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Stratigraphy and age of the human footprints-bearing strata in Jeju Island, Korea: Controversies and new findings

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ABSTRACT

The age of the human footprints found on the bedding plane of a reworked volcaniclastic deposit on Jeju Island, Korea, has been a subject of controversies in Korea for more than a decade. Two researchers that discovered the footprints and their colleagues have argued that the footprints belong to Paleolithic ‘hominids’ that lived in the Late Pleistocene (c. 19,000–25,000 cal yrs BP). They made their argument on the basis of the pre-Holocene radiocarbon ages of humic and humin organic matter in bulk sediment, but have ignored Holocene radiocarbon ages of mollusk shells and other age data from the volcaniclastic deposit and adjacent geologic units. They also refused to correlate the deposit with any well-defined and well-dated stratigraphic units in the study area but correlated it with an imaginary stratigraphic unit which they named “unnamed strata”. This study discusses the problems of their work published in a series of papers in the last decade by reviewing the stratigraphy and age of the geologic units in southwestern Jeju Island and presenting new sedimentologic and stratigraphic observations and new radiocarbon dating of mollusk shells. This study shows that the “unnamed strata” is the basal part of the Songaksan Tuff, which is the rimbeds of a coastal tuff ring that erupted c. 3700 yrs BP, and that the strata at the footprints site comprise the distal Songaksan Tuff at the base and a reworked volcaniclastic deposit (the Hamori Formation) above it. The human footprints, which are found in the topmost part of the Hamori Formation, should therefore postdate the eruption of the Songaksan volcano and belong to late Neolithic ‘humans’ who lived in the mid- to late Holocene.

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1. Introduction

In 2004 the Cultural Heritage Administration of Korea announced that human footprints were found on the bedding plane of a volcaniclastic deposit, named the Hamori Formation, at the southwestern coast of Jeju Island, Korea, together with diverse bird and mammal tracks (see media reports in: Cho, 2004; Huh, 2004). That announcement made a big sensation in Korea because the footprints were tentatively dated to be 50,000 years old and, if the age was correct, the discovery could open a new era of researching Paleolithic human's first movement and settlement on the Korean Peninsula. However, the age of the human footprints was immediately questioned by some geologists because the age was found to have been inferred from the K–Ar age (0.050 ± 0.023 Ma) of a trachybasalt lava inside the crater of a nearby volcano, named Songaksan (Korean Association for Conservation of Natural Heritages, 2002). The Cultural Heritage Administration of Korea thus commissioned a team of geologists and geochronologists in the Korea Institute of Geoscience and Mineral Resources (KIGAM) to investigate the absolute age of the footprints-bearing strata with all available dating techniques at that time. The KIGAM team obtained five ^{14}C ages of mollusk shells that range between 3862 ± 35 and 2995 ± 35 yrs BP, seven ^{14}C ages of humic and humin organic materials within bulk sediment that range between 7318 ± 40 and 15,161 ± 70 yrs BP, and two OSL ages of quartz sand grains of 6.8 ± 0.3 and 7.6 ± 0.5 ka, all from the Hamori Formation (Cho et al., 2005). The KIGAM team discarded the pre-Holocene humic and humin organic carbon ages because of wide age variations and age reversal. More importantly, they discarded the pre-Holocene ages because the footprints-bearing strata formed apparently in a nearshore setting when the sea level was almost identical to that at present. It was not likely that the deposit was uplifted c. 100 m to near the present sea level since its deposition in the pre-Holocene glacial period. The KIGAM team also discarded the mid- to late Holocene mollusk shell ages because they thought that the shells could have been deposited after the formation of the human footprints. They thus chose the quartz OSL ages as the most reliable depositional age of the footprints-bearing strata.

Despite the study of the KIGAM team (Cho et al., 2005) and other earlier and later studies (Kim et al., 1999; Sohn et al., 2002; Cheong et al., 2006; Cheong et al., 2007), which strongly indicate that the deposition of the footprints-bearing strata occurred during the Holocene, a

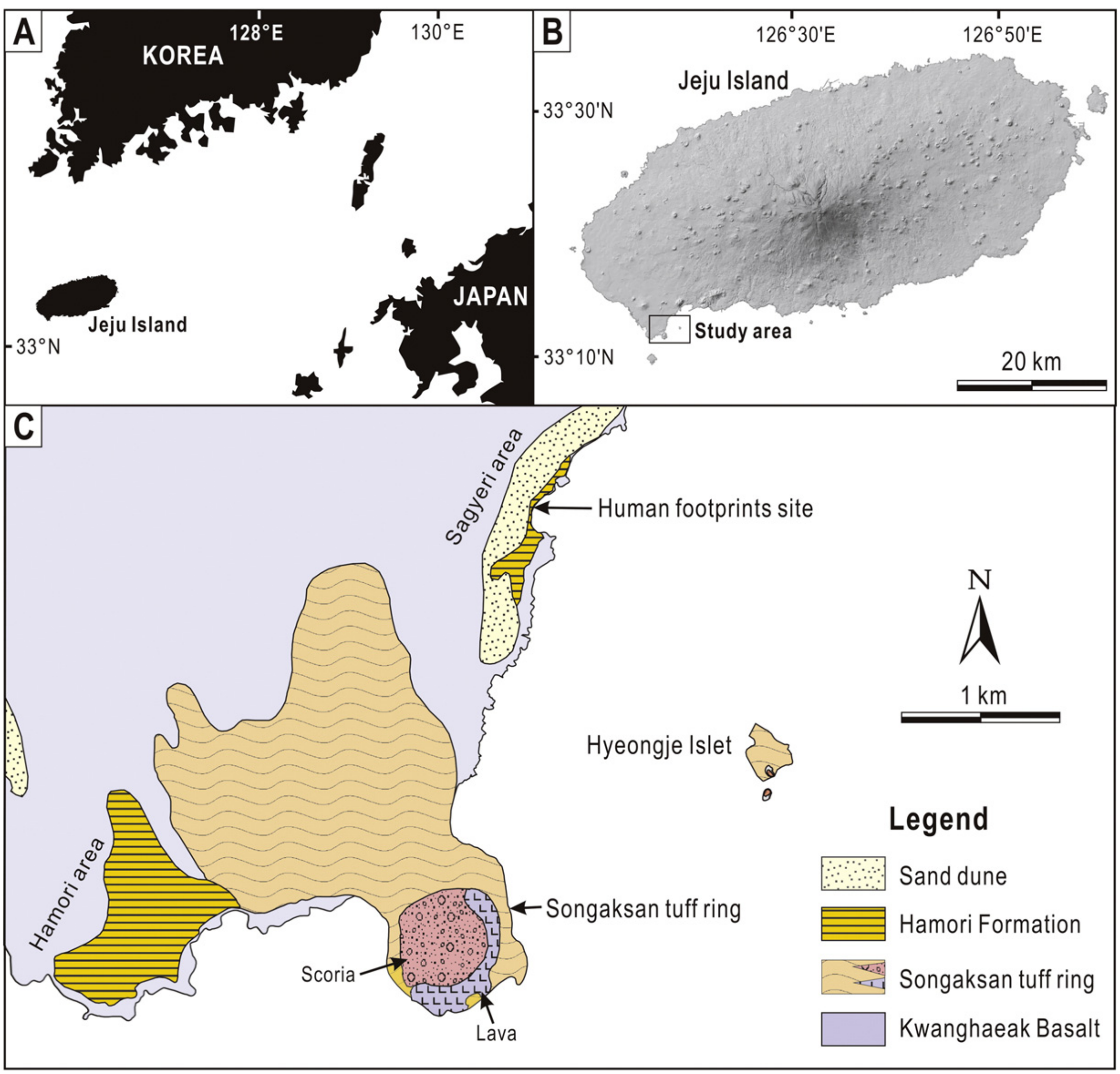


Fig. 1. Location map (A) and digital elevation model (B) of Jeju Island, and the geology (C) of the southwestern part of Jeju Island. After Park et al. (2000).

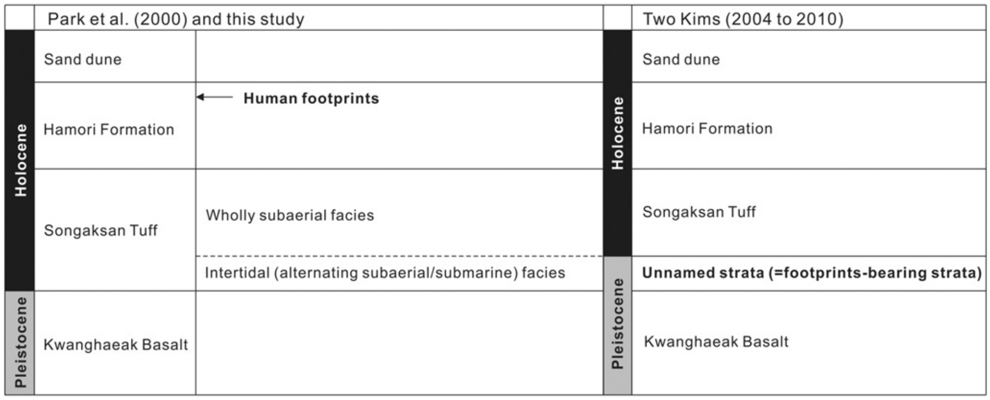


Fig. 2. Comparison of the stratigraphy and age of the strata at southwestern Jeju Island originally defined by Park et al. (2000) with those of the two Kims. This study confirms that the human footprints occur in the uppermost part of the Hamori Formation, whereas the two Kims argue that the footprints-bearing strata are pre-Holocene and correlative with another sedimentary formation, which they named the 'unnamed strata'.

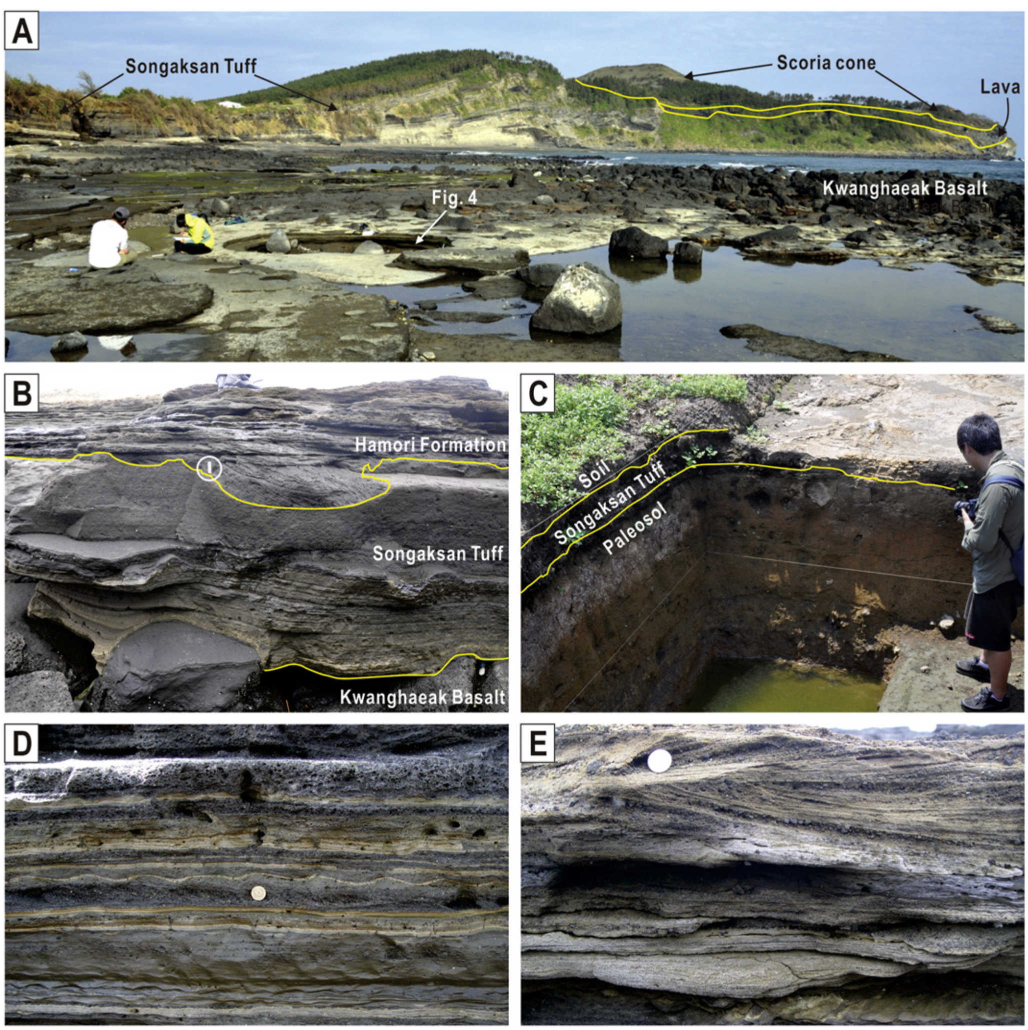


Fig. 3. (A) A view of the Songaksan tuff ring from the western coast during a low tide. The tuff ring has ponded lava and scoria cones inside the crater. The rimbeds of the tuff ring, named the Songaksan Tuff, thin rapidly from about 80 m near the crater rim to <10 cm in the distal areas. The basal portion of the rimbeds overlies the rugged upper surface of the Kwanghaeak Basalt in an intertidal zone, and was named the "unnamed strata" by Kim and Kim (2006). (B) The Songaksan Tuff lies directly upon the Kwanghaeak Basalt and is overlain by the Hamori Formation with a sharp erosional contact. (C) An archeological trench c. 700 m to the northeast of the human footprints site, showing the distal Songaksan Tuff above a paleosol. (D) Ripple cross-laminated tuffaceous sandstones intercalated with continuous mud drapes (light colored layers) within the Hamori Formation. (E) Cross-stratified basaltic tuffaceous pebbly sandstones of the Hamori Formation. The photo scale in B (circled) is 5 cm long. The coin in D and E is 2.3 cm in diameter. See Fig. 5 for the locations of the photographs.

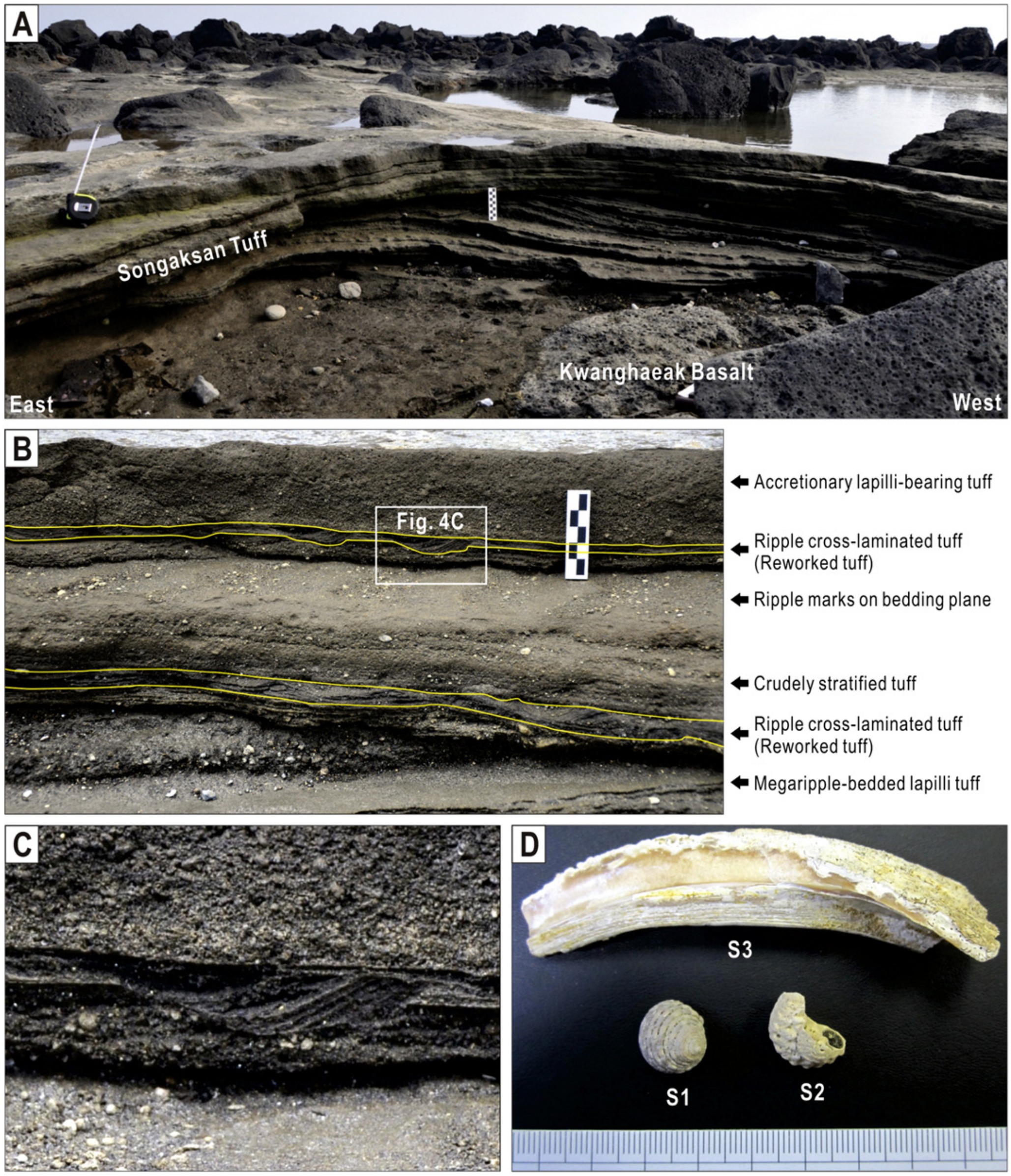


Fig. 4. (A) The lowermost lapilli tuff unit of the Songaksan Tuff upon the Kwanghaeak Basalt shows westward-dipping large-scale cross-stratification produced by a westward-flow pyroclastic surge. (B) Close-up of the planar-bedded tuff above the cross-stratified lapilli tuff of A, consisting of alternating primary and reworked (wave-worked) volcaniclastic deposits. (C) Close-up of the boxed area in B, showing the details of the reworked, ripple cross-laminated tuff. (D) Photograph of three mollusk shell specimens collected from the cross-stratified lapilli tuff of A that were used for radiocarbon dating. The photo scales are graduated in centimeters. The ruler in D is in millimeters. The location of the site is indicated in Fig. 3A.

few workers who discovered the footprints (J.Y. Kim and K.S. Kim; referred to as the 'two Kims' hereafter to avoid confusion with other workers having the same surname) have argued that the footprints were left by Paleolithic 'hominids' who walked along the shore of Jeju Island in the Late Pleistocene (Kim et al., 2004; Kim et al., 2006; Kim and Kim, 2006; Lockley et al., 2008; Kim et al., 2009). Their arguments were based on their conviction that the pre-Holocene organic carbon ages of Cho et al. (2005) are the only acceptable ages from the footprints-bearing strata. Recently they repeated their arguments with new coworkers and with new age data obtained from a deposit which they argue is correlative with the footprints-bearing strata (Kim et al., 2010). Here we review the stratigraphy and age of the volcanic and sedimentary formations in southwestern Jeju Island with new sedimentologic and stratigraphic observations together with new radiocarbon ages, and show that the two Kims' arguments are based on incorrect interpretations of the stratigraphy and age of the geologic formations in this area. We hope this paper can help to clarify the age of the human footprints, change the ideas about the timing of the arrival of hominids in the Korean Peninsula, and establish the Quaternary stratigraphy of southwestern Jeju Island where many Neolithic archeological sites have already been found and are excavated.

Table 1
AMS radiocarbon data for mollusk shell samples from Sohn et al. (2002) (SAS-1 and 2) and this study (S1 to S3).

Sample ID	Radiocarbon age (yrs BP)	$\delta^{13}C$ (‰)	LAB code	Note
SAS-1	3900 ± 100	−0.8	SNU00-216	Bivalve
SAS-2	4090 ± 90	1.5	SNU00-217	Abalone
S1	3740 ± 50	2.90	SNU13-029	Gastropod
S2	4130 ± 60	−1.29	SNU13-030	Gastropod
S3	3720 ± 50	5.00	SNU13-031	Bivalve

2. Geological setting

Jeju Island is the emergent portion of an intraplate basaltic volcanic field developed over the last c. 1.8 Ma on the c. 100-m-deep continental shelf in the southeastern Yellow Sea off the southern coast of the Korean Peninsula (Brenna et al., 2012) (Fig. 1A). The island is c. 70 × 30 km in size and consists of a broad and gently sloping lava shield and a 1950 m-high central peak with steeper flanks (Fig. 1B). The island is also dotted by at least 360 volcanic cones and craters. The earliest evidence for volcanism is represented by the subsurface Seoguipo Formation, which was formed by hydrovolcanic activity between c. 1.8 and 0.5 Ma and consists of numerous superposed phreatomagmatic volcanoes (tuff rings/cones) and intervening volcaniclastic sediments (Sohn and Park, 2004; Sohn et al., 2008). Later volcanic activity was dominated by lava effusion, producing the lava shield dotted by hundreds of volcanic cones and the 1950 m-high central peak (Mt. Hallasan) composed of a lava/dome complex (Brenna et al., 2012, 2015; Koh et al., 2013). Several tuff rings and tuff cones were built upon the lava shield by the hydrovolcanic activity which occurred mainly in the coastal regions in the Late Pleistocene and Holocene (Sohn

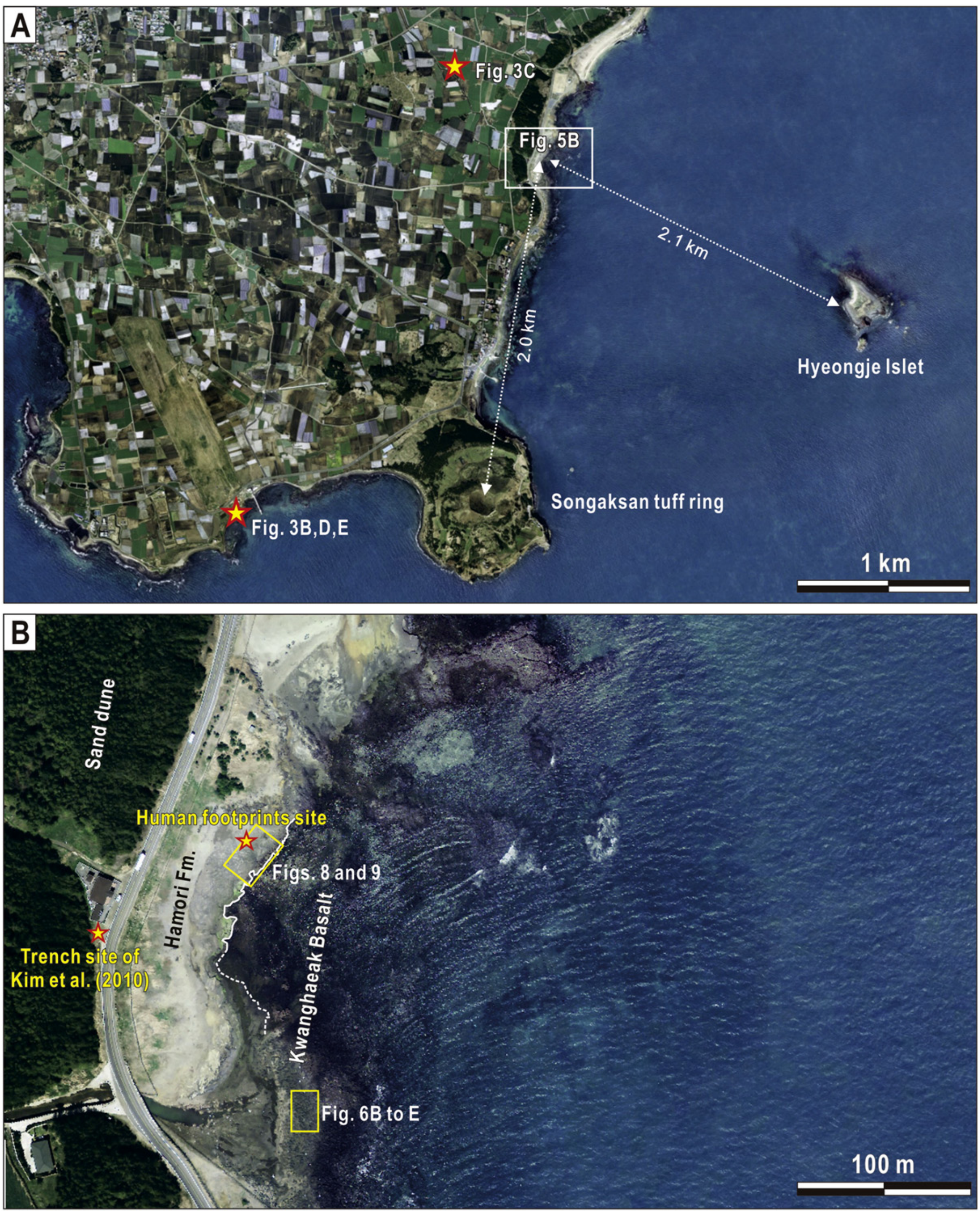


Fig. 5. Aerial view of the southwestern part of Jeju Island (A) and the human footprints site (B). The Kwanghaeak Basalt forms a broad and low-relief plateau upon which the Songaksan Tuff and other thin sedimentary formations accumulated.

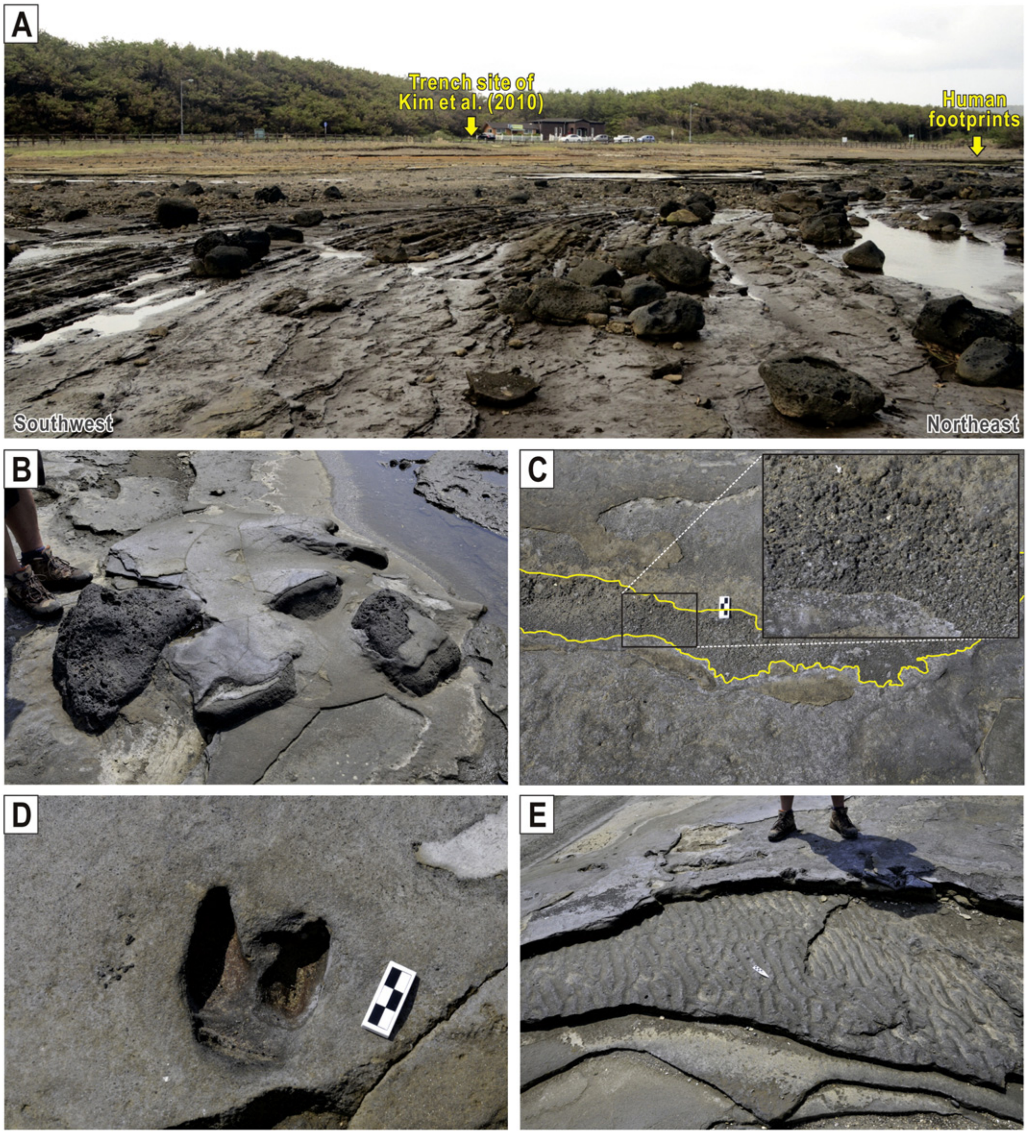


Fig. 6. (A) An overview of the volcaniclastic deposits at the Sagyeri area with the locations of the human footprints and the trench site of Kim et al. (2010), which are exposed mainly on an intertidal wave-cut terrace. Basalt boulders torn from the Kwanghaeak Basalt directly beneath the deposits are scattered on the surface. An aerial view of this area is given in Fig. 5B. (B) Primary airfall tuff bed mantling the protruded basalt blocks of the Kwanghaeak Basalt in the basal part of the volcaniclastic deposits at Sagyeri area. (D) Several centimeter-thick scoria lapilli layer intercalated in the basal part of the volcaniclastic deposits at Sagyeri area. (E) One of many footprints of Artiodactyla (a deer) on the upper surface of a tuff bed in the basal part of the volcaniclastic deposits at Sagyeri area. (B) Wave ripples exposed on the bedding plane of a reworked tuff intercalated between planar- to mantle-bedded primary tuffs with smooth bedding planes in the basal part of the volcaniclastic deposits at Sagyeri area. See Fig. 5B for the locations of the photographs.

et al., 2002; Cheong et al., 2007; Sohn et al., 2012). Historic eruptions in the 11th century are also recorded in ancient literature (Lee and Yang, 2006).

3. Stratigraphy and age

Major geologic units in the southwestern part of Jeju Island include the Kwanghaeak Basalt, the Songaksan Tuff, the Hamori Formation, and modern sand dune from oldest to youngest (Park et al., 2000) (Fig. 1C). The two Kims and their coworkers have argued that there is another sedimentary formation, which they named “unnamed strata”, between the Kwanghaeak Basalt and the Songaksan tuff in a number of papers (Kim et al., 2004; Kim et al., 2006; Kim and Kim, 2006; Kim et al., 2009; Kim et al., 2010) (Fig. 2), of which the true character will be discussed in Sections 4 and 5.

The Kwanghaeak Basalt forms an extensive, low-altitude and low-relief plain in this area, and is overlain by the other geologic formations. ^{40}Ar–^{39}Ar ages for the basalt range between 24.5 ± 112.6 and 148.1 ± 144.6 ka (Cho et al., 2005). Despite the wide age range with large errors, the age of the basalt is in general presumed to be Late Pleistocene.

The Songaksan Tuff is the rimbeds of the Songaksan tuff ring, which is a phreatomagmatic volcano produced by explosive interaction of ascending basaltic magma with surface and ground water in a nearshore environment, containing a scoria cone and ponded trachybasalt lava inside the crater (Chough and Sohn, 1990; Sohn et al., 2002) (Fig. 3A). The Songaksan Tuff extends a few kilometers from the crater, thinning rapidly from c. 80 m near the crater rim to <10 cm in distal areas and actually covering a much larger area than that depicted on the geological map (Fig. 1C). The tuff directly overlies the Kwanghaeak Basalt on coastal exposures (Fig. 3A, B) or overlies a meter-thick paleosol layer above the basalt in artificial trenches and archeological excavation sites in inland areas (Fig. 3C). OSL dating of quartz sand grains within the tuff that were accidentally derived from the sedimentary substrate beneath the volcanic succession of Jeju Island yielded an age of 7.0 ± 0.3 ka (Cheong et al., 2007).

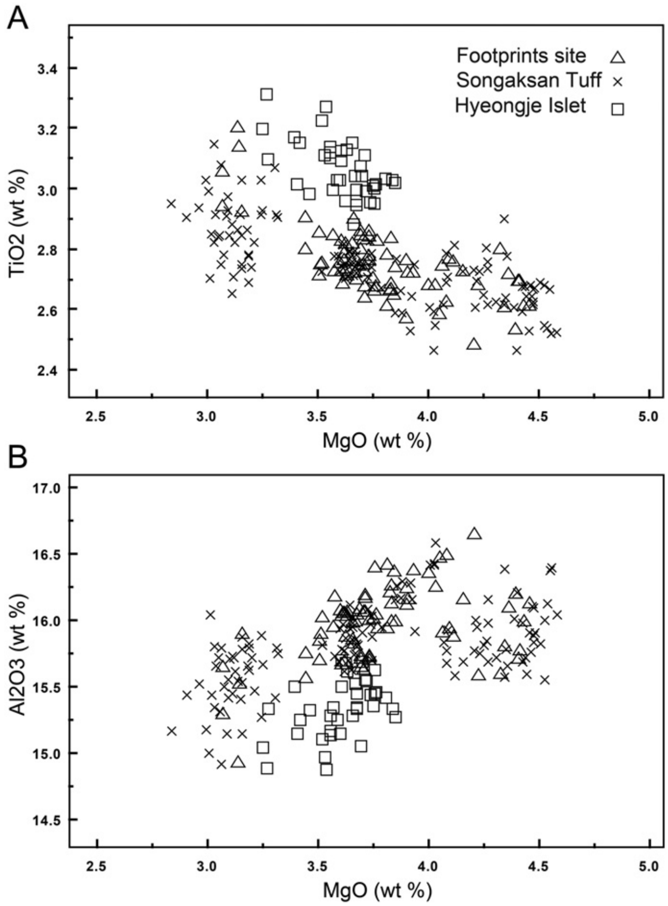


Fig. 7. Geochemical variations of tephras from the footprints site, the Songaksan tuff ring, and the Hyeongje Islet volcano (modified after Ahn et al., 2015). The tephras from the footprints site and the Songaksan tuff ring are not differentiable, whereas those from the Hyeongje Islet volcano have distinctly different geochemical signatures, indicating that the tephras of the footprints site originated from the Songaksan tuff ring.

The Hamori Formation is the product of erosion and reworking of the Songaksan Tuff, which commenced immediately after the eruption of the Songaksan tuff ring. The formation crops out along the northeastern and western coasts of the tuff ring (Fig. 1C), overlying either the distal rimbeds of the tuff ring erosionally (Fig. 3B) or the Kwanghaeak Basalt where the Songaksan Tuff was removed by erosion (Park et al., 2000). The formation exposed along the western coast of the tuff ring is up to a few meters thick and composed mainly of basaltic tuffaceous (pebbly) sandstone and siltstone that show planar stratification, low- to high-angle cross-stratification, climbing ripple and trough cross-lamination, and abundant ripple marks and mud cracks (Fig. 3D, E), suggesting deposition in a high-energy nearshore environment (Sohn et al., 2002). Radiocarbon dating of mollusk shells collected from the base of the formation gave an age of 3900 ± 100 and 4090 ± 90 yrs BP (Sohn et al., 2002) and 3840 ± 40 yrs BP (Cheong et al., 2006). ^{230}Th/^{234}U ages of six shell specimens range between 3434 ± 40 and 4980 ± 33 yrs ($2\sigma_m$) (Cheong et al., 2006). Quartz OSL ages of two specimens from the formation are 5.1 ± 0.3 ka (Cheong et al., 2007).

Although the depositional environment, age, and stratigraphy of the Hamori Formation exposed along the western coast of the Songaksan tuff ring (referred to as the "Hamori area" hereafter; Fig. 1C) were well constrained by detailed sedimentological and age dating studies (Chough and Sohn, 1990; Sohn et al., 2002; Cheong et al., 2006; Cheong et al., 2007), the two Kims have argued that there is another sedimentary formation (i.e., the unnamed strata) in this area between the Kwanghaeak Basalt and the Songaksan tuff (Fig. 2), and that the formation is correlative with the footprints-bearing strata on the northeastern coast of the Songaksan tuff ring (referred to as the "Sagyeri area" hereafter; Fig. 1C). They thereby presume that the human footprints formed much earlier than the eruption of the Songaksan volcano, i.e., in the Late Pleistocene, and have repeated this argument in a series of publications (Kim et al., 2004; Kim et al., 2006; Kim and Kim, 2006; Lockley et al., 2008; Kim et al., 2009; Kim et al., 2010). In an earlier work, the two Kims put forward a wrong hypothesis that the footprints-bearing strata were uplifted c. 100 m from near the shoreline at the Last Glacial Maximum to near the present shoreline in order to explain the occurrence of the "shallow shoreline facies" of the footprints-bearing strata near the present sea level and to defend their hypothesis of Paleolithic hominids (Kim and Kim, 2006). In the following sections, we provide evidence against the hypothesis and argument of Kim and Kim (2006) and their later works, which have been utilized as the reference to the stratigraphy and age of the footprints-bearing strata in the last decade.

4. The "unnamed strata"

Kim and Kim (2006) explain that the "unnamed strata" is a volcaniclastic deposit that is intercalated between the Kwanghaeak Basalt and the Songaksan Tuff in the Hamori area despite the absence of any such stratigraphic unit between them in this area (e.g., Fig. 3A, B). They have also claimed that the existence of the unnamed strata was confirmed not only by their own field observations but also by their personal communications with one of the authors of this paper (YKS). YKS described the occurrence of wave-worked volcaniclastic deposit at the bottom of the Songaksan tuff sequence in an earlier paper (Chough and Sohn, 1990), which is characterized by low- to high-angle cross-stratification and climbing ripple and trough cross-lamination. YKS interpreted these deposit features as resulting from reworking of volcaniclastic materials in a shallow sea when the Songaksan volcano erupted on a basalt plateau partly covered with very shallow sea water (Chough and Sohn, 1990). In 2002 YKS confirmed the occurrence of the reworked volcaniclastic deposit at the base of the Songaksan tuff sequence and explained the nature of the deposit in a personal communication with J.Y. Kim. However, YKS did not confirm the existence of the "unnamed strata", as opposed to the account of Kim and Kim (2006). We reiterate here that it is totally unnecessary to define a new stratigraphic unit between the Kwanghaeak Basalt and the Songaksan Tuff.

In addition to defining an unnecessary stratigraphic unit between the Kwanghaeak Basalt and the Songaksan Tuff, the two Kims have also argued that the "unnamed strata" is much older than the Songaksan Tuff (Fig. 2). They may have made such an interpretation because they were unfamiliar with the generally very short eruption duration of monogenetic volcanoes that commonly lasts only days to months (Simkin and Siebert, 1984, 2000). It is also worth noting that many tuff rings/cones, which commonly form in shallow seas or lakes or along their shores, show subaqueous to subaerial facies transitions (e.g., Sohn et al., 2012). Nevertheless these variations cannot be used to subdivide the rimbeds of a volcano into multiple stratigraphic units or geologic formations. In the following section, it is shown that the "unnamed strata" proposed by the two Kims is part of the Songaksan Tuff and has the same geologic age as the Songaksan Tuff, contrary to the assertion of these workers, who have argued for a Late Pleistocene age of the "unnamed strata" in the last decade.

5. Depositional features and age of the "unnamed strata"

The marine wave-worked basal portion of the rimbeds of the Songaksan tuff ring in the Hamori area, which was named the "unnamed strata" by Kim and Kim (2006), was only briefly described in an earlier paper by YKS because the paper focused on the depositional mechanics of pyroclastic surges on the basis of the facies analysis of subaerial pyroclastic surge deposits (Chough and Sohn, 1990). Recently the

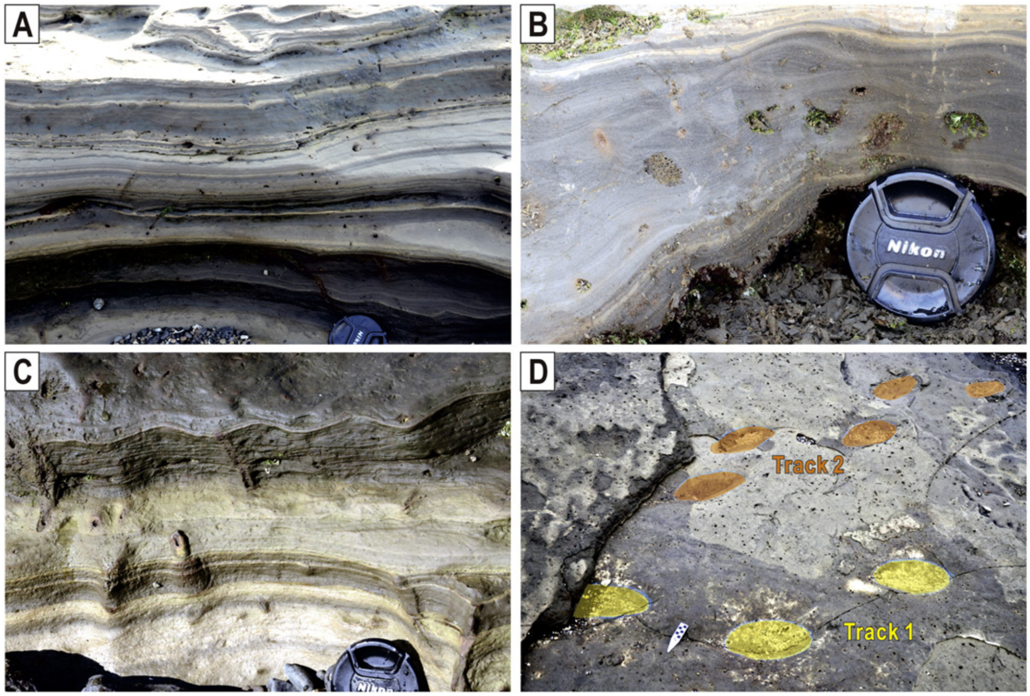


Fig. 8. Deposit features of the Hamori Formation at the Sagyeri area. (A) Parallel-laminated very fine sandstones (dark-colored) alternating with thin mud drapes (light-colored). (B) Climbing ripple cross-laminated very fine sandstone. (C) Parallel-laminated to wave ripple cross-laminated siltstone. (D) The human footprints exposed on the bedding plane in the uppermost part of the Hamori Formation. See Fig. 9 for the locations of the photographs.

basal portion of the rimbeds in the area was examined in detail in the medial to distal reach during low tides (Fig. 3A). This observation reveals that the lowermost depositional unit overlying the Kwanghaeak Basalt consists of primary lapilli tuff that shows large-scale cross-stratification produced by westward-migrating megaripple bedforms (Fig. 4A). The lapilli tuff is therefore interpreted to have been deposited by a westward-flowing pyroclastic surge when the tide was low and the depositional site was exposed above sea level. The lapilli tuff is overlain by a succession of alternating primary and reworked (commonly ripple cross-laminated due to reworking by waves) volcaniclastic deposits (Fig. 4B, C), which is in turn overlain transitionally by primary volcaniclastic deposits that were emplaced in a wholly subaerial condition. The alternating primary and reworked volcaniclastic deposits are interpreted to have resulted from alternating subaerial/submarine deposition and subsequent reworking of tephra in an intertidal zone, whereas the overlying volcaniclastic deposits accumulated by pyroclastic falls and surges above a high tide level in a subaerial condition (Yoon et al., 2013). The gradual facies change from the mixed primary and reworked volcaniclastic deposits at the base into the wholly subaerial, primary volcaniclastic deposits without a hiatus suggests that the whole volcaniclastic sequence, including the "unnamed strata", was produced by a single short-duration eruption of the Songaksan volcano without any significant break in eruption and deposition of tephra.

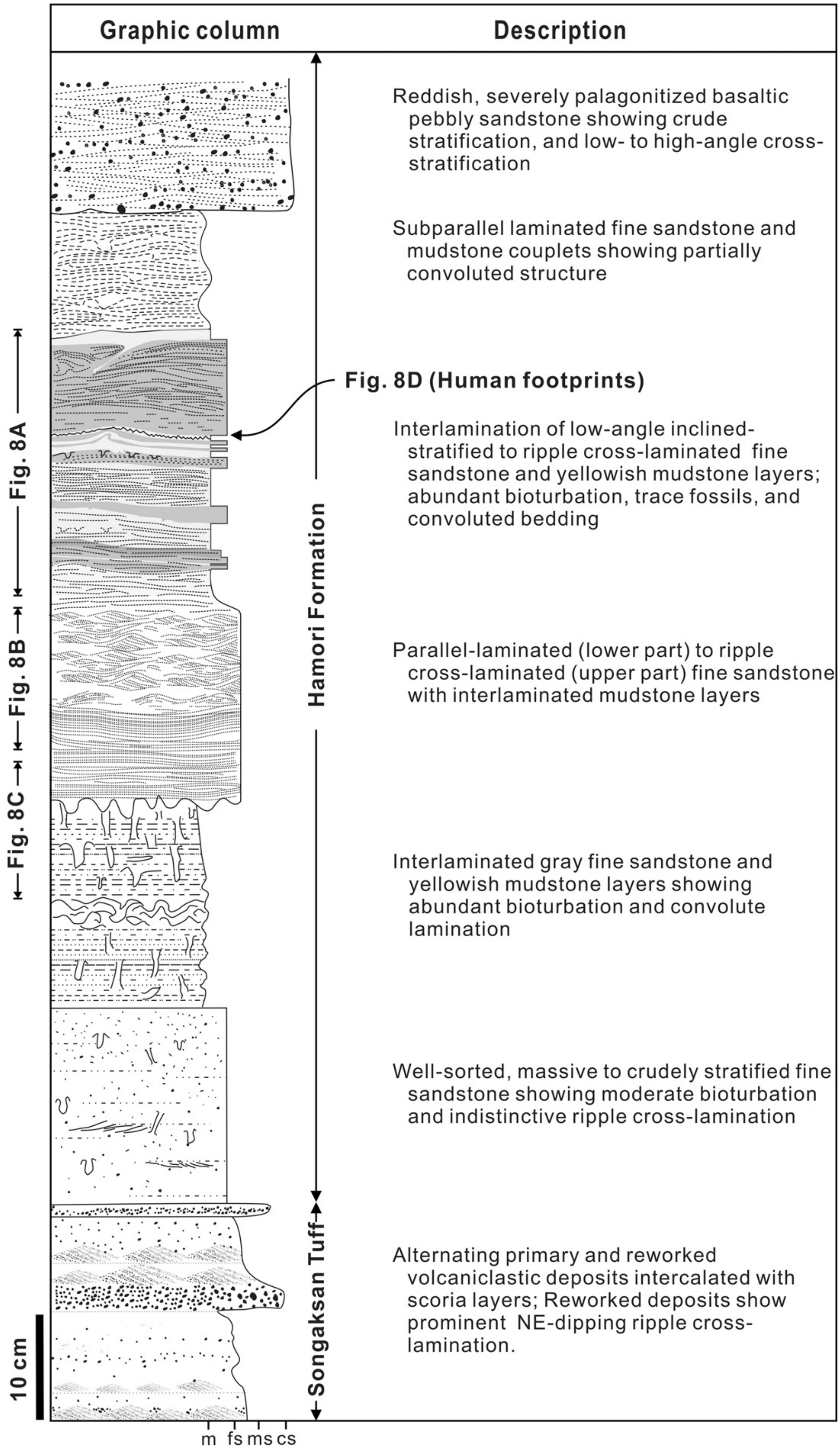
The megaripple-bedded lapilli tuff directly upon the Kwanghaeak Basalt (Fig. 4A) contains fairly abundant mollusk shells that are commonly intact or unbroken. These shells are interpreted to be the remains of the mollusks that have inhabited upon the basalt plateau (Kwanghaeak Basalt), which was periodically exposed during low tides, and have been picked up by the pyroclastic surge and then deposited within the lapilli tuff bed during the earliest eruptive phase of the Songaksan tuff ring. These shells are therefore interpreted to provide the most accurate and reliable age of the onset of the eruption of the Songaksan volcano, thereby providing also the lower age limit of the "unnamed strata".

Radiocarbon dating of three shell specimens (Fig. 4D) collected from the megaripple-bedded lapilli tuff (Fig. 4A) was made at Seoul National University, following the procedures described in Sohn et al. (2002). The radiocarbon ages of the shell specimens were found to be virtually identical to those of the shells collected from the base of the Hamori Formation, ranging between 3720 ± 50 and 4130 ± 60 yrs BP (Table 1). These age data indicate that the onset of the eruption of the Songaksan tuff ring and the onset of deposition of the Hamori Formation were almost contemporaneous on the geological time scale, and that there was only a short time gap between these two events that was beyond the limit of resolution of any presently available dating techniques. This is a reasonable result in view of the short eruption duration of hydromagmatic volcanoes and the immediate reworking of tephra in these volcanoes either in marine or lacustrine environments (e.g., Kokelaar and Durant, 1983; Cole et al., 2001; Németh et al., 2006; Németh and Cronin, 2007). It is also worth noting that the ca. 4 ka ^{14}C age is younger than the previously defined 7 ka OSL age of Cho et al. (2005) and Cheong et al. (2007), redefining the eruption age of the Songaksan volcano.

6. Sedimentology and stratigraphy of the strata at the Sagyeri area

The KIGAM team failed to find suitable materials for radiocarbon dating from the footprints site at the Sagyeri area, such as mollusk shells, charcoal, or plant debris (Cho et al., 2005). They could thus provide only the OSL ages of quartz sand grains and the radiocarbon ages of humic and humin organic materials within bulk sediment for the ages of the human footprints, which were either Holocene or pre-Holocene (Cho et al., 2005). The KIGAM team regarded the strata here to be stratigraphically equivalent to the Hamori Formation in the Hamori area, and obtained a few radiocarbon ages from the shells collected there, which ranged between 3855 ± 35 and 3779 ± 45 yrs BP. Their stratigraphic interpretation and the shell ages were not, however, properly incorporated into their final conclusions regarding the age of the footprints-bearing strata.

The insufficient age data and the lack of detailed sedimentologic and stratigraphic studies at the Sagyeri area have thus led to the controversies and confusion regarding the stratigraphy and age of the footprints-


Graphic column
Description
Reddish, severely palagonitized basaltic pebbly sandstone showing crude stratification, and low- to high-angle cross-stratification
Subparallel laminated fine sandstone and mudstone couplets showing partially convoluted structure
Fig. 8D (Human footprints)
Interlamination of low-angle inclined-stratified to ripple cross-laminated fine sandstone and yellowish mudstone layers; abundant bioturbation, trace fossils, and convoluted bedding
Parallel-laminated (lower part) to ripple cross-laminated (upper part) fine sandstone with interlaminated mudstone layers
Interlaminated gray fine sandstone and yellowish mudstone layers showing abundant bioturbation and convolute lamination
Well-sorted, massive to crudely stratified fine sandstone showing moderate bioturbation and indistinctive ripple cross-lamination
Alternating primary and reworked volcaniclastic deposits intercalated with scoria layers; Reworked deposits show prominent NE-dipping ripple cross-lamination.
Fig. 8A
Fig. 8B
Fig. 8C
Hamori Formation
Songaksan Tuff
10 cm
m
fs
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bearing strata. For example, Kim et al. (2009) gave an account of the strata in the Sagyeri area as if they have a somewhat different lithology from the Hamori Formation by inserting the word 'however' in a sentence, which reads: "*However* (italicized by the authors), the footprints-bearing strata of Sagaeri area on the northeast coast of Mt. Songak is mainly composed of basaltic granule conglomerate, basaltic pebbly sandstone, tuffaceous sandstone, and mudstone" (p. 2, Kim et al., 2009), although they were probably aware of the almost identical description of the Hamori Formation by Sohn et al. (2002), which reads: "The reworked deposits are composed of basaltic pebbly sandstone, basaltic tuffaceous sandstone and siltstone" (p. 11 of Sohn et al., 2002). Kim et al. (2009) also stated that the depositional environment of the strata at the Sagyeri area was a "shallow shoreline environment" with the implication that the "shallow shoreline environment" is somewhat different from the "nearshore environment", which was inferred for the depositional setting of the Hamori Formation in the Hamori area (Sohn et al., 2002). We agree that there was a difference in the wave regime between the Hamori and Sagyeri areas, resulting in some differences in depositional features, but we assert that subtle differences in deposit features cannot be the basis of the argument that the strata at the Sagyeri area and those at the Hamori area are stratigraphically different units. We think that much of these controversies can be resolved by proper sedimentologic and stratigraphic analysis of the previously unstudied strata at the Sagyeri area.

The footprints-bearing strata at the Sagyeri area are exposed mostly on a wave-cut bench, covering the Kwanghaeak Basalt and barely emergent above the high tide level (Figs. 5 and 6A). The basal portion of the strata, less than a meter thick, consists of mixed primary and reworked volcaniclastic deposits. The primary volcaniclastic deposits mantle the irregular upper surface of the Kwanghaeak Basalt (Fig. 6B). Continuous layers of accretionary lapilli or scoria lapilli are rarely intercalated (Fig. 6C). Footprints of mammals (Artiodactyla) are also found upon the bedding planes of the tuff (Fig. 6D). On the other hand, the reworked volcaniclastic deposits show ripple cross-lamination in cross-section and straight- to sinuous-crested ripple marks on the upper bedding planes (Fig. 6E), suggesting reworking of tephra by waves. This association of structures indicates that that the basal portion of the strata here was deposited by distal fallout of tephra upon the Kwanghaeak Basalt in association with reworking of the tephra in an intertidal zone. In other words, the deposition of these strata was coeval with the eruption of a volcano that supplied basaltic ash and rare scoria lapilli to the depositional site by primary pyroclastic processes.

Two possible sources of the tephra are the Songaksan tuff ring and a small islet named Hyeongje, which are the nearest volcanic edifices to the footprints site located c. 2 km to the south and the southeast, respectively (Fig. 5A). Hyeongje Islet is a severely dissected phreatomagmatic volcano with the similar lithology and stratigraphy of volcanic rocks to those of Songaksan, and could have supplied the tephra to the depositional site. Comparison of the major element compositions of the basaltic glass grains collected from a number of horizons of the footprints-bearing strata and these two volcanoes reveals that the tephra at the Sagyeri area has the same chemical composition as that of the Songaksan tuff ring (Fig. 7), of which a very detailed geochemical study has been carried out recently (Brenna et al., 2011). The Songaksan tuff ring is therefore interpreted to have been the major source of materials for either the primary or the reworked volcaniclastic deposits at the Sagyeri area, as it was for the Hamori area. In other words, the basal portion of the strata at the Sagyeri area, composed of mixed primary and reworked volcaniclastic deposits, is correlative with the Songaksan Tuff.

The remaining upper portion of the strata at the Sagyeri area is interpreted to be post-eruptive deposits that are correlative with the Hamori Formation, as originally defined by Park et al. (2000). It is in general finer-grained and better-sorted than the Songaksan Tuff at the base, consisting of very fine-grained tuffaceous sandstones, siltstones, and mudstones. The deposits are thin-bedded to laminated (Fig. 8A) and commonly climbing ripple cross-laminated (Fig. 8B) or wave ripple cross-laminated (Fig. 8C). Vertebrate and invertebrate trace fossils are much more abundant and diverse than in the basal portion, as described by Kim et al. (2009). The human footprints (Fig. 8D) are found at one horizon in the uppermost part of the succession (Fig. 9).

The overall fine grain size and the rarity of wave-generated structures and truncation surfaces in the Hamori Formation at the Sagyeri area suggest that the intertidal region was subject to weaker wave activity than at the Hamori area. This could have been due to the construction of the Songaksan volcano in the south, and possibly the Hyeongje Islet volcano in the southeast, which might have created a wave-protected, bay-like environment at the Sagyeri area. The supply of reworked volcaniclastic materials from the Songaksan volcano also appears to have decreased progressively with time after the cessation of the eruption of the volcano. As a result, the relative proportion of the sedimentary (= epiclastic) materials derived from inland areas is likely to have increased with time. The very low $\delta^{13}C$ values of the radiocarbon-dated organic matter from the footprints-bearing strata, which range between −27.00 to −33.43‰ (Cho et al., 2005), appear to indicate the derivation of the organic matter mainly from terrestrial sources (Lamb et al., 2006).

7. Problems with the trench section stratigraphy and ages of Kim et al. (2010)

Recently Kim et al. (2010) reported new radiocarbon ages of bulk sediment from a trench that was dug c. 80 m southwest of the footprints site, near the landward limit of the Hamori Formation (Figs. 5B and 6A). They explain that the trench section is divided into the Kwanghaeak Basalt, the "footprints-bearing strata" [We put quotation marks for the arbitrarily defined footprints-bearing strata in the trench section of Kim et al. (2010) to distinguish them from the actual footprints-bearing strata exposed on the Sagyeri coast], the "Hamori Formation" [We also put quotation marks for the Hamori Formation conceived by Kim et al. (2010) to distinguish it from the Hamori Formation defined by Park et al. (2000).], a paleosol layer, and sand dune in ascending order. They do not, however, explain how they defined or recognized the "footprints-bearing strata" and the "Hamori Formation" in the trench section and how they correlated these strata with the actual footprints-bearing strata and what they think is the Hamori Formation.

As already mentioned in Section 6, our observations of the stratigraphy and sedimentology of the strata at the Sagyeri area indicate that the basal portion of the strata can be correlated with the Songaksan Tuff and the rest with the Hamori Formation if we stick to the original definition of the formation (Fig. 9). The human footprints also occur obviously in the uppermost part of the Hamori Formation (Fig. 9). This is not an interpretation or an inference, but an actual observation that was made in-situ at the site of the footprints. We haven't found any reason to subdivide the Hamori Formation into the "footprints-bearing strata" and the "Hamori Formation", as has been done by Kim et al. (2010) and by the two Kims in their earlier papers (Fig. 2). Our observations show clearly that the "footprints-bearing strata" belong to the uppermost part of the "Hamori Formation" (Fig. 9). The trench section stratigraphy of Kim et al. (2010), which placed the "Hamori Formation" above the "footprints-bearing strata", is therefore erroneous. Without proper sedimentological/lithological description and stratigraphic analysis or

Fig. 9. Columnar log of the volcaniclastic deposits at the footprints site (= Sagyeri area), which consist of the thin basal portion of alternating primary to reworked volcaniclastic deposits that can be correlated with the Songaksan Tuff and the middle to upper portion consisting of reworked and generally fine-grained volcaniclastic fine sandstones, siltstones and mudstones that can be correlated with the Hamori Formation. See Fig. 5B for the location of the column.

correlation of the trench deposit, the radiocarbon ages of Kim et al. (2010) cannot be used to infer the age of the human footprints.

The very low $\delta^{13}C$ values of the radiocarbon-dated organic matter from the trench section (Kim et al., 2010), similar to those from the actual footprints-bearing strata (Cho et al., 2005), further question whether the organic matter ages can be equated with the deposition age of the strata, since these organic matters are most likely terrestrial in origin (Lamb et al., 2006) and could have been reworked for a long time prior to deposition at the trench site. As stated in Kim et al. (2010), radiocarbon dating of bulk sediment should be used when reliable materials, such as wood, charcoal, or plant macrofossils are not available for analysis. Kim et al. (2010), however, avoided dating or providing the radiocarbon ages of the mollusk shells, which are probably the most reliable materials for radiocarbon dating at the trench site, even though they had found “a lot of shell fragments” at the bottom of the trench. They justify their decision by stating that the shell fragments are “modern” and transported somehow by “an inflow of seawater through a cavity”. We question how they found that the shell fragments are modern, and how the shell fragments could be transported to the bottom of the trench section by an inflow of seawater through a cavity. We assume that the “modern” shell fragments at the bottom of the trench have similar radiocarbon ages to those found at the bottom of the Songaksan Tuff or the Hamori Formation. Irrespective of the radiocarbon ages of the shells, however, the stratigraphy of the footprints site indicate clearly that the human footprints are younger than the “modern” shell fragments, unless the shell fragments were really transported by “an inflow of seawater through a cavity”.

8. Conclusions

Two Korean geologists who discovered the human footprints on a volcaniclastic sedimentary deposit on Jeju Island have argued that the footprints belong to Paleolithic ‘hominids’ that lived in the Late Pleistocene (c. 19,000–25,000 cal yrs BP in their most recent paper) with their coworkers in the last decade (Kim et al., 2004; Kim et al., 2006; Kim and Kim, 2006; Kim et al., 2008; Lockley et al., 2008; Kim et al., 2009; Kim et al., 2010). Their arguments for the age were mainly based on the mostly pre-Holocene radiocarbon ages of humic and humin organic matter within bulk sediment, which was apparently derived from terrestrial sources and is not suitable to infer the deposition age of the footprints-bearing strata. Radiocarbon ages of mollusk shells, which can provide the most reliable ages for Late Pleistocene to Holocene specimens and have been obtained by a number of workers (e.g., Sohn et al., 2002; Cho et al., 2005; Cheong et al., 2006), were ignored by these workers probably because the mid- to late Holocene shell ages contradict their hypothesis of Paleolithic ‘hominids’. Shell fragments at the trench site have provided an opportunity to secure further accurate radiocarbon dates (Kim et al., 2010), but it is disappointing that to date, this opportunity has not been realized.

We conclude that the stratigraphic unit named the “unnamed strata” (Kim and Kim, 2006) is the basal part of the Songaksan Tuff, which is the rimbeds of a coastal tuff ring that formed c. 3700 yrs BP. New sedimentologic observations of the strata at the footprints site also indicate that the footprints-bearing strata belong to the upper part of the Hamori Formation, which consists of posteruptive and reworked volcaniclastic deposits above the distal Songaksan Tuff. The human footprints cannot therefore be older than c. 3700 yrs BP. The footprints should therefore be attributed to Neolithic or later ‘humans’ who lived in the mid- to late Holocene on Jeju Island.

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References

Ahn, U.S., Sohn, Y.K., Yoon, W.S., Ryu, C.K., Jeong, J.O., Kang, C.W., 2015. Geochemical fingerprinting of basaltic glass in tephra deposits underlying the human footprints-bearing strata in Jeju Island, Korea: provenance of tephra and age of the human footprints. J. Geol. Soc. Korea 51, 105–126 (in Korean with English abstract).
Brenna, M., Cronin, S.J., Nemeth, K., Smith, I.E.M., Sohn, Y.K., 2011. The influence of magma plumbing complexity on monogenetic eruptions, Jeju Island, Korea. Terra Nova 23, 70–75.
Brenna, M., Cronin, S.J., Smith, I.E.M., Sohn, Y.K., Maas, R., 2012. Spatio-temporal evolution of a dispersed magmatic system and its implications for volcano growth, Jeju Island Volcanic Field, Korea. Lithos 148, 337–352.
Brenna, M., Cronin, S.J., Kereszturi, G., Sohn, Y.K., Smith, I.E.M., Wijbrans, J., 2015. Intraplate volcanism influenced by distal subduction tectonics at Jeju Island, Republic of Korea. Bull. Volcanol. 77, 7.
Cheong, C.S., Choi, M.S., Khim, B.K., Sohn, Y.K., Kwon, S.-T., 2006. $^{230}Th/^{234}U$ dating of Holocene mollusk shells from Jeju Island, Korea, by multiple collectors inductively coupled plasma mass spectrometry. Geosci. J. 10, 67–74.
Cheong, C.S., Choi, J.H., Sohn, Y.K., Kim, J.C., Jeong, G.Y., 2007. Optical dating of hydromagmatic volcanoes on the southwestern coast of Jeju Island, Korea. Quat. Geochronol. 2, 266–271.
Cho, M.-G., 2004. Fossil footprints indicate ancient Jeju human life, Korea Joongang Daily, Seoul. http://koreajoongangdaily.joins.com/news/article/article.aspx?aid=2093310.
Cho, D.-L., Park, K.-H., Jin, J.-H., Hong, W., 2005. Age constraints on human footmarks in Hamori Formation, Jeju Island, Korea. J. Petrol. Soc. Korea 14, 149–156 (in Korean with English abstract).
Chough, S.K., Sohn, Y.K., 1990. Depositional mechanics and sequences of base surges, Songaksan tuff ring, Cheju Island, Korea. Sedimentology 37, 1115–1135.
Cole, P.D., Guest, J.E., Duncan, A.M., Pacheco, J.-M., 2001. Capelinhos 1957–1958, Faial, Azores: deposits formed by an emergent surtseyan eruption. Bull. Volcanol. 63, 204–220.
Huh, M.-M., 2004. Discovery of 50,000 year-old human footprint, The Dong-A Ilbo, Seoul. http://english.donga.com/srv/service.php3?biid=2004020774708.
Kim, K.S., Kim, J.Y., 2006. Review on the stratigraphy and geological age of the Hominid footprints-bearing strata, Jeju Island, Korea. J. Korean Earth Sci. Soc. 27, 236–246 (in Korean with English abstract).
Kim, K.H., Tanaka, T., Nakamura, T., Nagao, K., Youn, J.S., Kim, K.R., Yun, M.Y., 1999. Paleoclimatic and chronostratigraphic interpretations from strontium, carbon and oxygen isotopic ratios in molluscan fossils of Quaternary Seoguipo and Shinyangri Formations, Cheju Island, Korea. Palaeogeogr. Palaeoclimatol. Palaeoecol. 154, 219–235.
Kim, J.Y., Kim, K.S., Lee, C.Z., Lim, J.D., 2004. Occurrence of hominid and other vertebrate footprints of Jeju Island, Korea. In: Kim, J.Y., Kim, K.S., Park, S.I., Shin, M.K. (Eds.), Proceedings of International Symposium on the Quaternary Footprints of Hominids and Other Vertebrates, Namjejugun, Jeju, pp. 1–26.
Kim, J.Y., Kim, K.-S., Kim, S.H., 2006. A fossil feather from the Late Pleistocene deposits in Jeju Island, Korea. J. Korean Earth Sci. Soc. 27, 579–584.
Kim, J.Y., Kim, K.S., Lockley, M.G., Matthews, N., 2008. Homidid ichnotaxonomy: an exploration of a neglected discipline. Ichnos 15, 126–139.
Kim, K.S., Kim, J.Y., Kim, S.H., Lee, C.Z., Lim, J.D., 2009. Preliminary report on hominid and other vertebrate footprints from the Late Quaternary strata of Jeju Island, Korea. Ichnos 16, 1–11.
Kim, C.B., Kim, J.Y., Kim, K.S., Lim, H.S., 2010. New age constraints for hominid footprints found on Jeju Island, South Korea. J. Archaeol. Sci. 37, 3338–3343.
Koh, G.W., Park, J.B., Kang, B.-R., Kim, G.-P., Moon, D.C., 2013. Volcanism in Jeju Island. J. Geol. Soc. Korea 49, 209–230 (in Korean with English abstract).
Kokelaar, B.P., Durant, G.P., 1983. The submarine eruption and erosion of Surtra (Surtsey), Iceland. J. Volcanol. Geotherm. Res. 19, 239–246.
Korean Association for Conservation of Natural Heritages, 2002. Detailed Survey Report of Geological and Mineralogical Heritages. Cultural Heritage Administration of Korea, Daejon, p. 221 (in Korean).
Lamb, A.L., Wilson, G.P., Leng, M.J., 2006. A review of coastal palaeoclimate and relative sea-level reconstructions using $d^{13}C$ and C/N ratios in organic material. Earth-Sci. Rev. 75, 29–57.
Lee, K., Yang, W.-S., 2006. Historical seismicity of Korea. Bull. Seismol. Soc. Am. 96, 846–855.
Lockley, M.G., Roberts, G., Kim, J.Y., 2008. In the footprints of our ancestors: an overview of the hominid track record. Ichnos 15, 106–125.
Németh, K., Cronin, S.J., 2007. Syn- and post-eruptive erosion, gully formation, and morphological evolution of a tephra ring in tropical climate erupted in 1913 in West Ambrym, Vanuatu. Geomorphology 86, 115–130.
Németh, K., Cronin, S.J., Charley, D., Harrison, M., Garae, E., 2006. Exploding lakes in Vanuatu — “surtseyan-style” eruptions witnessed on Ambae Island. Episodes 29, 87–92.
Park, K.H., Cho, D.L., Kim, J.C., 2000. Geological Report of the Moseulpo-Hanlim Sheet. Korea Institute of Geology, Mining and Materials, Taejon.
Simkin, T., Siebert, L., 1984. Explosive eruptions in space and time: durations, intervals, and a comparison of the world's active volcanic belts. In: Committee, G.S., Council, N.R. (Eds.), Explosive Volcanism: Inception, Evolution, and Hazards. National Academy Press, Washington, D.C., pp. 110–121.

Simkin, T., Siebert, L., 2000. Earth's volcanoes and eruptions: an overview. In: Sigurdsson, H., Houghton, B.F., McNutt, S.R., Rymer, H., Stix, J. (Eds.), Encyclopedia of Volcanoes. Academic Press, San Diego, CA, pp. 249–261.

Sohn, Y.K., Park, K.H., 2004. Early-stage volcanism and sedimentation of jeju island revealed by the Sagye Borehole, SW Jeju Island, Korea. Geosci. J. 8, 73–84.

Sohn, Y.K., Park, J.B., Khim, B.K., Park, K.H., Koh, G.W., 2002. Stratigraphy, petrochemistry and quaternary depositional record of the Songaksan tuff ring, Jeju Island, Korea. J. Volcanol. Geotherm. Res. 119, 1–20.

Sohn, Y.K., Park, K.H., Yoon, S.H., 2008. Primary versus secondary and subaerial versus submarine hydrovolcanic deposits in the subsurface of Jeju Island, Korea. Sedimentology 55, 899–924.

Sohn, Y.K., Cronin, S.J., Brenna, M., Smith, I.E.M., Németh, K., White, J.D.L., Murtagh, R.M., Jeon, Y.M., Kwon, C.W., 2012. Ilchulbong tuff cone, Jeju Island, Korea, revisited: a compound monogenetic volcano involving multiple magma pulses, shifting vents, and discrete eruptive phases. Geol. Soc. Am. Bull. 124, 259–274.

Yoon, W.S., Kim, G.B., Yoon, S.H., Sohn, Y.K., 2013. Alternating Subaerial Pyroclastic and Marine Reworking Processes During Eruption of a Coastal Tuff Ring, Jeju Island, Korea: A High-Resolution Record of Holocene Sea-level, IAVCEI 2013 Scientific Assembly, July 20–24, Kagoshima, Japan.