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Forensic Profiling Analogue Approach for the Investigation of Natural Hazards – A Case Study from Onokoba Elementary School, Unzen Volcano, Japan

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Abstract. Internal temperature variations of pyroclastic flows and their deposits are arguably the most challenging data to acquire. As a preliminary study of the temperature variation inside pyroclastic flows, the remains of Onokoba Elementary School (Shimabara, Japan) were investigated. The elementary school is located in the close vicinity of Unzen volcano and was hit by one of the largest pyroclastic flows during the latest active period of the volcano on 15th of September 1991. This present preliminary study aims to determine the temperature exposure of various portion of the school building using field-forensic and urban geology. Natural hazard methods applied to the damaged materials exposed to high temperature have generated a temperature fingerprint the maximum temperature distribution. Charred wooden parts and plastic gutters installed on the schoolyard-side faced of the building turns out to be the most useful temperature indicators. The various deformation and alterations of the studied materials show significant differences in the temperature exposed to. Such differences on the second-floor section (between 75-110°C and 120-150°C) and on the first-floor section (above 435-557°C) of the building do not simply imply significant temperature heterogeneity in short distance (some ten to ≤100 m) inside the pyroclastic flow, but also points toward the possible effects of the building architecture on some key dynamic parameter of the pyroclastic flow. Such information may be important for planning future hazard mitigation actions.

Keywords: natural hazard; pyroclastic flow; emplacement temperature; field evidence; forensic geology; forensic geohazard profiling.

1. Introduction

Remote sensing methods have been applied at volcanic eruptions to gain additional information about the temperature of pyroclastic flows. Umakoshi et al. (1993) used the infrared thermal surveys indicated up to 658 °C at the forming lava dome and pyroclastic flows of Unzen Volcano. Denniss et al. (1998) applied satellite imagery and estimated the pyroclastic flow temperature at around ≥185-265°C during the eruption of Láscar Volcano (1993; Chile). Since the pioneering research of Aramaki and Akimoto (1957), several studies have been applying magnetic methods, namely thermal remanent magnetisation experiments on lithic and juvenile fragments and matrix material to estimate the temperature of pyroclastic flows (Table 1). Thermoremanent magnetisation (TRM) or progressive thermal demagnetisation (PTD) experiments and the determination of partial thermoremanence (pTRM) become the most popular ways to determine pyroclastic flow emplacement temperature (TE) or depositional temperature (TD) among the various methods.

Table 1. The estimation of pyroclastic flow emplacement temperature by various methods.

Volcano	Date	Temperature	Material/Method	References
Colima (Mexico)	1913	360–420°C	PDC/TRM, PTD	Sulpizio et al. (2014)
	2015	345–385 °C (valley-confined); 170–220 °C (unconfined distal)	Charred wood, lithic clasts/ reflectance, TRM	Pensa et al. (2015)
	18.52±0.044 ky; 9.370±0.4 ky	350°C	Volcanic debris avalanche/ TRM, PTD, pTRM	Clement et al. (1993)
Colli Albani (Peperino Albano Ign.; Italy)	16-36 ka, MIS3	240° and 350°C	PDC/TRM, PTD	Porreca et al. (2008)
		50-100 °C	Fossil remains of a vulture/ computer tomography	Iurino et al. (2014)
El Chichón (Mexico)	1982	250–330°C	PDC/TRM, PTD	Sulpizio et al. (2014)
		360°C (mean), 402°C; 360-400°C	Pumice flow./field m.; TRM	
Guadeloupe (France)	37.5 ky	350°C, 400°C; 530°C	Pumice; pyroclastic flow / TRM., aquisition of pTRM	Zlotnicki et al. (1984)
Láscar (Chile)	1993	≥185-265°C	Satellite imag.	Denniss et al. (1998)
		≥397°C	Lithic and juvenile clasts/ TRM	Paterson et al. (2010)
Los Humeros; Alchichica (Mexico)	Late Plio. / Early Pleist.	≥450°C (Los Humeros); 100 to 300°C (Alchichica)	Lithic clasts and matrix /TRM	Urrutia-Fucugauchi (1983)
Mont St. Helens (USA) (1)	1980	<100°C; 100-200°C; 300 and >600°C	Debris avalanche; lateral blast dep.; pyroc. dep./TRM	Banks and Hoblitt (1996)
		≥532°C, ≥509°C, 510–570°C and ≥577°C	Lithic and juvenile clasts/ TRM	Paterson et al. (2010)
Mont St. Helens (USA) (2)	n.a.	550-600°C; 375±25°C, 400-450°C	PDC; PDC or hot lahar/TRM, PTD, pTRM	Hoblitt and Kellogg (1979)
Mukaiyama (Niijima, Japan)	886 AD	<150°C up to 300 °C, 380 °C	Lithic and juvenile clasts (PDC)/TRM, PTD	Nakaoka and Suzuki-Kamata (2014)
Mt. Sambe (Japan) + Lab. (comb.) exp.	3530±100 y, 3710±100 y	502-603°C , (mean: 541±28°C); 482-543, (mean:516±17°C); 500°C, 560°C, 500-530°C	Carbonized woods; lithic clasts/H/C ratio (elemental analyzer); TRM,	Sawada et al. (2000)
Santorini (Greece)	~3600 y	c.a. 500°C	Ign., pumice flow/AF demag.	Wright (1978)
	<Late Pliocene	250 to ≥580°C	Ignimbrite lithic breccia, Plinian airfall dep./TRM, PTD	McClelland and Druitt (1989); Bardot and McClelland (2000)
Soufrière Hills (Montserrat)	1996-1997	99-121°C, 99-149°C, 200-250°C	PDC/Field measurements (1.5 m above the ground)	Cole et al. (1998)
		200-650°C; 130-420°C; 140-220°C	dome-collapse flow; derived-flow; pumice-rich flow /Field measurements	Calder et al. (1999)
		325–525 °C	Charred wood/Reflectance	Scott and Glasspool (2005)
Tungurahua (Ecuador)	2006	<250-300°C	Evidence exposed or not to high temperature/field obs.	Hall et al. (2013)
		<90°C; >540°C	Lithic and juvenile clasts/ TRM	Rader et al. (2015)

Volcano	Date	Temperature	Material/Method	References
Unzendake (Japan)	1990-1995	210-345°C; >420°C and 660°C	Gas and very fine ash; coarse grained ash and clast/field measurements	Suzuki-Kamata et al. (1992)
		≤658°C	Lava dome and PDC/Infrared thermal survey	Umakoshi et al. (1993)
		500°C; 300–600°C	Block-and ash flow (1991); PDC (rotation of blocks after deposition!)/TRM, PTD	Tanaka et al. (2004)
Vesuvius (Italy) (1)	79 AD	≥400°C	Ignimbrite (PDC)/TRM, PTD	Kent et al. (1981)
		180–380°C (240–340°C)	PDC/TRM, PTD	Cioni et al. (2004)
		100–140°C, 300–360°C	Lithic and roof tile fragments (PDC, ash-fall)/TRM	Zanella et al. (2007)
		~280°C to ~533-649°C, ~280-340°, ~520°C	Lithic and juvenile clasts/TRM	Paterson et al. (2010)
		240 °C and 370 °C	Charred wood/reflectance	Caricchi et al. (2014)
Vesuvius (Italy) (2)	<22 ky	270–370°C	PDC/TRM	Zanella et al. (2014)
Yufu (Japan)	2000 y	220-400°C (block-and-ash flow)	Juvenile clasts/TRM, pTRM	Saito et al. (2003)

Note: if TE ≤130 °C, the identified temperature may indicate VRM - viscous remanent magnetisation instead of depositional temperature (Bardot and McClelland, 2000). PDC - pyroclastic density current; PTD - progressive thermal demagnetization; pTRM - partial thermoremanence; TE – Emplacement temperature; TRM - Thermoremanent magnetization. y - year and ky – kiloyear data are interpreted in BP - before present.

Some of the volcanological research, e.g., Pollock et al. (2010) and Hall et al. (2013), used various components of the environment as evidence, if high-temperature exposure did happen or not during the hit of the pyroclastic flow. Such observations often use results from forensic and material science to support the characterisation of the pyroclastic flow (e.g., about the influence of heat exposure on various materials in Babrauskas [2002], and Café [2007]). One of the most commonly used in situ field indicator of pyroclastic flow temperature and object of further laboratory experiments is burnt wooden fragments, preserved in the volcaniclastic sediment (e.g., Sawada et al., 2000; Scott and Glasspool, 2005; Hall et al., 2013; Pensa et al. 2019). Along with the wooden remains, various fossils may be found in the pyroclastic flow sequences, such as in the case of Colli Albani (Italy) volcano: fossilised bird remains studied by Iurino et al. (2014) provided additional information about the temperature of Peperino Albano (PA) ignimbrite (Table 1).

As by the research of Ui et al. (1999) and Suzuki-Kamata et al. (2009), the frequent dome collapses and the pyroclastic-flow activity have resulted in the formation and sedimentation of block-and-ash flow volcaniclastic deposits during the latest eruption period of Unzen volcano, between 1991 and 1995. There are many attempts to characterise the nature of the pyroclastic density currents (PDCs). Detailed geological-geomorphological maps are drawn indicating the trail and spread of pyroclastic and debris flow (e.g., Nakada et al. 1999), accompanied by various studies about the physical parameters of the flows, such as temperature measurements and estimations from Suzuki-Kamata et al. (1992). The measurements showed 210-345 °C in the mixture of gas and very fine ash, and >420 °C and 660 °C were obtained from coarse-grained ash and clasts. Cole et al. (1998) and Calder et al. (1999) provided field temperature data from Soufrière Hills Volcano (Montserrat). The results from the former, (measured by industrial temperature patches, fixed 1.5 m above the ground in Tar River valley), indicated consistent 99-121 °C, 99-149 °C, and 200-250 °C within any one flow, and the differences between the flow temperatures was described as differences in the source materials. The latter study observed the highest maximum temperature in dome-collapse flows (200-650 °C), the lower maximum temperature in derived-flows (secondary flows derived from pyroclastic surges; 130-420 °C) and the lowest maximum temperature in pumice-rich flows (associated with lava fountains; 140-220 °C).

Investigation of damages appears on building is a way of research scientist may consider during the study of the nature of pyroclastic flows (e.g., Baxter et al., 2005; Spence et al., 2004; Ruggieri et al., 2020). Such studies help understand how pyroclastic flows affect the environment and provide additional information for future natural hazard mitigation. Following the description of Baxter et al. (2005), lateral loading, the directionality of the current, impacts corresponding to the dynamic pressure (with slow rise rate and without the peak overpressure or shock front with explosive blast) and materials carried by the flow (e.g., abrasion from natural blocks, fragments from buildings, vehicles and so on) are the main destructive components of a PDC. High temperature is known as one of the major causes of destruction (entering the building through possible openings and igniting combustibles), even in the periphery of the flow where the dynamic pressure is low (Baxter et al., 2005).

This study aims to introduce and propose a novel angle in profiling natural hazards. The proposed research strategy combines elements from e.g., forensic and urban geology, geomorphology, environmental studies and material science. The joint application of those fields should provide a novel and progressive way to reveal crucial information about natural phenomena causing environmental disasters. During the profiling of natural hazards, analogue to the profiling in criminal cases, evidence of the environmental disasters is observed and collected from natural and built environment. Furthermore, the results of the interdisciplinary research are compared and synthesised to gain information about the "behaviour" of the phenomena. In this particular case, the study of the pyroclastic and debris-flow sediments and the remains in built environment, following the 1990-1995 eruption period of Unzen volcano are proposed to develop the strategy for natural hazard profiling and gain novel information about the environmental disaster which hit Shimabara city (Japan). This research focuses on the nature of the pyroclastic flows by studying their effect on built environment, especially the marks of high temperature exposure.

2. Geological background and the studied site

Unzendake (Mt. Unzen) is a stratovolcano, located in the Shimabara Peninsula (32°45′41″ N, 130°17′56″ E, 1483 m – Heisei-Shizan elevation point; 32°45′36″ N, 130°17′32″ E, 1359 m – Fugendake triangulation point; Nagasaki, Japan) (JMA, 2013) (Figure 1a). The oldest formations related to the activity of Unzen Volcano is dated back to the Middle Pleistocene and can be found in the West-side of the volcano (e.g., Yasumiba Ignimbrite), along with some fan deposits. The younger stage of the volcanic history of Unzendake is started by the development of Nodake and Myokendake volcanoes. This stage is represented by Late Pleistocene formations, which appear around the Myogendake main edifice (the central part of the volcano) and can be found in the Southeast side of the volcano where Nodake materials are exposed, such as the Nodake Lava, Nodake Ignimbrite and Nodake Debris avalanche formations (Watanabe and Hoshizumi, 1995; Yamagata et al., 2004). The Holocene-Anthropocene is represented by the quasi-simultaneous formation of Fugendake (developed on Myogendake edifice) and

Mayuyama Volcano (formed on the foot of the Eastern slopes of Myogendake main edifice) (Ozeki et al., 2005). The development of Fugendake and Mayuyama was accompanied by the formation of syn- and post-eruptive volcanogenic deposits (volcanic apron and fan sediments) (Watanabe and Hoshizumi, 1995) (Figure 1b).

Some of the syn- and post volcanic (sedimentary) processes related to the development of Fungendake and Mayuyama caused environmental disaster in the vicinity of the volcano and claimed human lives (JMA, 2013). Following the 1663 eruption of Fugendake, a lahar occurred along the Akamatsu Valley (S and SE of the volcano) and caused flooding which killed over 30 people in 1664. The most horrific environmental disaster, related to Unzen volcanic area happened in 1792. Volcanic and earthquake activity started in 1791 and during the last stage of volcanic activity of Fugendake, the so-called Shimabara-Shigatusaku Earthquake occurred on 21st May 1792. The earthquake triggered a landslide resulting the collapse of the Eastern slope of Mayuyama. The c.a. 1.50×10-8 m3 of material (Miyamoto 2010; please note that JMA, 2013 suggests 4.4×10-8 m3) reached the sea at 100 m/sec speed with 30 m thickness at the landslide front caused one of the worst disasters in Japan and possible in the world history. The over 20 m hight tsunami, generated by the landslide destroyed many settlements and killed approximately 15,000 people along the shore of Ariake Bay (Miyamoto, 2010; JMA, 2013; Sass et al., 2016).

The last active period of Unzendake, the target of our study, started with earthquake swarms under Tachibana Bay, migrated toward the summit of the volcano in November 1989. The one year long seismic activity around the volcano is followed by the first phreatic eruption in November 1990. Following the continuous growth of the lava dome, its collapses lead to frequent pyroclastic flow activity, accompanied by debris flows between 1991 and 1995 (Nakada et al., 1999). Despite the evacuation of thousands of people (reaching a maximum of c.a. 11,000 people), the series of pyroclastic and debris flows claimed the life of more than 40 people.

The target location of the pilot research is the remains of Onokoba Elementary School and its neighbourhood, which area was exposed to the effect of pyroclastic flow on 15th of September 1991 (Nakada et al., 1999) (Figure 1c). The remain of the elementary school are preserved without any significant change following its destruction by the second pyroclastic flow hit the area (15th of September 1991), as a part of museum and observation spot collecting and exhibiting various memories about the last eruption period of Unzen volcano (Onokoba Sabo Mirai Museum; http://www.qsr.mlit.go.jp/unzen/oonokoba/miraikanpamphlet_english.pdf) (Figure 1c). The 15th of September 1991 pyroclastic flow was formed by the exogenous growth of the lava dome (including bulging of NE dome and older underlaying rocks), and the formation of the third lobe (Lobe 3) overriding Lobe 2 on 13th of August 1991. The dome collapse resulted in one of the largest pyroclastic flows, cascaded toward Oshigadani, a valley NE of the dome, and, following the local geomorphology, veered SE-E in the valley of Mizunashi River toward Onokoba (Ohnokoba, OnoKoba) (Figure 1b). The “main” part of the pyroclastic flow (unit 2 in Fujii and Nakada, 1999), identified as block-and-ash flow type, run down following the valley East. However, “unit 1” an ash-cloud surge type side branch of the pyroclastic flow run through the location of the elementary school (Fujii and Nakada, 1999; Nakada et al. 1999) (Figure 1b). Please find additional documentation, including pictures from the site in the publication of Unzen / Fugendake Eruption Disaster Record Creation Committee (2002).

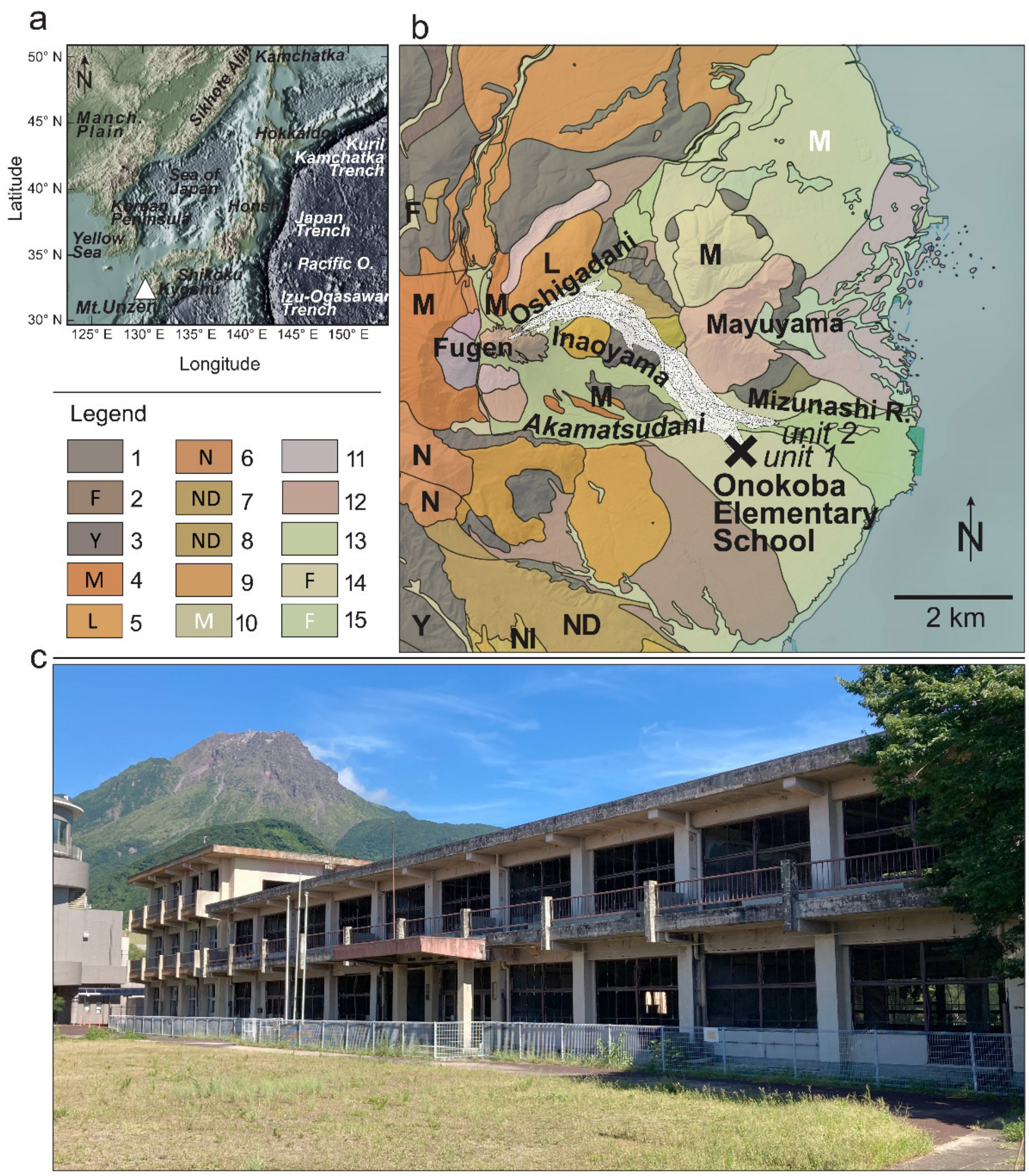

Figure 1. The studied site. a) The location of Mt. Unzen in Japan. The basic relief map is adapted from Amante and Eakins (2009)***; b) the geological map of Unzen volcano, including the track of the pyroclastic flow on 15th of September 1991 (white, transparent, textured polygons named unit 1 [ash-cloud surge] and unit 2 [block-and-ash flow], after*** Fujii and Nakada, 1999***). Color legend: 1-Older Unzen eruption products (Middle Pleistocene); 2-Fan deposit (Middle Pleistocene); 3- Yasumiba ignimbrite (Middle Pleistocene); 4-Myogendake main edifice (Late Pleistocene); 5-Lava flow (Late Pleistocene); 6-Nodake lava (Late Pleistocene); 7-Nodake debris avalanche (Late Pleistocene); 8-Nodake ignimbrite (Late Pleistocene); 9- Ignimbrite (Late Pleistocene); 10-Mayuyama volcano (Holocene); 11-Mayuyama collapse deposit (Holocene); 12-Tenguyama lava (Holocene); 13-Volcanic apron and fan (Holocene); 14-Fan deposit (Holocene); 15-Younger Unzen gravel fan (Holocene); c) the remains of the Onokoba Elementary School as is in July 2021. The geological map is modified after*** Watanabe and Hoshizumi (1995) ***and*** Gomez et al. (2021)***. The black cross in the map indicates the location of the elementary school.***

3. Research Method

The term "profiling natural hazard" (as well "natural hazard profiling", "hazard profiling") has been used in various way in various context. Hazard analysis is sometimes referred as hazard profiling in disaster risk management. Hazard analysis or profiling is a descriptive process, which follows hazard identification. It includes the description of the hazard, historical information about previous events appeared in the studied area, and discussion about the probability and possible influence of future events (Coppola, 2011).

Forensic geoscience was defined by Pye and Croft (2004, p. 1) "as a subdiscipline of geoscience that is concerned with applying geological and wider environmental science information and methods to investigations which may come before a court of law". As other fields of forensic science, forensic geology focuses on evidence connected to criminal activity, e.g., describes the perpetrator actions, via the study of trace evidence, such as soil and sediment samples, by methods used in geosciences. Such process may be the part of profiling during forensic investigations.

A new term and research field, forensic geohazard was born from the overlapping field of Earth and forensic science during the study of natural hazards, "when the geological risk is intertwined with forensic investigation" (Barone and Di Maggio, 2018; p. 1). In disaster hit areas forensic geohazard studies may play significant role e.g., in the search for missing persons (e.g., the so-called Rescue Radar) and also in the study of possible damage in the built environment (structures and buildings) and preventing further disasters (Barone and Di Maggio, 2018).

The idea how our proposal is reaching the process of forensic geohazard profiling is described in Figure 2. Forensic science refers to the studies of traces (information) that originated from criminal activity describing very general. Profiling is the analysis and discovering the connection between data, which can be used to characterise, identify and represent a human or non-human subject. In forensic science, the goal of forensic profiling (differs from offender profiling, which focuses on the psychological profile of the criminal) is the study of trace evidence to develop information which can be used to identify the perpetrator(s) and the environment of a crime (Geradts and Sommer, 2008).

As we already suggested above, the proposed research strategy is built on the basic purpose of forensic profiling, i.e. using traces of criminal activity (evidence) to characterise and identify a subject. In our case various research elements from e.g., forensic and urban geology, geomorphology, environmental studies and material science are combined. The joint application of those fields may provide a novel and progressive way to investigate the traces of natural disasters, identify them, and reveal crucial information about the phenomena causing environmental disasters (i.e., forensic geohazard profiling). During forensic geohazard profiling, analogue to the profiling in criminal cases, environmental disasters are observed and collected from natural and built environments (Figure 2).

Furthermore, the results of the interdisciplinary research are compared and synthesised to gain information about the nature of the phenomena. As a first step of this process, here we provide the preliminary results of field observation at Onokoba Elementary School. During the preliminary study mainly the facade facing S was investigated which is the opposite side of the building relative to the volcano ("schoolyard side", as it was referred in Yamada, 2019). As a summary, our investigation of natural hazards is analogue of forensic (geology) profiling. Trace evidence related to the PDC, found around Onokoba Elementary School was used to understand the nature of a phenomenon, i.e., the pyroclastic flow, which hit the building on 15th of September 1991.

There can be some concern about the reliability of the field observations during the study of natural hazards. The crime scene must be kept intact during criminal case investigation until the field observation finishes. In many cases, the studies of natural hazards are similar and may (must) happen right after the catastrophic event to observe and document the characteristics of the disaster without the restoration of the area. Such field studies may be necessary and not debatable from scientific point of view but raise some moral problem (Gomez and Hart, 2013; Gaillard and Gomez, 2015). In our case, the traces of the pyroclastic flow kept quasi "untouched" as the remains of Onokoba Elementary School keep as is, without any significant renovation after the hit of the ash-cloud surge.

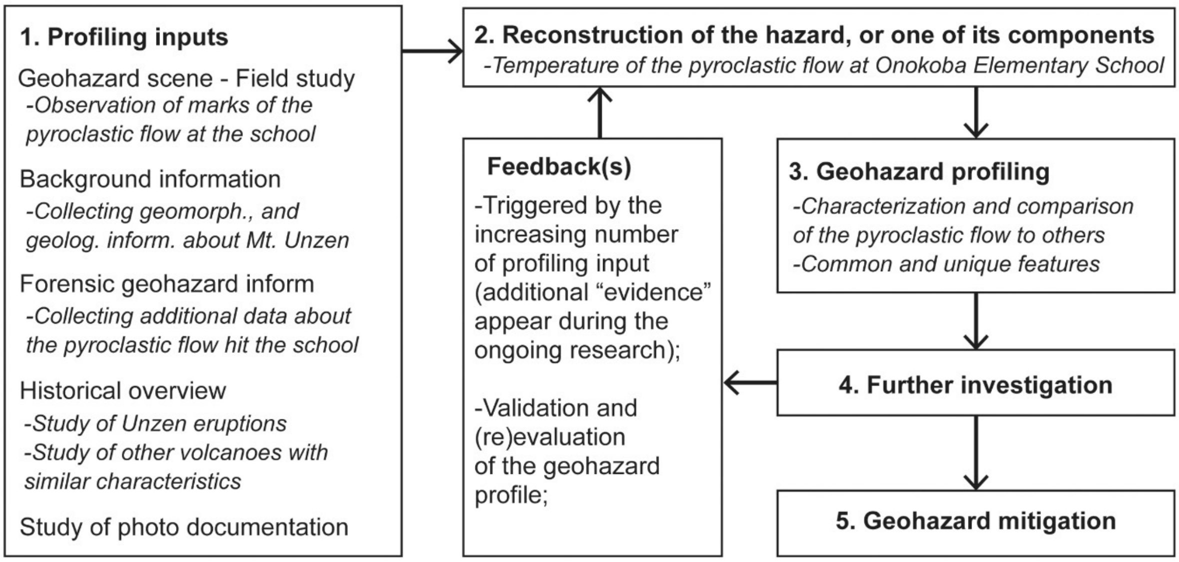

Figure 2. Forensic geohazard profiling workflow, applied during the study of Onokoba Elementary School. The workflow is the simplified and altered version of the criminal profiling workflow, introduced by Douglas et al. (1986).

4. Results and Discussion

4.1. Field observations and interpretation of the evidence

Based on the provisional damage scale, provided by Baxter et al. (2005) and the condition of the elementary school, the building suffered Level 2 and 3 damage (e.g., the windows on the schoolyard side are blown out and the frames are deformed, some inside wall are damaged or partly destroyed). Various degree of deformation of the steel window frame can be observed in almost every part of the studied facade of the building (Figure 3). Yamada (2019) studied such deformations, their orientation, the plunging direction of the volcaniclastics, transported by the surge and penetrated the window, and the distribution of window glass fragments and estimated the influence of the building on the pyroclastic flow. The model shows outstanding compressive force and vortex at the schoolyard side of the building, as well deceleration about 0.5 to 0.9 in the reduction ratio of velocity, and c.a. 0.2 to 0.7 in the reduction ratio of pressure.

The further part of the investigation around the remains of the Onokoba Elementary School was focused on the marks of high-temperature exposure. As it is summarised in Table 2, their characteristic evidence of exposure to high temperature was observed during the preliminary study of the location.

The appearance of charred wood suggests that the temperature reached minimum 120-150°C when the ash-cloud surge hit the school. In addition, the charcoal-looking appearance of the remains of the wood suggests the pyrolysis of the original material and indicates its ignition temperature and the possible minimum 190°C-260°C temperature of the pyroclastic surge at the entrance of the elementary school (Babrauskas, 2002; Café, 2007) (Figure 3). Caricchi et al. (2014) estimated 240 °C and 370 °C burning temperature and pyroclastic flow temperature by analysing in-situ charred woods at Herculaneum (Vesuvius, Italy). Surprisingly significant local differences in the temperature can be recognised due to the appearance of unburnt wooden pieces e.g., furniture in the two-floors part of the elementary school.

Table 2. Some of the observed and studied evidence of exposure to high pressure and temperature at Onokoba Elementary School (Shimabara, Japan)

Observed evidence	Location (position, surroundings, hight from ground, etc.)	Description
Deformed metal (steel) window frame	Schoolyard side, ground floor and 1st floor	Various degree and orientation of the bended window frame and other steel components
Charred wooden material	Over the main entrance from the schoolyard	C.a. 100% charred wood without any visible texture of the original wood
Deformed, melted, and burnt plastic gutters	Ground floor, in the corner at the pillars of the building; the lower part of the gutters has a metallic cover/metal gutter base part c.a. 1.5-1.8 m from the ground; metal rings are also recognisable above the metal gutter	Various level exposure to heat can be recognised on the plastic gutters: "scales", surface deformation and burning, soot on the surface, detachment and bending, melting and burning down

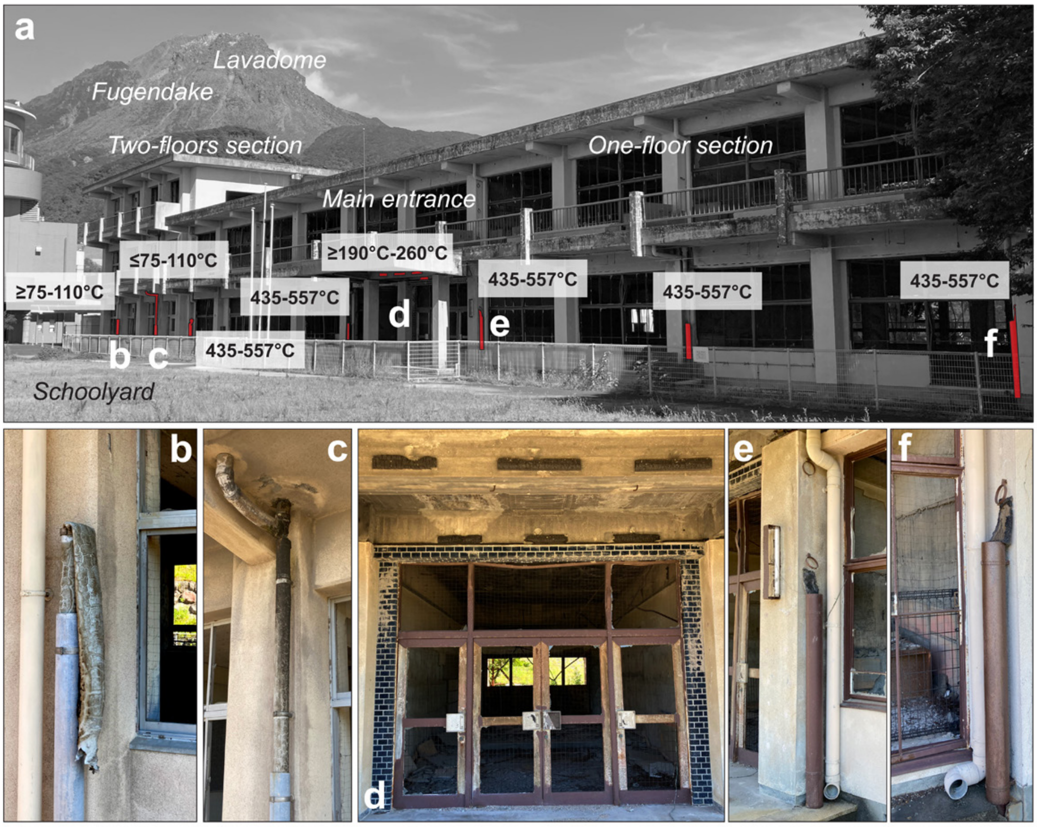

Figure 3. Some of the identified field evidence of high temperature exposure in the schoolyard-side of Onokoba Elementary School. a) The elementary school with the location of the studied evidence of high temperature exposure and the reconstructed temperature of the pyroclastic flow; b) melted and bended gutter with scales from the two-floors section of the building; c) partly melted gutter (upper part) with an increasing amount of soot at the upper part of the tube, possibly indicating higher temperature at the two-floors section of the elementary school; d) the main entrance of the building with burnt, charred wooden pieces above the doors; e and f) melted and ignited plastic gutters at the one-floor section of the building.

Plastic gutters complete the information gained by the study of the charred wooden pieces. The gutters at the one-floor section of the building (further from the volcano, Figure 1c and Figure 3) are fully burnt out from their lower half metallic base or only a deformed remain can be found. For example, the ignition temperature of e.g., PVC, one of the most commonly used plastic is 435-557°C (Café, 2007). In contrast melted but minimally burnt gutter (detached and bended but not destroyed) and an only partly deformed functioning gutter with scales and soot on its surface can be found at the two-floors section of the elementary school (Figure 3). Such marks may indicate higher temperature and the effect of burning in the surrounding, but definitely lower than the ignition temperature of the plastic gutters. The PVC melting point range is between 75-110°C (Café, 2007), which might be the minimum temperature of the pyroclastic surge around the two-floors high part of the building. Based on the appearance of slightly (non) damaged wooden parts and the melted but unburnt plastic gutters the temperature of pyroclastic surge may fall between 75-110°C and 120-150°C. Such low temperature may be surprising but has been already observed at some eruption (Table 1). The most convincing, out of the studies is the field measurements of Cole et al. (1998) at Soufrière Hills (Montserrat; 99-121°C, 99-149°C, and 200-250°C). Indirect way (i.e., estimated by various methods), low pyroclastic flow temperature was reconstructed during the eruption of e.g., Colima (≃170–220 °C; Pensa et al., 2015), Colli Albani (50-100 °C; Iurino et al., 2014), Mont St. Helens (<100°C, 100-200°C; Banks and Hoblitt, 1996), Mukaiyama (<150°C; Nakaoka and Suzuki-Kamata, 2014), Tungurahua (<90°C; Rader et al., 2015), and Vesuvius (100–140°C; Zanella et al. 2007).

4.2. Temperature heterogeneity in the pyroclastic flow(s)

As the temperature estimation shows, high temperature variability is expected in the pyroclastic surge that hit Onokoba Elementary School on 15th of September 1991. Various equipment, building parts installed only some (ten) meter distance from each other (e.g., the plastic gutters) indicates different temperature, i.e., suggests very high temperature heterogeneity in different parts of the pyroclastic flow. Such high temperature variability has not been investigated in detail, but some studies have already observed such differences and provide some explanation.

Field evidence of the heterogeneity in emplacement temperature of pyroclastic flow was observed following the pyroclastic flows appeared during the 2006 eruption of Tungurahua (Ecuador). In some locations, undamaged vegetation, uncharred woods, and unmelted plastic were found in some parts of the pyroclastic density surge deposits, indicating low temperature compared to other parts consisting of charred woods (c.a. 300°C) (Pollock et al., 2010; Hall et al., 2013).

Some controversial results were published about the emplacement temperature of the (Peperino Albano ignimbrite (Late Pleistocene, Colli Albani, Italy). Paleomagnetic measurements indicated 240° and 350°C emplacement temperature (Porreca et al., 2008), but the condition of the fossilised bird, found in the ignimbrite does not support this estimation and suggests much lower temperature during the deposition (50-100 °C; Iurino et al., 2014) (Table 1).

The paleomagnetic results of Rader et al. (2015) supports the observation described above. The broad range of reconstructed temperatures indicates thermal heterogeneity at the deposition time of Cotopaxi and Tungurahua PDC. The differences between lithic and juvenile clasts allow building a complex model with the focus on the importance of air entrainment and cooling during the pyroclastic flow. The studied PDCs are marked as "cold-matrix, hot-bomb" type of PDC, which name suggests that the density current "cooled by ingestion of large amounts of air during flow" (Rader et al. 2015, p. 83). In such type of PDC the fine-grained matrix most likely cooled down to nearly ambient temperature even before deposition, lithic fragments were heated to considerable temperature, and juvenile magmatic clasts barely cooled and remained hot even after deposition (appearance of post-depositional deformed fragments). In other words, there are differences in the temperature of the juvenile, lithic components and matrix found in PDCs due to e.g., the differences in their origin and their physical properties. The study of Rader et al. (2015) shed some light on the possible misinterpretation of emplacement temperature data reconstructed only from juvenile components, which may lead to overestimating the temperature or lithic clasts with a possible underestimation of the temperature.

Besides the temperature differences in the components of the PDC, topography may play significant role in the temperature (change) in the pyroclastic flow. Pensa et al. (2019) reconstructed 345–385 °C in valley-confined area, and much lower, 170–220 °C in unconfined, distal location. Based on paleomagnetic results, Nakaoka and Suzuki-Kamata (2014) explanation of the temperature variability in the PDC during the A.D. 886 eruption of Mukaiyama (Niijima Island, Japan) is that "low-temperature emplacement occurred by phreatomagmatic eruptions and ingestion of ambient air by the turbulent current" (Nakaoka and Suzuki-Kamata, 2014, p. 51).

We propose the following working hypothesis based on that information and the preliminary results. The field measurements of Suzuki-Kamata et al. (1992) showed 210-345°C in the case of a mixture of gas and very fine ash, expectedly similar to the ash-surge hit the elementary school. The topographic change during the travel of the pyroclastic flow, i.e., its arrival to the unconfined part of the Mizunashi River valley might significantly changed the temperature, similar to the case of Colima eruption (Pensa et al., 2019). In addition, the significant drop of the pressure and velocity of the surge suggested by Yamada (2019) provided less support for the ignition of various objects (higher pressure supports combustion). As the field observation shows, materials located at the two-floors section of the building were less exposed to higher temperature than the materials at the entrance or the one-floor section of the elementary school. It may suggest that the architecture of the building itself played some role in the temperature change of the pyroclastic flow in very short distance.

5. Conclusion

As one of the basic physical properties, the temperature of the pyroclastic flows hit Onokoba Elementary School were estimated based on the mark of high temperature exposure on some building material. The various state of alteration of the materials provided evidence to the possible high temperature variability in the pyroclastic flow between 75°C and ≥435°C.

Among the studied materials, the various state of alteration of plastic (gutters) provided the most detailed information about the temperature of the pyroclastic flow. The differences between the estimated temperature of the PDC at the two-floors section (between 75-110°C and 120-150°C) and one-floor section (above 435-557°C) of the building not simply indicate significant temperature heterogeneity in short distance (some ten to ≤100 m) inside the pyroclastic flow, but points toward the possible effects of the building architecture on some key physical parameter of the pyroclastic flow. Such information may be important for planning future hazard mitigation actions.

The preliminary results also appoint some possible future research in the area, including detailed thermomagnetic analysis of some building material and natural volcaniclastic sediments and the comparative analysis of charred wooden remains from damaged buildings and fragments preserved in the pyroclastic flow. Furthermore, stepwise combustion experiments, completed by scanning electron microscope studies, are also planned. Such laboratory experiments will support the determination of the alteration degree of building materials during high-temperature exposure and allow us to estimate more accurately pyroclastic flows.

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