Tephra Studies on Quaternary Explosive Eruptions in the Japanese Islands

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Japanese tephra studies have developed steadily in the last five decades. First two decades until 1976 brought fundamental ideas and techniques for correlation and for recognition of widespread co-ignimbrite ash falls. Geochemical and physical characterization of tephras advanced greatly in the third decade in 1980s. This enabled identification and distinction of many individual tephra layers and then compilation of tephra catalogs for solid tephrostratigraphic framework. VEI=7 classed large-scale eruptions had occurred at several calderas in Kyushu and Hokkaido Islands during the period from Middle Pleistocene to Holocene. Estimated average frequency is once in every a few ten thousand years. Their impacts on human society and ecosystem were analyzed through many disciplines of Quaternary research and turned out to have been very severe. Late Pleistocene and Holocene eruptive histories of medium-scale Plinian eruptions (VEI=4–6) are mostly documented and included in catalogs. Studies on their impacts on humankind during both pre-historical and historical ages confirmed severe volcanic hazards. The knowledge makes long-term prediction and volcanic hazard mitigation more reliable. Detailed stratigraphic and chronological studies on Holocene pyroclastic deposits helped to establish precise eruptive histories of some active volcanoes. Many recent works focused on Pliocene to Middle Pleistocene widespread tephras. Middle Pleistocene tephrochronology has provided information on regional changes of the frequency and magnitude of eruptions and magma discharge rate as a function of time. Studies of older distal tephras preserved in non-volcanic sediments let us know the occurrence of large-scale eruptions without any volcanic edifice preserved. The 10^6 year scale tephrochronology is revealing very long-term evolution of volcanic activity and magma discharge.

Keywords: Japanese Islands, explosive eruption, tephrochronology, Quaternary

I. Introduction

Violent volcanic activities often cause volcanic hazards, which have claimed more than 260,000 lives in the world since AD 1600 (Tilling, 1989). On the volcanic islands arc of Japan there are over 250 Quaternary volcanoes, which have repeated countless explosive eruptions. Within the 1500 years of historic records, severe damages and casualties by volcanic hazards have been reported (Japan Meteorological Agency, 2005). The mode, magnitude, and frequency of volcanic activities in Japan differ greatly in space and time owing to the wide geographic and temporal variety of magma properties and discharge rates, as well as of tectonic background. The mode and magnitude affect the scale of volcanic eruptions, while the frequency of eruptions determines the probability of eruptions in the future. For the sake of volcanic hazard mitigation, it is imperative to know the characteristic of volcanic hazards controlled by the scale and probabilities of explosive eruptions.

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gives estimate of the size of the eruption. Stratigraphy itself is a record of eruptive sequence with much geologic information. Many dating methods constrain the ages of tephra layers and related sediments. Thus the tephra study of explosive eruptions is one of the most promising approaches to volcanic hazard mitigation.

Tephras may record such small eruptions as VEI =1 (volcanic explosivity index : Simkin et al., 1981) to the largest ones of VEI =7. Small steam explosions usually leave thin layers of volcanic ash rich in accessory material within several hundred meters off the vent, while, the largest ones create huge calderas, voluminous ignimbrites and fall-out tephras mostly consisting of essential material and reaching hundreds to thousands of kilometers away from the vent.

Tephra records are subtle for small eruptions, but small eruptions tend to occur more frequently. For the present-day active volcanoes with many observed small eruptions, it is rather easy to forecast future activity for hazard mitigation. In a longer term, clustering of minor eruptions may occur after an interval. Tephrochronological recognition of past minor eruptions from inactive volcanoes is the only way to reveal the potential of volcanic hazards.

As to the large eruptions, tephra studies reveal the past occurrences of infrequent (once in $10^4$ years or less) but catastrophic eruptions. Such eruptions have potentials to destroy civilization and ecosystem over a very extensive areas ($10^4$ to $10^6$ km$^2$). This type of eruption is too infrequent to be taken into account for common hazard mitigation research. However, such large eruptions exceeding VEI=6 have occurred more than hundred times in Quaternary in the world.

Though modern society has never experienced an eruption larger than VEI=6, it is not possible to deny the chance of such a colossal eruption and resulting hazards. Therefore, evaluation of the probability and impact on our society and ecosystem is necessary. Interdisciplinary Quaternary research comprising geology, geomorphology, volcanology, archaeology, geochemistry, and geophysics is a feasible approach to this kind of very rare extreme natural hazards.

Tephrochronology is a way to study tephras with more emphasis on stratigraphy and chronology than physical process of tephra eruptions. Tephrochronology is a good tool for monitoring changes in frequency and magnitude of eruptions in Quaternary and for evaluating impacts on human activities and ecosystem both for the long term and short term.

Japanese tephrochronology in the last five decades has clarified the occurrence of Quaternary explosive eruptions and their impacts on humankind and ecosystem (e.g. Endo et al., 1986 ; Machida, 1991, 1999a ; Machida and Arai, 2003). This paper aims to review the Japanese achievements of tephrochronology on explosive eruptions in last a few million years, and to discuss about their implication on volcanic hazards and impacts on ecosystem.

II. Fundamental studies

Tephrochronology is based on recognition of an individual tephra layer erupted in a single eruptive cycle (Nakamura et al., 1963). Regional studies on Holocene to Late Pleistocene Plinian and sub-Plinian tephrostratigraphy mainly based on lithological characteristics established eruptive histories of distinctive active Quaternary volcanoes such as Izu-Oshima (Nakamura, 1964), Fuji (Machida, 1964), Asama (Aramaki, 1963) volcanoes.

Kobayashi (1972) described the principles and techniques of tephrochronology into details emphasizing that not only field observations but also petrographic analyses of tephra clasts are necessary for the distinction among tephra layers. Since 1970s petrographic analyses such as on refractive indices of volcanic glass shards and phenocrysts and on mineral assemblage have been employed (Arai, 1972). In 1980s various geochemical and physical analytical techniques on petrographic properties of tephras were introduced for more reliable distinction and correlation of tephras. Among them, the electron micro-probe analysis (EPMA) on major elements chemical composition (Furuta et al., 1986) and inductively coupled plasma (ICP) emission spectrometry on trace and rare-earth elements (Kikkawa, 1990) are extensively applied for glass shards in tephras for correlation of distal tephra layers intercalated in diffe-
The recent tephra and sediment sequences.

Compilation of these characteristic properties with stratigraphic position, precise age, distribution, and volume enables to catalog many tephras in and around Japan. Since Machida (1976) published the first catalog of tephras in Japanese Islands, new data and finding urged frequently revision and augmentation of the catalogs (Machida and Arai, 1992, 2003; Machida, 1999a, b). The latest catalogs include more tephras from recent smaller eruptions and older Pliocene to Middle Pleistocene tephras recognized and correlated in wide areas.

III. Implication of the studies on explosive eruptions and their impacts

1. Large-scale eruption

A large-scale eruption (VEI=7–8) accompanying caldera formation and pyroclastic flows forms voluminous ignimbrite and co-ignimbrite ash exceeding 100 km³ in volume. Precise information on stratigraphy and petrography of a tephra layer enables correlation of an ignimbrite with its co-ignimbrite air-fall ash in distant area hundreds to thousands kilometers away. One of the most significant findings in Japanese tephra studies is the recognition of the 26–29 ka widespread tephra (VEI=7) named Aira–Tn Tephra (AT: Machida and Arai, 1976) covering the whole area of the Honshu, Shikoku and Kyushu Islands (>4 × 10⁶ km³) (Fig. 1).

Since Machida and Arai (1976) introduced the concept of a widespread tephra, studies on a number of widespread tephras were carried out to provide information on the frequency and magnitude of extremely large eruptions. These studies clarified that VEI=7 class large-scale eruptions producing tephras more than 100 km³ had occurred at several caldera volcanoes in Kyushu and Hokkaido Islands. The frequency of such large-scale ignimbrite forming eruption in average is once in a few ten thousand years during Middle to Late Pleistocene and Holocene.

Modern human society has not experienced such a catastrophic eruptive event though it is not so infrequent in geologic time scale. It is difficult to estimate the influence of a future large-scale eruption on society and ecosystem because there is no scientific observation on such eruptions and their aftermath. However, recent archaeological studies with tephrochronology reconstructed the effects of past large-scale eruptions (e.g. Machida, 2002). The large-scale Holocene eruption of Kikai–Akahoya tephras (7.3 ka: Okuno, 2002) produced an ignimbrite and ash falls of over 170 km³ (Machida and Arai, 2003). The Koya pyroclastic flow in the late stage of the eruption buried southern part of the Osumi peninsula in south Kyushu Island. Influence of the eruption on Jomon culture and the vegetation in south Kyushu Island was discussed in a special issue of the Quaternary Research on the symposium “Environmental changes during the initial Jomon period in south Kyushu, Japan”. The Jomon culture between ca. 16 ka and 2.5 ka is Japanese mesolithic to neolithic age characterized by extensive use of fine potteries. Kuwahata (2002), in this issue, stressed that there was no discontinuity in the Jomon culture in the whole southern Kyushu before and after the Kikai–Akahoya eruption. On the contrary Machida (1984, 2002) proposed a major cultural discontinuity in the same period. Shinto (1994, 2001) also pointed out the extinction of a type of Jomon culture originated in south Kyushu based on the expansion of another type originated from north and north-middle Kyushu above the Kikai–Akahoya tephra.

The impact of this eruption on vegetation was also estimated by palynological and phytolith studies. Matsushita (2002) estimates the recovery of the lucidophyllous forests damaged by the pyroclastic flow to have begun 100 to 300 years after the eruption, while Sugiyama (2002) estimates it 600–900 years on the basis of phytolith analyses. Controversy over the discontinuity in the Jomon culture combined with the duration of damaged vegetation is informative to understand the effects of volcanic hazards caused by catastrophic large-scale eruptions (VEI=7) in the future.

However, accurate evaluation of the damages to the highly civilized society seems to be very difficult because the actual process of such enormous eruptive phenomena is far beyond our experience and knowledge. At this moment a significant contribution of Quaternary science for the society is the information on the
Fig. 1 Distributions of Late Pleistocene widespread tephras in and around the Japanese Islands and volcanic regions where maximum eruption of VEI=7 is reported in Late Pleistocene and Pliocene to Middle Pleistocene


possibilities of this type of eruptions demonstrating its repeated occurrence and catastrophic influence on human society. Also, interdisciplinary Quaternary research is one of the few ways to evaluate the impact this type of large-scale natural hazards.

2. Medium-scale to small-scale eruptions

Medium-scale Plinian eruptions with fall-out tephra volume of $0.1 - 10 \text{ km}^3$ (VEI=4-6) have occurred frequently at stratovolcanoes and calderas in Japan. Most of the Late Pleistocene and Holocene Plinian fall-out tephras of more than $0.1 \text{ km}^3$ in volume have been described and cataloged in 1990s (Machida, 2002; Machida and Arai, 2003). Using widespread tephras as time markers, the tephrostratigraphic framework of these tephras on the whole area of the Japanese Islands and surrounding seafloor was established before 2000 (Fig. 2-a). Machida and Arai (2003) published an almost complete catalog of these Late Pleistocene and Holocene tephras. More than 500 tephras are included in the catalog with stratigraphic position, age, distribution, volume, and petrographic properties.

A Plinian eruption potentially causes severe damages on local human communities and ecosystem because it frequently accompanies fall-out and pyroclastic flow. Many geological and archaeological studies evidenced the damages to human society of pre-historic age (Arai, 1993;
Machida, 2002). In case the damages coincide with social unrest or changes in legends or in documents, debates on the relationship between the natural hazard and social change often arise (e.g. Hirayama and Ichikawa, 1966; Tokui, 1993). Such debates about the effects of natural disaster on civilization tend to be manifestation of one’s belief, but more precise data on volcanic eruptions and tephra emplacement, and on the changes in human society and ecosystem will lead to better understanding of volcanic hazards. Better reconstruction of Plin-
ian eruptions on their mode, frequency and magnitude in each volcano is a key for understanding past hazards as well as for long-term forecast and mitigation of volcanic hazard.

Studies on minor Holocene pyroclastic deposits associated with Vulcanian, Strombolian and steam eruptions have been conducted to reconstruct eruptive history of individual volcanoes without destructive large-scale activities (e.g. Imura, 1995; Okuno, 1995). These studies are based on detailed lithological and stratigraphic description with many $^{14}$C dates. They have revealed eruptive histories of active volcanoes in Holocene such as Hakone, Norikura, Yakedake, Nikko–Shirane, Nasu volcanoes and so on. The information is mostly limited for Holocene because of the lack of stable soil section in the glacial age owing to periglacial environment around the summit of volcanoes. The minor tephas from small eruptions are distributed only on upper slopes of volcanic edifice. Though our knowledge on minor tephas is limited to Holocene, the information is useful because smaller eruptions usually occur more frequently than larger ones. In case a volcano has erupted minor tephas repeatedly in Holocene, there are better constraints on the forecast of the future events. Furthermore, longer geologic records of such small-scale eruptions help us to evaluate temporal clustering of eruptions as well as to know the possible clustered small events in the future.

3. Long-term tephrochronology

In the studies of long-term stratigraphy and chronology, recent works also focus on older tephas of Pliocene to Middle Pleistocene (Fig. 2–b, c). The long-term tephrochronology covering Middle Pleistocene has constructed long eruptive histories of several volcanoes in Japan such as Hakone volcano (Machida et al., 1974). Under favorable conditions of preservation and outcropping, long tephra record is a good source for monitoring changes of frequency and magnitude of eruptions more explosive than VEI = 3 (equivalent to the volume of 0.01 km$^3$). Then, we can estimate the temporal changes of magma discharge rate over a long period. In case of southern part of the Northeast Japan arc, many Quaternary volcanoes are characterized by one or two cycles of episodic high activities with repeated Plinian eruptions. The duration of these episodic activity differs greatly from a volcano to another, and the frequency of Plinian eruptions also varies greatly (Suzuki, 1996). These diversities indicate that each volcano has strong characteristics on the intensity of frequency of eruption through time. The temporal and spatial changes are most likely to have caused by regional tectonic setting, location and size of a magma chamber, and thermal and chemical properties of magma.

Though there are many Plio–Pleistocene tephra layers in sedimentary sections in Japan, we do not know much about volcanic activities before Middle Pleistocene because of the loss of proximal pyroclastic deposits and the edifice of source volcano by severe erosion.

Many distal fall-out tephas well preserved in non-volcanic sediments are indicative of as frequent occurrence of explosive eruptions as in Middle Pleistocene and later. Many of these older tephas were described as air-borne and water-laid tephas in marine or terrestrial sediments in sedimentary basins such as Kazusa and Osaka basins in the Honshu Island (Mitsuhashi et al., 1959; Yokoyama, 1969). Recent studies revealed more precise chronolitostratigraphy and spatio-temporal distribution of these tephas.

The correlations of these tephas were performed by advanced characterizing and dating techniques on tephra, with reference to reliable chronologies of marine and terrestrial sediments based on litho-, bio-, magneto-stratigraphy and oxygen-isotope stratigraphy (e.g. Machida et al., 1980; Kurokawa and Tomita, 2000; Kurokawa and Higuchi, 2004; Satoguchi et al., 2005). Consequently, these tephrochronological studies reconstructed precise stratigraphical framework of the Pliocene to early Quaternary sediments covering the entire areas of the Japanese islands except Hokkaido Island. In addition, for example, studies on Middle Pleistocene KMT tephra and Lower Pleistocene Ho–Kd39 tephra, which occur in the Kazusa sedimentary basin, provided information of the disappeared distant source tephas where only the vent or exposed pluton was preserved in the Hida Mountains of central Honshu Island (Harayama, 1990, 1994; Nagahashi et al., 2000; Suzuki, 2000). Kikkawa (1990) and Mizuno (2001) widely em-
ployed minor- and trace-element chemical composition by solution ICP emission spectrometry, and they showed that the source regions of tephras are estimated by the regional characteristics of their chemical compositions. On the other hand, tephrozones defined by stratigraphically clustering tephras with similar properties were discussed in the sedimentary sequences of Kazusa, Osaka, and Uonuma Groups (Satoguchi, 1997). A tephrozone possibly suggests a past localized activity of a volcano or a volcanic region that provided similar tephras to the basin only in the period of its high explosive activity. Temporal and spatial changes in long-term volcanic activities in the Japanese Islands will be further reconstructed by a combination of ICP analyses and detection of tephrozones even without identification of the source volcano.

In addition, tephrochronological studies covering the period from Pliocene to Middle Pleistocene revealed that large-scale eruptions with the deposition of voluminous ignimbrite have frequently occurred in and around the Hida Mountains of central Honshu Island (Nagashashi, 1998) and in northern Honshu Island (Yoshida et al., 2005) before Late Pleistocene (Fig. 1). In these regions, there is a sharp contrast between the older highly explosive activities and the present activity characterized by stratovolcanoes producing smaller Plinian deposits less than 100 km$^2$. Om–SK110 tephra (1.65 Ma) and Eb–Fukuda tephra (1.75 Ma) are extensively distributed in central Honshu Island and their source volcanoes are estimated to be in the Hida Mountains (Nagashashi et al., 2000; Machida and Arai, 2003). Hkd–Ku tephra (0.76 Ma) and Tmg–R4 tephra (2.0 Ma) were derived from calderas in northern Honshu Island and covered the central Honshu Island (Suzuki et al., 2005; Suzuki and Nakayama, 2007).

These million-year-scale changes in the mode of volcanic activities are explained as follows. One idea is that a period of low activity like today characterized by frequent and smaller eruptions is intervened between the periods of high activity with large-scale eruptions. The return period of the high activity is in an order of $10^5$ to $10^6$ years. An alternative idea based the long-term tephrostratigraphy and K–Ar dating of volcanic rocks claims that the difference of volcanic activities in the Hida Mountains is caused by secular change of magma activity (e.g. Oikawa, 2003). In this case, it is evident that the volcanic activity of 2.5 to 1.5 Ma with large-scale eruptions and caldera formation had changed to the current activity of 0.8 Ma to present with medium-scale eruptions and formation of stratovolcanoes, reflecting a change in the regional stress field from tension to compression. In the latter case, these variations are explained by the crustal stress regime controlled by plate motion. Also, Yoshida et al. (2005) showed that the similar variations caused by the same mechanism is recognizable in northern Honshu Island. Time span for these changes are on the order of more than $10^6$ years.

Such long-term changes of tectonic regime and hence volcanic activities are beyond the time-scale of human civilization and it is hard to be taken into account for human activities. It may be necessary to know the possibility of such extreme volcanic events in central and northern Honshu Island, but quantitative forecast and hazard mitigation of this type of eruptions will not be urgent for the society.

However, now Japan faces an important issue of geological disposal of high-level radioactive waste (Japan Nuclear Cycle Development Institute, 2005). The $10^5$ to $10^6$ year evaluation of magmatic activity is significant for the disposal. The magmatic activity does not cause only volcanic eruption and magma intrusion but also causes regional uplift and subsidence resulting in significant geomorphic changes. If the tectonic evolution is a trigger for an innovated magmatic system, it will also trigger new tectonic systems accompanying different fault systems and uplift/subsidence distribution. Studies on long-term explosive volcanism together with tectonic evolution will lead us to safer environments.

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日本列島の爆発的噴火に関するテフラ研究の動向

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【要 旨】

日本のテフラ研究は、過去50年間に着実に進歩した。1976年までの最初の20年間に、コイグニープライムアッシュの認定や対比法に関する基本的な概念や方法が導かれた。1980年代に、化学的手法に基づくテフラの記載法が飛躍的に発展した。これらは、多数のテフラの認定と識別を可能にし、テフラ層序構築のためのカタログ化にもつながった。中期更新世～完新世にかけては、VEI=7クラスの大規模噴火が九州・北海道の幾つかのカルデラ火山で発生し、その平均の発生頻度は数万年に1回程度である。これら噴火が人間社会や生態系に与えた影響が第四紀研究の諸分野を通じて分析され、その影響の大きさが明らかにされた。後期更新世～完新世に発生した中規模なブリニック式噴火（VEI=4～6）の噴火もおおよそが明らかにされ、カタログ化された。多数の研究は、先史時代・時期時代を含めてそれら噴火による人間への過酷な影響を明らかにした。その知見は、長期的な噴火予測と火山災害軽減をより确实なものとする、完新世小規模テフラの詳細な層序・編年研究は、いくつかの火山の詳細な噴火史を復元に役立った。最近の多数の研究は、中期更新世～鮮新世の広域テフラに注目している。中期更新世のテフロクロノロジーは、噴火の頻度や規模の変化、時間の関数としての噴出率の変化に関するデータを提供してきた。非火山性の堆積物中に保存されている、より古いテフラの研究は、山体が残されていない火山で生じた大規模噴火の発生を明らかにできる。10^2～10^5年スケールのテフロクロノロジー研究は、きわめて長期にわたる火山活動やマグマ噴出率の経年変化を明らかにできる。

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