Available online at www.sciencedirect.com
ScienceDirect
Quaternary Research 68 (2007) 213–219
QUATERNARY RESEARCH
www.elsevier.com/locate/yqres

Vertebrate burrows in late Pleistocene paleosols at Korean Palaeolithic sites and their significance as a stratigraphic marker

Hyoun Soo Lim [a,*], Yong Il Lee [b], Seonbok Yi [c], Cheong-Bin Kim [d], Chull-Hwan Chung [e], Heon-Jong Lee [f], Jeong Heon Choi [g]

[a] *Korea Polar Research Institute, Korea Ocean Research & Development Institute, Incheon 406-840, Korea*
[b] *School of Earth and Environmental Sciences, Seoul National University, Seoul 151-747, Korea*
[c] *Department of Archaeology and Art History, Seoul National University, Seoul 151-745, Korea*
[d] *Department of Science Education, Sunchon National University, Sunchon 540-742, Korea*
[e] *Faculty of Earth Systems and Environmental Sciences, Chonnam National University, Gwangju 500-757, Korea*
[f] *Division of History and Culture, Mokpo National University, Chonnam 534-729, Korea*
[g] *Isotope Research Team, Korea Basic Science Institute, Daejun 305-333, Korea*

Received 27 October 2005
Available online 5 July 2007

Abstract

A vertebrate burrow-bearing layer of late Pleistocene age is commonly found at many Paleolithic archaeological sites in Korea. The burrows are straight to slightly curved in horizontal (plan) view and gently inclined in lateral (sectional) view. They are interpreted as having been produced by rodent-like mammals based on their size and architecture. The significance of such burrow-bearing layers as a characteristic stratigraphic marker unit is demonstrated by high burrow abundance, consistent stratigraphic position, lack of stratigraphic recurrence at these sites, and widespread geographic extent. Three dating methods, tephrochronology, radiocarbon, and OSL dating, were used to infer the age of these burrow-bearing layers. The dating results indicate that they were formed between ca. 40,000 and 25,000 yr (MIS 3−2), and this suggests that this layer can be used as a stratigraphic time-marker in late Pleistocene paleosol sequences for this region.

Keywords: Late Pleistocene; Vertebrate burrow; Stratigraphic time-marker; Tephra; OSL; Radiocarbon

Introduction

Most terrestrial vertebrate trace fossils that have been studied are trackways, while burrows produced by fossorial vertebrates have been paid little attention. Although many kinds of vertebrates excavate burrows, few examples have been reported from the ancient record (Voorhies, 1975). The oldest fossil vertebrate burrows are Lower Devonian lungfish burrows from South Wales (Allen and Williams, 1981; O'Sullivan et al., 1986). Pre-Cenozoic vertebrate burrows have been reported from South Africa (Smith, 1987; Groenewald et al., 2001) and Antarctica (Miller et al., 2001). The best-known ichnofossil vertebrate burrows are *Daimonelix*, which are interpreted to have been produced by the Miocene beaver *Paleocaster* (Voorhies, 1975; Martin and Bennett, 1977), and the *Citellus* zone produced by late Pleistocene ground squirrels and other rodents (Tobin, 2004a, 2004b).

In Korea, vertebrate burrows have been found at Paleolithic archaeological sites (Lim et al., 2004). They have been recognized at several distant areas in stratigraphically consistent positions. Although burrower remains have not been found, based on burrow size and architecture the burrows are interpreted as having been constructed by rodent-like mammals (Lim et al., 2004). Most studies on penetrative burrows in continental deposits have focused on ichnology and their paleoenvironmental and paleoclimatic implications (e.g., Miller et al., 2001; Tobin, 2004a, 2004b; Hasiotis et al., 2004). In this study we primarily focus on the dating of the burrows and their chronostratigraphic implications. We describe the vertebrate

* Corresponding author. Fax: +82 32 260 6109.
E-mail address: tracker@kopri.re.kr (H.S. Lim).

0033-5894/$ - see front matter © 2007 University of Washington. All rights reserved.
doi:10.1016/j.yqres.2007.05.001

burrows found at many Korean Paleolithic archaeological sites, and then suggest the possibility that the stratigraphic layer containing these burrows can be used as a time-marker horizon of late Pleistocene age.

General geology

Located in the middle latitudes of the Northern Hemisphere (Fig. 1), the Korean Peninsula did not experience any glaciation during the Quaternary. However, the region contains abundant paleoclimatic records of Quaternary climatic changes (e.g., Lee, 1987; Yi et al., 1998; Kim, 2001; Lee and Yi, 2002). Most Quaternary paleosols found in Korea are late Pleistocene in age and are commonly underlain unconformably by fluvial or slope deposits. Only thin layers of Holocene paleosols are preserved above the Pleistocene paleosols due to active erosional processes caused by natural and/or anthropogenic factors. Pleistocene paleosols in Korea are either red to reddish brown soils or light brown soils (Kim, 2001). Red to reddish brown soils dating to the last interglacial period are overlain by less weathered light brown soils (Kim, 2001). On top of the light brown paleosols, soil-wedge structures are commonly found and are filled with yellowish brown, loose soil material. These have an irregular boundary and variable penetration depth from several centimeters to a few meters. Polygonal structures are also well developed on horizontal surfaces. The soil-wedge structures are generally regarded as having formed under dry or periglacial climates during Marine Isotope Stage (MIS) 2 (Kim, 2001; Shin, 2004). Although periglacial climate with the presence of perennial permafrost has not prevailed in Korea, temporary permafrost could have developed during the Last Glacial Maximum (LGM) due to high seasonal variation (Kim, 2001). Vertebrate burrows are recognized within the upper part of the light brown paleosol sequence, and below the soil-wedge structures, at seven Paleolithic archaeological sites in Korea (Fig. 1).

Methods

For this study we recorded burrow diameters and inclination angles; burrow architectures and the relationships between burrow fills and host soil materials were also described. Emphasis was placed on recording the stratigraphic position of paleosols with vertebrate burrows.

Chronological control is provided by tephrochronology, radiocarbon, and optically stimulated luminescence (OSL) dating. Tephrochronology is a geochronological technique that utilizes distinct layers of tephra—volcanic ash from a single eruption—as isochronous marker horizons. In this study, tephra analyses were carried out at three excavation sites, Asan, Jeongdongjin, and Naju (Fig. 1). Soil samples for tephra analysis were obtained at 5-cm intervals near the soil-wedge horizons (<1 m depth from the surface). Approximately 20 g of soils were taken from each sample and cleaned in an ultrasonic cleaner with distilled water. Cleaned samples were dried at 60 °C for 8 h, and the 125–250 μm fractions were separated by sieving. Volcanic glass was handpicked under a stereomicroscope, and glass morphologies were examined. Major element geochemistry of glass shards was used for tephra identification. Typically the chemistry of volcanic glass is laterally geographically homogeneous, allowing for correlation across significant distances (Westgate and Briggs, 1987). We used electron microprobe analysis to quantify the major-element chemistry of the volcanic glass because it allows analysis of discrete sites on glass shards, eliminating possible analytical errors due to the inclusion of mineral phases in the analyses (Carson et al., 2002). Concentrations of nine major elements (Si, Ti, Al, Fe, Mn, Mg, Ca, Na and K) were analyzed using an electron microprobe (JEOL JXA 8900R) at Seoul National University. Operating conditions were 15 kV accelerating voltage, 10 nA current, 10 μm beam diameter, and 140-s count time. Major element concentrations are reported as weight percent oxide compositions.

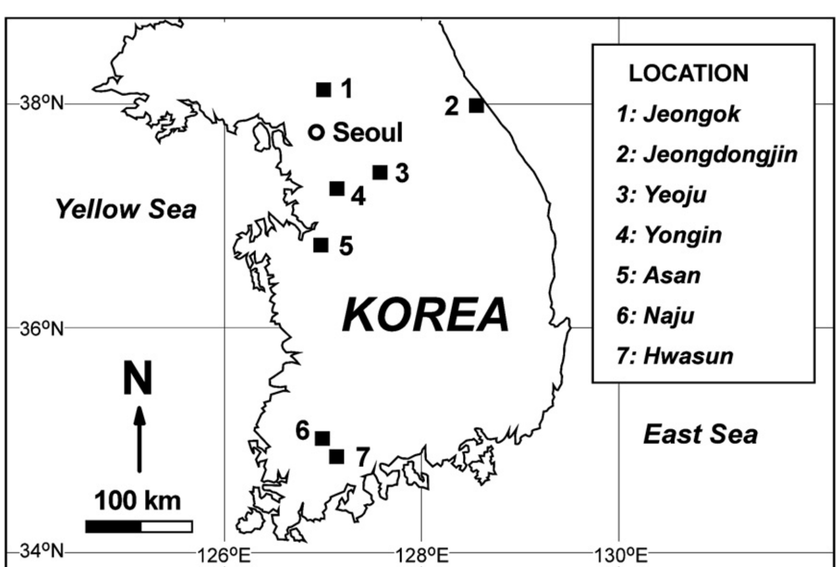

Figure 1. Locations of Paleolithic archaeological sites studied in Korea, indicated by solid squares with numbers.

Radiocarbon analyses were carried out for burrow-fill (clay and/or soil) samples containing 0.2–0.6 wt.% total organic carbon collected from the Jeongok, Yeoju and Yongin excavation sites (Fig. 1). Five burrow-fill samples were dated using conventional radiocarbon analysis with an extended counting time at Geochron Laboratories, USA.

Eleven sand and soil samples were collected from five excavation sites (Jeongok, Yeoju, Asan, Naju, and Hwasun) for OSL dating (Fig. 1). Except for the sample AS-1 (Asan), all samples were taken from horizons below the burrow interval. Sample analysis was carried out at the Korea Basic Science Institute. Samples were cleaned with 10% HCl, 10% H_2O_2, and HF in the laboratory. After cleaning, the remaining material (mainly quartz) was checked using IR stimulation for feldspar contamination. The 90- to 250-μm fractions were then recovered by sieving. Quartz OSL signals were measured using a Risø TL/OSL automated system (Bøtter-Jensen et al., 2000), and the SAR protocol (Murray and Wintle, 2000) was used to estimate D_e values. A blue (470±30 nm) LED array delivering 40 mW cm^{-2} was used as a stimulation light source, and signal detection was through 7 mm of U-340 filter. A $^{90}Sr/^{90}Y$ beta source (dose rate to quartz ~0.18 Gy s^{-1}) was used for laboratory irradiation. A high-resolution gamma spectrometer was used to measure the radioactive element concentrations in the samples (Murray et al., 1987), which were then converted to dose rates using the data presented by Olley et al. (1996).

Results

Occurrence and characteristics of vertebrate burrows

Schematic stratigraphic sections containing vertebrate burrows are shown in Figure 2. Cross-sectional shapes of vertebrate burrows found at Korean Paleolithic sites are either circular or elliptical (Figs. 3A and B). Burrows are typically straight to slightly curved in horizontal view and gently inclined in lateral view (Figs. 3C and D).

Burrow diameters range from 4 to 14 cm but are mostly 7–10 cm. Branching is not common, but several high-angle branches were observed in the Jeongok and Yeoju sites. Burrow length may reach a few meters. In general, burrow vertical penetration depths are approximately 1 m, and we found that they seem not to exceed 2 m. The thickness of the vertebrate burrow-bearing layer is about 1–2 m, but it reaches up to ~3 m in the Jeongok and Yeoju sites. Table 1 shows the characteristics of vertebrate burrows reported in this study.

These burrows are generally passively filled with soils and/or well-laminated clays (Fig. 3). Passively filled soils enter a burrow gravitationally, and they consist of material similar to the surrounding soils. However, laminated clays within the burrows appear to have formed by illuviation during rainfall events. Well-laminated and undisturbed sediments in the burrows confirm that the burrows were filled following abandonment. Compared to the surrounding soil matrix, which shows light brown to light reddish brown colors, passively infilled soils and laminated clays show light grey (or brown) and dark grey to dark reddish grey colors, respectively. This color contrast between the surrounding matrix and burrow fill makes it easy to recognize burrows in the field. Burrower remains, such as skeletons, incisors and claws, have not been found in burrow fills. Compared to other sites, burrow density (burrows/m^2) is relatively high in the Jeongok, Asan and Yeoju areas. Although the study areas are separated from each other by long distances, no significant difference in burrow morphology was found between sites.

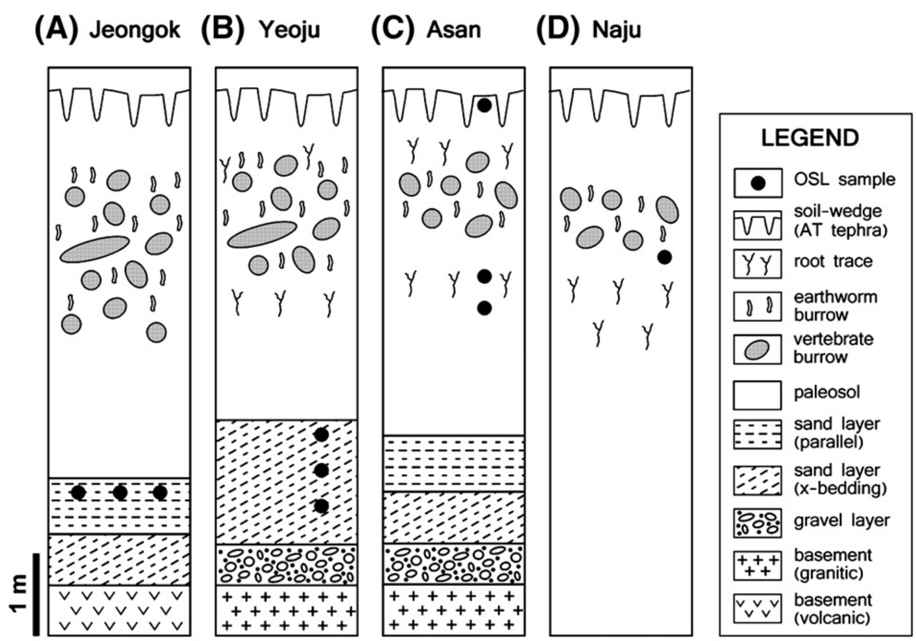

Figure 2. Simplified stratigraphic profiles from the Jeongok, Yeoju, Asan and Naju archaeological sites. Note the stratigraphically consistent position of the vertebrate burrow-bearing layers and their relationship to the soil-wedge layers.

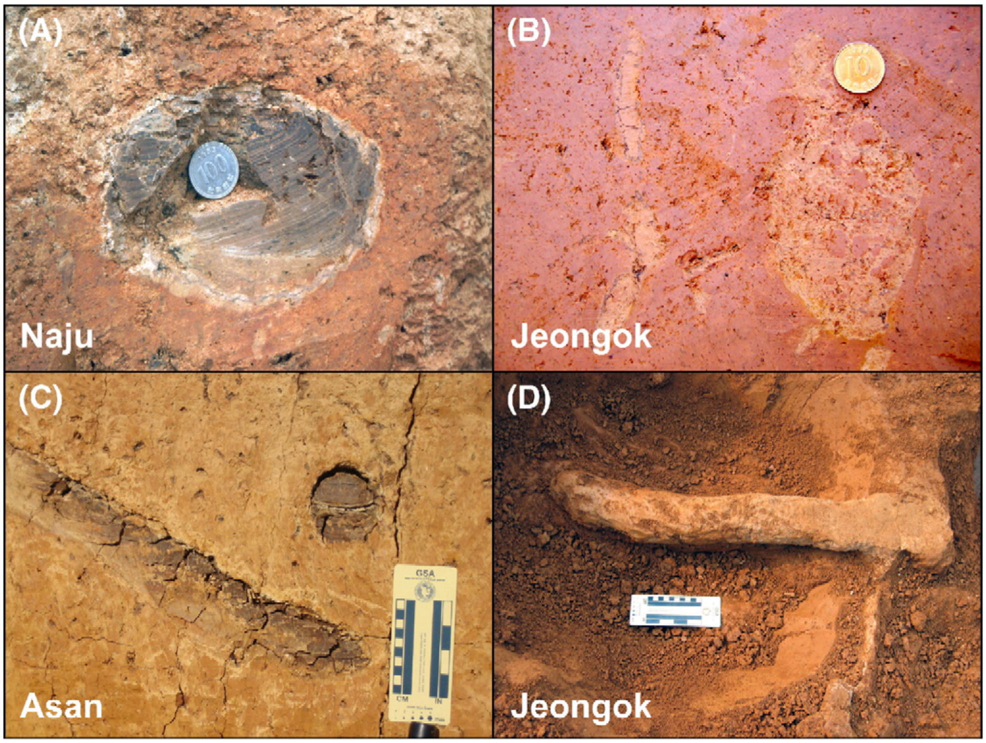

Figure 3. Photographs of vertebrate burrows found at the Paleolithic excavation sites. (A) Cross-section of a burrow showing well-laminated structure of clay fills in the upper part (from Naju). Note the light grey colored burrow lining. (B) A passively-filled vertebrate burrow to the right of more linear earthworm burrows (left) in the photo (from Jeongok). Note the color contrast between the burrow fills and the surrounding soil matrix. (C) Gently inclined and straight large burrows in vertical section (from Asan). (D) Plan view of subhorizontal and slightly curved large burrows (from Jeongok).

OSL dating

The OSL data and ages for the samples from six Paleolithic sites are summarized in Table 4. The AS-1 sample from the Asan site is the youngest with an OSL age of 29.0±1.6 ka, whereas all other ages are older than 40,000 yr. Because the AS-1 sample was collected from slightly below the soil-wedge horizon containing AT tephra (Fig. 2C), the OSL age (29.0±1.6 ka) is thought to be reasonable. Except for the AS-1 sample, all samples were taken from horizons below the burrow-bearing layer, and thus the OSL ages represent the maximum age of the burrowing event. The OSL ages show relatively consistent ages, mostly from 40,000 to 65,000 yr.

Table 1
Characteristics of large burrows found at Korean Paleolithic excavation sites

Characteristics	Description
Diameter (cm)	Mostly 7–10 cm, range from 4 to 14 cm
X-sectional shape	Circular or elliptical
Architecture	Gently inclined to subhorizontal, straight to slightly curved (Figs. 3C and D)
Branching	Not common, but several high angle branches were observed in burrows from Jeongok and Yeoju
Penetration depth	Typically about 1–2 m (0.5 to 4.0 m below the surface).
Burrower remains	None
Burrow fill	Well-laminated clays and passive infills (and/or backfill)

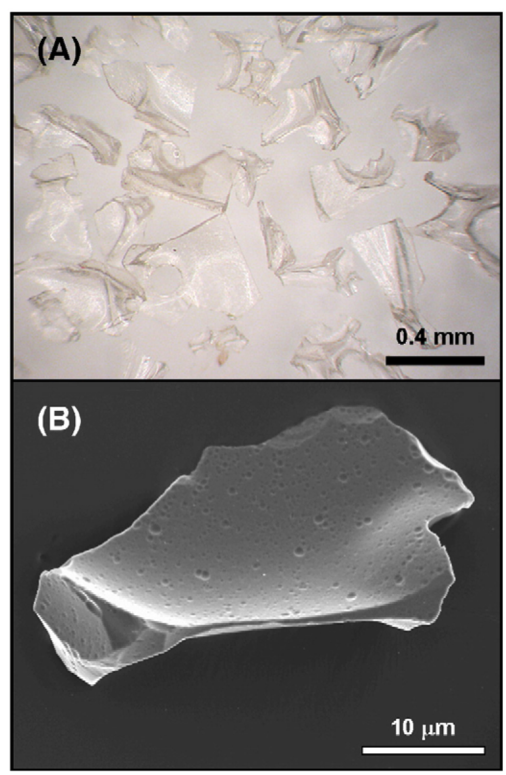

Figure 4. Photographs of representative volcanic glass shards originated from the Aira–Tanzawa (AT) volcano. (A) Typical transparent bubble-wall type glass shards (from Asan). (B) SEM microphotograph of the bubble-wall type glass shard (from Naju).

Radiocarbon dating

Radiocarbon dating was carried out on five burrow-fill samples, and the results are shown in Table 3. The data have a relatively wide age range (ca. 18,000 to >36,540 yr). In general, laminated clay samples show younger ages than passively filled soil samples. Radiocarbon ages are similar to, or older than, the eruption age of the Aira volcano (ca. 25,000 yr).

Tephra analysis

Volcanic ash (tephra) layers are important and useful marker horizons for stratigraphic correlation and age determination, and Quaternary tephra layers in and around Japan have been well identified and catalogued (Machida and Arai, 1992; Machida, 1999). At the Asan, Naju and Jeongdongjin sites, thousands of bubble-wall and pumiceous volcanic glass shards were successfully extracted from the soil-wedge layer overlying the burrows. The most common shards are bubble-wall and bubble-wall junction types (Fig. 4). Such glass shards were derived from the walls of gas bubbles (vesicles), and from the junctions of two or more vesicles. Less common are pumiceous glass shards with many gas-bubble holes, similar to the vesicles contained in pumice, that formed as gas dissolved in the rapidly expanding magma during eruption. Most glass shards are transparent, but some are a pale brown color.

Major element compositions of 130 volcanic glass samples from three of our study sites are presented in Table 2. Comparison with the geochemistry of widespread tephras derived from the Japanese Islands indicates that the volcanic glasses from the Asan, Naju and Jeongdongjin sites have similar compositions to the Aira-Tanzawa (AT; ca. 25,000 yr) and Kikai-Tozurahara (K-Tz; ca. 90,000–95,000 yr) tephras (Machida, 1999). In general, it is often difficult to distinguish AT tephra from K-Tz tephra, other than by age, because they have very similar colors, morphologies and refractive indices (Machida and Arai, 1992). The K-Tz tephra can be distinguished from the samples of this study because the age of K-Tz tephra (ca. 90,000–95,000 yr) is much older than the OSL ages (ca. 40,000–65,000 yr) of sediments taken from horizons below the burrow-bearing layers. Moreover, this distinction is also supported by the absence of β-quartz, which is common in the K-Tz tephra layer (Machida and Arai, 1992; Danhara et al., 2002). The compositional similarity of most major elements between the AT tephra and the volcanic glasses found at our Asan, Naju, and Jeongdongin sites suggests that the latter may also have originated from the eruption of the Aira volcano in Japan at ca. 25,000 yr ago (Machida and Arai, 1992).

Interpretation and discussion

Although the study areas are widely separated from each other, the burrow-bearing layers are recognized at roughly consistent stratigraphic positions, and no significant difference in burrow morphology was found between areas. This implies that they are likely to have been produced by the same kind of animal. Due to the lack of burrower remains, our only evidence as to its identification is found in the size of the burrow and the overall burrow architecture (Reichman and Smith, 1987; Laundre, 1989; Miller et al., 2001). Based on these criteria, the burrows are interpreted to have been produced by rodent-like mammals (Lim et al., 2004), probably ground squirrels (e.g., Özkurt et al., 2005). However, further study is needed to confirm this interpretation.

It is not easy to determine the age of these burrowing events because the ages of both the burrow fill and the surrounding soil matrix do not indicate exactly when these burrows were produced. Radiocarbon dating of burrow fills can determine the age of organic materials in the fills, but this may only indicate the age of pedogenic organic accumulation within the burrows and not the actual age of the burrowing activity itself. OSL dating of the surrounding matrix only gives a maximum age limit on the burrowing event (Tobin, 2004b). In order to constrain the age of these burrowing events, the soil-wedge layers overlying the burrow-bearing layer, burrow-fill materials, and soil and fluvial sand samples underlying the burrow layer, were dated using tephrochronology, radiocarbon, and OSL techniques. Thus, our work provides a range of bracketing ages for these burrows, and not a precise age on the burrow formation itself.

The radiocarbon ages of the burrow-fill samples (Table 3) show a relatively wide range. However, the sedimentology of the dated materials should be taken into account in order to

Table 2
Summary of the widespread Quaternary tephra layers found in Korea (Machida, 1999)

Tephra	Age (ka)	Major element composition of volcanic glass (wt.%)									No. of analyses	Reference and remark
		SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O		
K-Ah	6.3	74.7	0.53	13.1	2.5	0.08	0.5	2.0	3.8	2.8	36	Furuta et al. (1986)
AT	22–25	77.9	0.13	12.3	1.3	0.04	0.13	1.1	3.6	3.5	46	Furuta et al. (1986)
Aso-4	84–89	72.7	0.37	14.6	1.5	0.1	0.4	1.1	4.5	4.7	36	Furuta et al. (1986)
		74.0	0.45	13.9	1.6	0.1	0.4	1.1	4.4	4.2	20	Machida et al. (1985)
		72.0	0.48	15.3	1.7	0.1	0.5	1.5	4.6	3.8	4	bimodal
K-Tz	90–95	79.0	0.22	12.0	1.1	0.05	0.2	1.0	3.2	3.2	44	Machida and Arai (1992)
Ata	95–110	74.7	0.48	13.5	2.2	0.1	0.5	1.9	4.0	2.8	11	Furuta et al. (1986)
Naju		78.33	0.12	12.22	1.19	0.03	0.13	1.14	3.41	3.41	40	This study
Asan		78.01	0.13	12.69	1.21	0.05	0.13	1.12	3.12	3.56	50	This study
Jeongdongjin		78.44	0.12	12.78	1.19	0.05	0.13	1.12	2.74	3.44	40	This study

The chemical compositions of volcanic glasses found at the Naju and Jeongdongjin Paleolithic sites are nearly identical to those of the AT tephra.

Table 3
Radiocarbon dating results of burrow-fill material

Sample code	Lab. number	Site	Depth from the surface	Materials	Age (^{14}C yr BP)
JG-1	GX 31776	Jeongok	110–123 cm	Burrow fill (clay + passive fill)	20,840 ± 450
JG-2	GX 31777	Jeongok	216–230 cm	Burrow fill (passive fill)	30,490 + 4760–2590
Y-B1	GX 31778	Yeoju	50 cm	Burrow fill (clay)	17,600 ± 610
Y-B2	GX 31779	Yeoju	150 cm	Burrow fill (clay + passive fill)	> 36,540
YPB-1	GX 31780	Yongin	50 cm	Burrow fill (clay)	21,470 ± 700

interpret the radiocarbon ages properly. Sample JG-2 is a passively-filled soil sample, but two samples (Y-B1 and YPB-1) are laminated clay samples that settled out from stagnant waters after the burrows were abandoned. Two other samples (JG-1 and Y-B2) are mixtures of laminated clays and passive fills. Since the deposition of laminated clays was preceded by the passive infill of soil materials (Lim et al., 2004; Fig. 3A), the radiocarbon ages of laminated clay samples are generally younger than those of the passive-fill samples.

Within the upper soil-wedge layer (Fig. 2), the presence of AT tephras dating to ca. 25,000 yr (Machida and Arai, 1992; Machida, 1999; Miyairi et al., 2004) was identified in the Asan, Naju and Jeongdongjin areas. In addition, the AT tephra has also been found at several archaeological sites including the Jeongok site (Yi et al., 1998; Danhara et al., 2002). Among the widespread tephra deposits the rhyolitic AT tephra is the most prominent marker-tephra of the late Pleistocene, and it occurs extensively on land and in marine sediments around Japan and Korea (Machida and Arai, 1992; Machida, 1999). The AT tephra can be used as an important time-marker indicating sediments of the last glaciation of the late Pleistocene (Machida, 1999). Because the vertebrate burrow-bearing layer is positioned stratigraphically below the soil-wedge horizon containing AT tephra, the minimum age of the burrowing event is constrained at ca. 25,000 yr by the age of the AT tephra (Table 4).

Except for the AS-1 sample, all samples for OSL dating were taken from horizons below the burrow-bearing layer (Fig. 2). Most of these samples have OSL ages between 40,000 and 65,000 yr. Such consistency in ages strongly indicates that the age of the widespread vertebrate burrow-bearing layers in late Pleistocene paleosols in Korea is younger than 40,000 yr. Taken together, our results indicate that the age of the burrow-bearing layer is between ca. 40,000 and 25,000 yr. We suggest that this burrow-bearing layer can be used as a time-marker in late Pleistocene paleosol sequences from Korea. Additionally, it has been recognized that relatively cold climate prevailed in Korea during this period (MIS 3−2). While there is no direct evidence to show a positive correlation between the climate and burrow density, it is quite likely that high burrow abundance may reflect the severe climatic conditions during this period. The age, architecture, and size of these burrows in Korea are remarkably similar to those of the *Citellus* zone in Nebraska (ca. 22,000 to 40,000 yr), which is defined as a regionally extensive biohorizon with abundant burrows and remains of ground squirrels and other rodents (Tobin, 2004a, 2004b). Although further study is needed to clarify the affinities of these burrows, the synchronous occurrence and architectural resemblance of burrows in both regions (NE Asia and N. America) may suggest a similar burrower as well as similarities in paleoclimatic and paleoenvironmental conditions during this cold period.

Conclusions

A vertebrate burrow-bearing layer, produced by rodent-like mammals, is commonly found at many Paleolithic archaeological sites in Korea. The usefulness of this burrow-bearing layer

Table 4
Summary of OSL dates

Sample Code	Materials	Dose rate (Gy/ka)	Equivalent dose (Gy)	Water content (%)	Aliquots used (n)	OSL age* (ka)	Site
JG-HT1	Sand	4.15 ± 0.10 (3.88 ± 0.09)	224.31 ± 10.71	16.6 (23.8)	18	54.0 ± 2.9 (57.8 ± 3.1)	
JG-HT3	Sand	4.07 ± 0.10 (3.37 ± 0.08)	164.41 ± 12.04	13.3 (34.1)	18	40.4 ± 3.1 (48.8 ± 3.8)	Jeongok
JG-HT4	Sand	4.29 ± 0.10 (4.09 ± 0.09)	199.80 ± 14.30	14.8 (19.6)	18	46.6 ± 3.5 (48.9 ± 3.7)	
YJ-1	Sand	3.93 ± 0.09 (3.86 ± 0.09)	221.38 ± 12.00	19.8 (21.8)	16	56.4 ± 3.3 (57.4 ± 3.4)	
YJ-2	Sand	4.15 ± 0.09 (4.07 ± 0.09)	225.00 ± 4.61	22.9 (25.0)	16	54.3 ± 1.7 (55.3 ± 1.7)	Yeoju
YJ-3	Sand	3.59 ± 0.08 (3.53 ± 0.08)	233.98 ± 19.00	23.2 (25.2)	16	65.1 ± 5.5 (66.3 ± 5.6)	
AS-1	Soil (SW layer)	2.88 ± 0.07 (2.82 ± 0.07)	83.52 ± 2.52	27.3 (29.5)	15	29.0 ± 1.6 (29.6 ± 1.2)	
AS-4	Soil	3.31 ± 0.09 (3.25 ± 0.09)	189.57 ± 9.76	27.6 (29.7)	15	57.3 ± 3.3 (58.4 ± 3.4)	Asan
AS-5	Soil	3.05 ± 0.08 (2.98 ± 0.08)	181.21 ± 11.32	26.6 (29.4)	15	59.5 ± 4.0 (60.9 ± 4.1)	
YQ3-12	Soil	2.80 ± 0.07 (2.76 ± 0.07)	169 ± 15	26.2 (27.9)	8	60 ± 6 (61 ± 6)	Naju
H-1	Sand	2.77 ± 0.07 (2.76 ± 0.07)	150.7 ± 7.7	20.1 (20.6)	15	54.5 ± 3.1 (54.7 ± 3.1)	Hwasun

AS-1 (Asan) sample was collected from slightly below the soil-wedge (SW) layer. Others were taken from horizons below the vertebrate burrow-bearing layers (see Fig. 2).

* Numbers in bracket indicate the values calculated on the basis of the saturated water content.

as a characteristic stratigraphic unit is demonstrated by the presence of high burrow abundance at these sites, consistent burrow stratigraphic position and lack of stratigraphic recurrence at such sites, and widespread geographic extent throughout Korea. In order to establish the age of the burrowing event(s), burrow-fill materials and sediments taken from the horizons directly below the burrows were dated by radiocarbon and OSL techniques. AT tephra (ca. 25,000 yr) was identified in the soil-wedge layer overlying the burrow-bearing layer. The eruption age of the AT tephra, and the OSL ages of sediments below the burrowed horizon, constrain the minimum and maximum ages of the burrowing event. The dating results indicate that the geologic age of this burrow-bearing layer is ca. 40,000–25,000 yr (MIS 3−2). Therefore we suggest that this burrow-bearing layer can be used as a stratigraphic time-marker in late Pleistocene paleosol sequences in Korea. Because this vertebrate burrow-bearing layer is easily identified in the field, this time-marker is expected to prove very useful to Quaternary geologists and Paleolithic archaeologists in this region.

Acknowledgments

This work was supported by a grant from the Korea Science & Engineering Foundation (R01-2003-000-10592-0), and the Korea Polar Research Institute (PE07010 to H.S. Lim). We are grateful to Drs. Grant D. Zazula and Robert J. Tobin, whose comments greatly improved the manuscript. Of great help were the comments by the editors Drs. Bax R. Barton and Derek Booth. We wish also to thank Jeong Cheol Lee (Gijeon Institute of Cultural Properties) and Hwan Il Kim (Jungang Research Institute of Cultural Heritage) for support in the field.

References

Allen, J.R.L., Williams, B.T., 1981. Beaconites antarcticus: a giant channel-associated trace fossils from the Lower Old Red Sandstone of South Wales. The Welsh Geological Journal 16, 255–269.

Bøtter-Jensen, L., Bulur, E., Duller, G.A.T., Murray, A.S., 2000. Advances in luminescence instrument systems. Radiation Measurements 32, 523–528.

Carson, E.C., Fournelle, J.H., Miller, T.P., Mickelson, D.M., 2002. Holocene tephrochronology of the Cold Bay area, southwest Alaska Peninsula. Quaternary Science Reviews 21, 2213–2228.

Danhara, T., Bae, K., Okada, T., Matsufuji, K., Hwang, S., 2002. What is the real age of the Chongokni Paleolithic site? A new approach by fission track dating, K–Ar dating and tephra analysis. In: Bae, K., Lee, J. (Eds.), Paleolithic Archaeology in Northeast Asia. Yeoncheon County and the Institute of Cultural Properties, Hanyang University, pp. 77–116.

Furuta, T., Fujioka, K., Arai, F., 1986. Widespread submarine tephras around Japan—Petrographic and chemical properties. Marine Geology 72, 125–142.

Groenewald, G.H., Welman, J., MacEachern, J.A., 2001. Vertebrate burrow complexes from the Early Triassic Cynognathus Zone (Driekoppen Formation, Beaufort Group) of the Karoo Basin, South Africa. Palaios 16, 148–160.

Hasiotis, S.T., Wellner, R.W., Martin, A.J., Demko, T.M., 2004. Vertebrate Burrows from Triassic and Jurassic Continental Deposits of North America and Antarctica: their paleoenvironmental and paleoecological significance. Ichnos 11, 103–124.

Kim, J.Y., 2001. Quaternary geology and assessment of aggregate resources of Korea for the national industrial resources exploration and development. Quatenary International 82, 87–100.

Laundre, J.W., 1989. Horizontal and vertical diameter of burrows of fine small mammal species in southeastern Idaho. Great Basin Naturalist 49, 646–649.

Lee, D.-Y., 1987. Stratigraphical research of the Quaternary deposits in the Korean Peninsula. The Korean Journal of Quaternary Research 1, 3–20.

Lee, Y.I., Yi, S., 2002. Characteristics of Pyeongchang-ri Paleolithic-site paleosols, Yongin-si, Gyeonggi-do, Korea: implications for archaeogeolgoical application. Journal of the Geological Society of Korea 38, 471–489.

Lim, H.S., Lee, Y.I., Lee, Y.W., Yi, S., Chang, S., Kim, C.-B., 2004. A preliminary study of large burrows at Jeongok and Naju Paleolithic sites, Korea. Journal of Geological Society of Korea 40, 559–566.

Machida, H., 1999. The stratigraphy, chronology and distribution of distal marker-tephras in and around Japan. Global and Planetary Change 21, 71–94.

Machida, H., Arai, F., 1992. Atlas of Tephra in and Around Japan. University of Tokyo Press. 276 pp.

Machida, H., Arai, F., Momose, M., 1985. Aso-4: a widespread tephra and its implications to the events of Late Pleistocene in and around Japan. Bulletin of the Volcanological Society of Japan 30, 49–70.

Martin, L.D., Bennett, D.K., 1977. The burrows of the Miocene beaver *Palaeocastor*, western Nebraska, U.S.A. Palaeogeography, Palaeoclimatology, Palaeoecology 22, 173–193.

Miller, M.F., Hasiotis, S.T., Babcock, L.E., Isbell, J.L., Collinson, J.W., 2001. Tetrapod and large burrows of uncertain origin in triassic high paleolatitude floodplain deposits, Antarctica. Palaios 16, 218–232.

Miyairi, Y., Yoshida, K., Miyazaki, Y., Matsuzaki, H., Kaneoka, I., 2004. Improved ^{14}C dating of a tephra layer (AT tephra, Japan) using AMS on selected organic fractions. Nuclear Instruments and Methods in Physics Research B 223–224, 555–559.

Murray, A.S., Wintle, A.G., 2000. Luminescence dating of quartz using an improved single-aliquot regenerative-dose protocol. Radiation Measurements 32, 57–73.

Murray, A.S., Martin, R., Jonston, A., Martin, P., 1987. Analysis for naturally occurring radionuclides at environmental concentrations by gamma spectrometry. Journal of Radioanalytical and Nuclear Chemistry Articles 115, 263–288.

Olley, J.M., Murray, A.S., Roberts, R.G., 1996. The effects of disequilibria in the uranium and thorium decay chains on burial dose rates in fluvial sediments. Quaternary Science Reviews (Quaternary Geochronology) 15, 751–760.

O'Sullivan, M.J., Cooper, M.A., MacCarthy, L.A.J., Forbes, W.H., 1986. The paleoenvironment and deformation of Beaconites-like burrows in the Old Red Sandstone at Gortnsbinna, SW Ireland. Journal of the Geological Society of London 143, 897–906.

Özkurt, Ş, Yiğit, N., Çolak, E., Sözen, M., Gharkheloo, M.M., 2005. Observations on the ecology, reproduction and behavior of *Spermophilus* Bennett, 1835 (Mammalia: Rodentia) in Turkey. Turkish Journal of Zoology 29, 91–99.

Reichman, O.J., Smith, S.C., 1987. Burrows and burrowing behavior by mammals. Current Mammalogy 2, 197–235.

Shin, J.-B., 2004. Loess–paleosol stratigraphy of Dukso and Hongcheon areas and correlation with Chineseloess–paleosol stratigraphy: application of Quaternary loess–paleosol stratigraphy to the Chongokni Paleolithic site. Ph.D. dissertation, Yeonsei University, Seoul, 200 p.

Smith, R.M.H., 1987. Helical burrow casts of therapsid origin from the Beaufort Group (Permian) of South Africa. Palaeogeography, Palaeoclimatology, Palaeoecology 60, 155-17.

Tobin, R.J., 2004a. Taphonomy of ground squirrel remains in a Late Pleistocene ichnofabric, Nebraska, USA. Palaeogeography, Palaeoclimatology, Palaeoecology 214, 125–134.

Tobin, R.J., 2004b. Ichnology of a late Pleistocene ichnofabric, Nebraska, USA. Palaeogeography, Palaeoclimatology, Palaeoecology 215, 111–123.

Voorhies, M.R., 1975. Vertebrate burrows. In: Frey, R.W. (Ed.), The Study of Trace Fossils. Springer, New York, pp. 325–350.

Westgate, J.A., Briggs, N.D., 1987. Dating methods of Pleistocene deposits and their problems: V. tephrochronology and fission-track dating. In: Rutter, N.W. (Ed.), Dating Methods of Pleistocene Deposits and their Problems. Geoscience Canada Reprint Series, vol. 2, pp. 31–38 (Ottawa).

Yi, S.B., Soda, T., Arai, F., 1998. New discovery of Aira–Tn ash (AT) in Korea. Journal of the Korean Geographical Society 33, 447–454.