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Age and Stratification of Dinosaur Eggs and Clutches from Seonso Formation, South Korea

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Abstract: The absolute age of lapilli tuff in sedimentary formation that contains dinosaur fossils in the Boseong area, Korea was determined radiometrically against volcanic rocks below and above the fossil-bearing horizons. The sanidine in the lapilli tuff below the fossil-bearing horizon (Seonso formation) has an ^{40}Ar-^{39}Ar age of 81.1±1.4 Ma. The Pilbong tuff above Seonso formation has an ^{40}Ar-^{39}Ar age of 81.0±2.4 Ma. An andesite dyke intruding all sedimentary units yields an ^{40}Ar-^{39}Ar age of 42.4±2.5 Ma. Thus 81 Ma age can be regarded as the best estimate for the age of the Seonso Formation and the associated the dinosaur eggs. This age correlates well with dinosaur fossil finds in the Haenam and Koseong regions of Korea. The occurrence of dinosaur eggs and clutches attests to the existence of dinosaurs in southern Korea at least inCampanian times.

Keywords: Seonso Formation, dinosaur eggs and clutches, ^{40}Ar-^{39}Ar age, Campanian

Introduction

The first discoveries of Asian dinosaur remains were made in China and Mongolia in the 1910s and 1920s (Andrews, 1932). These early discoveries included skeletons and egg clutches (Andrews, 1932; Mikhailov et al., 1994). In Korea the first fossil vertebrate remains were discovered in 1972. These included fragments of dinosaur eggshell from the Hasandong Formation in southeastern Koseong county, province of South Gyeongsang (Yun and Yang, 1997). Since that time, more than 20 dinosaur fossil sites have been identified in this county, although only a few have been officially documented in the literature. Trackway sites (with up to ten thousand tracks) comprise the majority of dinosaur fossil localities in Korea (Yang, 1982; Lim et al., 1989, 1994; Lockley et al., 1997; Huh et al., 1996; Baek and Seo, 1998), but only two sites have produced skeletal material (Lee et al., 1997; Paik et al., 1998).

A new location was found in 1999 in the upper part of the Cretaceous Seonso formation in the Boseong area of southern Korea (Fig. 1). The Seonso formation is a lacustrine sedimentary assemblage with a well-developed bedding. It has already yielded more than 200 dinosaur eggs and 17 clutches (Huh et al., 1999).

The purpose of this study was to obtain absolute age constraints for the dinosaur eggs and clutches and to correlate the dinosaur fossil sites between Korea and China. Possible correlations in dinosaur sites between Mongolia and elsewhere in east Asia will be recognized as data for these areas becomes available.

Geological setting

The bedrock of the Boseong area is made up of Cretaceous volcanic and sedimentary rocks (Fig. 1). The oldest rock in the study area is a lapilli tuff which is exposed along coastal area between Seonso and Pilbong. It is overlain conformably by the Seonso formation, which in turn is conformably overlain by the Pilbong tuff. Andesite dykes truncate tuffs and Seonso formation. The Seonso formation mainly consists of a pebbly mudstone and sandstone. The

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pebbles are rounded and poorly sorted, while consisting of granitic gneiss, quartzite, schist, andesite, lapilli tuff, and tuffaceous sandstone. The age of the Seonso formation is constrained by the ages of the lapilli tuff and the Pilbong tuff. The andesites dykes postdate both tuffs. The excellent state of preservation of the eggs and clutches indicates that they were buried in situ and hence are the same age as the Seonso Formation.

Lapilli tuff

The lapilli tuff is the lower member of a volcanic sequence comprising a red to grey felsic lapilli tuff, andesitic lapilli tuff, breccia and pumice. The formation has fiamme and welded texture. The strike of the Formation on the coast at Seonso is N10-30°E and the dip is 15°NW. The lapilli fragments show flow and welded texture with their length in 5-30 mm. The thickness of this unit at Seonso village is at least 20 m, as the base is not exposed on land. The Seonso-coast is dominated by felsic lapilli tuffs, while the Pilbong-coast is dominated by andesitic lapilli tuffs and pyroclastic breccias. Phenocrysts of quartz and feldspar are common in the felsic lapilli tuff but are rare in the andesitic lapilli tuff. Quartz phenocrysts occur as anhedral to euhedral single crystals up to about 3 mm in length and are corroded. Plagioclase phenocrysts are smaller than the quartz phenocrysts they tend to occur as subhedral to euhedral single crystals or as aggregates that are partly altered to sericite and calcite. The plagioclase shows albite and albite-calsbad twin and is partly altered to sericite and calcite. Sanidine phenocryst also occurs as euhedral to subhedral grains about 2-3 mm in length. Groundmass consists of shards and fragments of glass, very fine-grained cryptocrystalline ash, and showing flow and vesicular texture. The breccias are andesite and trachyte in composition and contain cryptocrystalline, amygdaloidal or porphyritic andesitic or trachytic blocks or bombs from 4 to 50 cm in size set in a matrix of fine-grained volcanic material. They also contain small amounts of accidental pebbles of granite, quartzite and schist.

Seonso Formation

The Seonso formation is widely distributed. Being well bedded, it trends N45-55°E and dips 40°NW. It is exposed along the coastline for about 4 km. The thickness of this formation, near Seonso village, is about 30 m. The formation is a repetitive sandstone-mudstone sequence with a characteristic well-developed laminar bedding in sandstone. Graded bedding and cross bedding are common. Sandstone at the base of the formation is frequently coarse-grained and pebble bearing. In certain places, this pebble bearing sandstone occurs as lenses, several meters long, or as U-shaped channel infillings. The pebbles in channel gravels consist of granite gneiss, quartzite, mica schist, lapilli tuff, andesite, and trachytic rocks. The color of the pebble sandstone is greenish to pale gray or variegated. The sandstone is made up of quartz grains, though some volcanic and marble grains are present. The sandstone beds grade upwards into a sandy mudstone and into a mudstone. The Seonso Formation contains a 0.8-1.0 m thick calcic paleosol, with rhizolithes, worm borrows, and dinosaur eggs.

Pilbong tuff

This unit consists mainly of rhyolitic fragments. It overlies conformably the Seonso Formation and extends for 4 km along the coast from Pilbong to Cheongam. The strike and dip are N30°W and 30°NE respectively. The color of the rock is a dark pink to pinkish grey, although locally it can be dark brown. The variability in color may be the result of weathering, but it may also be a feature of the depositional environment. This is similar to the Seonso Formation, which is a pale red to dark red depending on the degree of exposure to oxidation during sedimentation. Phenocrysts in the rocks are plagioclase, quartz and orthoclase, and a small amount of opaque minerals as microphenocrysts. The plagioclase is altered. Quartz phenocrysts are elliptical in shape and are corroded.

Andesite dyke

An andesite dyke is part of a dyke swarm found along 1.5 km of coast between Seonso and Pilbong villages. It strikes N40°W to N, dips vertically; it is 1-3 m in thickness and cuts all formations. Major minerals present are plagioclase, clinopyroxene (diopside), hornblende, and opaque mineral. Plagioclase phenocrysts are subhedral to euhedral and show oscillatory zonings indicative of rapid cooling. In a thin section, subhedral to euhedral clinopyroxene phenocrysts exist as colorless or pale brown. Fresh clinopyroxene is found as microphenocrysts where the dyke has a trachytic texture. Calcite and clay minerals occur as the alteration products.

Dinosaur egg fossils

Perfectly preserved dinosaur eggs were found in outcrops of the Seonso Formation between Cheongam and Pilbong villages (Fig. 1) along a 3 km stretch of shoreline. This find contains 17 clutches and about 200 eggs, plus many fragments of eggs (Fig. 2A, B). The clutches are 0.5 to 1.5 m in diameter, and on average are 30 m apart, though two clutches are only 1 m apart. They are found mainly in four areas at five different stratigraphic levels. Clutches contain 3 to 15 eggs, although some eggs have invariably been weathered out and the actual number of eggs per nest was probably up to 30. In size, the eggs are 9-20 cm and the shell thicknesses are 1.5-2.2 mm (Fig. 2C1, C2, D1, D2). In shape the eggs are disk-like, spherical or subspherical. Morphologically, they are spheroolithic and faveoloolithic (Huh and Zelenitsky, 2002). The characteristics of the eggshells, such as their vesicle structures, surface decorations, shapes and sizes, indicate that the eggs are of herbivorous ornithopod and sauropod dinosaurs (Hirsh and Zelenitsky, 1997; Huh and Zelenitsky, 2002).

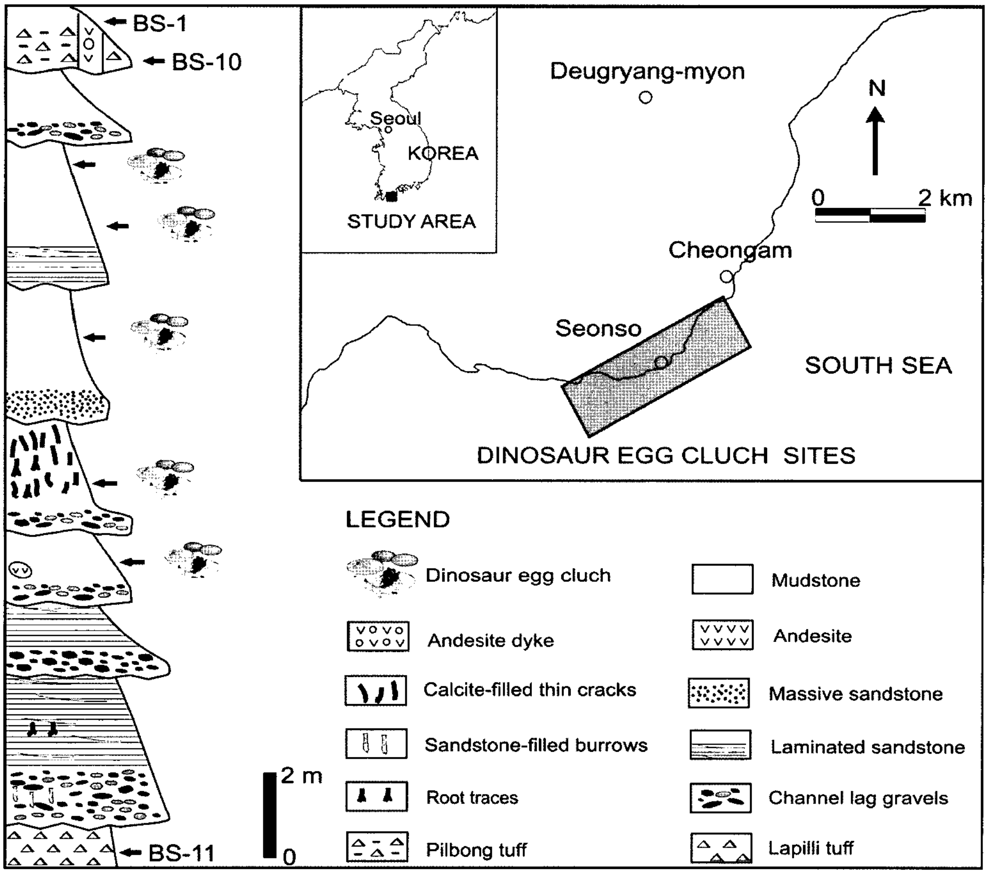

Fig. 1. Location of the study area and simplified stratigrphic section of the formation with dinosaur eggs and clutches.

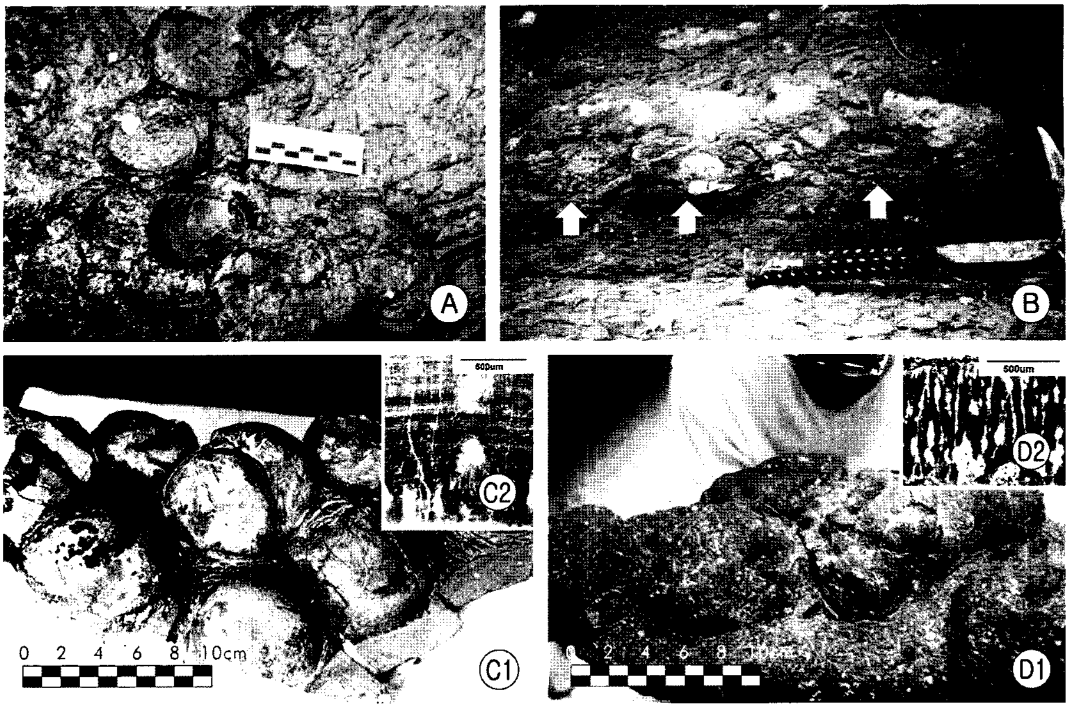

Fig. 2. Dinosaur eggs and nests as seen in outcrops. Dinosaur eggs and nests as seen in outcrops (arrow: dinosaur eggs). C1. Top view of an unhatched Dendroolithus egg clutch (DRCC-B106). C2. Radial thin section of eggshell from 3a. D1. Top view of hatched Faveoloolithus egg clutch (DRCC-B110). D2. Radial thin section of eggshell from 4a.

^{40}Ar-^{39}Ar Age Determinations

The ^{40}Ar-^{39}Ar age determinations were done at the Korea Basic Science Institute (KBSI). For the ^{40}Ar-^{39}Ar ages, samples have been irradiated in the IP11 position of the "Hanaro" reactor in Korean Atomic Energy and Research Institute (KAERI). Irradiation duration was 96 h. The total fast neutron fluence reached 2.7×10^{16} n/cm^2, and the J-value was 0.0003057 ±0.0000057 calculated from the GA550 biotite (97.2± 0.3 Ma, Mcdougall and Rosandic, 1974). The plateau age, which is defined by Ludwig (2003), is applied to derive the ^{40}Ar-^{39}Ar age of the analyzed samples. However, in the case of no remarkable age plateau, we used ^{40}Ar-^{39}Ar age integrated from the several steps of age spectrum. If the integrated ages are compatible to those of derived from the inverse isochron diagram, the ages have a geologic meaning.

Ar isotope ratio was measured using 5400 (Micromass) mass spectrometer in static mode with a double collector system. The procedural blank is less than 1×10^{-9} ccSTP (4.46×10^{-14} mol) for ^{40}Ar and is nearly of atmospheric composition. Mass discrimination was monitored daily using atmospheric argon. Calculation of ages and errors followed the method described by Uto et al. (1997).

Results

Precise ^{40}Ar-^{39}Ar age can be derived from the well-defined plateau in the age spectrum and from the x-intercept value of the inverse isochron diagram. In this study, a clear age plateau is not defined. However, the well defined isochron in the inverse isochron diagram and the consistency of the integrated age and isochron age should be accepted as a reliable age for the volcanic rocks. Furthermore, the similarity of the isotope composition of initial $^{40}Ar/^{36}Ar$ (y-intercept in inverse isochron diagram) to atmospheric Ar ratio is additional support for this age. All ^{40}Ar-^{39}Ar ages in

Table 1. Detailed 40Ar-39Ar analytical data and integrated ages of tuff and dyke from the Boseong area

Step Temp. (°C)	^{40}Ar atm (%)	^{39}Ar (%)	$^{37}Ar_{ca}/^{39}Ar_k$	$^{40}Ar^*/^{39}Ar_k$	Age (Ma), 2σ
BS-1 Whole rock					
780	0.02	1.01	0.59	1938.788	0.42±362.07
850	68.76	2.73	20.53	899.633	528.48±0.15
920	13.89	6.6	0.559	291.409	38.25±1.06
1000	41.17	16.1	0.356	106.44	41.37±0.39
1050	55.99	26.74	0.286	82.229	43.43±0.33
1110	79.62	44.27	0.29	56.225	42.24±0.21
1170	75.46	63.79	0.37	59.664	42.49±0.17
1220	92.09	77.77	0.577	48.132	41.85±0.26
1280	81.75	88.68	0.948	57.093	44.07±0.37
1340	76.32	95.37	1.281	58.1	41.93±0.54
1400	49.48	100	1.298	84.888	39.73±1.02
Integrated age					42.40±0.25
BS-10 Whole rock					
700	3.71	1.47	0.125	900.829	31.60±0.91
780	14.18	3.28	0.132	406.299	54.16±0.45
850	39.91	6.89	0.138	164.797	61.70±0.20
920	62.51	14.27	0.123	112.922	66.14±0.08
1000	88.61	34.06	0.091	92.953	76.94±0.03
1060	92.41	50.92	0.078	97.085	83.65±0.03
1115	92.13	63.51	0.074	99.593	85.51±0.04
1170	93.63	73.14	0.084	94.765	82.75±0.05
1220	94.83	79.2	0.119	89.971	79.65±0.08
1280	82.01	83.69	0.16	104.023	79.64±0.11
1340	89.46	87.63	0.185	96.249	80.37±0.13
1400	73.47	97.33	0.359	112.007	76.91±0.05
1450	51.82	100	0.932	147.723	71.73±0.22
Integrated age					81.00±2.40
BS-11 Sanidine					
750	7.89	8.29	2.989	1480.811	63.59±2.22
820	40.27	14.57	1.993	388.097	84.43±2.21
880	32.28	24.14	6.694	473.706	83.21±1.49
930	40.27	32.18	6.34	362.282	79.43±1.87
980	65.03	37.9	4.335	240.765	84.86±1.65
1040	83.41	44.33	4.784	180.11	81.55±1.65
1100	76.13	52.63	4.604	188.963	78.15±1.33
1160	66.01	61.52	4.202	219.483	78.64±1.25
1220	63.35	71.5	3.305	217.493	74.78±1.23
1280	21.02	81.41	2.985	686.366	78.18±1.09
1340	45.46	88.22	4.752	337.538	83.25±0.45
1400	7.18	95.41	8.188	264.27	87.23±0.57
1450	4.59	100	13.833	236.69	86.25±0.99
Integrated age					81.10±1.40

1: Ratio of radiogenic ^{40}Ar vs ^{39}K

the following section are the integrated ages calculated from the age spectra.

The lapilli tuff has a partially welded texture; stratigraphically it is 10 m below the fossiliferous unit of the Seonso Formation near Seonso village. It is a massive pale pink to light gray felsic tuff that consists predominantly of lithic fragments and quartz. Plagioclase, sanidine, and oxides occur as minor constituents. Secondary minerals are calcite, chlorite, sericite, and epidote. Sanidine separation from this

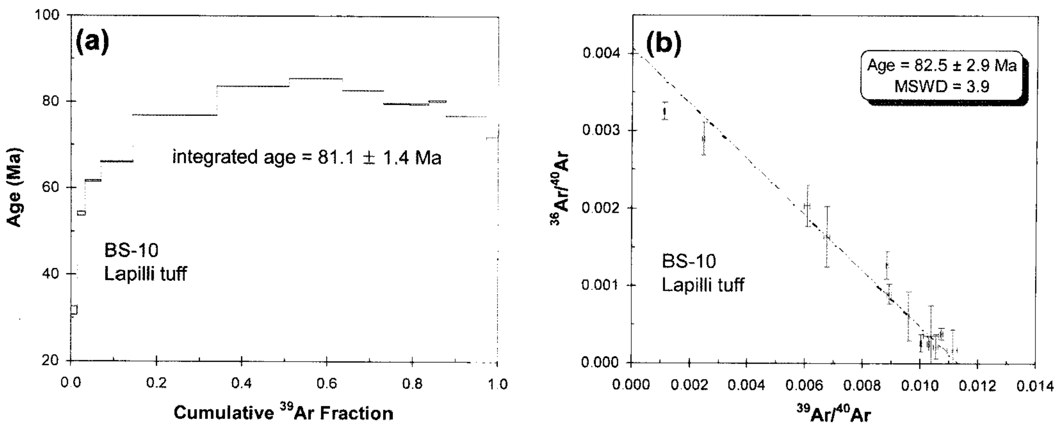

Fig. 3. (a) ^{40}Ar-^{39}Ar age spectrum and (b) inverse isochron for lapilli tuff (BS-10). The box height in each step in age spectrum and length of the error bar represents the 2 σ uncertainties.

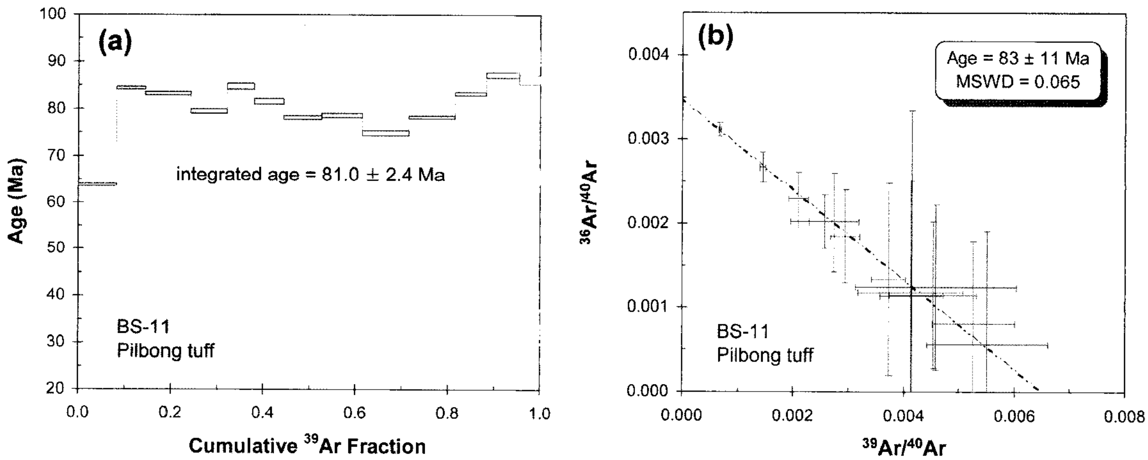

Fig. 4. (a) ^{40}Ar-^{39}Ar age spectrum and (b) inverse isochron for Pilbong tuff (BS-11).

sample yielded an ^{40}Ar-^{39}Ar (BS-11) age of 81.1±1.4 Ma age (Table 1).

The Pilbong tuff collected is an andesitic tuff, stratigraphically 20 m above the fossiliferous unit of the Seonso Formation near Pilbong. This rock is glassy with lithic fragments and phenocrysts of feldspar and quartz. ^{40}Ar-^{39}Ar whole rock ages determined for this rock unit (BS-10) are 81.0±2.4 Ma (Table 1).

The andesite dyke is from a 2 m wide dyke in Seonso village. It is fine-grained, gray to dark gray; it intrudes the lapilli tuff, the Seonso Formation, and the Pilbong tuff. An ^{40}Ar-^{39}Ar whole rock age for this rock (BS-1) is 42.4±0.25 Ma (Table 1).

Discussion

Geochronology and dinosaur eggs and clutches

During the early Cretaceous, the Korean peninsula, as a result of the northward subduction of the Izanagi Plate, experienced sinistral brittle shearing in a retroarc setting with the development a number of pull-apart basins (Chun and Chough, 1995). These basins collected non-marine sedimentary and volcanic material. The Gyeongsang basin, comprised of the Gyeongsang Supergroup, is the most representative one of the such pull-apart basins in the mid- and late-Cretaceous of Korea (Chun and Chough, 1995, Kim,

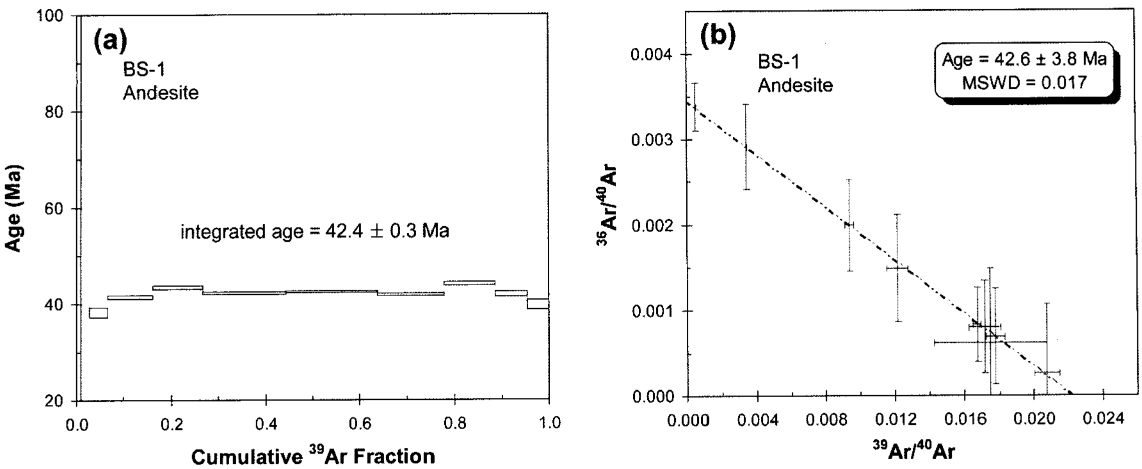

Fig. 5. (a) ^{40}Ar-^{39}Ar age spectrum and (b) inverse isochron for andesite (BS-1).

S.B. et al., 1997; Lee, 1999).

The lapilli tuff (BS-11, sanidine), which predates the Seonso Formation, has an ^{40}Ar-^{39}Ar age of 81.1±1.4 Ma; while the Pilbong tuff (BS-10), which postdates the Seonso Formation, has an ^{40}Ar-^{39}Ar age of 81.0± 2.4 Ma. Within the ranges of uncertainties, these ages are identical. The best estimate for the age for these two as well as the dinosaur eggs is probably 81 Ma.

The age of 42.4±0.25 Ma obtained from andesitic dyke is significant, because it is the youngest subvolcanic event in southwest Korea. Tertiary volcanic activity in the Pohang-Ulsan region of southeastern Korea is well documented (Yoon, 1997; Song et al., 1998).

In summary, the age of the dinosaur eggs and the deposition age of Seonso Formation is estimated as ca. 81 Ma on the basis of the ages for the lapilli and the Pilbong tuffs. The insignificant age differences between these two tuff layers suggest that the deposition of Seonso Formation was very rapid.

Regional correlations

Some 10,000 dinosaur footprints have now been found at numerous sites throughout Korea (Kim, 2000). Dinosaur bones have been found at three sites (Namhae, Koseong, Boseong), and dinosaur eggs at the following five sites: Hadong, Boseong, Ansan, Koseong, Sacheon (Huh et al., 2006). The dinosaur footprints found in Korea are relevant to the absolute age determinations of Cretaceous volcanic rocks in the Haenam, Koseong, Yeosu, and Ansan areas. At Haenam, volcanic rocks are 78-93 Ma old as dated by Rb-Sr whole rocks, which is Campanian to Cenomanian (Kim et al., 2003). At Koseong, volcanic rocks are dated as 85-86 Ma by K-Ar whole rock analysis, which is Santonian (Kim and Paik, 2000). At Yeosu area, oldest sedimentary deposit of the area is the volcanic pebble bearing conglomerate of the Jeokgeumdo and its deposition age is ca. 81Ma or less by K-Ar whole rock (Park et al., 2003). The deposition age of the Chudo shale, which belongs to stratigraphically upper sequence and bears many dinosaur footprints, is at least ca. 77 Ma by K-Ar whole rock (Park et al., 2003). Conglomerate of the Mokdo was deposited at ca.72-70 Ma by K-Ar whole rock (Park et al., 2003). The deposition age of the dinosaur fossil deposit of the Sado is at least ca. 65 Ma by K-Ar whole rock (Park et al., 2003). All the investigated volcanic and sedimentary rocks of the Yeosu islands were formed during the late Cretaceous and dinosaurs lived until the at least Cretaceous in this area (Park et al., 2003). At Ansan, the determination of K-Ar ages of volcanic rocks was 97 Ma, the same as the maximum geological age of dinosaur eggs found in the syngenetic sedimentary formation in Lake Shiwa. Clearly, there is a possibility of correlation

Table 2. K-Ar analytical data for the volcanic rocks from Boseong area

Sample	Rock type	Material	K (%)	^{40}Ar rad [1] (10^{-10} mol/g)	$^{40}Ar_{rad}$ / $^{40}Ar_{total}$	Calculated age[2] (Ma, of year)
BS-1	andesitic pebble	whole rock	1.692	39.847	0.6348	94.2±2.8 Ma
BS-4	lapilli tuff	whole rock	1.003	53.187	0.3232	74.9±1.5 Ma
BS-3	lapilli tuff	whole rock	2.379	12.995	0.7351	77.9±2.3 Ma

[1]Concentration of radiogenic ^{40}Ar in mol/g determinared by isotope diution using a ^{38}Ar tracer. Overall one-sigma analytical uncertainties assigned±1%.
[2]The age is calculated using the average of respecrive analyses with the following constants; $^{40}K=1.67\times10^{-2}$ atom % of K; $Xe=0.581\times10^{-10}$; $=4.96210^{-10}y^{-1}$; and ($^{40}Ar/^{38}Ar$) atoms=295.5 (Steiger and Jäger, 1977)

between the following: the Uhangri Formation, Haenam, containing dinosaurs, pterosaurs and web-footed bird tracks (79-81 Ma); the Seonso Formation, Boseong, containing dinosaur eggs and cluches (Huh et al., 1999); the sedimentary rocks, Koseong, containing dinosaur footprint (85-86 Ma) (Kim and Paik, 2000). Thus all five fossil finds, (at Boseong, Haenam, Koseong, Yeosu, Ansan), are possibility of the same age-Late Cretaceous, 81 Ma.

Elsewhere in eastern Asia, there are many dinosaur fossil finds. Mongolia, China, Korea and Japan moved as a block towards Siberia in the late Jurassic. This block closed the Mongo-Okhostk Ocean during the Early Cretaceous to form Paleolaurasia with North America and Europe (Enkins et al., 1992). Presently it is not possible to relate the Boseong site to other sites in eastern Asia. This is partly due to the lack of radiometric ages, as well as real differences in ages. The age of Mesozoic sedimentary rocks in China ranges from middle Triassic to late Cretaceous. An ^{40}Ar-^{39}Ar mineral age for volcanic rocks associated with dinosaur fossils in China is 124.6±0.3 Ma (Swisher III et al., 1999). Dinosaur fossils have been excavated from Cretaceous rocks in Mongolia and a few fossils have been found in sedimentary rocks in Japan (Zhen et al., 1985; Azuma and Tomida, 1995; Azuma and Currie, 2000), but absolute ages for these are lacking. Thus on the basis of absolute ages, correlations of the Korean dinosaur sites with other eastern Asian sites has to await the availability of radiometric ages in China, Mongolia and Japan.

Conclusions

Numerous dinosaur eggs and clutches have been discovered in the Cretaceous Seonso Formation of Korea. The characteristics of the eggshells, such as their vesicle structures, surface decorations, shapes and sizes, indicate that they are from herbivorous ornithopod and sauropod dinosaurs. They are found in four main areas along a 3 km stretch of coastal outcrops, and at five different stratigraphic levels. Most of the eggs are found in clutches containing 3 to 15 eggs. The eggs are 9-20 cm in size, they are disk-like, spherical or subspherical in shape. The thicknesses of the eggshells are about 1.5-2.5 mm. The surfaces of the eggshells are smooth or ragged, spheroolithic or faveoloolithic. The ^{40}Ar-^{39}Ar age for the lapilli tuff and the Pilbong tuff that predate and postdate the Seonso Formation is 81 Ma, and thus all 3 formations are indistinguishable in terms of age. Hence 81 Ma is the age we assign to the fossil eggs at Boseong. The youngest rock dated is an andesite dyke, which has an ^{40}Ar-^{39}Ar age of 42.4±0.25 Ma, and relates to other Tertiary volcanic activity that is well documented in the Korean peninsula. The occurrence of dinosaur eggs and clutches attests to the existence of dinosaurs in southern Korea in at least Campanian times.

Acknowledgments

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