The Island Arc (2003) **12,** 132–144

Thematic Article

Dinosaur tracks from the Cretaceous of South Korea: Distribution, occurrences and paleobiological significance

MIN HUH,[1,*] KOO GEUN HWANG,[1] IN SUNG PAIK,[2] CHULL HWAN CHUNG[1] AND BO SEONG KIM[3]

[1]*Faculty of Earth Systems and Environmental Sciences and Korea Dinosaur Research Center, Chonnam National University, Gwangju 500-757, Korea (email: minhuh@chonnam.ac.kr),* [2]*Department of Environmental Geosciences, Pukyong National University, Pusan 608-737, Korea and* [3]*Mokpo Museum of Natural History and Culture, Mokpo 530-701, Korea*

Abstract Abundant dinosaur fossils including dinosaur footprints, eggs and nests, teeth and bones have been found from the Cretaceous non-marine deposits of Korea. Among them, dinosaur tracks are the most distinctive, and some track sites are among the most famous in the world. Until now, 27 dinosaur track localities have been discovered from the Cretaceous strata in the Gyeongsang Basin and several small basins. Ornithopod tracks are most abundant at most Korean track sites, and most of them are identified as *Caririchnium*; that is, large ornithopod footprints with wide hoof impressions. Most theropod tracks are found in Neungju Basin and they consist of various types of small or medium-sized bird-like footprints, and other large footprints. Sauropod tracks are also abundant in the Gyeongsang Basin. The sauropod tracks vary in size, shape, and pattern of trackway, and suggest that diverse sauropods existed in this area. These diverse tracks in South Korea suggest that various dinosaurs flourished at the margins of lakes distributed in the southern part of the Korean Peninsula during the Cretaceous.

Key words: Cretaceous, dinosaur tracks, Korea, ornithopod, sauropod, theropod.

INTRODUCTION

The first dinosaur fossil remains discovered in Korea were dinosaur eggshell fragments, which were found in 1972 from the Cretaceous Hasandong Formation in Hadong County of Gyeongsang Province (Yun & Yang 1997). Since that time approximately 30 dinosaur fossil sites including footprints, eggs and nests, bones and teeth have been reported in this country, although relatively few have been described in the literature. Recently, four dinosaur egg localities with complete egg clutches (Boseong, Siwha, Goseong and Tongyoung) were discovered from the Cretaceous deposits (Huh *et al*. 1999a; Lee *et al*. 2000a; Huh & Zelenitsky 2002). The dinosaur bones, dinosaur teeth and pterosaur tracks have been found at various localities (Chang *et al*. 1982; Kim 1983; Huh *et al*. 1996, 1998; Lockley *et al*. 1997; Paik *et al*. 1998; Paik 2000; Park *et al*. 2000; Hwang 2001; Hwang *et al*. 2002a, b). With the dinosaur fossils, the other vertebrate fossils including turtles, fishes and pterosaurs have been found at some localities (Lee *et al*. 2001). In Korea, track sites (dinosaur, pterosaur, and bird) comprise the majority of dinosaur fossil localities.

Until now, 27 dinosaur track localities have been discovered from Cretaceous non-marine deposits including Gyeogsang Basin and several small basins; and mainly dinosaur tracks have been found from the coastal area in southern part of the Korean Peninsula (Fig. 1; Table 1). In the present paper we review the dinosaur tracks from South Korea and report their distribution and occurrences, and discuss Cretaceous dinosaur tracks from Korea and other countries.

*Correspondence.

Received 7 May 2002; accepted for publication 29 December 2002.

GEOLOGICAL SETTING

Several Cretaceous sedimentary basins (non-marine) are distributed in South Korea. All of

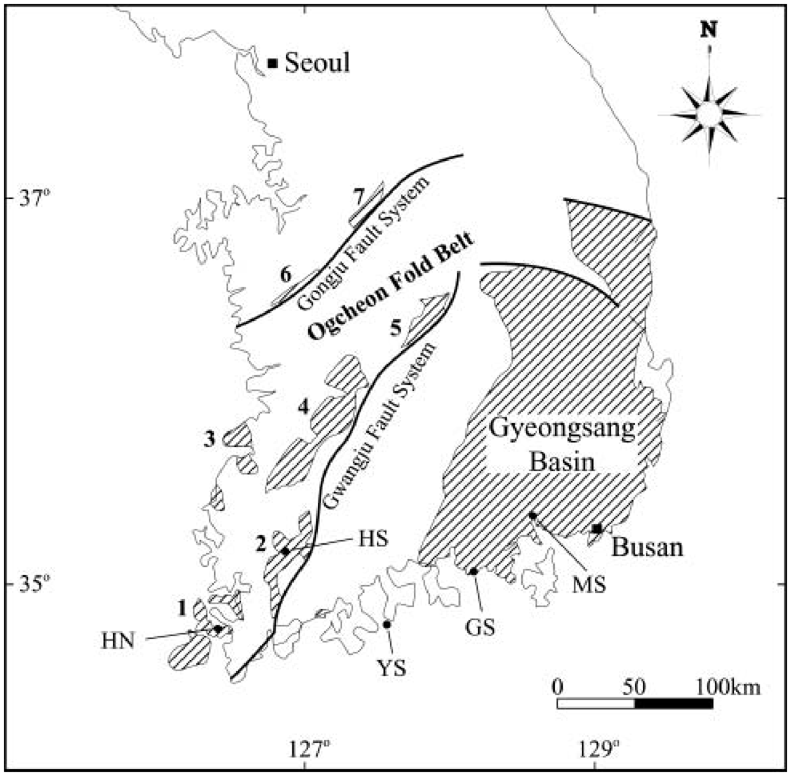

Fig. 1 Distribution of Cretaceous basins (shaded) and the main dinosaur track sites, as related to the fault patterns in the South Korean Peninsula. Numbers indicate smaller Cretaceous non-marine basins: 1, Haenam; 2, Neungju; 3, Kyokpo; 4, Jinan; 5, Yeongdong; 6, Gongju; 7, Eumseong. HN, Haenam dinosaur track site; HS, Hwasun dinosaur track site; YS, Yeosu dinosaur track site; GS, Goseong dinosaur track site; MS, Masan dinosaur track site.

Table 1 Systematic list of dinosaur ichnotaxa from the Cretaceous of South Korea

Dinosaur Ichnotaxa	Occurrence	Stratigraphy	Material
Class Reptilia			
Superorder Dinosauria			
Order Ornithischia			
Suborder Ornithopoda			
Ichnofamily indet.			
	Yusu-ri, Nadong-myeon, Jinju	Hasandong Fm. (GB)	30 tracks
	Geomjeon-ri, Sachen	Jinju Fm. (GB)	6 trackways
	Gupo-ri, Sachen	Jinju Fm. (GB)	11 tracks
	Gain-ri, Namhae	Haman Fm. (GB)	
	Yongsan-ri, Haman	Haman Fm. (GB)	11 trackways
	Dukmyeong-ri, Hai-myeon, Goseong	Jindong Fm. (GB)	170 trackways
	Dapo-ri, Nambu-myeon, Geojae	GB)	3 trackways
	Donghae-myeon, Goseong	Jindong Fm. (GB)	35 trackways
	Hail-myeon, Goseong	Jindong Fm. (GB)	14 trackways
	Georu-myeon, Goseong	Jindong Fm. (GB)	4 trackways
	Maam-myeon, Goseong	Jindong Fm. (GB)	3 trackways
	Hoewha-myeon, Goseong	Jindong Fm. (GB)	21 trackways
	Gaecheon-myeon, Goseong	Jindong Fm. (GB)	2 trackways
	Jindong-ri, Jindong-myeon, Masan	Jindong Fm. (GB)	10 tracks
	Gohyun-ri, Jindong-myeon, Masan	Jindong Fm. (GB)	200 tracks
	Hwang-ri, Tongyeong	Jindong Fm. (GB)	40 tracks
	Yugok-dong, Chung-gu, Ulsan	Jindong Fm. (GB)	65 tracks
	Cheonchon-ri, Dudong-myeon, Ulsan	Geoncheonri Fm (GB)	200 tracks
	Geomun-ri, Changryeong	Geoncheonri Fm (GB)	
	Jaeo-ri, Geumseong-myeon, Euiseong	Sagog Fm. (GB)	100 tracks
	Mancheon-ri, Euiseong	Sagog Fm. (GB)	
	Uhang-ri, Hwangsan-myeon, Haenam	Uhangri Fm. (HB)	7 trackways
	Sado, Hwajeong-myeon, Yeosu	(NB)	695 tracks
	Chudo, Hwajeong-myeon, Yeosu	(NB)	1230 tracks
	Nangdo, Hwajeong-myeon, Yeosu	(NB)	907 tracks
	Mokdo, Hwajeong-myeon, Yeosu	(NB)	50 tracks
	Seoyu-ri, Buk-myeon, Hwasun	(NB)	330 tracks

Table 1 *Continued*

Dinosaur Ichnotaxa	Occurrence	Stratigraphy	Material
Suborder Theropoda			
Ichnofamily indet.			
	Yusu-ri, Nadong-myeon, Jinju	Hasandong Fm (GB)	6 tracks (a trackway)
	Geomjeng-ri, Sachen	Jinju Fm. (GB)	5 tracks
	Jinseong-myeon, Jinju	Haman Fm. (GB)	
	Gajin-ri, Jinju	Haman Fm. (GB)	3 tracks
	Dukmyeong-ri, Hai-myeon, Goseong	Jindong Fm. (GB)	15 trackways
	Hail-myeon, Goseong	Jindong Fm. (GB)	2 trackways
	Donghae-myeon, Goseong	Jindong Fm. (GB)	4 trackways
	Hoewha-myeon, Goseong	Jindong Fm. (GB)	1 trackway
	Cheonchon-ri, Seo-myeon, Gyeongju	Geoncheonri Fm. (GB)	4 trackways
	Geomu-ri, Changryeong-myeon, Changryeong	Geoncheonri Fm. (GB)	
	Jaeo-ri, Euiseong	Sagog Fm. (GB)	
	Mancheon-ri, Euiseong	Sagog Fm. (GB)	1 trackway
	Guam-ri, Jeomgog	Jeomgog Fm. (GB)	34 tracks
	Uhang-ri, Hwangsan-myeon, Haenam	Uhangri Fm. (HB)	1 trackway
	Seoyu-ri, buk-myeon, Haenam	(NB)	909 tracks
	Sado, Hwajeong-myeon, Yeosu	(NB)	38 tracks
	Chudo, Hwajeong-myeon, Yeosu	(NB)	21 tracks
	Nangdo, Hwajeong-myeon, Yeosu	(NB)	55 tracks
Suborder Sauropodomorpha			
Infraorder Sauropoda			
Ichnofamily indet.			
	Jinseong-myeon, Jinju	Jinju Fm. (GB)	
	Gammyeong-ri, Haman-myeon, Haman	Haman Fm. (GB)	13 tracks
	Gain-ri, Namhae	Haman Fm. (GB)	
	Yongsan-ri, Haman	Haman Fm. (GB)	1 trackway
	Myeongkwan-ri, Gunbuk-myeon, Haman	Jindong Fm. (GB)	20 tracks
	Dukmyeong-ri, Hai-myeon, Goseong	Jindong Fm. (GB)	65 trackways
	Donghae-myeon, Goseong	Jindong Fm. (GB)	28 trackways
	Georyu-myeon, Goseong	Jindong Fm. (GB)	1 trackway
	Hail-myeon, Goseong	Jindong Fm. (GB)	2 trackways
	Maam-myeon, Goseong	Jindong Fm. (GB)	1 trackway
	Hoewha-myeon, Goseong	Jindong Fm. (GB)	39 trackways
	Gaecheon-myeon, Goseong	Jindong Fm. (GB)	2 trackways
	Younghyun-myeon, Goseong	Jindong Fm. (GB)	1 trackway
	Hogye-ri, Masan	Jindong Fm. (GB)	150 tracks(7tws)
	Jaeo-ri, Geumseong-myeon, Euiseong	Sagog Fm. (GB)	200 tracks(?)
	Mancheon-ri, Euiseong	Sagog Fm. (GB)	1 trackway
	Mogok-ri, Jinyang-myeon, Gyeongsan	Banyaweol Fm. (GB)	16 tracks
	Yongho-dong, Daechang-myeon, Yeongcheon	Geoncheonri Fm. (GB)	12 tracks
	Cheonchon-ri, Seo-myeon, Gyeongju	Geoncheonri Fm. (GB)	13 tracks
	Yongmyeong-ri, Geongju	Geoncheonri Fm. (GB)	204 tracks
	Uhang-ri, Hwangsan-myeon, Haenam	Uhangri Fm. (HB)	2 trackways
	Sado, Hwajeong-myeon, Yeosu	(NB)	23 tracks
	Chudo, Hwajeong-myeon, Yeosu	(NB)	508 tracks
	Seoyu-ri, Buk-myeon, Hwasun	(NB)	48 tracks

GB, Gyeongsang Basin; HB, Haenam Basin; NB, Neungju Basin; ts, tracks; tws, trackways; indet., indeterminate.

them are pull-apart (or trans-tensional) basins formed by the northward subduction of the Izanagi Plate (Chough *et al.* 2000), and consist of alluvial fan, fluvial plain, and lacustrine deposits, and volcanics. Dinosaur tracks usually occur in the lacustrine deposits in which thinly interlaminated fine-grained sandstones and siltstones–mudstones prevail.

The Gyeongsang Basin is the largest one, consisting of a 9000-m-thick sequence of deposits assigned to the Gyeongsang Supergroup. It is divided into the Sindong, Hayang, and Yucheon groups, in ascending stratigraphical order (Chang 1975). The Sindong and Hayang groups consist of an ascending sequence of alluvial fan, fluvial, and lacustrine deposits, respectively, whereas the

Yucheon Group is composed of volcanics in addition to alluvial and lacustrine deposits (Um *et al.* 1983; Choi 1985). The Jindong Formation, in which dinosaur tracks are common, is the uppermost part of the Hayang Group, and has been assigned to the Late Cretaceous (Paik *et al.* 2001).

In the west of the Gyeongsang Basin, several subordinate basins including the Haenam and Neungju basins are present (Lee 1999; Chough *et al.* 2000). A number of dinosaur tracks are preserved both in the Haenam and Neungju basins. The Haenam Basin sequence consists of andesitic tuffs and flows, rhyolite, and the epiclastic Uhangri Formation. Dinosaur, pterosaur and bird tracks occur in the Uhangri Formation, consisting of alluvial fan, lacustrine delta, and lake deposits (Chun & Chough 1995). The K–Ar age of the tuff (84–85 Ma) (Huh *et al.* 1997) and the frequent intercalations of volcanics indicate that the sequence of the Haenam Basin is correlated with the uppermost part of the Hayang Group to Yucheon Group in the Gyeongsang Basin (Fig. 2).

The Neungju Basin consists of acidic tuffs, lava flows, and epiclastic deposits. Dinsoaur tracks are present in the lacustrine deposits in which thinly interlaminated fine-grained sandstones and siltstones–mudstones are common. The frequent occurrence of volcanics in the Neungju Basin suggests that its geologic age is assigned to the Late Cretaceous. The sequence in Yeosu area has not yet been examined stratigraphically. However, its lithology, represented by tuffs, lava flows, and epiclastic non-marine deposits, implies that it is correlated with the sequence of the Neungju Basin (Fig. 2). Dinosaur tracks of the Neungju Basin also occur in thinly interlaminated fine-grained sandstones and siltstones–mudstones.

DINOSAUR TRACK LOCALITIES AND THEIR FEATURES

More than 27 dinosaur track sites have been found in South Korea (Table 1). Most reveal dinosaur footprints discovered from the coastal area in the

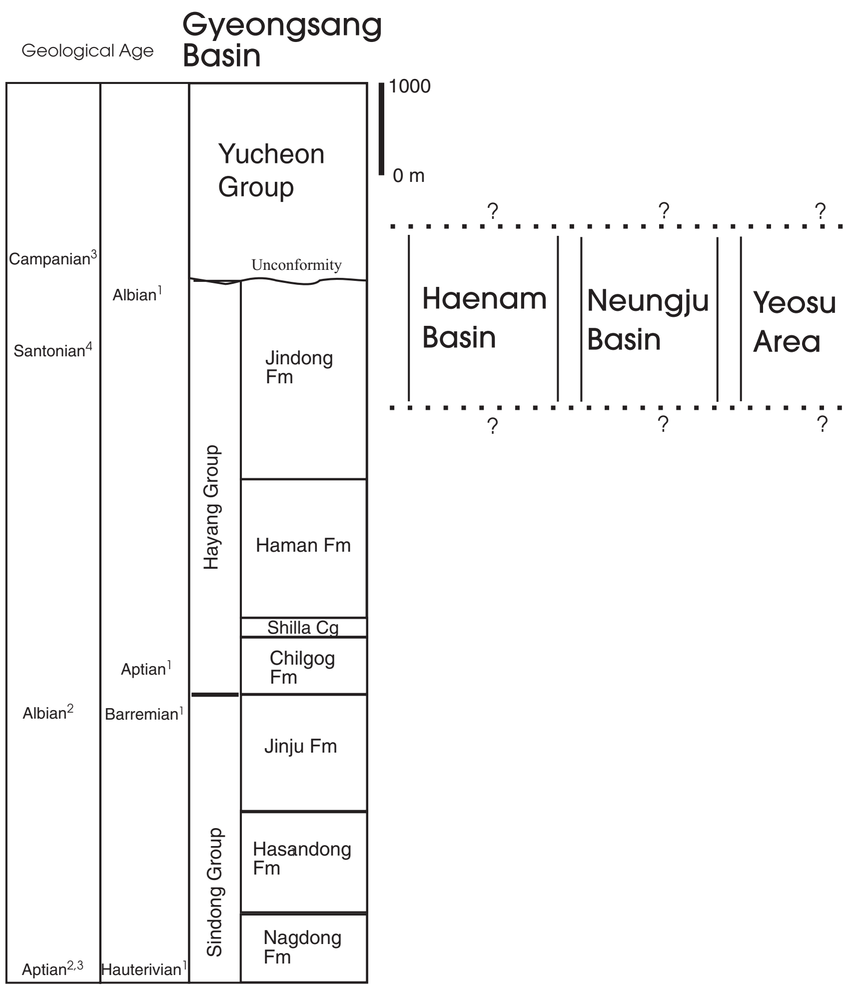

Fig. 2 Stratigraphic correlation of dinosaur track-bearing Cretaceous sedimentary basins in Korea. [1]Biostratigraphy (pollen and chorophyte): Seo (1985); Choi (1985); Yi *et al.* (1993). [2]Biostratigraphy (mollusc): Yang (1982). [3]Magnetostratigraphy: Doh and Kim (1994); Doh *et al.* (1994). [4]K–Ar age: Paik *et al.* (2001).

southern part of the Korean Peninsula. Although many dinosaur track sites have been found in Korea, detailed research on dinosaur tracks has been carried out only at some track sites (Lim 1991; Lim *et al.* 1994). The main dinosaur track sites are as follows.

The Haenam site (Uhang-ri, Hwangsan-myeon, Haenam-gun, south-western part of Cheollannam-do Province) is one of the unique and large fossil sites in Korea. The site contains the Uhangri Formation of Haenam Basin. The geological age of the Uhangri Formation has been estimated as Cenomanian to Campanian by Rb–Sr and K–Ar (Kim *et al.* 2002). The area is the large fossil site exposed by excavations carried out from 1996 to 1998 (Huh *et al.* 1998; Fig. 3a,b). At the site, a total of 528 dinosaur tracks including 105 unusual large tracks were found. Among them, ornithopod tracks comprise 72% of the total tracks (Huh *et al.* 1997; Hwang 2001). The unusual tracks have been interpreted as manus-only sauropod trackways (Lee & Huh 2002) or as distinctive ornithopod traces (Hwang 2001). In addition to the dinosaur tracks, various kinds of fossils including 443 pterosaur tracks, thousands of web-footed bird tracks, silicified wood, ostracoda, trace fossils and scattered

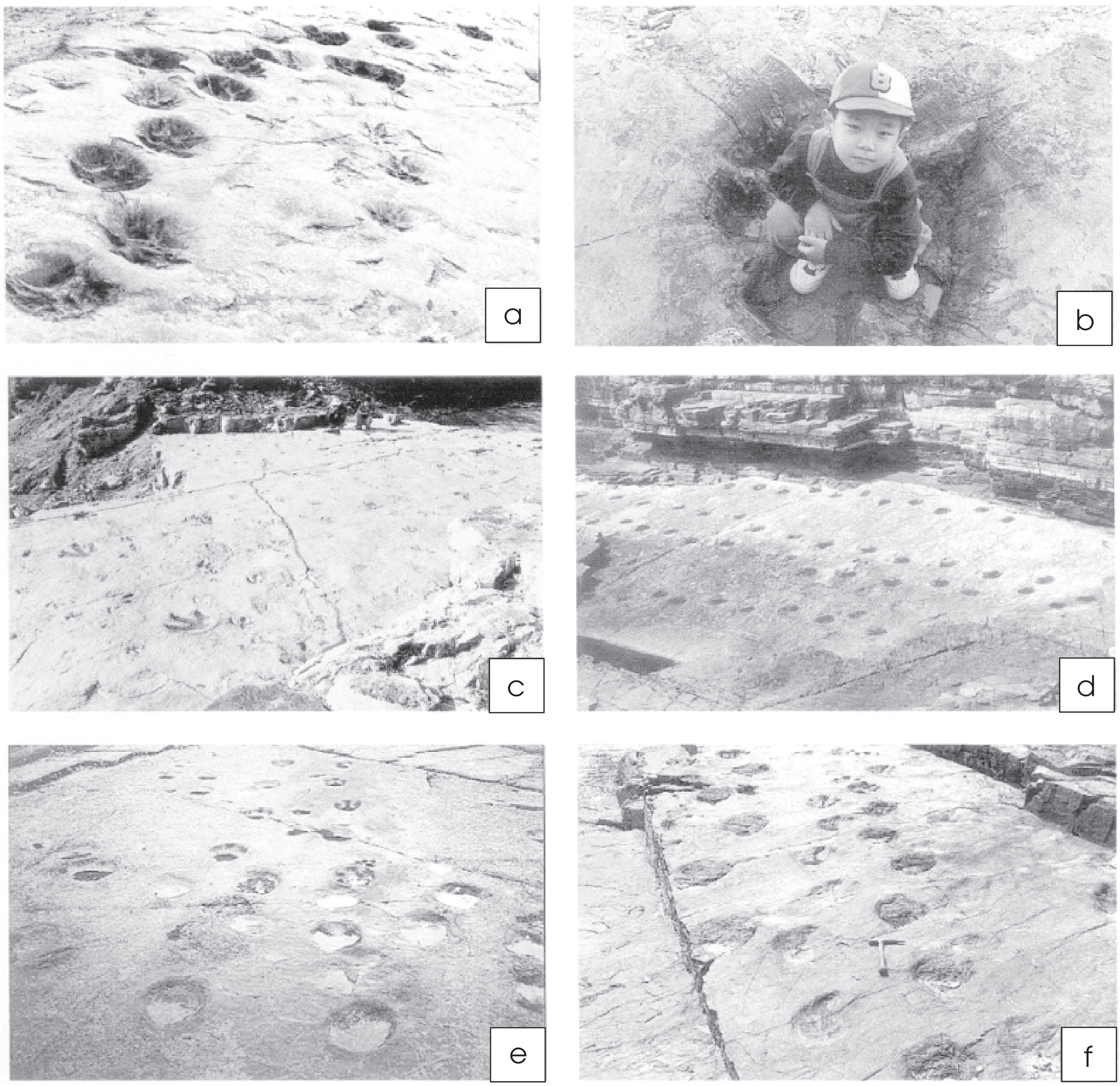

Fig. 3 Photographs showing the dinosaur track and trackways in outcrop. (a,b) Haenam; (c) Hwasun; (d) Yeosu; (e) Goseong; (f) Masan.

pterosaur bones have also been found (Huh *et al.* 1998). The pterosaur tracks have been assigned to a new genus, *Haenamichnus uhangriensis* (Hwang *et al.* 2002b). The web-footed bird tracks, which are the oldest ones in the world, were previously identified as *Uhangrichnus chuni* and *Hwangsannipes choughi* (Yang *et al.* 1995).

The Hwasun site (Seoyu-ri, Buk-myeon, Hwasun-gun, north-eastern part of Cheollannam-do Province) is located in the Neungju Basin, and contains various dinosaur footprints. Based on geological age dating, the fossil site has been determined as Upper Cretaceous (81–77 Ma; Huh *et al.* 2001b). At the site, 73 trackways including approximately 1800 footprints of theropods and sauropods have been discovered. Long theropod trackways (approx. 50 m) are characteristic in the area (Fig. 3c). Mud cracks and ripple marks are comon in the sequences containing the dinosaur tracks (Huh *et al.* 1999b, 2001b).

Yeosu site (Hwajeong-myeon, Yeosu-city, south-eastern part of Cheollannam-do Province), which was recently discovered, is one of the largest dinosaur track sites in Korea. This site consists of five isolated dinosaur fossil sites (islands): Chudo, Sado, Nangdo, Mokdo and Jeokgeumdo. A total of 3500 dinosaur footprints have been found from the islands of the Cretaceous deposits. The ornithopod tracks are dominant (81%). At this site, an 84-m-long ornithopod trackway, which is one of the longest dinosaur trackways in the world (Huh *et al.* 2001a,c) occurs (Fig. 3d). The area, also, yields other fossils such as silicified wood, plant fossils, bivalves, and invertebrate trace fossils (Huh *et al.* 2001a).

The Goseong site (Deokmyeong-ri, Hai-myeon, Goseong-gun, south-western part of Gyeongsang-nam-do Province) is one of the largest dinosaur track sites in the world (Fig. 3e). The first discovery of the dinosaur footprints in Korea was reported from the Cretaceous Jindong Formation in Goseong area (Yang 1982). Since then, detailed studies on dinosaur tracks have been carried out in the Deokmyeong-ri, Hai-myeon area (Lim 1991; Lockley *et al.* 1992; Lim *et al.* 1994) and the other areas (Lee *et al.* 2000b). At this site a total of 412 mapped trackways (249 ornithopod, 139 sauropod and 24 theropod trackways) were found (Lim *et al.* 1994). The ornithopod trackways are the most dominant (61%) at the Goseong site (Lee *et al.* 2000b). Along with dinosaur tracks, numerous bird tracks were also found in the area including a new bird ichnotaxon, *Jindongornipes kimi* (Lockley *et al.* 1992) and the previously known *Koreanaornis* first reported from the Haman Formation (Kim 1969).

Masan site (Hogye-ri, Masan City, south-western part of Gyeongsangnam-do Province) consists of distinct ornithopod and sauropod tracks with bird tracks. Seven sauropod trackways were first recognized from the Jindong Formation in this site (Paik *et al.* 2001; Hwang *et al.* 2002a). In these trackways 105 footprints are observed, and the distinct shape of four digits oriented subparallel to the trackway is well preserved in places (Fig. 6b). The various positions of manus print to pes print have been observed in this area. The direction and speed of dinosaur locomotion shown in four trackways are similar to each other. Such occurrence is interpreted to be the result of group locomotion, suggesting that Hogyeri trackways were not made by youngsters but, at least, by subadults. It is interpreted that the Hogyeri trackways were produced by small sauropods (hip height of 2 m and a locomotion speed of 0.34–1.9 m/s) walking on a dry mudflat (Hwang *et al.* 2002a).

DINOSAUR ICHNOFAUNA

ORNITHOPOD TRACKS

Occurrence

Ornithopod tracks have been found at several sites throughout South Korea, including the Hasandong Formation, the Jindong Formation, the Uhangri Formation, and the Yeosu area, as indicated in Table 1. The ornithopod footprints are found at all track sites and make up a larger portion than any other types of footprints in Korea (Lim 1991; Lim *et al.* 1994; Lockley 1994; Huh *et al.* 1997; Huh & Paik 2001; Hwang 2001). This indicates that ornithopod dinosaurs flourished on a large scale across the Korean Peninsula during the Cretaceous.

The ornithopod footprints found in Korea can be divided into two groups according to their shapes: one has the shape of a very broad three-toed *Iguanodon*-like footprint, and the other has the shape of *Caririchnium* (Fig. 4). The *Caririchnium* shape exhibits subparallel digit impressions and a wide pad impression, while the *Iguanodon*-like footprint has a rather wide angle of digit impressions and a narrow pad impression. A large number of well-preserved *Caririchnium* footprints has been found in the Uhangri Formation, the Jindong Formation and in the Yeosu area

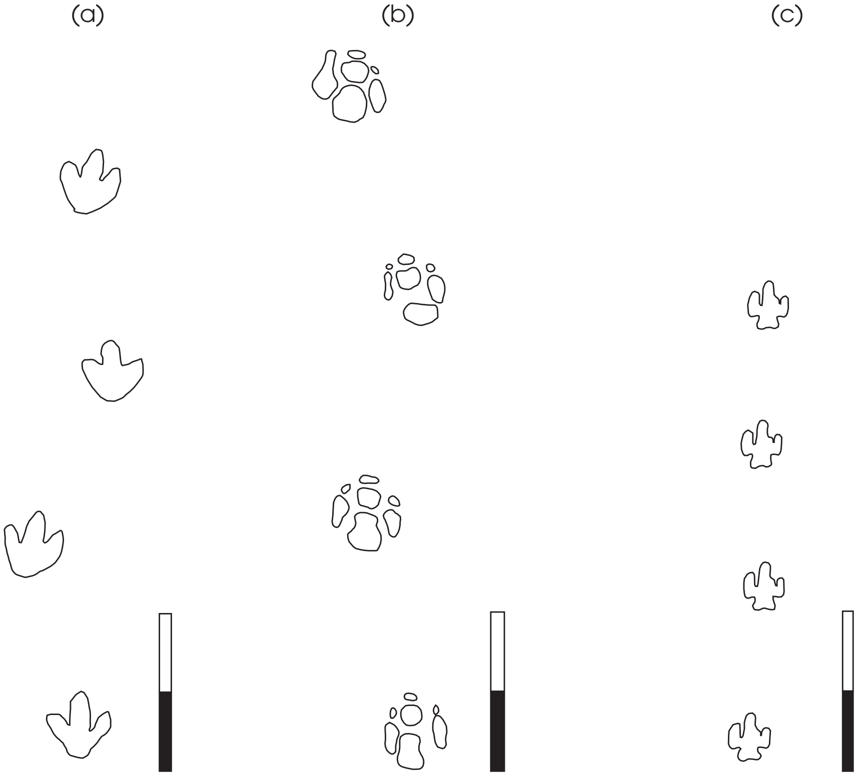

Fig. 4 Various types of orinthopod tracks from South Korea (scale bar = 1 m). (a) *Iguanodon*-like tracks from Yeosu track site. (b) *Caririchnium* from Uhangri Formation. (c) *Caririchnium* from Jindong Formation.

(Fig. 4b,c). All of them comprise bipedal trackways consisting of large tridactyl pes impressions with broad metatarsal–phalangeal pads, thick digital pads and large hoof impressions. The pes impressions are rotated inward toward the axis of the trackways. Among these, the *Caririchnium* footprints found in the Uhangri Formation are large-sized foot impressions (35–44 cm in length) with very wide hoof impressions, different from the reported *C. magnificum* from the Rio do Peixe Group of Brazil (Leonardi 1984), *C. loenardii* from the Dakota Group of eastern Colorado (Lockley 1987), and *C. protohadrosaurichnos* from the Woodbine Formation, Texas (Lee 1997; Hwang 2001).

Discussion

While *C. magnificum* (Leonardi 1984), *C. leonardii* (Lockley 1987), and *C. protohadrosaurichnos* (Lee 1997) have been discovered in Lower–'mid' Cretaceous strata, the ornithopod tracks in Korea have been identified as being younger. Age determination has shown the Uhangri Formation (and the Jindong Formation) as belonging to Late Cretaceous strata. The ornithopod tracks in the Uhangri and Jindong Formations seem to have been made by adults, based on the foot length of 30–40 cm (Lockley 1994), and the wide hooves of Uhangri ornithopod tracks. This demonstrates that the ornithopod dinosaurs developed wider hooves as their size increased. This may be related to the fact that hadrosaurid body fossils are found in the Late Cretaceous strata (Norman 1985). Although hadrosaurid body fossils have not yet been found in Korea, skull fragments of a lambeosaurid from the Upper Cretaceous Ryugase Group and a Hadrosauridae tooth from the Upper Cretaceous rock in Kawakami have been discovered in Japan, indicating the existence of Late Cretaceous hadrosaurids in South-East Asia (Matsukawa & Obata 1994). All Korean ornithopod dinosaurs represent bipedal animals, and so differ from those of other areas that indicated bipedal and quadrupedal animals (Leonardi 1984; Lockley 1987; Lee 1997). The ornithopod tracks from the Early Cretaceous Tetori Group correspond to the Korean tracks in bipedal behavior (Matsukawa *et al.* 1995).

THEROPOD TRACKS

Occurrence

Theropod tracks have been found in Cretaceous fossil beds in the southern part of the Korean Peninsula, including the Hwasun area, the Jindong Formation, the Uhangri Formation, and the Yeosu area. Approximately 1400 theropod footprints and

73 theropod tracks have been found in the Hwasun Dinosaur Fossil Site in the Neungju Basin (Huh *et al.* 1999b, 2001b). The Korean theropods seem to have flourished across the Peninsula during the Cretaceous, as did the ornithopods.

The theropod footprints found in Korea exhibit various shapes. First, the footprints from the Hwasun area are bird-like with extremely narrow digit impressions and a wide splay (divarication) of the digits (Fig. 5a). The footprints are 22 cm long on average, and are similar to *Argoides* from Morocco of the Early Jurassic as well as the unnamed track from Utah, in both size and shape (Lockley & Hunt 1995). However, they may be more closely compared to *Magnoavipes* (Lee 1997; Lockley *et al.* 2001) in both morphology and time. The second shape, another bird-like dinosaur foot impression from the Hwasun area, is a medium-sized foot impression with slightly thicker digits than the first one (Fig. 5b). These footprints have slender toe impressions and constitute narrow trackways (Huh *et al.* 1999b, 2001b). Their shape and size are similar to those of *Ornithomimipus* from the Late Cretaceous (Sternberg 1926). The third is the large theropod tracks of various sizes of footprints, from 25 to 50 cm with distinct and sharp claw impressions (Fig. 5c). Its shape and size are similar to those of the trackway of the large theropod from the Middle Jurassic of Oxfordshire (Lockley & Meyer 1999). The fourth is a foot impression (average 41 cm long) from Haenam and Hwasun. These consist of wide heel impressions, short digit impressions, and sharp claw impressions, which show a resemblance to *Hadrosaurichnus* (Alonso 1980; Fig. 5d).

Discussion

Hadrosaurichnus was first named for tracks from Argentina based on web traces between the digit impressions (Alonso 1980). These, however, are probably theropod tracks, as indicated by their sharp claw impressions, elongated shape, and long step (M. Lockley pers. comm., 2001). Thus *Hadrosaurichnus* is an unfortunate name.

The Korean theropod tracks, containing not only Jurassic-type but also Cretaceous-type tracks, indicate that various theropods survived in Korea during the Late Cretaceous (Fig. 5). Most of the Korean theropod tracks are large-sized footprints, >40 cm in length, although footprints shorter than 20 cm also coexist. This indicates a tendency of increasing theropod size, compared to Jurassic theropods (Lockley *et al.* 2001). This tendency can be also seen in the huge theropod track from the Raton Formation in New Mexico, USA (Lockley & Hunt 1995; Huh *et al.* 2001b).

SAUROPOD TRACKS

Occurrence

Most of the sauropod tracks in Korea have been found in the Upper Cretaceous strata in the fossil

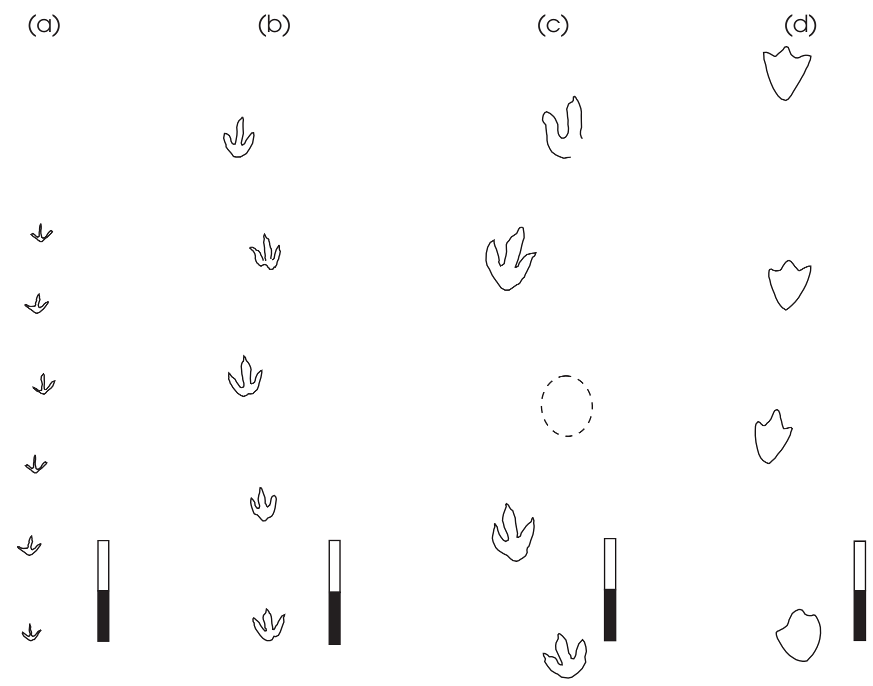

Fig. 5 Various types of theropod tracks from South Korea (scale bar = 1 m). (a) Small-bird-like tracks from Hwasun track site. (b) Medium-bird-like tracks from Hwasun track site. (c) Large theropod tracks from Hawsun track site. (d) Theropod tracks resembling *Hadrosaurichnus* from the Uhangri Formation.

sites of Yeosu, Heanam, Hwasun and in the Jindong Formation of the Goseong area. The sauropod tracks from the Jindong Formation, which contain 110 trackways, are varying from 10 cm to 115 cm in foot length. Most of the footprints are small-sized, with a diameter from 20 cm to 40 cm (Lim 1991; Lockley 1994; Lee *et al.* 2000b; Hwang *et al.* 2002a). The various positions and ratios of manus print to pes print and the sizes of the footprints of the Jindong Formation indicate that different sauropod dinosaurs lived on the Korean Peninsula during the Late Cretaceous period (Lee *et al.* 2000b; Hwang *et al.* 2002a). Moreover, the seven trackways excavated from the Jindong Formation in Hogyeri, Masan City, clearly indicate the characteristics of sauropods (Fig. 6a,b). The sauropod footprints, in which digit impressions are well-preserved, offer important information for the understanding of the sauropod tracks from the Jindong Formation (Hwang *et al.* 2002a). The footprints found in Hogyeri, Masan City, are 42 cm long and 25 cm wide, with the forefoot and the hind foot overlapping. The forefoot left a transversely oval footprint without a trace of the hoof (i.e. posteriorly concave), upon which the hind footprint is placed with its back jutting slightly out. The back of the forefoot has the shape of a hollowed hoof, and it is deeper than the hind footprint. In the hind footprint, four stubby digit impressions are distinct. The digits are slightly curved and parallel to the trackway (Fig. 6b). Lockley and Rice (1990) and Lockley *et al.* (1994) have noted the common occurrence of manus tracks that are deeper than pes tracks.

Discussion

The small-sized sauropod footprints from the Jindong Formation are considered as belonging to juvenile *Brontopodus* sauropods (Fig. 6a; Lockley 1994). The well-preserved sauropod footprint from Masan City (Fig. 6b) exhibits differences from other *Brontopodus* prints, with less curved digit impressions, as well as dull claw impressions that are different from the sharp digits of *Brontopodus* or *Breviparops* (Farlow *et al.* 1989; Ishigaki 1989).

Lockley (1994) assumed that the footprints from the Jindong Formation, which vary in size from 16 cm to 100 cm, belonged to one species, and he interpreted the small-sized sauropod footprints as belonging to juvenile dinosaurs, in accordance

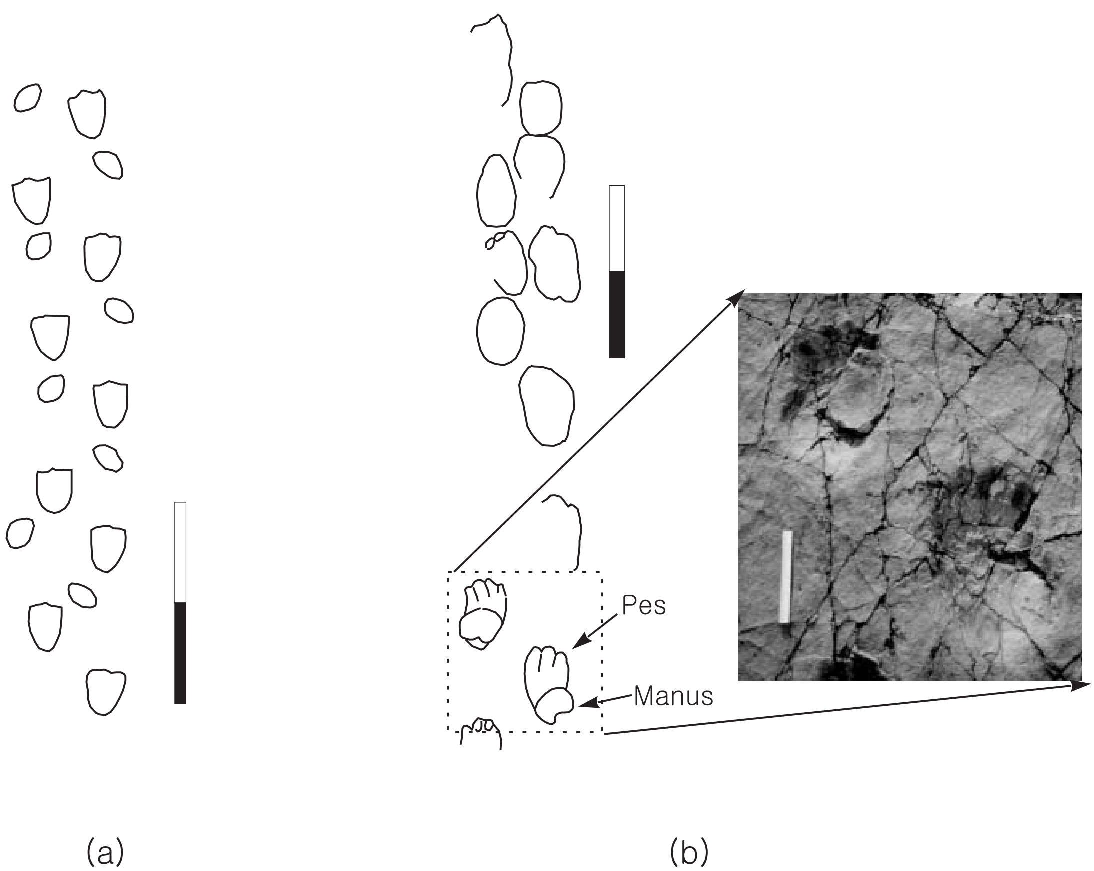

Fig. 6 Small-sauropod tracks found in Jindong Formation of Goseong (a) and Masan track sites (b). Scale bar = 1 m.

with the growth formula of *Maiasaura*. The distribution curves of the small-sized sauropod tracks from the Jindong Formation, however, reach their peak at the size of 30–40 cm, and decline sharply after 52 cm (Lockley 1994; Lee *et al.* 2000b; Hwang *et al.* 2002b). When the rapid growth rate of dinosaurs is considered (Erickson *et al.* 2001), the sauropod trackways in Hogyeri, Masan might not belong to one species. Lim (1991) divided the sauropod footprints from the Jindong Formation into the four types, and Lee *et al.* (2000b) noted that the diverse sauropods lived during the Jindong time based on the manus position, heteropody and track morphology. Considering the discoveries of other fossils from the Hasandong Formation such as the skeleton structure of Euhelopodidae (Dong *et al.* 2001) and the tooth fossils of Euhelopodidae, Camarasauridae, and Titanosauridae (Park *et al.* 2000), it seems that diverse sauropod dinosaurs of varying sizes are thought to have existed in the Cretaceous of the Korean Peninsula.

DISCUSSION

Similar ornithopod tracks compared to those of the Jindong Formation in Korea have been found in the Yangji Group of China and the Tetori Group of Japan. This suggests that the Japan Islands were an eastern extension of the Asian Continent during the Early Cretaceous (Matsukawa & Obata 1994; Matsukawa *et al.* 1995). As mentioned here, most of the dinosaur tracks occur in the Late Cretaceous deposits in the Korean Peninsula, whereas dinosaur footprints in Japan are concentrated in the Early Cretaceous. The Late Cretaceous nonmarine basins in Korea formed in the overriding continental plate and the frontal part of the arc, caused by the oblique convergence of an extensional basin (Chun & Chough 1995). During the Cretaceous it is possible that some dinosaurs migrated or moved to inland habitats (Lucas & Hunt 1989). The Cretaceous dinosaur tracks in the Korean Peninsula vary in distribution: ornithopod tracks are found all over the country, while theropod tracks seem to be concentrated in the Neungju Basin, and sauropod tracks in the Gyeongsang Basin (Lim 1991; Huh *et al.* 1997, 1999b, 2001a, 2001b,c; Hwang 2001). At this point it is difficult to tell whether the distribution of these dinosaur tracks resulted from environmental differences in the lake surroundings, or ecologic differences within the dinosaur species themselves, as yet incomplete sampling, or some yet undiscovered phenomenon.

CONCLUSIONS

Twenty-seven dinosaur track sites have been found in the non-marine Late Cretaceous strata distributed in South Korea, and they suggest that dinosaurs flourished at the margins of lakes located in the southern part of Korea during the Cretaceous.

Ornithopod tracks are the most abundant, and most of them are identified as *Caririchnium*; that is, large orithithopod footprints with wide hooves.

Most of theropod tracks in Korea are found in Neungju Basin located in the south-western part of the Korean Peninsula, and these tracks consist of various types of small or medium bird-like footprints (cf. *Magnoavipes*) and larger footprints.

Sauropod tracks are abundant in Gyeongsang Basin located in the south-eastern part of the Korean Peninsula. These sauropod tracks are various in size, shape and pattern of trackway, and probably indicate that diverse sauropods lived in this area.

During the Cretaceous it is possible that some dinosaurs migrated or moved to inland habitats.

ACKNOWLEDGEMENTS

We would like to express thanks to members of the Dinosaur Excavation Team of Korea Dinosaur Research Center at Chonnam National University for their efforts in excavating the track sites. We also thank Dr Martin Lockley, University of Colorado at Denver, for the helpful reviews and comments. The present study has been funded by the Korean Science and Engineering Foundation (KOSEF R01-1999-00053).

REFERENCES

Alonso R. 1980. Icnitas de dinosaurios (Ornithopoda, Hadrosauridae) en el Cretacico superior del norte Arentina. *Acta Geologica Lilloana* **15**, 55–63.

Chang K. H. 1975. Cretaceous stratigraphy of southeast Korea. *Journal of the Geological Society of Korea* **11**, 1–23 (in Korean with English abstract).

Chang K. H., Seo S. J. & Park S. O. 1982. Occurrence of a dinosaur limb bone near Tabri, southern Korea. *Journal of the Geological Society of Korea* **18**, 195–202 (in Korean with English abstract).

CHOI D. K. 1985. Spores and pollen from the Gyeongsang Supergroup, southeastern Korea and their chronologic and paleoecologic implications. *Journal of the Paleontological Society of Korea* **1**, 33–50.

CHOUGH S. K., KWON S. T., REE J. H. & CHOI D. K. 2000. Tectonic and sedimentary evolution of the Korean peninsula: A review and new view. *Earth Science Reviews* **52**, 175–235.

CHUN S. S. & CHOUGH S. K. 1995. The Cretaceous Uhangri Foramtion, SW Korea: Lacustrine margin facies. *Sedimentology* **42**, 293–322.

DOH S. J., HWANG C. S. & KIM K. H. 1994. A paleomagnetic study of sedimentary rocks from Kyeongsang Supergroup in Milyang Subbasin. *Journal of the Geological Society of Korea* **30**, 211–28 (in Korean with English abstract).

DOH S. J. & KIM K. H. 1994. A paleomagnetic study of Cretaceous Rocks from the Euiseong Area. *Journal of Korean Economic and Environmental Geology* **27**, 263–79 (in Korean with English abstract).

DONG Z., PAIK I. S. & KIM H. J. 2001. A preliminary report on a sauropod from the Hasandong Formation (Lower Cretaceous), Korea. *In* Deng T. & Wang Y. (eds). *Proceedings of the Eighth Annual Meeting of the Chinese Society of Vertebrate Paleontology*, pp. 41–53. China Ocean Press, Beijing.

ERICKSON G. M., ROGERS K. C. & YERBY S. A. 2001. Dinosaurian growth patterns and rapid avian growth rates. *Nature* **412**, 429–33.

FARLOW J. O., PITTMAN J. G. & HAWTHORNE M. 1989. *Brotopodus birdi* Lower Cretaceous sauropod footprints from the U.S. Gulf coastal plain. *In* Gillette D. D. & Lockley M. G. (eds). *Dinosaur Tracks and Traces*, pp. 371–94. Cambridge University Press, New York.

HUH M., LEE Y. N. & HWANG G. K. 1998. [*A Research Report on the Haenam Dinosaur Site, Korea.*] Chonnam National University Museum, Gwangju (in Korean).

HUH M., LIM S. K. & YANG S. Y. 1996. [First discovery of pterosaur tracks from Asia.] *Journal of the Geological Society of Korea* **32**, 526–8 (in Korean).

HUH M., LIM S. K., YANG S. Y. & HWANG K. G. 1997. A preliminary report on the Cretaceous dinosaur tracks from the Uhangri Formation, Haenam, Korea. *Journal of the Paleontological Society of Korea, Special Publication* **2**, 1–16.

HUH M. & PAIK I. S. 2001. Current studies on Korean dinosaurs. *In Proceedings of the International Kanazawa Workshop on Geological and Environmental Aspects of the Circum-Japan Sea Region: Toward the 21th Century*, pp. 23–8. Kanazawa University, Kanazawa, Japan.

HUH M., PAIK I. S., CHUNG C. H., PARK J. B. & KIM B. S. 2001c. [Dinosaur tracks from Islands in Yeosu, Cheollanam-do, Korea.] *Journal of the Geological Society of Korea* **37**, 653–8 (in Korean).

HUH M., PAIK I. S. & HWANG K. G. 1999b. [*A Basic Report on the Hwasun Dinosaur Site, Korea.*] Dinosaur Research Center at Chonnam National University, Gwangju (in Korean).

HUH M., PAIK I. S., KIM K. S., KO Y. G., KIM J. B. & JUNG C. H. 2001b. *A Research Report on the Dinosaur Fossils from Hwasun Area, Cheollanam-Do Province, Korea*. Dinosaur Research Center at Chonnam National University, Gwangju.

HUH M., PAIK I. S., KO Y. G. *et al.* 2001a. *A Basic Research Report on the Dinosaur Fossils from Yosu area, Cheollanam-do, Korea*. Dinosaur Research Center at Chonnam National University, Gwangju.

HUH M., PAIK I. S., LEE Y. I. & KIM H. K. 1999a. [Dinosaur eggs and nests from Boseong, Chullanam-do.] *Journal of the Geological Society of Korea* **35**, 229–32 (in Korean).

HUH M. & ZELENITSKY D. K. 2002. A rich nesting site from the Cretaceous of Bosung County, Chullanam-do Province, South Korea. *Journal of Vertebrate Paleontology* **22**, 716–18.

HWANG K. G. 2001. Dinosaur and pterosaur tracks from the Late Cretaceous Uhangri Formation, Haenam, SW Korea. PhD Thesis, Chonnam National University, Gwangju, Korea.

HWANG K. G., HUH M., LOCKLEY M. G., UNWIN D. M. & WRIGHT J. L. 2002b. New pterosaur tracks (Pteraichnidae) from the Late Cretaceous Uhangri Formation, SW Korea. *Geological Magazine* **139**, 421–35.

HWANG K. G., HUH M. & PAIK I. S. 2002a. Sauropod tracks from the Cretaceous Jindong Formation, Hogyeri, Masan-city. *Journal of the Geological Society of Korea* **38**, 361–75.

ISHIGAKI S. 1989. Footprints of swimming sauropods from Morocco. *In* Gillette D. D. & Lockley M. G. (eds). *Dinosaur Tracks and Traces*, pp. 83–6. Cambridge University Press, New York.

KIM B. K. 1969. A study of several sole marks in the Haman Formation. *Journal of the Geological Society of Korea* **5**, 243–58.

KIM C-B., HUH M., CHEONG C-S., LOCKLEY M. G. & CHANG H-W. 2003. Age of the pterosaur and web-footed bird tracks associated with dinosaur footprints from South Korea. *The Island Arc* **12**, 125–31.

KIM H. M. 1983. Cretaceous dinosaurs from Korea. *Journal of the Geological Society of Korea* **19**, 115–26 (in Korean with English abstract).

LEE D. W. 1999. Strike–slip fault tectonics and basin formation during the Cretaceous in the Korean Peninsula. *The Island Arc* **8**, 218–31.

LEE Y. N. 1997. Bird and dinosaur footprints in the Woodbine Formation (Cenomanian), Texas. *Cretaceous Research* **18**, 849–64.

LEE Y. N. & HUH M. 2002. Manus-only sauropod tracks in the Uhangri Formation (upper Cretaceous), Korea and their paleobioloogical implications. *Journal of Palentology* **76**, 558–64.

LEE Y. N., JEONG K. S., CHANG S. K., CHOI M. Y. & CHOI J. I. 2000a. The preliminary research on the dinosaur Eggs and nests found in the reclaimed area south to the Siwha Lake, Gyeonggi Province, Korea. *Journal of the Paleontological Society of Korea* **16**, 27–36.

LEE Y. N., YANG S. Y., SEO S. J. *et al.* 2000b. Distribution and paleobiological significance of dinosaur tracks from the Jindong Formation (Albain) in Kosong County, Korea. *Journal of the Paleontological Society of Korea, Special Publication* **4**, 1–12.

LEE Y. N., YU K. M. & WOOD C. B. 2001. A review of vertebrate fauna from the Gyeongsang Supergroup (Cretaceous) in South Korea. *Palaeontology, Palaeoclimatology, Palaeoecology* **165**, 357–73.

LEONARDI G. 1984. Le impronte fossili di dinosauri. *In* Bonaparte J. F., Colbert E. H., Currie P. C. *et al.* (eds). *Sulle Orme dei Dinosauri*, pp. 161–86. Erizzo Editrice, Venice, Italy.

LIM S. K. 1991. Trace fossils of the Cretaceous Jindong Formation, Koseung, Korea. PhD Thesis, Kyungpook National University, Daegu, Korea.

LIM S. K., LOCKLEY M. G., YANG S. Y., FLEMING R. F. & HOUCK K. 1994. A preliminary report on sauropod tracksites from the Cretaceous of Korea. *Gaia: Revista de Geociencias, Museu Nacional de Historia Natural, Lisbon, Portugal* **10**, 109–17.

LOCKLEY M. G. 1987. Dinosaur footprint from the Dakota Group of Eastern Colorado. *Mountain Geologist* **24**, 107–22.

LOCKLEY M. G. 1994. Dinosaur ontogeny and population structure: Interpretations and speculations based on fossil footprints. *In* Carpenter K., Hirsch K. F. & Horner J. R. (eds). *Dinosaur Eggs*, p. 372. Cambridge University Press, New York.

LOCKLEY M. G., HUH M., LIM S. K., YANG S. Y., CHUN S. S. & UNWIN D. M. 1997. First report of pterosaur tracks from Asia, Chullanam Province, Korea. *Journal of the Paleontological Society of Korea, Special Publication* **2**, 17–32.

LOCKLEY M. G. & HUNT A. P. 1995. *Dinosaur Tracks and Other Fossil Footprints of the Western United States*. Columbia University Press, New York.

LOCKLEY M. G. & MEYER C. A. 1999. *Dinosaur Tracks and Other Fossil Footprints of Europe*. Columbia University Press, New York.

LOCKLEY M. G., PITTMAN J. G., MEYER C. A. & SANTOS V. F. 1994. On the common occurrence of manus-dominated sauropod trackways in Mesozoic carbonates. *Gaia: Revista de Geociencias, Museu Nacional de Historia Natural, Lisbon, Portugal* **10**, 119–24.

LOCKLEY M. G. & RICE A. 1990. Did '*Brontosaurus*' ever swim out to sea? Evidence from brontosaur and other dinosaur footprints. *Ichnos* **1**, 81–90.

LOCKLEY M. G., WRIGHT J. L. & MATSUKAWA M. 2001. A New Look at magnoavipes and so-called 'Big Bird' tracks from Dinosaur Ridge (Cretaceous, Colorado). *Mountain Geologist* 38, 137–46.

LOCKLEY M. G., YANG S. Y., MATSUKAWA A., FLEMING F. & LIM S. K. 1992. The track record of Mesozoic birds: Evidence and implications. *Philosophical Transactions of the Royal Society of London, Series B* **336**, 213–16.

LUCAS S. G. & HUNT A. P. 1989. Alamosaurus and the sauropod hiatus in the Cretaceous of the North American western interior. *Geological Society of America Special Paper* **238**, 75–85.

MATSUKAWA M., FUTAKAMI M., LOCKLEY M. G., CAO ZHENYAO C. C. & BOLOTSKY U. L. 1995. Dinosaur footprints from the Lower Cretaceous of eastern Manchuria, northeastern China: Implication for the recognition of an ornithopod Ichnofacies in East Asia. *Palaios* **10**, 3–15.

MATSUKAWA M. & OBATA I. 1994. Dinosaur and sedimentary environment in the Japanese Cretaceous: A contribution to dinosaur facies in Asia based on molluscan palaeontology and stratigraphy. *Cretaceous Research* **15**, 101–25.

NORMAN D. 1985. *The Illustrated Encyclopedia of Dinosaurs*. Salamander, London.

PAIK I. S. 2000. Bone chip-filled burrows associated with bored dinosaur bone in floodplain paleosols of the Cretaceous Hasan-dong Formation, Korea. *Palaeogeography, Palaeoclimatology, Palaeoecology* **157**, 213–25.

PAIK I. S., KIM H.J. & LEE Y. I. 2001. Dinosaur track-bearing deposits in the Cretaceous Jindong Formation, Korea: Occurrence, palaeoenvironments and preservation. *Cretaceous Research* **22**, 79–92.

PAIK I. S., LEE Y. I., LEE Y. U., CHEONG D. K. & KIM S. J. 1998. Dinosaur beds in the Cretaceous Hasandong Formation in the vicinity of Jinju City, Gyeongnam, Korea. *Journal of the Paleontological Society of Korea* **14**, 14–32 (in Korean with English abstract).

PARK E. J., YANG S. Y. & CURRIE P. J. 2000. Early Cretaceous dinosaur teeth of Korea. *Journal of the Paleontological Society of Korea. Special Publication* **4**, 85–98.

SEO S. J. 1985. Lower Cretaceous geology and paleontology (Charophyta) of central Gyeongsang Basin, South Korea. PhD Thesis, Kyungbuk National University, Daegu, Korea.

STERNBERG C. 1926. Dinosaur tracks from the Edmonton Formation of Alberta. *Geological Survey of Canada Bulletin* **44**, 85–7.

UM S. H., CHOI H. I., SON J. D. *et al.* 1983. [Geological and geochemical studies on the Gyeongsang Supergroup in the Gyeongsang Basin.] *Korea Institute of Energy and Resources, Bulletin* **36**, 1–124 (in Korean).

YANG S. Y. 1982. On the dinosaur footprints from the Upper Cretaceous Gyeongsang Group. *Journal of the Geological Society of Korea* **18**, 37–48 (in Korean with English abstract).

YANG S. Y., LOCKLEY M. G., GREBEN R., ERICKSON B. R. & LIM S. K. 1995. Flaming and duck-like bird tracks from the Late Cretaceous and Early Tertiary: Evidence and implications. *Ichnos* **4**, 21–34.

YI M. S., CHOI S. J. & YUN H. S. 1993. Cretaceous palynomorphs from the Iljik (Ilchik) Formation in the Euiseong (Uisong) area, Korea. *Journal of the Paleontological Society of Korea* **9**, 166–79.

YUN C. S. & YANG S. Y. 1997. Dinosaur eggshells from the Hasandong Formation, Gyeongsang supergroup, Korea. *Journal of the Paleontological Society of Korea* **13**, 21–36.