig. 11. Yanomaki (Komaki) halloysite deposits in Yokota district, Shimane Prefecture.



Clay vein in deposit I

Clay vein in deposit II

Clay vein in Yokota district

Fig. 12. Stereographs of clay veins in the Yanomaki (Komaki) halloysite deposits and the clay veins in the surrounding granitic rocks in Yokota district, Shimane Prefecture.

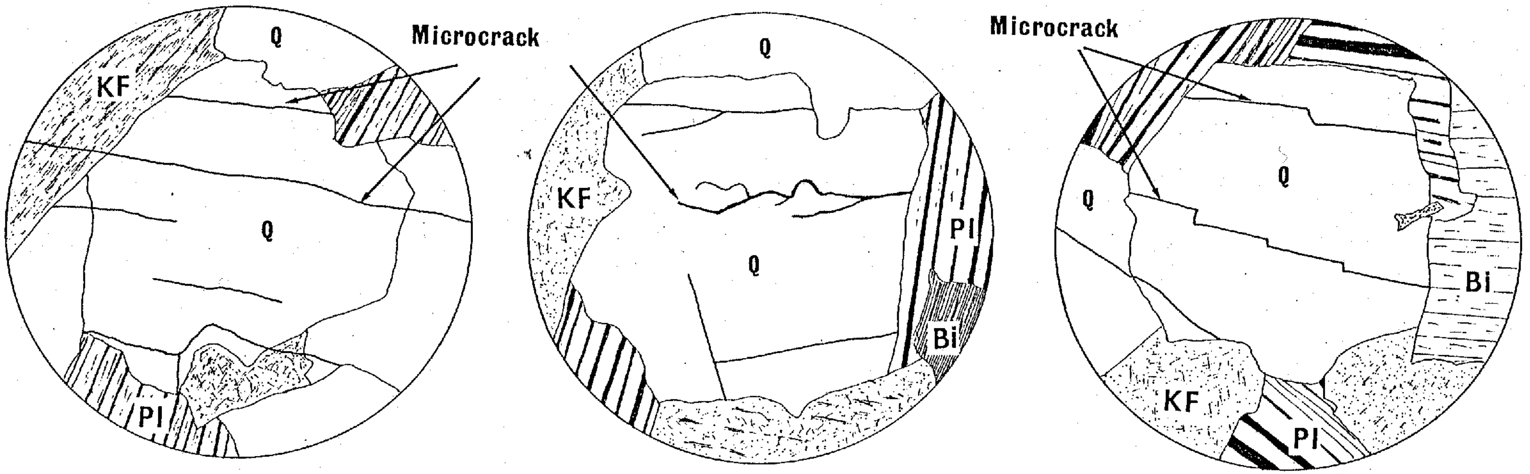
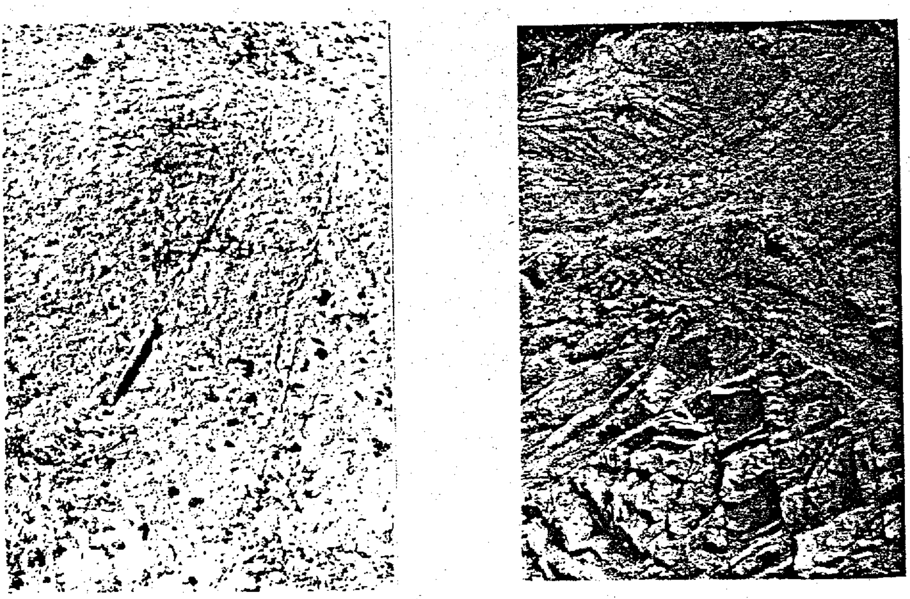
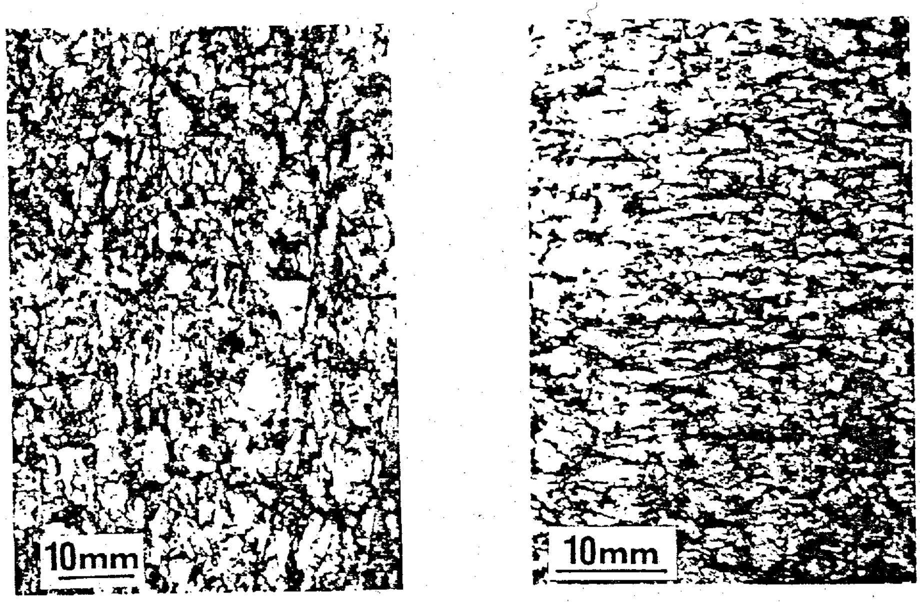


Fig. 13. The microcracks observed under the microscope.
Q: Quartz, KF: K-feldspar, Pl: Plagioclase, Bi: Biotite.



A. Clay veins in Yanomaki (Komaki) halloysite deposit (deposit I)

B. Fracture pattern in granitic rocks in Yokota district



C. Vertical microcracks in granitic rocks

D. Lateral microcracks in granitic rocks

Plate 2. Fractures developed in clay deposit and granitic rocks.

cracks are shown in Plates 2-C and D. Since the thin sections were prepared parallel and perpendicular to the ground surface, the orientation of microcracks could be measured only in the horizontal and vertical planes. It has been generally accepted that the microcracks developed on the vertical plane are caused by the unloading (Plate 2-C) (Okamura, 1965; Hashikawa and Miyahara, 1974; Hashikawa, 1978a, b and 1985). The poles of the orientation of the microcracks were measured on both planes and the results were plotted on the equal-area stereographic nets. The measurement was performed on the samples collected from three districts in Hiroshima Prefecture and results of the Kyogoyama in the Ohno district are shown in Fig. 14 as a typical example. As is seen in the figure, two concentrated directions whose dips are nearly vertical are recognizable, i.e., N0° - N30°W and N40° - 60°E. The results of the other two districts, one is Nakatsuokagawa in Ohno district and the other is the western part of Hiroshima city, two distinct dominant directions have been confirmed, N40° - 80°E in the former and N - S in the latter (Fig. 15). As was already stated, these directions are almost coincide with those of clay veins developed in the respective district (see, Figs. 14 and 15).

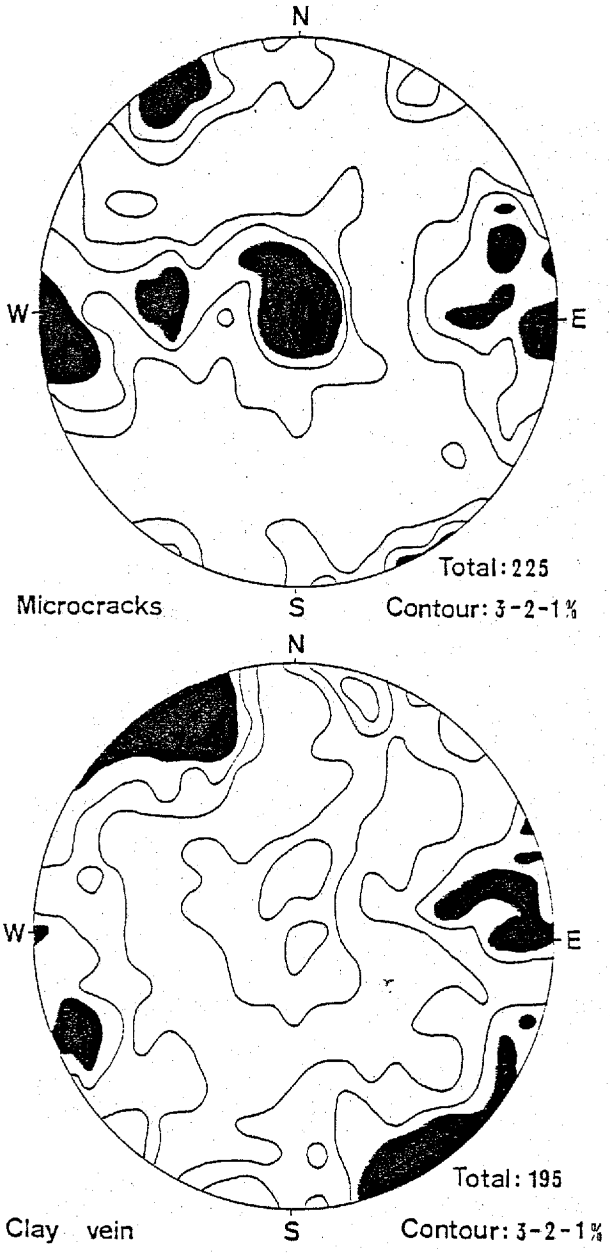


Fig. 14. Stereo diagram showing the preferred orientation of microcracks and clay veins in granitic rocks at Kyogoyama, Ohno district, Hiroshima Prefecture.

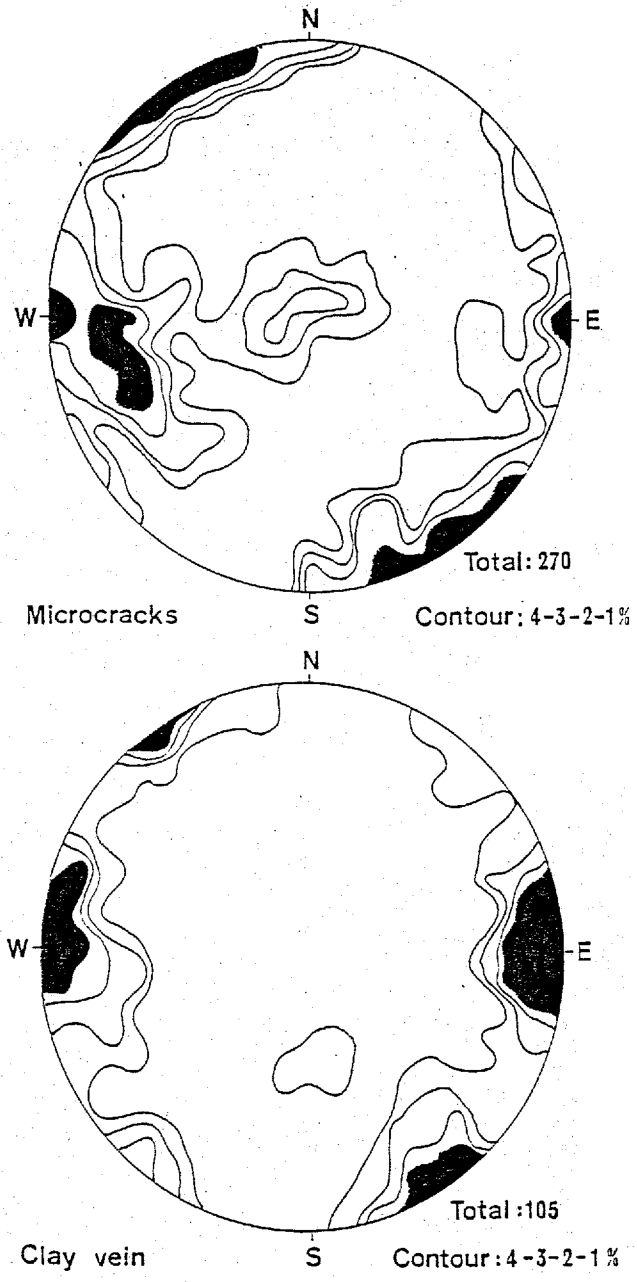


Fig. 15. Stereo diagram showing the preferred orientation of microcracks and clay veins in granitic rocks in Hiroshima district.

IV. CONSTITUENT CLAY MINERAL

The constituent clay minerals of the clay veins, the alteration products of plagioclase in the host granitic rocks and the clay deposits will be described in this chapter. Detailed procedures of the mineral identifications were already described in the previous papers (Kitagawa et al., 1978a, b, c, 1979a and 1981).

A. CLAY VEINS

The clay veins consist mainly of mica clay mineral(sericite), smectite, interstratified mineral of mica and smectite (mica/smectite), kaolin minerals (kaolinite and halloysite) associated with small amount of interstratified mineral of kaolin and smectite (kaolin/smectite) and chlorite. Quartz is commonly associated with clay minerals and calcite and/or zeolite (laumontite, stilbite and heulandite) are occasionally found in the clay veins. Most of the clay veins are composed of more than two kinds of clay minerals and the main mineral assemblages are presented in Table 2.

It is to be noted that the constituent minerals commonly change from the lower to the upper parts in the vertical direction of the veins. Typical examples are shown in Fig. 16. In a vein at Kure City, the constituent mineral changes gradually from mica clay mineral to interstratified mineral (mica/smectite) from the lower to the upper parts of the vein within only 3m. In a vein at Kurahashi-cho (middle in Fig. 16), interstratified mineral

	Main constituent clay mineral	Associated clay mineral
Frequent occurrence	Kaolin mineral	
	Kaolin mineral	Smectite
	Smectite	
	Smectite	Kaolin mineral
	Smectite	Mica clay mineral
	Mica clay mineral	
	Mica clay mineral	Smectite
Common occurrence		
	Kaolin mineral	Mica clay mineral
	Smectite	Mica/Smectite
	Smectite	Mica clay mineral, Kaolin mineral
	Mica/Smectite	
	Mica/Smectite	Mica clay mineral
	Mica/Smectite	Smectite
	Mica clay mineral	Kaolin mineral
	Mica clay mineral	Smectite, Kaolin mineral
Uncommon occurrence		
	Smectite	Chlorite
	Mica clay mineral	Chlorite
	Mica/Smectite	Kaolin mineral
	Mica/Smectite	Smectite, Kaolin mineral
	Kaolin mineral	Smectite, Mica clay mineral

Table 2. Mineralogical assemblages of clay minerals in clay veins.

(mica/smectite) and smectite from the lower to the upper parts. In Mirasaka-cho, smectite, interstratified mineral (kaolin/smectite) and kaolin mineral from the lower part to the upper parts. The variation of the main constituent clay minerals of the veins in the vertical direction has been fully confirmed at the Nukui dam-site, Kake-cho, Yamagata-gun in Hiroshima Prefecture. As is obvious in Fig. 17, the main constituent mineral of the each vein changes from mica clay mineral in the relatively lower altitude to smectite in the higher altitude passing through the interstratified minerals of mica and smectite in the middle altitude. The constituent clay minerals of the veins developed in the Kumogi granite mass, Kanagi district, Shimane Prefecture vary markedly from mica clay mineral to kaolinite as is evident in Fig. 18, the former distributes mainly at the lower level while the latter at the relatively higher level.

The regional variation of the constituent minerals was examined in the Kure-Higashihiroshima district. Mica clay mineral is observed at the relatively lower level (less than 200m) while kaolin minerals at the higher level in the Kure district (0-500m in altitude). In the Higashihiroshima district, on the other hand, smectite is restricted at the lower level of less than 300m altitude, whereas kaolin minerals distribute at all the levels.

Based on the facts described above, it may be concluded that the main constituent mineral of the veins varies from

mica clay mineral to interstratified minerals of mica and smectite, smectite and kaolin minerals from the lower to the higher altitudes in the range between 400m and 800m (Fig. 19). Between the zones of smectite and kaolin minerals, interstratified minerals of kaolin and smectite is observable in some places. Moreover, within several meters of a vein, change of the clay mineral is recognizable. As is shown in Fig. 20, the constituent clay mineral of the veins found in the granitic rocks varies from place to place, i.e., each district has its characteristic constituent minerals as are summarized in Table 3. This is mainly because of the difference of the level of the respective outcrops situated
as seen in Fig. 19.

B. CLAY DEPOSITS

I. MITOYA SERICITE DEPOSITS

Concerning the clay minerals of the sericite (mica clay mineral) deposits of the district, the author has already reported in detail, especially on the ores of the Nabeyama and Igi deposits (Kitagawa et al., 1982). That is, the ores are composed mainly of mica clay mineral(sericite) with a small amount of kaolinite, smectite, chlorite and interstratified minerals of mica and smectite.

2. IWAYA SERICITE DEPOSITS

As is seen in Fig. 9, Iwaya deposit is in vein-form and the ores are consist of mostly mica clay mineral with a small amount of smectite.

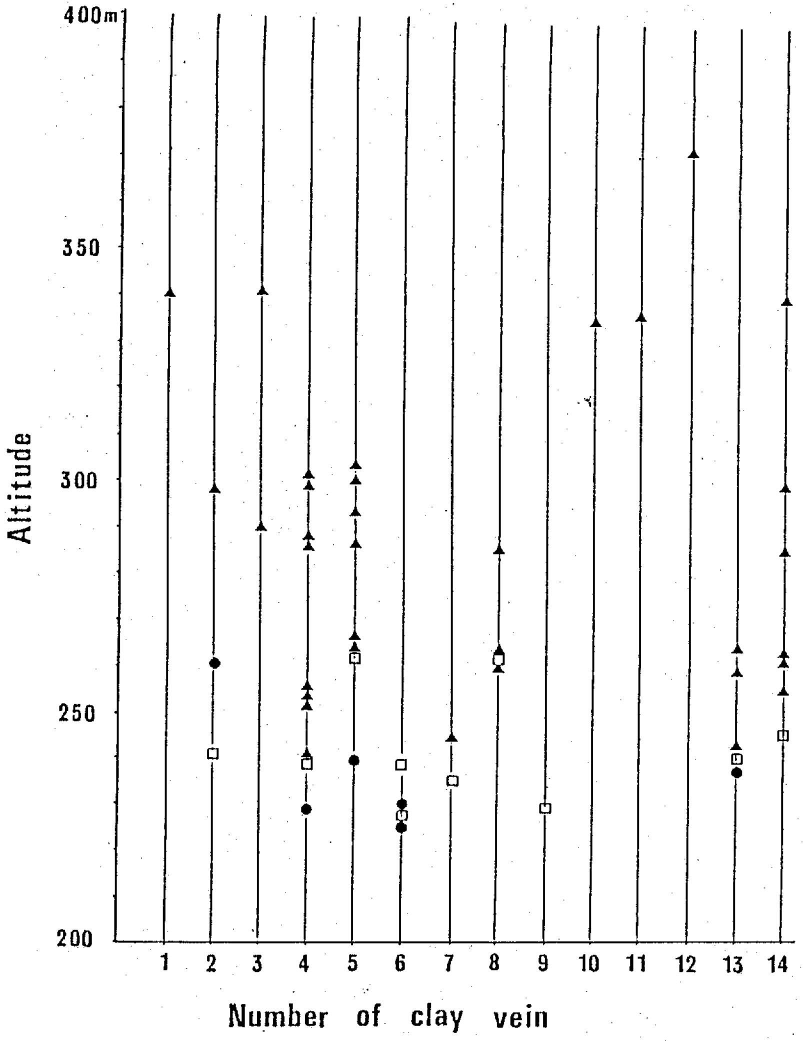


Fig. 17. Variation of main constituent clay minerals of clay veins in the vertical direction at Nukui, Kake-cho, Hiroshima Prefecture. Numbers of clay veins are same as those of Fig.3

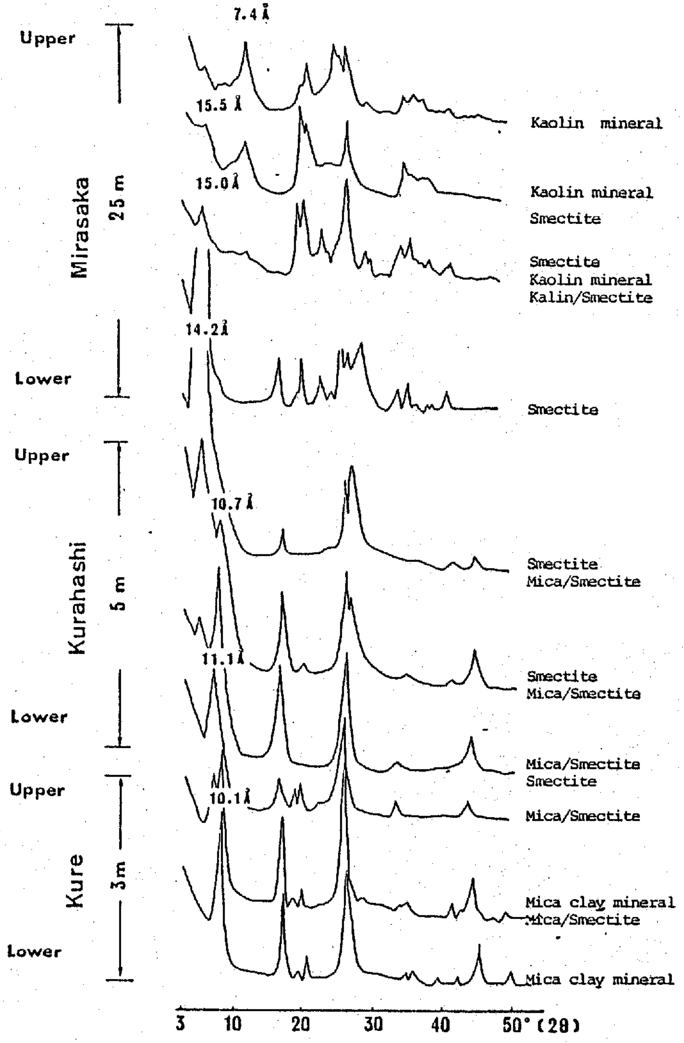


Fig. 16. X-ray powder diffraction patterns of clay minerals collected from clay veins at Kure, Kurahashi and Mirasaka, Hiroshima Prefecture.

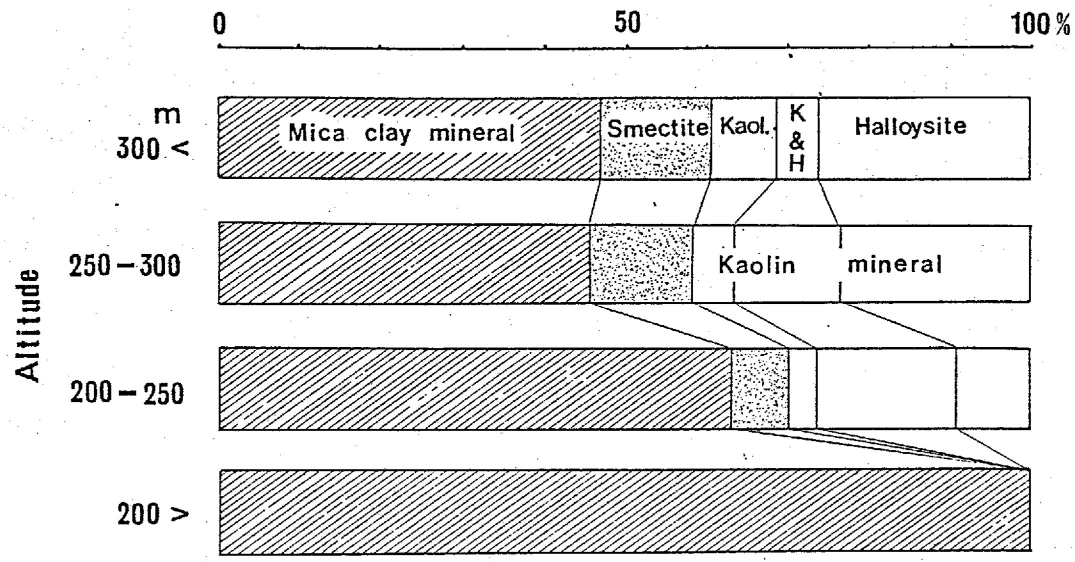


Fig. 18. Vertical variation of constituent clay minerals of clay veins in the Kumogi granite mass in Kanagi district, Shimane Prefecture.

District	Main constituent clay mineral	Altitude (m)
Kure	Mica clay mineral, Smectite	0 - 500
Higashihiroshima	Kaolin mineral, Smectite	100-500
Ohno	Kaolin mineral, Smectite	0 - 600
Hiroshima	Smectite, Mica clay mineral	0 - 400
Kamo	Mica clay mineral, Smectite	200-400
Kohdachi	Kaolin mineral	150-350
Miyoshi	Kaolin mineral, Smectite	200-300
Mizuho	Mica clay mineral, Smectite, Kaolin mineral	300-550
Kanagi	Mica clay mineral, Kaolin mineral	150-350
Yokota	Smectite, Kaolin mineral	400-600
Mitoya	Mica clay mineral, Smectite	100-300

Table 3. Main constituent clay minerals in respective districts.

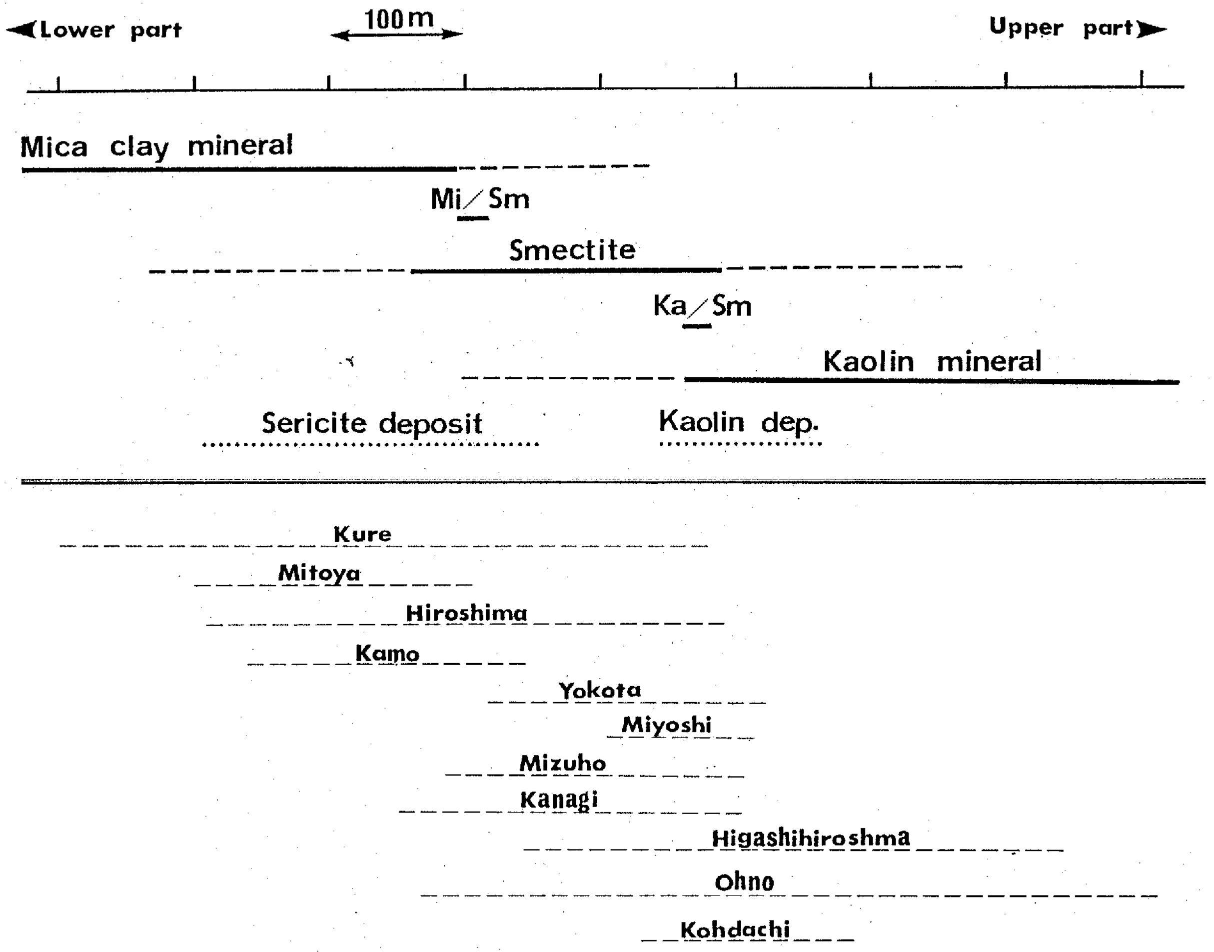


Fig. 19. Schematic diagram showing variation of constituent clay mineral of clay veins in the vertical direction.

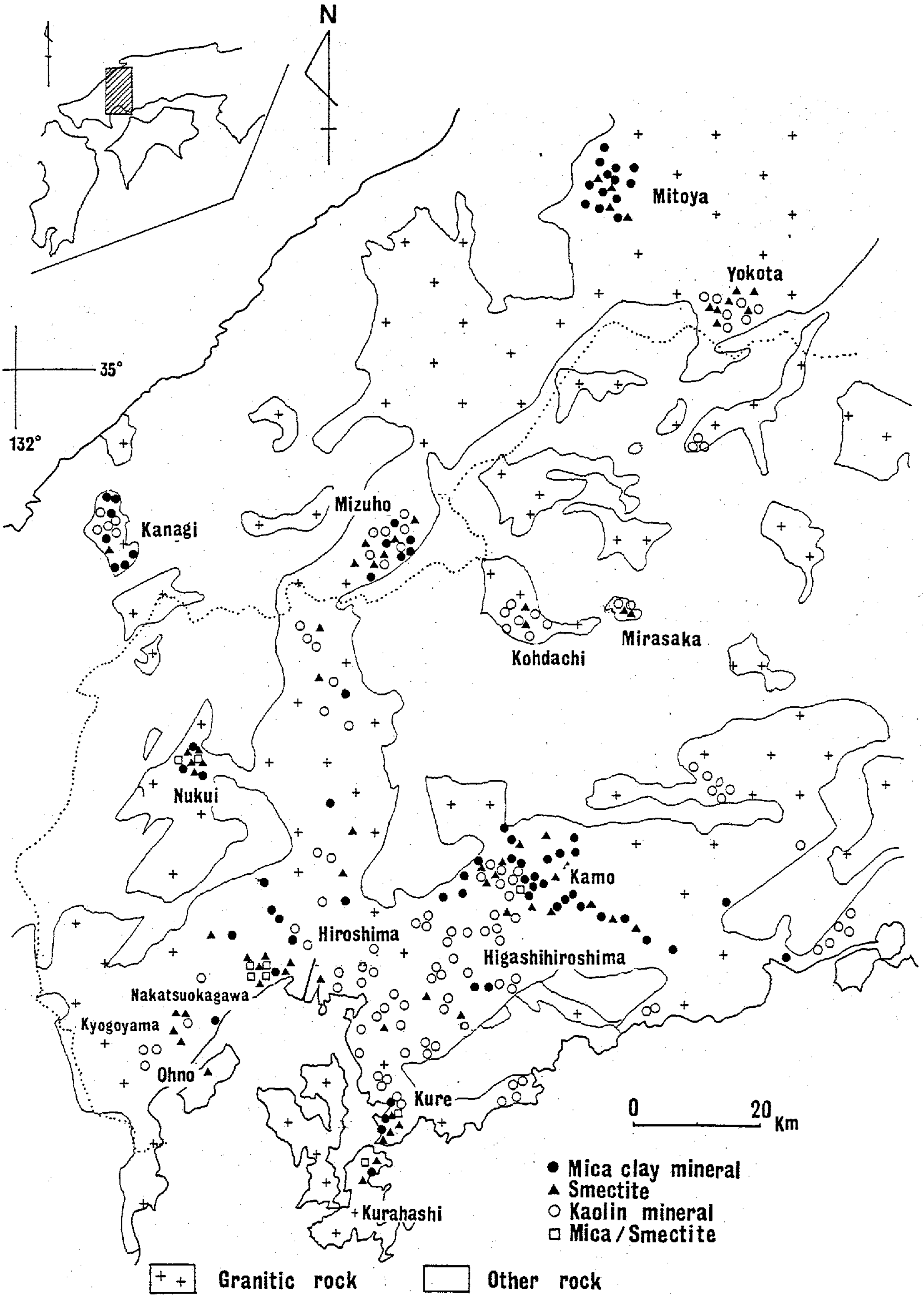


Fig. 20. Distribution of clay veins and their main constituent clay mineral in granitic rocks in Hiroshima and Shimane Prefectures.

3. KOHDACHI KAOLIN DEPOSIT

The ore of the Kohdachi kaolin deposit is composed mainly of kaolinite and halloysite with a small amount of mica clay mineral. Moreover, the deposit can be divided clearly into two zones as to the mineral assemblages: one is kaolinite zone and the other kaolinite-halloysite zone (Kitagawa and Kakitani, 1979b).

4. YANOMAKI(KOMAKI) HALLOYSITE DEPOSIT

The Yanomaki deposit is composed of two ore bodies with sharp boundaries to the host granitic rock. The clay minerals of the ore are composed of halloysite, kaolinite and mica clay mineral associated with a small amount of smectite. Based on the mineral assemblage, the ore body can be divided into three zones, i.e., the central halloysite zone through the halloysite-kaolinite zone and the marginal zone of kaolinite-mica clay mineral.

The constituent clay minerals of these clay deposits are summarized in Table 4.

C. CLAY MINERALS DERIVED FROM PLAGIOCLASE

Among the constituent minerals of the host granitic rocks, plagioclase is easily altered to clay minerals as well as biotite. In general, the mineral in question alters directly to kaolin minerals (kaolinite and halloysite) under the weathering conditions (Nagasawa and Kunieda, 1970; Kitagawa and Kakitani, 1977a; Nagasawa, 1978; Tsuzuki, 1985). However, plagioclase in the granitic rocks

	Clay deposit			
	Mitoya sericite deposit	Iwaya sericite deposit	Kohdachi kaolin deposit	Yanomaki halloysite deposit
Halloysite			+ + +	+ + +
Kaolinite	+		+ + +	+ +
Smectite	+	+	+	+
Mica/Smec.	+			
Mica clay	+ + +	+ + +	+	+ +
Chlorite	+			

+++: abundant, ++: moderate, +: minor

Table 4. Constituent clay minerals of clay deposits in granitic rocks in Hiroshima and Shimane Prefectures

of the district of the present study is often altered to mica clay mineral, smectite and interstratified mineral together with or without kaolin minerals. Several typical examples will be described below.

General tendency of the alteration of plagioclase to clay minerals in the granitic rocks are shown in Figs. 21, 22 and 23. As is evident in Fig. 21, in the Kumogi granite mass, Kanagi district, the northwestern parts whose altitude is relatively lower (180-250m), mica clay mineral is predominant whereas, in the central parts, relatively higher parts (250-350m), smectite is predominant. In the Yokota district, Shimane Prefecture, plagioclase alters to mica clay mineral, smectite and kaolin minerals (Fig. 22). Furthermore, as is clear in the figure, kaolin minerals are found mainly at the higher level, whereas mica clay mineral and smectite at the lower level. Regional variation of the alteration of the mineral in Hiroshima and Shimane Prefectures is represented in Fig. 23.

It may be concluded that plagioclase of the host granitic rocks alters commonly to mica clay mineral, smectite and kaolin minerals. It is to be noted that mica clay mineral prevails at the geographically lower parts, whereas kaolin minerals at the higher parts.

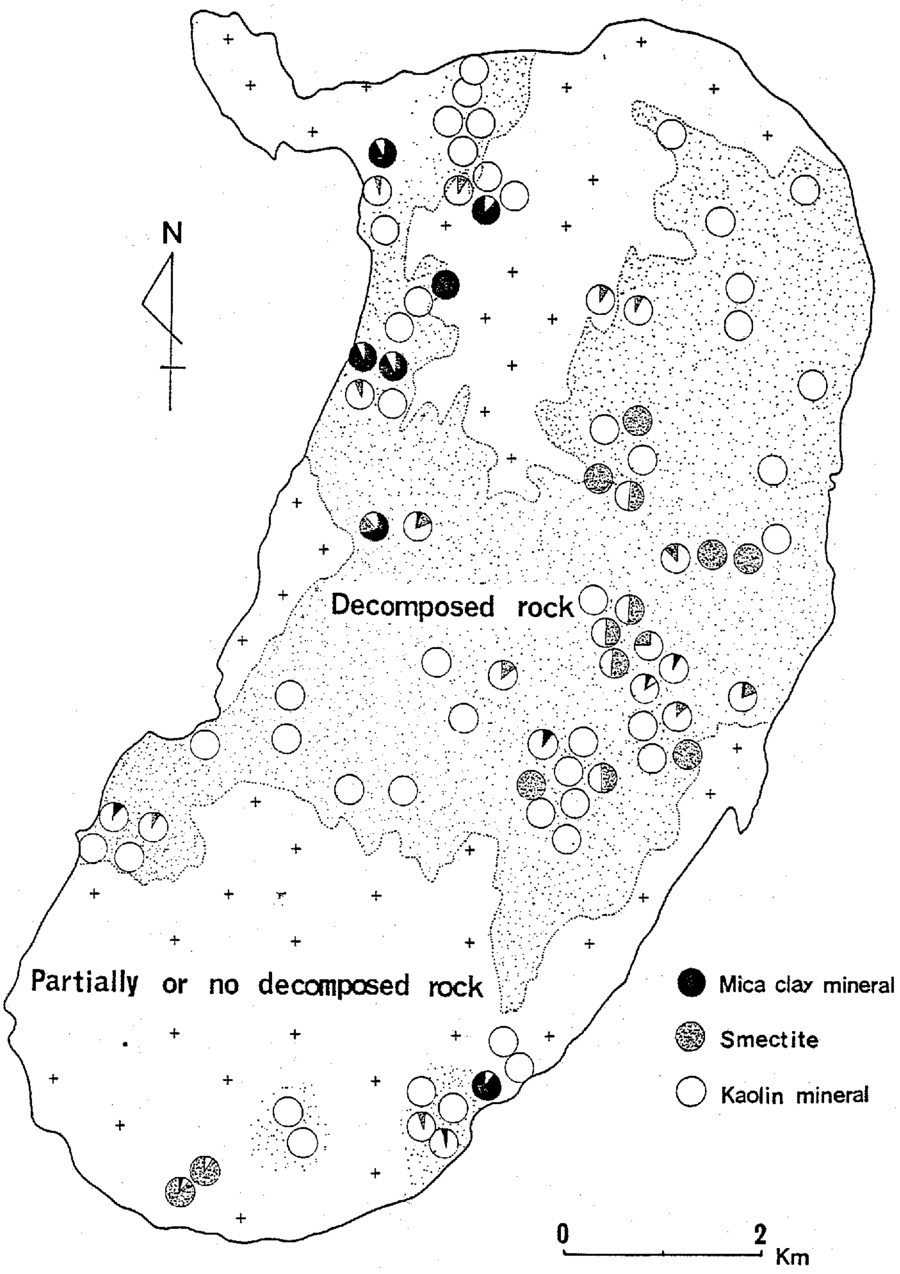


Fig. 21. Clay minerals altered from plagioclase in the Kumogi granite mass in Kanagi district, Shimane Prefecture.

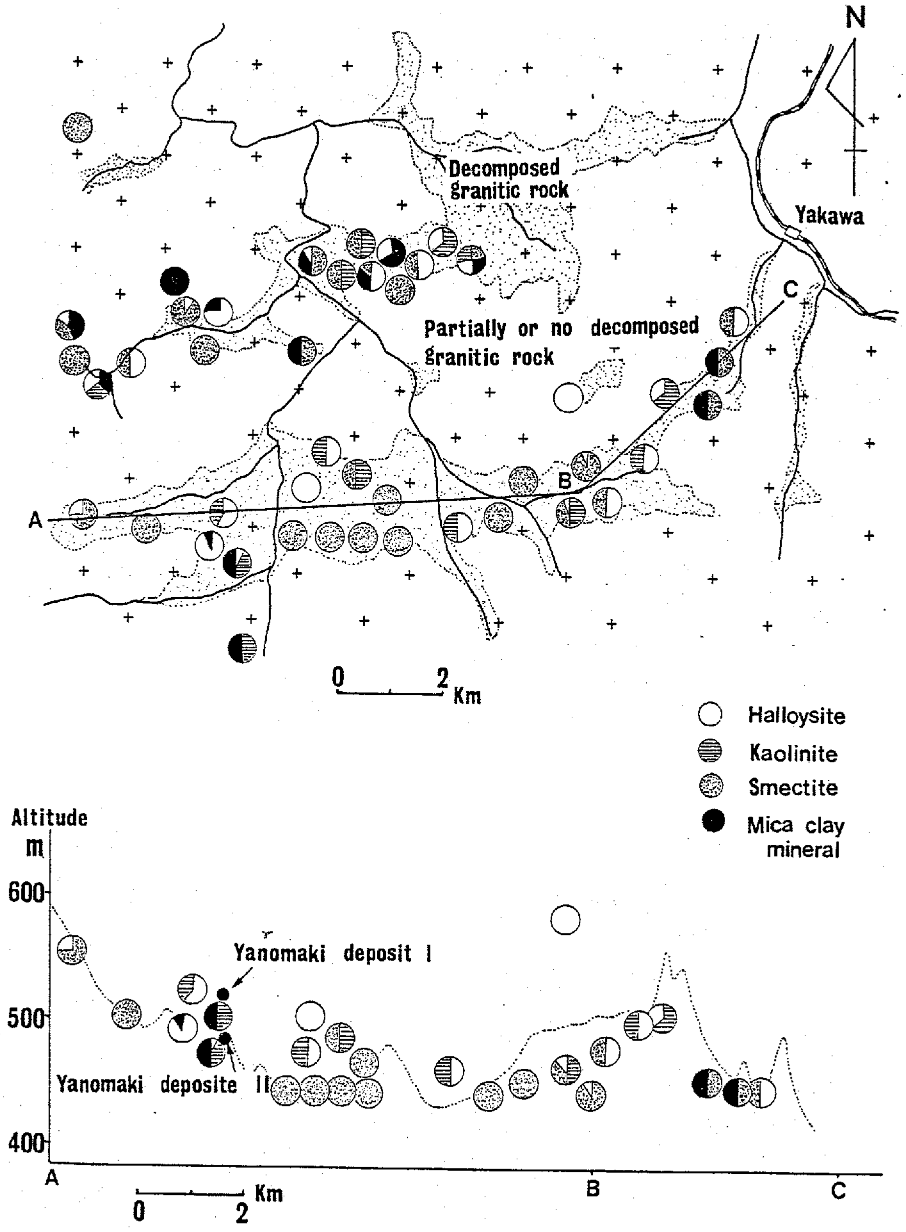


Fig. 22. Constituent clay minerals found in plagioclase in Yokota district, Shimane Prefecture.

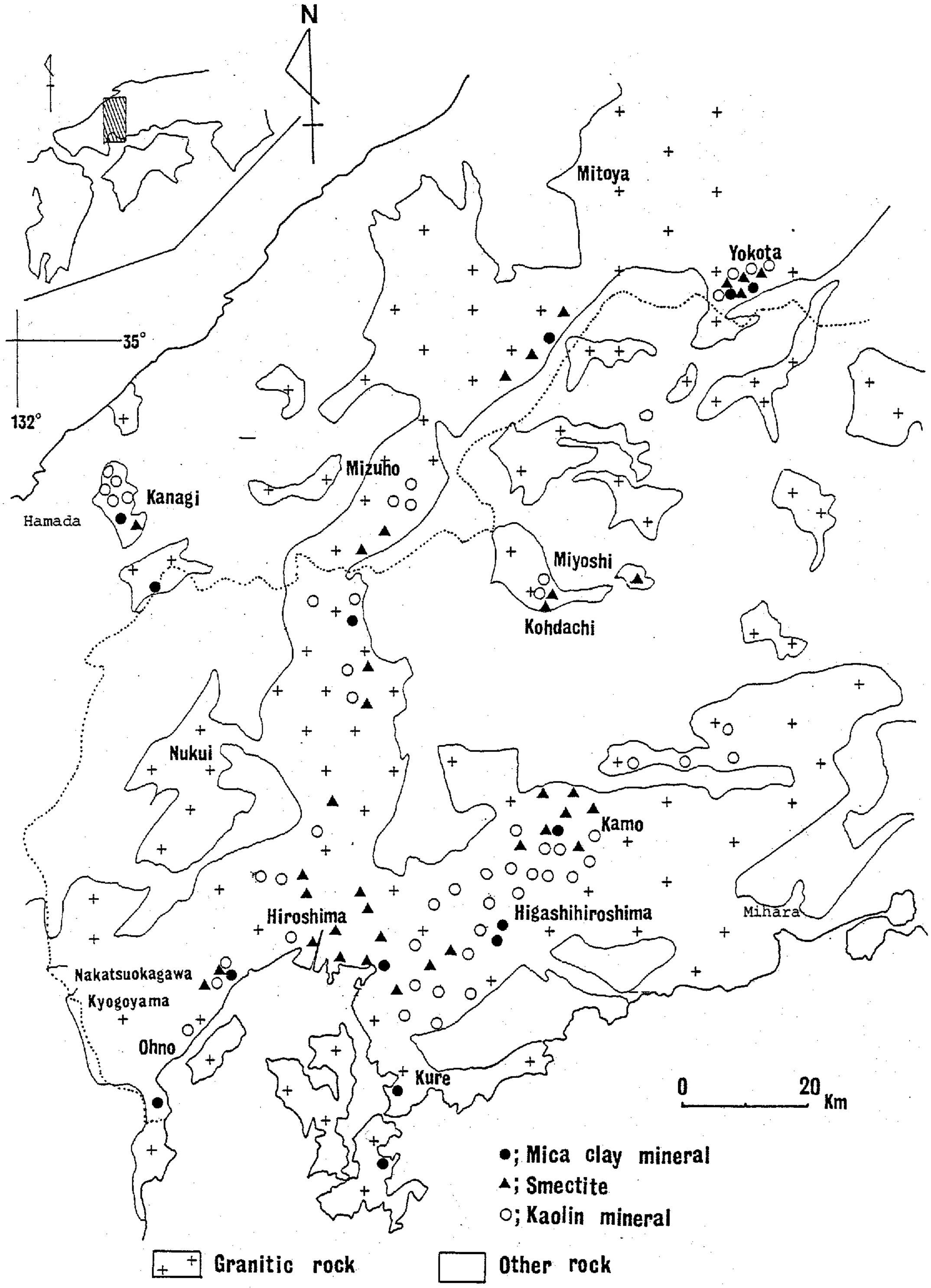


Fig. 23. Clay mineral found in plagioclase in granitic rocks distributed in Hiroshima and Shimane Prefectures.

V. MINERALOGICAL CHARACTERISTICS OF CLAY MINERALS

Concerning the clay minerals collected from various occurrences, the writer and his co-workers have reported some mineralogical characteristics such as filling temperature of fluid inclusion in calcite, hydrogen and isotopic composition, microtopographs of clay mineral crystals, morphology of halloysite, dehydration temperature of constituent water and suspention pH (Kitagawa and Kakitani, 1977a, 1978a, b, c; 1979; 1981; Kitagawa et al., 1981a, b; 1982; 1983; 1984). In Table 5, the main results are summarized with the difference of the mode of occurrence of clay minerals. Since these characteristics of the mineral are related intimately to the formation conditions of the mineral, the results will be described briefly below.

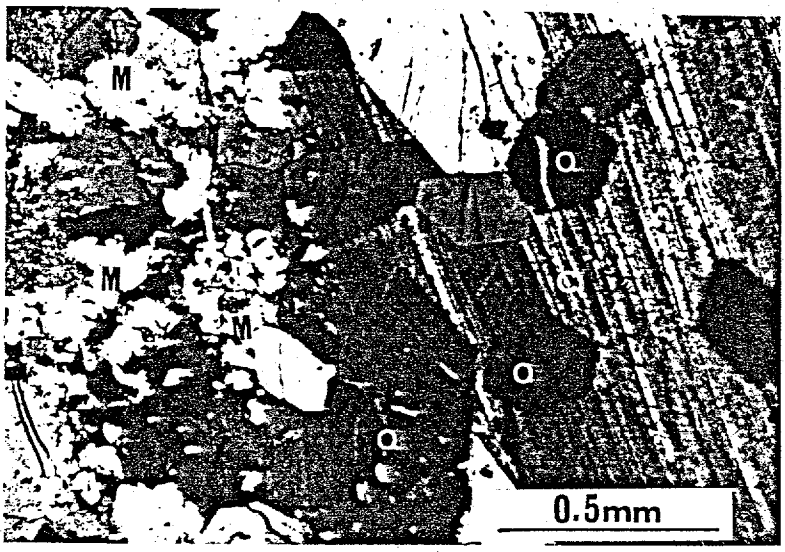
A. FILLING TEMPERATURE OF INCLUSION

As was described in the previous chapter, mica clay mineral in the sericite deposits of the Mitoya district coexist intimately with calcite (Plate 3). Fortunately, fluid inclusions are common in the calcite crystals and the filling temperatures of these inclusions were measured in order to estimate the temperature of formation of the ore deposit, i.e., mica clay mineral itself. As is shown in Fig.24, the filling temperatures of the Nabeyama and Igi deposits are in the range between 220°- 270°C (average is 240°C) and 215°- 280°C (average is 241°C), respectively.

B. HYDROGEN AND OXYGEN ISOTOPE

Constituent clay mineral	Color	Polytype	Morophology	size	DTA dehydration	Chemical composition	pH
			Clay vein				
Mica clay mineral	green pale-green white pink	2M 1M 1Md	hexagonal elongated-tabular form irregular-plate	0.5-5μm	single & double-endothermic peak (500°-750°C)	muscovite-phengitic composition	4-9
Mica/Smec.	green pale-green		elongated-tabular form partly folded-irregular lamella	0.5-2μm	double-endothermic peak (500°-700°C)	intermediate of mica and smectite	
Smectite	green pink		partly folded-irregular lamella	0.5-2μm	single & double-(500°-700°C)	montmorillonite composition	
Kaolinite	white		hexagonal irregular-plate	0.5-2μm	500-550°C		4-7
Halloysite	white		tubular-form	0.2-3μm	<500°C		4-7
			Clay deposit				
Mica clay mineral	green pale-green white pink	2M 1M 1Md	hexagonal elongated-tabular form irregular-plate	0.5-10μm	single & double-endothermic peak (500-750°C)	muscovite-phengitic composition	4-9
Mica/Smec.	green		partly folded-lamella	0.5-2μm	double-endothermic peak	intermediate of mica and smectite	
Smectite	green pink		partly folded irregular-plate	0.5-2μm	single & double (500°-700°C)	montmorillonite composition	
Kaolinite	white		hexagonal irregular-plate	0.5-2μm	500-550°C		6-7
Halloysite	white		tubular-form	0.2-3μm	<500°C		5-6
			Alteration Products of plagioclase in granitic rock				
Mica clay mineral	green pale-green white	2M 1M 1Md	heagonal elongated-tabular form	0.3-3μm	single & double-endothermic peak (500-700°C)	phengitic composition	4-9
Mica/Smec.	green		partly folded irregular-plate	0.5-1μm	double-endothermic peak	intermediate of mica and smectite	
Smectite	green pink		partly folded irregular-lamella	0.5-2μm	single & double (500-700°C)	montmorillonite composition	
Kaolinite	white brown		hexagonal irregular-plate	0.2-1μm	500-550°C		
Halloysite	white yellow		tubular	0.2-3μm	<500°C		6-7

Table 5. Mineralogical characteristics of clay minerals in granitic rocks.



Calcite and quartz associated with mica clay mineral
C:Calcite, Q:Quartz, M:Mica clay mineral

Plate 3. Microphotograph of the thin section.
(Nabeyama deposit in Mitoya district)

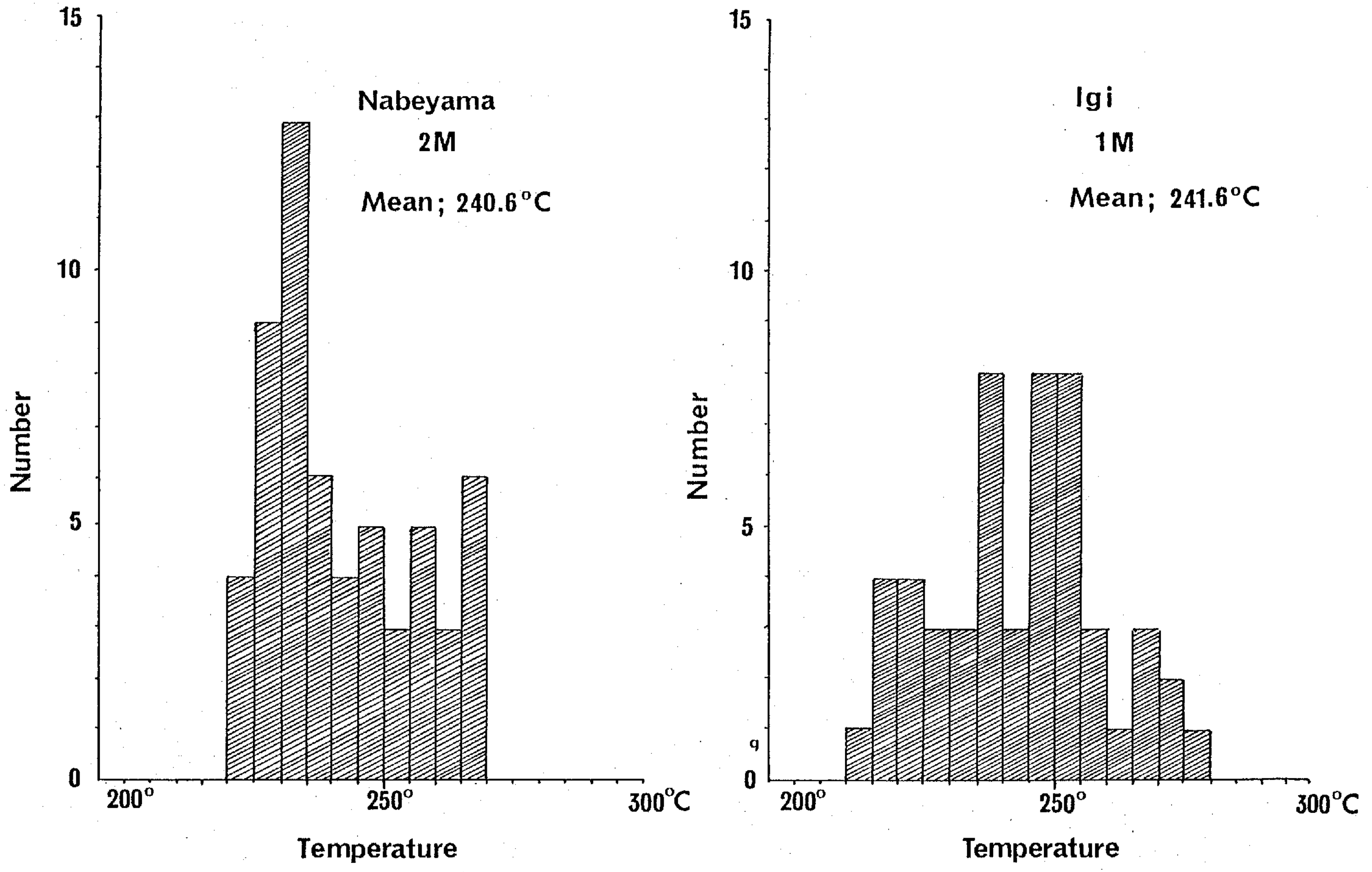


Fig. 24. Histgram of filling temperature of fluid inclusion in calcite collected from the Nabeyama (2M mica clay mineral) and the Igi (1M mica clay mineral) deposits, in Mitoya district, Shimane Prefecture.

The isotopic ratios of hydrogen and oxygen in mineral reflect the environmental conditions at the formation (Matsuhisa et al., 1980). Therefore δD and δO values of mica clay mineral, smectite, interstratified mineral and kaolin minerals collected from clay veins and deposits were measured. As is evident in Table 6, each mineral has its own characteristic value regardless of their mode of occurrence. The results clearly suggest that all of the clay minerals are formed under almost the same environmental conditions.

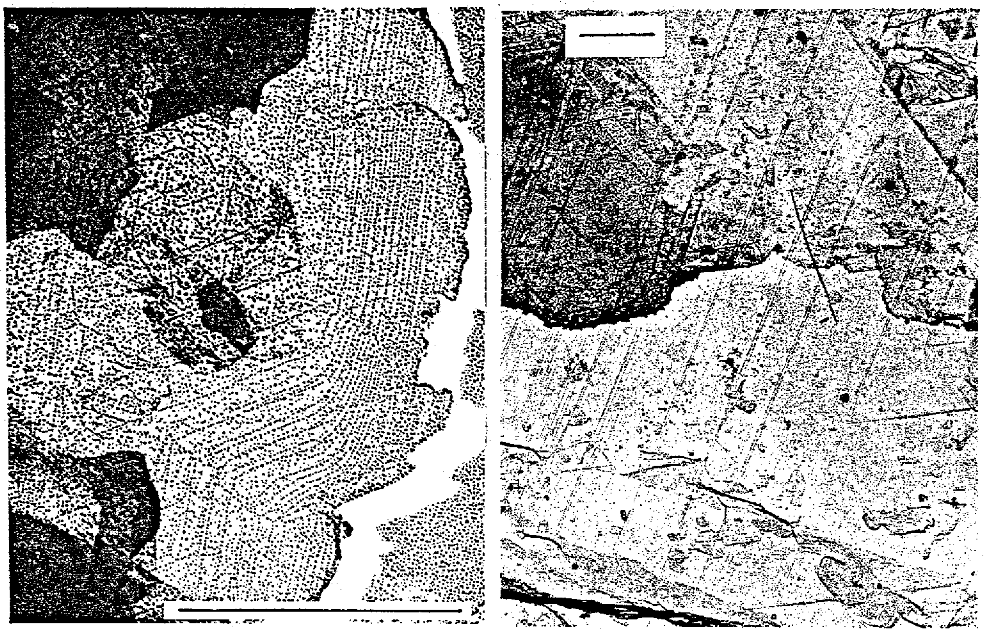
C. MICROTOPOGRAPH OF CRYSTAL SURFACE

Growth pattern on crystal surface varies according to the formation conditions. Using the decoration technique of electron microscopy (Kitagawa et al., 1983), surface microtopographs of as-grown surface have been examined on the clay minerals collected from clay veins and deposits as well as on the alteration products of plagioclase in the host granitic rocks. Among these minerals, spiral growth pattern is observable only on the crystal surfaces of 1M and 2M mica clay minerals and kaolinite (Plates 4, 5 and 6). On the crystal surfaces of 1Md mica clay mineral and smectite show no special growth pattern (see Plate 4).

Morphologies of the growth spirals are roughly classified into a) polygonal and b) circular or malformed circular. Characteristics of the observed pattern together with the range of step separations are listed in Table 7.

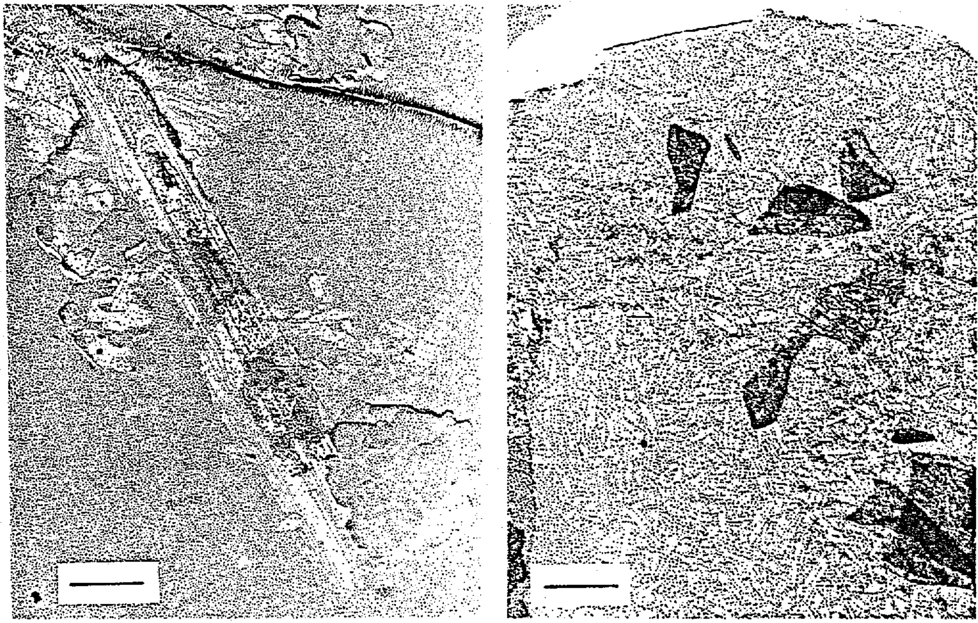
Clay mineral	The mode of occurrence of clay veins				
	Type 1	Type 2	Type 4	Type 5	Deposit
Kaolinite			-67.5		-65.8
Smectite		-86.4 -88.1 -89.1			
Mica/Smectite	-77.3	-76.2 -74.0		-75.1	
Mica clay mineral		-68.1		-67.6 -69.3	

Table 6. δD values (‰) of clay minerals.



Interlaced polygonal spiral
(2M, Mitoya, Type 5 vein)

Paired step
(2M, Kanagi, Type 5 vein)



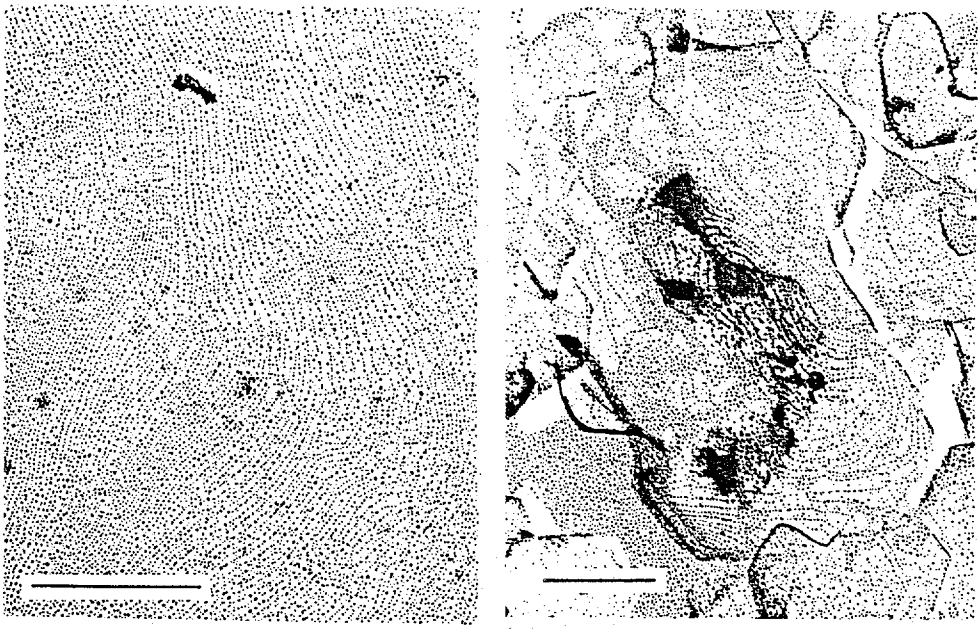
Polygonal spiral
(1M, Nabeyama deposit)

Two-dimension nucleation
growth(1Md, Miyoshi, Type 2)

Plate 4. Surface microtopographs of mica clay minerals.
The scale-line represents 1μm.

Interlaced polygonal spiral
(Kanagi, Type 5 vein)

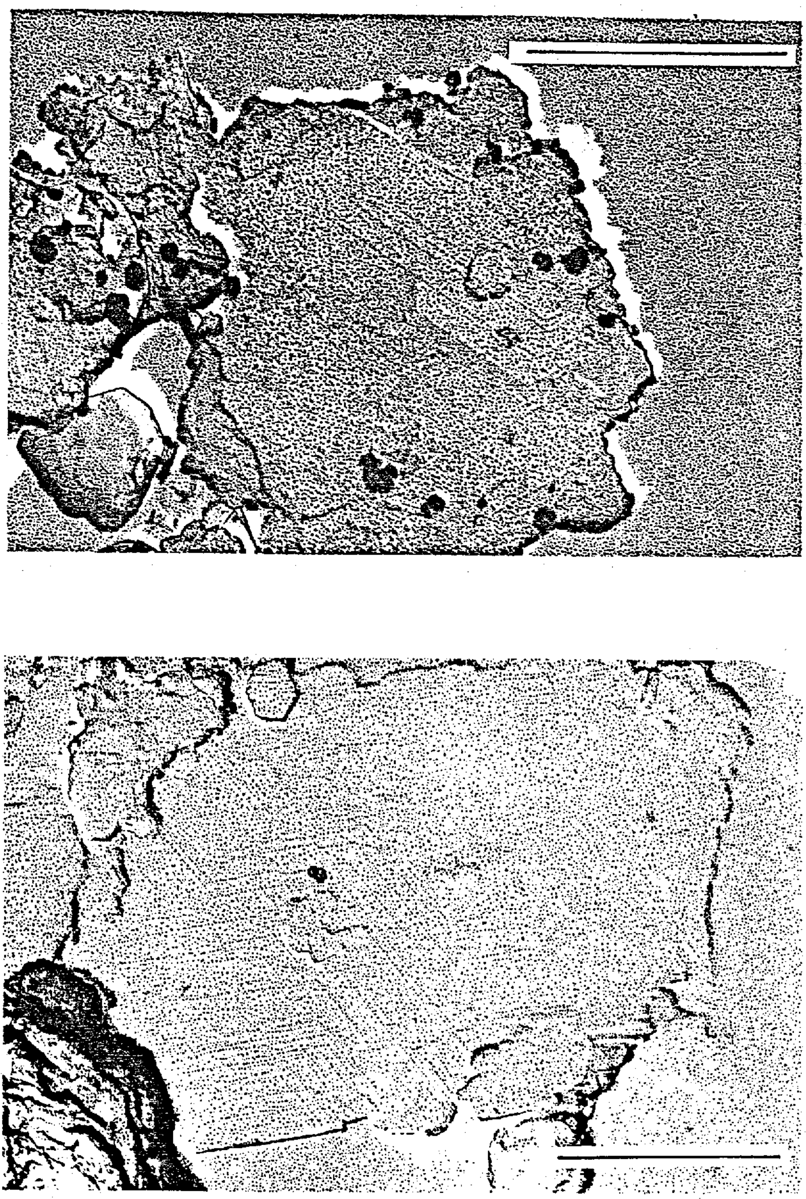
Interlaced polygonal spiral
(Nabeyama deposit)



Malformed circular spiral
(Mitoya, Type 2 vein)

Circular spiral
(Iwaya deposit)

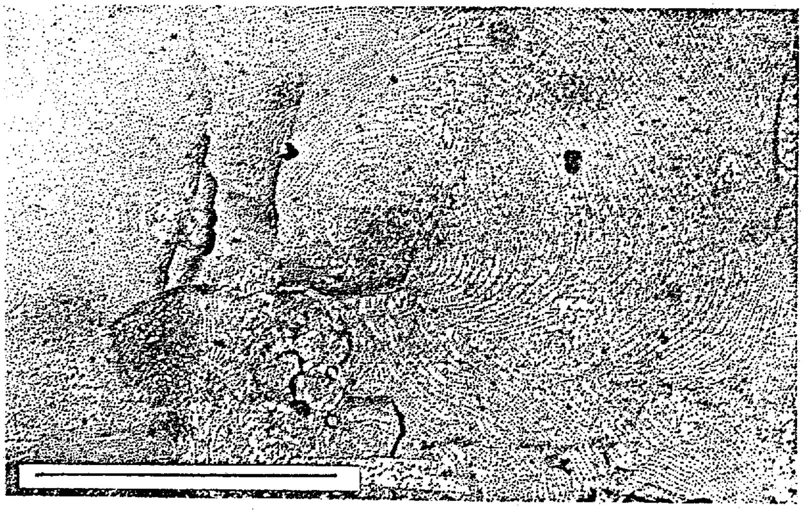
Plate 5. Surface microtopographs of mica clay minerals
The scale-line represents 1μm.



Polygonal spiral on kaolinite crystal surface in Khoachi kaolin deposit

Plate 6. Surface microtopographs of kaolinite. The scale-line represents 1μm.

Mica clay mineral from Iwaya deposit, showing coalescence of several crystals (Type 2)



Circular spiral on mica clay mineral showing coalescence of several crystals (Type 2)

Plate 7. Mica clay mineral showing coalescence of crystals. The scale-line represents 1μm.

As is shown in the table, circular or malformed circular patterns are found on the clay minerals from the Type 2 vein ,whereas polygonal patterns are on those from the Types 1 and 5 veins, kaolin and sericite deposits as well as those of alteration products of plagioclase. It is to be noted that the step separation of the polygonal pattern is two to ten times wider than that of circular spirals. Moreover, paired step or interlacing pattern is commonly observed on the surface of mica clay mineral, especially on 2M polytype (Plates 4 and 5). Appearance of coalescence pattern is characteristic in the circular spirals which is mainly found in the minerals from fissure-filling vein (Type 2)(Plate 7).

D. MORPHOLOGY OF HALLOYSITE

Among kaolin minerals, halloysite is characteristic in its crystal morphology of tubular form. Moreover, the formation of the mineral both under the weathering condition and by the hydrothermal activity have been well established by many investigators up to the present (e.g. Parham, 1969; Nagasawa and Kunieda, 1970; Shimizu, 1972 and 1978; Nagasawa and Miyazaki, 1975; Keller, 1976a, b, c and 1977 a, b; Kitagawa and Kakitani, 1977a; Tazaki, 1977 and 1978; Nagasawa, 1978). Therefore, it is worthwhile to examine the variation of the tubular form of the mineral between the two origins, i.e., weathering and hydrothermal. For the purpose of the comparative studies, halloysite of reliably weathering and hydrothermal origins were collected. As for

Specimen (Clay vein) Mica clay mineral	Polygonal spiral	Circular spiral	Interlacing or paierd spiral	Coalescence	Spacing of layers (Å)
Type 1					
Takaya (Kamo district)	o				200-1000
Type 2					
Kumogi-3 }(Kanag dis.)		o			100-500
Kumogi-4		o	o	o	100-500
Mitoys-1		o			50-500
Mitoya-2		o			100-500
Mitoya-3		o		o	100-500
Mitoya-4		o	o		50-500
Mitoya-5		o		o	50-500
Mitoya-6		o		o	100-500
Type 5					
Kumogi-1 }(Kanagi dis.)	o		o		100-5000
Kumogi-2		o	o		100-500
Kure	o				300-1000
Daiwa (Kamo district)	o		o		100-500
Specimen (Clay deposit)					
Iwaya sricite dep.		o	o	o	100-500
Nabeyama (Mitoya) dep.	o		o		100-5000
Nabeyama (Mitoya) dep.	o		o		100-5000
Igi (Mitoya) dep.	o		o		100-500
Yanomaki (Komaki) dep.	o				100-1000
Specimen (Clay deposit) Kaolinite					
Kohdachi kaolin dep.	o		o		100-1000

Table 7. Summary of surface microtopograph of mica clay mineral and kaolinite.

the weathering origin, halloysite from typical weathering residual deposits such as Hongkong kaolin were used in addition to the specimens obtained from the plagioclase in the granitic rocks in sediments, halloysite from khodachi (Matsumoto, 1965; Kitagawa and Kakitani, 1979b), Komaki (Matsumoto, 1965; Kitagawa and Kameoka, in press) and Shokozan deposits (Kinozaki, 1963; Matsumoto, 1968) were used as the hydrothermal origin.

To describe the morphological characteristics, the length and width of halloysite tubes collected from clay deposits, clay veins and altered products from plagioclase were measured and the results are shown in Fig. 24. As is evident in the figure, diameters of halloysite tube of the hydrothermal origin are concentrated in certain area, especially in the range of 0.05-0.06 microns, whereas those of weathering origin show none of such concentration. Tube length, on the other hand, indicates no information concerning their origin. To confirm the characteristic distribution of the values of the tube diameter, the relation between the mean value and the standard deviation for the diameter of respective specimens are plotted in Fig. 26. The results shown in Figs. 25 and 26 clearly suggest that the tube diameters of halloysite of the hydrothermal origin are restricted within the dotted line shown in Fig. 26.

As an application of the established criterion described above, the mean values and the standard deviations

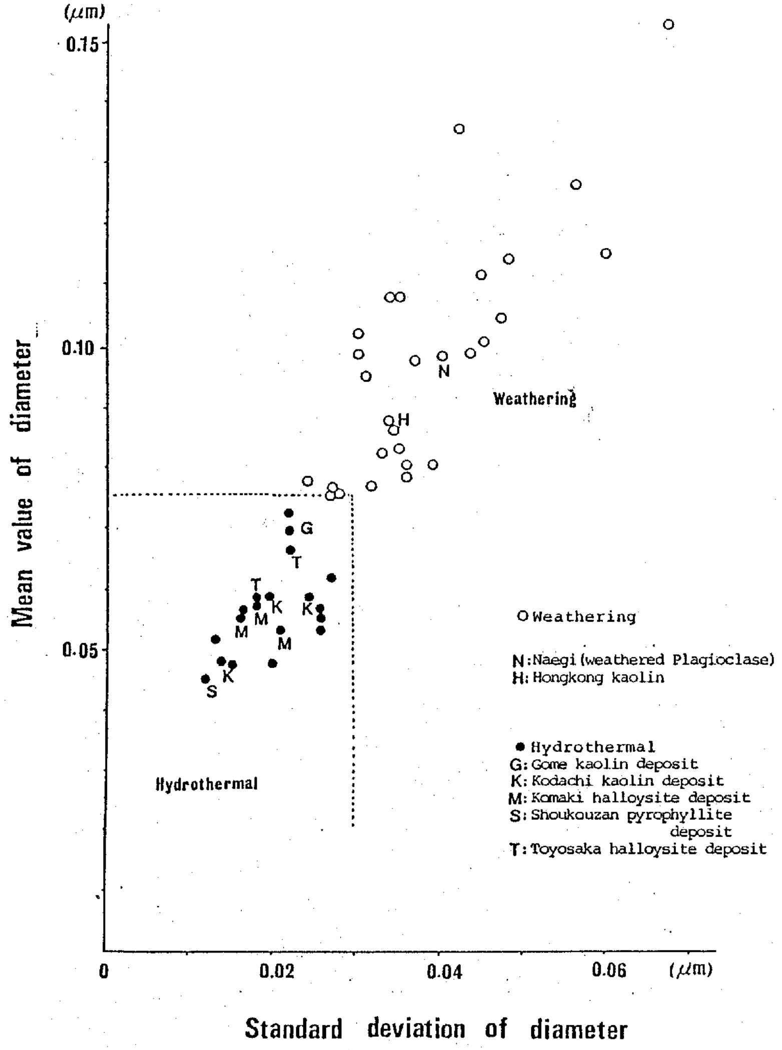


Fig. 26. The mean value and standard deviation for diameter of tubular halloysite formed by hydrothermal and weathering alteration.

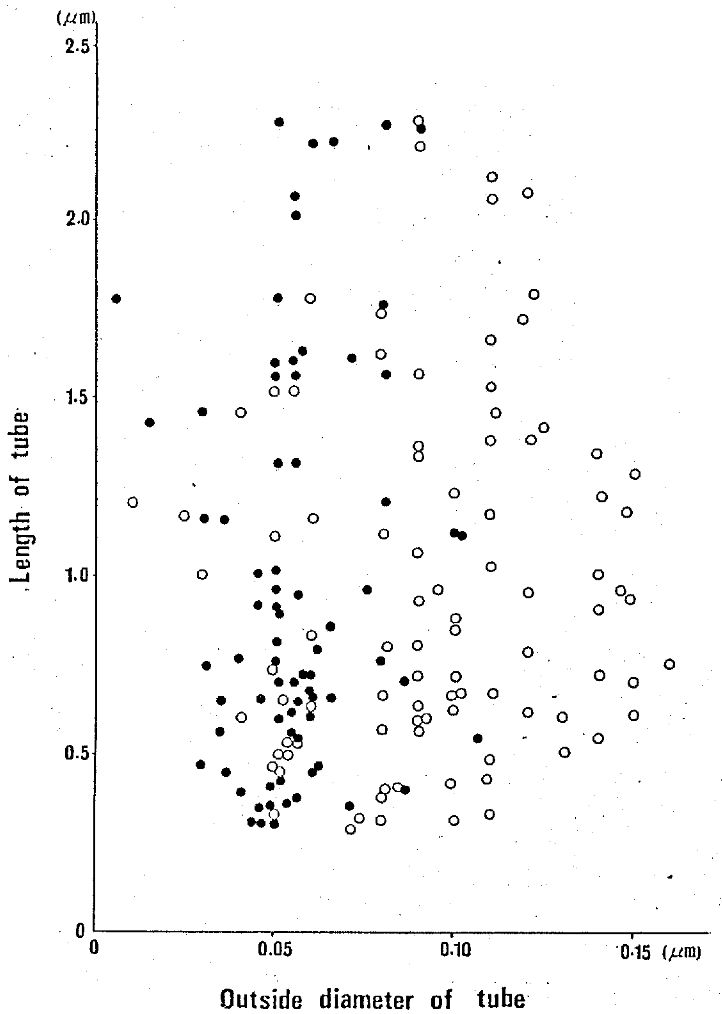


Fig. 25. Relation between length and diameter of halloysite tube formed by hydrothermal and weathering alteration.

of the diameter of halloysite crystals collected from palgioclase in the host granitic rocks were plotted in Fig. 27. As is clear in Fig. 27, halloysite altered from plagioclase show no remarkable concentration suggesting that the halloysite are formed both by weathering and hydrothermal activity. Fig. 28 shows the same values of halloysite crystals collected only from the clay veins of various types developed in the granitic rocks. As is clear in the figure, the values are markedly concentrated in the restricted area, suggesting the hydrothermal origin of the minerals.

Furthermore, the distribution of the tube-width of the halloysite crystals can be divided into three types (Types A, B and C) by more detailed observation as is shown in Fig. 29, i.e., Type A with the smallest values concentrated in the range of less than 0.01 microns, Type B with relatively wide range of the values and Type C with wide range of the values but characterized by the maximum frequency in the range less than 0.01 microns. Halloysite crystals of Type A are ascribed to the hydrothermal origin, Type B to weathering and Type C to the mixtures of the two origins. Typical distributions of the tube width and transmission electron microphotographs of the three types are shown in Fig. 29 and in Plates 8 and 9, respectively

Using this method, halloysite crystals obtained from plagioclase of the host granitic rocks of the Kanagi district (Kumogi granite mass) and Mizuho districts were examined. The results clearly indicated that halloysite

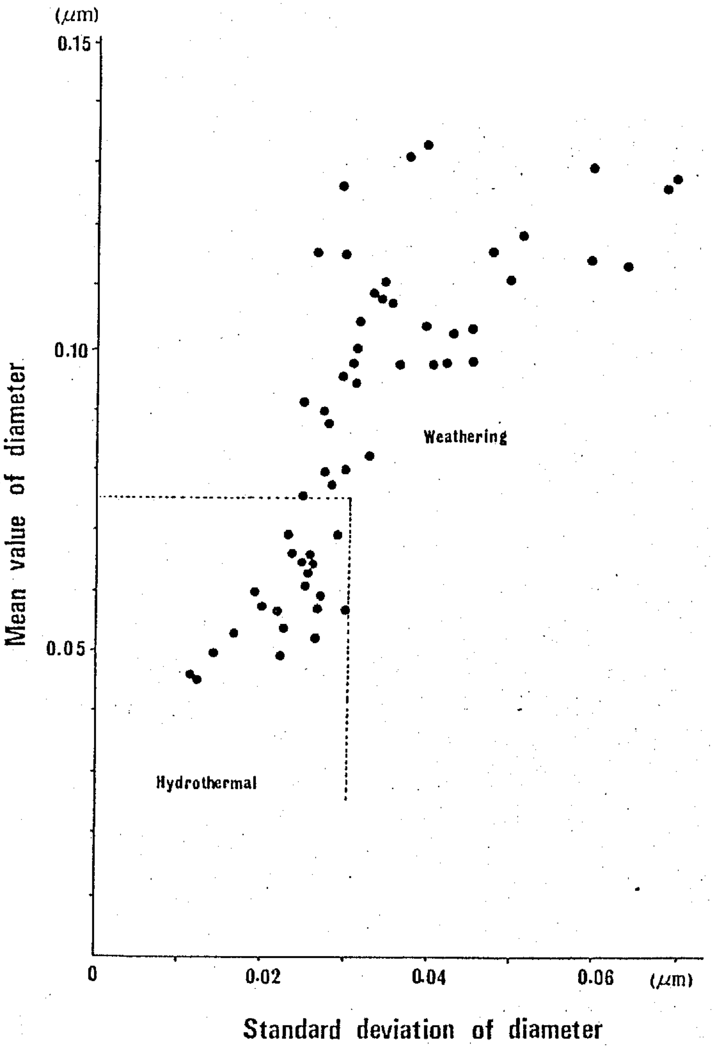


Fig. 27. The mean value and standard deviation for diameter of tubular halloysite formed by hydrothermal and weathering alteration.

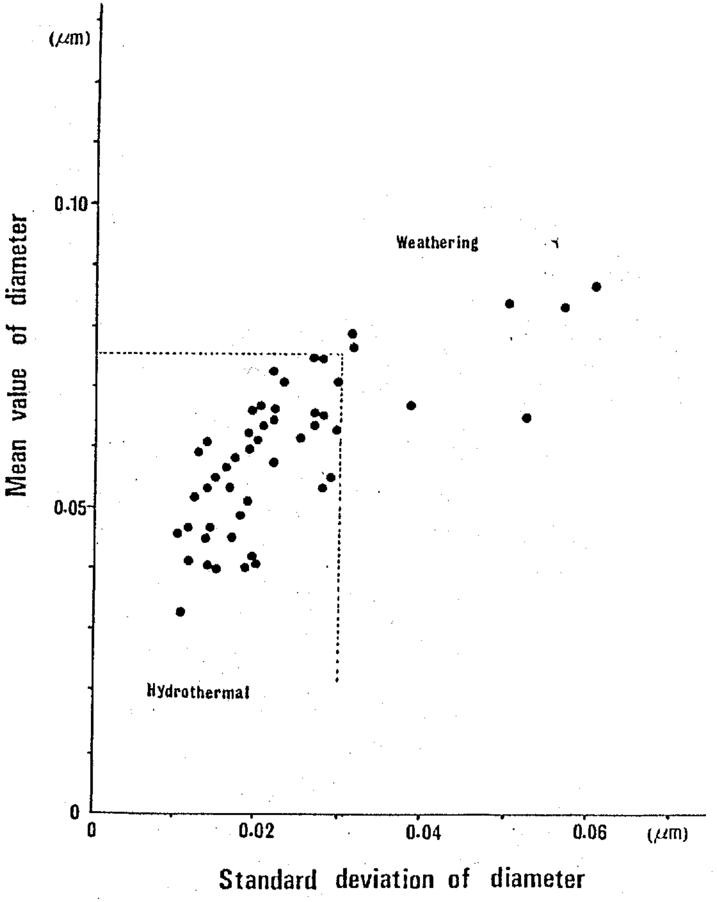


Fig. 28. The mean value and standard deviation for diameter of tubular halloysite in clay veins.

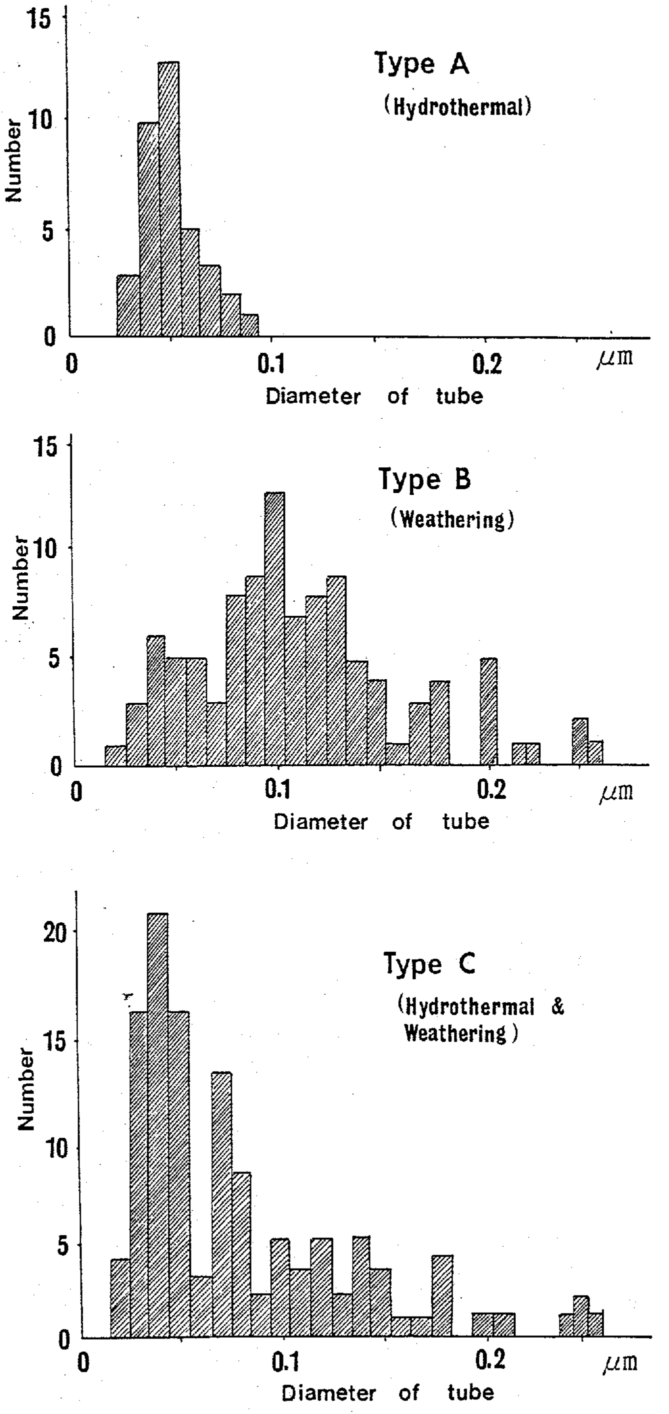
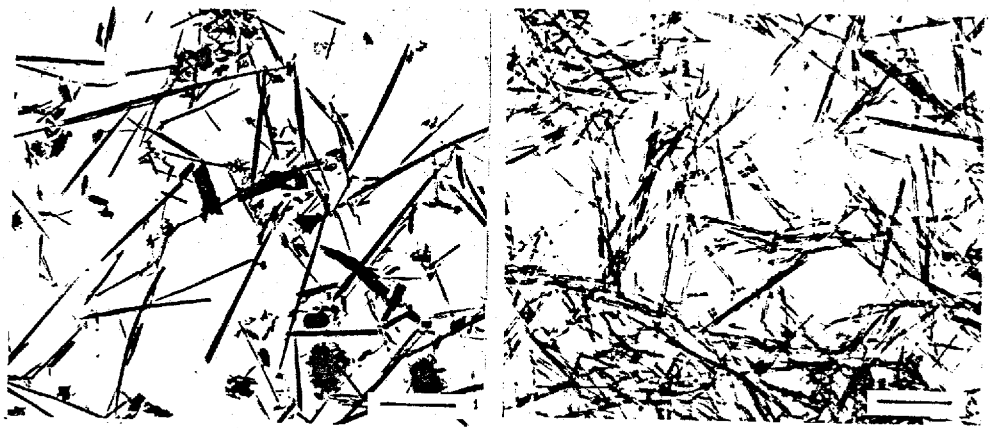
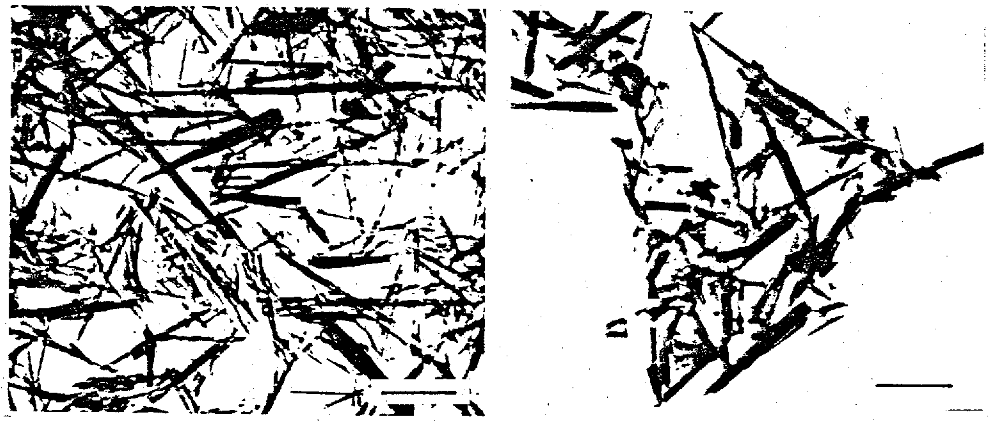


Fig. 29. Three typical histgram of diameter of tubular halloysite.



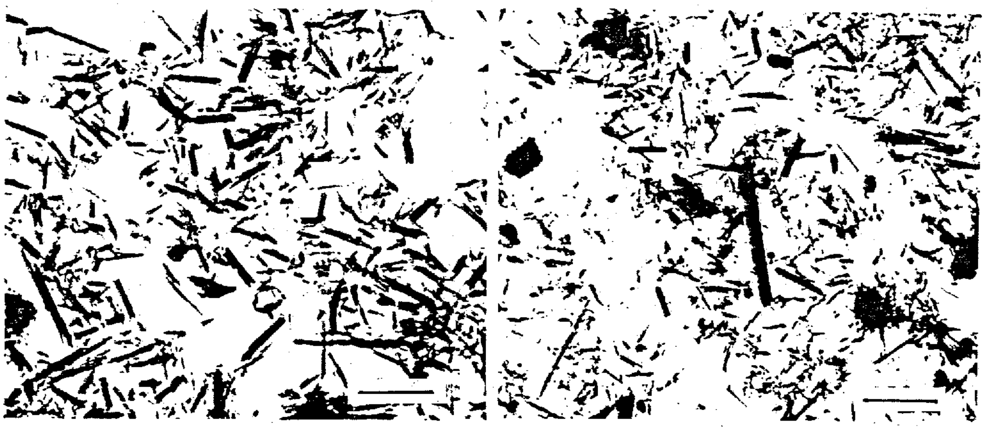
Type A, Kumogi granite mass
(Kanagi district)

Type A, Yanomaki (Komaki)
halloysite deposit



Type B, Kumogi granite mass
(Kanagi district)

Type B, Kamo district

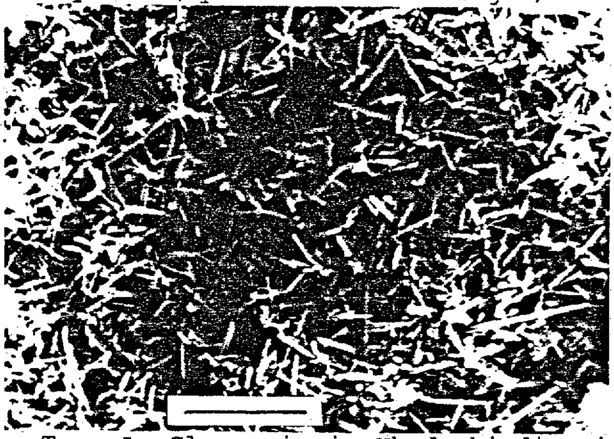


Type C, Kumogi granite mass
(Kanagi district)

Type C, Kamo district

Plate 8. Morphology of tubular halloysite in granitic rocks taken under transmission electron microscope (TEM).
The scale-line represents 1μm.

Type A, Yanomaki(Komaki) halloysite deposit (Hydrothermal in origin)



Type A, Clay vein in Khodachi district (Hydrothermal in origin)

Type B, Halloysite found in plagioclase (Weathering in origin)

Plate 9. Morphology and texture of tubular halloysite taken under scanning electron microscope(SEM). The scale-line represents 2μm.

crystals of Type A which is ascribed to the hydrothermal origin are found in the remarkably decomposed regions, i.e., in the middle and northwestern parts of the Kumogi granite mass (Fig. 30) and in the middle part of the Mizuho district (Fig. 31).

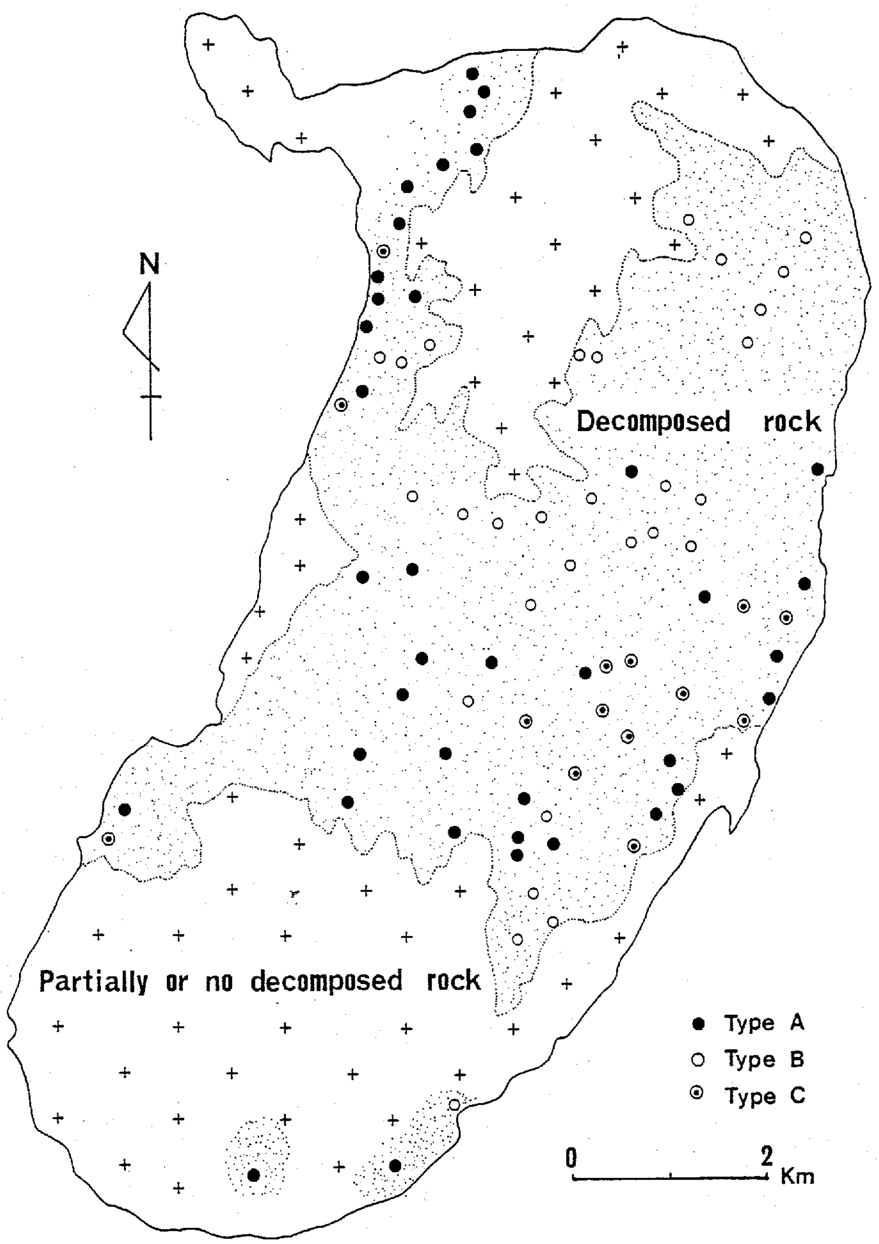


Fig. 30. Distribution of three types of halloysite in the Kumogi granite mass in Kanagi district, Shimane Prefecture.

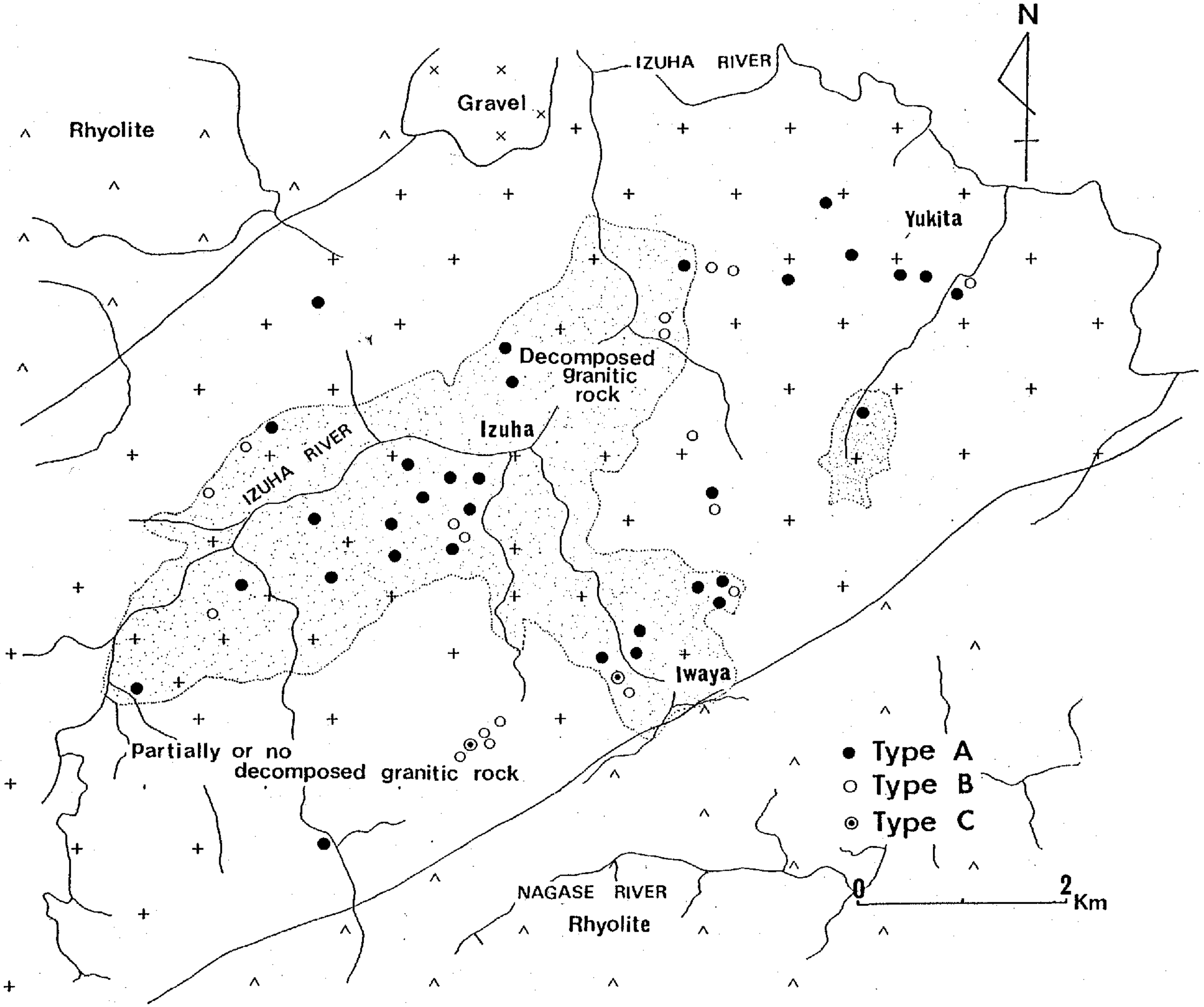


Fig. 31. Distribution of three types of halloysite formed in plagioclase in granitic rock at Mizuho district, Shimane Prefecture.

VI. DISCUSSION

The main purpose of this paper is to establish the significance of the hydrothermal activities on the decomposition of the granitic rocks. In the preceding chapters, important characteristic features observed in the decomposed granitic rocks have been described particularly on the clay veins and clay deposits developed commonly in the granitic rocks distributed widely in Hiroshima and Shimane Prefectures. Based on the results obtained, the complicated mechanisms of the decomposition process of the granitic rocks will be discussed from the two important view points, fracturing system related to the paleo-stress fields and clay mineralogy in relation to the formation conditions.

A. FORMATION MECHANISM AND AGE OF FRACTURES

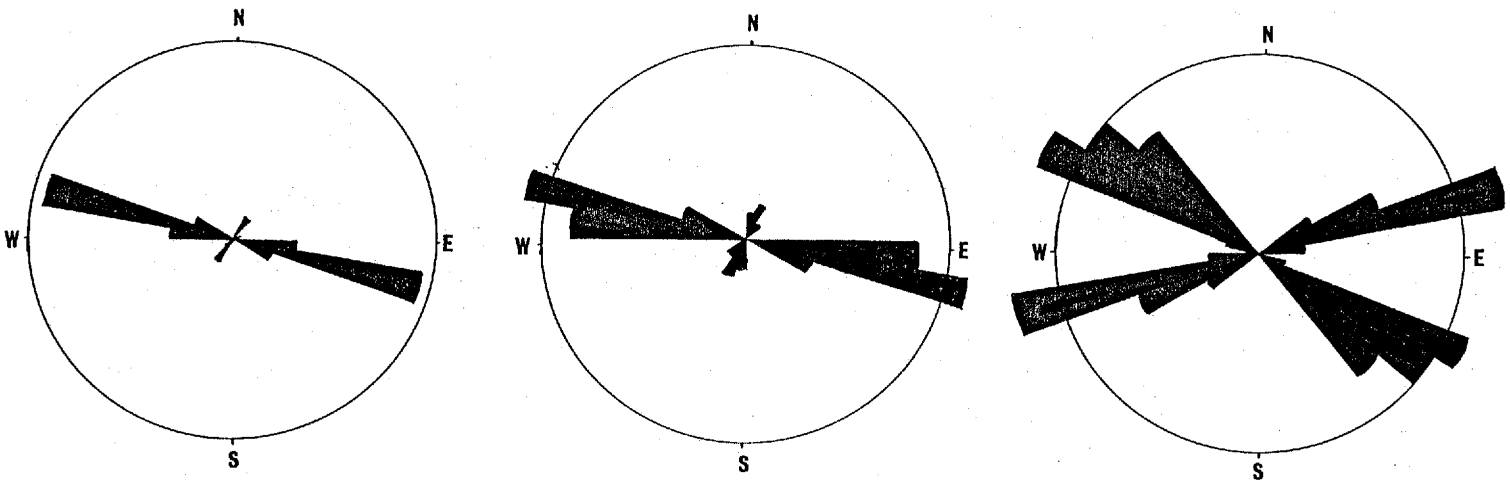
First of all, it may reasonably be assumed that the clay veins developed in the granitic rocks represent the fractures which have been formed after the solidification stage subsequent to the magmatic activity. Furthermore, a systematic fracturning pattern within granitic rocks has been controlled by the stress fields of the respective district.

The fracture patterns of clay veins developed in the granitic rocks in Hiroshima and Shimane Prefectures will be analysed.

As a typical example of the analysis of the stress field, the Kamo district is chosen. In this district, clay veins of Types 1, 2, 4 and 5 are commonly developed and the results of the orientation (strike and dip) analyses are shown in Fig. 32 as rose diagrams. As shown in the figure, the strikes of the veins of Types 1 and 5 are concentrated in the direction of N60° - 80°W, whereas those of Type 2 are concentrated in two directions, N40° - 70°W and N60° - 80°E. It is to be noted that the direction of the former exactly corresponds to the bisectional direction of the latter two. Moreover, the Type 2 veins have characteristic features of the conjugated fractures and accompanying slickensides occasionally. These facts strongly suggest that the Type 2 veins are the shear fractures formed under the regional stress field of the district. Consequently, veins of Types 1 and 5 are ascribed to the tention fractures. The greatest principal stress axis inferred from the analytical data is N80° - 90°W in the Kamo district. In such manner, the stress fields of the respective districts have been analysed (Fig. 10) and the results obtained are schematically summarized in Fig. 33. As is clear in the figure, at least four greatest principal stress axes are distinguishable in the district of Hiroshima and Shimane Prefectures.

Clay veins developed in and around the clay deposits are also ascribed to the shear and tention fractures, since their orientations coincide with those of clay veins in the respective granitic rocks.

Preferred orientations of the microcracks developed in the constituent minerals of the host granitic rocks have



Type 1
Total; 32, Max: 59.4 %

Type 5
Total; 48, Max: 45.8 %

Type 2
Total; 133, Max: 22.6 %

Fig. 32. Histgram of strike of clay veins classified based on the mode of occurrence in Kamo district, Hiroshima Prefecture.

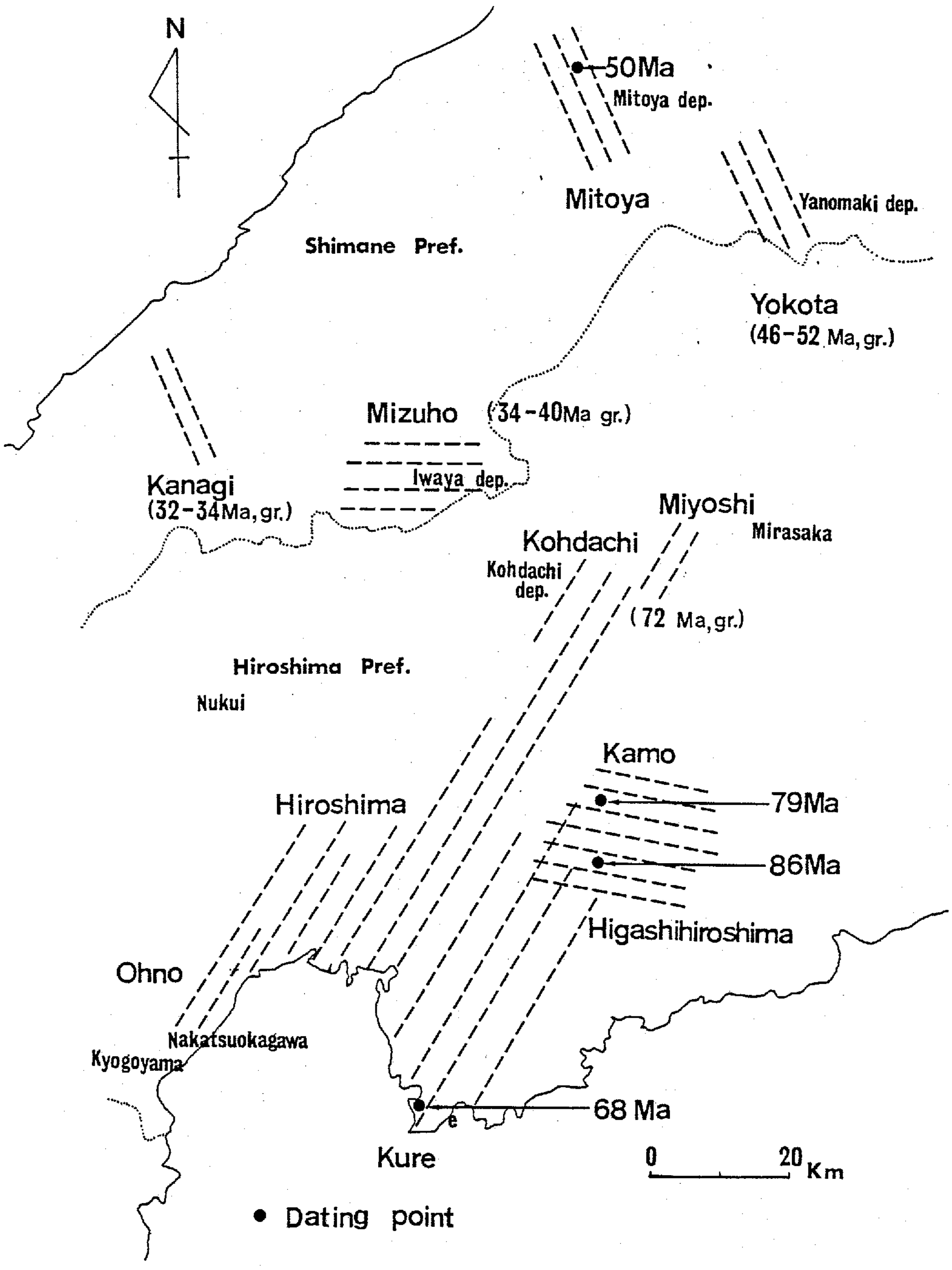


Fig. 33. Schematic representation of tectonic stress trajectories together with the geological ages.

been analysed using the same analytical method. For example, two distinct preferred directions of the microcracks were recognized in the Kyogoyama, Ohno district and Hiroshima district (see, Figs. 14 and 15). The greatest principal axis derived from the two directions is approximately NE-SW based on the assumption that the microcracks are the conjugated fractures. The direction thus obtained well coincides with that of clay veins, suggesting that the microcracks and the clay veins have been formed under the same stress field of the district.

Concerning the formation ages of these fractures, K-Ar ages of mica clay minerals obtained from clay veins and clay deposits will be useful. The available data from the previously published literatures are summarized in Fig. 33. The data are taken from Ishihara et al. (1980) and Kitagawa and Kakitani (1981). Furthermore, the K-Ar ages of the host granitic rocks are also available. That is, the Sanyo granitic complex in Hiroshima Prefecture are dated at 70-92 Ma (Kawano and Ueda, 1966; Shibata and Ishihara, 1974a and b) and San'in granitic complex in Shimane Prefecture at 25-63Ma (Kawano and Ueda, 1966; Shibata and Ishihara, 1974; Ishihara, 1974 and 1978). These data are also plotted in Fig. 34. As is evident in the figure, the ages of clay minerals and those of granitic rocks are identical with each other within the analytical error. The concordance in the ages indicates that the clay minerals in the clay veins and clay deposits have been formed by the post magmatic activities of the host granitic rocks of the

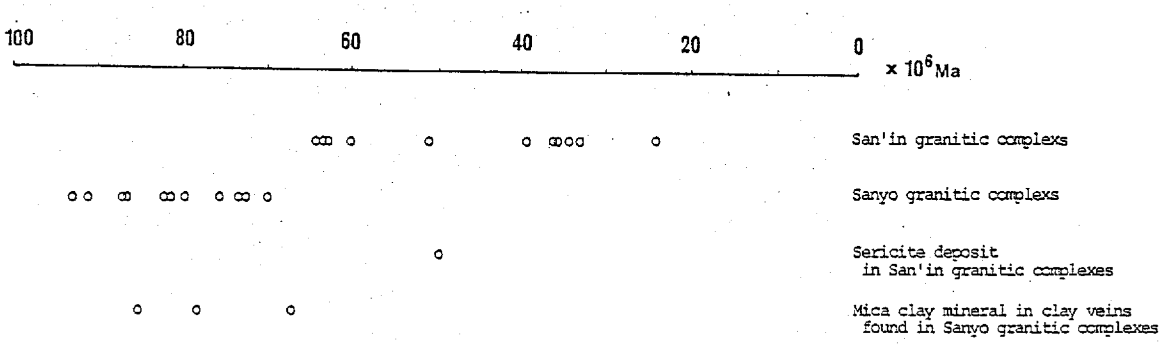


Fig. 34. K-Ar ages of mica clay mineral and granitic rocks in Hiroshima and Shimane Prefectures.

Locality	Age of granite	Age of mica clay mineral	Greatest principal stress axis
Kanagi district	32 - 34 Ma		NW - SE
Mizuho district	34 - 40		E - W
Mitoya district	51	50 Ma	NW - SE
Yokota district	46 - 62	64	NW - SE
Miyoshi district	72		NE - SW
Kure district		68	NE - SW
Kamo district	70 - 79	79, 86	ESE - WNW

Table 8. Relation between tectonic stress and its ages.

respective districts. In Table 8, the formation ages of the granitic rocks and clay minerals together with the greatest principal axis of the respective ages are present. Thus, it is furthermore reasonably concluded that the greatest principal stress axis has been changed from ESE-WNW to NE-SW and finally NW-SE during the geological ages from Cretaceous to Palaeogene periods.

B. FORMATION CONDITION OF CLAY MINERALS

In this chapter, the physico-chemical condition of the formation stage of clay minerals will be discussed based on the available data such as temperature estimation derived from isotopic ratios and filling temperatures, sequence of mineral assemblages and microtopographs of crystals.

It has been well established that the formation temperature and the origin of the water are closely related to the isotope ratios of hydrogen and oxygen of a given mineral (Scheppard et al., 1969; O'Neal and Taylor, 1969; Savin and Epstein, 1970; Lawrence and Taylor, 1971; O'Neeal and Kharaka, 1976; Suzuoki and Epstein, 1976; Lombardi and Sheppard, 1977).

The isotopic ratios of oxygen and hydrogen of mica clay minerals in the Kumogi granite mass (Kanagi district) have been measured to find the precipitation temperature and it was estimated at 250°C. (Matsuhisa et al. 1980). Although the isotopic ratio obtained by the present author is only for hydrogen, δD values (-67.6‰ - -77.3‰) for the mica clay minerals collected from the clay veins are very similar to that (-78‰) of Matsuhisa et al.(1980)(see, Fig. 35). Furthermore, the δD values (-67.5‰) of kaolinite collected from the clay veins well coincide with those of the Khodachi kaolin deposit (-65.8‰)(Table 6). In spite of the differences in the mode of occurrences, δD values of the related mineral also coincide with each other suggesting the same formation condition, i.e., hydrothermal. If we plot these values on the fractionation-temperature diagram proposed by Marumo et al.(1980), the formation temperature of kaolinite is roughly estimated between 70° and 150°C (Fig. 36).

The mineral sequence of mica clay mineral —— interstratification of mica and smectite —— smectite —— kaolin minerals from the lower to upper levels obseved in the alteration products in the host granitic rocks as well as in a vein also give us some important information concerning the formation conditions of clay minerals. That is, almost the same mineral sequences have been established in various geothermal areas (Sigvaldason, 1962; Sumi, 1966, 1968; Takashima,1972; Hayashi, 1973; Hayashi and Yamasaki, 1975; Kinbara and Ohkubo, 1978). Typical examples of the mineral sequences found in Satsunan (Kagoshima Pref.) and Ohnuma (Iwate Pref.) geothermal areas are presented in Fig. 37. Mineral sequence of mica clay mineral —— interstratification —— smectite —— kaolinite is generally recognized in these areas. This sequence exactly coincided with those obtained in the present study.

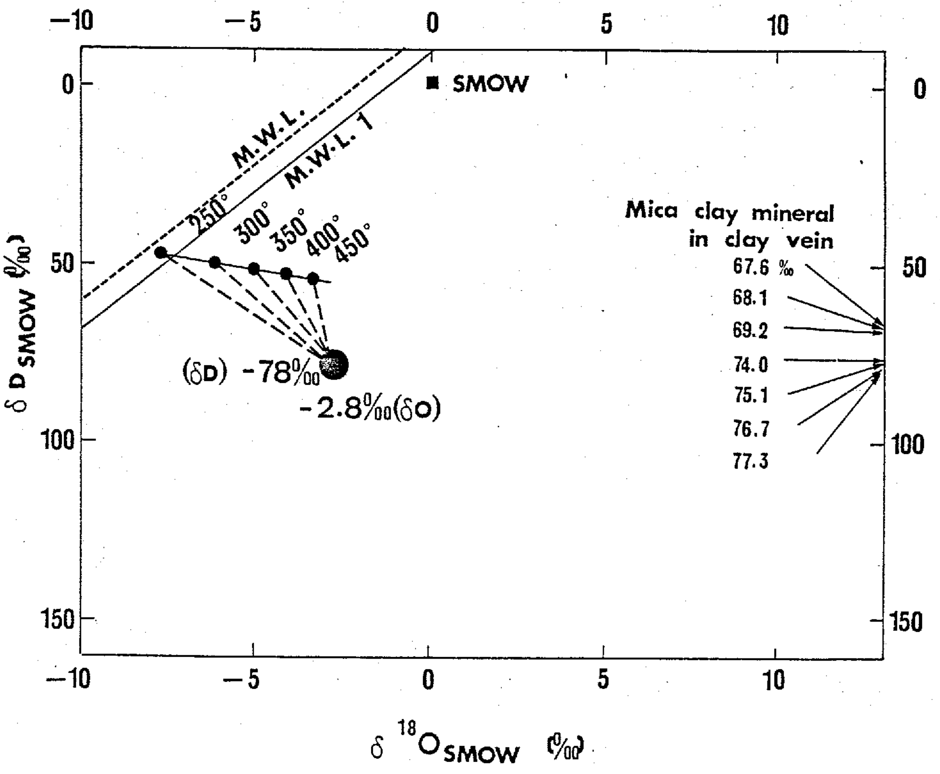
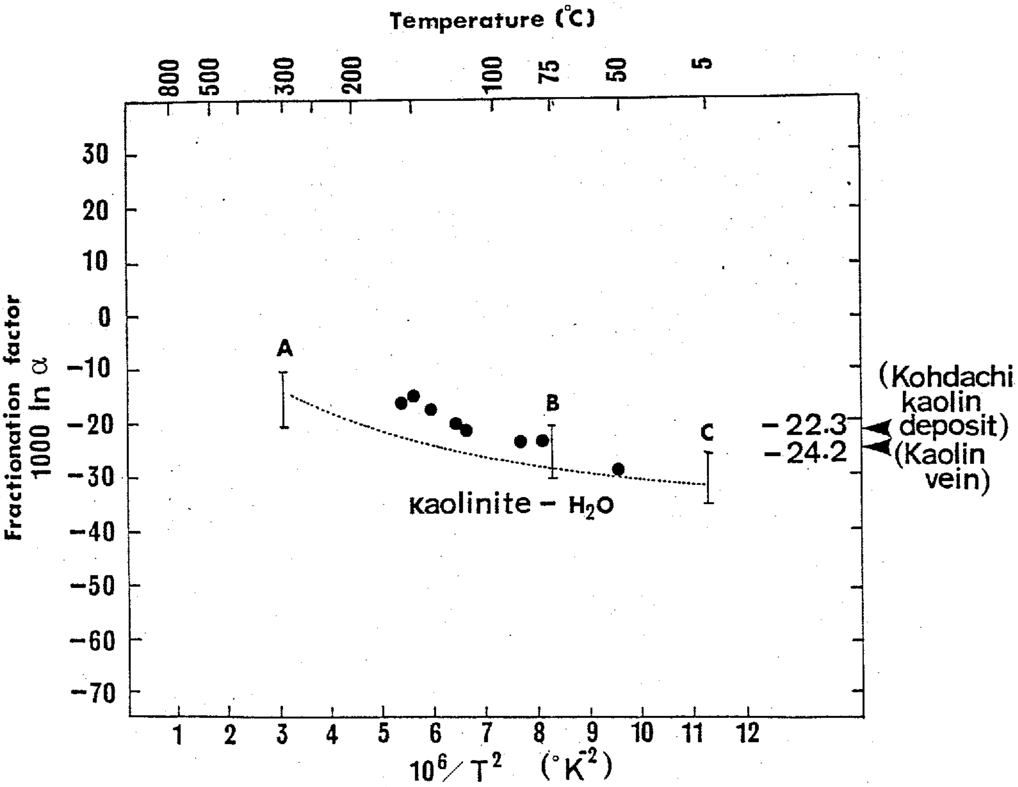


Fig. 35. A ploted of δD versus δO for water and mica clay mineral from clay vein in the Kumogi granite mass in Kanagi district, Shimane Prefecture.
The caluculated isotopic composition of the hydrothermal waters equilibrated with mica clay mineral (large solid circles) in veins is shown by small solid circles with parameter of temperature (after Matsuhisa, et al., 1980)).
M.W.L. 1 and 2: Standard for the meteoric water lines by Craig (1961) and Sakai and Matsubaya (1977).
SMOW: Standard mean ocean water.



●: Kaolinite, Dickite(Ohnuma) (Marumo et al., 1980)

A: Sheppard and Taylor (cited in Sheppard et al.,1969)
Preliminary laboratory calibrations of kaolinite-H_2O

B: Sheppard et al.(1969) Coexisting kaolinite and water
from Fountain Paint Pot. Yellowstone

C: Savin and Epstein (cited in Sheppard et al., 1969)
Data on natural kaolinites from zones of deep weathering

Fig. 36. Temperature dependance of fractionation factors between kaolinite and water (after Marumo et al., 1980) and fractionation of kaolinite in clay vein and clay deposit.

Moreover, the range of formation temperature of the respective minerals can be obtained from Fig. 37.

Comparative examinations between the two temperatures lead to the formation temperatures of mica clay mineral: 200° - 300 °C, interstratified minerals of mica and smectite: 150° - 200°C, smectite: 100° - 200°C and kaolin mineral: 50°- 150° C, respectively.

Microtopographs of clay minerals are also usuful for confirming the formation environment of the minerals. Since the development of the decoration technique of electron microscopy, various kinds of microtopographs of clay minerals have been observed and characteristic microtopographs for the different environmental conditions have been established (Baronnet, 1972; Sunagawa and Koshino, 1975; Sunagawa et al., 1975; Sunagawa, 1977; Tomura et al., 1979). The important results of these researches are summarized as follows; 1) Spiral growth indicates that the crystals are formed in either solution or vapor where unconstrained growth is possible, 2) Coalescence of crystals can occur predominantly in violently moving solution than in static solution, 3) Step separation versus step high ratios of the crystals growth in vapor phase is much larger than those formed in hydrothermal solutions.

Common development of circular spirals with relatively narrower step separation in the clay minerals from Types 1, 2 and 5 clearly indicates that the minerals have been formed from hydrothermal solutions and not by solid-state

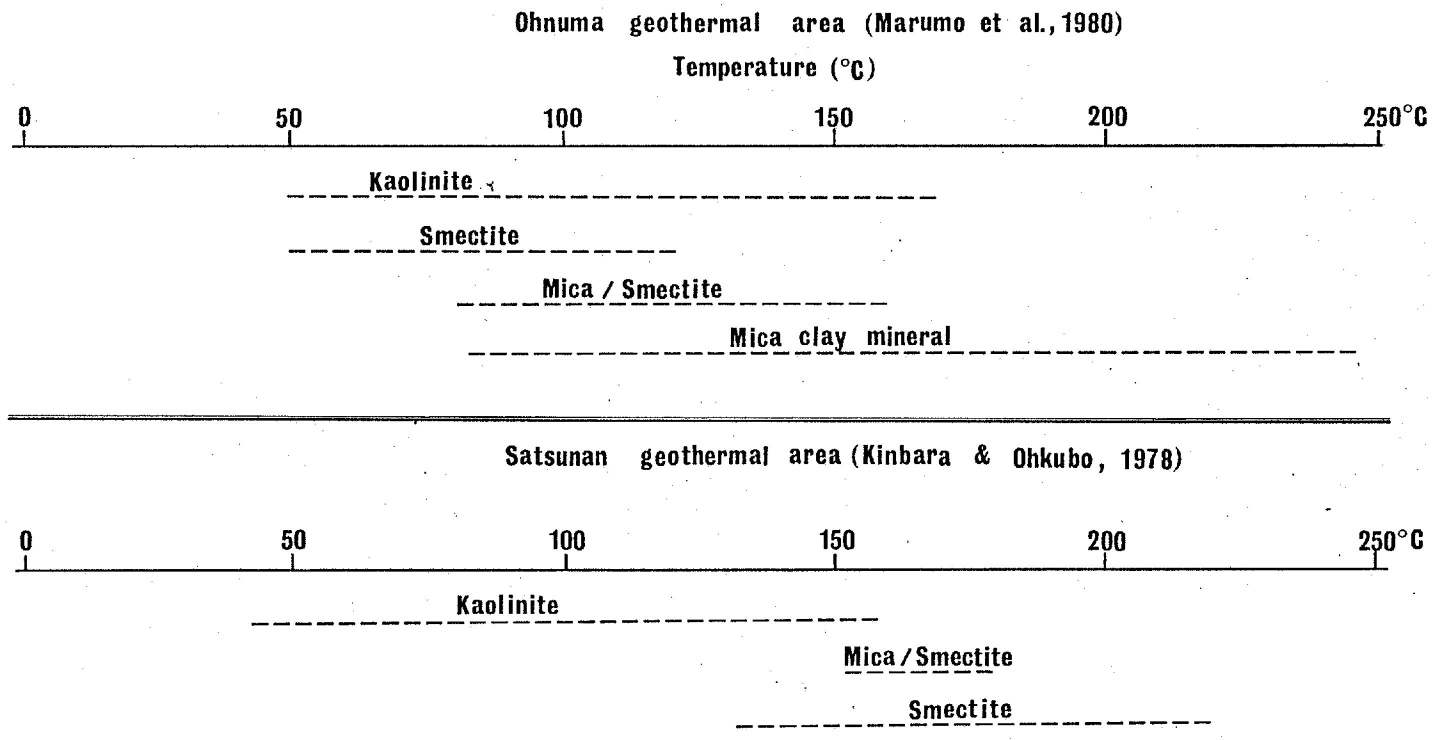


Fig. 37. Relation between alteration minerals and measured temperature in the Ohnuma and Satsunan geothermal areas.

crystallization in which growth is constrained (Plates 5, 6 and 7). Coalescence is often encountered in the clay minerals from Type 2 and the fact also suggests the growth from hydrothermal solutions. Polygonal spirals from Type 5, on the other hand, indicate the formation condition of hydrothermal metasomatism. Thus, all of the observed microtopographs are ascribed to the formation condition related to certain hydrothermal activity.

In spite of the previous researches on the formation of clay minerals under the weathering condition(Kashiwagi, 1963; Miura, 1966 and 1967; Ohyagi, 1968; Ohyagi et al., 1969; Miyahara, 1977; Khono, 1985), present results strongly indicate the hydrothermal origin of the clay minerals. Only in the case of kaolin minerals, especially for halloysite, evidence of weathering origin is recognized. Considering the fact that decomposition of the granitic rocks can be represented by the amounts of clay mineral formation, it may be concluded that the decomposition of the granitic rocks of the investigated area is mainly the results of hydrothermal activities subsequent to the granitic activity as well as the weathering during the geological ages.

VII. CONCLUDING REMARKS

Based on the results obtained in this study, the most possible decomposition process of the granitic rocks of the district will be explained:

First, nearly vertical fractures and microcracks have been developed within the granitic rocks under the regional paleo-stress field of the respective districts after the solidification stage of the granite. The clay veins and clay deposits were formed filling the fractures by clay minerals from hydrothermal solution of meteoric origin.

To be noted is that the constituent minerals of the host granitic rocks and clay deposits formed by the metasomatism were formed by the same activity in more or less extent. The clay mineral species have been gradually changed according to their geographical vertical positions. That is, the mineral sequence of mica clay mineral —— interstratified mineral —— smectite —— kaolin minerals from the depth to the upper levels was gradually formed during the geological ages.

The horizontal fractures such as lamination and sheeting joints have developed near the ground surface by unloading. The horizontal microcracks are ascribed to the same formation mechanism. The part where the fractures are densely developed is generally decomposed remarkably. This is because the place is favorable for weathering process in addition to the hydrothermal activity of relatively earlier stage.

The fracture system, location of clay deposits and clay veins are illustrated schematically in Fig. 38 together with the degree of the decomposition.

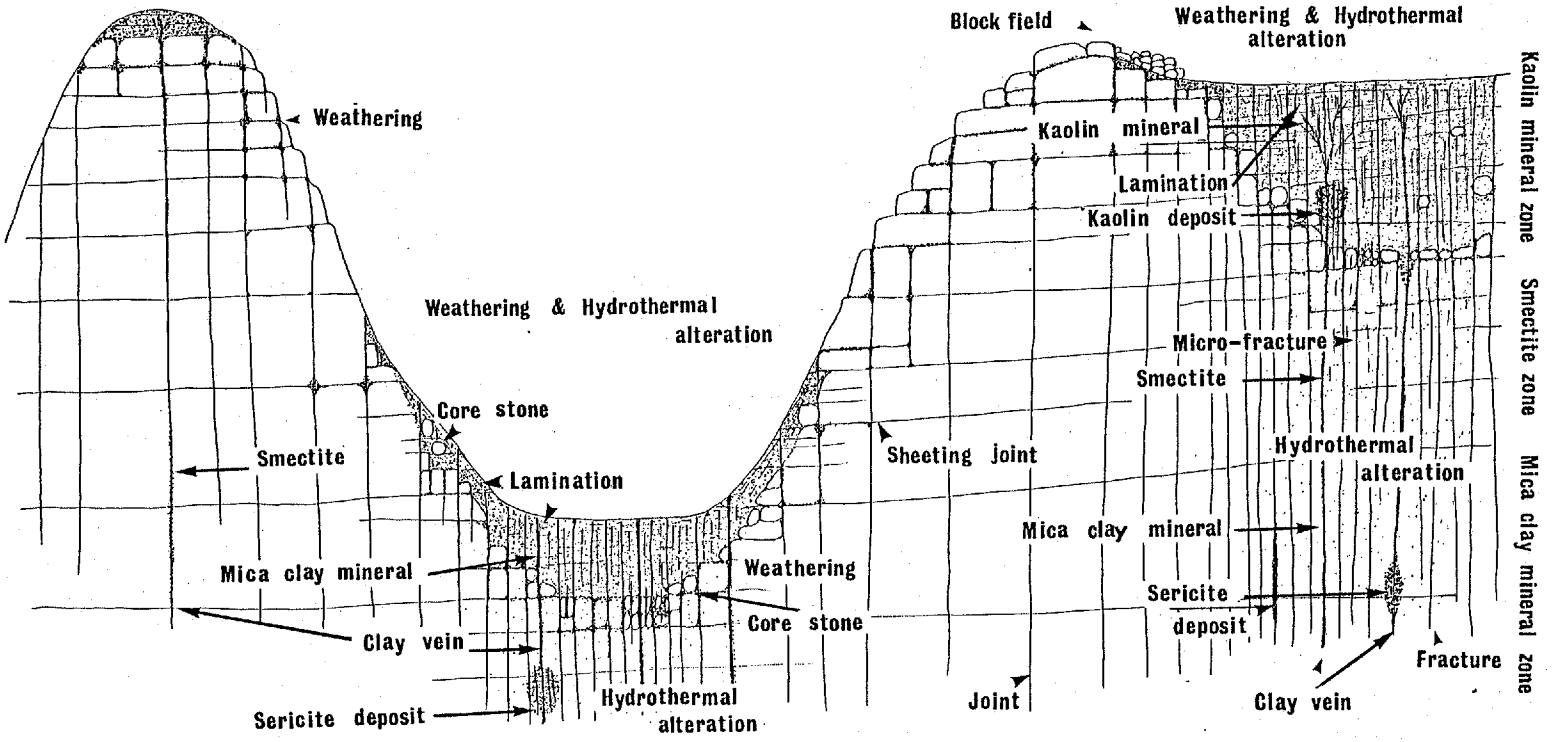


Fig. 38. Schematic profile of decomposed granitic rock.

REFERENCES

Baronnet, A. (1980): Polytypism in mica; A survey with emphasis of the crystal growth aspect. Current topics in materials Sci., Vol.5, E. Kaldis ed., North-Holland Pub.

Craig, H.(1961): Isotopic variations in meteoric water, Science, Vol.133, 1702-1703.

Hashikawa, K. and Miyahara, K.(1974): Fracture of the weathered granitic rocks and its engeneering significance(in Japanese). Engeneering Geol., Vol. 15, 47-57.

Hashikawa, K. (1978a): On an Anistotropic effect to the P-wave velocity affected by the sheeting joint in weathered granitic rocks and its analysis(in Japanese). Engineering Geol., Vol.19, 21-29.

Hshikawa, K.(1978b): Weathering structure of the granitic rocks in the dessected pediment (in Japanese). Engeneering Geol., Vol.12, 22-29.

Hashikawa, K.(1985): Studies on the planar fracturing structures developed in the Surficial part of granite mass. Geol. rep. Hiroshima Univ., No.25, 1-37.

Hayashi, M.(1973): Hydrothermal alteration in the Ohtake geothermal area, Kyushu, Chinetsu, vol.10, 9-45.

Hayashi, M. and Yamazaki, T.(1975): Interstratified mineral of mica and montmorillonite from the Ohtake geothermal area in Ohita Prefecture and environmental conditions of formation, Prof.Toshio Sudo memorial, 48-58

Ishihara, S.(1977): The magnetite-series and illmenite-series granitic rocks, Mining Geol., Vol.27, 293-305.

Ishihara, S., Shibata, K., Kitagawa, R. and Kakitani, S.(1980): K-Ar ages of sericites from the Chugoku district, Japan, Bull. Geol. Surv. Japan, Vol.3I, 221-224.

Iwao, S.(1953): Pale green sericite deposits in Iishi district, Shimane Prefecture with special reference to the wall rock alteration (in Japanese), Chicho geppou, Vol.4, 223-238.

Kakitani,S. and Kitagawa, R.(1977): Clay minerals in the veins and veinlets found in the granitic rocks of Hiroshima Prefecture, J.Miner. Soci. Japan, Vol.I3, spec. 187-196.

Kawano,Y. and Ueda,Y.(1964): K-Ar dating on the igneous rocks in Japan(I)(in Japanese), J.Japan Assoc. Miner. Pet. Econ. Geol., 51, 127-148.

Keller, W.D.(1976a): Scanning electron micrographs of kaolins collected from diverse environments of origin-I, Clay Clays Miner.,24, 107-113.

Keller, W.D.(1976b): Scanning electron micrographs of kaolins collected from diverse environments of origin-II, Clay Clays miner., 24, 114-117.

Keller, W.D.(1976c): Scanning electron micrographs of kaolins collected from diverse environments of origin-III, influence of parent material on flint clays and flint-like clays, Clay Clays Miner., 24, 162-264.

Keller, W.D.(1977a): Scanning electron micrographs of kaolins from diverse environments of genesis-IV, Georgia kaolin and kaolinizing source rocks, Clay Clays Miner., 25, 311-345.

Keller, W.D.(1977b): Kaolins collected in Austraria and Japan on field trips of the sixth and seventh clay conferences, Clay Clays Miner., 25, 347-364.

Kinbara,K. and Ohkubo,T.(1978): Hydrothermal altered rocks found in an exploration Bore-hole(No.SA-I) Satsunan geothermal area, Japan(in Japanese), J.Japan Assoc. Miner. Pet. Econ. Geol., 76, 176- 179.

Kitagawa, R. and Kakitani, S.(1977): Alteration of plagioclase in granite during weathering, J.Sci.Hiroshima Univ., C, Vol.7, 183-197.

Kitagawa, R. and Kakitani, S.(1978a): The pale green clay vein in the granitic rock at the Ondo-cho district, Hiroshima Prefecture(in Japanese), J.Clay Sci. Japan, 18, 1-10.

Kitagawa, R. and Kakitani, S.(1978b): The white clay vein in the granitic rock at the Hachihonmatsu district, Hiroshima Prefecture(in Japanese), J.Clay Soci. Japan, Vol.I8, 31-39.

Kitagawa, R. and Kakitani, S.(1978c): Mode of occurrence and mineralogy of clay veins in granitic rocks with special reference to the genesis of clay minerals in them(in Japanese), J.Miner. Soc. Japan, Vol.13, 357-359.

Kitagawa, R. and Kakitani,S.(1979a): Modes of occurrence and mineralogy of mica clay minerals in the Hiroshima and San'in granitic complexes(inJapanese), J. Miner. Soc. Japan, Vol.14, 3-19.

Kitagawa, R. and Kakitani, S.(1979b): The mode of occurrence and mineralogy of Khodachi kaolin deposit and clay veins found in its host rock(in Japanese), Miner. Geol., Vol. 29, 217-226.

Kitagawa, R. and Kakitani, S., Kuroda, Y., Matsuo, S. and Tsuzuki, T.(1980): Hydrogen isotope ratios of clay minerals constituting clay veins found in granitic rocks of Hiroshima Prefecture(in Japanese), J.Geol.Soci.Japan, Vol.86, 167-177.

Kitagawa, R. and Kakitani, S.(1981): K-Ar ages of mica clay minerals in clay veins found in granitic and rhyolitic rocks of Hiroshima Prefecture, Japan, J.Japan Assoc. Miner. Pet. Econ. Geol., Vol.76, 176- 179.

Kitagawa, R. and Kakitani, S., Takeno,S. and Nishida, Y.(1981): Topographic examination and genesis of clay veins found in the Kumogi granite mass in Shimane Prefecture, Southwest Japan, J. Japan Assoc.Miner.Pet. Econ.Geol., Vol.76, 262-272.

Kitagawa,R., Kakitani, S. and Minato, S.(1981): The formation process of mica clay mineral, montmorillonite mineral and interstratified mineral of mica-swelling layer in clay veins found in granitic rocks(in Japanese), J.Clay Sci. Soci. Japan, 21, 141-152.

Kitagawa, R. and Kakitani, S.(1981): Lath-shaped mica clay mineral(in Japanese), J.Miner. Soci. Japan, 15, Spec., 107-115.

Kitagawa, R., Kakitani, S. and Hunaki, A.(1982): Mica clay minerals occurring in the sericite deposits at the Mitoya district, Iishi-gun, Shimane Prefecture (in Japanese), J.Clay Soci.Japan, Vol. 22, 54-67.

Kitagawa, R. and Okuno,T.(1983): Formation mechanism of clay veins found in granitic rock in Higashihiroshima district, Hiroshima Prefecture(in Japanese), J. Clay Sci. Japan,Vol. 23, 45-60.

Kitagawa, R., Takeno, S. and Sunagawa, I.(1983): Surface microtopograpies of sericite crystals formed in different environmental conditions, Miner.J., Vol.11, 282-296.

Kitagawa, R.,Hirosawa, H.,Nagai,K.and Nobushita,T.(1984): The shape and genesis of halloysite formed by alteration of granitic and rhyolitic rocks(in Japanese), J.Clay Soci.Japan, Vol.24, 20-33.

Kitagawa,R. (1985): The formation mechanism of clay veins found in granitic rocks and the alteration mechanism of granitic rocks(in Japanese), Professor Hironao Yoshida Memorial, 93-117.

Kitagawa, R. and Kameoka, H.(1986): The mode of occurrence and mineralogy of Komaki halloysite deposit and alteration of its surrounding granitic rock(in Japanese), J. Clay Soci.Japan, Vol.26 (in press).

Lawrence,J.R. and Taylor,Jr(1972): Hydrogen and oxygen isotope systematics in weathering profiles, Geoc. Cosm.

Acta, Vol.36, 1377-1393.

Marumo,K., Nagasawa,K. and Kuroda,Y.(1980): Mineralogy and hydrogen isotope geochemistry of clay minerals in the Ohnuma geothermal area, Northeastern Japan., Earth and Planetary Sci. Letter, 47, 255-262.

Matsuhisa,Y., Imaoka,I. and Murakami,N.(1980): Hydrothermal activity indicated by oxygen and paleogene cauldron, Southwest Japan, Mining Geol., Special issue, No.8, 49-65.

Matsumoto,K.(1965): On some kaolin deposits related to the granite in Chugoku district, Japan(in Japanese), Geol.Rep. Hiroshima Univ., No.14, 385- 395.

Matsumoto, K.(1968):On the geology and pyrophyllite deposits of the Yano Shokozan mine, Hiroshima Prefecture, Geol. Rep. Hiroshima Univ., No. I6, 1- 33.

Minato,H.(1969):Mica clay mineral, The clays of Japan, Ed.1969 international clay conf. Japan, 96- 102.

Miura, K.(1966):On the granitic rocks and their collapse at Kamo district, Shimane Prefecture(in Japanese), J.Japan Assoc. Miner. Pet. Econ. Geol., Vol.56, 256-283.

Miura, K.(1967):On the granitic rocks and their collapse at Kano district, Shimane Prefecture(in Japanese), J.Japan Assoc. Miner. Pet. Econ. Geol., Vol.57, 11-24.

Miura, K. and Hata, A.(1970):The collapse related to rock joints and joints clay of weathered granites, Econ., Vol.11, 6-38.

Miyahara, K.(1977):Study on the weathering of granite in

Hiroshima Prefecture, Japan, J. Sci. Hiroshima Univ., C, Vol. 7, 297-299.

Nagasawa, K. and Kunieda,K.(1970): Geology and mineralogy of clay deposits in the Naegi district, Gifu Prefecture(in Japanese), Mining Geol., 20, 361-377.

Nagasawa, T. and Miyazaki, S.(1975): Mineralogical properties of halloysite as related to its genesis, Proc. Int. Clay Conf., 257-265.

Nagasawa, K.(1978): A study on the formation and transformation of kaolin minerals(in Japanese), Rep. Earth Sci. Shizuoka Univ., Vol.3, 17-33.

Okamura,Y.(1965): Strucuture of the granite mass of the Kurokami island, Tokuyama island, Tokuyama city Yamaguchi Prefecture(in Japanese), Geol. Rep. Hiroshima Univ., No. 14, 307-316.

O'Neil,J.R. and Taylor, H.P., Jr.(1969): The oxygen isotope and cation exchange chemistry of feldspar, Amer. Miner., Vol.52, 1414-1437.

O'Neil, R. and Kaharaka,Y.K.(1976): Hydrogen and oxygen isotope exchange reactions between clay minerals and water, Geochi. Cosmochi. Acta, Vol.44, 241-246.

Ohyagi, N.(1968): Weathering-zone structure and landslides of the area of granitic rocks in Kamo-daito, Shimane Prefecture(in Japanese), Bousaiken houkokusyo, Vol.14,

Ohyagi, N., Uchida, T. and Suzuki, H.(1969): Clay minerals of weathering zone in Kamo-Daito granodiorite region, Clay minerals and their formation sequence in weathering(in Japanese), Bousaiken Houkokusyo, Vol.2, 21-44.

Parham,W.(1969): Halloysite-rich tropical weathering products of Hong Kong, Proc. Intern. Clay Conf., 1, 403-416.

Sakai, H. and Matsubaya, O.(1977): Stable isotopic studies of Japanese geothermal systems, Geothermics, Vol.5, 97-124.

Savin, S.M. and Epstein, S.(1970): The oxygen and hydrogen isotope geochemistry of ocean sediments and shales, Geochi. Cosmochi. Acta, Vol.34, 43-64.

Shibata, K. and Ishihara, S.(1974a): K-Ar ages of the major tungsten and molybdenum deposits in Japan, Econ, Geol., Vol. 69, 1207-1214.

Shibata, K. and Ishihara, S.(1974): K-Ar ages of biotites across the central part of the Hiroshima granite(in Japanese), J. Geol. Soci. Japan, Vol.80, 431-433.

Shimizu,H.(1972): Kaolin mineral transformation during weathering and diagenesis(in Japanese), J. Clay Sci. Soci. Japan, Vol.4 , 137-142.

Shimizu, H.(1978): Micromorphology of halloysite produced by weathering of plagioclase in volcanic ash, Int. Clay Conf., 4I5-422.

Sheppard,S.M.F., Nielsen, R.L. and Taylor, H.P.(1969): Oxygen and hydrogen isotope ratios of clays from porphyry copper deposits, Econ. Geol. Vol.64, 755-777.

Sigvaldason,G.E.(1962): Epidote and related minerals in two deep geothermal drill holes, Reykjavik and Hveragerdi, Iceland, U.S. Geol. Surv. Prof. Paper, 450-E, 77-79.

Sumi, K.(1966): Hydrothermal rock alteration of the Matsusaka geothermal area, Iwate Prefecture(in Japanese), Mining. Geol., Vol.16, 261-271.

Sumi, K.(1968): Hydrothermal rock alteration of the Matsukawa geothermal area, Northeast Japan, Rep. Geol. Surv. Japan, 1-42.

Sunagawa, I., Koshino, Y., Asakura, M. and Yamamoto, T.(1975): Growth mechanism of some clay mineral, Fortschr. Miner., Vol.52, 217-224.

Sunagawa, I. and Koshino, Y.(1975): Growthspirals on kaolin group minerals, Amer. Miner., Vol.60, 407- 412.

Sunagawa, I.(1977): Natural crystallization, J. Crystal growth, Vol.42, 214-223.

Suzuoki, T. and Epstein, S.(1976): Hydrogen isotope fractionation between OH-bearing minerals and water, Geochi. Cosmochi. Acta, Vol. 40, 1229- 1240.

Takashima, I.(1972): Hydrothermal rock alteration in Takenoyu geothermal area, Kumamoto Prefecture, Japan(in Japanese), Bull. Geol Surv. Japan, Vol.23, 721-728.

Tazaki, K.(1977): Formation of clay minerals from plagioclase, Miner. J., Vol.I3, 172-177.

Tazaki, K.(1978): Micromorphology of halloysite produced by weathering of plagioclase in volcanic ash, Inter. Clay Conf., 415-422.

Tomura, S., Kitamura, M. and Sunagawa, I.(1979): Surface microtopography of metamorphic white micas, Phys.

Chem., Vol.5, 65-81.

Tsuzuki,Y.(1985): Thermodynamics and kinetics of weathering and hydrothermal alteration(in Japanese), J. Geol. Soci. Japan, Vol.91, 699-718.

参考論文

1. Alteration of plagioclase in Granite during weathering.
   Jour. Sci. Hiroshima Univ., (1977)
2. 広島県下の花こう岩中に細脈として産する粘土鉱物
   鉱物学雑誌　(1977)
3. 花こう岩中にみられる粘土細脈の産状と成因
   鉱物学雑誌　(1978)
4. 広島県賀茂郡八本松町の花こう岩中にある白色粘土細脈
   粘土科学　(1978)
5. 広島県安芸郡音戸町の花こう岩中にある青緑色粘土細脈
   粘土科学　(1978)
6. 広島花こう岩と山陰花こう岩中に細脈として産する雲母粘土鉱物
   鉱物学雑誌　(1979)
7. 甲立カオリン鉱床とその周辺の粘土細脈
   鉱山地質　(1979)
8. K-Ar ages of sericite from the Chugoku disrtict, Japan.
   Bull. Geol. Surv. Japan　(1980)
9. 広島県下の花こう岩中の細脈として産する粘土鉱物とその水素同位体比
   地質学雑誌　(1980)
10. 短冊状雲母粘土鉱物の鉱物学的特徴
    鉱物学雑誌　(1981)
11. Topographical examination and genesis of clay veins found in the kumogi granite mass in Shimane Prefecture, southwest Japan.
    J. Japan. Assoc. Min. Pet. Econ. Geol. (1981)
12. 花こう岩中の粘土細脈を構成する雲母粘土鉱物、モンモリロナイト鉱物、雲母－膨潤層混合層鉱物
    粘土科学　(1981)
13. K-Ar ages of mica clay minerals in clay veins found in granitic and rhyolitic rocks of Hiroshima Prefecture, Japan.
    J. Japan. Assoc. Min. Pet. Econ. Geol. (1981)
14. 島根県飯石郡三刀屋町付近のセリサイト鉱床中の雲母粘土鉱物
    粘土科学　(1982)

15. Effect of transition elements upon the nucleation and the morphology of magnetite in silicate melts of basaltic composition.
J. Sci. Hiroshima Univ. (1983)

16. Surface microtopograpies of sericite crystals formed in different environmental conditions.
Miner. Jour. (1983)

17. 東広島市付近に分布する花こう岩中の粘土細脈の形成機構
粘土科学 (1983)

18. 花こう岩及び流紋岩の変質作用により生成されたハロイサイトの形状と成因
粘土科学 (1984)