Orientation Analysis and Formation Ages of Fractures Filled with Clay Minerals (Clay Veins) in Hiroshima and Shimane Prefectures, Southwest Japan

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Key words : paleostress field, clay vein, granite, K-Ar age, clay mineral, fracture

Abstract

Fractures filled with clay minerals (clay veins) occur extensively in granitic and rhyolitic rocks throughout Hiroshima and Shimane Prefectures, southwest Japan. The main constituent clay minerals are mica clay mineral, smectite and kaolin mineral. Based on K-Ar dating of mica clay mineral, the formation age of the clay veins is almost the same or slightly predates the emplacement age of the host or surrounding granitic rocks. Therefore, it is suggested that most of the clay veins were formed immediately after solidification of the host or surrounding granitic rocks.

The orientations of the clay veins in 13 specific regions in Hiroshima and Shimane Prefectures were systematically analyzed, and 20 K-Ar ages of constituent clay minerals (mainly mica clay mineral) within the veins of each region were determined, i.e. 31 – 80 Ma.

The orientation analysis of fractures suggests that most of the fractures were formed under a regional stress field. The azimuth of maximum principal stress axis appears to have varied at least several times during period from the Cretaceous to Palaeogene in Hiroshima and Shimane Prefectures. The maximum compression stress directions vary from WNW-ESE to NE – SW, E – W, NW – SE or NNE-SSW, E – W and finally N – S or NW – SE, over a ca. 50 million year period. Comparing these results with those obtained previously from dyke orientations, the azimuths of maximum compression stress axis are broadly resemble.

Thus, orientation analysis of clay veins is a useful technique to determine paleostress fields in granitic terrain.

1. Introduction

Several types of fracture are developed in granitic and rhyolitic rocks in Hiroshima and Shimane Prefectures, southwest Japan. Clay minerals are filling in certain types of fracture. According to KITAGAWA^{2)~4)} and MIURA and HATA⁵⁾, clay veins occur along certain types of fracture, such as small faults and joints. The main constituent minerals of clay veins are mica clay minerals (sericite), smectite and kaolin minerals^{2)~4)}. Based on the measurement of isotopic ages, it has been proposed that these clay minerals were formed from

hydrothermal solutions post-granitoid emplacement^{6),7)}. Therefore, it is suggested in this paper that the formation ages of clay veins in granitic rocks can be used to determine the timing of geological events.

In this study, the formation age of clay veins has been determined using K-Ar dating techniques. In addition, the orientations of clay veins in granitic and rhyolitic rocks distributed throughout Hiroshima and Shimane Prefectures have been systematically analyzed.

Fractures in igneous rocks can be formed by various processes, such as applied tectonic stresses, release of confining pressure or cooling processes¹⁸⁾. In this study, fractures filled with clay minerals are considered to have formed mainly as the result of a regional tectonic stress field as discussed below.

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In general, analyses of paleostress fields have been carried out using several methods, such as the orientation of dykes⁸⁾ and fractures, such as faults⁹⁾ and joints^{10)~12)}. In this study, the maximum compression stress direction in Hiroshima and Shimane Prefectures has been determined by orientation analysis of clay veins with known a formation age.

2. Regional geology and analytical methods

Cretaceous to Tertiary granitic and rhyolitic rocks are widely distributed in Hiroshima and Shimane Prefectures.

Clay veins within these rocks are classified into four types on the basis of their fracture patterns. These four types are described below and schematically illustrated in Fig. 1.

Type 1 clay veins are formed along the margins of small intrusive rocks such as granite porphyry, quartz

porphyry and felsite. The clay veins vary in thickness from about 1 cm to 1 m.

Type 2 clay veins occur in sub-vertical fractures (1 mm to several tens of cm in width), characterized by the development of slickenside.

Type 3 clay veins are developed along small fractures, 1 mm to 10 mm in width, and characteristically occur in swarms.

Type 4 clay veins are aligned with microfractures (<1 mm in width).

More than one type of vein can be developed at the outcrop scale. The veins can be traced along strike for up to several kilometers (Fig. 2).

After analysis of the preferred orientations of the strike and dip of veins, areas which contain similar orientations of clay veins were classified into district region. Based on this orientation analysis and the host rock type, 13 regions in Hiroshima and Shimane Prefectures

Fig. 1 Schematic illustration of clay veins of the four types classified based on the characteristics of fractures.

Fig. 2 Development of clay veins (fracture filling with clay minerals) of each type with their strikes in Kamo region, Hiroshima Prefecture.

Table 1 Strikes and dips of clay veins classified on the basis of the mode of occurrence in respective regions (see text for explanation).

Region	Locality	Host Rock	Type of vein	Color	Constituent clay mineral
1. Kure-Higashihiroshima	Kure-city, Hiroshima Pref.	Biotite granite (Cretaceous)	4	Pale-green	Mica clay mineral with M/S
2. Ohno	Ohno-cho, Aki-gun, Hiroshima Pref.	Biotite granite (Cretaceous)	3	Green	Mica clay mineral
3. Kamo	Takaya, Higashihiroshima, Hiroshima Pref.	Biotite granite (Cretaceous)	1, 3	Green	Mica clay mineral with kaolinite
4. Takehara	Takehara-city, Hiroshima Pref.	Rhyolite (Cretaceous)	2	Green	Mica clay mineral with kaolinite
5. Hiroshima-Kake	Nukui, Kake-cho, Yamagata, Hiroshima Pref.	Biotite granite (Cretaceous)	4	Green	Mica clay mineral with smectite
6. Kohdachi-Miyoshi	Miyoshi-city, Hiroshima Pref.	Rhyolite (Cretaceous)	2	Pale-green	Mica clay mineral with kaolinite
7. Toyohira-Chiyoda	Toyohira-cho, Yamagata, Hiroshima Pref.	Biotite granite (Cretaceous)	2	Pale-green	Mica clay mineral
8. Ohasa	Ohasa-cho, Yamagata Hiroshima Pref.	Biotite granite (Cretaceous)	2	Pale-green	Mica clay mineral
9. Shobara	Shobara-city, Hiroshima Pref.	Rhyolite (Cretaceous)	4	Pale-green	Mica clay mineral
10. Mizuho	Mizuho-cho, Ochi-gun Shimane Pref.	Biotite granite (Tertiary)	2	White	Mica clay mineral
11. Kanagi	Kanagi-cho, Iga-gun, Shimane Pref.	Biotite granite (Tertiary)	2	White	Mica clay mineral with kaolinite
12. Yokota	Komaki, Yokota-cho, Nita, Shimane Pref.	Biotite granite (Tertiary)	4	White	Mica clay mineral
13. Mitoya	Mitoya-cho, Iishi-gun, Shimane Pref.	Ho-Bi granite (Tertiary)	4	Green	Mica clay mineral with kaolinite

Fig. 3 Stereo diagrams on Schmidt net showing the preferred orientation of poles of fractures filled with clay minerals (clay veins) observed in various regions. Lower hemisphere projection.

The number of clay veins measured and the contour intervals appear next to each diagram.

are classified (see Table 1). These are: Kure-Higashihiroshima, Hiroshima-Kake, Ohno, Kamo, Chiyoda, Ohasa, Mizuho, Kanagi, Yokota and Mitoya (all granite region) and Takehara, Kohdachi-Miyoshi and Shobara (all rhyolite regions).

According to KITAGAWA *et al.*^{2)~4)}, the main constituent clay minerals within clay veins are mica clay minerals, smectite and kaolin minerals. It is possible to date the formation of mica clay minerals (containing K ions) using the K-Ar dating method. K-Ar dating techniques used in this study follow the methods reported by NAGAO *et al.*¹⁴⁾ and ITAYA *et al.*¹⁵⁾. The K-Ar ages were determined on 20 samples collected from clay veins in 13 regions. The sample localities and characteristics of these clay veins are summarized in Table 1.

3. Results

3.1 Orientations of clay veins

The orientations of clay veins distributed in several of

the regions classified above (Ohno, Takehara, Hiroshima-Kake, Ohasa and Yokota) are shown in Fig. 3 as contoured diagrams. As shown in Fig. 3, almost all veins dip vertically. Therefore, the strike of veins in all of the measured regions are illustrated in Fig. 4 as a rose diagram. These results indicate that within each region, the clay veins have two or three dominant orientations. The dip and strike of the dominant orientations of the different type clay veins in each region are summarized in Table 2.

3.2 Age determination of clay minerals

The results of the age determinations of the selected mica clay minerals are shown in Table 3 and also illustrated in chronological order with the K-Ar ages of the host or surrounding granitic rocks^{16),17)} in Fig. 5. As shown in Fig. 5, the ages of the mica clay minerals vary from 31 Ma to 80 Ma. The ages of clay minerals, together with the azimuths of the maximum principal stress axis obtained from the fracture (vein) orienta-

Fig. 4 Histograms of the strikes of clay veins (fractures) in each region.

Table 2 The characteristics of clay veins determined the K-Ar ages in 13 regions.

Region	Type of vein	Strike	Dip
1. Kure-Higashihiroshima	2, 3	N0°-20°E, E-W, N40°-70°E	70°-90°
2. Ohno	2, 3	N0°-30°W, N40°-70°E	60°-90°
3. Kamo	1, 4 2, 3	N60°-90°W N50°-90°E, N40°-80°W	70°-90° 70°-90°
4. Takehara	1, 4 2, 3	N40°-50°E N-S, N30°-50°E, E-W	70°-90° 70°-90°
5. Hiroshima-Kake	2, 3	N0°-10°E, N60°-80°E	60°-90°
6. Kohdachi-Miyoshi	2, 3 4	N-S, N20°-30°E, N50°-60°E N20°-60°E	70°-90° 70°-90°
7. Toyohira-Chiyoda	1, 2, 3, 4	N-S, E-W, N20°-60°E	60°-90°
8. Ohasa	2, 3	N30°-50°E, N30°-60°W	70°-90°
9. Shobara	2, 3, 4	E-W	70°-90°
10. Mizuho	1, 4 2, 3	E-W, N40°-60°W N40°-70°E, N30°-70°W	60°-90° 60°-90°
11. Kanagi	4 2, 3	N-S, N50°-80°W N-S, N50°-80°W	70°-90° 70°-90°
12. Yokota	2, 4	N30°-60°W, N0°-20°E, N80°-90°E	60°-90°
13. Mitoya	2, 4	N10°-20°E, N50°-60°W	70°-90°

Table 3 The K-Ar ages determined of mica clay minerals collected from clay veins in each region.

Region	K% (wt)	Age (Ma)
1. Kure-Higashihiroshima	9.02	68.4 ± 3.4
2. Ohno	5.86	76.6 ± 3.8
3. Kamo	5.88 6.85	80.2 ± 2.4 79.5 ± 4.0
4. Takehara	2.68	75.7 ± 3.7
5. Hiroshima-Kake	6.41	74.3 ± 3.7
6. Kohdachi-Miyoshi	2.44	76.5 ± 3.8
7. Toyohira-Chiyoda	6.36	70.7 ± 3.5
8. Ohasa	4.38	38.3 ± 1.9
9. Shobara	4.09 3.17	66.6 ± 3.3 67.2 ± 2.1
10. Mizuho	8.13	36.4 ± 1.8
11. Kanagi	8.23 2.41 8.23	31.4 ± 1.6 32.2 ± 1.6 34.7 ± 1.6
12. Yokota	4.81	55.6 ± 2.8
13. Mitoya	4.59 7.77 6.50 8.15	45.6 ± 2.3 48.5 ± 2.4 50.3 ± 2.5 50.6 ± 2.5

tions of each region are summarized in Table 4.

4. Discussion

Fractures in rocks can result from a number of different processes. Some of the forces that generate fractures can originate within the rock mass, whereas others form from externally applied stressfields¹⁸⁾. Fractures within igneous rocks can be formed by applied tectonic

Fig. 5 The K-Ar ages of mica clay minerals collected from clay veins and their host or surrounding granitic rocks with the azimuth of maximum principal stress axis based on the fracture systems of clay veins in each region.

stress, releasing of confining pressure within the magmatic bodies or cooling processes¹⁸⁾.

Because of the near vertical dips of the clay veins ana-

Table 4 Tectonic stress, formation ages of clay minerals and the K-Ar ages of their host or surrounding granitic rocks in each region. *: KAWANO and UEDA¹⁶⁾, **: SHIBAT and ISHIHARA¹⁷⁾.

Region	K-Ar ages (Ma)		Azimuth of maximum principal stress axis
	Clay vein	Host or surrounding Granitic rock	
Kanagi	31.4, 32.2, 34.7		NW - SE, N-S
Mizuho	36.4	34*, 40**	E - W
Ohasa	38.3	38**	E - W
Mitoya	45.6, 48.5, 50.3,	51*	NW - SE, NNE-SSW
Yokota	50.6 55.6		NW - SE
Shobara	66.6, 67.2		E - W
Kure-Higashihiroshima	68.4	76*	NE - SW
Toyohira-Chiyoda	70.7	80**	NE - SW
Hiroshima-Kake	74.3	76†, 80**	NE - SW
Takehara	75.7		NE - SW
Kohdachi-Miyoshi	76.5	87*	NE - SW
Ohno	76.6	82**	NE - SW
Kamo	79.5, 80.2		WNW - ESE

Fig. 6 Histograms of the strikes of clay veins classified on the basis of the fracture types in the Kamo region, Hiroshima Prefecture.

lyzed in this study, characteristic orientation patterns can be illustrated using only the strike of the fractures. As an example of the orientation analysis, the results from the Kamo region are shown in Fig. 6 as rose diagrams, where Type 1, 2, 3 and 4 clay veins are commonly well developed (Fig. 2). Type 1 and 4 clay veins dominantly strike $N60^{\circ} - 80^{\circ}W$, whereas those of Types 2 and 3 are orientated in two directions. $N40^{\circ} - 70^{\circ}W$ and $N60^{\circ} - 80^{\circ}E$. It is noted that the direction of the former ($N60^{\circ} - 80^{\circ}W$) corresponds to the intersection line of the latter two vein-sets ($N40^{\circ} - 70^{\circ}W$ and $N60^{\circ} - 80^{\circ}E$).

BLES and FEUGA¹⁾ have suggested that tensional failure take place in a plane parallel to the azimuth of the maximum stress axis, on the basis of uniaxial compressive rock failure tests, and also produces conjugate fractures under the triaxial compression test. Magma intruded into tensile fractures typically form dykes⁸⁾. There-

fore, the strike and dip of dykes correspond to those of the compression direction¹⁸⁾.

By analogy with these fracture systems, the types 2 and 3 fractures appear to correspond to conjugate fractures, and are associated with slickensides in some cases. This suggests that many veins of Types 2 and 3 are shearing fractures formed by compression stress. Type 1 and Type 4 veins have broadly similar orientations. Consequently, Types 1 and 4 veins possibly formed as tension fractures in response to the same compression events. The azimuth of the maximum principal stress axis deduced from the data is $N80^{\circ} - 90^{\circ}W$ in the Kamo region. Although all four types of veins are not always developed in each region (Table 2), it may be possible to determine the paleostress field in each region. In other regions, two or three dominant vein directions were analyzed (Table 2 and Fig. 4). Based on the analytical data, clay veins are considered to have formed main-

Fig. 7 Schematic representation of azimuth of maximum principal stress axis based on the orientation analysis of clay veins in each region.

Numbers represent K-Ar ages (Ma) of mica clay mineral filled in fractures.

ly under a single regional tectonic stress field. The calculated maximum principal stress axis is schematically summarized in Fig. 7. At least seven maximum principal stress axis can be distinguished in Hiroshima and Shima-
mane Prefectures. There are WNW – ESE, NE – SW, E – W, NW – SE, NNE – SSW, N – S and NW – SE.

The K-Ar ages of mica clay minerals from each region range from Cretaceous to Palaeogene (Table 4). The ages of granitic rocks distributed in Hiroshima and Shima-
mane Prefectures have been determined by KAWANO and UEDA¹⁶⁾ and SHIBATA and ISHIHARA¹⁷⁾. The formation ages of most clay minerals are similar to, or slightly younger than the K-Ar ages of the host or surrounding granitic rocks (Fig. 5). It is considered that the clay minerals formed immediately after solidification of the host granitic magmas. Therefore, the formation

time of the clay veins was closely similar to the intrusive event.

The K-Ar ages of clay minerals in each region, together with the direction of the maximum principal stress axis, are summarized in Table 4 and Figs. 5 and 7. It is concluded from these results that the maximum principal stress axis changed several times during the period from the Cretaceous to the Palaeogene. In chronological order, their changes are WNW – ESE (79 – 80 Ma), NE – SW (68 – 76 Ma), E – W (66 – 67 Ma), NW – SE (45 – 55 Ma) or NNE – SSW (45 – 50 Ma), E – W (36 – 38 Ma) and finally again N – S or NW – SE (31 – 34 Ma).

According to YOKOYAMA and HARA⁸⁾, the maximum principal stress axis in the inner zone of southwest Japan can be divided into five distinct populations, with

reference to the intrusion age of Late Mesozoic to Early Tertiary dykes, i.e. E-W (I phase), NW-SE (II phase), NNW-SSE and NNE-SSW (III phase), NNW-SSE and NNE-SSW (IV phase) and E-W (V phase). Unfortunately, the emplacement ages of these dykes are currently unconstrained. However, comparing the results of this study with these of YOKOYAMA and HARA⁸⁾, it indicates that some maximum principal stress axes are similar, such as WNW-ESE: I phase, NNE-SSW: III or IV phase and E-W: V phase.

5. Conclusion

It is possible to determine the formation ages of clay veins in granitic rocks by dating mica clay minerals. The analysis of the extension directions of clay veins developed in granitic rocks is a useful technique to determine the paleostress field in granitic terrains.

The results mentioned above indicate that the maximum principal stress axis in Hiroshima and Shimane Prefectures changed several times during the period from the Cretaceous to the Palaeogene, e.g. WNW-ESE, NE-SW, NW-SE or NNE-SSW, E-W, N-S or NW-SE in chronological order.

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広島県と島根県に分布している粘土鉱物をうめた 割れ目（粘土細脈）の配行解析と形成年代

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要 旨

広島県や島根県に分布している花崗岩や流紋岩中には、割れ目をうめて、いわゆる粘土細脈が多く認められる。この粘土細脈中の主な粘土鉱物は雲母粘土鉱物、スメクタイト、カオリン鉱物である。雲母粘土鉱物の K-Ar 年代測定を行ったところ、その形成年代は母岩の花崗岩や周辺の花崗岩の K-Ar 年代とほとんど同じか、あるいはやや若い値を示す。このことは粘土鉱物をうめている割れ目（粘土細脈）は花崗岩が固結後間もない時期に形成されたことを示している。

そこで、広島県と島根県に分布している花崗岩地域と、周辺に花崗岩が存在している一部流紋岩地域を13の領域に分け、粘土細脈の配行（走向、傾斜）を調べた。またその領域からそれぞれ代表的脈を20選び、その K-Ar 年代測定を行なった。その結果、粘土細脈の K-Ar 年代は31-80 Ma である。

また、粘土鉱物をうめている割れ目（粘土細脈）の配行の解析から、それらは広域圧縮応力場で形成され、最大圧縮応力の方向は白亜紀から古第三紀にかけて少なくとも数回変化したと推定された。すなわち、約5000万年の間に WNW-ESE, NE-SW, E-W, NW-SE あるいは NNE-SSW, E-W そして最後に N-S あるいは NW-SE である。

今回の結果と従来貫入岩から求められている応力場の変遷とを比較すると類似点が多い。すなわち、今まで割れ目や貫入岩の配行解析から求めていた応力場解析に対して、具体的年代を特定することができることを意味している。このことから少なくとも広島県や島根県の花崗岩分布地域においては、粘土細脈の配行解析は古応力場の変遷を知る上で一つの有効な方法であることを示している。