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Thematic Article

Age of the pterosaur and web-footed bird tracks associated with dinosaur footprints from South Korea

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Abstract An absolute age has been determined for the Cretaceous Uhangri Formation in which web-footed bird tracks, pterosaur tracks and dinosaur tracks have been discovered recently. This combined track discovery is a first from Asia. There is one other similar find in the world, however, the Uhangri site is greater in abundance and frequency. Moreover, the size of the pterosaur tracks indicates that the track maker had a wingspan of 10 m or more. Well-preserved tuffaceous rocks in the formation made it possible to measure geological age by Rb–Sr and K–Ar methods. Rb–Sr whole rock ages for the volcanic rocks are: 96.0 ± 2.5 Ma (MSWD = 0.354) for lapilli andesitic tuff, 81.0 ± 2.0 Ma (MSWD = 0.296) for felsic tuff and 77.9 ± 4.1 Ma (MSWD = 4.41) for Hwangsan welded tuff. K–Ar ages are younger, 83.2–68.8 Ma. The layer containing fossil tracks of pterosaurs and web-footed birds are preserved in black shale sandwiched by the lapilli andesitic tuff and felsic tuff, and are thus 96–81 Ma in age. Dinosaur footprints are dated at 96–78 Ma. Thus the pterosaurs, web-footed birds and dinosaurs coexisted in the same environment from Cenomanian to Campanian time.

Key words: Cenomanian to Campanian, Cretaceous Uhangri Formation, dinosaur tracks, pterosaur, Rb–Sr age, web-footed bird.

INTRODUCTION

The Uhangri fossil site is about 20 km west of the town of Haenam on the south-western tip of the Korean Peninsula (Fig. 1). This was on the coast in the southern part of Haenam Bay, but after construction of the Kumho bank dam it is now on the shore of an artificial lake. The upper part of the Cretaceous Uhangri Formation is well exposed in the Haenam area. The exposure of the fossil-bearing bed is about 30 cm in thickness, dipping 20° to the southwest. For 2 km along the shoreline extensive stripping and excavations of six levels at three sections were done from 1996 to 1998 (Huh *et al.* 1998). This yielded 443 pterosaur tracks, thousands of web-footed bird tracks, 514 dinosaur tracks of ornithopod and sauropod, several tens of silicified and calcified woods, tens of thousands of ostracoda fossils, tens of trace fossils, and tens of pterosaur and dinosaur-bones (Huh *et al.* 1998). Among the dinosaur tracks, a new ornithopod morphotype has been recognized and further study on these unusual dinosaur tracks and pterosaur tracks is in progress (Huh *et al.* 1996, 1997; Lockley *et al.* 1997; Hwang *et al.* 2002; Lee & Huh 2002).

The purpose of this study is to provide absolute age data for the timing of the coexistence of the pterosaur and the web-footed bird that are associated with the dinosaurs and to enhance the understanding of the evolution and paleoenvironments of the web-footed bird and the pterosaur in Middle to Late Cretaceous. Another objective is to establish age constraints for volcanic rocks that are

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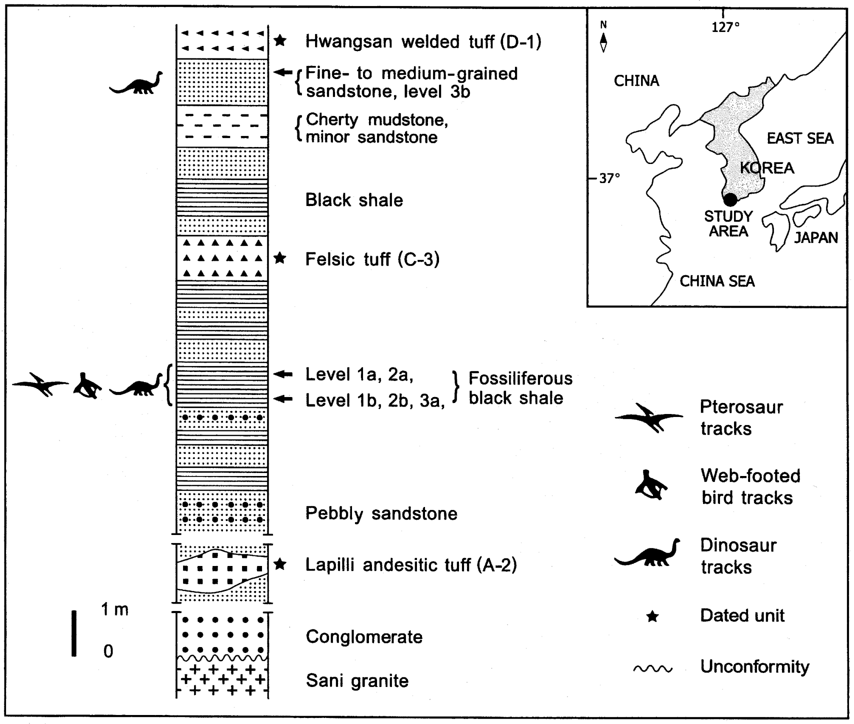

Fig. 1 Location map of study area and simplified stratigraphic section of the Uhangri Formation showing fossil track position.

intercalated with Mesozoic fossiliferous layers throughout East Asia.

FOSSIL-BEARING UHANGRI FORMATION

The Uhangri Formation (Cretaceous) is a lacustrine sedimentary succession with prominent bedding. It comprises approximately a 400 m-thick interlayered epiclastic sequence of conglomerate, sandstone, chert, mudstone and felsic to intermediate tuff, lava, and shale. Numerous geological studies in the area have been done with respect to the stratigraphy and sedimentology (Chun & Chough 1995; Lee & Lee 1976), including the pterosaur and the dinosaur tracks (Lockley *et al.* 1997; Huh *et al.* 1998) and the web-footed bird tracks (Yang *et al.* 1995).

The clastic sedimentary facies of the formation indicates overlapping subaqueous delta lobes forming a transition from epiclastic alluvial plain to shallow lake. The formation comprises a large variety of non-marine silisoclastic sedimentary rocks, divisible into six characteristic facies sequences, representing deposition in alluvial fan delta and lacustrine environments. It contains thick sequences of both sandstone/cherty mudstone and sandstone/black shale with considerable lateral continuity (Chun & Chough 1995). Sporadic volcanism in the hinterland provided abundant pyroclastic flows which were reworked into the Uhangri sequence. Volcanic rocks of the Uhangri Formation, in stratigraphic order, consist of lapilli andesitic tuff, felsic tuff, and Hwangsan welded tuff.

The lapilli andesitic tuff is located about 35 m below the fossiliferous black shale (Fig. 1). The tuff is 80–100 cm in thickness and 20 m in length, and provides a maximum age for the fossil-bearing layer. The dated samples were collected from the lenticular bed of the lapilli andesitic tuff that is conformably intercalated in conglomerate and sandstone beds. The lapilli andesitic tuff is composed mainly of andesitic and felsic pyroclastics, which alternate with amygdaloidal andesite, fine andesite and basalt. Andesitic pyroclastics, which consist of coarse tuff and lapilli tuff, are mostly crystal-lithic tuffs. The crystal fragments are mainly angular feldspar and quartz, hornblende, epidote, and opaque minerals.

The felsic tuff, 60–80 cm in thickness, is located about 2 m above the main fossiliferous layers (Fig. 1). The dated samples were collected from medium- to coarse-grained, pale pink felsic tuff. It is intercalated in black shale and mudstone including the fossiliferous layers. The rock consists of lithic fine tuff and crystal tuff. It has porphyritic texture with phenocrysts of quartz, plagioclase and a minor amount of K-feldspar in glassy or crypto crystalline and partly welded groundmass.

The Hwangsan welded tuff is about 10 m above the fossiliferous black shale (Fig. 1). This rock consists of quartz, plagioclase and K-feldspar phenocrysts, and lithic fragments in matrix of devitrified glass shards. The lithic fragments are elongated andesite and devitrified pumice fragments and glass shards. Some glassy materials are altered to chlorite and sericite. The dated samples were selected from the lower part of the welded tuff.

PTEROSAUR AND WEB-FOOTED BIRD TRACKS

1. The tracks on level 1a (Fig. 1): There are 263 dinosaur tracks in the black shale bed (Fig. 2). The bed consists of calcified and silicified woods with dinosaur tracks. Most of the tracks consist of *Caririchnium*-like forms indicative of ornithopod ichinospecies. A new ornithopod ichnospecies has been recognized by its characteristic broad digit and hoof impressions. Six trackways of *Caririchnium* and one of a theropod way were also identified (Huh *et al.* 1998; Hwang 2001).
2. The tracks on levels 1b and 2b (Fig. 1): The lower part of the black shale bed is the only place in the world where pterosaur, web-footed bird and dinosaur tracks have been found together on the same horizon. On this level 443 pterosaur and thousands of bird tracks have been found. These pterosaur tracks are the world's largest known pterosaur footprints (33 cm in length; Fig. 2f) and also, they form the largest trackway (7.3 m in length) in the world (Huh *et al.* 1996; Lockley *et al.* 1997). Furthermore these are also the oldest web-footed bird tracks (81 Ma, as shown below). Level 2b has a dinosaur trackway. The pterosaur tracks have been assigned to the new genus *Haenamichnus* which accommodates the new ichinospecies *H. uhangriensis* (Hwang *et al.* 2002; Fig. 2e,f). The web-footed bird tracks were previously identified as *Uhangrichnus chuni* and *Hwangsanipes choughi* (Lockley *et al.* 1992; Yang *et al.* 1995; Unwin *et al.* 1997; Fig. 2g).
3. The tracks on level 2a (Fig. 1): The 106 dinosaur tracks found here are on the same level as level

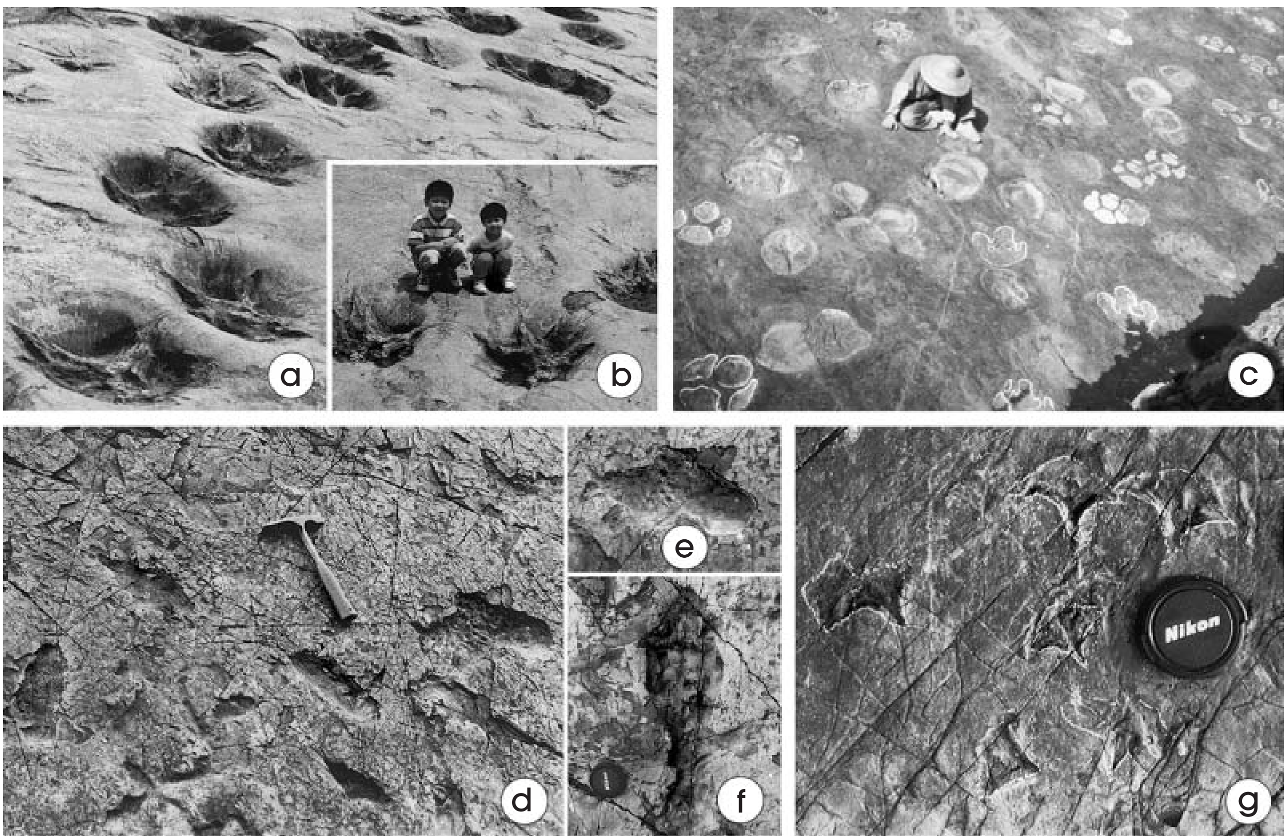

Fig. 2 (a,b) Unusual dinosaur tracks (level 3a). All tracks are circular in shape showing very deep and shallow footprints (av. width: 87 cm, length: 85 cm, depth: 21 cm). A total of 105 tracks were excavated. (c) Ornithopod dinosaur tracks (level 1a). (d) Pterosaur tracks inside the web-footed bird tracks are on the same surface. (e) Double (manus and pes) tracks including the web-footed bird tracks (m: manus, p: pes) (See the tracks in part (d)). (f) Largest pes track in the world. (g) Web-footed bird tracks with silicified woods. The track is the oldest in the world with webbing traces.

1a, but 100 m to the east. Most of the tracks here are of ornithopods. The shape of tracks is nearly circular and most of them are poorly preserved. Fragmented bones also have been found on this level.

4. The tracks on level 3a (Fig. 1): There are very large, peculiar tracks in the black shale here (Fig. 2a,b,d,e). On the inside the tracks have 2–6 star shaped protrusions. These unusual tracks have been interpreted as manus-only sauropod tracks (Lee & Huh 2002) or as distinctive ornithopod traces (Hwang 2001).
5. The tracks on level 3b (Fig. 1): Here, 27 sauropod tracks occur indistinctly on the thick sandstone bed plane. These seem to be the reflections of the tracks preserved on the lower bedding. The dimensions of the pes tracks are 70–130 cm in length and 67–110 cm in width. The size of the manus tracks ranges from 51 to 67 cm length and 40 to 50 cm in width.

ANALYTICAL METHODS

Isotopic analyzes including chemical treatment and mass spectrometry were done at the Korea Basic Science Institute. Whole rock powders were spiked with a mixed ^{87}Rb–^{84}Sr tracer solution and dissolved with a HF-$HClO_4$ mixture in Teflon vessels. Separation of Rb and Sr followed standard cation exchange chromatography. Total procedural blanks were below 0.2 ng for Sr and Rb. Rb–Sr isotopic analyzes were carried out on a VG 54–30 thermal ionization mass spectrometer. Measured $^{87}Sr/^{86}Sr$ ratios were normalized to $^{86}Sr/^{88}Sr = 0.1194$ and further corrected for contribution from added spikes. Average measured $^{87}Sr/^{86}Sr$ ratio of SRM987 is 0.710241 ± 0.000011 ($n = 8$, 2 sigma SE). Rb–Sr isochron ages and regression parameters were calculated after Ludwig (1994) and errors reported with the ages are one sigma. The decay constants used were: $\lambda^{238}U = 1.55125 \times 10^{-10}$/year; $\lambda^{235}U = 9.8485 \times 10^{-10}$/years (Steiger & Jäger 1977).

Potassium analysis was carried out on an atomic absorption spectrophotometer (Unicam 989) using Cs buffer. Replicate analyzes of standard material (RGM-1) indicate that the accuracy and reproducibility of this method is within 2%. Argon analysis was done by isotope dilution using ^{38}Ar spike on mass spectrometer (VG5400) in static mode with a double collector system. The procedural blank is less than 1×10^{-9} cm^3 at STP (4.46×10^{-14} mol) for ^{40}Ar and is nearly of atmospheric composition. Mass discrimination was monitored daily using atmospheric argon. Analysis of standard samples ensured argon analyzes accuracy of ±2%. Data reduction and age calculation follows the methods of Dalrymple & Lanphere (1969) and Nagao *et al.* (1996). K–Ar ages are reported with one sigma errors and were calculated using the following isotopic constants: $\lambda_{\epsilon} = 0.581 \times 10^{-10}$/year; $\lambda_{\beta} = 4.963 \times 10^{-10}$/year; $^{40}K/K = 0.0001167$ (Steiger & Jäger 1977).

RESULTS

Rb–Sr and K–Ar isotopic data are presented in Tables 1 and 2, and sample locations are shown in Fig. 1. The dated samples were taken from the uppermost 30–40 cm of a freshly cut profile.

LAPILLI ANDESITIC TUFF (A-2)

Subsamples A-2a and A-2b are matrix; sample A-2c is a felsic fragment. The Rb–Sr isotopic data define a line of best fit (MSWD = 0.354) which corresponds to an age of 96.0 ± 2.5 Ma (Fig. 3). Duplicate measurement of this sample yielded K–Ar ages of 83.2 ± 2.4 and 83.0 ± 2.4 Ma.

Table 1 Rb–Sr analytical data for tuff and volcanic rocks of the Uhangri Formation

Sample	$^{87}Sr/^{86}Sr$	2sigma SE	Rb (p.p.m.)	Sr (p.p.m.)	$^{87}Rb/^{86}Sr$
A-2a	0.710881	0.000014	107.7	324.8	0.9599
A-2b	0.710563	0.000011	104.3	426.6	0.7077
A-2c	0.709844	0.000013	106.7	1599.8	0.1930
C-3a	0.710501	0.000013	53.7	188.2	0.8254
C-3b	0.710531	0.000014	53.8	186.1	0.8372
C-3c	0.711264	0.000014	109.6	211.9	1.4975
C-3d	0.711173	0.000010	89.2	185.4	1.3923
D-1a	0.712124	0.000014	111.6	129.9	2.4873
D-1b	0.711706	0.000013	102.9	135.5	2.1969
D-1c	0.710531	0.000011	77.4	212.5	1.0547
D-1d	0.710896	0.000011	93.4	184.3	1.4664

Table 2 K–Ar analytical data for tuff and volcanic rocks of the Uhangri Formation

Sample	Material	K^{40} (%)	Ar_{rad} (10^{-10} mol/g)	$^{40}Ar_{rad}$ / $^{40}Ar_{total}$	Calculated age (Ma. of year)
A-2	whole rock	3.60	11.87	0.5845	83.0 ± 2.4 Ma
A-2	whole rock	2.87	9.50	0.3213	83.2 ± 2.4 Ma
C-3	whole rock	1.45	4.51	0.0635	78.4 ± 2.3 Ma
D-1	whole rock	2.87	7.70	0.3297	67.8 ± 2.0 Ma

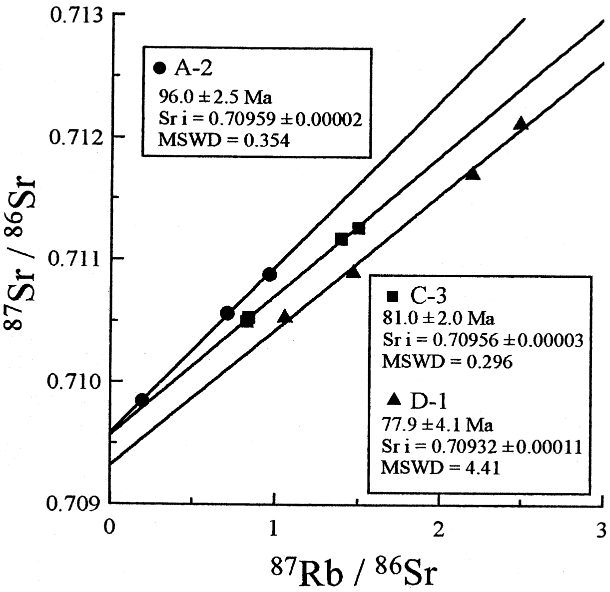

Fig. 3 Rb–Sr isochron plots for tuff and volcanic rocks of the Uhangri Formation.

FELSIC TUFF (C-3)

Subsamples C-3a and C-3b are matrix; C-3c and C-3d are feldspar fragments. The Rb–Sr isotopic data define an isochron with an age of 81.0 ± 2.0 Ma (MSWD = 0.296, Fig. 2). K–Ar age for this rock is 70.7 ± 2.1 Ma.

HWANGSAN WELDED TUFF (D-1)

Subsamples D-1a and D-1b are from matrix, D-1c is an andesitic fragment, and D-1d is a pink feldspar fragment. The data define an isochron age of 77.9 ± 4.1 Ma (MSWD = 4.41, Fig. 2). The K–Ar age for the rock is 68.8 ± 2.0 Ma.

DISCUSSION

ISOTOPIC AGES

The K–Ar ages reported here are much younger than the Rb–Sr ages. This is probably due to Ar loss, which may have been caused by subsequent hydrothermal activity (Kim & Nagao 1993) related to the Hwangsan welded tuff and intrusive subvolcanic rocks. This alteration is severe in some places and the tuffaceous rocks have been altered to clay deposits. The Rb–Sr data for the two critical felsic tuffs, below and above the fossiliferous black shale, is collinear within experimental error. This diminishes any possibility of xenocrystic matter in the analyzed samples and enhances the reliability of the ages. Also the $^{87}Sr/^{86}Sr$ initial ratios (0.70932–0.70959) are in the range of Upper Cretaceous and Lower Tertiary volcanics in East Asia continental margin (Terakada & Nohoda 1993; Kim & Park 1996). Hence we suggest that the Rb–Sr ages, 78–96 Ma, can be regarded as best estimates for the ages of the tuff rocks of the Uhangri Formation. Accordingly, the ages of the pterosaur and the web-footed bird are 96–81 Ma, though more likely they are *ca* 81 Ma, based on their proximity to the felsic tuff dated 81 Ma.

RELATIONSHIP BETWEEN PTEROSAUR AND WEB-FOOTED BIRDS

In recent years, the ichnological record of Mesozoic birds has increased substantially. The first reported occurrence of pterosaur and bird tracks together, in the same locality and horizon, was in the Upper Cretaceous Blackhawk Formation of Utah, USA by Lockley *et al.* (1992). The Uhangri occurrence is the second of its kind in the world. These two occurrences provide information on the ecologic relationship between pterosaurs and web-footed birds, particularly in lake margin settings where their tracks are readily preserved. The Uhangri fossil site is particularly noteworthy as it provides a large amount of data on the frequency and relative abundance of the various footprints. It is speculative but possible that large pterosaurs included small birds in their diet, though this remains to be proven. The Uhangri tracks are important in a number of ways. Firstly, they are the first pterosaur tracks found in Asia. Secondly, they are the largest pterosaur tracks ever found. Thirdly, they show that large Cretaceous pterodactyloids made progress in quadrupedal plantigrade fashion, not bipedally as has been suggested (Bennett 1997). Fourthly, they are preserved in association with bird tracks, unequivocal evidence that birds and pterosaurs lived in the same habitats, though the large disparity in size, morphology and terrestrial style of progression all point to rather different ecologic roles for these two groups of flying vertebrates (Huh *et al.* 1996; Lockley *et al.* 1997; Hwang *et al.* 2002).

TIME AND SPACE IMPLICATION OF PTEROSAUR AND WEB-FOOTED BIRDS IN EAST ASIA

The Uhangri Formation rests unconformably on the Sani granite dated at 179 ± 3 Ma by U–Pb zircon age (Kim *et al.* 2002). The youngest member of the formation is the Hwangsan welded tuff dated here at 77.9 ± 4.1 Ma. The youngest fossil track layer is just below the Hwangsan welded tuff, and the main fossiliferous layer are about 6 m below that. At about 35 m below the main fossiliferous layer is the lapilli andesitic tuff (Fig. 1). This tuff (sample A-2) has been dated as 96 ± 2.5 Ma by the Rb–Sr method. The oldest fossil layers are level 1b, 2b, 3a, and younger layers are 1a and 2a (Fig. 1). Not immediate above them is the felsic tuff (sample C-3), dated at 81 ± 2 Ma. The youngest fossil tracks are of sauropods found in sandstone (level 3b, Fig. 1) just below the Hwangsan welded tuff. This tuff (sample D-1) has been dated as 77.9 ± 4.1 Ma. These ages indicate that pterosaurs, web-footed birds and dinosaurs coexisted here between 96 and 78 Ma. Since the Late Jurassic, Mongolia, China, Korea, and Japan moved, as a block, to Siberia to form Paleolaurasia with North America and Europe, together with the closing of the Mongo–Okhotsk ocean during the Early Cretaceous (Enkin *et al.* 1992). Although pterosaur, web-footed bird, and dinosaur tracks from Korea have recently been identified in detail (Lockley *et al.* 1992; Lim *et al.* 1994), these are not correlated with those in Japan and China yet. The tracks found in Korea provide new knowledge of Asian vertebrate ichnology, and permit correlation with other regions (Europe and North America) where tracks have been studied in detail. Further studies will hopefully fill in the gaps in the Jurassic and Cretaceous track records across the large region of the Asian continent between Uzbekistan and Korea (Lockley *et al.* 1997).

CONCLUSIONS

Rb–Sr ages for volcanic tuffaceous material in the Uhangri Formation successfully bracket the age of the fossils found in this formation. The main fossil layers, which contain the pterosaur, web-footed bird and dinosaur footprints, are between 96 and 81 Ma in age, though 81 Ma is probably a reasonable age estimate for this layer as it is close to the dated horizon. The younger layer, which contains dinosaur tracks, is similarly between 81 and 78 Ma in age. However, as both are stratigraphically close to the 81 Ma, this is probably a good single age estimate for age of these fossils. The initial $^{87}Sr/^{86}Sr$ ratios are typical of volcanic rocks of similar age found in East Asia. The K–Ar ages measured on the same rocks are younger, 83–69 Ma, and could have suffered Ar loss due to subsequent hydrothermal and other volcanic activity that has been documented for the area, and thus should be regarded as minimum ages. The occurrence of tracks of pterosaurs, early web-footed birds and dinosaurs at same horizon attests to their coexistence in the same environment in the Cenomanian to Campanian.

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