90,000-year phytolith record from tephra section at the northeastern rim of Aso caldera, Japan

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Abstract

Vegetation history during the last 90,000 years has been reconstructed using the phytolith record obtained from a tephra section located at the northeastern rim of Aso caldera, southwestern Japan. The phytolith assemblage from the section revealed that grassland vegetation dominated by Gramineae consistently occurred for 90,000 years. Sparse vegetation composed of *Sasa* sect. Crassinodi (cool-temperate dwarf bamboo) and *Zoysia* (lawn) was considered to be established within 1,000 years after the catastrophic Aso-4 eruption (89 ka). The *Sasa* grassland dominated by *Sasa* sect. Crassinodi existed continuously at the northeastern caldera rim between 89 and 13.5 ka. The dominance of *Sasa* sect. Crassinodi in the grassland suggests that the Aso caldera rim during the period was under a cooler and drier climate. Plants other than *Sasa* dwarf bamboo declined during the period of 75-66 ka (MIS4) whereas *Pleioblastus* sect. Nezasa (warm-temperate dwarf bamboo), Andropogoneae (pampas grass) and *Zoysia* existed in the *Sasa* grassland between 66-30 ka (MIS3). During the period from 30 to 13.5 ka (MIS2) corresponding to the Last Glacial Maximum (LGM), phytoliths from plants other than *Sasa* dwarf bamboo and fern are only present in small numbers, suggesting that they declined in response to a cool climate during the LGM. *Sasa* grassland, which had continued since 89 ka, existed after 13.5 ka at the northeastern rim of Aso caldera. In the earlier stage of the Holocene, phytoliths of *Sasa* sect. Crassinodi and *Sasa* sect. Sasa etc. dominated, but *Pleioblastus* dwarf bamboo became a constituent of the grassland around 8 ka. The proportion of *Pleioblastus* dwarf bamboo (mainly *Pleioblastus* sect. Nezasa) in the grassland increased and continued flourishing until the present, although *Sas*a gradually decreased. In addition, arboreal phytoliths were recognized at several Holocene horizons. These phenomena indicate that grassland vegetation composed mainly of *Sasa* and *Pleioblastus* dwarf bamboos with sparse trees dominated at the northeastern rim of the Aso caldera in Holocene time.

Keywords: Aso caldera; dwarf bamboo; Gramineae; grassland; phytolith; vegetation history

1. Introduction

Aso Volcano, located in central Kyushu, southwestern Japan, is one of the largest caldera volcanoes in the world. The last caldera forming eruption (Aso-4 eruption) at ca. 90 ka (Matsumoto et al., 1991) is the largest scale eruption which occurred at Aso Volcano and produced multiple gigantic pyroclastic flows (Watanabe, 1978). The Aso-4 pyroclastic-flow deposits with a volume of more than 200 km^3 cover most of central Kyushu (Machida and Arai, 2003), and the flows ran across the sea and reached an area about 150 km from the source (Ono and Watanabe, 1983). Therefore, the catastrophic Aso-4 eruption devastated almost all vegetation around the Aso caldera, and it is thought that a primary succession started above the extensive pyroclastic plateau just after the eruption.

The Aso caldera and its surrounding area are occupied by the largest-scale grassland in Japan. The grassland reaches an area of approximately 220 km^2 and is a semi-natural grassland mostly composed of *Miscanthus* (pampas grass), *Pleioblastus* (warm-temperate dwarf bamboo) and *Zoysia* (lawn) grasslands. Phytolith records were obtained from two tephra sections around Aso caldera, and demonstrated that grassland vegetation dominated by Gramineae has been continuous around the Aso caldera over the last 30,000 years (Miyabuchi and Sugiyama, 2006, 2008). Furthermore, charcoal records obtained in and around Aso caldera suggest a possibility that the grassland was established in response to frequent fire events (Ogura et al., 2002; Miyabuchi et al., 2010, 2011; Kawano et al., 2011). However the vegetation history around Aso caldera prior to 30,000 years ago has remained unknown until this present study.

Environmental reconstructions of the Aso caldera region were conducted based on a pollen record obtained from lake deposits inside the caldera (Iwauchi and Hase, 1992; Hase et al., 2011). They recognized large amounts of arboreal pollen from the Last Glacial Age, and indicated that forest was mainly formed under cool-temperate to sub-arctic conditions at 24-17 ka (calibrated ^{14}C age), followed by a change to temperate conditions with a predominance of deciduous trees, and subsequently followed by warm-temperate conditions to the present consisting largely of evergreen trees. However, the dry exterior of the caldera has received little attention due to the lack of such deposits. Pollen analysis is restricted to wet environments including lakes, swamps and high moors due to poor preservation. Furthermore, pollen data lack the taxonomic resolution necessary to identify different grass taxa. In contrast, opal phytolith analysis can provide more detailed information about vegetation reconstructions of grassland ecosystem, which exists in a dry environment such as the area surrounding Aso caldera.This paper presents the 90,000-year phytolith record from a tephra section located at the northeastern rim of Aso caldera, and discusses vegetation history after the catastrophic Aso-4 pyroclastic-flow eruption.

2. Regional setting and study site

The Aso caldera, 25 km north-south and 18 km east-west (Fig. 1), was formed by four gigantic pyroclastic-flow eruptions of andesitic to rhyolitic magma from ca. 270 ka to 89 ka (Ono et al., 1977; Matsumoto et al., 1991). The caldera-forming Aso pyroclastic-flow deposits are divided into four units: Aso-1 (270 ka), Aso-2 (140 ka), Aso-3 (120 ka) and Aso-4 (89 ka) in ascending order (Ono et al., 1977). Post-caldera cones have arisen near the center of the caldera since the Aso-4 eruption at 89 ka (Ono and Watanabe, 1985), and have produced voluminous fallout tephra and lava flows. At least seventeen cones are visible on the surface, but the shapes and structures of the central cones vary depending on their chemistry, which ranges from basalt to rhyolite (Ono and Watanabe, 1985). Nakadake Volcano (1506 m asl), which is the only active central cone in Aso caldera, is one of the most active volcanoes in Japan. At the post-caldera cones, explosive eruptions have frequently occurred although they have been much smaller than the caldera-forming stage eruptions. A thick tephra sequence (<100 m thick at the eastern caldera rim) erupted from the post-caldera central cones is preserved above the Aso pyroclastic-flow plateau, especially east of caldera, because tephra dispersal is affected by the prevailing west to southwest wind direction. The eruptive history of the post-caldera central cones and the magma discharge rate over the last 89,000 years were evaluated based on the integrated stratigraphy of thick fallout tephra deposits (Miyabuchi, 2009).

The post-caldera central cones divide the Aso caldera into the northern part (Asodani Valley) and the southern part (Nangodani Valley). Intra-caldera lakes were formed multiple times both in the Asodani and Nangodani Valleys due to ponding of the outlet (western edge) of Aso caldera by central cone lava flows (Watanabe, 2001). The last intra-caldera lake existed in the Asodani Valley prior to 8.9 ka (calibrated ^{14}C age) and thereafter swampy and fluvial environments occurred (Hase et al., 2003; Miyabuchi et al., 2010). The thick lake sediments result in a flat topography around 500 m asl, and the Kurokawa River flows westward in the center of the valley. The northern caldera wall ranges from 300 to 500 m in height and is composed of pre-Aso volcanic rocks and the overlying Aso pyroclastic-flow deposits (Ono and Watanabe, 1985). Flattened slopes less than 1-2° radiating outward from the caldera rim are formed by deposition of gigantic pyroclastic flow deposits.

Soil samples for phytolith analysis were obtained from a tephra section (33°00'20.2"N, 131°07'22.4"E, 813 m asl) near Teno Village (hereafter "Teno section"), located at the northeastern rim of Aso caldera (Fig. 1). The largest-scale grassland in Japan occurs behind the caldera rim. Current vegetation around the study section is grassland dominated by *Pleioblastus* sect. Nezasa and *Miscanthus sinensis*.

Based on 30 years of record (1971-2000) from the Japan Meteorological Agency, the mean annual temperature of the Asosan Weather Station (32°52.8'N, 131°04.4'E, 1142 m asl) is 9.6 °C. The mean temperature in the hottest month (August) is 20.2 °C, whereas mean temperatures from January to February are below freezing. The mean annual precipitation is 3250 mm, and the mean monthly rainfall exceeds 600 mm in June and July. The climate of the Aso caldera region is therefore characterized by cool air temperature and high precipitation.

3. Material and method

3.1. Stratigraphy of tephra section

The Teno tephra section is a 15 m high road cut along a forest road descending the caldera wall. A black humic soil, including Kikai Akahoya ash (K-Ah; Machida and Arai, 1983, 2003) at 7.3 ka (Okuno, 2002) near the center (ca. 0.9 m depth), occurs between the surface and 1.64 m depth (Figs. 2 and 3). The base of the black soil around Aso caldera was dated at 13.5 ka (Miyabuchi et al., 2004). The portion between 1.64 and 3.96 m depth is a brown soil including thin ash-fall deposits. The Aira-Tn tephra from southern Kyushu (AT; Machida and Arai, 1983, 2003) at 29 ka (Okuno, 2002) and the Kusasenrigahama pumice (Kpfa; Watanabe et al., 1982) at 30 ka (Miyabuchi, 2009) are recognized at 3.6 m depth and 4.21 m depth, respectively. A buried black humic soil exists between 4.39 and 4.65 m depth (base; 32 ka). A brown soil including several ash-fall, scoria-fall and pumice-fall deposits occurs below 4.65 m depth. Aso central cone pumice 4 (ACP4), biotite-rich Aso central cone pumice 5 (ACP5) and Aso central cone pumice 6 (ACP6), which are key pumice beds around Aso caldera (Takada, 1989), are identified at 6.02 m, 6.42 m and 7.51 m depth, respectively. Dacitic porphyritic pumiceous lapilli of Handa pyroclastic-flow deposit (Ono et al., 1977; Kamata, 1997) from Kuju Volcano (10 km NE of Aso Volcano) are scattered in a brown soil just below the ACP6 pumice. Yamasaki pumices 1 to 5 (YmP1-YmP5), which are well-stratified ash layers including pumice clasts (Miyabuchi et al., 2003), occur between 9.73 and 10.61 m depth. Ogashiwa pumice (OgP), which is a key tephra bed northeast of Aso caldera and contains abundant orthopyroxene needles (Miyabuchi et al., 2003), exists at 12.9 m depth. The Aso-4 pyroclastic flow deposit (89 ka; Matsumoto et al., 1991) exists below 14.04 m depth. The eruption ages for key tephra layers below Kpfa were estimated stratigraphically for a representative section NE of the caldera (Miyabuchi, 2009) as follows: ACP4 (51 ka), ACP5 (55 ka), ACP6 (60 ka), Handa pyroclastic-flow deposit (61 ka), YmP1-YmP5 (67-68 ka) and OgP (79 ka).

3.2. Analytical methods

Total of 58 soil samples was collected from the Teno section. Phytoliths were extracted from soil samples using the techniques developed by Fujiwara (1976). Each sample was dried (105 °C, 24 h) and then 0.02 g of artificial glass beads 40 μm in diameter was added to a dried sample per 1.0 g as an exotic marker, equivalent to 3.0×10^5 grains of glass beads in a 1 g sample. Soil organics were removed by heating of samples (550 °C, 6 h). The material was then dispersed in an ultrasonic bath (300 W, 42 kHz, 10 min), and particles coarser than 20 μm were extracted by a precipitation method. Phytoliths and glass beads were mounted in Eukitt mounting medium. Identification and quantification of phytoliths were performed under a polarizing microscope at 400× magnification, and continued until more than 400 glass beads were counted. This technique was nearly statistically equivalent to a close scanning of the entire area of one microscope slide. Phytolith concentrations per unit weight were calculated by the following formula: $(G_g \times P_c)/G_c$, where G_g: the total numbers of glass beads in the sample equivalent to 1 g, P_c: the number of grains of one phytolith morphotype counted in the scan, G_c: the number of glass beads counted in the scan. The present study focuses on bulliform cell (motor cell) type phytoliths that are produced by some Gramineae, although many previous studies used short cell type phytoliths originating from grass leaf epidermis for their identification (e.g., Twiss et al., 1969; Kondo and Sase, 1986). Bulliform cell types are relatively large (ca. 40-60 μm in diameter) and can be easily extracted from soil samples and observed, and identification of phytoliths of bulliform cells produced by Gramineae plants has been established (e.g., Sugiyama and Fujiwara, 1986). Identification of phytolith morphotypes of bulliform cells was based on Fujiwara (1976), Fujiwara and Sasaki (1978), Kondo and Sase (1986), Sugiyama and Fujiwara (1986), Sugiyama et al. (1988), Sugiyama (1999, 2001a) and Kondo (2010). The classification of Suzuki (1996) was used for Bambusoideae.

4. Results

Results of phytolith analysis at the Teno section are shown in Fig. 3. Based on characteristics of soil layers and the analytical results, the tephra sequence of the site was divided into five zones: Zone 5 to 1 in ascending order. Zone 5 was composed of brown soil layers including the OgP pumice. Zone 4 was an alternating bed of ash- and minor scoria-fall deposits and brown soil layers. Zone 3 was composed mostly of brown soil layers interbedded between several pumice-fall deposits, but the uppermost 0.26 m was humic black soil. Zone 2 was brown soil including thin ash-fall deposits. Zone 1 comprised black humic soil layers, including the K-Ah ash. According to the ages of marker tephra layers, ages of boundaries of Zone 5/4, 4/3, 3/2 and 2/1 were approximately 75 ka, 66 ka, 30 ka and 13.5 ka.

Phytolith concentrations at the Teno section displayed notable differences among the five zones (Fig. 3). The concentrations in Zone 5 increased upward prior to ca. 80 ka (sample 97) and thereafter decreased. The soil layer (the lowermost sample: 102) directly above the Aso-4 pyroclastic-flow deposit showed the lowest phytolith concentration of approximately 14,000 grains/g in all horizons of the section. Soil samples in Zone 4 had relatively low phytolith concentrations (mainly <59,000 grains/g) although a peak of 102,000 grains/g was recognized at ca. 68 ka (sample 77). Phytolith concentrations in Zone 3 were evidently higher than those in Zone 4, and ranged from 55,000 to 143,000 grains/g (peak at ca. 60 ka; sample 37). The concentrations in Zone 2 decreased again and variable between ca. 20,000 and 78,000 grains/g. Phytolith concentrations in Zone 1 were high and soil layers except the horizon of K-Ah ash included more than 84,000 grains/g. The concentrations were especially high at horizons in the last 7.3 ka (above K-Ah ash). The soil horizon overlying the K-Ah ash exhibited the highest phytolith concentration of approximately 189,000 grains/g in all soil samples.

According to observations under the polarizing microscope, bulliform cell type phytoliths, husk hair origin phytoliths, rod-shaped phytoliths, stem origin phytoliths and other unclassified phytoliths originating from Gramineae were mainly identified, and small amounts of fern and arboreal phytoliths were also recognized (Fig. 4). Bambusoideae phytoliths of *Sasa* sect. Crassinodi type and *Sasa* sect. Sasa etc. type (both cool-temperature dwarf bamboos) continuously predominated from Zone 5 to Zone 2 (Fig. 3). In Zone 5, other Gramineae phytoliths such as Andropogoneae A type (pampas grass), *Zoysia* (lawn) and Paniceae type were observed. In contrast, arboreal phytoliths could not be recognized except in one soil layer (sample 98) in Zone 5. Small amounts of Andropogoneae A type phytoliths were recognized in Zone 4.

In Zone 3, Andropogoneae A type and *Zoysia* phytoliths were contained in most horizons. Moreover, *Pleioblastus* sect. Nezasa type phytoliths (warm-temperature dwarf bamboo) occur continuously in the zone. Phytoliths except for *Sasa* dwarf bamboo and fern were rarely observed in soil samples of Zone 2.

In Zone 1, Bambusoideae phytoliths of *Sasa* sect. Crassinodi type predominated prior to about 8 ka (sample 7-9), but the amounts gradually decreased around 8 ka. In contrast, *Pleioblastus* sect. Nezasa type phytoliths were dominantly observed in horizons of the last 8 ka (sample 0-6). *Pleioblastus* sect. Nipponocalamus type phytoliths (warm-temperature dwarf bamboo) increased as well as *Pleioblastus* sect. Nezasa type phytoliths. Other Gramineae phytoliths such as Andropogoneae A type, *Miscanthus* type (pampas grass) and Paniceae type were also recognized in most horizons. Arboreal phytoliths could be observed in several horizons in Zone 3 and 1.

5. Discussion

5.1. Vegetation history during the past 90,000 years at the northeastern caldera rim

On the basis of the phytolith record obtained from this study, the vegetation history during the last 90,000 years at the northeastern rim of Aso caldera is interpreted as follows. The Aso-4 eruption at 89 ka (Matsumoto et al., 1991) is the largest eruption at Aso Volcano and produced multiple gigantic pyroclastic flows. The Aso-4 pyroclastic-flow deposits with a volume of more than 200 km^3 cover most of central Kyushu (Machida and Arai, 2003), and the flows ran across sea and reached an area about 150 km from the source (Ono and Watanabe, 1983). The catastrophic Aso-4 eruption devastated almost all vegetation around the Aso caldera, and it is thought that a primary succession started above the extensive pyroclastic plateau shortly after the eruption. Because the brown soil (16 cm thick) overlying the Aso-4 pyroclastic-flow deposit contains a small amount of phytolith grains, sparse vegetation composed of *Sasa* sect. Crassinodi and *Zoysia* is considered to have been established within 1000 years after the catastrophic eruption. *Sasa* (cool-temperate dwarf bamboo) grassland dominated by *Sasa* sect. Crassinodi existed at the northeastern caldera rim between 89 and 75 ka (Zone 5) corresponding to MIS 5. The grassland was accompanied by *Zoysia* (lawn) and Andropogoneae (pampas grass). Trees were scare because arboreal phytoliths are only detected in one sample in Zone 5.

During Zone 4 (75-66 ka) and Zone 3 (66-30 ka), the *Sasa*-dominated grassland continued at the study site. However, plants other than *Sasa* dwarf bamboo declined in Zone 4. Since Zone 4 corresponds to a moderately cooler period of MIS4, the decline of plants other than *Sasa* dwarf bamboo is thought to be attributed to the cool climate. In contrast, *Pleioblastus* sect. Nezasa (warm-temperature dwarf bamboo), Andropogoneae and *Zoysia* were part of the grassland composition during Zone 3. The existence of *Pleioblastus* sect. Nezasa indicates that Zone 3, corresponding to MIS 3, was a warmer period than Zone 4.

Between 30 and 13.5 ka (Zone 2), although *Sasa* grassland composed of *Sasa* sect. Crassinodi and *Sasa* sect. Sasa etc. occurred continuously, phytoliths except *Sasa* dwarf bamboo and fern were rarely observed in the zone. Phytolith concentrations in this period were relatively lower than other periods, suggesting limited vegetation. Cold and dry climate prevailed, indicated by the oxygen stable isotope variation from the sediment from the Sea of Japan (Oba, 1991) and phytolith records obtained from southern Kyushu (Sugiyama, 2004) suggest that the Last Glacial Maximum (LGM) in southwestern Japan including Kyushu Island appeared between 29 and 15 ka. Therefore, plants other than *Sasa* dwarf bamboo and fern declined during Zone 2 in response to a cool climate during the LGM.

Sasa grassland, which had continued since 89 ka, existed after 13.5 ka (Zone 1) at the northeastern rim of Aso caldera. In the earlier stage of the Holocene, phytoliths of *Sasa* sect. Crassinodi and *Sasa* sect. Sasa etc. dominated, but *Pleioblastus* dwarf bamboo, which occurs under a warm climate, became a constituent of the grassland around 8 ka. The proportion of *Pleioblastus* dwarf bamboo (mainly *Pleioblastus* sect. Nezasa) in the grassland increased and continued flourishing until the present, although *Sasa* gradually decreased. Andropogoneae and *Miscanthus* pampas grasses and Paniceae appeared in the Holocene, although their proportions were much smaller than those of *Sasa* and *Pleioblastus* dwarf bamboos. In addition, arboreal phytoliths were recognized at several Holocene horizons. These phenomena indicate that grassland vegetation composed mainly of *Sasa* and *Pleioblastus* dwarf bamboos with sparse trees dominated at the northeastern rim of the Aso caldera in Holocene time (<13.5 ka).

Recent phytolith studies revealed that climate change from cool to warm conditions resulted in transition of the principal component of grassland vegetation from *Sasa* to *Pleioblastus* in Japan (e.g., Sugiyama, 2001b). This transition can be observed remarkably in Holocene time. However, the prominent increase of *Pleioblastus* dwarf bamboo as a result of warming is not recognized in Zone 3 (MIS3) and Zone 5 (MIS5). This suggests that the warming during these periods in the Aso caldera region were much smaller than that in the Holocene (Zone 1).

Basically, *Sasa* grassland dominated by *Sasa* sect. Crassinodi dwarf bamboo occurred consistently from 89 to 8 ka. The dominance of *Sasa* sect. Crassinodi in the grassland suggests that the northeastern caldera rim prior to 8 ka was under a cool and dry climate. The *Sasa* grassland gradually declined from 8 ka, and *Pleioblastus* dwarf bamboo (mostly *Pleioblastus* sect. Nezasa), which occurs under a warm climate, became a constituent of the grassland.

5.2. Comparison of 30,000-year grassland vegetation to other areas around Aso caldera

The present study demonstrates that grassland vegetation dominated by Gramineae plants has continued at the northeastern rim of Aso caldera during the last 90,000 years. Prior to this study, no phytolith or pollen records have been reported in respect to the period prior to 30 ka around the caldera. Recently, two phytolith records were obtained from tephra sections east (Namino section; Fig. 1) and west (Kawahara section) of the caldera (Miyabuchi and Sugiyama, 2006, 2008). Phytolith assemblages from both sites revealed that grassland vegetation dominated by Gramineae consistently occurred for more than 30,000 years. Prior to 13.5 ka, vegetation both east and west of the caldera was composed mainly of *Sasa* dwarf bamboo although the vegetation east of the caldera (main fallout tephra dispersal) had considerably declined not only due to the cool climate during the LGM but also by frequent thick tephra deposition due to intense volcanic activity between 30 and 13.5 ka. This remarkable decline of vegetation cannot be recognized at the northeastern caldera rim, because the study site is away from tephra dispersal axes, as well as west of the caldera.

During the Holocene (<13.5 ka), *Miscanthus* grassland dominated in the eastern area whereas *Sasa* and *Pleioblastus* grassland existed in the western area. The principal component of Holocene grassland vegetation west of the caldera changed from *Sasa* to *Pleioblastus* around 10 ka. The 30,000-year phytolith assemblage obtained from this study is similar to that from the tephra section west of Aso caldera, although the timing of the transition is different. Yamada et al. (1997) noted that grassland vegetation has continued on the western foot of Aso Volcano for 30,000 years according to their phytolith analysis. Kawano et al. (2011) reported two Holocene phytolith records at the northern caldera rim (ASOK and ASOS sites; Fig. 1), and their phytolith assemblages and transitions are consistent with the result from this study. Thus, there is a distinct difference in the Holocene grassland vegetation transition between the western to northeastern area (*Sasa* and *Pleioblastus* grassland) and the eastern area (*Miscanthus* grassland) of Aso Volcano. However, all phytolith records obtained around Aso caldera reveal that grassland vegetation dominated by Gramineae plants has continued over the last 30,000 years. As vegetation inferred from all phytolith records prior to 13.5 ka was composed mainly of *Sasa* dwarf bamboo, the *Sasa*-dominated grassland existed all around Aso caldera after the Aso-4 pyroclastic-flow eruption at 89 ka.

5.3. Factor maintaining grassland vegetation around Aso caldera

The southwestern part of Japan, including Kyushu Island, is characterized by a warm and pluvial climate. The climax vegetation in the Aso Volcano region is lucidophyllous forest (evergreen broad-leaved forest) including *Castanopsis sieboldii* below 600 m. Mixed forest is dominated by *Abies firma* and *Illicium anisatum* at elevations between 600 and 800 m, and deciduous forest composed mainly of *Fagus crenata* above 800 m asl (Suzuki, 1975). The pollen record obtained from the Uchinomaki core inside the caldera (Fig. 1) recognized large amounts of arboreal pollen and indicated a vegetation transition from a mixed forest of conifer and deciduous broad-leaved trees through conifer forest, deciduous broad-leaved forest, to evergreen broad-leaved forest since Last-Glacial (Iwauchi and Hase, 1992; Hase et al., 2011). Furthermore, Miyabuchi et al. (2010) also detected small amounts of arboreal phytoliths continuously in the Senchomuta drill core obtained in the northern part of Aso caldera. These pollen and phytolith records suggest that forest vegetation existed in some places inside the Aso caldera even during the LGM. Thus, there is a distinct difference in vegetation transition between the inside and outside of the Aso caldera.

Grassland vegetation in wet climate regions is established in response to soil conditions, volcanic activity, fire events and human activities. Under a warm and pluvial climate, the establishment and continuation of grassland is thought to be related to fire regime and/or human impacts. Miyabuchi et al. (2010) demonstrated that charcoal particles were abundant during the last 6000 years, and the peak amount of charcoal particles was consistent with that of *Miscanthus* phytoliths. This finding suggests that the existence of *Miscanthus* grassland is related to fire events. Ogura et al. (2002) reported that soil layers younger than 9.7-9.5 ka contained abundant charcoal fragments at the northern caldera rim. Kawano et al. (2011) presented charcoal records at the northern caldera rim (Fig. 1) and demonstrated that fire events have occurred continuously near the sections at least since the early Holocene. These charcoal records suggest that fire has continually disturbed the vegetation and contributed to the establishment and/or continuation of grassland around the northern rim of the Aso caldera. Miyabuchi et al. (2011) presented macroscopic charcoal records obtained from two sections around Aso caldera, and revealed that fire events occurred more frequently at the east than the west of caldera during Holocene time. Although anemochorous *Miscanthus sinensis* pampas grass can be easily established in a bare ground, it is difficult for *Miscanthus sinensis* grassland to continue under natural condition for a long time after its establishment (Yamane, 1973). Human activity including mowing, grazing and burning is needed for the continuation of *Miscanthus* grassland (e.g., Otaki, 1997). Burning, which is the efficient method to maintain grassland vegetation, is performed every spring around Aso caldera today. The consistent presence of *Miscanthus* grassland in combination with high fire activity east of Aso caldera in the Holocene suggests that the *Miscanthus* grassland was attributed to burning as a consequence of anthropogenic activities (Miyabuchi et al., 2011).

Fossil diatom record (Hase et al., 2003) and the stratigraphy of the Senchomuta core (Miyabuchi et al., 2010; Fig. 1) state that the last intra-caldera lake existed in the center of the Asodani Valley (northern part of Aso caldera) prior to 8.9 ka. Thereafter, the center of the valley (caldera floor) changed to swampy and fluvial environments. There is a possibility that these environments limited human activities. Several Paleolithic archaeological sites (>13 ka) were discovered along the rim and outside of Aso caldera (e.g., Obata et al., 2001). Even in the Jomon period (ca. 13-2.3 ka), the archaeological sites existed at the foots of the caldera wall, and archaeological sites appeared in the center of the Asodani Valley in the Yayoi period (ca. 2.3-1.7 ka) (e.g., Kuma, 1999). Thus, human activities have been recognized outside the Aso caldera since Paleolithic time, whereas the first human colonization in the caldera happened during the last part of the Jomon period (ca. 3.3-2.8 ka). Grassland dominated by *Sasa* and *Pleioblastus* dwarf bamboos that established and continued along the caldera rim and the surrounding area over 90,000 years is related to human activity.

6. Conclusion

Phytoliths preserved in a tephra section at the northeastern rim of Aso caldera, central Kyushu, southwestern Japan, reveal the vegetation history during the last 90,000 years. The phytolith record demonstrates that grassland vegetation dominated by Gramineae consistently occurred for 90,000 years around the caldera. *Sasa* grassland dominated by *Sasa* sect. Crassinodi (cool-temperate dwarf bamboo) existed from 89 to

8 ka. The *Sasa* grassland gradually declined from 8 ka, and *Pleioblastus* (mostly *Pleioblastus* sect. Nezasa; warm-temperate dwarf bamboo) became a constituent of the grassland.

Grassland vegetation in wet climate regions including Aso caldera is believed to be established in response to soil conditions, volcanic activity, fire events and human activities. Charcoal records obtained around Aso caldera suggest that fire has continually disturbed the vegetation and contributed to the establishment and/or continuation of grassland around the caldera. Phytolith and macroscopic charcoal records obtained from east and west of Aso caldera revealed that fire events occurred more frequently to the east rather than the west of the caldera during Holocene time, and that *Miscanthus* (pampas grass) grassland occurred consistently in combination with high fire activity east of Aso caldera after 13.5 ka. Because numerous prehistoric archaeological sites have been discovered along the rim and outside the Aso caldera from ca. 30 ka, the occurrence of fire may have been caused by human activities. Therefore, the dominance of Gramineae (mainly Bambusoideae) in the grassland around Aso caldera for 90,000 years is attributed to anthropogenic activities.

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Figure captions

Fig. 1. Location of study site (solid circle) at the northeastern rim of Aso caldera, central Kyushu, SW Japan. .Phytolith and charcoal records of Namino and Kawahara sites (solid squares) are provided by Miyabuchi et al. (2011). Pollen analysis of the Uchinomaki core (solid triangle) was performed by Iwauchi and Hase (1992) and Hase et al. (2011). Kawano et al. (2011) reported phytolith and charcoal records at ASOK and ASOS sites (solid squares). The relief map was produced by Kashmir 3D using the 50-m-mesh DEM data published by the Geographical Survey Institute (Japan).

Fig. 2. Photographs of the studied tephra section. (A) Upper part of the section. (B) Lower part of the section.

Fig. 3. Phytolith diagram of tephra section at the northeastern rim of Aso caldera. Ages (calibrated ^{14}C dates) of the Kikai Akahoya (K-Ah) ash and Aira Tn (AT) are from Okuno (2002). Ages of other key tephra layers are from Miyabuchi (2009).

Fig. 4. Micro-photographs of the phytolith morphotypes recognized in this study.