INITIATION OF ALPINE GRASSLAND AND WET MEADOW SOILS ON SNOWY HIGH MOUNTAINS IN CENTRAL JAPAN: A TEPHROCHRONOLOGICAL ESTIMATE

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Abstract Initiation ages of peaty and mucky soils on snowy high mountains in central and northern Honshu, Japan, were estimated by tephrochronology and radiocarbon dating. Three typical snowy mountains, Chokai, Gassan and Tairappyo, were selected. To identify tephras in such soils, their stratigraphy and lithofacies were investigated. Petrographic characteristics such as mineral composition and refractive indices of volcanic glass shards and phenocrysts of each tephra were also examined. Principal time-marker tephras identified were as follows: the *Asama-Kusatsu* or the *Asama-YP* (*ca.* 16000 cal yr BP), the *Kikai-Akahoya* (*ca.* 7200 cal yr BP), the *Myoko-Akakura* (*ca.* 6600 cal yr BP), the *Myoko-Otagirigawa* (*ca.* 4700 cal yr BP), the *Towada-Chuseri* (*ca.* 6300 cal yr BP), *etc.* The Pleistocene tephra was found only in basal sand and gravel layers underlying upper soils. Conversely, the Holocene tephras were usually identified in upper soils. Samples from the basal part of humic soils were dated as about 11000, 10000 and 7800 cal yr BP. Occurrence of the time marker tephras in these soils and radiocarbon dates indicate that alpine humic soil formation did not occur at the latest stage of the last glacial in the study mountains. Atmospheric warming and humidification after the Younger Dryas termination (*ca.* 11000 to 10000 cal yr BP) would have caused new formation of such soils. Alpine grassland and wet meadow soils have been formed since the early to mid Holocene.

Key words: alpine grassland soils, alpine wet meadow soils, snowy high mountains, tephrochronology, radiocarbon dating, Honshu Island

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1. Introduction

Alpine grassland soils and wet meadow soils (Osumi, 1970; Osumi and Kumada, 1971) both composed mainly of muck and peat layers often occur on snowy high mountains in central and northern Honshu Island, Japan. These soils mantle gentle slopes on the leeward side of the winter monsoon, where snow accumulates deeply in every year (Fig. 1).

Although some reports have appeared on these soils (*e.g.*, Osumi, 1970; Osumi and Kumada, 1971; Yamanaka, 1983; Koizumi *et al.*, 1984; Kariya, 1994), their formation history and paleoenvironmental implications are matters to which adequate attention has not been directed, owing to the lack of Quaternary pedological investigations.

Since soil formation, slope development and plant succession on high mountains would have always been in action ceaselessly, collecting for parameters such as distribution, formation history and paleoclimatic back grounds of these soils will contribute not only to Quaternary pedology but also climatic geomorphology and paleoecology in snowy high mountains in Japan (Yamanaka, 1983; Kariya, 1994).

These soils often include thin tephra layers (Osumi *et al.*, 1971; Yamanaka, 1983; Koizumi *et al.*, 1984). Identification and correlation of such tephras should permit establishing their chronology because the ages and sources of many tephras in and around the Japanese archipelago have been largely determined during the past several decades (*e.g.*, Machida and Arai, 1992). Besides, these soils are appropriate for radiocarbon dating owing to high organic material content.

In this paper, the authors describe representative time marker tephras embedded in alpine grassland and wet meadow soils on typical snowy mountains in Honshu. Radiocarbon dates obtained from the soils are also reported. The ages of initiation of these soils are discussed under study based on tephra ages and radiocarbon dates. Pedological characters of these soils in the mountains have already been indicated by Koizumi *et al.* (1984), Kariya (1994, 1995a) and Sasaki (1995).

2. Study Mountains

Field investigation was conducted on the mountains of Chokai, Gassan and Tairappyo (Fig. 1). Outline of natural environments of each mountain is summarized as follows:

Mount Chokai: Chokai (2236 m asl) is one of the late Quaternary major strato volcanoes in northern Honshu. The forest limit of *Fagus crenata* lies at about 1100 m asl and above which, *Sasa kurilensis* field, dwarfed scrub community and snow-bed plant community dominate. Although this vegetational zone is considered to be substantially occupied by subalpine coniferous forests, some snowy high mountains in Honshu such as Chokai, Gassan and Tairappyo lack it. Such a zone is often called a "*pseudo alpine* zone" due to its landscape resemblance to a pure alpine zone. Several dendroecologists (*e.g.*, Sugita, 1992) suggest causes for the absence of subalpine coniferous forests in these mountains but no detailed information is available in this regard. Soil surveys were carried out in and around small snowpatch hollows (Fig. 2). Maximum snow depth in the

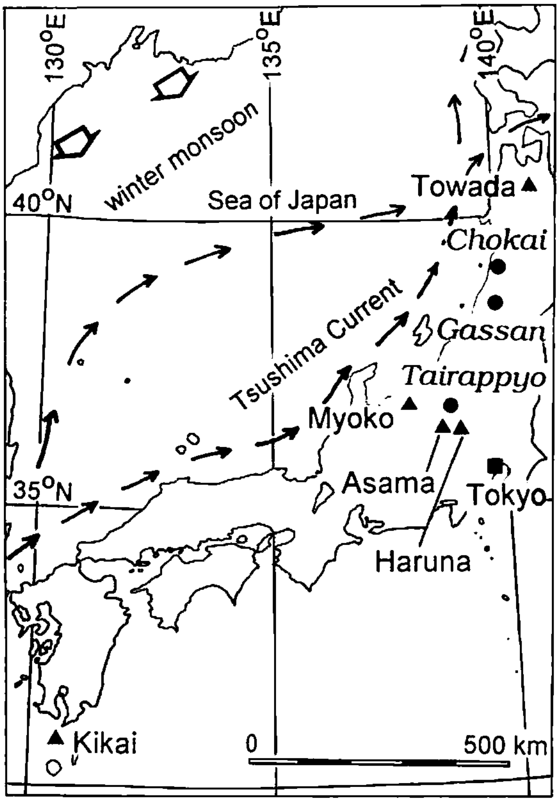

Fig. 1 Map showing the study mountains (closed circles) and the volcanoes (closed triangles) which have erupted the time-maker tephras described in this article

hollows is found to be 5 to 10 m (Sasaki, 1995). Mean annual air temperature around the surveyed site is estimated as 6.4℃, based on long-term meteorological data at Sakata situated about 30 km southwest of Chokai.

Mount Gassan: Gassan (1984 m) is an dissected volcano, formed during the mid Pleistocene (Fig. 2). The altitude of the forest limit of *F. crenata* is about 1400 m. Vegetational components above the forest limit are essentially the same as those of Chokai. Field evidence was gathered from many sites above the forest limit (Fig. 2). All surveyed sites are covered with deep snow a few to ten meters thick (Kariya, 1995b). Mean annual air temperature on the summit of Gassan is estimated as −0.8℃ (Kariya, 1995b). Summer (June to September 1995) precipitation recorded near the pit G3 was found to be about 800 mm (Fig. 2).

Mount Tairappyo: Tairappyo (1984 m) belongs to the Mikuni Mountains, the backbone range of Honshu, and consists of Tertiary volcanic and sedimentary rocks. Fossil solifluction smooth slopes formed during the last glacial spread around the summit of Tairappyo and the main divide (Takada, 1986). The forest limit of *F. crenata* lies at

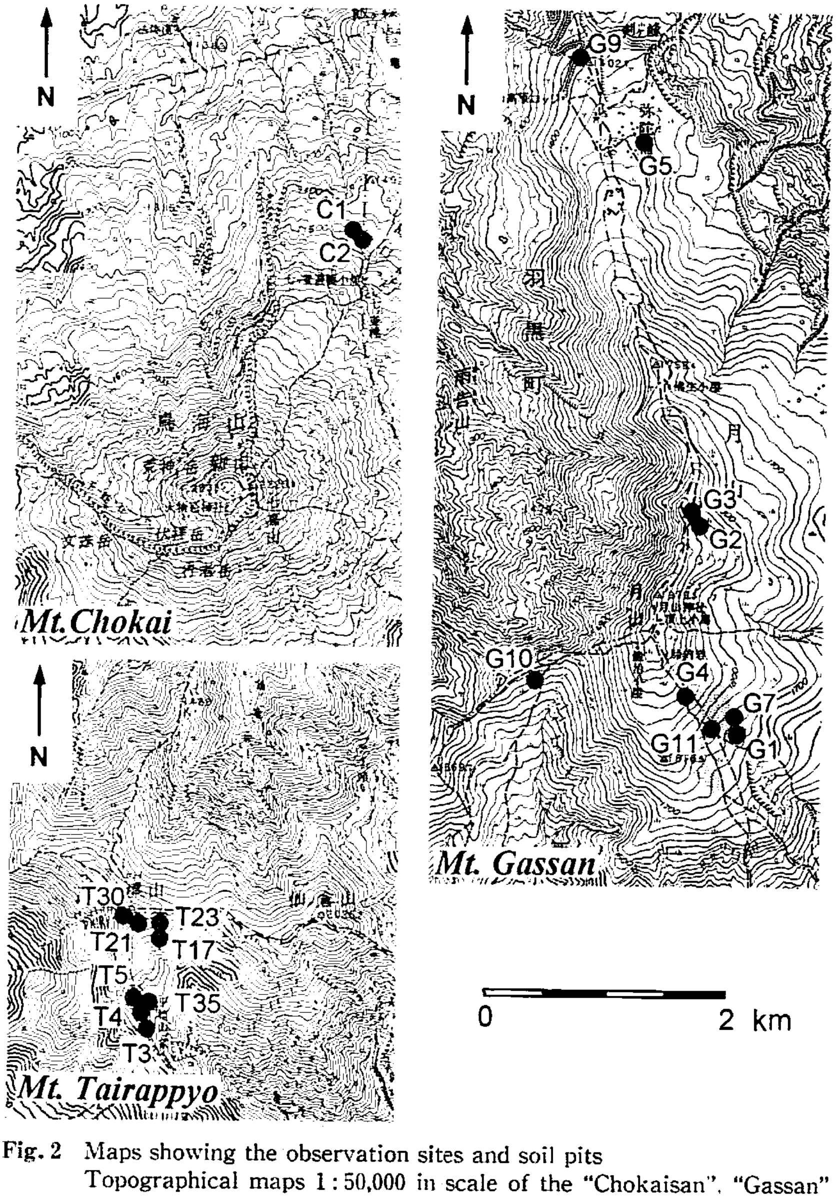

Fig. 2 Maps showing the observation sites and soil pits
Topographical maps 1 : 50,000 in scale of the "Chokaisan", "Gassan" and "Shima" districts, published by the Geographical Survey Institute are used as base maps. Contour interval, 20 m.

about 1600 m. Whereas vegetational components above the forest limit are the same as those of Chokai and Gassan, small patches of *Abies mariesii* are distributed sporadically. Field surveys were conducted at many sites on south-facing slopes above the forest limit (Fig. 2). The maximum snow depth on these slopes is estimated as a few to five meters.

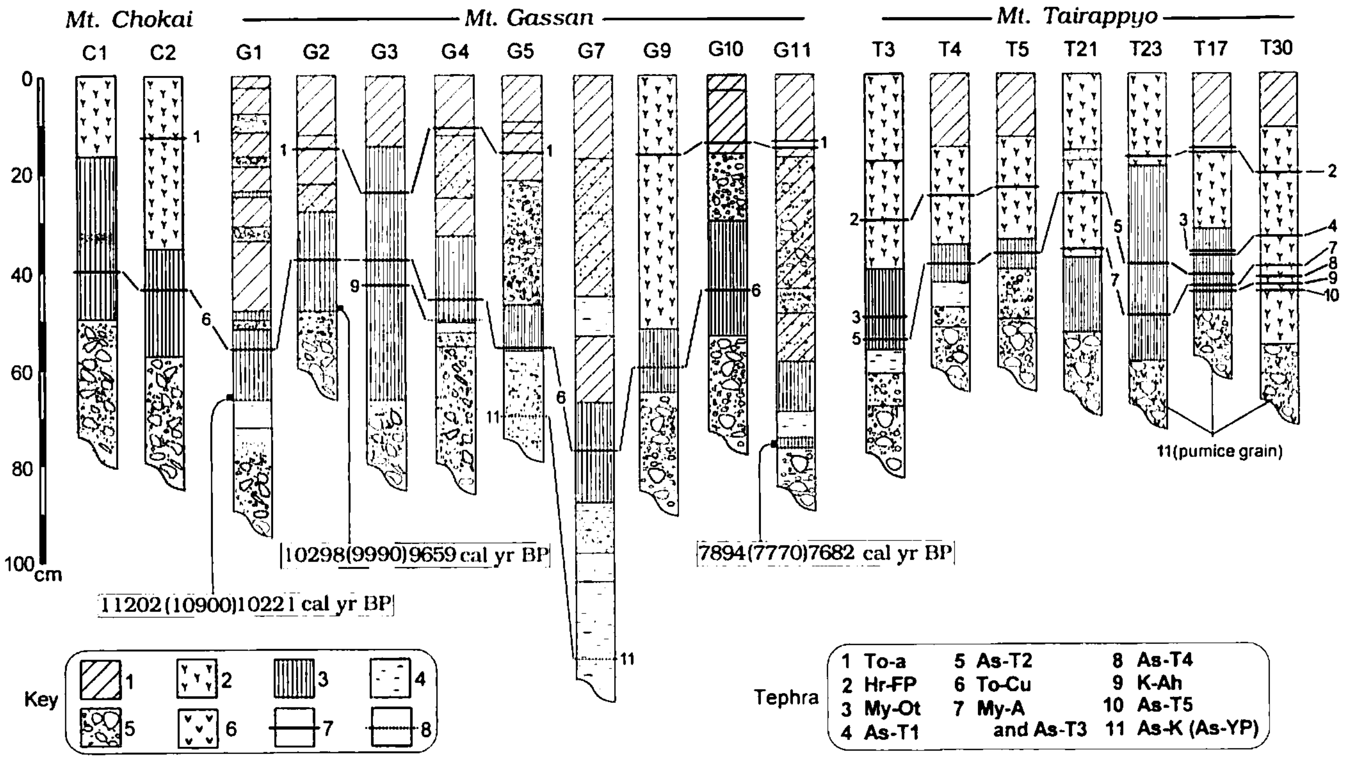

Fig. 3 Columnar sections of the soil pits investigated

Their locations are shown in Fig. 2. Radiocarbon ages obtained from G1, G2 and G11 were converted to calendar years from AD 1950 as zero, using the computer program CALIB 3.0 (Stuiver and Reimer, 1993). 1, loamy soil layer with humus; 2, peat layer; 3, well decomposed peat or muck layer; 4, silt layer; 5, sand and gravel layer; 6, pumice grains; 7, thin tephra layer; 8, horizon containning dispersed fine grains of tephra.

Mean annual air temperature around the summit of Tairappyo is found from calculation to be −0.6 to 0.1℃ (Suzuki, 1992).

Annual precipitation of maritime Japanese high mountains is quite considerable and induced primarily by heavy snow fall in winter. This is because the Tsusima Warm Current flows into the Sea of Japan from south to north and supplies the winter monsoon from the Siberian Continent with much vapor (Fig. 1).

3. Methods

Determination was first made of horizons and lithofacies of tephras and soil layers at each site. Secondly, petrographic properties such as mineral composition and shape of volcanic glass shards of each tephra were described by microscopic observation. Finally, refractive indices of volcanic glass shards, hornblende and orthopyloxene phenocrysts were measured. To identify and correlate individual tephras with those that are known, the results from these examinations were compared with a comprehensive catalog for Japanese tephras (Machida and Arai, 1992) and previous studies. Several soil samples were collected from Gassan and treated for radiocarbon dating. Soil organic matter composed mainly of humic acid and humin was chemically extracted from samples with HCl solution for dating (Kariya, 1994).

In Japan, various nomenclatures of tephras are in use, leading to considerable confusion (Machida, 1977). In this article, thus, names, abbreviations and nomenclatures of Machida and Arai (1992) are used. Age of each tephra was referred to the comprehensive catalog and other authors. Radiocarbon ages of tephras and soil samples were converted to calendar year using the calibration computer program, CALIB 3.0 (Stuiver and Reimer, 1993).

4. Results

The soil pits investigated are shown in Fig. 3 and the results of analysis of tephras, in Table 1.

The soils (Fig. 3) observed can be classified according to litho-stratigraphic profiles and forming materials as follows: a) those consisting of an upper loamy or sandy soil layer with humus and lower buried muck and/or peat layers (*e.g.*, G3, G5, T4, T17 and T30), b) those consisting of an upper peat layer and a lower buried muck layer (*e.g.*, C1, C2, G9, G10, T3 and T21). The former is correlated with alpine grassland soils and the latter, alpine wet meadow soils (Osumi, 1970; Osumi and Kumada, 1971). Several to six tephra layers comprised mainly of vitric ash are often embedded in the soils.

The Asama Kusatsu or the Asama YP tephra (*ca.* 16000 cal yr BP)

At no pits are there distinctive tephra layers embedded in basal silt, sand and gravel layers (*i.e.*, slope forming materials) below upper soils. However, a horizon containing dispersed volcanic glass shards of the *Asama-Kusatsu* or the *Asama-YP* tephras (As-K or

Table 1 Petrographic properties of the time-marker tephras found from the study mountains

Tephra	Pit	(1) Vol. glass	(2) Phenocrysts	(3) Ref. index	(4) Remarks
Towada-a (To-a, AD 915)					
	C2	pm > bw	opx, cpx	n.d.	
	G3	pm > bw	opx, cpx	1.498-1.504 (gl-n)*	a)
Haruna-Futatsudake-Ikaho (Hr-FP, the mid 6th C)					
	T17	pm	ho > opx	1.502-1.504 (gl-n) 1.672-1.676 (ho-n_2) 1.708-1.711 (opx-γ)	
Myoko-Otagirigawa (My-Ot, *ca.* 4700 cal yr BP)					
	T17	pm	opx, ho, cpx	1.496-1.499 (gl-n) 1.680-1.695 (ho-n_2) 1.706-1.717 (opx-γ)	
Asama-Tairappyo No. 1 (As-T1)					b)
	T17	pm	opx > cpx	1.512-1.516 (gl-n) 1.706-1.710 (opx-γ)	
	T30	pm	opx > cpx	1.513-1.516 (gl-n) 1.705-1.709 (opx-γ)	
Asama-Tairappyo No. 2 (As-T2)					b)
	T17	pm	opx > cpx, ho	1.511-1.516 (gl-n) 1.706-1.711 (opx-γ)	
Towada-Chuseri (To-Cu, *ca.* 6300 cal yr BP)					
	C2	pm	opx, cpx	n.d.	
	G3	pm	opx, cpx	1.506-1.508 (gl-n)*	a)
Myoko-Akakura (My-A, *ca.* 6600 cal yr BP) and *Asama Tairappyo No. 3* (As-T3)					b), c)
	T17	pm	opx, cpx, (ho)	1.496-1.514 (gl-n) 1.706-1.716 (opx-γ)	
	T30	pm	opx > cpx, (ho)	1.497-1.512 (gl-n) 1.706-1.717 (opx-γ)	
Asama-Tairappyo No. 4 (As-T4)					b)
	T30	pm	opx > cpx	1.514-1.518 (gl-n) 1.706-1.711 (opx-γ)	
Kikai-Akahoya (K-Ah, *ca.* 7200 cal yr BP)					
	G3	bw		1.507-1.513 (gl-n)*	a)
	T17	bw		1.508-1.513 (gl-n)*	
	T30	bw		1.509-1.513 (gl-n)	
Asama-Tairappyo No. 5 (As-T5)					b)
	T30	pm	opx > cpx	1.515-1.519 (gl-n) 1.708-1.711 (opx-γ)	
Asama-Kusatsu or *Asama-YP* (As-K, As-YP, *ca.* 16000 cal yr BP)					
	G5	pm > bw		1.500-1.504 (gl-n)*	a)
	G7	pm > bw		1.500-1.503 (gl-n)*	a)
	T17	pm	opx, cpx	n.d.	

(1) Types of volcanic glass shards are: pm, pumiceous; bw, bubble-wall. (2) Major mafic minerals except for magnetite are presented in decreasing amount order. Abbreviations: opx, orthopyroxene; cpx, clinopyroxene; ho, hornblende. (3) Refractive index with asterisk mark (*) was determined with RIMS 86. (4) a): Kariya (1994). b): The As-T1, T2, T3, T4 and T5 are tentative designations by the authors. c): The My-A tephra appears to overlap the As-T3. A set of these two tephras would be correlated with the tephra-X in Ozegahara (Sakaguchi, 1976; Arai, 1980).

As-YP, *ca.* 16000 cal yr BP ; Machida and Arai, 1992) is detected barely from such clastic layers in Gassan (G5 and G7: Fig. 3, Table 1: Kariya, 1994). Additionally, a basal sand and gravel layer in Tairappyo sometimes contains yellow pumice grains (< 2 mm) of the As-K tephra (Fig. 3; Takada, 1986). Fossil solifluction lobes and lens-like sedimentary structures of coarse sands are buried in such a sand and gravel layer with the As-K pumice grains (Fig. 4). On the other hand, none of the As-K or the As-YP tephra can be found from upper soils in Chokai, Gassan and Tairappyo.

The As-K and the As-YP tephras are considered to be a series of plininan ejecta within the same eruption cycle of Asama, a major active volcano in central Japan (Fig. 1; Aramaki, 1963). Although the distributions of these tephras in proximal areas have been clarified (*e.g.*, Arai, 1979), those in distal areas remain to be determined in some cases, owing to the difficulty involved. Since the petrographic characteristics of these two tephras are alike (Machida and Arai, 1992), it is difficult to discriminate between them in distal areas.

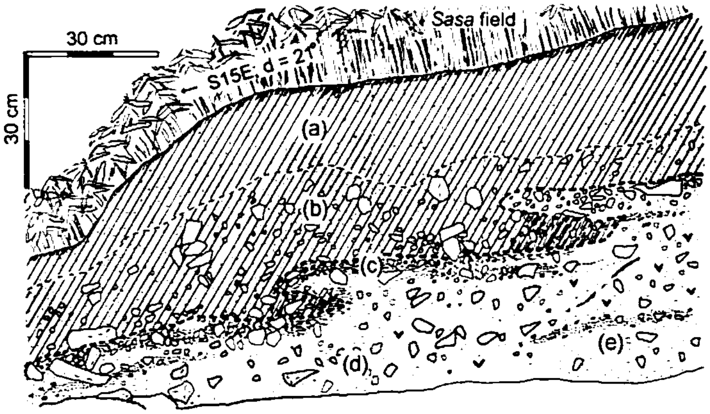

Fig. 4 Buried solifluction lobes at T35 on Mount Tairappyo
(a): loamy to sandy soil layer with humus; (b): sandy soil layer with humus and gravels; (c): accumulation layer of iron; (d): sand and gravel layer containing yellow pumice grains (< 2 mm) of the As-K tephra; (e): lens-like structures of coarse sands, probably formed by sheet wash.

The Kikai Akahoya tephra (*ca.* 7200 cal yr BP)

A thin layer of the *Kikai-Akahoya* tephra (K-Ah, *ca.* 7200 cal yr BP: Machida and Arai, 1978, 1992) consisting mainly of abundant bubble-walled volcanic glass shards is observed in buried muck layers on Gassan and Tairappyo (G3, G4, T17 and T30: Fig. 3, Table. 1: Kariya, 1994).

The K-Ah tephra was ejected from the gigantic submarine caldera, Kikai, to the south of Kyushu Island about 1200 km southwest of the northeastern Honshu. A conspicuous vitric tephra layer in alpine grassland and wet meadow soils was first described in the northern Japanese Alps (about 36° N, 137° E: Osumi, 1970: Osumi *et al.*, 1971), and was subsequently found to be correlated with the K-Ah tephra by Machida and Arai (1978). In distal areas, this tephra is characterized by high bubble-walled glass shards content (Machida and Arai, 1978, 1992). This feature facilitates distinguishing it from the others.

The Towada Chuseri (*ca.* 6300 cal yr BP) and the Towada a (AD 915) tephras

The *Towada-Chuseri* (To-Cu, *ca.* 6300 cal yr BP; Hayakawa, 1983; Machida and Arai, 1992) and the *Towada-a* (To-a, AD 915; Machida *et al.*, 1981; Machida and Arai, 1992) tephras spreading the whole northern Honshu are found in Chokai and Gassan. These two tephras were erupted from the Towada caldera about 160 km north of Chokai (Fig. 1) and their lithofacies are alike. Identification of the To-Cu and the To-a tephras must thus be made on the basis of both stratigraphic position and petrographic properties. For example, the refractive index of volcanic glass shards of the To-a tephra is significantly less than that of the To-Cu (Table 1). Besides, the To-Cu tephra is often embedded at several or ten centimeters above the K-Ah tephra, or about 40 to 50 cm deep below the surface in Gassan (*e.g.*, G3 and G4; Fig. 3).

The Haruna, Myoko and Asama tephras (the mid to late Holocene)

Seven tephras differing from the As-K and the K-Ah are identified in upper soils on Tairappyo. It is clear that most of them are of the mid to late Holocene because they are embedded above the K-Ah (Fig. 3, Table 1). The sources of these tephras are correlated with Haruna, Myoko or Asama (Fig. 1), as evident from their unique petrographic properties. Brief descriptions are given in the following sections and details will be shown in other papers.

Haruna: Almost throughout Tairappyo, relatively thicker tephra layers with white pumice grains can be observed in the upper part of sections, about 20 to 30 cm below the surface (Fig. 3). This tephra contains much green hornblende and consequently can be easily distinguished from the others in Tairappyo (Table 1).

Two notable tephras erupted from Haruna volcano during the latest Holocene are characterized by much green hornblende (Arai, 1979). The *Haruna-Futatsudake-Ikaho* tephra (Hr-FP, the mid 6th century; Arai, 1979; Machida and Arai, 1992) was blown to the northeast but another to the east. The tephra layer embedded in the upper part of sections is correlated with the Hr-FP.

Myoko: At T17, the second and fifth tephra layers from the top are comprised mainly of volcanic glass shards and hornblende. In particular, volcanic glass shards in the second layer contain microlites. The minimum value of refractive index of these glass shards ($n=1.496$) is somewhat less than those of other tephras (Table 1).

The Holocene tephras from Myoko are characterized by hornblende and volcanic glass with microlites (*e.g.*, Hayatsu, 1992; Machida and Arai, 1992). Besides, refractive indices of volcanic glass shards of the Myoko tephras are relatively low (Hayatsu, 1992; Machida and Arai, 1992). Myoko has ejected several tephras during the Holocene (Hayatsu, 1992), the major ones being the *Myoko-Akakura* (My-A, *ca.* 6600 cal yr BP; Hayatsu, 1992; Machida and Arai, 1992) and the *Myoko-Otagirigawa* tephras (My-Ot, *ca.* 4700 cal yr BP; Hayatsu, 1992; Machida and Arai, 1992). Thus, the two tephras described above would be correlated with the My-Ot and the My-A tephras.

However, it should be pointed out that the volcanic glass shards in the fifth layer at G17 have a high refractive index ($n=1.514$) which appears essentially the same as that of the Holocene Asama tephras (described next). The fifth layer at G17 would thus consist of the different overlapping tephras that originated from the My-A and some Asama ejecta. A similar tephra layer is identified in other sections (T21, T23 and T30). Arai (1980) found a unique tephra layer designated as the tephra-X (Sakaguchi, 1976) in Ozegahara moor about 40 km east of Tairappyo. This tephra is composed primarily of two overlapping tephra layers whose petrographic properties differ considerably.

Asama: All of the rest contains large amount of two-pyroxene phenocrysts and volcanic glass shards but no hornblende, except in the case of the tephra with the My-A (Table 1). As shown in Table 1, refractive indices of orthopyroxene of such tephras are from 1.705 to 1.711 (γ) and volcanic glass shards, from 1.511 to 1.519 (n). The petrographic properties of these tephras are basically the same. The Holocene tephras of Asama contain two-pyroxene but no hornblende (Arai, 1979). The refractive indices of the volcanic glass shards of Asama tephras are significantly higher than those of Myoko and Haruna during the Holocene (*e.g.*, Arai, 1979). Indeed the distributions of the Holocene tephras of Asama have long been studied in proximal areas (*e.g.*, Aramaki, 1963; Arai, 1979), but their basic stratigraphy and ages have not always been established owing to over abundance of the tephra layers. Although several tephras found in Tairappyo are considered to have originated from Asama on the basis of their petrographic properties, they have not yet been correlated with any tephras in the vicinity of the volcano. Thus, the authors tentatively named the above tephras in Tairappyo as the *Asama-Tairappyo Nos. 1* to *5* from top to bottom (As-T1 to T5; Fig. 3, Table 1). As already stated , the My-A is most likely mixed with the As-T3 tephra.

Radiocarbon ages of buried muck layer

Three samples from the basal part of buried muck layers in Gassan were dated as follows: 11202 (10900)10221 cal yr BP at G1 (Kariya, 1994), 10298 (9990)9659 cal yr BP at G2 (Kariya, 1994), and 7894 (7770)7682 cal yr BP at G11. It is evident that these ages are available from stratigraphical point of view because the To-Cu and/or the K-Ah tephras are embedded at about 10 cm above the sampling horizon at each section.

5. Discussion

The As-K (or the As-YP) tephra is found only in basal sand and gravel layer, never in upper soils in Gassan and Tairappyo. These facts indicate no soil cover around 16000 cal yr BP in these mountains. Fossil solifluction lobes and lens-like structures of coarse sands in Tairappyo indicate occurrence of active periglacial mass-wasting and slope wash at or after 16000 cal yr BP. It has been suggested that climatic geomorphological zones would have dropped about 1000 to 1500 m in central Honshu during the last glacial, and most high mountains in this area presumably belonged to periglacial zones (*e.g.*, Takada, 1986). Periglacial and some related geomorphic processes acting on mountain slopes most likely prevented soil formation during this period. Also, thermal conditions that would have permitted plant communities to survive as sources of humus had probably been inadequate.

The radiocarbon ages from G1 and G2 on Gassan, considered to be the oldest in the mountain (Kariya, 1994), show that humic soil formation started since the early Holocene: about from 11000 to 10000 cal yr BP. These ages show close agreement with values for the Younger Dryas termination in Europe and other regions including Japan (*e.g.*, Lotter, 1991; Johnson *et al.*, 1992; Igarashi *et al.*, 1993). Indeed the ages showing the Younger Dryas termination, determined by various chronological methods (*i.e.*, radiometric dating, ice-flow modeling, lacustrine varve and tree-ring counting), differ slightly, but span 10500 to 11500 cal yr BP (Machida, 1995). Atmospheric warming since the Younger Dryas termination may have induced complete stabilization and vegetation establishment in mountain slopes, followed by soil formation.

The mid Holocene marker tephras such as the K-Ah, the To-Cu, the My-A, and the As-T5 to T3 are often embedded in the lower parts of buried muck and peat layers on all mountains of this study and usually found within several to ten centimeters from the base of such soil layers (Fig. 3). In addition, the radiocarbon age from G11 in Gassan indicates that formation of muck layers started about 7800 cal yr BP. From these facts, it can thus be concluded that alpine grassland and wet meadow soils formation had already been taking place from the early to mid Holocene.

Atmospheric warming after the Younger Dryas termination had probably permitted stabilization of periglacial slopes and vegetation encroachment. However, peat and muck layers usually occur on wet slopes inundated with snow-melt and/or spring water, so that initiation of peat and muck layers during the period from the early to mid Holocene cannot be explained merely as due to an increase in air temperature. During the last glacial, the Tsushima Current probably had not flowed into the Sea of Japan because of the low stand of sea level (*e.g.*, Arai *et al.*, 1981). Snowfall during the last glacial should thus have been noticeably less than at present (*e.g.*, Koizumi, 1982). Climatic amelioration following the late glacial to the early Holocene caused a full inflow of the Tsushima Current at about 9000 cal yr BP (*e.g.*, Arai *et al.*, 1981). The initiation of muck and peat layers formation on the study mountains is considered to have been induced by two environmental changes — increasing air temperature and snowfall — from the late glacial to the early Holocene. Humidification of the ground surface due to increased snowfall would certainly promote muck and peat layers formation.

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