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TephroArchaeology in the North Pacific

edited by

Gina L. BARNES
SODA Tsutomu

Access Archaeology

Archaeopress Access Archaeology

Archaeopress Publishing Ltd
Summertown Pavilion
18-24 Middle Way
Summertown
Oxford OX2 7LG

www.archaeopress.com

ISBN 978-1-78969-172-6
ISBN 978-1-78969-173-3 (e-Pdf)

Cover Illustration:
Alaid Volcano viewed from Shumshu Island, northern Kurils off the tip of Kamchatka.
Photo: B. Fitzhugh 2016

Dedicated to

ARAI Fusao & MACHIDA Hiroshi
who together paved the way for
TephroArchaeology in the North Pacific

"In Japan, they've got some very very good preservation, but there are some tremendously compelling things…. We need to know about this; they're doing really really good work." Payson Sheets

"The data in Japan is so incredibly rich and the archaeology is so fantastic that there is huge potential here within one cultural area for us all to get together and map out some of these differences. I think it could set a standard for us who have much less data to compare." Robin Torrence

TABLE OF CONTENTS

* * * * *

Chapter 6 MURAKAMI Yoshinao

Chapter 7 Keith PRATT

Chapter 8 MARUYAMA Kōji

Preface

TephroArchaeology Becomings

The way volcanic eruptions affect human life has become a widespread topic of archaeological research. I owe special gratitude to Payson Sheets, Robin Torrence, and Felix Riede for introducing me to this field of study beyond Japan. Their publications together with those of many other colleagues have provided a rich array of assessments of human interaction with volcanoes from the modern era into deep time (e.g. Sheets & Grayson 1979; Torrence & Grattan 2002; Grattan 2006; Grattan & Torrence 2007; Riede 2015, 2016). These works segue into those from the Earth Sciences by geologists becoming more interested in the effects of volcanic eruptions on human society (e.g. Chester 1993; Cashman & Giodorno 2008; Cronin, Nemeth & Neall 2008; Donovan 2010; Lockwood & Hazlett 2010). Many works deal broadly with many kinds of disasters (e.g. Cooper & Sheets 2012; Mata-Prelló et al. 2012; Stewart & Gill 2017), but in this volume, we will restrict ourselves particularly to examining human responses to volcanic eruptions and specifically in the North Pacific.

This book is mainly the product of a Forum on TephroArchaeology, organized by Gina Barnes and SODA Tsutomu[1] for the 2016 meeting of the World Archaeology Congress (WAC8) in Kyoto. It was followed by a similar Forum on Archaeological Volcanology at the 2017 Society for American Archaeology (SAA) meeting in Vancouver, organized by Felix Riede, Gina Barnes, and Payson Sheets. For a discussion of these forum titles, their meanings and suitabilities, please see the Introduction (Chapter 1). Most of the chapters herein were first presented at the WAC8 Forum, but other timely papers were included to widen the scope of the volume; discussion from the SAA Forum formed a major framework for the presentations herein. We thank the editors of the WAC One World Archaeology Series for allowing this publication not to be included in their series, as they have first right of refusal for volumes based on WAC conference papers.

Due to the WAC8 Forum being held in Japan with mainly Japanese participants, the volume is naturally geared to the practice of tephroarchaeology in that country, though what is presented here barely scratches the surface of the work being done there. The remit of the Forum was to concentrate on the methods and techniques of excavating in tephra. Unsolicited comments by Payson Sheets and Robin Torrence, taken from SAA and WAC8 Forum discussions respectively with their permission, shine a light on the potential significance of the Japanese data to worldwide tephroarchaeology. SODA Tsutomu reports on the history of tephroarchaeology in Japan where the term originates (Chapter 2); KUWAHATA Mitsuhiro comments on the measurement of volcanic disasters by tephra depth (Chapter 3) and also writes on eruption effects on medieval agriculture in southern Kyushu (Chapter 12). The Towada eruption of 915 AD is covered from different angles by MURAKAMI Yoshinao and KOBAYASHI Masashi (Chapter 6) and MARUYAMA Kōji (Chapter 8), dealing with lahar-buried villages and population movements respectively. With Chapter 9, HORAGUCHI Masashi reviews Gunma Prefecture tephroarchaeology, setting the stage for detailed excavation reports on the tephra-preserved Kanai settlements by SUGIYAMA Hidehiro (Chapter 10) and agricultural reconstruction efforts in Chapter 11 by SAKAGUCHI Hajime. The agricultural theme is continued by Gina BARNES in Chapter 13 on tephrogenic soils and their potential, and Chapter 14 by NOTO Takeshi and Gina BARNES presents an overview of Japanese agriculture and cultivation recovery techniques in Gunma.

WAC8 Forum topics, however, were not exclusively limited to Japan: participants broadened this regional focus, with Gerry OETELAAR's Chapter 4 investigating landscape change on the Northern Great Plains of North America, and with Torill Christine LINDSTRØM's Chapter 15 dealing with psychological behaviour in the face of volcanic eruptions, drawn from several examples around the world. It is unfortunate that

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[1] Soda's surname appears with a macron (Sōda) in this volume when indicating a publication in Japanese.

Ezra Zubrow's WAC8 Forum presentation on Kamchatka, and the southern Kyushu data presented by MAGOME Ryodo and MORISAKI Kazuki, could not be included here. Keith PRATT's paper on Mt Paektu eruptions (Chapter 7) was first given at the Association for Korean Studies in Europe (AKSE) conference in April 2017 for a panel on the sociology of Mt Paektu; it appears here by invitation. Chapter 5 by Ben FITZHUGH, Caroline FUNK and Jody BOURGEOIS is a welcome addition, growing out of interaction at the SAA Forum; dealing with the Kuril and Aleutian arcs, it justifies the chosen title for the volume. MACHIDA Hiroshi's contribution (Appendix E) is a translation by Gina BARNES of a chapter published in the *Atlas of Tephra in and around Japan* (Machida & Arai 1992, 2003, 2011; hereafter, the *Atlas of Tephra*), included here by invitation. Machida's co-author, ARAI Fusao, is now deceased, but he would have been glad to be included as he was involved with archaeology from early on (cf. Arai 1971). The Introduction and Appendices A–D by Gina BARNES are additions to round out the volume methodologically, providing crucial geographical and geological information for archaeologists new to the field; cross-references among all the appendices and other chapters have been added editorially with the authors' permission.

This volume is also designed to bring Japanese work on volcanic disaster studies to the English-speaking world. Until now, only two people have had a voice in this discussion: SHIMOYAMA Satoru, who very unfortunately passed away prematurely, and MACHIDA Hiroshi, who continues his valuable research after retirement. Shimoyama's work (1999, 2002a,b) has continued to influence volcanic disaster studies on an international scale as well as within Japan. In addition to sharing the research area of southern Kyushu with Shimoyama, KUWAHATA Mitsuhiro continues that methodological involvement in disaster archaeology. Machida is a tephrochronologist who has consistently published in English from 1980 (Machida 1980), contributing to one of the first collations on tephrochronology deriving from the NATO Advanced Study Institute symposium (Self & Sparks 1981; Machida 1981). By 1984, he had begun exploring tephrochronology for archaeological use within Japan (Machida 1984), including prehistoric data in relevant sections of the *Atlas of Tephra*. In the early 1990s, he collaborated with Robin Torrence in archaeological work in Papua New Guinea (Machida 1996), and he has continued his concern with archaeology in Japan (Machida 2000; Machida 2002; Machida & Sugiyama 2002). In 2011 he was honoured with a commemorative volume of *Quaternary International* (Lowe et al. 2011).

The impact that Shimoyama and Machida have had on the field is due primarily to their ability to work in English. This is not a trivial comment, as the major wall (*kabe*) between Japanese and worldwide archaeology is the language barrier. Most local Japanese archaeologists do not speak or read English, and in turn how many of us speak or read Japanese? The archaeological literature in Japan is voluminous. In its heyday (1970s and '80s), 40 shelf feet of archaeological reports were being produced by prefectural archaeological units every year (see Barnes 1990 for reasons why). Public archaeologists work to an annual schedule tied by construction contract deadlines; they have little time for extra research and little leeway to make their discoveries known to the wider world, or even read about world archaeology. Of course, there is a cohort of Japanese archaeologists that interacts internationally – two cohorts, in fact: one that studies non-Japanese archaeology of various foreign countries, and the other that writes about Japanese archaeology in English. The latter tend to be few and far between as well as theoretically oriented, while the archaeological papers on Japan in this volume come directly from the excavators themselves. They reveal the wealth of data, extraordinary methodologies and discoveries, and valuable comparative materials for the general field of TephroArchaeology.

For several Japanese archaeologists represented in this volume, this is their first publication in the English language. Kuwahata, Maruyama, Kobayashi, Sugiyama, Murakami, Horaguchi, and Sakaguchi all work or have worked in archaeological units and present knowledge gleaned from or inspired by their local excavations. The reader will notice that their chapters are entirely localized, with few citations of theory or even problem-orientation. This is bottom-up archaeology, defining the problems as they are met, and solving them along the way. Nevertheless, this inductive approach is very fruitful, and the detail of work presented here is astounding, with several unprecedented discoveries: Who would have thought to identify the direction of pyroclastic flow from rock impact traces? Or estimate eruption timings from footprint overlays? Or deduct seasonality of tephra fallout from the preserved stage of the agricultural cycle? All such findings require attention to minute detail and rigorous care in excavation.

Several of the Japanese chapters contain discussions of methodology. These are given without reference to developments in the field elsewhere precisely because of the language barrier. Many of their observations form independent confirmation of what researchers in other countries have also concluded from their archaeological volcanology studies. It is heartening to know that archaeologists around the world can come to the same conclusions, and it is good to have Japanese archaeologists speak in their own voices. Activities of tephroarchaeologists in Japan continue, with a large panel having been offered at the November 2017 regional meetings of the Japan Archaeological Association organized by Kuwahata. Researchers from around Japan contributed their findings and insights to his panel entitled "New Developments in TephroArchaeology". The papers are now available in the special issue of *Archaeology Quarterly* (*Kikan Kōkogaku* 146, February 2019), in Japanese with English table of contents on p. 117.

Except for Kuwahata, who submitted his two manuscripts in English, the translation and editing of the Japanese chapters have been carried out by myself. Many of the authors have sufficient reading ability to double-check these efforts, and for those with little confidence in their English skills, I hope this exercise has improved them. It takes enormous effort and good will on both sides to produce a final product, and I would like to thank all authors for their patience and cooperation, both in preparation for the Forum and during the editing process. I hope they are pleased with their debut on the international stage and will continue to think of publishing internationally. Many thanks are due the international authors who agreed to have their work published in this volume and who bore with me through a long editing process.

In closing, I would like to add a personal acknowledgement to the Department of Earth Sciences at Durham University, which has generously supported an affiliation that allows off-site access to scientific journals. Without such access, this research – for my own contributions and in editing others – would have been impossible. I am eternally grateful and hope that this book is useful to the field.

Gina L. Barnes (GLB) Durham, February 2019

Special thanks to David W. Hughes, who has worked his usual magic in proof-reading the volume.

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Stylistic Notes

- All Asian names occur surname first; when the whole name is given, the surname is in small capitals. Non-Asian names linked with Asian names (e.g. as co-authors) also have the surname in small caps.
- East Asian terms in chapters are given characters in the Glossary.
- Measurements are given in metric; mm = millimetre, cm = centimetre, m = metres, km = kilometres, dm = diameter
- Korean names are given in McCune-Reischauer transliteration, with South Korean government alternatives in parentheses.
- Macrons are eliminated from the names of the main Japanese islands (properly Kyūshū, Honshū, and Hokkaidō).
- BC/AD are used instead of BCE/CE; the former are more visually distinct, and the latter do not avoid the issue that year 0 (the birth of Christ) is used as the watershed – a meaningless year in East Asian history: nothing 'in common' about it.
- Figure sources are given at the end of each chapter rather than in captions.
- Figures are cross-referenced throughout the volume in the format 'Chapter number: Figure number'.
- Spelling is British or English according to author/translator preference.
- Multiple references to edited volumes in bibliographies are referred to the editor(s) entry.
- The bibliography style is unique to this volume.
- NASA = National Aeronautics and Space Administration.
- Author/editor entries in bibliographies are limited to three persons, plus et al.
- 4th-level sub-headings are not listed in the Table of Contents.

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Recurrent Abbreviations (exclusive of bibliographies)

- # = number
- aDNA = ancient DNA
- b. = born
- BCE or bc = uncalibrated ^{14}C dates given in the Smithsonian's Global Volcanism Program
- BP, bp = lit. before present:
    bp *sensu stricto* = uncalibrated radiocarbon date; before present = 1950
    BP *sensu stricto* = calibrated or true calendar date, calendar years before present
- ca. = circa, 'about'

- cal. = radiocarbon date calibrated by wiggle-matching to dendrochronological date
- CBS = Changbaishan volcano
- ^{14}C = radiocarbon, carbon isotope 14
- ch. = chapter
- CVL = Commission on Volcanic Lakes
- DPRK = Democratic People's Republic of Korea = North Korea
- DRE = Dense Rock Equivalent
- EDMA = Energy Dispersive (X-ray) Micro-analysis
- EPMA = Electron Probe Micro-Analysis
- est. = estimated
- GARF = Gunma Archaeological Research Foundation
- GSC = Geological Survey of Canada
- HPD = Highest Posterior Density (used in radiocarbon calibrations)
- IAVCEI = International Association of Volcanology and Chemistry of the Earth's Interior
- IWGCL = International Working Group on Crater Lakes
- JAA = Japanese Archaeological Association
- JMA = Japan Meteorological Agency
- ka (used in science publications), see kya
- Kor. = pronunciation in the Korean language
- kya = thousand years ago
- Kyōi = Kyōiku Iinkai = Board of Education
- LIP = Large Igneous Provinces
- Maibun = Research Institute for Buried Cultural Properties
- ME = Millennium Eruption (of Mt Paektu)
- ML = 'local magnitude', the original Richter scale for measuring earthquake strength; includes Mb (body-wave magnitude), Ms (surface-wave magnitude), and Mw (moment magnitude)
- msl (metres above sea level)
- Mt = mountain (-shan in Chinese, e.g. Changbaishan; -san in Japanese and Korean, e.g. Paektu-san)
- mya = million years ago
- Nabunken = Nara Research Institute for Cultural Properties
- n.d. = no publication date given
- NSF = National Science Foundation, USA
- PDC = pyroclastic density current = pyroclastic flows & surges
- pH = lit. 'potential of Hydrogen': a measure of relative acidity or alkalinity of a substance
- PI = Principal Investigator
- PRC = People's Republic of China
- r. = reigned
- SAA = Society for American Archaeology
- uncal. = uncalibrated radiocarbon date
- 'unpg.' in citations means 'unpaginated', becoming more common in online materials and difficult for quotation attribution
- USGS = United States Geological Survey
- VEI = Volcano Explosivity Index
- WAC = World Archaeology Congress

Tephra abbreviations (references to volcanoes in Index II)

- A-Ito (Ito pumice), see Aira
- As-A, As-B, As-C (Asama tephra), see Asama
- Aso-4 tephra, see Aso
- AT (Aira-Tanzawa volcanic ash), see Aira
- B-Tm (Baekdu–Tomakomai tephra), see Paektu
- FA = Hr-FA
- FP = Hr-FP
- Hk-TP (Hakone-Tokyo pumice), see Hakone
- Hr-FA (Futatsudake Ash), see Haruna
- Hr-FP (Futatsudake Pumise), see Haruna
- K-Ah (Akahoya tephra), see Kikai
- K-Ky (Kōya pyroclastic surge), see Kikai
- Km-11, Km-12, Km(gr), see Kaimondake
- KS1 eruption, see Ksudach
- Ku-a, Ku-b (Kumakura ash), see Kumakura
- On-Pm I (Ontake pumice I), see Ontake
- To-a (Towada-a ash), see Towada

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CHAPTER 1

Introduction to TephroArchaeology

Gina L. BARNES [*]

An Archaeological Sub-discipline in Japan

‘TephroArchaeology’[1] is a translation of the Japanese word *kazanbai kōkogaku* (lit. volcanic ash archaeology), referring to a sub-discipline of archaeology that has developed in Japan in the last few decades. The Japanese term was coined by archaeologist SHINTŌ Kōichi and developed by geologist ARAI Fusao. The historiography of the field’s development within Japan is written by SODA Tsutomu (Chapter 2), who translated the term into English as ‘tephroarchaeology’. That Japan should take the lead in formalizing such an archaeological sub-discipline is not surprising, given the geographical prominence of volcanoes in that country. Active volcanoes in Japan account for 10% of the world’s total, up to 110 in number depending on the source reference and definition.

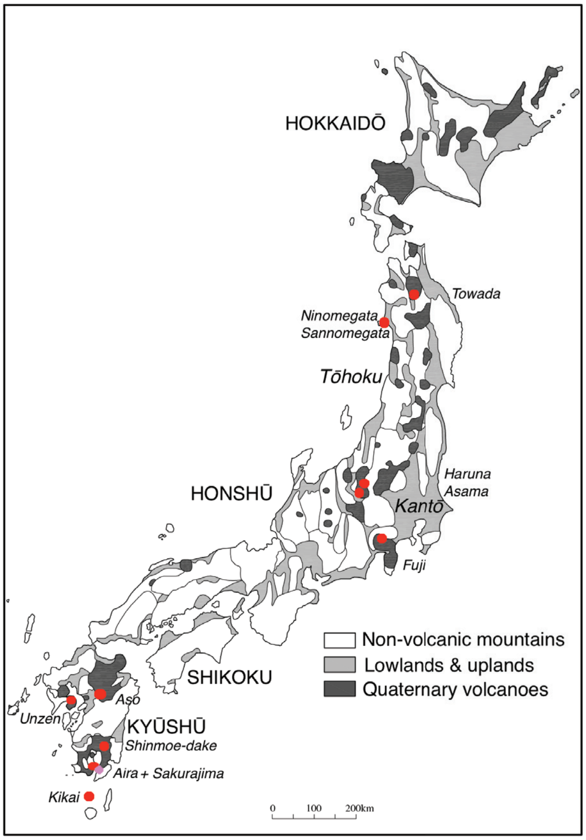

FIGURE 1 VOLCANIC FOOTPRINTS IN JAPAN
Volcanoes mentioned in this chapter are red/pink

In Japan, the definition of ‘active volcano’ has been modified through time. The first list of active volcanoes was made by the Committee for Predicting Volcanic Activity, formed in 1974 of university specialists and government workers in hazard prevention (Nakata 2005). At that time, 66 volcanoes were recorded as active within the last thousand years. The list was revised in 1999 (active within two thousand years), and in 2003 (active within ten thousand years) (Yamasato 2005). By 2006, 108 volcanoes were listed as active during the last 10,000 years (Aizawa 2006), and the current list (JMA 2013) has 111 entries. This list does not include volcanoes that erupted prior to the Holocene; earlier volcanoes are considered ‘inactive’ or even eroded, but their products still exist in the landscape and have formed important sources of stone for artefact and architectural use from prehistoric into modern times. Moreover, eruptions prior to the 10 kya cut-off point for Active Volcanoes, such as Aira at 30,000 years ago, have been very disruptive to prehistoric life and should not be ignored.

[1] It is idiosyncratically capitalized here to visually distinguish it from other sub-disciplines: ‘tephrochronology’ and ‘tephrostratigraphy’.

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TephroArchaeology is only one of several sub-disciplines to have developed in Japan in the last 40 years. Three of them can be considered under what I call 'Tectonic Archaeology': those that deal with direct effects of being located in a tectonically active subduction zone region. These are TephroArchaeology, Earthquake Archaeology (*jishin kōkogaku*), and Tsunami Archaeology (*tsunami kōkogaku*).[2] The focus of TephroArchaeology on volcanic ash has been conditioned by the fact that although active volcanoes have a relatively small footprint in the Japanese landscape (Figure 1), every inch of the archipelago has been subject to tephra cover of varying quantities (Machida 1980: 29). However, some areas have been more affected than others due to the clustered distribution of the volcanoes. In particular, archaeologists in Kagoshima and Miyazaki Prefectures[3] in southern Kyushu (Shimoyama 2002a; Chapter 12 herein) and Gunma Prefectures (Shiraishi 1992; Tsude 1992; and Chapters 9, 10 and 11 herein) have found themselves excavating sites that have been heavily covered with tephra layers. These are the two areas in Japan in which the sub-discipline developed, and its nature is due to the condition of the archaeological record – not from a perspective of Quaternary volcanological processes or terminology. More recently, excavations involving tephra layers have increasingly been acknowledged in Aomori, Akita and Iwate Prefectures of the northern Tōhoku region (Chapters 6 and 8), extending the reach of TephroArchaeology throughout Honshu.[4]

Japanese contributions to disaster studies began around the turn of this century (Shimoyama 1997, 1999, 2002b; Machida & Sugiyama 2002). Recently, a movement in Japan has emerged to recombine the several sub-disciplines named above, that developed somewhat separately, into an archaeology of all sorts of natural disasters (Okamura et al. 2013; Okamura 2015). A Disaster Archaeology database is currently being established at the Nara National Research Institute for Cultural Properties (Nabunken) by reviewing published site reports and collating information (Okamura 2015: 251). This resumes the early efforts of Shimoyama (1997, 2002b) and the presentation of the archaeology of natural disasters at previous World Archaeology Congresses (WAC4, WAC5) (Shimoyama 1999; Torrence & Grattan 2002; Grattan & Torrence 2007). However, the emphasis of this research in examining past disaster damage and resiliency differs from that proposed by Gould (2007), which deals with current disasters and the recovery of information, aligned with forensic anthropology.

Grattan and Torrence (2007: 11) spoke of a 'new discipline' prefacing their collected volume on the cultural impacts of volcanic eruptions; however, they did not give it a name, referring instead to the "science of environmental catastrophes" noted by Leroy (2006). In contrast, this volume takes the formulation of the Japanese sub-discipline of TephroArchaeology as its starting point and investigates the various aspects of volcanic disasters primarily in the North Pacific, most of which range far beyond consideration of volcanic ash *per se*. For a view from the Southwest Pacific, see Cronin et al. (2008); for other areas of the world, see Harris (1999); and for a geological introduction similar to this, see Elson & Ort (2018).

A Briefing on Volcanic Matters

Although it is always tedious to have to explain specialist jargon or terminology, the chapters herein may be using frameworks and concepts derived from volcanology that are unfamiliar to archaeologists. This section aims to provide as much of a background as necessary to put the chapters in context and note where within them the terms and concepts are being used. This introduction is augmented by: Appendix

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[2] See review articles by Barnes (2010, 2015, 2017). The effects of both volcanic eruptions and tsunami, however, are acknowledged to be further widespread than the subduction zone itself. For a quick review of the geological development of Japan and introduction to terminology, see Barnes (2003, 2008).

[3] See Appendix A-1 for prefecture, district, and island locations and boundaries.

[4] The literature in Japanese on excavations in these prefectures is too vast to list! See individual chapters for site-specific references.

B, providing a basic geological background in elements, minerals, and magma as relevant to volcanology; Appendix C, contextualizing Pacific Rim volcanoes within the North Pacific subduction zones; and an Index which lists terms related to volcanoes and tephras (as well as archaeological sites). Volcanoes worldwide mentioned in this volume appear in Figure 2. More can be discovered in the Global Volcanism Program (2013) of the Smithsonian Institution, the Volcano Hazards Program (USGS n.d.), and in Volcano World (OSU 2017) etc., while Japanese volcanoes are described online at the JMA (2013 in English, 2017 in Japanese).

Volcanic Ash or Tephra?

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FIGURE 2 WORLDWIDE LOCATIONS OF VOLCANIC ACTIVITY MENTIONED IN THIS VOLUME
For Japan and Cascadia, see Appendix C; for the North Pacific, see Chapter 5: Figure 1

'Volcanic ash' was historically and mistakenly equated with wood ash, and even its formal term as a 'pyroclast' ('fire fragment') perhaps encourages this line of thinking. However, in a geological context, 'ash' is simply a measure of particle size: pyroclasts less than 2mm. These are extruded from a volcano during an explosive eruption which pulverizes the magma and rock surrounding the volcanic vent. Volcanic ash has variable composition: it may contain rock particles, fragments of glass bubbles, and individual mineral crystals that had already formed within the magma. It can be divided into coarse ash (2 mm–0.06 mm) and fine ash (<0.06 mm) – the latter may also be called 'dust' (Lowe & Hunt 2001).

Ironically, the term 'tephra' originally meant 'ash' in Greek, but it has been adopted in geology to encompass particles of all sizes, including ash, referring specifically to those materials aerially extruded during a volcanic eruption. This definition differentiates tephra from lava, which generally seeps out of a volcano as a viscous substance on the ground except as ejected in fire fountains and as lava bombs. Tephra is divided into size classes: ash (<2 mm), lapilli (2–64 mm), then bombs and blocks (>64 mm). Lava bombs are ejected as fluid and solidify during flight (forming pointed ovoid shapes like an American or rugby football), while rock blocks are ejected as solids (Tucker 1991: table 10.1).

These latter projectiles can be very large in size and are potentially quite dangerous. In order to be inclusive of all sizes of volcanic ejecta, the term 'tephra' is now preferred to that of 'volcanic ash' – a term which should be confined to describing ash-sized particles.

Tephra Deposition

Tephra is usually deposited on the ground in one of three ways, in addition to the actual ejection of large projectiles: through fallout from an eruption column and ash cloud; by heavy, dense clouds of ash and rock fragments rolling down the flanks of a volcano as ‘pyroclastic flows’; or as lighter ‘pyroclastic surges’ composed mainly of ash. Pyroclastic flows and surges cross the landscape in different ways, affecting how they will be discovered in the archaeological record. Pyroclastic flows tend to follow established stream valleys leading down the mountain’s flanks, and they can cut deeper valleys as described for Mt Paektu [Baekdu][5] in Chapter 7. Their remains thus concentrate in hollows. Surges, on the other hand, can flow over hills but still settle thicker in depressions than on rises (Figure 3). These contrast with the more even blanketing by aerial fallout of tephra. Thus, the discovery of thinner or thicker tephra layers in a confined area of archaeological excavation may not represent the wider depositional situation – even before erosion, weathering, etc.

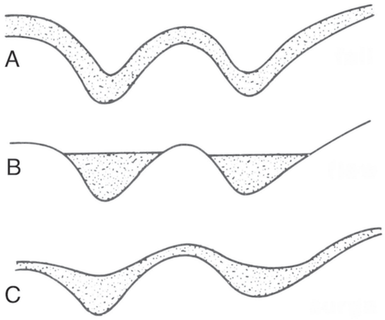

FIGURE 3 TEPHRA LAYERING BY DEPOSIT TYPE
A Ash fallout blanketing
B Pyroclastic flow in hollows
C Pyroclastic surge draping the topography

Along with pyroclastic flows, lahars can be highly dangerous; these are water-saturated tephra flows that may start as landslides and then flow down hollows in the landscape – including river valleys where the tephra may be put into suspension in the water and be carried great distances. Lahar movement may coincide with deposition if the tephra is extremely wet; or rain-saturated tephra deposits may move at any time – even years – after their deposition. Barring the first possibility of wet tephra flowing upon deposition to form a primary deposit, by definition lahars are secondary deposits of tephra. They can consist of fine-grained mudflows of volcanic ash (the original meaning of *lahar* in Indonesian), or a lahar can be full of rocks and large-size tephra (then referred to as blocky debris flows). Lahars and debris flows travel much slower than pyroclastic flows but can extend many kilometres. Lahar damage associated with the 6th-century eruptions of Mt Haruna are discussed for Gunma Prefecture in Chapters 9, 10, and 11, while Chapter 6 deals with lahar deposits having intruded into and buried standing houses in 10th-century Tōhoku.

The eruption sequence of a volcano can change during a single eruption or between eruption events (Soda 1993, 2006). For example as presented in Chapter 10, a 6th-century volcanic event begins with a volcanic ash fallout, then a pyroclastic surge, and finally a pyroclastic flow during the same eruption. Although several ‘styles’ of eruption are used to classify volcanic activity, as presented below, the idiosyncratic nature of individual eruptions is also becoming more recognized and studied (Cashman & Biggs 2014). In reconciling the general or common aspects of volcanic eruptions with the unique histories of individual volcanoes, the archaeologist is in a position to increase this geological knowledge through detailed excavation.

Tephra deposition is ideally depicted as lobate areas of decreasing tephra thicknesses, with the direction of ash deposition determined by the prevailing winds (Figure 4); these distributional trajectories can vary with wind patterns from season to season, so the tephra from different eruptions of the same volcano will not always fall in the same direction. Moreover, animations of tephra-fall distribution from the 2010 eruption of Eyjafjallajökull in Iceland rather put paid to the idealistic view of the interactions between

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[5] This volume uses the McCune-Reischauer transcription system for Korean; the South Korean government spelling is given in square brackets on first mention.

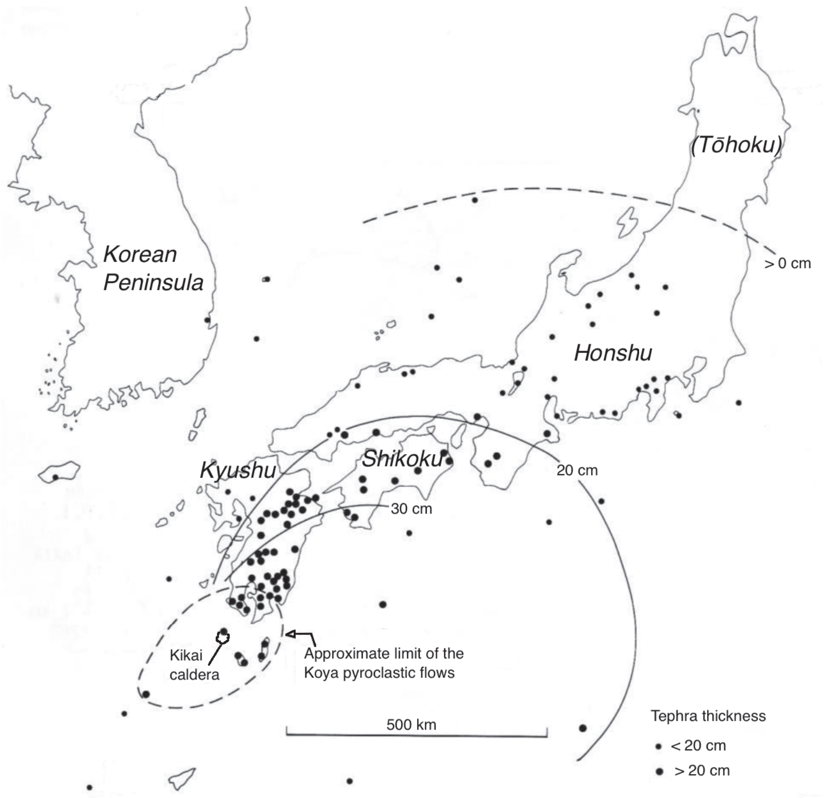

FIGURE 4 ISOPACH DISTRIBUTION OF AKAHOYA (K-AH) TEPHRA erupted from Kikai off southern Kyushu ca. 7300 bp

tephra and wind (Crowe 2010; djxatlanta 2010; NASA 2010); this dissonance has yet to be incorporated into ongoing archaeological fieldwork.

From modern assessments, a tephra fall between 10 and 15 cm deep and lasting for 5 to 7 days will kill pasture plants, crops and soil microbes – leaving the area sterile for up to a year; if more than 15 cm of tephra falls, all vegetation is killed, and "soil formation must begin again from this 'time zero'" (USGS n.d, unpg.). These statistics suggest that the 500 km^3 Dense Rock Equivalent (DRE) of tephra deposition from the Kikai eruption (Tatsumi et al. 2018) exterminated living things in most of the south-western Japanese Islands, including all of Shikoku and most of Kyushu. This is confirmed by investigations that found a hiatus of ca. 900 years before reoccupation of the land from the north and west (Machida & Sugiyama 2002). According to breaking news, there is a 1% chance of a large eruption from a massive lava dome in Kikai caldera within the next 100 years, following activity there in 1934–1935 (Tatsumi et al. 2018). Such lava domes form at the end of an eruption and often collapse later, becoming deadly pyroclastic flows.

Pumice & Scoria

Cross-cutting the size classes presented above, tephra can take different forms depending on the chemical composition of the parent magma. Two important types are pumice and scoria; both are vesicular glasses, formed of magma froth and riddled with holes which were once gas bubbles. Pumice is a product of high-silica magma, whereas scoria forms from low-silica magma (see Appendix B-3). A common name for scoria is 'cinders' – another mistaken analogy with burned material – and scoria extrusions are often said to form 'cinder cones'. Cinders are most commonly of lapilli size, though large bombs do exist.

Pumice is more common than scoria in the Northern Pacific because subduction zone magmas have intermediate to high levels of silica. We are mostly aware of small pumice rocks which we use as bathing utensils. However, like scoria, it can occur in all size-ranges and can be deposited as a pyroclastic flow or fallout (Yagi et al. 2006: table 1),[6] accumulating to be several hundred metres thick. Pumice tends to exist for long periods as unconsolidated material and is subject to erosion during that time. Southern Kyushu

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[6] The term 'airfall' is deemed passé by Lowe & Hunt (2001); 'fallout' or tephra-fall' are preferred.

Island still sports deep deposits of pumice called *shirasu* (Figure 5). It was emplaced by the Ito pyroclastic flow during the eruption of the Aira Caldera 29–30 thousand years ago.

With sand of an average grain size (0.062–1 mm), the *shirasu* is unconsolidated and therefore easily dug but too deep to excavate from the top; it has presumably buried numerous Palaeolithic sites, some of which have been excavated during road cuts.

Tephrochronology & Tephra Characterization

Lowe distinguishes between broad and strict definitions of tephrochronology. The former encompasses "all aspects of tephra studies and their application" (2017: 4, fig. 2). The latter is more of concern here: a tephra layer comprising an event-based distribution of sediment across the Earth's surface whose primary deposition provides a natural "stratigraphically fixed tie-point" that allows correlation between locations on a shared time-plane (Lowe 2017: 1). Correlation of distributions relies on accurate tephra characterizations or fingerprints, obtainable through both field observation and laboratory procedures. Once identified, these key tephra layers form a contemporaneous marker bed over broad swaths of landscape, continuous or even discontinuous.

FIGURE 5 SHIRASU PUMICE IN ROAD CUT, SOUTHERN KYUSHU

In Appendix E, Machida and Arai outline the steps leading to tephra identification (separating it from non-tephra sediments) and characterization (distinguishing features of each tephra) – first in the field and then in the lab. Proper field observations are extremely important, as they often provide defining characteristics for a tephra which cannot be known through lab analyses. This means that tephra samples should be taken not by archaeologists but by tephrochronologists, who can make a proper examination of in situ deposition. This is particularly important in distinguishing different strata of tephra from a 'single' eruption that may undergo several stages, as characterized for the Haruna Hr-FA tephra (Sōda 2006).

Laboratory procedures include optical and scanning electron microscopy, electron probe and geochemical analyses (Lowe 2017: table 3); Machida and Arai also describe the uses of refractive index for tephra characterization (Appendix E-6), a method developed in the early 1970s (Arai 1972). Geochemical analyses with electron microprobe can reveal the chemical composition of individual mineral crystals and glass shards. The identification of a previously unknown tephra from Mt Samalas in Indonesia, by correlating the composition of single flakes of volcanic glass from an Iceland core with the composition of pumice deposits near the Samalas volcano that erupted in 1257, have been been taken as fact despite the tentative conclusions of the researchers (Lavigne et al. 2013; Lavigne & Guillet 2015). But as Lane et al. (2011: 87) caution, the chemical compositions of tephra which erupted at different times from the same volcanic system may have similar compositions; therefore "it seems that composition alone is insufficient for the correlation of some widespread tephra layers: good stratigraphic information and/or robust dating control are also essential."

Despite the 'chronology' in tephrochronology, the absolute age of the tephra may be unknown and be dated only through association with cultural materials or relationship with other dated tephra in stratigraphic sequences. Even in these cases, one tephra type still may provide an “age-equivalent dating method” (Lowe 2017: 1) because it represents a slice of time that is correlated over a widespread area via the distribution of the tephra.

FIGURE 6 PEACE BODHISATTVA SCULPTURE OF OYA TUFF
disused tuff quarry, Utsunomiya City, Tochigi Prefecture

Lithified & Weathered Tephra

Tephra when solidified becomes a sedimentary rock – even though it is of igneous origin. Volcanic ash forms tuff, a soft carvable rock (Figure 6) much quarried for use in architecture. If the volcanic ash is extremely hot when laid down, as in a pyroclastic surge, it may lithify as welded tuff, with the clasts welded together. Pyroclastic flow sediments, particularly those containing much pumice and/or blocky material, lithify as ‘ignimbrites’ or as welded tuff. Ash that accompanies the pyroclastic flow is co-ignimbrite ash.

The weathering of tephra, whether lithified or unconsolidated, produces various types of clays dependent on climate, precipitation, flora, and its chemical composition (see Chapter 13). Exposure to water will leach out the alkali and alkaline elements (calcium–Ca, sodium–Na, magnesium–Mg, and potassium–K), leaving concentrations of aluminium–Al, silicon–Si, and iron–Fe (Velde & Meunier 2008: 132, 249). These, together with oxygen-O and hydrogen–H, are the building blocks of 2:1 structure clays (Figure 7) which support agriculture around the world.

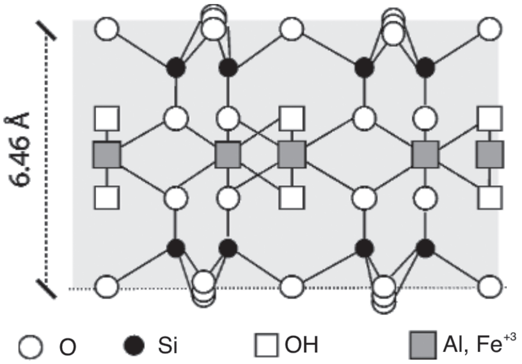

FIGURE 7 ATOMIC POSITIONS IN A 2:1 CRYSTAL STRUCTURE OF CLAY

Weathering of tephra by water alone can take close to a million years, as documented for New Zealand (Lowe 1986). Once plants ‘install themselves’ on a rock surface, however, plant/rock interaction can form clays within years or decades. The type of plant grown influences the type of clay formed. Soils that are derived from volcanic ash are called ‘andosols’, with *ando* being a Japanese word meaning ‘dark earth’; nevertheless, andosols (or andisols) in Japan are actually called *kurobokudo* ‘black fluffy earth’ (see Chapter 13). The clay species typical of andosols include gibbsite, kaolinite/halloysite, and smectite as well as the alteration products allophane and imogolite (Shoji et al. 1993). The island of Honshu (at least) in Japan has been called an island of smectite (Taylor & Eggleton 2001: fig. 2.48). ‘Imogolite’ is also a Japanese word derived from *imo+ko* meaning ‘potato child’ (*imogo*) – obviously an agricultural reference. Chapter 14 deals further with these agricultural implications, hoping to shed light on the argument whether volcanic ash soils are good for agriculture or not.

Other forms of tephra are also important in Japan. Weathered pumice is often called *miso-tsuchi* – earth with the grainy consistency (and colour!) of miso, the fermented soybean cooking ingredient. Perhaps the most notorious unconsolidated tephras are those incorporated into the Kantō Loam – deep deposits of weathered Middle–Late Pleistocene loess and redeposited volcanic ash from Mt Fuji and Mt Hakone that contain many Palaeolithic sites within them. In Chapter 2, Soda cautions that the volcanic ash in the Kantō Loam layers is of secondary deposition, not primarily laid in an eruption.

Describing Volcanoes and Their Eruptions

Several distinctions have been made above that follow from magma chemistry, volcanic structures, and the many modes of eruption. These multi-dimensional aspects interact in different ways to produce volcanic products of unique specificity. Space allows only brief characterizations of these below. For details, see the Smithsonian's webpage 'Types and Processes Galleries' in the Global Volcanism Program (2013) and Sigurdsson et al. (2015).

Magma Types

Magmas are primarily categorized by their silica contents along a continuum from rich to poor (Appendix B: Figures B-1, B-3, Table B-2). In the past, silica-rich magmas have been described as 'acid' because it was originally thought that silicic acid was a major component. This has been disproved, and now the term 'felsic' is preferred, derived from the magma's feldspar and silica contents. Silica-poor magmas are classified as 'mafic', derived from their manganese and iron contents; magmas virtually lacking in silica are 'ultra-mafic'. And in between rich and poor are the intermediate magmas. Chemically, these three compositions are described from rich to intermediate to poor as having the composition of rhyolite (rhyolitic), andesite (andesitic), and basalt (basaltic). Thus, rhyolitic products are rich in silica, basalt is poor in silica, and andesite is intermediate between the two. The greater the silica content of a magma, the more viscous it is, preventing it from flowing freely.

These magma types influence both the energy of the eruption and the shape of the volcanic pile. Most silica-poor (basaltic) lava is emitted slowly in 'effusive eruptions'; their low viscosity allows gas to escape gradually. Silica-rich (rhyolitic) magmas tend to be more explosive in nature because their viscous nature does not allow continuous de-gassing: the gas builds up pressure in the magma and causes 'explosive eruptions'. These different magma types lead to different shapes of volcanic edifices produced.

Volcano Shapes

Most basaltic volcanoes emit lava slowly, in effusive eruptions, spreading over large areas. Flood basalts that flow from *fissure vents* can cover hundreds of square kilometres and accumulate to several kilometres deep, forming Large Igneous Provinces (LIP). The Siberian Traps (Figure 2) are one such example of an LIP. Hot spots and magma plumes, which arise from deep in the Earth's mantle usually within a tectonic plate, characteristically form basaltic *shield volcanoes* which are broad and low, such as the Hawaiian Island volcanoes. Mt Paektu (Chapter 7) apparently began as a shield volcano before building into a cone with a change in magma composition. Fissure vents on these volcanoes can also be responsible for outpourings of lava. Basaltic volcanoes, however, are not immune to the pressures of gas or the addition of water, both of which increase explosivity. *Cinder cones* and *spatter cones* can form from explosively emitted basalt, resulting in piles of small particles in the first instance or droplets of solidifying magma in the second.

As magma becomes silica-rich, more tephra than lava is extruded through more explosive eruptions, forming *stratovolcanoes*. Cone-shaped volcanoes are young stratovolcanoes, so named for the multiple eruptions that build up layers of tephra, leading them also to be called *composite volcanoes*. These are the idealized Fujiyamas of the world. Some composite volcanoes have multiple vents and build a small mountain range with different peaks formed from different eruptions, making them *compound volcanoes*. Mt. Haruna in Japan is such a compound volcano, with the Futatsudake vent having exuded tephra that caused great damage in 6th-century Japan, as discussed in Chapters 9, 10, and 11. Stratovolcano products are usually andesitic to dacitic (intermediate to medium-rich in silica) in composition and often host a crater lake less than 1 km in diameter after eruption.

Two other types of craters can occur on flat land: *maars* and *tuff rings*. Both result from the interaction of water with a magma source and cause explosive distribution of pyroclastic material. Maars were initially identified in southern Germany, but Lake Nyos in Cameroon is one of those existing worldwide. Laacher See (Riede 2017)[7] is often called a maar, but its crater resulted from a Plinian eruption rather than the more maar-like eruption caused by a mixture of water and magma. There are three maars in northwestern Japan that are named as 'lagoons'; two are mentioned in Chapter 8 as Ninomegata and Sannomegata (Figure 1 above).

Silica-rich magma may form a *lava dome* during the last stage of eruption within the volcanic crater itself, as with the current dacite cone at Mt Haruna; or a dome may build up through time and at vents other than the main crater. They can be very unstable, and dome collapse can cause great pyroclastic flows (Figure 8).

Mega-eruptions can occur on stratovolcanoes or shield volcanoes; the summit and flanks of the volcano are subject to collapse inwards to form *calderas*, after emptying tremendous amounts of material from the magma chamber. Some calderas form in clusters, doming the landscape before erupting and collapsing; these are the largest and often most difficult to recognize as belonging to a volcano. The classic case is Yellowstone Park in the north-central United States, the park itself consisting of three overlapping calderas.

FIGURE 8 THE CO-IGNIMBRITE ASH CLOUD OF A PYROCLASTIC FLOW
Caused by lava dome collapse at Mt Unzen, Kyushu
as caught on film on 8 June 1991 by co-editor SODA Tsutomu, who hails from Nagasaki Prefecture

The most recent Yellowstone caldera formed 640,000 years ago, measuring 48 x 72 km – smaller than the previous erupted caldera (NPS 2017). New caldera fields have been elucidated across the

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[7] Also known as Lachaer See.

Nevada–Utah state borders; the largest known eruption 30 million years ago, ejecting about 5500 km^3 of pyroclastic material which solidified to form the Wah Wah tuff, came from an unnamed oval caldera about 40 x 87 km in area (Best et al. 2013; King n.d.).

There are 14 caldera volcanoes in Japan (JMA 2013), one of which is Mt Aso in central Kyushu, which erupted 70–90,000 years ago; the caldera is 25 km in diameter, and the pyroclastic flows from its eruptions cover most of Kyushu Island. Towada Lake in northern Japan sits in a 10 km diameter caldera that formed through many eruption events, one forming a smaller caldera 2 km across within the caldera lake. Towada is a grand tourist attraction – as so many caldera lakes are. Towada last erupted in 915 AD through a small volcano, Ogurayama, sited on the smaller crater rim. Chapter 8 assesses the effects on the populations of northern Tōhoku of the Towada eruption together with the 10th-century Mt Paektu eruption. Crater Lake in Oregon is a caldera about 9.5 km across; the eruption that formed it around 6800 years ago spread Mazama Ash over much of northwestern North America. Its effects on the landscape are investigated in Chapter 4.

Eruption Styles

As mentioned above, volcanic eruptions are classified along a continuum of effusive to explosive styles. Effusive eruptions consist mainly of lava flows and tend to be basaltic, while the explosive eruptions involve the fragmentation of magma and country rock (the rock through which the magma intrudes) to form pyroclasts, produced by andesitic to rhyolitic magmas. However, any volcanic vent or fissure, regardless of edifice type or magma chemistry, can produce either and/or both styles at different stages of eruption or in different eruptions. This makes tracing the eruption history of a volcano (and its several vents) very complicated and involves multiple lava/tephra identifications and dating. Tephrostratigraphy and tephrochronology are the two sub-disciplines charged with these analyses.

There are six or seven 'styles' of eruptions, often named after the volcanoes where the conditions were first described – Hawaiian, Strombolian, Plinian, Vulcanian, Pelean, etc.; but the number of styles and their descriptions often overlap, partly due to historical progress in characterizing them. Generally, the styles move from effusive Hawaiian-style basaltic eruptions to super-explosive rhyolitic eruptions of Ultra-Plinian style (King n.d.). Included in the last are supervolcano eruptions such as Yellowstone and the Wah Wah Springs volcano (Best et al. 2013). The styles are based on the volume of erupted tephra and the eruption column height (USGS 2016). The severity is measured on the Volcanic Explosivity Index; from VEI 2 upwards, the scale is logarithmic. Thus, the Wah Wah Springs pyroclastic emissions (VEI 8) in the southwestern USA, at 5500 km^3 DRE, were 5000 times greater than the Crater Lake eruption (VEI 7) at 150 km^3 DRE in the northwest (King n.d.). From VEI 6 upwards, volcanic eruption columns can send gases and particles into the stratosphere (>15–50 km), making them a global hazard. The explosive styles and their products are (Figure 9): *Strombolian*: cinder cones; *Phreatomagmatic*: base surges and maars; *Sub-Plinian* & *Vulcanian*: composite volcanoes, lava, tephra, small pyroclastic surges; *Plinian*: tephra, pyroclastic surges, small to medium caldera formation; *Ultra-Plinian*: enormous pyroclastic surges, tephra (mainly small glass shards), with large caldera and pyroclastic terrace formation.

Explosivity is increased by both gas pressure and the presence of water, be it groundwater, lakes, or ice and snow cover, etc. Magma reacts to water as hot oil does, so any water that meets magma can cause a reaction, instantly turning the water to steam and driving the explosion of the magma (often called 'phreatomagmatic' or hydromagmatic explosions). Volcanoes with crater lakes or that are covered with snow and ice, therefore, comprise a greater hazard than those that are not. Eruptions may also be termed 'phreatic' when water is turned to steam and expelled with country rock but not involving molten magma.

We tend to think of volcanic eruptions as single events in time, but in fact they are often comprised of a series of events, as illustrated by Mt Unzen in Nagasaki Prefecture, Japan (JMA n.d.). Historical eruptions are documented for 1663, 1792, and 1798; but beginning in 1922 through 1989, earthquakes occurred repeatedly every few years and almost annually from 1966. These presaged a large phreatic eruption in 1990 which was surrounded by earthquake tremors before and after. Then in 1991, small eruptions of lava and earthquakes continued until pyroclastic flows, caused by the collapse of the growing lava dome, began on May 24th. The pyroclastic flow on June 3rd comprised one of the most devastating volcanic events of recent times, killing 43 people including several volcanologists and damaging 179 buildings. Another pyroclastic flow on June 8th (Figure 8) damaged 207 buildings, and on September 15th a third pyroclastic flow damaged 218 buildings. Lava dome growth and collapse, causing more pyroclastic flows, continued through 1996, but from 1997 onwards there was a switch back to earthquake tremors that decreased in frequency over time.

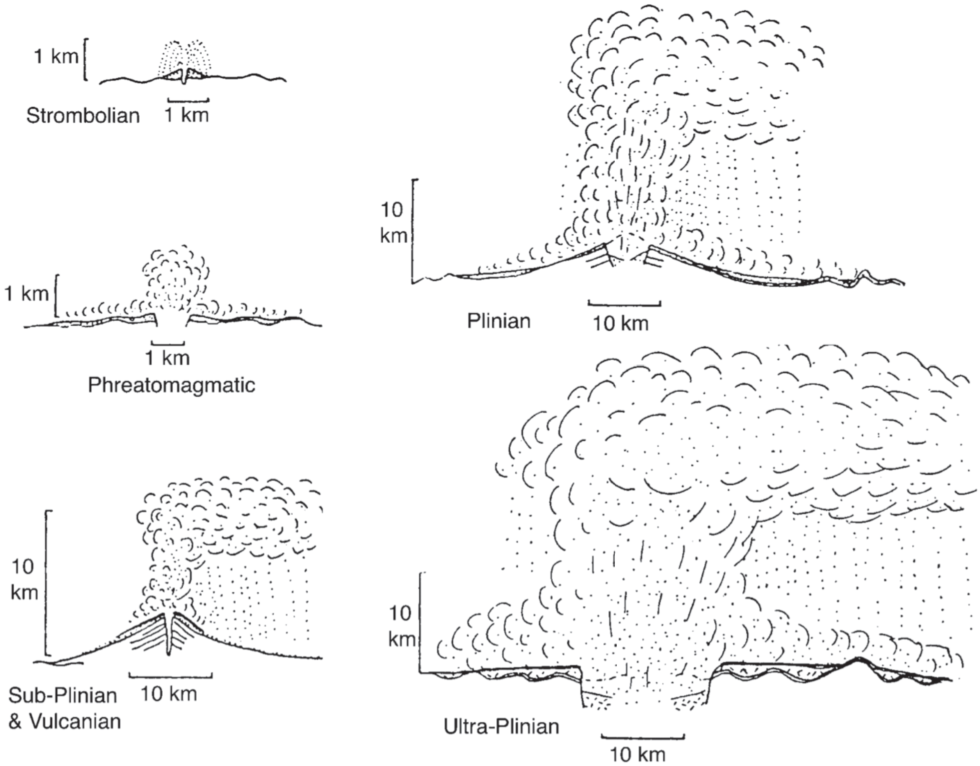

FIGURE 9 THE VARIOUS STYLES OF ERUPTION AND THEIR VOLCANIC STRUCTURES

Each of these volcanic events potentially leaves stratigraphic evidence that records stresses on local populations of plants, animals, and humans. It is the job of archaeology to retrieve information on how each of these populations were affected by or reacted to such volcanic hazards, be they single events or multiple events through time. The main variables in terms of human behaviour and choices made when confronted with volcanic eruptions are discussed in Chapter 15.

Gas Emissions

In the Forum discussions noted in the Preface, one concern was whether 'tephroarchaeology' was a justifiable name for this new field of endeavour because volcanic gases are not tephra but nevertheless should be considered for their role in causing disasters due to volcanic eruptions. Included here, therefore, is basic information about volcanic gases so that more consideration might be given to this issue in future tephroarchaeological research. The same is true of the next section on volcanic epi-phenomena.

The major forms of gas extruded, both from explosive pyroclastic and slower lava eruptions, are carbon dioxide (CO_2), sulphur dioxide (SO_2), and the halogens fluorine (F) and chlorine (Cl), in addition to water vapour (H_2O). As we all now know, carbon dioxide is a major greenhouse gas that contributes to climate warming. In contrast, sulphur dioxide can be converted in the atmosphere into acid rain and sulphate aerosols through several complicated chemical routes (Khoder 2002). The aerosols serve to reflect sunlight and cool the atmosphere, somewhat counteracting the action of greenhouse gases. In great quantities, following a large volcanic eruption such as Tambora in 1815 (Wirakusumay & Rachmat 2017), the aerosols can change seasonal and yearly climate until they are dispersed (Robock 2000). Eruption columns which reach the stratosphere (>15 km) can put aerosols into circulation through the jet streams and affect the entire globe. Surface temperatures cool 1 or 2 °C, which together with bad weather and tephra fallout can damage crops and affect harvests for up to two years (e.g. Lavigne & Guillet 2015). Eventually these aerosols and acid rain lead to ocean acidification.

Gases from Flood Basalts

Flood basalts are a specific type of magma extrusion through crustal fissures rather than volcanic edifices. The eruptions can be fire fountains many metres high and/or continuous lava flows; pyroclasts can also be extruded from the fire fountains, and gases may be released both directly through magma degassing before and during the eruption and from the flowing lava. Flood basalt flows are generally thought to be a product of hot spot activity.

The Laki fissure eruption in Iceland in 1783–1784 is classified as a flood basalt and provides the classic case of disastrous effects from volcanic gas release (Thordarson & Self 1993, 2003; Thordarson et al. 1996). Approximately 235 megatons (Mt)[8] of water, 122 Mt of sulfur dioxide, 15 Mt of chlorine, and 7 Mt of fluorine were released, affecting local plant and animal life (Thordarson & Self 2003: 7-4, 7-6, 7-13). Large numbers of cattle died of fluor poisoning within 2 to 14 days of the Laki eruption, while overall more than 60% of grazing livestock died within a year from chronic fluorosis in the affected area (Ibid.: 7-3).

Such devastation by gas emissions is generally archaeologically undetectable; the Laki cattle bones did not remain in the archaeological record. In an attempt to assess fluorine poisoning on the human population, researchers recently exhumed human skeletal material from two church graveyards in use at that time and analyzed the fluorine content of teeth and bones, but they were unable to find any evidence of skeletal fluorosis (Gestsdóttir, Baxter & Gísladóttir 2006). Despite this finding, it is estimated that 20% of the Icelandic population died from the aftereffects of gas emissions: illness (scurvy, respiratory and heart problems, acid rain burns); crop and forage failure, malnutrition, and a 3-year famine; and environmental stress (Thordarson & Self 2003). Efforts to attribute increased mortality in England during the Laki eruption, however, have not been successful (BGS 2013). More than 80% of the Laki sulphur dioxide emissions were lofted 10 to 15 km into the lower stratosphere; the bulk of these were converted to sulphuric aerosols through combination with water, forming the sulphuric cloud ('haze') that spread over the northern hemisphere and caused unusual weather patterns and crop failures all the way to Japan (Thordarson & Self 2003).

Within the geographic remit of this volume lie the Columbia River flood basalts of the northwestern United States (Reidel & Tolan 1992: fig. 1B). The most accepted hypothesis for the creation of these basalts is a hot spot for mantle plume action – possibly the same mantle plume that is responsible for Yellowstone Park volcanics (Reeg n.d.). But because the Columbia River basalts erupted between 17 and

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[8] Mt = megaton = 1 x 10^9 kg

15 million years ago (mya), they had no impact on human communities. Other flood basalt provinces in the western North Pacific – Emeishan in southwestern China (260 mya) and the Siberian Traps (250 mya) in Russia – are even older (cf. Jerram & Widdowson 2005). The Emeishan sequence is 4–5 km thick (Jerram et al. 2016) and was formed within one to two million years (Zheng et al. 2010; Shellnutt 2014).

Flood basalt eruptions have been characterized as much more dangerous than volcanic eruptions: flows can persist over years and decades intermittently through centuries and millennia, all the while emitting copious amounts of gas and lava. Saunders & Reichow (2009: unpg.) estimate that a single 'flow field' of 1500 km^3 would bury the whole of the UK beneath about 6 metres of lava, or Greater London beneath about 1 km. Assuming a total volume of 3 million km^3 for the Siberian Traps, this could bury the whole of western Europe beneath more than 1 km of basalt, or the whole of the UK beneath about 12 km.

The climatic effects of very large flood basalt emissions are potentially disastrous, as they have been linked to three or four of the mass extinctions when concurrent with meteoric impacts (White & Saunders 2005; Rampino 2016). Human society has not yet been exposed to this extreme situation, though we are carrying out our own form of environmental extinctions. But the climate effects from Laki were severe enough to generate concern about the possible effects on previous communities in the archaeological record.

Gas Emissions From Volcanoes

There has been a tendency to dismiss gas emissions from volcanoes (rather than fissures) as unimportant. For example, Mt Asama in Japan erupted the same year as Laki, in 1783, but the amount of sulfur dioxide was described as "inconsequential", at 0.2% of the SO_2 mass-produced by the Laki eruption (Thordarson & Self 2003: 7-2). However, Etna, Stromboli and Vesuvius (discussed in Chapter 15) also erupted in 1783, contributing to the dry acid fogs that damaged crops in the Mediterranean Basin. Calculations of gas emitted from large volcanic eruptions show that several, including Mt Paektu discussed in Chapter 7, come within an order of magnitude of Laki's emissions (Figure 10), and halogen emissions from two of the volcanoes exceeded Laki.

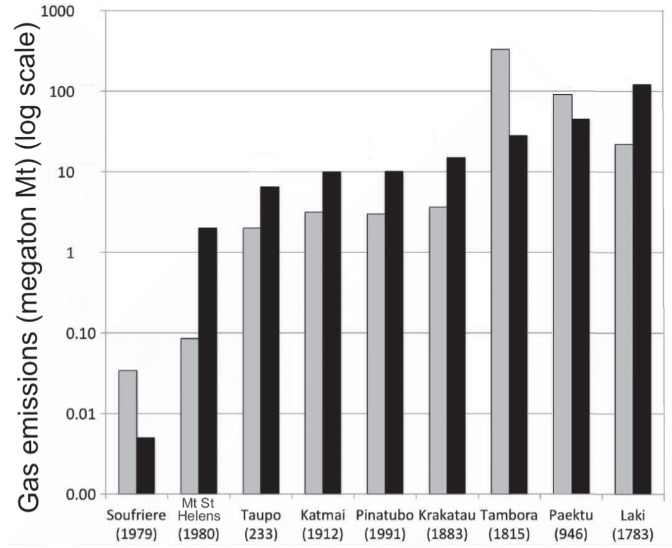

FIGURE 10 COMPARATIVE GAS EMISSIONS FROM LARGE VOLCANIC ERUPTIONS

Grey = Halogens: F (Fluorine) + Cl (Chlorine)
Black = S (Sulphur)

A rather different kind of gas hazard is the eruption of gases – carbon dioxide (CO_2) or methane (CH_4) – through lakes; these are called lake overturns or 'limnic eruptions'. Some of these gas accumulations result from biogenic decay mechanisms, while others are volcanically fed as at Lake Kivu between the Congo and Rwanda (Nayar 2009) and Lakes Nyos and Monoun in Cameroon (Kusakabe 2017). In either case, the gases are kept dissolved in the lower stratified water column until they exsolve and erupt catastrophically. The mechanisms are hotly debated, but in the cases of Nyos and Monoun Lakes, it is clear from its geochemistry that the carbon dioxide derives from the mantle through a basalt dike (Kusakabe 2017: fig. 29).

The eruptions of such gas concentrations are lethal; because CO_2 is heavier than air, the gas cloud follows the valleys – as pyroclastic flows do – suffocating all life before the cloud disperses. The 1986 Lake Nyos eruption instantaneously killed more than 8000 cattle and 1746 humans (Kusakabe 2017: 2, 6). At Lake Kivu, "gaps in layers of plankton fossils at the bottom of the lake suggest that such paroxysms have struck several times in the past 5,000 years" (Nayar 2009: 322). Kusakabe compiled oral traditions of previous possible lake eruptions that specifically documented people moving across the landscape, giving motivation for migrations that might be seen in the archaeological record. Without such documentary records – oral or written – that detail these effects of volcanic gas release on local and distant populations, how are archaeologists to identify and assess their impact on prehistoric populations? Lacustrine coring is one approach; Barker and Bintliff (1999) further suggest the use of EDMA[9] to recover evidence from sediments of toxic gases which might have adhered to or been incorporated into tephra and deposited with it. Only since the limnic eruptions in the mid-1980s have scientists become aware of the hazard associated with volcanic lakes, either maars or crater lakes. After the Nyos maar eruption, an International Working Group on Crater Lakes (IWGCL) was convened, which was formalized in 1993 as the Commission on Volcanic Lakes (CVL, under the auspices of IAVCEI, the International Association of Volcanology and Chemistry of the Earth's Interior).[10]

Thunder & Lightning

The epi-phenomena of storm-like emissions of volcanoes have rarely been considered by archaeologists – even though such effects have been known since Pliny the Elder recorded their occurrence during the eruption of Mt Vesuvius in 79 AD. The sounds of the eruptions have been compared to thunder, as described in Chapter 4 on behalf of prehistoric Native American populations on the Great Plains. Within the last 200 years, volcanic lightning has been recorded over 200 times (Weirup 2010; McNutt & Williams 2010; Cimarelli et al. 2016). In 2016 scientists in two different studies documented two different ways lightning is generated within ash plumes: by ash particle friction in the lower ash plume as recorded for Sakurajima (Cimarelli et al. 2016), and by ice particle collision with charged ash particles in the upper troposphere (Van Eaton et al. 2016). The impact of the sight and sound of lightning generation during volcanic eruptions – what Elson and Ort (2018) describe as a 'full sensory experience' – must have added further terror and awe for those affected.

Archaeological Implications

The sub-discipline of TephroArchaeology

The point of the above review is to emphasize the fact that TephroArchaeology cannot be isolated from volcanic processes; these are very complicated and not understood in detail by most archaeologists. There is more to TephroArchaeology than just digging in tephra or discovering it in excavated strata. The term needs to be understood in its widest context of everything related to volcanic eruptions, and as Soda admits below, we may well be on our way to adopting 'Volcanic Archaeology' or 'Archaeological Volcanology' as umbrella terms (cf. Elson & Ort 2018; Riede 2015a,b). Whatever the name of the sub-discipline, there are two aspects that must be addressed: how archaeologists, through special methodologies, can retrieve information on 1) the sequences of volcanic events during (and after) an eruption, and on 2) a micro-timescale that reveals human reactions to each of those events.

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[9] EDMA = Energy Dispersive (X-ray) Micro-analysis

[10] See the CVL website at https://iavcei-cvl.org/

The ‘archaeology’ part of the proffered umbrella terms is quintessentially cultural: this sub-discipline is primarily concerned with the effects of volcanic eruptions on *past* societies – in Riede’s term, it is the study of ‘palaeosocial volcanology’ (Riede 2015b). It meets the field of ‘historic social volcanology’ (Scarlett, forthcoming) which leads into ‘social volcanology’ as dealing with volcanic hazards, mitigation, and studies of resilience in *today’s* population (e.g. Donovan 2010; Donovan, Oppenheimer & Bravo 2012). The special issue “Volcanoes and Human History” (Cashman & Giordano 2008) brought together archaeology and oral history, while studies in the sociology of volcanoes are often published in the *Journal of Applied Volcanology*, begun in 2009, and *Quaternary International* (Riede ed. 2016). We look forward to seeing similar studies in the new open access journal, *Volcanica*. TephroArchaeology is one method by which palaeosocial volcanology can be conducted. It comprises the archaeological techniques of capturing the data needed for social analysis beyond standard cultural change. Moreover, archaeologically excavated data can feed back into volcanology to inform on the minutiae of eruptions that would not necessarily be discovered by geologists.

Nevertheless, volcanology is the bedrock for TephroArchaeological studies, and the crucial tool is for archaeologists to be able to recognize tephra in the field in all its forms – the various macro-deposits discussed above as well as the presence of cryptotephra, discoverable only microscopically. The second step is to have the tephra characterized and dated. The characterization of tephra involves many procedures, which are outlined in Appendix E. These form the basis for coordinating tephras across the landscape and through time.

SODA Tsutomu (Chapter 2 herein) provides a history of the development of this sub-discipline in Japan, going back to the 19th-century scholars who first took an interest in tephra deposits – including the traveller who sketched the picture of houses buried in an eroded lahar (see Chapter 6: Figure 2). He contextualizes the geological and archaeological work that led up to the definition of the field called *kazanbai kōkogaku* (volcanic ash archaeology). Once entering the current era, he gives a detailed overview of the tephra deposits that have affected one of the homelands of TephroArchaeology, Gunma Prefecture. The story would be incomplete without an explanation of the role tephra dating played in the Palaeolithic scandal of 2000 at Kami-Takamori site. Both Soda and Machida had expressed reservations about site stratigraphy, and Soda called for a re-evaluation of the site in 1991. His views, as well as reservations about the site by ODA Shizuo and Charles Keally, were rejected, indeed involving personal persecutions due to the traditional academic and Japanese social characteristics of bowing to authority and non-confrontational interaction. Perhaps this incident was needed to shake up the field to allow criticism and critique to have a place in academic exchange. Soda finishes with a discussion of new avenues of research being taken in TephroArchaeology in Gunma Prefecture.

KUWAHATA Mitsuhiro has written a response to the initial concept of TephroArchaeology by expanding its original remit in prehistory to investigate historic volcanic disasters and analysis of artefacts incorporating tephra. His presentation of Tokui’s graph (Chapter 3: Figure 1) on the disturbance gradient of damage in volcanic disasters forms the background for several further discussions in this volume. The procedures he specifies for dealing with tephra in the field and in the laboratory are illustrated with tephra sections from some of the sites excavated in southern Kyushu, the second homeland of TephroArchaeology.

Tracking Human Behaviour

There is a huge range of *volcanic* behaviour that must be met by appropriate *human* behaviour in order to survive. The reality of sudden and/or multiple eruptions or shifting eruption styles that cannot be predicted increases risk; perhaps the wide range of possibilities is one aspect that causes complacency when decisions should be made about what to do in the face of an impending or ongoing eruption. Torill Christine LINDSTRØM, in Chapter 15, presents some of the psychological mechanisms inherent in facing volcanic eruption risk – a new perspective that can be added to other limiting factors she names that can also determine responses, such as geography, culture, and social and physical restraints.

The Kurile and Aleutian volcanic arcs (Appendix C-1), which form the northern border of the Pacific Rim, are younger and compositionally different from the Japan arc which forms the stage of most of the chapters herein. The northern arcs present geographic and climatic challenges that are absent further south, and so they provide good comparative material to monitor small-group colonization of difficult terrain under environmental constraints as well as volcanic hazards. Chapter 5, by Ben FITZHUGH, Caroline FUNK, and Jody BOURGEOIS, takes issue with the standard interpretation of abandonment in the face of volcanic disasters in the Kuril and Aleutian archipelagos. Despite geological and climatological similarities between the arcs, the authors find that geographical constraints are foremost, conditioning different behavioural patterns between the island chains. Most notably, the abandonments that are apparent in the archaeological record cannot be explained by volcanic activity.

The potential long duration of intermittent volcanic activity means that each eruption, from onset to cessation, will inspire different sets of behaviour through time and between individuals or groups according to their beliefs, perceptions, preparedness, and social contexts. MARUYAMA Koji deals with two successive 10th-century eruptions in Chapter 8: the 10th-century eruption of Mt Towada, now known as Lake Towada in the northern Tōhoku area of Honshu Island, Japan (Appendix C-4), and Mt Paektu (Baekdu or Changbaishan) on the border between China and North Korea (Appendix C-8). Maruyama has painstakingly extracted data on the presence of these two tephras in pit-dwellings in northern Tōhoku that have previously been recorded in published archaeological reports. Going beyond mere abandonment as a generalized response, he has archaeologically assessed contemporaneous settlements which show either depopulation or population increases; by matching these trends with ceramic data, he proposes differential migration patterns between the areas. By considering together areas that *were* and *were not* affected by tephra fallout, he has modelled differential responses among peoples of differing cultural affiliations. The strength of his analysis lies in not limiting his study to areas affected by the eruptions *per se* but broadening it to include contemporaneous sites that reveal the radiating social effects of survivor behaviour. Moreover, such behaviour appears to have been conditioned by the nature of the social structure, varying from egalitarian societies beyond the reach of the archaic state to those close by and benefitting from state interaction.

Following the 10th-century Mt Towada eruption, a lahar buried many houses further north in Akita Prefecture. In Chapter 6, MURAKAMI Yoshinao describes in detail how the lahar entered standing houses at the Katakai-Ienoshita site, in Akita Prefecture, preserving them upright; careful observation of ceramics caught in the lahar allow them to be interpreted as swept off a shelf inside a house. Similar to the woven fence at Kanai in Gunma Prefecture (Chapter 10), several pieces of architectural organic matter were preserved by the lahar, allowing more detailed reconstructions of the buildings. The presence of these structures in the ground has been known for a long time, having eroded out of a flood bank and been documented in the early 19th century; to have sketches and text to compare with current excavation findings doubles the interpretive strength of the materials. The interesting aspect of one of the sketches (Chapter 6: Figure 2) is that the house is basically a pit-house, with ladders leading down inside, and yet the roof does not extend to the ground as in prehistoric pit-houses but is supported on board walls lining the inside of the pit. The excavated pit-houses at Katakai-Ienoshita were unusual in having surrounding ramparts rather than deep pits, and two were found with indoor hearth and flue systems. One of these pit-houses was connected to a pillared building beside it, giving rise to speculations on the varying use of these architectural structures in the 10th century. Paddy fields were discovered adjoining the residential area, allowing insights into Medieval farming practices in the far north of Honshu Island.

Moving into central Honshu, SODA Tsutomu in Chapter 2 discusses the volcanics of the Central Honshu and Fuji volcanic zones (see Appendix C-5, C-6) and the formation of the Kantō loam. Within Central Honshu, HORAGUCHI Masashi provides a general contextual overview in Chapter 9 of the two active volcanoes in Gunma Prefecture, Asama and Haruna, and an exposition of repeated eruptions affecting society from the Kofun Period (250–710 AD), through the Heian Period (794–1183), to the Edo Period (1603–1868). Horaguchi is particularly interested in human reactions to eruptions at the various sites, and he proposes a series of distinctions in activities based on terminology in Japanese. He extols the detail of preserved settlements, never before obtained in Gunma archaeological excavations, and promotes three key uses of tephra cover. His work sets the stage for the ensuing chapters on Gunma sites, Chapters 10 and 11 by Sugiyama and Sakaguchi, respectively.

The data from the Kanai sites in Gunma Prefecture, discussed by SUGIYAMA Hidehiro in Chapter 10, provide unparalleled insights into human reactions to a 6th-century eruption of the Futatsudake vent on Mt Haruna: these reactions were one of leisurely acceptance and one of reverential finality. The two Kanai sites, Higashi-ura and Shimo-shinden, were differentially hit by tephra fallout, a pyroclastic surge, then a pyroclastic flow. The detailed effects of these are documented in rock impact traces, tomb scouring, and hut flattening. Footprints of humans and horses reveal some had time to escape, while others were not so lucky – as several skeletal remains of both have been preserved in the tephra. The 'man in armour' is an exceptional find. Many sets of armour have been excavated from tombs as funerary goods, but this is the first time one has been found being worn. The man, facing the oncoming pyroclastic flow, knelt in a ditch, took off his helmet, turned it around so that it faced him, spread out the cheek flaps, and bowed his head onto the helmet crown before being consumed in the ashes. A woman nearby splayed out in the ditch shows more panic in trying to escape. Underneath the tephra, an elite settlement has been revealed, with a 3-metre high woven fence partitioning off the main residence. Unparalleled insights into their residential structures, gardening efforts, and ritual concerns make Kanai one of the most important sites for understanding Kofun-Period society in this frontier region.

The main aim of Chapter 11 by SAKAGUCHI Hajime is to assess the seasonality and timing of two volcanic eruptions in the 6th century in Gunma Prefecture by comparing the conditions of paddy fields and irrigation canals buried by tephra fallout and lahars with the modern agricultural cycle. He is able to narrow down the time of year of both these eruptions to one month during the late spring/early summer planting seasons. This involved detailed analysis of field and canal construction with added footprint data. Concomitant with his analysis, he reveals that the local farmers in the 6th century would work through 10 cm tephra depositions and 5 cm thick lahars to continue their seasonal agricultural tasks. It is not likely that they had experienced previous episodes of light volcanic activity, so what made them carry on with complacency? Did they rely on folk wisdom shared within the greater community? Why, in that case, did they not anticipate the devastating lahars that followed? Were they themselves able to escape? We are left with a human story that is illuminated by the results at the Kanai Higashi-ura site.

At the southern end of Japan, KUWAHATA Mitsuhiro writes in Chapter 12 about field systems in the mid-2nd millennium in Miyazaki Prefecture, Kyushu. Two active volcanoes, Shinmoe-dake in the Kirishima Volcanic Zone (see Appendix C-7) and Sakurajima (a parasitic volcano on the rim of the Aira Caldera in Kagoshima Bay), have regularly covered the region in volcanic ash. Both paddy fields and extensive ridge-and-furrow traces have been excavated from underneath tephra erupted in the late 15th and early 18th centuries. Kuwahata reveals efforts to restore fields to productivity after the tephra fallout; in only one out of four cases were the fields abandoned.

In Chapter 13, Gina BARNES continues the study of tephra affecting agricultural systems by examining soils that develop from tephra deposits and assessing their productivity. After a brief introduction to the place of tephra-derived soils in soil taxonomy schemes, she focuses on the formation of andosols, emphasizing the black andosols (*kurobokudo*) found under grasslands in the Japanese Islands. These have incited much hypothesizing about their generation – the most convincing argument proposing that these appeared simultaneously with the peopling of Japan after 40,000 BP and resulted from the firing of the landscape. For what purposes, it remains for archaeologists to specify. As tephra-derived soils have often been thought to be infertile for agriculture, the geochemistry and nutritional values of andosols are examined in general in Chapter 13 with details in Appendix D.

The succeeding Chapter 14 by NOTO Takeshi and Gina BARNES provides an overview of the historical materials on agricultural innovations to compare with excavated evidence in Gunma Prefecture. This topic ranges more widely than just farming tephrogenic soils, but land-use patterns can partly be explained by soil infertilities caused by tephra weathering. The problem of swidden agriculture is discussed, but only as one of several strategies using fire to control plant growth and provide arable and pasture lands. The discovery of field systems under tephra, especially under successive burial events by tephra deposition, allows the exploration of mechanisms for restoring or redeveloping fields, as in Chapter 11. However, examined in light of the historical documents, a broader, more detailed view emerges that links directly to political systems of different periods – as also shown in Chapter 8. The impact of socio-political systems on people's behaviour in the face of disaster is a new direction in tephroarchaeological studies that can be studied comparatively through time as well as cross-culturally.

Gerry OETELAAR's Chapter 4 is unique in using the Mazama tephra deposits at excavated archaeological sites to understand landscape evolution on the northwestern Great Plains upon retreat of the ice sheet. Mt Mazama, now known as Crater Lake, belongs to the Cascade Range of volcanics in northwestern North America (Appendix C-2). Oetelaar details changes in northwestern Great Plains terrain after tephra-fall from the volcanic eruption hundreds of miles to the southwest. He investigates terrace, dune and alluvial fan formation, and explores the drying out of ice-block potholes. Such landscape reconstruction for specific periods of time and specific locales is essential for understanding the potential for human occupation as dependent on the flora and fauna – and particularly water and fuel supplies – within those micro-environments. Oetelaar then in turn examines the behaviour of prehistoric inhabitants in occupying these new landforms – which in the main are not volcanically generated. He makes the important point that groups reoccupying ancestral areas buried by tephra must have made use of landmarks to guide them back. One might envision that any drastic landform changes (such as rerouting of rivers) would have interfered with their objectives. Moreover, trails across such changing landscapes would have to be forged anew. The feedback loops of tephra cover > geomorphological change > archaeological discovery > geomorphological reconstruction > and behavioural interpretation are fully interdisciplinary.

Finally, we are honoured to have Chapter 7 written by a historian. Keith PRATT delves into the science of Mt Paektu, an unusual example of alkaline volcanics far from the active subduction zones (Appendices B-3, C-8). He evaluates the histories of both China and Korea for evidence of eruptions of Mt Paektu – both before and after the Millennium Eruption of 946 AD. In addition to laying bare Korean political reactions to the 10th-century eruption, Pratt exposes modern-day North Korean elite claims and ritual concerns involving Mt Paektu. These works provide interestingly different perspectives on human behaviour than those gleaned from artefacts and settlement remains. It should be remembered that eruptions even in pre- or proto-historical periods probably exerted great pressure on political as well as social systems, though evidence may be more difficult to obtain. In any case, the detail offered by historical sources are rich and varied but still may not give us the full picture. Assumptions must still be made about people's motives – as Pratt surmises that the northward building of garrisons on the Korean Peninsula in the 10th century was prompted by the desire to reincorporate Mt Paektu into the political realm. This chapter exemplifies the necessary inter-disciplinary nature of volcanic disaster research and the onus on each individual researcher to completely grasp the science behind volcanic eruptions. But it also has cautionary lessons for non-historians who use historical documents in trying to understand both the geologic event and the archaeological remains.

Prospectus

With contributions from psychologists, historians, archaeologists, soil scientists, geologists, volcanologists, tephrochronologists, geographers, and botanists, TephroArchaeology is becoming an accepted sub-field in the North Pacific. Further collaborations among these with politics, social science, religious studies, oral history, and research in volcanic epi-phenomena are all signposted within the chapters offered here. We look forward to such future interdisciplinary studies.

One of the points of doing TephroArchaeology is to help prepare for future volcanic disasters, as discussed in the WAC8 and SAA Forums as mentioned in the Preface. However, as Kling (2016: unpg.) notes,

> Jumping from 'doing science' to 'applying science' is not easy. It requires a much broader understanding of the natural 'system', which includes not only the underlying science but various social and political aspects as well.

We have argued here for a closer discipline familiarity and collaboration between archaeologists and volcanologists, but even this volume just scratches the surface of what needs to be done to bring volcanic hazard research to public policy planning.

Figure Sources

Figure 1 after Barnes 2003: fig. 4, based on Yonekura et al. 2001: fig. 1.3.2; base map by Durham Archaeological Services
Figure 2 after Outline World Map Images 2009-2018 [http://www.outline-world-map.com/blank-thick-white-world-map-b3c], modified by GLB; licensing conditions are "royalty free for any legal purposes" with the copyright displayed
Figure 3 after Tucker 1991: fig. 10.7, modified by GLB
Figure 4 after Machida 1984: fig. 1, modified by GLB
Figure 5 By Ray_go (Own work) CC BY-SA 3.0 unported, via Wikimedia Commons [https://commons.wikimedia.org/wiki/File%3AShirasu_Cliff.jpg]
Figure 6 photo by author
Figure 7 after Velde & Meunier 2008: fig. 1.4, modified by GLB
Figure 8 photo by SODA Tsutomu
Figure 9 after Machida & Arai 1992: fig. 18, modified by GLB
Figure 10 after Iacovino et al. 20 16: fig. 1A, modified by GLB

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