Holocene history of intentional fires and grassland development on the Soni Plateau, Central Japan, reconstructed from phytolith and macroscopic charcoal records within cumulative soils, combined with paleoenvironmental data from mire sediments

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Abstract

Phytolith and macroscopic charcoal in cumulative soils on the Soni Plateau, Central Japan, were evaluated to clarify the Holocene history of intentional fires and grassland development, and to compare the findings with those derived from pollen and charcoal records in sediments taken from a nearby mire in the previous study. Prior to ~1500 cal BP, Bambusoid short-cell phytoliths and *Pleioblastus*-type and Bambusoideae-type bulliform cell phytoliths were abundant with scarce charcoal fragments (<1000 fragments/cm^3). In contrast, since ~1500 cal BP Andropogoneae-type bulliform cell phytoliths and Bilobate short-cell phytoliths were dominant with abundant charcoal fragments (>1000 fragments/cm^3). Based on correlating these records with pollen and charcoal records in mire sediments, prior to ~1500 cal BP, dwarf bamboo flourished on the forest floor under largely fire-free conditions, whereas since ~1500 cal BP, grassland dominated by Japanese pampas grass has been sustained by periodic intentional burning that has continued until the present day.

Keywords Fire history · Phytolith · Charcoal fragment · Vegetation change · Grassland · Holocene · Cumulative soils

1. Introduction

Pollen, phytoliths, and charcoal fragment in sediments (e.g., lake, bog, and swamp sediments) and in soils provide important information that enables the reconstruction of past environmental change. In particular, analyses of charcoal fragments, combined with other indicators such as pollen and phytoliths, provide clues to the relationship between fire and vegetation change in the past (e.g., Swain, 1973; MacDonald et al., 1991; Piperno and Becker, 1996; Pitkänen and Huttunen, 1999; Niemanna and Behling, 2009; Inoue et al., 2011).

Inoue et al. (2011) examined macroscopic charcoal and pollen in mire sediments from the Soni Plateau, Central Japan, where grassland is subjected to intentional burning, to clarify the history of intentional fires and grassland development. The results showed the pattern of vegetation change over a period of 7500 yrs. Until 1500 cal BP, forests of *Abies*, *Quercus*, and *Fagus* had stood under a largely fire-free environment, whereas after 1500 cal BP (dated to at least 1000 cal BP), periodic intentional fires resulted in the development and persistence of grassland dominated by Gramineae. However, the palynological record is influenced by vegetation patterns at the regional scale or larger, in addition to local vegetation; consequently, the record within mire sediments probably reflects vegetation not only on the Soni Plateau but in adjacent areas. Furthermore, although Inoue et al. (2011) assumed that Gramineae grassland has been sustained on the plateau for at least 1000 years, the genus and species of Gramineae remains unclear.

Because phytolith records generally provide information on local vegetation in closed habitats (e.g., Piperno, 1988; Stromberg, 2004) and because cumulative soils provide a continuous record of environmental change during the Holocene or since the late Pleistocene, previous studies have sought to reconstruct vegetation change in a local area by investigating the records of phytoliths within cumulative soils or paleosols (e.g., Piperno and Becker, 1996; Fredlund and Tieszen, 1997; Kariya et al., 2004). Furthermore, the morphotypes of herbaceous phytoliths can be identified to the level of the subfamily, tribe, or genus (e.g., Twiss et al., 1969; Kondo and Sase, 1986; Mulholland and Rap, 1992), whereas certain types of herbaceous pollen can be identified to the family level (e.g., Gramineae).

In this study, to clarify the history of intentional fire and grassland development on the Soni Plateau, Central Japan, in greater depth than previously attempted, we evaluated the records of phytoliths and charcoal within cumulative soils at a site located close to mire sediments where a previous study evaluated pollen and charcoal records. The phytolith record was assessed because it is likely to provide useful information on grassland development upon the plateau. Here, we compare the paleoenvironmental records derived from cumulative soils and from mire sediments, showing that a combination of indicators (i.e., pollen, phytoliths, and charcoal) in a distinct type of deposit (lake sediments and cumulative soils) in a local area may enable an in-depth reconstruction of the paleoenvironment.

2. Study Site

The Soni Plateau of Central Japan is a small bowl-shaped depression of 600–700 m in diameter at an altitude of 700–850 m (Fig. 1). Okame-ike mire (size, 2.4 ha) is located in the bottom of the depression. According to meteorological data recorded at Oouda Climatological Station (34°29′01″N, 135°56′01″E; elevation, 349 m; Japan Meteorological Agency, 2001), located ~12 km from Soni Plateau, the annual mean temperature (1979–2000) in the region is 12.7°C. The annual precipitation (1979–2000) is 1728 mm at Soni Climatological Station (34°31′01″N, 136°09′07″E; elevation, 610 m; Japan Meteorological Agency, 2001), which is located on the plateau.

The Soni Plateau is situated in the cool temperate zone. The climax vegetation in this area is cool-temperate deciduous broad-leaved forest, but most of the present vegetation consists of plantations of *Cryptomeria japonica* (Japanese cedar) and *Chamaecyparis obtusa* (Japanese cypress) or secondary forest of *Pinus densiflora* (Japanese red pine) and *Quercus serrate* (a kind of deciduous oak), except for the area of the depression (Inoue et al., 2011). Almost the entire bowl-shaped depression (ca. 38 ha) on the plateau is covered with grassland, dominated by *Miscanthus sinensis* (Japanese pampas grass) and locally by *Sasa nipponica* (a kind of dwarf bamboo). The grassland is burnt intentionally every year to enhance its survival. Based on Editorial Committee of the History of Soni Village (1972), the grassland is likely to have been burnt intentionally for at least 100 years. Okame-ike mire is covered with floating island consisting of *Phragmites australis* (reed grass) roots.

3. Materials and Methods

3.1. Materials

Soils of the Soni Plateau are characterized by a thick (up to 70 cm) black high-humic A-horizon that is loosely compact (Fig. 2; a detailed description is provided below). The soils also include a large amount of volcanic glass. These characteristics led us to classify the soils as Andisols (e.g., Japanese Society of Pedology, 2003, 2007), as also indicated on a soil map of Nara Prefecture (1986). Andisols are generally considered to develop upward cumulatively and are treated as a type of cumulative soil (e.g., Hosono and Sase, 1997; Torii et al., 1998; Japanese Society of Pedrogy, 2007; Inoue et al., 2011), which is consistent with a downward increase in the radiocarbon age of humin in the soils (see Section 4.1). Therefore, in this study we treated the soils on the plateau as cumulative soils. Ongoing analyses of the chemical properties of the soil will enable a formal assignment of the soil type.

We collected soil samples from soil profiles at two sites (Sites 1 and 2, Fig. 1). In the soil profile at Site 1 (34°31′10″N, 136°09′45″E), A horizon occurs at 0–70 cm depth and B horizon at 70–98 cm depth. The A horizon is divided into six horizons: 0–14 cm depth (soil color is olive black; 5Y 2/2, grain size is silt, compactness is very loose, and many roots are included), 14–25 cm depth (black; 2.5Y 2/1, clay, loose, and few roots), 25–32 cm depth (brownish black; 2.5Y 3/1-2/1, clay, soft, and few roots), 32–40 cm depth (brown; 10YR 4/3-4/4, clay, soft, and few roots), 40–58 cm depth (dark brown; 10YR 3/3, silty clay, loose, and very few roots), and 58–70 cm depth (olive brown; 2.5Y 3/3-4/3, silty clay, loose, and very few roots). In the B horizon (70–98 cm depth), the soil color is bright yellowish brown (2.5Y 6/6), grain size is silty clay with fine sand, compactness is soft, and there are no roots. In the soil profile at Site 2 (34°31′06″N, 136°09′42″E; Fig. 2), A horizon occurs at 0–70 cm depth and B horizon at 70–90 cm depth. The A horizon at this site is divided into four horizons: 0–12 cm depth (soil color is olive black; 5Y 2/2, grain size is silt, compactness is very loose, and many roots are included), 12–22 cm depth (brownish black; 2.5Y 3/1-3/2, clay, soft, and few roots), 22–30 cm depth (dull yellowish brown; 10YR 4/3-5/3, silty clay, soft, and few roots), and 40–70 cm depth (brownish gray; 10YR 4/1, clay-silt, loose, and very few roots). In the B horizon (70–90 cm depth), soil color is bright yellowish brown (2.5Y 7/6-7/8), grain size is silty clay with gravel, compactness is soft, and there are no roots. This description follows the methodology proposed by the Japanese Society of Pedology (1997).

From the soil profile at each site, we collected soil samples (~10 cm thick) consisting of a single soil horizon. The samples for analyses of phytoliths and macroscopic charcoal were collected from 0–70 cm depth at Site 1 and from 0–78 cm depth at Site 2.

Humin and humic acid samples were extracted from soils by chemical treatment and were dated by AMS radiocarbon methods (Table 1). Radiocarbon dates were calibrated to calendar years using the program Calib Rev 6.0 (http://intcal.qub.ac.uk/) and the IntCal09 calibration dataset (Reimer et al., 2009).

3.2. Phytolith analysis

Phytoliths were extracted from the soil samples (1 cm^3) following the successive procedures proposed by Kawano et al. (2007): oxidation of organic matter using 30% H_2O_2; removal of calcium carbonate using 3N-HCl; removal of clay according to Stoke’s law. Prior to these treatments, a known number of glass beads (100,000 grains) of 45 μm in diameter was added to each sample to estimate the phytolith concentration (Fujiwara, 1976). Phytoliths were mounted on microscope slides with Eukitt mounting medium. Microscopic observations were performed at 400× magnification, and phytoliths were counted (including 300 glass beads) from each sample. Gramineae phytoliths were identified following Sasaki et al. (2004) and Kawano et al. (2011) (Fig. 3). The percentage values for each phytolith type were calculated based on the total phytolith counts, including unidentified types.

3. 3. Charcoal analysis

To extract charcoal fragments from the soil samples (0.5 cm^3), 10% KOH was first added to each sample for 24 hrs. The samples were then gently washed through a sieve (mesh size: 125 μm). To each residue (>125 μm) was added 7.5% HCL for 24 hrs to disperse particles.

The samples were then gently washed through a series of nested sieves (mesh sizes: 125 μm, 250 μm, and 1 mm) to yield the 125–250 μm, 250 μm–1 mm, and >1 mm fractions. Charcoal fragments, which were recognized as black, opaque, angular fragments showing cellular features, were identified and counted under a stereomicroscope. From these data, charcoal abundances (particles/cm^3) were calculated.

4. Results

4.1. Age data

Table 1 lists the ^{14}C age data and ages in calibrated calendar years (2σ error) of humic acid and humin in each soil sample, along with the laboratory code. The calendar ages range from 0 to ~9000 cal BP. Figure 4 shows the mean values of the maximum and minimum ages (cal BP) within 2σ error for each sample.

4.2. Phytoliths

Figure 5 shows the frequency of phytolith occurrence at Sites 1 and 2. These diagrams are divided into two local phytolith zones (Son 1-1 and 1-2 at Site 1, and Son 2-1 and 2-2 at Site 2) based on marked changes in the morphotype of the phytoliths. Similar trends in phytolith frequency were found at both sites. In zones Son 1-1 and Son 2-1, Bambusoid short-cell phytoliths were dominant (25.6–37.8% in Son 1-1; 28.3–42.1% in Son 2-1), and the following components are abundant relative to zones Son 1-2 and Son 2-2: *Pleioblastus*-type bulliform cell phytoliths (4.2–5.6% in Son 1-1; 4.7–8.5% in Son 2-1), Bambusoideae-type bulliform cell phytoliths (up to 2.6% in Son 1-1; up to 5.7% in Son 2-1), and Jigsaw-puzzle-shaped phytoliths (up to 2.8% in Son 1-1; up to 2.0% in Son 2-1).

Zone Son 1-2 and Son 2-2 were dominated by Bilobate short-cell phytoliths (24.9–34.0% in Son 1-2; 30.7–31.8% in Son 2-2) and Andropogoneae bulliform cell phytoliths (3.1–4.3% in Son 1-2; 4.8–5.1% in Son 2-2). Saddle and Rondel short-cell phytoliths, and *Sasa*-type and *Phragmites*-type bulliform cell phytoliths show little variation in their percentage values among the samples (Saddle: 12.8–16.0% in Son 1-2 and 11.%–19.4% in Son 2-2; Rondel: 1.5–4.4% in Son 1-2 and 2.7–5.8% in Son 2-2; *Sasa*-type: 0.8–5.4% in Son 1-2 and 2.7–11.2% in Son 2-2; *Phragmites*-type: 0.6–3.4% in Son 1-2 and 0–2.4% in Son 2-2). Elongate phytoliths show an upward decrease in abundance in Son 1-1 (from 32.2 to 10.3%) and in Son 2-1 (from 31.5 to 8.9%), but show little change in Son 1-2 (11.3–12.0%) and in Son 2-2 (10.4–11.4%). The phytolith concentrations show a gradual upward increase at both sites (from 34,000 to 516,000 grains/cm^3 at Site 1, and from 32,000 to 357,000 grains/cm^3 at Site 2).

4.2. Macroscopic charcoal

Given that there were very few charcoal fragments having >1 mm in size, fragments were counted in the 125–250 μm and 250 μm–1 mm fractions. We treated charcoal of 125 μm–1 mm in size as macroscopic charcoal. In the lower part of the soil at each site (below 25 cm depth at Site 1 and below 22 cm depth at Site 2), charcoal concentrations were low and show little change with depth (205–785 grains/cm^3 at Site 1 and 95–443 grains/cm^3

at Site 2). In the upper part of the soil at each site (above 25 cm depth at Site 1 and above 22 cm depth at Site 2), the charcoal concentrations were high and show a gradual upward increase (up to 4736 grains/cm^3 at Site 1 and 2629 grains/cm^3 at Site 2) (Fig. 5).

5. Discussion

5.1 Chronology of cumulative soils

Based on the radiocarbon dating on both humin and humic acid samples from four soil horizons (14–25 cm and 32–40 cm depth at Site 1, 12–22 cm and 30–40 cm depth at Site 2), the ^{14}C and calendar year ages of humin samples were consistently older than the ages of humic acid samples. Because humin compounds are larger than humic acid, the latter tends to move downward within the soil horizons, whereas the former shows little movement in soils. This explains the difference in ages obtained for humin and humic acid samples in the same horizons. The ages obtained for humin samples should provide a more reliable estimate of the age of sedimentation of the soil, even though, in dating cumulative soils, humic acid is generally used for radiocarbon dating. The ages obtained for humic acid samples within the B horizon are similar to the age of the lowest A horizon, indicating that most of the humic acid in the B horizon was added after the formation of the mineral fragments within the B horizon. Consequently, we calculated an age–depth curve based mainly on age data for humin samples (Fig. 4), indicating that A horizon in soils has been deposited since 6500 cal BP at Site 1 and 8500 cal BP at Site 2. The age–depth curves indicate sedimentation rates of 0.03–0.14 mm/yr at Site 1 and 0.02–0.09 mm/yr at Site 2 (Fig. 4). Based on the age–depth curves, the boundary age between zones Son 1-1 and Son 1-2 would be estimated at 1200 cal BP, and that between Son 2-1 and Son 2-2 was would be estimated at 1700 cal BP. These suggest that change in the phytolith assemblage occurred approximately 1500 cal BP on the Soni Plateau.

5.2 Vegetation history reconstructed from the phytolith records

Based on the change in phytolith records and the results of radiocarbon dating, the history of vegetation on the plateau is reconstructed as follows.

5.2.1 The period 8500 to 1500 cal BP, corresponding to Son 1-1 and 2-1

The phytolith records for the period 8500 to 1500 cal BP are characterized by the predominance of Bambusoid short-cell phytoliths, with Bambusoideae-type, *Sasa*-type and *Pleioblastus*-type bulliform cell phytoliths. Saddle, Rondel, and Elongate short-cell phytoliths, which are common in dwarf bamboo and other Gramineae species, were relatively abundant. Because Bambusoid short-cell phytoliths and Bambusoideae-type bulliform cell phytoliths are derived from *Sasa* and *Pleioblastus*, the dominance of these genera implies that dwarf bamboo flourished as grassland or forest floor vegetation during this period. *Phragmites* bulliform cell phytoliths, which were recognized in most samples, are derived from *Phragmites* (probably *Phragmites* *australis* (reed grass)). This species probably grew in the Okame-ike mire located close to the sampling points, and this mire has existed at its current site since at least 8500 cal BP, which is consistent with the fact that the mire has sediments deposited since at least 7500 cal BP (Inoue et al., 2011).

5.2.2 The period ~1500 cal BP to present, corresponding to Son 1-2 and 2-2

Biobate short-cell phytoliths were the most dominant short-cell phytolith morphotype in the soil since ~1500 cal BP. Furthermore, Andropogoneae-type bulliform cell phytoliths were more abundant than other bulliform cell phytolith morphotypes. These phytolith types are produced by Japanese pampas grass (*Miscanthus sinensis*) (e.g., Kondo, 2010). Today, the plateau is covered with grassland, dominated by Japanese pampas grass with isolated patches of dwarf bamboo (*Sasa nipponica*). The consistency of the phytolith assemblages since ~1500 cal BP in Son 1-2 and Son 2-2 suggests that grassland dominated by Japanese pampas grass has existed on the plateau for the last 1500 years.

5.3 Fire history reconstructed from charcoal records

Abundant macroscopic (125 μm-1 mm in size) charcoal fragments and high charcoal fluxes were found in zone Son 1-2 and 2-2 (Figs. 5 and 6). Charcoal fluxes were determined by multiplying concentrations by sedimentation rate in Fig.4. Because such fragments are not transported far from their source before settling (e.g., Blackford, 2000; Whitlock and Larsen, 2001), those within cumulative soils examined in the present study are likely to have been derived from fires on site or close to the sampling points. Temporal changes in charcoal concentrations and fluxes do not necessarily represent a change in the fire regime; however, the marked difference in charcoal concentration at ~1500 cal BP presumably reflects a major change in the frequency of fires on the Soni Plateau. Given that present-day grassland on the plateau is sustained by annual intentional burning, the abundant charcoal found in the uppermost soils is considered to reflect periodic (almost annual) burning in modern days.

In Japan, it is difficult to maintain grassland without strong disturbances such as fire (e.g., Iwaki, 1971; Shimada et al., 1973), because the high precipitation in Japan generally results in the growth of forests. The dormant bud of Japanese pampas grass exists underground, meaning that fire disturbs only tree buds (not grass buds); consequently, periodic fires prevent the transition to forest and maintain a grassland environment (e.g., Shimada et al., 1973; Iwanami, 1988). Intentional fire is one of the major methods of grassland maintenance in Japan (Tsujino, 2011). Accordingly, the high proportions of Biobate short-cell phytoliths and Andropogoneae-type bulliform cell phytoliths (produced by Japanese pampas grass) in Son 1-2 and Son 2-2, in combination with large amounts of charcoal fragments, imply that the grassland has been maintained by intentional fires for the last ~1500 years. Based on the records of phytoliths and macroscopic charcoal within the analyzed soils, we conclude that prior to ~1500 cal BP, dwarf bamboo flourished as grassland or on the forest floor, whereas after ~1500 cal BP, grassland dominated by Japanese pampas grass was sustained by periodic intentional fires on the plateau.

5.4 Comparison of the paleoenvironmental records in cumulative soil and in mire sediments

Our phytolith and charcoal records within cumulative soils reveal that dwarf bamboo flourished prior to ~1500 cal BP, whereas after ~1500 cal BP, grassland composed mainly of Japanese pampas grass has been sustained by periodic intentional fires on the plateau. Because the pollen record within mire sediments (Inoue et al., 2011) shows that the plateau was dominated by forest prior to ~1500 cal BP (Fig. 6), the dwarf bamboo probably flourished on the forest floor. This interpretation is consistent with the fact that the soil deposited prior to ~1500 cal BP contains up to 2.8% of tree-type phytoliths. The frequent fires since ~1500 cal BP are demonstrated by the abundance of charcoal in both the cumulative soils and mire sediments. The large amount of Gramineae pollen in mire sediments deposited since ~1500 cal BP should be derived mainly from Japanese pampas grass, which flourished on the plateau during this period, as indicated by the phytolith record. Based on the results of Inoue et al. (2011) and our study, we conclude that prior to ~1500 cal BP, forest having dwarf bamboo flourishing on the forest floor had developed under largely fire-free conditions. Since ~1500 cal BP, however, periodic intentional fires have prevented the development of forest on the plateau, resulting in the dominance of Japanese pampas grass.

The charcoal fluxes in cumulative soil are similar to those in mire sediments between 7000 cal BP and over 1000 cal BP: 1–4 fragments/cm^2 yr in cumulative soils and 0–6 fragments/cm^2 yr in mire sediments; since over 1000 cal BP: 20–60 fragments/cm^2/yr in cumulative soils and 10–600 fragments/cm^2/yr (mainly, 10–100 fragments/cm^2 yr) in mire sediments. These findings indicate that the charcoal influx was not dependent on deposition type. In addition, in both cumulative soil and mire sediments, the charcoal fluxes since over 1000 cal BP are about 10–15 times higher for those between 7000 cal BP and over 1000 cal BP. Inoue et al. (2011) reported abundant charcoal (>100 fragments/cm^3) and high charcoal fluxes (>10 fragments/cm^2 yr) in mire sediments deposited at ~7000 cal BP, indicating frequent fires over a short period at this time. In this study, however, this spike in charcoal abundance was not found in cumulative soil, possibly because fires over such a short period produce insufficient charcoal fragments to be preserved in soil.

5.5 Background of grass developments since ~1500 years ago

In Japan, grass such as Japanese pampas has traditionally been used as a building material (e.g., thatch for roofing) and as a fertilizer (e.g., Iwaki, 1971; Tsujino, 2011). In particular, grass has been used as a fertilizer for rice and other crops in Japan for more than 1,500 yrs (Mizumoto, 2003; Tsujino, 2011). It is assumed that a large grassland is needed to ensure a harvest of them. Furthermore, until ~100 years ago on and around the Soni Plateau, each commune had an area of grassland from which to harvest grass for use as fertilizer, and the grassland areas were subjected to intentional fire each year (Editorial Committee of the History of Soni Village, 1972). Because the Kinki District was historically the political and commercial center of Japan and because farmers were given land rights since 8th century, manor developed in the region. Therefore, it is assumed that the development of grassland via intentional burning since ~1500 cal BP was linked to increased fertilizer demand due to the expansion of the area planted with crops at this time.

6. Conclusion

We examined phytoliths and macroscopic charcoal fragments in cumulative soils deposited since 8500 cal BP on the Soni Plateau, Central Japan. Based on the present results and those reported in a previous study based on the pollen and charcoal records within nearby mire sediments (Inoue et al., 2011), indicate that the history of intentional fires and vegetation change is consistent between the records derived from mire sediments and from cumulative soils. Based on these results, we arrived at the following conclusions. The change from dwarf bamboo to Japanese pampas grass at ~1500 cal BP, as inferred from the phytolith record in cumulative soils, coincided with a transition from forest to grassland, as inferred from the pollen record in mire sediments. The abundance of charcoal in both the cumulative soils and mire sediments deposited since ~1500 cal BP indicates intentional fires (probably, periodic burning). Therefore, prior to ~1500 cal BP, dwarf bamboo flourished on the forest floor under a largely fire-free condition, whereas since ~1500 cal BP, grassland dominated by Japanese pampas grass has been sustained by periodic burning.

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References

Blackford, J. 2000: Palaeoclimatic records from peat bogs. *Trends in Ecology & Evolution* 15, 193-198.

Editorial Committee of the History of Sone Village 1972: *History of Soni Village (Soni Sonshi)*. Soni: Soni Village (in Japanese).

Fredlund, G.G. and Tieszen, L.T. 1997: Phytolith and carbon istope evidence for late Quaternary vegetation and climate change in the southern Black Hills, South Dakota. *Quaternary Research* 47, 206-217.

Fujiwara, H. 1976 Fundamental studies of plant opal analysis-On the silica bodies of motor cell of rice plants and their near relatives, and the method of quantitative analysis. *Archaeology and Natural Science (Biannual Journal of the Japanese Society for Scientific Studies on Cultural Property)*, 9, 15-29 (in Japanese).

Hosono, M and Sase, T. 1997 Preliminary discussion on the genesis of Kuroboku Soils. *Daishiki*, 29, 1-9 (in Japanese).

Inoue, J., Nishimura, R. and Takahara, H. 2011**:** A 7500-year history of intentional fires and changing vegetation on the Soni Plateau, Central Japan, reconstructed from macroscopic charcoal and pollen records within mire sediment. *Quaternary International* doi:10.1016/j.quaint.2010.08.012.

Inoue, Y., Hiradate, S., Sase, T., Hosono, M., Morita, S. and Matsuzaki, H. 2011: Using ^{14}C dating of stable humin fractions to assess upbuilding pedogenesis of a buried Holocene humic soil horizon, Towada volcano, Japan. *Geoderma*, doi: 10.1016/j.geoderma.2011.08.011

Iwaki, H. 1971: *Ecology of grassland (Sougen no Seitai).* Tokyo: Kyoritsu Shuppan (in japanese).

Iwanami, Y. 1988: Intentional fire in grassland (Sougen no hiire). In Yano, N., editor,*Vegetation in japan (Nihon no Shokusei)*. Tokyo: Tokai University Press, 117-124 (in japanese).

Japan Meteorolofical Agency 2001. *Normal value of Automated Meteorological Data Acquisition System (1971-2000).* Tokyo : Japan Meteorological Business Support Center. (in Japanese)

Japanese Society of Pedology 1997. *Handbook of soil survey (Dojou chousa handbook).* Tokyo: Hakuyuusha (in Japanese).

Japanese Society of Pedology 2003. *Unified soil classification systems of Japan- 2nd approximation (2002)-.* Tokyo: Hakuyuusha (in Japanese).

Japanese Society of Pedology 2007. *We love and preserve soil (Dojou wo aisi, dojou wo mamoru).* Tokyo: Hakuyuusha (in Japanese).

Kariya, Y., Sugiyama, S. and *Sasa*ki, A. 2004: Changes in opal phytolith concentrations of Bambusoideae morphotypes in Holocene peat soils from the pseudoalpine zone on Mount Tairappyo, central Japan. *The Quaternary Research* 43, 129-137.

Kawano, T., Sasaki, N., Hayashi, T. and Takahara, H. 2011: Grassland and fire history since the late-glacial in northern part of Aso Caldera, central Kyusyu, Japan, inferred from phytolith and charcoal records. *Quaternary International* doi:10.1016/j.quaint.2010.12.008.

Kawano, T., Takahara, H., Nomura, T., Shibata, H., Uemura, S., Sasaki, N. and Yoshioka, T. 2007: Holocene Phytolith Record at *Picea glehnii* Stands on the Dorokawa Mire in Northern Hokkaido, Japan. *The Quaternary Research* 46, 413-426.

Kondo, R. 2010: *Illustrated catalog of phytolith (Plant Opal Zuhu).* Sapporo: Hokkaido University Press. (in Japanese)

Kondo, R. and Sase, T. 1986: Opal phytolith, their Nature and Application. *The Quaternary Research* 25, 31-63 (in Japanese).

MacDonald, G. M., Larsen, C. P. S. , Szeicz, J. M. and Moser, K. A. 1991**:** The reconstruction of boreal forest fire history from lake sediments: a comparison of charcoal, pollen, sedimentological, and geochemical indices. *Quaternary Science Review* 10, 53–71.

Mizumoto, K. 2003: *Modern ages told by grass mound (Kusayama no kataru kinsei).* Tokyo; Yamakawa Shuppansha Ltd. (in Japanese).

Mulholland, S. C. and Rapp, G. Jr. 1992: Amorphological classification of grass silica-bodies. “Phytolith systematicks: Emerging Issues” (Rapp, G. Jr. and Mulholland, S. C., eds.), 65-89. New York : Plenum.

Niemann, H. and Behling, H. 2009: Late Holocene environmental change and human impact inferred from three soil monoliths and the Laguna Zurita multi-proxi record in the southeastern Ecuadorian Andes. *Vegetation History and Archaeobotany* 19, 307-316.

Pitkänen, A. and Huttunen, P. 1999**:** A 1300-year forest-fire history at a site in eastern Finland based on charcoal and pollen records in laminated lake sediment. *The Holocene* 9, 311–320.

Piperno, R. D. 1988: Phytolyth Analysis: An Archaeolofical and Geological Perspective. *Academic Press.*

Piperno, R. D. and Becker, P. 1996: Vegetational History of a Site in the Central Amazon Basin Derived from Phytolith and Charcoal Records from Natural Soils. *Quaternary Research* 45, 202-209.

Reimer, P.J., Baillie, M.G.L., Bard, E., Bayliss, A., Beck, J.W., Blackwell, P.G., Bronk, Ramsey, C., Buck, C.E., Burr, G.S., Edwards, R.L., Friedrich, M., Grootes, P.M., Guilderson, T.P., Hajdas, I., Heaton, T.J., Hogg, A.G., Hughen, K.A., Kaiser, K.F., Kromer, B., McCormac, F.G., Manning, S.W., Reimer, R.W., Richards, D.A., Southon, J.R., Talamo, S., Turney, C.S.M., van der Plicht, J., Weyhenmeyer, C.E. 2009. IntCal09 and Marine09 radiocarbon age calibration curves, 0–50,000 years cal BP. *Radiocarbon* 51, 1111–1150.

Sasaki, N., Kawano, T., Takahara, H. and Sugita, S. 2004: Phytolith evidence for the700-year history of a dwarf-bamboo community in the sub-alpine zone of Mt.Kamegamori, shikoku Island, Japan. *Japanese Association of Historical Botany* 13, 35-40.

Shimada, Y., Kawanabe, S., Kayama, R. and Itou, S. 1973: *Ecology of grassland (Kusachi no Seitaigaku).* Tokyo: Tsukuji shokan (in japanese).

StrÖmberg, C. A.E. 2004: Using phytolith assemblages to reconstruct the origin and spread of grass-dominated habitats in the great plains of North America during the late Eocene to early Miocene. *Palaeogeography, Palaeoclimatology, Palaeoecology* 207, 239–275.

Swain, A.M. 1973: A history of fire and vegetation in northeastern Minnesota as recorded in lake sediments. *Quaternary Research* 3, 383-390.

Torii, A., Kaneko, S. and Araki, M. 1998: Genesis of Ando-soils of three sites in the Kinki District, Japan, with special reference to parent materials and past vegetation. *The Quaternary Research*, 37, 13-24 (in Japanese).

Tsujino, A. 2011: History of relationship between human and nature in Japanese Islands. In Yumoto, T., editor, *What is environmental history? (Kankyoushi toha nanika).* Tokyo: Bun-ichiSogo Shuppan, 33-51 (in Japanese).

Twiss, P. C., Suess, E. and Smith, R. M. 1969: Morphological classifica- tion of grass phytoliths. Soil Science Society of America 33, 109–115.

Whitlock, C. and Larsen, C. 2001: Charcoal as a fire proxy. “Tracking Environmental Change using Lake Sediments, vol. 3. Terrestrial, Algal, and Siliceous Indicators” (Smol, J. P., Birks, H. J. B., & Last, W. M., eds.) *Kluwer Academic Publisher, Dordecht.* 75-97.

Figure captions

Fig. 1 Topographic map showing the location of the sampling sites. The map is part of the 1:5000 topographical map of Soni Village, as issued by the Soni Village Office. Contour interval is 50 m.

Fig. 2 Photograph of a soil profile on the Soni Plateau (Site 2). The A horizon occurs at depths of 0–70 cm and the B horizon occurs at depths of 70–90 cm.

Fig. 3 Phytolith morphotypes extracted from cumulative soils collected on Soni Plateau. (a), (b) Bambusoid (short cell). (c) Saddle. (d) Cross. (e) Bilobate. (f) *Phragmites* type (Bulliform cell). (g) *Sasa* type. (h) Andropogoneae type. (i) Rondel (short cell). (j) Complex-bilobate. (k) *Pleioblastus* type (Bulliform cell). (l) Jigsaw puzzle shaped (tree type). (m) Point shaped (other type). (n) Elongate (o) Pooideae (short cell).

Fig. 4 Age–depth curves for humin and humic acid samples from the Soni Plateau. Circles and squares indicate the calibrated calendar ages of humin and humic acid samples, respectively. The depth value of each point is the average of the uppermost and lowermost depth of each sample. The age value of each point is the average of the maximum and minimum of each age (Cal BP year) within 2σ error. Table 1 lists the range of depths and ages (Cal BP, 2σ error) for each sample. At Site 1, the A horizon occurs at 0–70 cm depth and the B horizon at 70–98 cm depth; at Site 2, the A horizon occurs at 0–70 cm depth and the B horizon at 70–90 cm depth (dotted line).

Fig. 5 Percentage occurrence of phytoliths and number density of macroscopic charcoal fragments in cumulative soils at Sites 1 and 2 on the Soni Plateau. Non-parenthetic ages are presented in calendar years, calibrated from the ^{14}C age of humin samples in the soil. Parenthetic ages are presented in calendar years, calibrated from the ^{14}C age of humic acid samples.

Fig. 6 Comparison of the phytolith and charcoal records within cumulative soils of the present study and the pollen and charcoal records within mire sediments (Inoue et al., 2011).

Table 1. Radiocarbon ages of cumulative soils on the Soni Plateau. ^{14}C dates were calibrated to calendar years using the program Calib Rev 6.0 (http://intcal.qub.ac.uk/) and the IntCal09 calibration dataset.

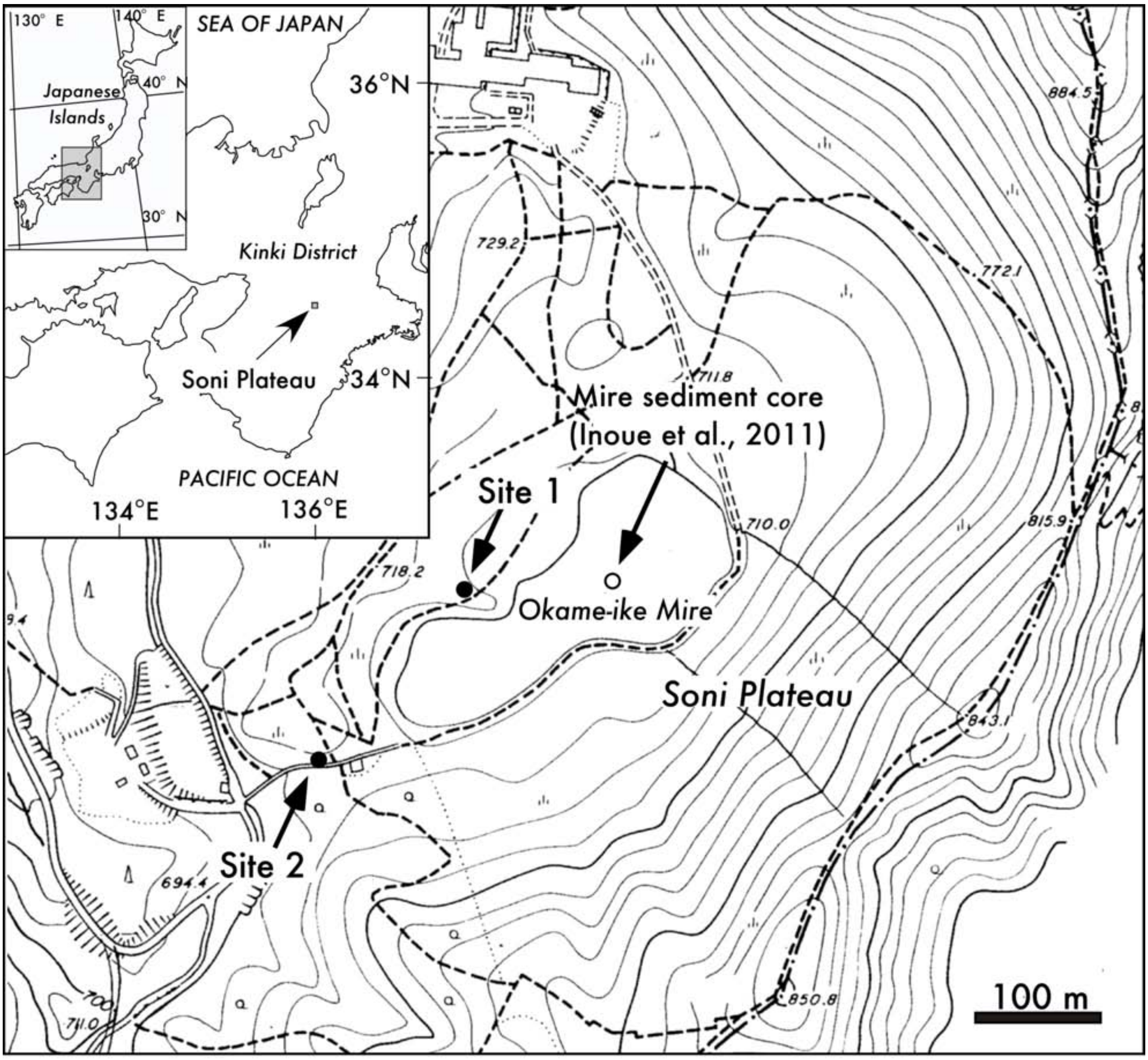
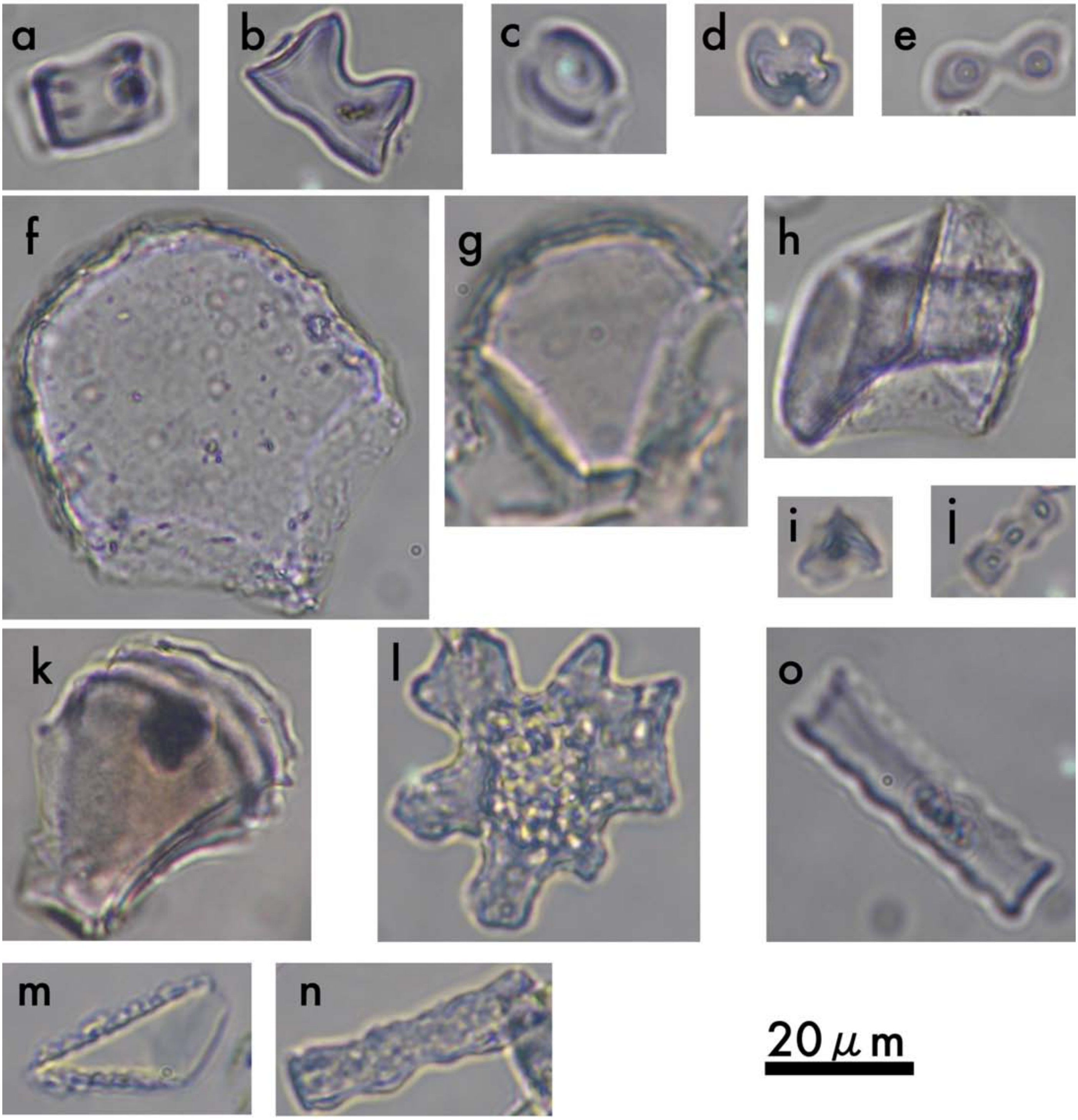


Fig. 1 (Okunaka et al.)

Fig. 2 (Okunaka et al.)



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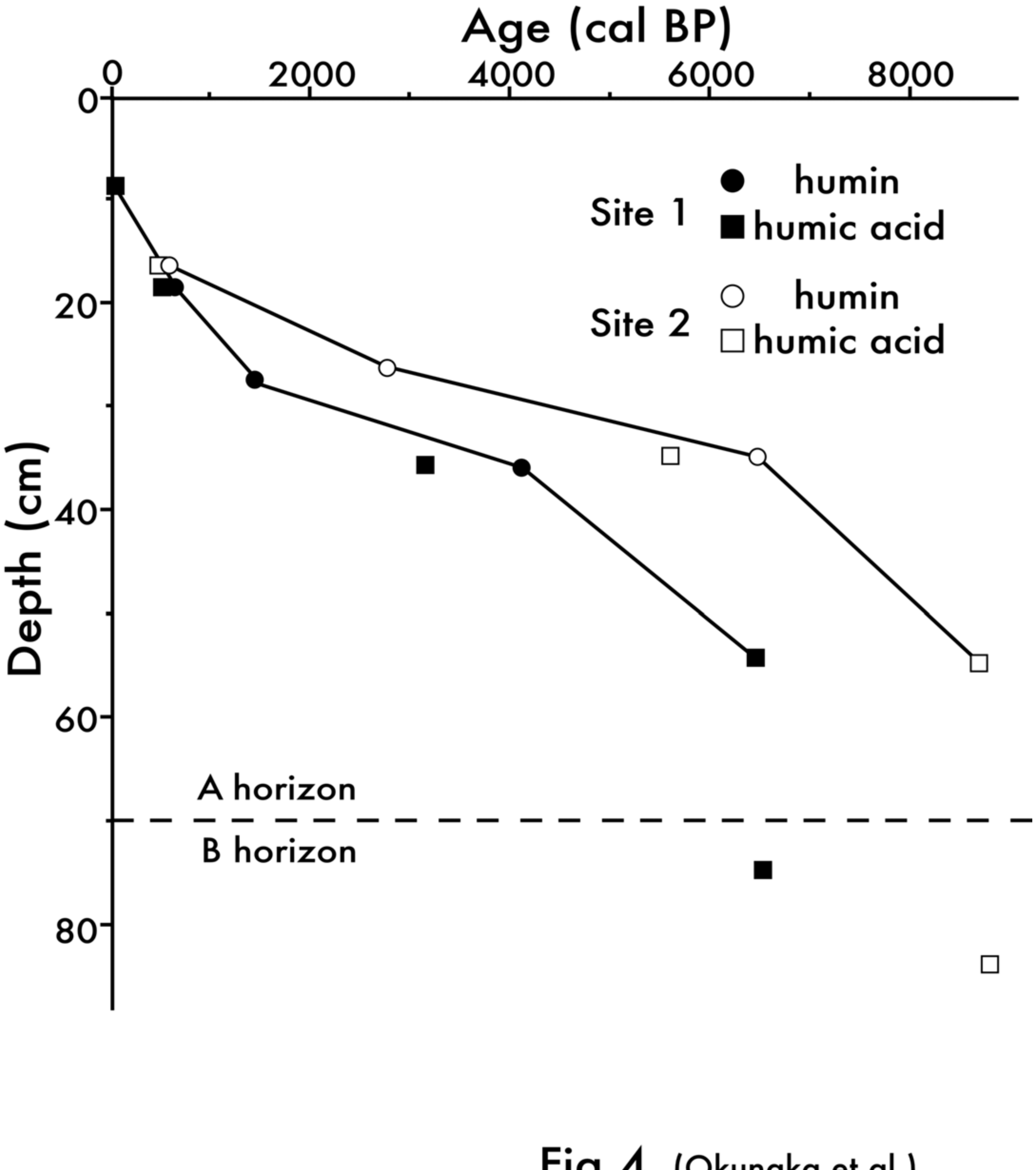

Fig.4 (Okunaka et al.)

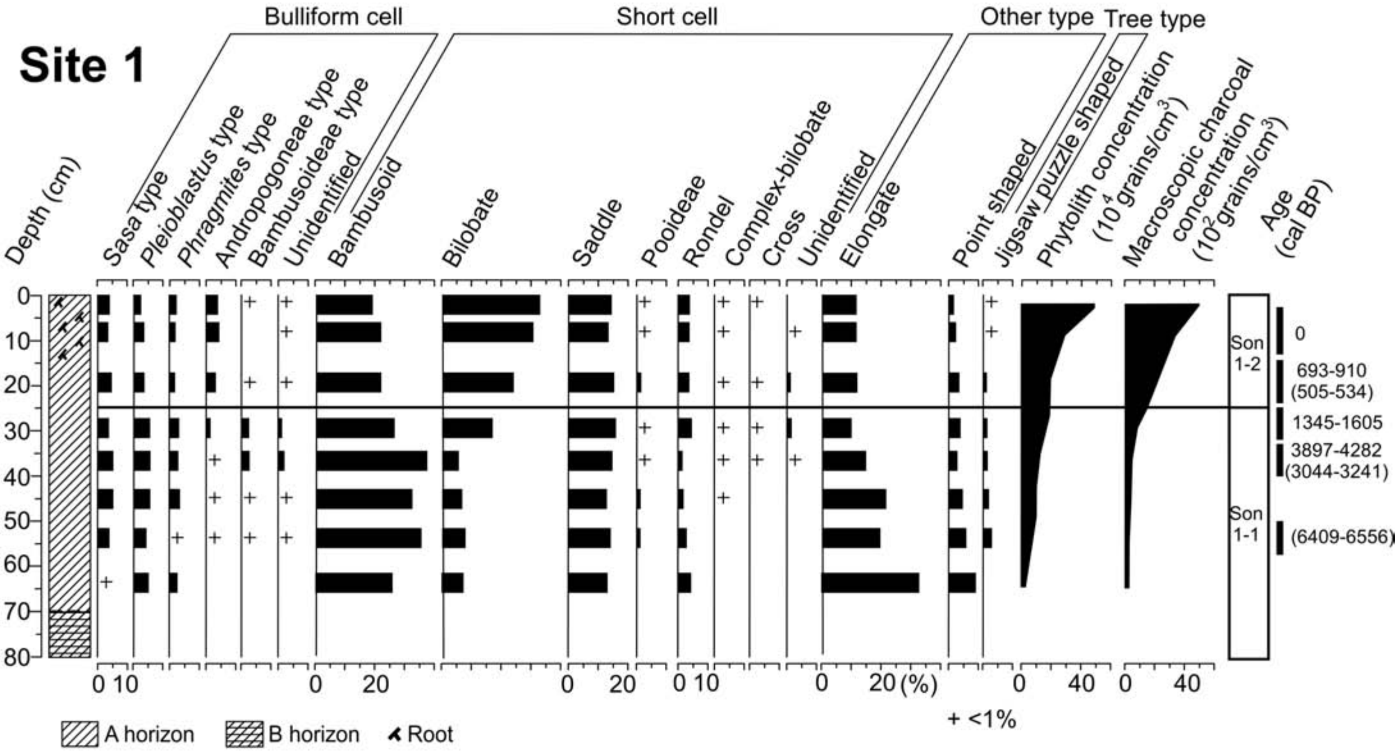

Fig.3-1 (Okunaka et al.)

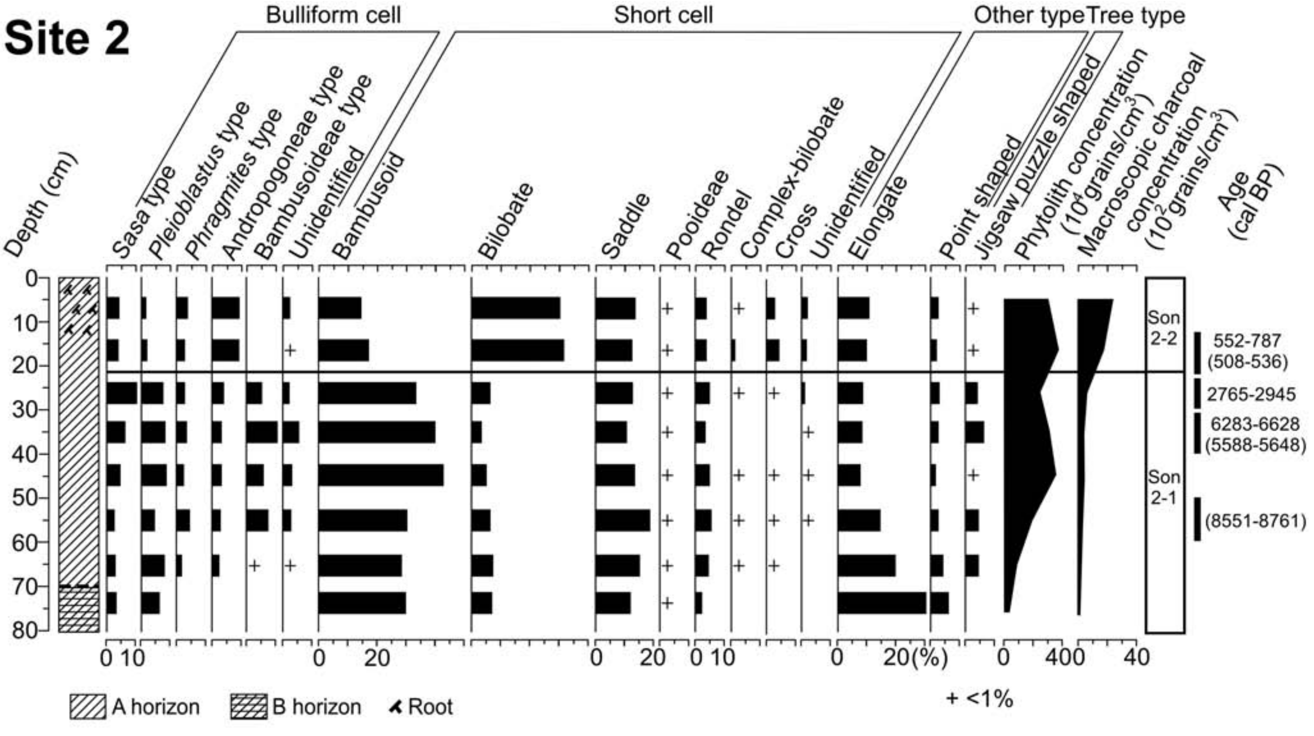

Fig.3-2 (Okunaka et al.)

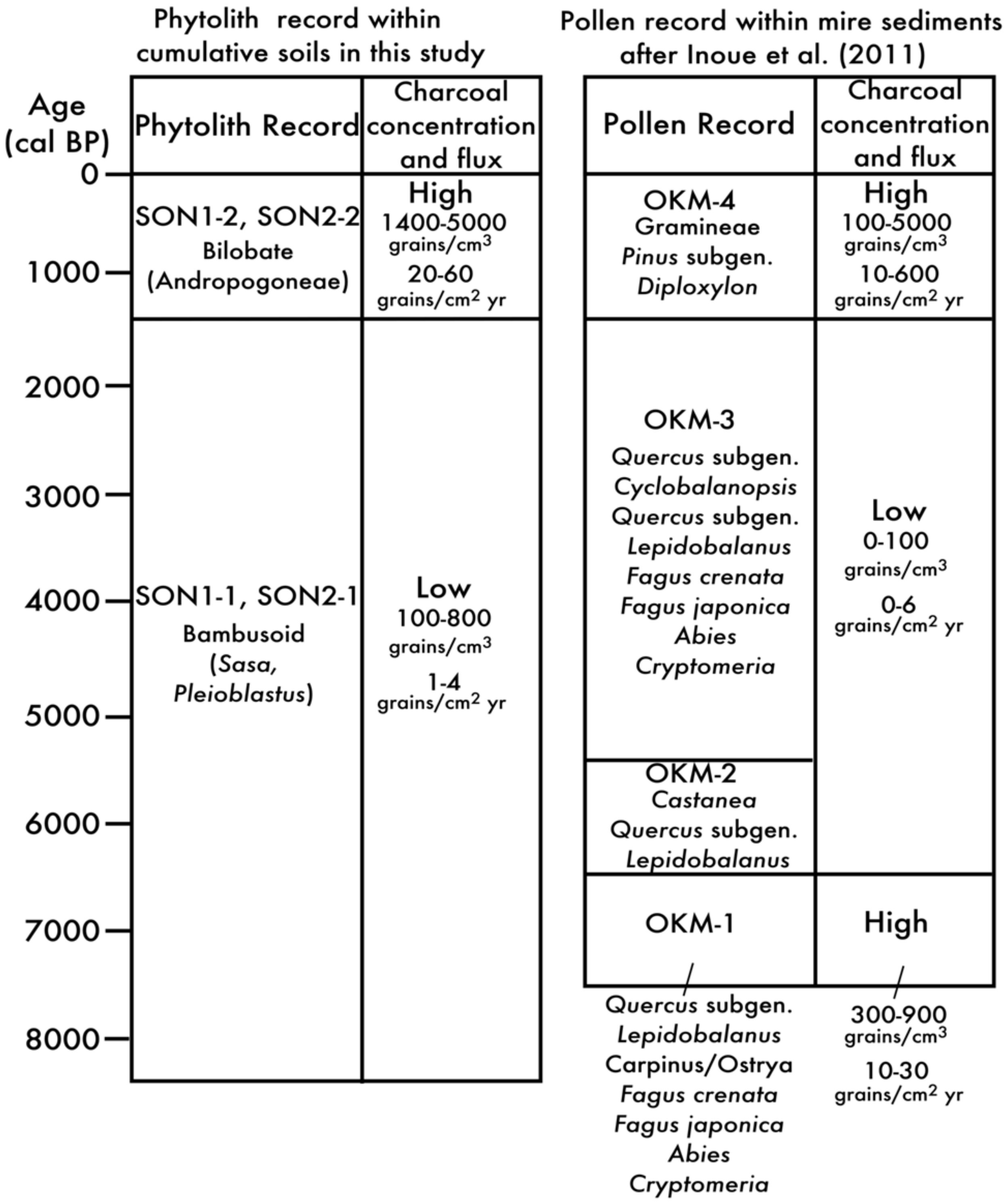

Fig.5 (Okunaka et al.)