1. Introduction

Lahars are mixture of water, volcanic sediments, and rocks involving other debris and trees enroute during travel. Lahars are one of the most hazardous volcanic phenomena as the lahar can travel long distance along rivers and cause flood and damages in the volcanic foot areas (e.g., Mt. Nevado del Ruiz Volcano, Colombia [1]). In the cases of well investigated stratovolcanoes, the repetitive lahars have been recognized historically and geologically (e.g., Onetapu Formation of Mt. Ruapehu [2] and Mt. Rainier [3]).

The recent studies on lahars deposits of NE Japan active stratovolcanoes (Mt. Bandai [4], Mt. Adatara [5], and Mt. Chokai [6, 7]) revealed the frequent events of lahars implying high volcanic risks. However, few studies of lahars at Zao volcano have been conducted other than a study on lahars deposits in the eastern foot of the volcano, although the past lahar phenomena were recorded in written accounts. In Zao volcano, many volcanic tremors have been detected since 2013 that indicates elevated risks associated of a future eruption. Therefore, studies on lahars deposits in this volcano are one of the urgent issues for lahar hazard prevention and mitigation for the local communities.

During an archaeological excavation from 2020 to 2021 of the Fujiki ruin (Fig. 1(a)), conducted by Kaminoyama City Office, lahar deposits were newly exposed. This exposure is very important because outcrops of lahar deposits are rare in the western foot of the Zao. In this article, the facies description of the lahar deposits as well as granulometry, componentry, the X-ray diffraction (XRD) clay mineral analysis, and $^{14}C$ dating are presented. Combining these data, the depositional features and source materials of the lahar deposits are discussed. The future risks of the lahar in the western foot of Zao volcano are also discussed.
Geologic and Petrologic Characteristics of the Lahar Deposits at the Western Foot of Zao Volcano

2. Geologic Background

2.1. General Geology of the Zao Volcano

In NE Japan, many Quaternary volcanoes are aligned in the north–south direction. The Zao volcano is one of the representative active stratovolcanoes in the volcanic front, having a crater lake at the summit area (Fig. 1(b)). This volcano has the most extensive written eruption records among volcanoes in NE Japan. Its volcanic activity, which started approximately 1 Ma, has been divided into six stages [8]. The latest stage (Stage 6) caused the formation of the horseshoe-shaped Umanose caldera (∼1.7 km in diameter) in the summit area at ca. 35 ka. After the 35 ka event, numerous eruptions occurred from inner part of the caldera. The eruptive products during the latest stage are mostly composed of pyroclastic deposits. [8] subdivided the pyroclastic deposits of stage 6 into five units of the Kumanodake, Komakusadaira, Kattadake (ca. 33–12.9 ka), Umanose (ca. 9.0–4.1 ka), and Goshikidake (ca. 2.0 ka to present) units. During the eruption period resulting in Kumanodake, Komakusadaira, and Kattadake units, phreatomagmatic eruptions were predominant. In contrast, alternation of phreatic and magmatic eruptions had taken place during Umanose and Goshikidake units activities. The present crater Okama was formed at the western part of the Goshikidake around 1200 CE. Since then, middle to small sized (VEI = 0–2) eruptions from the Okama crater continued.

This volcano has many historic eruption records (e.g., [8]). Among these, the written accounts of lahars, especially during the last eruption episode of summit crater Okama in 1894–97 CE, are found [8, 9]. Most of the records described the lahars in the eastern part of this volcano. The eastern part is the main area where the lahars flowed down, because the summit horseshoe-shaped caldera opens to the east direction.

2.2. Geography of Western Part and Western Foot of the Zao Volcano

The main rivers that flow down to the west from the summit area are the Zaogawa River and the Sen-ninzawa River (Fig. 1(a)). Pyroclastic deposits of the Stage 6 and the products of previous stages are distributed in the summit area (the area characterized by a gentle slope in Fig. 1(a)) and along the river valley. The Neogene deposits and an early Pleistocene volcano distribute in the western foot [10] (the areas of dissected terrain in Fig. 1(a)). In the downstream area, a small volcanic fan and river terraces have developed along the Zaogawa River.

3. Analytical Methods

The facies observation, granulometric analysis, componentry analysis, 14C dating, and XRD analysis of the deposits were carried out in this study.

Fig. 1. Locality map of Zao volcano and Fujiki ruin. The hillshade map is from the Geospatial Information Authority of Japan.
3.1. Field Observation

Fieldwork, observation and sampling of the deposits was conducted on June 8, 16, and 22 and July 6 and 16, 2020. The field observation was carried out under the permission from the Kaminoyama City Office and the contractor, Sankyo Engineering Co., Ltd., who are responsible for the archaeological excavation of the Fujiki ruin. The Fujiki ruin is located at the medial part of the small volcanic fan.

3.2. Granulometric Analysis

The granulometry of the samples were analyzed by dried sieving using stainless sieves in the range of −1 to 4 φ and a laser diffraction particle size analyzer (Microtrac 3300EX) at the Yamagata Research Institute of Technology in the range of 5 to 12 φ.

3.3. Componentry Analysis

The componentry analysis on 0–1 φ size particles was conducted using a binocular microscope. The particles were classified into scoria, gray dense andesite, white lithic fragment, beige lithic fragment, free crystals, and dull colored rounded particles. Relative abundances of these types were examined.

3.4. X-Ray Diffraction Analysis

The mud fraction (<1/16 mm) of the samples were used for XRD analysis. The fractions were dried by an oven and powdered using an agate mill. The powdered samples were placed in a glass holder for the XRD analysis, using X-ray diffractometer (MiniFlex II, Rigaku Corp.) in the Faculty of Science of Yamagata University. Measurements were conducted at 5° per minute from 2° to 60° using a CuKα target X-ray tube with an acceleration voltage of 30 kV and a filament current of 16 mA. Integrated XRD software (PDXL2, Rigaku Corp.) and databases of the International Centre for Diffraction Data and the Inorganic Crystal Structure Database of the Crystallographic Society of Japan were used for identifying minerals.

3.5. Radiocarbon (14C) Dating

Charcoal samples were collected for the radiocarbon (14C) dating. The analysis was carried out by the Yamagata University High Sensitivity Accelerator Center using accelerator mass spectrometry (AMS). The samples were chemically pretreated by the acid/alkali/acid (AAA) method. The obtained data were calibrated using IntCal20 [11].

4. Results

In the Fujiki ruin, a great deal of the Jomon earthenware was excavated from a paleosol layer [12]. The paleosol layer covers a basal gravel deposit. Above the paleosol layer, two sets of lahar deposits, L1 and L2 in descending order, were observed. The sedimentary facies, grain size, component, and XRD characteristics of these lahar deposits are described in the following sections. The 14C dating result of the charcoal samples collected from interbedding paleosol layer is described as well.

4.1. Facies Description

Generalized columnar section is presented in Fig. 2. Units L1 and L2 are subdivided into L1-1 and L1-2, and L2-1 and L2-2, respectively. The photographs of representative exposures are presented in Figs. 3(a) and (b). The close-ups of the L1 and L2 deposits are in Figs. 3(c)–(f). In addition, a muddy deposit (M) is observed immediately below the L1-2 deposits. The facies of unit M is briefly described.

4.1.1. Units L1-1 and L1-2

Units L1-1 and L1-2 are less than ca. 40 and 20 cm thick, respectively. The boundary between these units is usually sharp (Fig. 3(f)) and undulated, but gradational in some parts (Fig. 3(e)). The unit L1-2 has an erosive base (Figs. 3(b) and (e)).

Unit L1-1 is characterized by parallel to low-angle cross-stratification and the alternation of finer-grained laminated layers and coarser-grained layers (Fig. 3(f)). The laminae are discontinuous. The finer layers tend to have erosive bases. In the coarser layers, the lapilli trains can be observed. The lapilli (clasts) are imbricated or horizontally aligned. Locally, the upper part (~20 cm thick) of the unit L1-1 is massive and includes soil component in the matrix, which indicates reworked origin (Fig. 3(e)). Subrounded to angular granules, pebbles, and subrounded cobbles are included in a light beige sandy to muddy matrix. Granules mostly comprise gray andesite (ca. 70%) and white and beige lithic fragments (ca. 30%). Pebbles
mostly comprise gray andesite. White lithic fragments are subordinately included. Cobbles are gray andesite.

Unit L1-2, except for lower part, is massive, ungraded, poorly sorted (Figs. 3(c) and (f)), and matrix supported, and includes subrounded to angular granules, pebbles, and some subrounded cobbles in a pale-blue sandy to muddy matrix. Granules mostly comprise gray andesite (ca. 70%) and white lithic fragment (ca. 30%). Pebbles mostly comprise gray andesite. White lithic fragments are subordinately included. Cobbles are gray andesite. In the lower part of unit L1-2, diffusely laminated part (mostly <2 cm thick) is observed (Fig. 3(f)). The lamination is usually parallel to the bedding plane. The laminated part gets thicker (ca. 8 cm), where it shows cross stratifications (part of dune structure: Fig. 3(e)), before it disappears.

4.1.2. Units L2-1 and L2-2

Units L2-1 and L2-2 are less than ca. 35 and 30 cm thick, respectively. The thicknesses of these units vary and these units disappear laterally (Figs. 3(a) and (b)). The boundary between units L2-1 and L2-2 is usually sharp and undulated but gradational in part. The top of the unit L2-1 is undulated by moderate wavelengths. The base of unit L2-2 is disturbed by the bioturbation (Fig. 3(d)).

Unit L2-1 is massive, ungraded, poorly sorted, and matrix supported, and encompasses subangular to subrounded granules and pebbles in a beige sandy to muddy matrix (Fig. 2(d)). Rounded and angular pebbles are rarely observed. Granules mostly comprise gray andesite (ca. 70%) and white and beige lithic fragments (ca. 30%). Pebbles mostly comprise gray andesite with subordinate white lithic fragments.

Unit L2-2 is characterized by diffuse stratification, poorly sorted, and matrix-supported, and comprises mostly subangular to subrounded granules in a beige sandy to muddy matrix (Fig. 3(d)). The diffuse stratification is identified by an alternation of finer- and coarser-grained layers. Pebbles are rarely included. Granules mostly comprise gray andesite (ca. 60%) and white and beige lithic fragments (ca. 40%). Pebbles are mostly gray andesite. It is noted that granule- to pebble-sized aggregates, composed of fine particles, are observed.

4.1.3. Unit M

Unit M is weakly laminated, ungraded, and moderately sorted, and is composed of dark brown muddy matrix with sparsely distributed pebbles (Fig. 3(f)). The pebbles consist of mud clasts and tend to imbricate up-stream ward. Lenticular intercalation of a brown sandy layer is recognized in the lower part.

4.2. Grainsize Characteristics

The grain size distributions of matrix of individual units are shown in Fig. 4. All units show wide range of size distribution, that indicates the matrix of all units are poorly sorted. Units L1-1, L1-2, and L2-1 are positively (fine) skewed which have high values in the range of −1 to 2 φ, whereas unit L2-2 has a peak in 1 to 2 φ. The mud contents (>4 φ) are higher (7.2–8.8%) in units L1-2, L2-1, and L2-2 than unit L1-1 (3.7%).

4.3. Componentry Characteristics

The photographs of each component; scoria, gray andesite, white lithic fragment, beige lithic fragment, free crystals, and dull colored rounded particles are presented in Fig. 5. The scoriae are black–dark gray vesiculated particles, showing slag shape (Fig. 5(a)). The gray andesite is light–dark gray and dense (Fig. 5(b)). The color of some
of this type (dense andesite) is partly changed to brown. The white and beige lithic fragments are dense to loose massive particles (Figs. 5(c) and (d)), composed mainly of hydrothermally altered clay minerals partly with plagioclase and pyroxene crystals. The difference of the color of the white and beige is probably from weathering. Free minerals are colorless minerals, pyroxene, and minor biotite (Fig. 5(e)). The dull colored rounded particles are dense and massive (Fig. 5(f)).

The results of the component analysis are shown in Table 1. In all units, the most abundant type is the white and/or beige lithic fragments. The former is predominant in units L1-2 and L2-1, whereas the latter is predominant in unit L1-1. In unit L2-2, the proportion of these two are nearly equal. The gray andesite is common. The scoria (5–10%) is present in all units. Free minerals and dull colored rounded particles are less than 5% in all units. The colorless minerals are most abundant among the free mineral grains.

4.4. XRD Results

The results of XRD analysis are presented in Table 2. Silica minerals (quartz, cristobalite, and tridymite), plagioclase, pyroxenes, sulfates (alunite), clay minerals (kaolin-group minerals, and smectite), and mica were detected. All units include these minerals except for pyroxenes and smectite. Pyroxenes and smectite are minorly included only in L1-1 and L2-1. These units include kaolin-group minerals, however, its intensity is subtle. Quartz and alunite are minorly included in unit L1-1.

4.5. Radiocarbon ($^{14}$C) Ages

$^{14}$C dating result of a charcoal sample is presented in Table 3 as well as the reported $^{14}$C age [12]. The charcoal sample, ca. 0.5 cm in length, was collected from a paleosol layer, ca. 2 cm below the base of the muddy unit. The total thickness of the paleosol layer (between units L1 and L2) is ca. 20 cm. The obtained age is ca. 4 cal ka. Thus, the L1 unit is younger than ca. 4 ka. The reported age of a charcoal sample, ca. 30 cm in length is ca. 5.2 cal ka [12]. The sample was collected form a paleosol layer about 18 cm below the bottom of L2-2. Assuming the paleosol sedimentation rate is constant, the age of the bottom of the L2 is estimated to be ca. 4.6 cal ka.

<table>
<thead>
<tr>
<th>Table 1. The results of the component analysis.</th>
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<tbody>
<tr>
<td><strong>Unit name</strong></td>
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<tr>
<td>L1-1</td>
</tr>
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<td>L1-2</td>
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<tr>
<td>L2-1</td>
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<tr>
<td>L2-2</td>
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</tbody>
</table>

More than 400 particles were counted under a binocular microscope. ⊚, <5%; +, 5–15%; ++, 15–25%; ⊚, 25–35%; ⊚, 35–45%.

<table>
<thead>
<tr>
<th>Table 2. Bulk mineral assemblages of the lahar deposits identified by XRD.</th>
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<tr>
<td><strong>Unit name</strong></td>
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<td>L1-1</td>
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<td>L1-2</td>
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<td>L2-1</td>
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<td>L2-2</td>
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</table>

Abbreviations of minerals: Qz, quartz; Crs, cristobalite; Trd, tridymite; Opx, orthopyroxene; Aug, augite; Alu, alunite; Kln, kaolin-group minerals; Pl, plagioclase; Sme, smectite; Mica, biotite or illite.

The X-ray intensities of each mineral are shown as +++, very intense (>2000 cps); ++, intense (200–2000 cps); +, weak (80–200 cps); r, rare.
5. Discussion

5.1. Depositional Features of the Lahar Deposits

5.1.1. Units L1-1 and L1-2

Repetitive alternation of coarser- and finer-grained layers, low-angle cross-stratification, and lapilli trains in the coarser-grained layers of unit L1-1 indicate a deposition from a hyperconcentrated flow (e.g., [13]).

The massive, ungraded, poorly sorted, and matrix-supported features of unit L1-2, except for the lower part, indicate rapid transportation–deposition without grain separation and thus this unit is interpreted to be deposited from a debris flow [14]. The andesitic pebbles and cobbles would be entrained while flowing down the river.

The parallel laminated lower part of unit L1-2, showing better sorting and parallel to low-angle cross-lamination, is considered to be the deposition under a normal streamflow condition [14].

5.1.2. Units L2-1 and L2-2

The massive, poorly sorted, and matrix-supported characteristics of unit L2-1 indicate a rapid and en masse sedimentation from a debris flow [14]. The andesitic pebbles would be entrained while flowing down the river.

The diffuse stratification, poorly sorted, and matrix-supported characters of unit L2-2 indicate rapid deposition of sediment under a traction carpet developed in a hyperconcentrated flow [13, 14].

5.1.3. Unit M

The unit M directly overlies a paleosol layer, that shows sudden inundation of the area by a flow. The weakly laminated, ungraded, moderately sorted, sparsely distributed pebbles, and dark brown colored muddy matrix characteristics reflecting high percentage of mud contents of this unit indicate a rapid deposition from a muddy flow. The lenticular brown sandy layer in the lower part would be a deposition from a preceding flow.

5.2. The Origin of the Materials of the Lahar Deposits

The component analysis indicated that L1 and L2 units have high abundance of white and beige lithic fragments in the matrix. The white lithic fragments are inferred to originate from phreatic or phreatomagmatic eruption products. The existence of alunite detected by the XRD analysis and relatively high percentages of pale-gray or beige mud particles measured by the granulometric analysis support this interpretation. Therefore, the L1 and L2 units were caused by lahars; i.e., associated with volcanic activity rather than non-volcanic alluvial/fluvial processes. Considering 5–10% scoriae are included, the deposits likely incorporate products of phreatomagmatic eruptions.

The set of hyperconcentrated flow and debris flow deposits is of common features of those caused by a lahar event [15, 16]. In the Fujiki archaeological site, unit L2-2 (hyperconcentrated flow deposits) and overlying unit L2-1 (debris flow deposits) as well as unit L1-2 (debris flow deposits) and overlying L1-1 (hyperconcentrated flow deposits) can be regarded as an example of the set. This succession indicates flow transformation between debris flow and hyperconcentrated flow in a single laharc event [16].

5.3. The Timing of Formation of the Lahar Deposits

Based on the \( ^{14} \)C data and the stratigraphy, the age of unit L1 was estimated to be younger than 4.0 cal ka and that of unit L2 to be ca. 4.6 cal ka. According to the tephrostratigraphic study by [17], seven phreatomagmatic eruption events intermittently occurred during ca. 4.5 to ca. 2.8 ka at the summit area. The age of units L1 and L2 correspond to that of the third to seventh events and the first event at the summit area, respectively. Therefore, the lahars, which caused L2 and L1 units, would have occurred shortly after the corresponding eruption events.
5.4. The Lahar Hazard Risks in Western Foot of the Zao Volcano

This study firstly revealed the existence of the lahar deposits in the western foot of Zao volcano. This finding is very important for the lahar hazard risk evaluation. The lahars in Zao volcano tend to flow down to the east, because the summit caldera opens to the east. Therefore, the lahar risk assessment of the western foot tends to be overlooked, although simulations of lahar distribution in Zao volcano by [18] indicates that the western foot, especially along the Zaogawa River, has a potential lahar hazard risk. This study clarified that the lahar flowed down to the west of the volcano in the past. This fact emphasizes the necessity to consider the lahar risk in the western foot of Zao volcano, too. The lahar deposits found in this study indicate that the lahars were probably triggered by phreatomagmatic eruptions. The phreatomagmatic eruption products are generally fine grained due to the violent explosivity and can influence on mobility of lahars if enough amount of water is supplied. The snowmelt, river water, and groundwater (including the fluid of the hydrothermal system) are possible candidates of the water to generate lahars. Some of the products during ca. 4.5 to ca. 2.8 ka phreatomagmatic eruptions distributing around the summit area are relatively thick [17], and therefore these would have been the source materials for the lahar. Therefore, the lahar risk at Zao will increase especially after the phreatomagmatic eruptions as well as phreatic eruptions.

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