Short Article

Petrography and fission-track age of the middle Pleistocene Shoubu volcanic ash, western Shikoku, Japan

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The Shoubu volcanic ash is intercalated with the middle Pleistocene Iyoki Formation, western Shikoku, Japan. The ash has been petrographically correlated with several widespread tephras, but detailed geochemical correlations have yet to be made. We therefore examine the lithology, petrography, glass geochemistry, and fission-track (FT) ages of the Shoubu ash in an attempt to establish robust, detailed correlations. The petrography and chemical composition of glass show vertical trends in the Shoubu ash. The FT age of the lowest unit indicates that eruptions began at 0.53±0.12 Ma. Although the Shoubu ash has previously been interpreted as a single, homogeneous volcanic ash, the results indicate that it either comprises several volcanic ashes or records a compositional change within a single eruptive sequence.

Keywords : Pleistocene, western Shikoku, Shoubu volcanic ash, petrography, fission-track age

I. Introduction

The Shoubu volcanic ash (Fig. 1 ; Kashima, 1996 ; Mizuno, 2001 ; Yamashita et al., 2006), regarded as a widespread tephra, is intercalated with gravel conglomerate of the middle Pleistocene Iyoki Formation, Uchiko-cho, western Shikoku, Japan (Banno et al., 2010 ; referred to as the Ozu Formation by Yamashita et al. (2006)). The correlation of the Shoubu ash with tephra of the Hohi volcanic zone (Fig. 1-a ; Kamata, 1989), based on the characteristics (e.g., sedimentology, lithology, and petrology) of the Shoubu ash, would provide information on the nature of large-volume explosive volcanism that occurred in the Hohi volcanic zone at ca. 0.6 Ma. The volcanic ashes were deposited from pyroclastic flow/co-ignimbrite plumes (i.e., pyroclastic density current deposits), downwind of the volcanoes in Shikoku. However, little such work has been done to date. In addition, the Shoubu ash has not been recognized elsewhere. The lithology and petrography of the Shoubu ash were reported by Yamashita et al. (2006), who reported laminar structures but did not provide full details of the sedimentology of the ash. Kashima (1996) reported a FT age of 0.60 ± 0.13 Ma for a volcanic ash intercalated within the Iyoki Formation; however, the lithofacies and petrography of the ash, as well as the exact outcrop location, were...
Mizuno (2001) suggested that the Shoubu ash is similar to the Yokoo pyroclastic flow deposit within the Oita Group. Banno et al. (2010) reported that the Shoubu ash is more likely related to the Seiganji pumice fall deposit (Mizuno et al., 1989; Yoshioka et al., 1997), the Yufugawa pyroclastic flow deposit (Hoshizumi et al., 1988; Yoshioka et al., 1997), or the Nada pumice fall deposit (Ishizuka et al., 2005). It is necessary to resolve the correlation of the Shoubu volcanic ash with other tephras in central Kyushu; however, the geochemical data necessary for detailed correlations have yet to be reported. Therefore, multiple data sets, including stratigraphy and sedimentology (e.g., distinguishing between primary and reworked deposits), chronology, petrology, and petrochemistry, are needed for the reliable correlation of tephras in Shikoku and central Kyushu.

Here, we present the results of lithological, petrographic, and petrochemical observations and analyses, as well as the FT age, of the Shoubu volcanic ash in the outcrop described by Yamashita et al. (2006). The results indicate that the Shoubu ash consists of several different volcanic ashes or that it records a compositional change during a single eruption sequence.

II. Geologic overview

The Uchiko area comprises a mountain basin in the lower Hiji River region (Yamashita et al., 2006). The Ozu and Uchiko basins that developed on the Sanbagawa metamorphic complex are thought to be elongate east-west and erosional basins along lineaments (Kumahara, 1988). The Uchiko basin is bounded to the south by mountains such as Mt. Kannan and Mt. Tomisu, and the margins of the mountain region are locally characterized by hills and terraces. The basement to the Uchiko basin is the Sanbagawa metamorphic complex and the Mikabu belt (Suyari et al., 1991). The gravels that make up the hills and terraces lie unconformably on these basement rocks. The pre-terrace sediments are divided into the underlying Tomisuyama Formation and the overlying Iyoki Formation by Banno et al. (2010).

Fluvial sediment of the Iyoki Formation is distributed along the Oda and Nakayama rivers, and occurs as scattered outcrops at Kamisasugai, Niiya, Kitayama, Kawanouchi, Ronden, Shiromawari, Iyoki, and Osechuo. The formation is up to 30 m thick at Iyoki and Shiromawari, and ≤20 m thick at other sites. The formation consists mainly of gravels containing clasts of schist, chert, and quartz, and it is interbedded with silt, sand, and tephra horizons at Kamisugai, Shoubu, and Iyoki (Banno et al., 2010).

The outcrop of Shoubu volcanic ash that is described in this study occurs in a road cutting at Uchiko-cho Shoubu (33°34’10”N, 132°37’47”E). The outcrop is 253 cm wide and 70 cm high. Banno et al. (2010) reported three tephras in the Iyoki Formation at several locations, although it is unclear which of these tephras is the Shoubu volcanic ash.
III. Lithofacies

The Shoubu volcanic ash conformably overlies sandy silts (S-L) and is conformably overlain by gravelly sands (S-U ; Fig. 2). The Shoubu ash consists of three units (Units S-1, S-2, and S-3), described here from bottom to top. Unit S-1 is a yellow-pink-green stratified volcaniclastic sandy silt (7 cm thick) that consists of alternating beds of volcaniclastic silt and volcaniclastic very fine to fine sand. Unit S-2 consists of volcaniclastic sandy silt (28 cm thick). Unit S-3 is a reddish brown medium- to fine-sand-sized volcaniclastic unit with gravel (20 cm thick). Unit S-2 is subdivided into two sub-units: a white stratified unit (S-2-1, 18 cm thick) and an overlying greyish-green non-stratified unit (S-2-2, 10 cm thick ; Fig. 2). Unit S-2-1 consists of alternating beds of volcaniclastic silt and volcaniclastic very fine to fine sand. Part of unit S-2-1 is cross-bedded. Units S-2-2 and S-3 are massive ash beds. Unit S-3 is composed mainly of pumice fragments (1-3 mm). In addition, S-3 contains coarse grains of weathered biotite (≦ 2 mm) and white volcanic fragments (1-5 mm).

IV. Methods of sample analysis

Grains of volcanic glasses, minerals, and rock fragments were counted for approximately 2000 grains (in the grain-size intervals of 1/4-1/8 and 1/8-1/16 mm), 800 grains (1/2-1/4 mm), and all grains (1-1/2 mm). Volcanic glasses were classified as plate-Y-shaped, intermediate between plate-Y- and fiber-sponge-shaped, fiber-sponge-shaped, and blocky based on the classification of Machida and Arai (2003).

Refractive index values of volcanic glasses were measured on 1/8-1/16-mm-fraction samples using the Measuring Actual Immersion Oil Temperature (MAIOT) system : Furusawa Geological Survey, Inc. instruments. Thirty glass shards were measured for each sample.

Major-element compositions of volcanic glasses were determined using a scanning electron microscope (SEM ; JSM-6510LV, JEOL) with an energy dispersive X-ray spectrometer (EDS ; X-MAX50, Oxford Instruments) at the Faculty of Science, Ehime University, Japan. For quantitative analyses, operating conditions were an accelerating voltage of 15 kV and a beam current of 0.8 nA. ZAF correction was performed using standard samples. Standards used were NIST 620 glass, obsidian (Astimex Scientific), and K2O glass (Astimex Scientific). Between 13 and 17 glass shards were analyzed in each sample. All compositional values discussed in the results are normalized to a total of 100 wt.%. Thin sections for SEM-EDS were prepared following Iwasaki and Sakakibara (2004) and Sakakibara et al. (2009).

The age of unit S-1 of the Shoubu ash was determined using zircon FT dating by Kyoto
Fission-Track, Japan. We used the standard protocol for Quaternary tephra outlined by Danhara (1995) in the FT analysis. Following the method employed by Sakakibara et al. (2009), a 115 g sample of S-1 was pretreated and yielded 500 zircons, including abundant colorless, transparent, euhedral crystals. Spontaneous tracks were etched at 225° C for 45 hours.

V. Results

1. Petrography

The Shoubu ash is dominated by volcanic glass and phenocrysts (Table 1 and Fig. 2). Furthermore, it contains accidental rock fragments including weathered mineral grains and bedrock. S-2-1 and S-2-2 are especially rich in such rock fragments in the 1/2-1 mm interval. The proportion of rock fragments decreases slightly in S-3 compared with S-2 (1/16-1/8 and 1/2-1 mm intervals). The glass content in the 1/16-1/8 and 1/4-1/2 mm intervals decreases upwards from S-1 to S-2-2, although S-3 contains a large amount of pumice sized >1 mm. Although phenocryst contents vary among samples, the phenocrysts are dominated by plagioclase and biotite with minor clinopyroxene, orthopyroxene, hornblende, and opaque minerals.

Clinopyroxenes occur as stubby anhedral crystals that are green under plane polarized light, whereas orthopyroxenes are subhedral elongate or columnar crystals that are pale green to pale brown under plane polarized light. Hornblendes are elongate subhedral columnar crystals that are green under plane polarized light. Biotite occurs in all stratigraphic units as coarse subhedral to euhedral hexagonal or platy grains with long-axis lengths of 1/2–1 mm. Most biotite grains have been altered by weathering. Opaque minerals are subhedral and hexagonal or tabular. Most plagioclase grains are subhedral and tabular. Plagioclase and opaque mineral contents increase upwards from S-1 to S-2-2 (Table 1 and Fig. 2). S-1 and S-3 are biotite-rich units. The abundance of volcanic glass tends to increase with decreasing glass grain size.

In the 1/16-1/8 mm interval, S-1 is composed mainly of fiber-sponge-shaped glass (Table 1 and Fig. 2). Upward in the section, towards unit S-2-2, the amount of plate-Y-shaped and intermediate-shaped glass fragments increases and the amount of fiber-sponge-shaped glass fragments decreases. The proportion of blocky glass fragments (relative to the total glass content) is similar in S-1, S-2-1, and S-2-2. S-3 is composed mainly of plate-Y-shaped glass. S-1, S-2-1, and S-2-2 contain approximately 20% of blocky glass fragments, more than in other tephras erupted from volcanoes in Kyushu (Machida and Arai, 2003).

2. Refractive index values of volcanic glasses

Glasses in S-1 have refractive index values of n = 1.497–1.503 (Table 1 and Fig. 3), with a mean value of 1.501, and with a main peak at 1.501 and a sub-peak at 1.498. Glasses in S-2-1 have values of 1.495–1.502 with a mean of 1.499, and the main peak at 1.500 and the sub-peak at 1.497, whereas S-2-2 glasses have values of 1.494–1.501 with a mean of 1.497 and a peak at 1.496. Glasses in S-3 have values of 1.496–1.502 with a mean of 1.498 and a peak at 1.497.

The distributions of refractive index values for S-1 and S-2-1 show two peaks. The peaks have similar shapes in both samples but show a shift to lower refractive index values from S-1 to S-2-1. The proportion of glass with low

Table 1 Modal compositions and refractive index values of the Shoubu volcanic ash

<table>
<thead>
<tr>
<th>Sample</th>
<th>Modal compositions (%)</th>
<th>Glass shape (%)</th>
<th>Refractive index Glass (n)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S-U</td>
<td>V.G. 0.1 Cpx 0.8 Opx 0.8 Hbl 0.6 Qtz 0.4 Pl 0.8 Oth 0.2 RF 0.8</td>
<td>PY 0.0 MD 0.0 FS 0.0 BL 0.8</td>
<td>1.496-1.502 (1.497)</td>
</tr>
<tr>
<td>S-3</td>
<td>2.3 0.8 0.6 4.9 0.6 4.2 61.0 0.0 0.1 26.2</td>
<td>83.7 14.3 0.0 2.0</td>
<td>1.494-1.501 (1.496)</td>
</tr>
<tr>
<td>S-2-2</td>
<td>14.3 0.2 0.4 3.0 0.1 1.7 44.3 0.0 0.1 35.9</td>
<td>29.3 31.0 12.1 27.6</td>
<td>1.495-1.502 (1.497, 1.500)</td>
</tr>
<tr>
<td>S-2-1</td>
<td>38.2 0.1 0.3 2.1 0.0 0.4 38.6 0.0 0.1 20.1</td>
<td>22.3 21.5 35.4 20.8</td>
<td>1.497-1.503 (1.498, 1.501)</td>
</tr>
<tr>
<td>S-1</td>
<td>69.0 0.2 0.2 0.9 1.6 0.4 20.3 0.0 0.0 7.3</td>
<td>13.0 5.5 56.3 25.2</td>
<td>1.497-1.503 (1.498, 1.501)</td>
</tr>
<tr>
<td>S-4</td>
<td>0.2 0.1 0.1 1.4 0.0 0.5 13.2 0.0 0.0 84.6</td>
<td>25.0 0.0 75.0 0.0</td>
<td>1.496-1.502 (1.497)</td>
</tr>
</tbody>
</table>

refractive index values shows an increase from S-1 to S-2-1. The single peak in S-2-2 is lower than the lower peak in S-2-1. S-2-2 and S-3 show similar distributions of refractive index values. However, the peak in S-3 is slightly higher than that in S-2-2.

3. Chemical compositions of volcanic glasses

The S-1 glasses have SiO$_2$ contents of 75.9–78.1 wt.%, with a bimodal distribution diverging at 77.0 wt.% (Table 2 and Fig. 4). These glasses also have bimodal distributions of Al$_2$O$_3$, FeO, and CaO. The S-2-1 glasses have SiO$_2$ contents of 76.2–78.2 wt.%, and S-2-2 glasses have SiO$_2$ contents of 76.6–78.2 wt.%. Similarly to the S-1 glasses, the glasses in S-2-1 and S-2-2 have a bimodal distribution of SiO$_2$ content with peaks either side of 77.0 wt.% (the distribution is not as clear in the S-2-2 glasses), and that also have bimodal distributions of Al$_2$O$_3$, FeO, and CaO. In contrast, the S-3 glasses have a narrow range of SiO$_2$ contents (77.1–77.8 wt.%).

The major-element compositions of volcanic glasses in S-1, S-2-1, and S-2-2 are the same within error. The bimodality of glasses in S-1, S-2-1, and S-2-2 indicates an acidic group and a basic group. The refractive index values of volcanic glasses from S-1 and S-2-1 also have bimodal distributions, consistent with the major-element data discussed above. However, we could not distinguish a bimodal distribution in the refractive index measurements of S-2-2. The major element compositions and trends in S-3 glasses differ to those in the other units (Fig. 4).

4. Fission-track dating

Fission-track dating of 30 zircons from S-1 yielded an age of 0.53±0.12 Ma (Table 3). These 30 zircons were chosen at random, and their young age means that the measured ages are highly variable, although a P ($\chi^2$) value of 35% indicates that the data are validated by the $\chi^2$ test, and the grains can be regarded as belonging to a single age population. These zircons have U concentrations of 68–239 ppm with a mean of 130 ppm.

VI. Discussion and conclusions

Unit S-1 is a volcanic ash that is rich in fiber-sponge-shaped glasses and poor in accidental fragments. This unit yields a FT age of 0.53±0.12 Ma. This age cannot be directly compared with the age of 0.60±0.13 Ma reported by Kashima (1996), because Kashima provided no detailed descriptions of the sampling location or the method used for FT age measurements. However, these ages are the same within error. Other FT ages have been obtained for volcanic ash beds that are equivalents of the Shoubu ash, given the similar petrography of the Iyoki Formation. These ages are 0.62±0.08 Ma (Iyoki: Loc. 21 of Banno et al. (2010)) and 0.65±0.11 Ma (Izushi: Loc. 2 of Banno et al. (2010)). These tephras, which are possibly one of the biotite-bearing tephras of the large-volume pyroclastic density currents at the Hohi volcanic zone (Banno et al., 2010), are the key to understanding the volcanic history of the Hohi volcanic zone during 0.5–0.6 Ma.

Unit S-2 is cross-bedded and has a higher content of accidental rock fragments than S-1, indicating it is a reworked tephra. The bimodal refractive index values and compositions (SiO$_2$, Al$_2$O$_3$, FeO, and CaO) of the glasses in units S-1 and S-2 may indicate compositional heterogeneity within the magma reservoir. Indeed, the compositional data indicate a zoned magma reservoir with magmas of variable SiO$_2$ content. Low refractive indices of glasses are related to high SiO$_2$ content, and vice versa (Cassidy et al., 1969). It is generally accepted that the petro-
Table 2  Major-element compositions of volcanic glass shards in the Shoubu volcanic ash

<table>
<thead>
<tr>
<th>Shoubu volcanic ash</th>
<th>S-1</th>
<th>S-2</th>
<th>S-2-1</th>
<th>S-2-2</th>
<th>S-3</th>
</tr>
</thead>
<tbody>
<tr>
<td>(wt.%)</td>
<td>Ave. (n=3)</td>
<td>S.D.</td>
<td>Ave. (n=12)</td>
<td>S.D.</td>
<td>Ave. (n=14)</td>
</tr>
<tr>
<td>SiO₂</td>
<td>76.0 0.15</td>
<td>77.9 0.17</td>
<td>76.4 0.20</td>
<td>77.8 0.19</td>
<td>76.6 -</td>
</tr>
<tr>
<td>TiO₂</td>
<td>0.2 0.02</td>
<td>0.2 0.05</td>
<td>0.2 0.08</td>
<td>0.2 0.06</td>
<td>0.1 -</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>13.5 0.15</td>
<td>12.6 0.22</td>
<td>13.2 0.11</td>
<td>12.5 0.10</td>
<td>13.0 -</td>
</tr>
<tr>
<td>FeO</td>
<td>1.0 0.08</td>
<td>0.8 0.12</td>
<td>1.0 0.05</td>
<td>0.7 0.07</td>
<td>1.0 -</td>
</tr>
<tr>
<td>MnO</td>
<td>0.2 0.24</td>
<td>0.1 0.05</td>
<td>0.1 0.03</td>
<td>0.1 0.04</td>
<td>0.1 -</td>
</tr>
<tr>
<td>MgO</td>
<td>0.2 0.03</td>
<td>0.1 0.04</td>
<td>0.2 0.02</td>
<td>0.1 0.03</td>
<td>0.2 -</td>
</tr>
<tr>
<td>CaO</td>
<td>1.1 0.06</td>
<td>0.9 0.06</td>
<td>1.0 0.12</td>
<td>0.8 0.05</td>
<td>1.0 -</td>
</tr>
<tr>
<td>Na₂O</td>
<td>3.7 0.05</td>
<td>3.4 0.23</td>
<td>3.7 0.26</td>
<td>3.6 0.10</td>
<td>3.6 -</td>
</tr>
<tr>
<td>K₂O</td>
<td>3.8 0.12</td>
<td>4.0 0.15</td>
<td>4.2 0.41</td>
<td>4.0 0.09</td>
<td>4.3 -</td>
</tr>
<tr>
<td>P₂O₅</td>
<td>0.1 0.06</td>
<td>0.0 0.03</td>
<td>0.1 0.04</td>
<td>0.0 0.03</td>
<td>0.1 -</td>
</tr>
<tr>
<td>Total</td>
<td>100.0 0.00</td>
<td>100.0 0.00</td>
<td>100.0 0.00</td>
<td>100.0 0.00</td>
<td>100.0 0.00</td>
</tr>
<tr>
<td>(Total)</td>
<td>92.3 0.00</td>
<td>93.8 0.00</td>
<td>94.0 0.00</td>
<td>94.4 0.00</td>
<td>88.2 0.00</td>
</tr>
</tbody>
</table>

(Total) show average of raw total. Ave.: average, S.D.: standard deviation. ①: acidic group, ②: basic group.

Table 3  Result of fission-track dating undertaken in this study

<table>
<thead>
<tr>
<th>Sample</th>
<th>No. of crystals</th>
<th>Spontaneous A (cm⁻²)</th>
<th>N₀</th>
<th>Induced A (cm⁻²)</th>
<th>N₁</th>
<th>Dosimeter N₀</th>
<th>N₁</th>
<th>Pr(χ²) (%)</th>
<th>r</th>
<th>U ppm (Ma)</th>
<th>Age ± 1σ Ma</th>
</tr>
</thead>
<tbody>
<tr>
<td>S-1</td>
<td>30</td>
<td>2.41×10⁴</td>
<td>22</td>
<td>1.12×10⁴</td>
<td>1025</td>
<td>7.087×10⁴</td>
<td>3628</td>
<td>35</td>
<td>0.39</td>
<td>130</td>
<td>0.53 ± 0.12</td>
</tr>
</tbody>
</table>

ρ = density, N = total number of counted tracks. The fission track analyses used the external-detector method (ED2 method of Gleadle, 1981), and ages were calculated using a NIST-SRM612 dosimeter glass and an age-calibration factor of CED2 = 550 ± 3 (1σ: standard errors; Danhara et al., 2003). Pr(χ²) is the probability of obtaining the χ² value for ν degrees of freedom, where ν = the number of crystals-1 (Gallbraith, 1981); r is the correlation coefficient between ρ₁ and ρ₀; ρ₁ and ρ₀ indicate densities of spontaneous and induced tracks, respectively. U is the uranium content of zircon (ppm). Zircons were irradiated with thermal neutrons in the pneumatic tube of the JRR-4 unit of the Japan Atomic Energy Research Institute (JAERI) reactor, Tokai, Ibaraki, Japan.
graphic characteristics of some tephras differ considerably between units (e.g., Nishida, 1991; Nakamura and Hirakawa, 2003). The results of this study show consistent trends between major element compositions and the refractive indices of glasses. In sedimentary environments in which reworking occurred, tephras are considered to be mixed (e.g., Urabe and Kataoka, 2013; Kataoka and Nagahashi, 2014). It may be that two tephras from different origins were mixed to produce units S-1 and S-2. If the proportion of each of the mixed tephras is different in each unit, this would be recorded by differences in refractive index and the chemical composition of glass. The bimodal distributions of the refractive index values and compositions (SiO$_2$, Al$_2$O$_3$, FeO, and CaO) of the glasses in the units S-1 and S-2 may indicate the mixing of two tephras.

Therefore, units S-1 and S-2 are part of a single volcanic ash but they have distinct chemical compositions. Otherwise, they consist of two tephras (a high-SiO$_2$ tephra and a low-SiO$_2$ tephra).

Unit S-3 is composed mainly of pumice fragments (1-3 mm in size) and contains coarse grains (weathered biotite ≤2 mm) and white volcanic fragments (1-5 mm). In addition, the glass morphology and chemical composition (SiO$_2$=75.9–76.6 and 77.6–78.2 wt.%) of the glasses in S-3 differ from those (SiO$_2$=77.1–77.8 wt.%) in the lower units (S-2 and S-2). Based on these occurrences, S-3 is considered not to be reworked tephra from the lower units. Unit S-2 is intercalated with reworked beds without soil horizons between the units.

These observations suggest that the generation of unit S-3 followed the formation of units S-1 and S-2 from the same magma chamber after a hiatus in eruptive activity. An alternative explanation is that unit S-3 differs compositionally from units S-1 and S-2, but that all three units were deposited over a short period of time.

The present results show that the Shoubu volcanic ash comprises several volcanic ashes of different origin or records compositional changes within a single eruptive sequence. When such a volcanic ash sequence is considered as individual units, it is important to document the differences in mafic mineral contents and glass composition in different layers to enable correlation with other tephras as a marker layer. Nishida (1991) reported vertical trends in the composition of colored glass of the Azuki volcanic ash, and these trends provide clues to the eruption style of the source volcano and the evolution of volcanic ejecta. The variations described above, from the outcrop in Uchiko-cho, will be useful for undertaking correlations with other tephras in Kyushu and for reconstructing the history of volcanic activity in the Hohi volcanic zone. Future work should record the detailed petrology and geochemistry of tephras from large-scale eruptions of central Kyushu during the same period, and to verify whether sub-unit variations correspond to the variations within the Shoubu volcanic ash, or resulted from the mixing of various other tephras.

Acknowledgements

We thank Ms. Hiromi Akamatsu (Ehime University, Japan) for help with making thin sections. We would like to thank the two anonymous referees and Dr. Kotaro Yamagata (Joetsu University of Education, Japan) for useful suggestions that helped there to improve the original manuscript.

References


四国西部に分布する中期更新世菖蒲火山灰の岩石記載
およびフィッショントラック年代

中村千怜*1,2 佐野栄*1 佐野栄*1 佐野栄*1 佐野栄*1 佐野栄*1 佐野栄*1 佐野栄*1 佐野栄*1

キーワード：更新世、四国西部、菖蒲火山灰、岩石記載、フィッショントラック年代

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