A study on the environment and time of precipitation of fracture fillings in rock on coastal outcrops of Yakushima Island, Japan

Tomoaki MATSUSHITA1), Masahiko OSADA2), Manabu TAKAHASHI3) and Yukiyasu FUJII4)
1) Rock Mechanics Lab., Department of Civil and Environmental Engineering, Saitama University
2) Geosphere Research Institute, Saitama University
3) National Institute of Advanced Industrial Science and Technology
4) Fukada Geological Institute

ABSTRACT

This paper describes the petrological and geochemical features as well as the ages of rock fractures filled mainly with carbonates on coastal outcrops on Yakushima Island, Japan. Microscopic observation, SEM observation, and XRD analysis were used to investigate the composition and microscopic texture of the fracture fillings. In addition, AMS 14C dating was performed to estimate their ages. Microscopic observation indicated that the fillings contain not only cementing materials, but also lithic fragments from the host rock and bioclasts. The results also showed that the fillings in a sample have layered structures parallel to the fracture surface. SEM observation showed that the cement is composed of micrites and exhibits the characteristic textures of beachrock. The cement was identified as Mg-calcite through XRD analysis. Further, aragonite was clearly detected in one sample. AMS 14C dating of seventeen samples of fracture fillings indicated that the ages range from 2,460 to 5,130 years BP which is younger than that of the uplifted coral at Yakushima Island (approximately 5,300–5,600 years BP). Furthermore, the results showed that there is a 2,000–2,700 year variation even though the samples were collected from a single fracture.

KEYWORDS: Yakushima Island, coastal outcrops, rock fracture fillings, carbonates, radiocarbon dating

1. INTRODUCTION

Fracture fillings in rock contain useful information on paleohydrogeology. For example, mineralogical, petrological and geochemical features of fracture fillings can provide information on the source and nature of fluids in which they were precipitated (Wallin and Peterman 1999; Blyth et al. 2000; Iwatsuki et al. 2002; Benedicto et al. 2008). Ages of fracture fillings are also an important factor when estimating the time of past hydrogeological events such as the history of host rock cooling and fracturing processes (Kamineni and Stone 1983; Yoshida et al. 2000, 2005), the time of infiltration of groundwater into a fault (Lin et al. 2003) and the precipitation rate of minerals (Neymark and Paces 2000; Neymark et al. 2002; Paces et al. 2010). Therefore, it is necessary to accumulate such detailed data from different fracture fillings.

Rock fractures filled mainly with carbonates are frequently observed on coastal outcrops of granite and sedimentary rock on Yakushima Island, Japan. The ages of the fillings are several thousand years before present (BP) and are remarkably younger than the ages of hydrothermal (Kamineni and Stone 1983; Yoshida et al. 2000, 2005) and low-temperature fillings (Kamineni and Stone 1983; Yoshida et al. 2000, 2005; Lin et al. 2003; Asahara and Tanaka 2007; Watanabe et al. 2008) in rock fractures. Therefore, these fillings can provide detailed information on precipitation processes in rock fractures for several thousand years.

In this study, the occurrence, composition, microscopic structure and age of the fracture fillings was investigated in order to estimate the environment and time of precipitation.

2. STUDY AREA

2.1 Yakushima Island

Yakushima is an almost circular island having a circumference of approximately 135 km and belongs to the Nansei Island chain in Japan. It is located approximately 60 km south of Cape Sata on Osumi Peninsula in Kagoshima prefecture (Fig. 1a). The island has a subtropical climate and is one of the highest precipitation areas in Japan due to typhoons and orographic rainfall.

Yakushima granite has intruded into the sedimentary rock of the Shimanto accretionary complex in the central part of the island (Fig. 1b). Yakushima granite was formed 14-13 Ma (Shibata and Nozawa 1967) and consists mainly of quartz,
plagioclase, K-feldspar, biotite, and orthoclase megacryst (Anma et al. 1998). The accretionary complex is composed mainly of mudstone and sandstone (Nagahama and Sakai 1972) and has been regionally affected by contact metamorphism associated with the intrusion of granite (Ishikawa 1965).

Holocene uplifted corals are frequently distributed in intertidal and supratidal zones on Yakushima Island as well as other islands in the Nansei Island chain (Nakata et al. 1978). Relative sea level rapidly increased after the last glacial period (Nakada and Lambeck 1988) and reached several meters higher than the present sea level approximately 6,000 years ago around the Nansei Islands (Pirazzoli et al. 1984; Nakada et al. 1991; Hongo and Kayanne 2009). Later, relative sea level gradually decreased until it reached its present level (Nakada et al. 1991). Therefore, it is believed that coral reefs around the Nansei Islands were relatively uplifted due to the sea drop.

2.2 Fracture fillings

Rock fractures sealed by a mainly pink-colored filling are common on coastal outcrops of Yakushima Island. The fillings were identified as carbonates due to their reaction with hydrochloric acid in the field. It has also been observed that these sealed fractures, which have a convex shape protruding several cm above the host rock, have solidified (Fig. 2a) although many fractures have been eroded by physical and chemical weathering (Fig. 2b). Following on from Matsushita et al. (2013), they are referred to as “solidified fractures” in this study.

Fracture fillings were collected from the outcrops of granite on Inakahama coast and the outcrops of sedimentary rock along Onoaida, Harutahama and Kurio coasts (Fig. 1b) for microscopic

Fig. 1 a) A map of the Nansei Islands, Japan, b) A geological map of Yakushima Island.

Fig. 2 Coastal outcrops of granite on Yakushima Island. a) Solidified fracture, b) Eroded fractures.

Fig. 3 Solidified fracture in granite and uplifted coral (right side) on Inakahama coast. The arrows indicate the positions from where the samples were collected and the values show the horizontal distance from the uplifted coral.

Fig. 4 Fracture fillings in sedimentary rock along Onoaida coast. a) Two rock fractures (left: N50°W46°SW, right: N2°W34°SW), b) A schematic cross section of the right fracture showing sampling elevations.
Fig. 5 Microscopic images with crossed nicols of fracture fillings in granite (a,b) and sedimentary rock (c,d).

a) Various types of fragments. b) Relatively large fragment in a crack. The length of the fragment is about 0.16 mm and the width of the crack is about 0.24 mm. c) Fragments of mudstone. d) Layered structures at x plane of YKI1103-50 sample. Qtz: quartz, Fs: feldspar, Bt: biotite, Bc: bioclast, Ms: mudstone
Inakahama coast (Fig. 5a, b) and in sedimentary rock from Onoaida coast (Fig. 5c, d). The microscopic observation revealed that the fracture fillings consist of various types of fragments and cementing materials. The fragments include bioclasts and lithic fragments from granite (Fig. 5a) or sedimentary rock (Fig. 5c). Relatively large fragments were frequently observed within fractures and cracks. For example, a fragment about 0.16 mm in length was present in a crack of approximately 0.24 mm width (Fig. 5b). Clogging had occurred in the left side of the crack. This implies that the crack experienced flow drive strong enough to transport the large fragment in the past. Fig. 5d shows a cross section along the x plane of the fracture fillings (YKI1103K50) in sedimentary rock. There are two layers parallel to the fracture surface. The bottom layer contains many fragments including relatively larger grains. On the other hand, the upper layer contains a few fragments of relatively smaller size. This implies that the fracture fillings were precipitated in multiple stages.

The cementing materials of the fracture fillings are composed of very fine crystals and fill the cracks (Fig. 5b) and the pore space between fragments (Fig. 5a, d).

3.2 SEM observation

SEM observation was performed for freshly broken and gold-coated samples with JEOL ISM-5600LV (15-20 kV) to observe the crystal morphology of cementing materials.

Fig. 6 shows the SEM images of the cementing materials of the fracture fillings in (a) granite and (b) sedimentary rock. They are mainly composed of micrites that are microcrystalline calcites several µm in diameter. In addition, these micrites frequently aggregate and form pseudo-peloidal textures (indicated with arrows in the figures) that show subpherical to elliptical bodies. These are the characteristic textures of beachrocks (Rey et al. 2004; Vieira and De Ros 2006; Vousdouskas et al. 2007).

3.3 XRD analysis

XRD analysis was performed to identify cementing materials of fracture fillings. Two samples of fillings and the uplifted coral were collected from Inakahama coast (Fig. 3). Four samples of fillings were collected from the fracture on Onoaida coast (Fig. 4b). All samples were powdered in an agate mortar and were analyzed with a Rigaku RINT-2100S diffractometer with CuKα radiation (50 kV, 250 mA).

The results for the fracture fillings in granite and sedimentary rock are shown in Fig. 7a and 7b respectively. It is obvious that the cementing materials are Mg-calcite which is calcite generally containing 5-18 mol% MgCO₃ (Garrels and Wollast 1978). On the other hand, aragonite was also detected clearly in the sample collected from the lowest position at Onoaida coast (Onoaida 90 in Fig. 7b). In addition, the result shows that the uplifted coral contains two types of carbonates that are Mg-calcite and aragonite.

4. RADIOCARBON DATING

AMS ¹⁴C dating was performed on fracture fillings. The NEC 9SDH-2 utilizing AMS system-based 3MV pelletron tandem accelerator was used for ¹⁴C measurement with high sensitivity in which the standard material was oxalic acid. In the tests, isotopic fluctuation for each sample was corrected by using a carbon stable isotope ratio that was also measured on AMS, and the conventional AMS ¹⁴C ages were obtained. Next, the obtained result was calibrated to calendar year using the OxCalv 4.0.5 or OxCalv 4.1.7 program with Marin04 curve although the marine reservoir effect is not the same in all locations.

AMS ¹⁴C dating was performed for twenty samples: three samples of the uplifted coral (nos. 1-3) and seventeen samples of the fracture fillings.
The uplifted coral was collected from the intertidal zone on Inakahama coast (Fig. 3). The fracture fillings were sampled from different locations: nos. 4-15 samples were collected from the fractures in granite at Inakahama coast, no. 16 and nos. 17-20 samples were collected from the fractures in sedimentary rock on Harutahama coast and Onoaida coast respectively. Among them, samples 8-15 and 17-20 were collected from a single fracture in granite (Fig. 3) and sedimentary rock (Fig. 4) respectively. The elevations of all samples are range from 0 to +3 m a.s.l.

The results are listed in Table 1. The standard variation for AMS $^{14}$C age is ±20-40 years and the range of calendar year is shown as time interval of 1σ. A carbon stable isotope ratio is expressed in δ$^{13}$C with reference to the PDB (Pee Dee Belemnite) standard. The value may indicate its source or help to reveal chemical reaction between minerals and water.

From the results, it is clear that AMS $^{14}$C ages of the uplifted coral range from 5,320 to 5,600 years BP which correspond to the ages of uplifted corals in the intertidal zone along the southeast coast (Ambô) in Yakushima Island (Nakata et al. 1978). Many researchers have also reported that uplifted corals in the intertidal zone along the coasts of the Nansei Islands are dated as late Holocene (Nakata et al. 1978; Yokoyama et al. 1996; Kawana 2001). On the other hand, the ages of the fracture fillings range from 2,460 to 5,130 years BP. Evidently, their ages are younger than those of the uplifted coral. In addition, there are 2,000-2,700 year variations even in samples that

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Table 1 Results of radiocarbon dating for fracture fillings and uplifted coral

<table>
<thead>
<tr>
<th>No.*</th>
<th>sample name</th>
<th>location sample</th>
<th>position(m)</th>
<th>δ$^{13}$C(‰) [AMS]</th>
<th>$^{14}$C age (yrBP)</th>
<th>Calendar year [1σ]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>YKI0811I-1</td>
<td>Inakahama coral</td>
<td>-</td>
<td>2.70±0.26</td>
<td>5,320±40</td>
<td>3,766BC - 3,671BC</td>
</tr>
<tr>
<td>2</td>
<td>YKI0811I-2</td>
<td>Inakahama coral</td>
<td>-</td>
<td>1.27±0.30</td>
<td>5,350±40</td>
<td>3,802BC - 3,692BC</td>
</tr>
<tr>
<td>3</td>
<td>YKI0903-00</td>
<td>Inakahama coral</td>
<td>-</td>
<td>2.76±0.57</td>
<td>5,600±40</td>
<td>4,091BC - 3,971BC</td>
</tr>
<tr>
<td>4</td>
<td>YKI0811E</td>
<td>Inakahama fillings</td>
<td>-</td>
<td>3.79±0.27</td>
<td>4,260±30</td>
<td>2,475BC - 2,373BC</td>
</tr>
<tr>
<td>5</td>
<td>YKI0811H2</td>
<td>Inakahama fillings</td>
<td>-</td>
<td>4.10±0.72</td>
<td>4,910±30</td>
<td>3,356BC - 3,247BC</td>
</tr>
<tr>
<td>6</td>
<td>YKI0811C-1</td>
<td>Inakahama fillings</td>
<td>-</td>
<td>3.51±0.21</td>
<td>4,600±30</td>
<td>2,902BC - 2,843BC</td>
</tr>
<tr>
<td>7</td>
<td>YKI0811E-2</td>
<td>Inakahama fillings</td>
<td>0.2</td>
<td>3.55±0.77</td>
<td>4,610±30</td>
<td>2,919BC - 2,842BC</td>
</tr>
<tr>
<td>8</td>
<td>YKI0811D2</td>
<td>Inakahama fillings</td>
<td>0.2</td>
<td>3.19±0.26</td>
<td>2,680±30</td>
<td>469BC - 376BC</td>
</tr>
<tr>
<td>9</td>
<td>YKI0903-07</td>
<td>Inakahama fillings</td>
<td>0.7</td>
<td>5.73±0.52</td>
<td>4,620±30</td>
<td>2,914BC - 2,852BC</td>
</tr>
<tr>
<td>10</td>
<td>YKI0903-09</td>
<td>Inakahama fillings</td>
<td>0.9</td>
<td>3.57±0.74</td>
<td>4,190±30</td>
<td>2,402BC - 2,267BC</td>
</tr>
<tr>
<td>11</td>
<td>YKI0903-13</td>
<td>Inakahama fillings</td>
<td>1.3</td>
<td>2.84±0.37</td>
<td>4,340±30</td>
<td>2,594BC - 2,482BC</td>
</tr>
<tr>
<td>12</td>
<td>YKI0903-19</td>
<td>Inakahama fillings</td>
<td>1.9</td>
<td>4.33±0.40</td>
<td>4,060±30</td>
<td>2,201BC - 2,076BC</td>
</tr>
<tr>
<td>13</td>
<td>YKI0903-22</td>
<td>Inakahama fillings</td>
<td>2.2</td>
<td>4.37±0.59</td>
<td>4,210±30</td>
<td>2,420BC - 2,295BC</td>
</tr>
<tr>
<td>14</td>
<td>YKI0903-27</td>
<td>Inakahama fillings</td>
<td>2.7</td>
<td>4.13±0.42</td>
<td>4,060±30</td>
<td>2,201BC - 2,076BC</td>
</tr>
<tr>
<td>15</td>
<td>YKI0903-30</td>
<td>Inakahama fillings</td>
<td>3.0</td>
<td>3.72±0.56</td>
<td>3,560±30</td>
<td>1,547BC - 1,442BC</td>
</tr>
<tr>
<td>16</td>
<td>YKI1103H1</td>
<td>Harutahama fillings</td>
<td>-</td>
<td>-2.61±0.16</td>
<td>2,470±20</td>
<td>2,484BC - 2,396BC</td>
</tr>
<tr>
<td>17</td>
<td>YKI1103-10</td>
<td>Onoaida fillings</td>
<td>0.10-0.16</td>
<td>0.77±0.53</td>
<td>5,130±20</td>
<td>3,592BC - 3,515BC</td>
</tr>
<tr>
<td>18</td>
<td>YKI1103-50</td>
<td>Onoaida fillings</td>
<td>0.38-0.50</td>
<td>-0.52±0.43</td>
<td>3,950±20</td>
<td>2,027BC - 1,937BC</td>
</tr>
<tr>
<td>19</td>
<td>YKI1103-70</td>
<td>Onoaida fillings</td>
<td>0.72-0.78</td>
<td>-0.73±0.43</td>
<td>2,460±20</td>
<td>191BC - 107BC</td>
</tr>
<tr>
<td>20</td>
<td>YKI1103-90</td>
<td>Onoaida fillings</td>
<td>0.90-0.95</td>
<td>5.18±0.44</td>
<td>3,970±20</td>
<td>2,053BC - 1,949BC</td>
</tr>
</tbody>
</table>

* Samples 8-15 and 17-20 were collected from a single fracture in granite and sedimentary rock respectively.
** Positions of the samples 8-15 and 17-20 indicate horizontal distance from the uplifted coral (Fig. 3) and distance from the top of the fillings (Fig. 4) respectively.
were collected from a single fracture in granite or sedimentary rock.

It also shows that $\delta^{13}$C values for the uplifted coral range from 1.27 to 2.76 % which correspond to the values of dissolved inorganic carbon (DIC) in seawater, $\pm 2$ % (Stuiver and Polach 1977) or $\pm 1.4$ to $+2.0$ % (Ishizaka et al. 1977). On the other hand, $\delta^{18}$O values of the fracture fillings have wide variations of $-2.61$ to $+5.73$ %. The variation may imply a difference in their sources and compositions or their precipitation processes.

5. DISCUSSIONS

5.1 Similarities of fracture fillings in granite and sedimentary rock

Fracture fillings in granite and sedimentary rock show good agreement in occurrences, compositions, and ages. The fractures in both rocks are distributed in intertidal and supratidal zones (less than 3 m above mean sea level). The fillings are mainly composed of cement and various kinds of fragments including bioclasts and lithic fragments from the host rock. The cement is mainly Mg-calcite which is composed of micrites. In addition, the results of the dating showed that the fillings in both rocks have almost same age range. Therefore, it can be concluded that the fractures filled with carbonates were formed regardless of the host rock type.

These features of fracture fillings in both rocks also show good agreement with beachrock that is hard cemented beach-sediments with a majority of calcium carbonate. Beachrock is often observed in the intertidal and supratidal zones of tropical, subtropical, and temperate coasts (Vousdoukas et al. 2007). In Japan, there is a considerable amount of beachrock along the coasts of the Nansei Islands (Yonetani 1963; Takenaga 1965; Kawana and Pinazzoli 1984; Omoto 2001, 2004). However, beachrock is rarely observed on Yakushima Island. The composition of beachrock is commonly adjacent beach-sediments that are mainly fragments of rock and bioclasts, and these are cemented with mainly Mg-calcite and/or aragonite (Bernier et al. 1997; Gischler and Lomando 1997; Webb et al. 1999; Calvet et al. 2003; Rey et al. 2004; Vieira and De Ros 2006; Vousdoukas et al. 2007). Most of the dated beachrock is thought to be 1,000-5,000 years old (Vousdoukas et al. 2007), with few being more recent (Yonetani 1963; Takenaga 1965; Holail and Rashed 1992; Bernier et al. 1997).

5.2 Source of cements

5.2.1 Quantification of MgCO$_3$ in Mg-calcite

Mg-calcite is one of the most common precipitates in marine environments and generally contains 5-18 mol% MgCO$_3$ depending on sea water temperature (Garrels and Wollast 1978). In order to quantify MgCO$_3$ in marine carbonates, XRD analysis is a good tool because the crystal structure of Mg-calcite varies with the amount of MgCO$_3$. In this section, we will carry out the quantification of MgCO$_3$ in fracture fillings based on the results of Goldsmith and Graf (1958). They reported the linear relationship between the d-value of the [hkl]=[104] peak and the Mg-content over the range of 0-20 mol% MgCO$_3$.

The results of XRD analysis of the fracture fillings (Fig. 5) showed that the diffraction angle of the [104] peak ranges from $29.73^\circ$ to $29.90^\circ$. In addition, the d-value of the [104] peak could be calculated by the Bragg’s law and compared to the results of Goldsmith and Graf (1958). As a result, it was revealed that the fracture fillings contain 9.9-15.0 mol% MgCO$_3$. These values are typical of marine carbonates containing 11-16 mol% MgCO$_3$ (Garrels and Wollast 1978; James and Choquette 1990) and are almost same as for beachrock with 8.2-15.2 mol% MgCO$_3$ (Calvet et al. 2003).

5.2.2 Origin of carbon

A carbon stable isotope ratio ($\delta^{13}$C) can provide information on the origin of carbon. From the results of the dating, the $\delta^{13}$C values of the fracture fillings except for six samples (no. 9 and nos. 16-20) are almost same as for the cement of beachrock with the $\delta^{13}$C values between +1.0 and 4.9 %. (Holail and Rashed 1992; Bernier et al. 1997; Webb et al. 1999; Calvet et al. 2003). These might be typical for marine carbonates which were precipitated from seawater with isotopic equilibrium (Holail and Rashed 1992; Bernier et al. 1997; Webb et al. 1999). On the other hand, the heavier $\delta^{13}$C value of marine carbonates may be caused by CO$_2$ degassing from seawater (Calvet et al. 2003) or microbes (James and Choquette 1990). Omoto (2004) suggested that the $\delta^{13}$C values for beachrocks may be influenced by the combined effects of seawater and freshwater. As the $\delta^{13}$C values of DIC in freshwater are commonly lighter between -14 and -10 % (Stuiver and Polach 1977), the fracture fillings with lighter $\delta^{13}$C values (e.g., nos. 16-19 samples) may slightly contain the carbon species derived from freshwater. Therefore, it can be speculated that the cements were mainly supplied from both seawater and freshwater.

5.3 Causes of age variations

It is well known that the relative sea level around the Nansei Islands became several meters higher than the present sea level approximately 6,000 years BP (Nakata et al. 1978; Yokoyama et al. 1996). As coral reefs are generally developed below low-tide level, it is estimated from the results of AMS $^{14}$C dating that the coral at Yakushima Island was uplifted approximately 5,300-5,600 years BP due to relative sea level drops. Furthermore, the results for the fracture fillings suggest that they were precipitated in rock fractures after the coral was uplifted.
However, the ages between individual fracture fillings are remarkably different even though the samples were collected from the same site or an even single fracture. The causes of the age variations will be covered in the next section. Before the evaluation of the causes, we assumed a simple model for the precipitation process of fracture fillings (Fig. 8). If they were supplied from the opening at ground surface into the fracture and precipitated orderly from the bottom to top within the fracture, it is expected that the age at higher elevations would be younger than that at lower elevations. Therefore, we investigated the relationship between the elevations and ages of the fracture fillings in granite (Fig. 3) and sedimentary rock (Fig. 4).

5.3.1 Effects of elevation of fracture fillings

The elevations of the fracture fillings in granite were measured by digital photogrammetry (Fujii et al. 2009). Firstly, two digital photos of same object were taken from different directions. Secondly, three-dimensional (3D) co-ordinates of the object were calculated by using 3-D digital photogrammetric software with the two photos. Thirdly, the vertical distance (elevation) of fracture fillings from sea level was calculated using their 3D co-ordinates. The accuracy of this technique could be calculated as follows,

\[ \sigma_{xy} = \frac{H}{C} \delta_{CCD} \quad (1) \]

\[ \sigma_z = \frac{H}{B} \sigma_{xy} \quad (2) \]

where, \( \sigma_{xy} \) is horizontal resolution to photo-plane, \( \sigma_z \) is vertical resolution to photo-plane, \( \delta_{CCD} \) is the resolution of CCD, H is the distance from a camera to an object, B is the distance between two cameras, and C is the focal length of the camera lens. In this study, \( \delta_{CCD} \) was 0.0078 mm, H was 900 mm, B was 7,280 mm, and C was 24 mm. Therefore, \( \sigma_{xy} \) was 2.4 mm and \( \sigma_z \) was 19.1 mm.

The results are shown in Fig. 9a. The elevations of each sample measured by digital photogrammetry were plotted with the vertical resolution to photo-plane (\( \sigma_z \)) in the figure. It is obvious that the samples except for the closest sample to the uplifted coral (YKI0811D2) are distributed approximately 0.6 m above sea level. On the other hand, the YKI0811D2 sample is distributed 0.1 m above the other samples. The relationship between the elevations and the ages of the samples is shown in Fig. 9b. Although the sample which was collected at the highest position was youngest, the relationship was not clear.

In addition, we investigated the relationship between the elevations and the ages of the fracture fillings in sedimentary rock. Four samples were collected from the fracture at different elevations (Fig. 4b) and AMS \( ^{14} \)C dating was conducted. The results show that their ages become older at higher elevations (Fig. 10). However, the result of the sample which was collected at the lowest position (YKI1103-90) disagreed with this tendency. Furthermore, this sample contained not only Mg-calcite but also aragonite (Fig. 7b). If the age of aragonite was different to that of Mg-calcite (Kindler and Bain 1993), the disagreement might be caused by aragonite. Additional investigations...
are required to provide more information to understand the relationship between the elevations and ages of fracture fillings.

5.3.2 Effects of bioclasts in fracture fillings

The other causes of age variations might be bioclasts. Microscopic observation revealed that the fracture fillings commonly contain bioclasts (Fig. 5a) which may have different ages to the cements. Especially, it was obvious that the uplifted coral is significantly older than the fracture fillings (Table 1). If fracture fillings contain many bioclasts, their age may become older. The effects of bioclasts on the age variations are as follows.

Firstly, the content of bioclasts in fracture fillings was estimated from cross sections of a sample based on stereology (Kobayashi and Yoshinaka 1994). Using thin sections on the x, y and z planes of the YKI1103-50 sample, we measured the total area of cement, rock fragments and bioclasts in each section with image processing software (Image). The results are listed in Table 2. An areal proportion is a total area of a material on the surface of a sample divided by the total area of each section. The results show that the areal proportion of bioclasts was approximately 3 % maximum. This value can be equivalent of the maximum content of bioclasts in fracture fillings.

Secondly, the effects of bioclasts on the age variations were evaluated using an isotopic mass balance equation. We assume that fracture fillings are composed of two materials: cement and bioclasts. In this case, the isotopic mass balance equation is expressed as follows:

\[ \Delta^{14}C = \Delta^{14}C_{\text{bioclast}}\alpha + \Delta^{14}C_{\text{cement}}(1-\alpha) \]  (3)

where, \( \Delta^{14}C \) is the density of \( ^{14}C \), and \( \alpha \) is the areal proportion of bioclasts. In addition, the \( \Delta^{14}C_{\text{cement}} \) was determined as -263.5 ‰ that of the youngest age of the fracture fillings (2,460 yrBP) in Table 1. The \( \Delta^{14}C_{\text{bioclast}} \) used two values: -1,000 ‰ and -554.8 ‰. The former is the limitation value for the calculation (more than 100,000 yrBP). The latter is the oldest age (6,500 yrBP) of uplifted corals and bioclasts within the beachrock on the coasts of the Nansei Islands (Nakata et al. 1978; Kawana and Nakata 2001; Omoto 2005, 2009). These values were substituted into Eq. (3), and \( \Delta^{14}C \) of fracture fillings was obtained. \( ^{14}C \) age \( (T) \) could be calculated with the following equation (Stuiver and Polach 1977), using Libby half life (5,568 years).

\[ T = -8033 \cdot \ln (\Delta^{14}C/1000 - 1) \]  (4)

The calculation results are shown in Fig. 11. The horizontal axis is the content of bioclasts in fracture fillings. The vertical axis is the increment age of fracture fillings due to bioclasts. The increment age was calculated by subtracting 2,460 yrBP from the obtained age in Eq. (4). Therefore, the increment age of fracture fillings will be zero, if they have no bioclasts. In addition, the maximum content of bioclasts was recalculated because we assumed that fracture fillings are composed of the two materials discussed above. From the results in Table 2, the maximum content was 3.4 ‰. Therefore, it is estimated that the increment age was approximately 106 years (indicated arrows in Fig. 11) if the age of the bioclasts was 6,500 yr BP. This means that the effect of bioclasts on the age of fracture fillings was not significant.

5.3.3 Effects of layered structures

Microscopic observation also revealed that fracture fillings contain layered structures parallel to the fracture surface (Fig. 5d). Yoshida et al. (2000; 2005) reported layered fracture fillings parallel to the fracture surface in Kurishishi granodiorite in the Kamaishi mine. The mineralogy of the layered fillings changed from high-temperature types (200-400°C), e.g. epidote, prehnite and laumontite, close to the host rock and low-temperature types (less than 200 °C), such as chlorite, zeolite and calcite, which are close to the unconfined fracture surface. Lin et al. (2003) also reported layered calcite veins parallel to the fracture surface in Nojima fault, Japan. These structures indicate that multiple precipitation events have occurred in these rock fractures.

In addition, it is possible that the ages of fracture fillings are different in each layer.
Neymark et al. (2002) and Paces et al. (2010) conducted U-series dating for layered silica minerals that were collected in the unsaturated zone at Yucca Mountain, USA. They reported that the youngest ages are found in subsamples from outer layers and the oldest ages are from the innermost layers. Therefore, the age variations might be caused by the layered structures of fracture fillings.

6. SUMMARY

The present study presented the petrological and geochemical features as well as the ages of fracture fillings on coastal outcrops on Yakushima Island, Japan. The fracture fillings were found to be remarkably younger than hydrothermal and low-temperature fillings reported by many previous studies. The obtained results are described as follows.

The fractures are frequently distributed in the intertidal and supratidal zones. Microscopic observation revealed that the fracture fillings contain cementing materials and various kinds of fragments such as lithic fragments from host rock and bioclasts. The results also showed that the fillings have layered structures parallel to the fracture surface of a sample. SEM observation showed that the cement is mainly composed of micrites and exhibits the characteristic textures of beachrock. The cement was identified as Mg-calcite through XRD analysis. In addition, aragonite was clearly detected in one sample. AMS $^{14}$C dating revealed that the ages of the fracture fillings are younger than that of the uplifted coral. Furthermore, there is a 2,000-2,700 year variation age even though the samples were collected from a single fracture. The age variations might be caused by layered structures contained within.

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