

Chapter 2

Dinosaurs of Korea

2.1 Dinosaur Tracks

Numerous tracks of ornithopods, theropods, and sauropod dinosaurs have occurred in the Cretaceous basins mainly located in south east and south of the Korean Peninsula. In addition, diverse fossils of dinosaur bones, teeth, eggshells, skin impressions, and tail traces have been also discovered, though these are relatively uncommon compared with dinosaur tracks. This chapter presents visual images of well-preserved and paleontologically significant tracks, bones, teeth, and eggshells of dinosaurs.

The first discovery of dinosaur tracks at the Cretaceous Jindong Formation on the southern coastal area of Dukmyeongri, Hai District, Goseong County (Yang 1982) stimulated subsequent research into vertebrate ichnology in Korea. Although measured data of over 360 dinosaur tracks at Dukmyeongri were provided, Yang (1982) did not provide a systematic description of dinosaur tracks and trackways. In addition, Yang (1982) tentatively classified Dukmyeongri dinosaur tracks into seven types (Type 1, Type 2-1, 2, Type 3-1, 2, Type 4-1, 2) mainly based on track size, length/width of track, number of digits, and rotation of digits. He made no mention of the dinosaurs that could have made these tracks, such as theropods, sauropods, and ornithopods.

Subsequently, Lim (1990), who was a Ph.D. student supervised by Yang, extensively surveyed the evidence at Dukmyeongri and discovered numerous (around 5000) dinosaur tracks. Lim (1990) also made informal attempts to differentiate dinosaur tracks into two categories: Q type (quadrupedal, presumably all sauropods) and B type (bipedal ornithopods and theropods), and further subdivided these into several subcategories (Q1–Q4 and B1–B9). Some authors have used the Q and B types devised by Lim (1990) for the classification of dinosaur tracks (e.g., Seo 1992; Baek and Seo 1998). However, this scheme is not effective because there is too much disagreement among independent observers as to the category to which a particular dinosaur track belongs (Lockley et al. 2006).

Table 2.1 Statistics of identified trackways of dinosaurs from the Cretaceous Period in Korea

Location	Basin	Theropod trackways	Sauropod trackways	Ornithopod trackways	Total trackways	References
Hai District, Goseong County	Gyeongsang Basin	16 (4%)	120 (31%)	252 (65%)	388 (100%)	Lim et al. (1994)
8 districts, Goseong County	Gyeongsang Basin	16 (5%)	139 (34%)	249 (61%)	410 (100%)	Lee et al. (2000b)
15 track sites	Gyeongsang Basin	38 (7%)	161 (29%)	366 (64%)	565 (100%)	Lee et al. (2001)
25 track sites	Gyeongsang Basin	28 (6%)	148 (33%)	269 (61%)	445 (100%)	Huh et al. (2003) ^a
85 track sites	Gyeongsang Basin	106 (12%)	295 (33%)	502 (55%)	903 (100%)	Kim and Kim (2016)
Uhangri, Haenam County	Haenam Basin	1 (10%)	2 (20%)	7 (70%)	10 (100%)	Huh et al. (2006a)
Seoyuri, Hwasun County	Neungju Basin	66 (87%)	?3 (4%)	7 (9%)	76 (100%)	Lockley et al. (2012a)

^aTrack sites of the Yeosu area were included in the Neungju Basin instead of the Gyeongsang Basin

As shown in Table 2.1, statistics of identified trackways made by theropods, sauropods, and ornithopods was, for the first time, carried out in the Hai District of Goseong County by Lim et al. (1994). Among the 516 identified dinosaur trackways from the Cretaceous Jindong Formation at the Sangjok, Dukmyeongri, Bonghwagol, and Silbawi sites located on the southeastern coast of Hai District, southwest of Goseong County, proportions of theropod, sauropod, and ornithopod trackways are 16 (4%), 12 (31%), and 252 (65%), respectively (Lim et al. 1994). The remaining 128 trackways which are not attributable to any types of dinosaur are worthy of further research.

In addition, Lee et al. (2000b) reported 410 identified trackways from the Jindong Formation of eight districts including Donghae, Hoehwa (misspelled as Hoewha by Lee et al.), and other districts, as well as Hai District, Goseong County. According to Lee et al. (2000b), proportions of identified trackways of theropods, sauropods, and ornithopods are 16 (5%), 139 (34%), and 249 (61%), respectively. Lee et al. (2001) first reviewed vertebrate faunas from the Gyeongsang Supergroup distributed in the Gyeongsang Basin and reported 565 identified trackways of dinosaurs from the 15 track sites. Proportions of identified trackways of theropods, sauropods, and ornithopods are 38 (7%), 161 (29%), 366 (64%), respectively. Dinosaur tracks from the Cretaceous Period at 25 track sites including those at Hwasun, Yeonsu, Ulsan, and Geogjae, which were not reported by Lee et al. (2001), were also reviewed by Huh et al. (2003).

Huh et al. (2003) reported that proportions of identified trackways of theropods, sauropods, and ornithopods are 28 (6%), 148 (33%), and 269 (61%), respectively. Huh et al. (2003) regarded that track sites in the Yeosu area, where only a number of tracks was shown, were included in the Neungju Basin instead of Gyeongsang Basin. However, it seems questionable that the number of new data (445 trackways) from many more track sites is much smaller than the number three years earlier (565 trackways), which may possibly be related to sources of indistinct trackways and data. Nonetheless, it is noteworthy that the proportions of identified trackways of theropods, sauropods, and ornithopods from the Goseong area and the Gyeongsang Basin are quite similar to each other: 4–7, 29–34, and 61–67%, respectively, though there are considerable difference in the number of identified trackways between them.

Recently, Kim and Kim (2016) compiled data about the Cretaceous vertebrate tracks from track sites previously reported in Korea. Their compiled data comprise identified tracks and trackways of vertebrates from 85 track sites, including the track sites at Hadong; Bito Island; Namhae; Duhori, Goseong; Tongyeong; Chilgok; Yeongcheon; Daegu; Gyeongsan; Gunwi; Cheongsong; and Yeongyang previously recorded in papers, reports, abstracts, and an unpublished thesis, as well as track sites reported by Lee et al. (2001) and Huh et al. (2003).

According to Kim and Kim (2016), there are 11,872 dinosaur tracks and 1058 dinosaur trackways from the Gyeongsang Basin, and 14,278 tracks and 1372 trackways from the Korean Peninsula. Among the dinosaur trackways from the Gyeongsang Basin, the proportions of identified trackways attributable to theropods, sauropods, and ornithopods are 106 (12%), 295 (33%), and 502 (55%), respectively (Kim and Kim 2016). The remaining trackways (255), which is about 23% of total dinosaur trackways (1158 trackways) from the Cretaceous of the Gyeongsang Basin, were not even assigned to theropods, sauropods, or ornithopods trackways. Instead, they were only assigned to dinosaur trackways, which means further systematic research on these tracks and trackways is necessary.

The Uhangri track site in the Haenam Basin is characteristically abundant with pterosaur and web-footed bird tracks, but there are relatively few identified trackways attributed to theropods (1), sauropods (2), and ornithopods (7) (Huh et al. 2003). However, the Seoyuri track site of the Neungju Basin, Hwasun County, reveals a predominant abundance of theropod trackways (66 = 87%) with a minor occurrence of identified trackways of sauropods (3 = 4%) and ornithopods (7 = 9%) (Huh et al. 2006a), which is very unusual compared with the proportions of dinosaur tracks from the Cretaceous Period at other track sites in Korea.

The proportions of different dinosaur groups represented by identified trackways at the Cretaceous Jindong Formation track sites of Hai District, Goseong County, where dinosaur tracks and trackways have been most abundantly recorded in Korea, are shown in Fig. 2.1 (Lim et al. 1994).

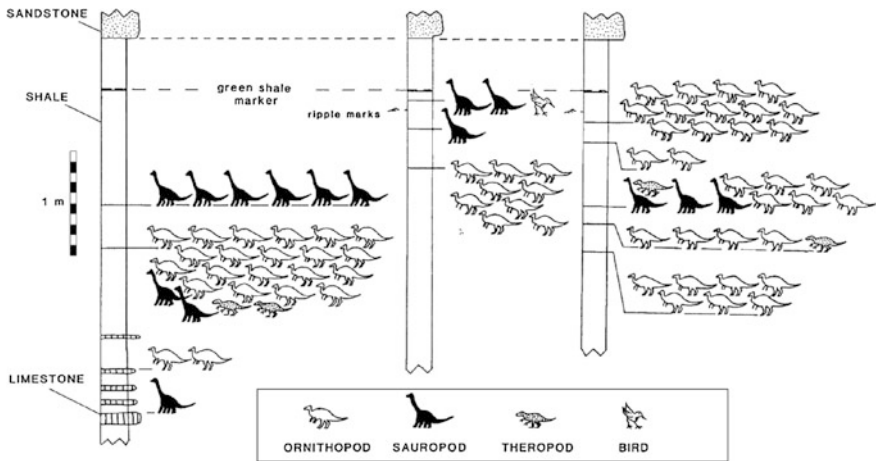


Fig. 2.1 Proportions of different dinosaur groups represented by identified trackways at the Cretaceous Jindong Formation at track sites in the Hai District, Goseong County. *Source* Lim et al. (1994)

2.1.1 Ornithopod Tracks

Among 1072 trackways of dinosaurs previously recorded from the Cretaceous Period in Korea, ornithopod tracks and trackways are the most abundant (over 50%) (Kim and Kim 2016). In particular, an abundance of ornithopod tracks and trackways have been discovered at the Jindong Formation of the Gyeongsang Basin, the Uhangri Formation of the Haenam Basin, and the Jangdong Tuff of the Neungju Basin.

Figure 2.2 presents examples of ornithopod trackways from among the total of approximately 250 identified ornithopod trackways at the Jindong Formation, Goseong County (Lim 1990; Lim et al. 1994; Lockley 1994; Lee et al. 2000b). Figure 2.2a, e show the ornithopods that made the tracks as mostly moving to the northwest. Figure 2.2b–c, f–g show the ornithopods moving predominately southwest. Seven parallel to subparallel ornithopod trackways show movement to the southeast (Fig. 2.2d). A sauropod trackway in Fig. 2.1g shows an almost northward direction of movement. It is perhaps noteworthy that the main trackway trend (southwest) is more or less perpendicular to the wave ripple crest trends (Lockley et al. 2006). Parallel and subparallel ornithopod trackways in the Goseong area suggest that these ornithopods were gregarious in nature. As shown in Figs. 2.3 and 2.4, ornithopod tracks from the Jindong Formation, Goseong area, are mostly 25–35 cm in size and of a *Caririchnium*-like tridactyl morphology (Lockley 1994; Lockley et al. 2006, Figs. 2.3 and 2.4). The tracks are slightly wider than they are long. The digit impressions are mesaxonic, relatively thick and short, with rounded distal termination. Digit II and III impressions are almost parallel to

slightly diverged at a low angle. The heel margin impressions are smoothly rounded or have a distinctively bilobate pattern (see Fig. 2.4). Impressions of manus and claw are not observed.

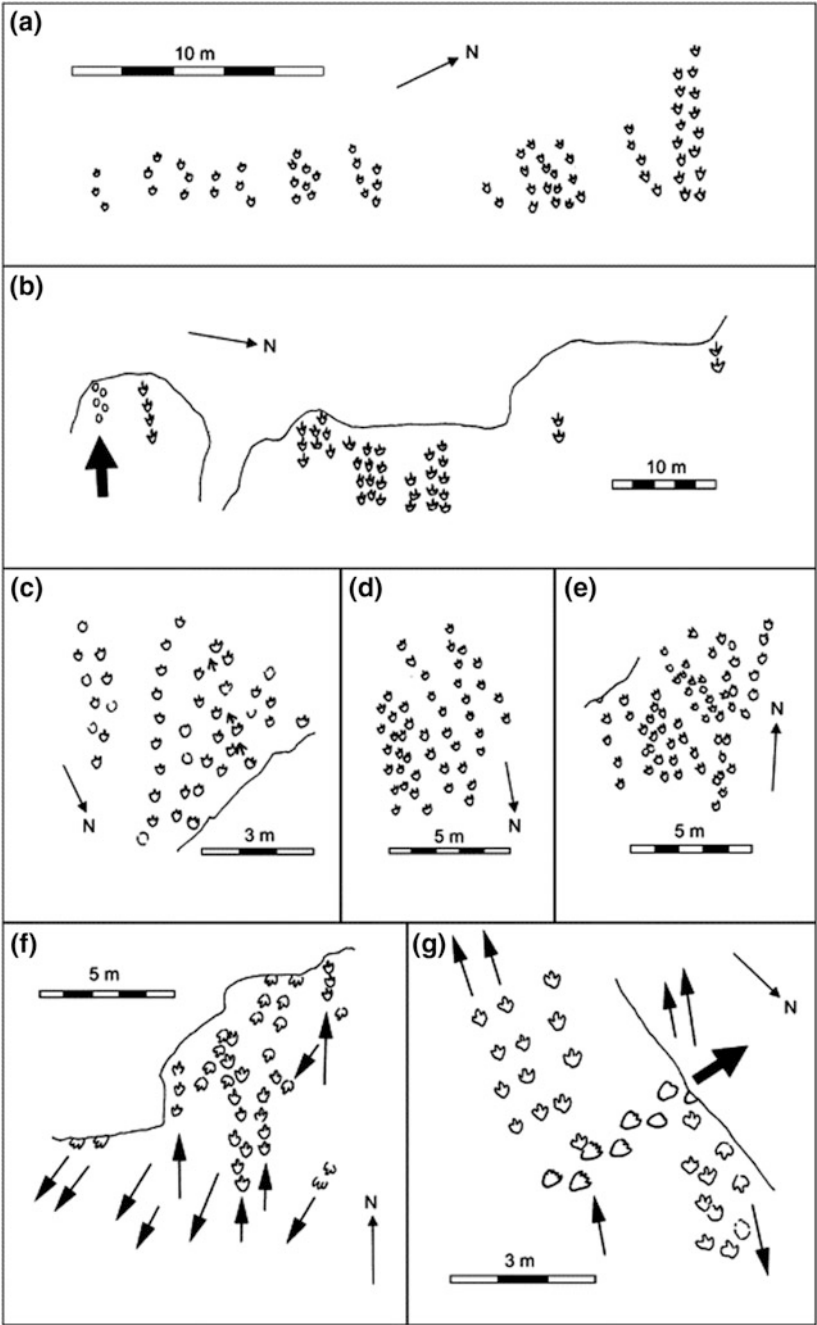
It is especially noteworthy that manus impressions in ornithopod trackways have never been observed at the Jindong Formation, Goseong area (Lockley et al. 2006). It is commonly known that small-sized early ornithopods are generally bipedal and large-sized late ornithopods are habitually quadrupedal and facultatively bipedal. Three probable explanations are possible for the absence of manus tracks. (1) There may have been overprinting of manus tracks with pes tracks. However, there is no double-printing that would provide evidence for this supposition (Lockley et al. 2006). (2) The facultative bipedalism of the ornithopod track makers may be relevant. However, it is probably unlikely that all ornithopod track makers only displayed facultative bipedal locomotion. (3) Shallow and very small (strong heteropody) manus impressions may have been unnoticed or overlooked in the field. The recent discovery of quadrupedal ornithopod trackways such as *Caririchnium kyoungsookimi* (Lim et al. 2012) and *Caririchnium yeongdongensis* (Kim et al. 2016), and several trackways personally observed in the field by the senior author, and *Caririchnium*-like probably quadrupedal tracks from the Uhangri Formation (Huh et al. 1997, Fig. 3) may partly indicate this possibility.

In this regard, it may be necessary to mention that all large ornithopods were quadrupedal, at least facultatively (Leonardi 1997) and manus track preservation bias is a key factor for identifying a trackmaker (Castanera et al. 2013). Absence of evidence is in no way evidence of absence! Further research and careful reexamination of “bipedal” ornithopod tracks and trackways from the Cretaceous Period in Korea is necessary.

Ornithopod trackways from the Chudo and Sado sites at the Yeosu area also show parallel to subparallel orientation (Lockley et al. 2012c, Fig. 2.5). Trackway directions are variable; northeast (five trackways at Chudo 5 and nine trackways at Chudo 4), southeast (four trackways at Chudo b2), southwest (five trackways at Chudo 6), west (seven trackways at Chudo 0), and south (eleven trackways at Chudo 3). However, deviation between trackways at the Chudo 6 site is minimal and inter-trackway spacing is extremely regular (Fig. 2.5). This regularity is strongly suggestive of gregarious behavior (Lockley et al. 2012b). The longest trackway from Chudo 6 (Fig. 2.6) measures 84 m and is currently the world's longest confirmed ornithopod trackway.

Ornithopod trackways are well-known from the Cretaceous Period in Europe, the North and South Americas, and East Asia. Though the informed and taxonomically incorrect name ‘*Iguanodon* tracks’ was introduced as early as the 1860s (Sarjeant et al. 1998), the only six valid ichnogenera have been named from the Cretaceous Period: *Amblydactylus*, *Caririchnium*, *Hadrosauropodus*, *Iguanodontipus*, *Jiayinosauropus*, and *Ornithopodichnus*, which were recently reviewed by Lockley et al. (2014).

New ornithopod tracks from the Lower Cretaceous Jindong Formation, Masan area, were first described as *Ornithopodichnus masanensis* (Kim et al. 2009), which is recognized as a distinctive robust tridactyl track showing weak mesaxony slightly



◀**Fig. 2.2** Maps of parallel and subparallel ornithopod trackways from the Jindong Formation, Gosoeng area. *Notes a–e* Tracks from the Sangjok section showing 19, 11, 8, 7 and 10 individuals, respectively (after Lockley 1989; Fig. 3C; Lim 1990; Lim et al. 1989, Fig. 35.1). *f* trackways from the Dukmyeongri section (remapped by M. G. Lockley after Lim 1990, Fig. 16.49) showing seven trackways heading southwest and four to the north. *g* trackways from the Bonghwagol section (after Lim 1990, Fig. 16.89) showing five trackways heading southwest and one northeast, with a sauropod trackway heading west-northwest. However, the ornithopod trackways are much deeper than the sauropod trackways at this location (Lockley et al. 2006)

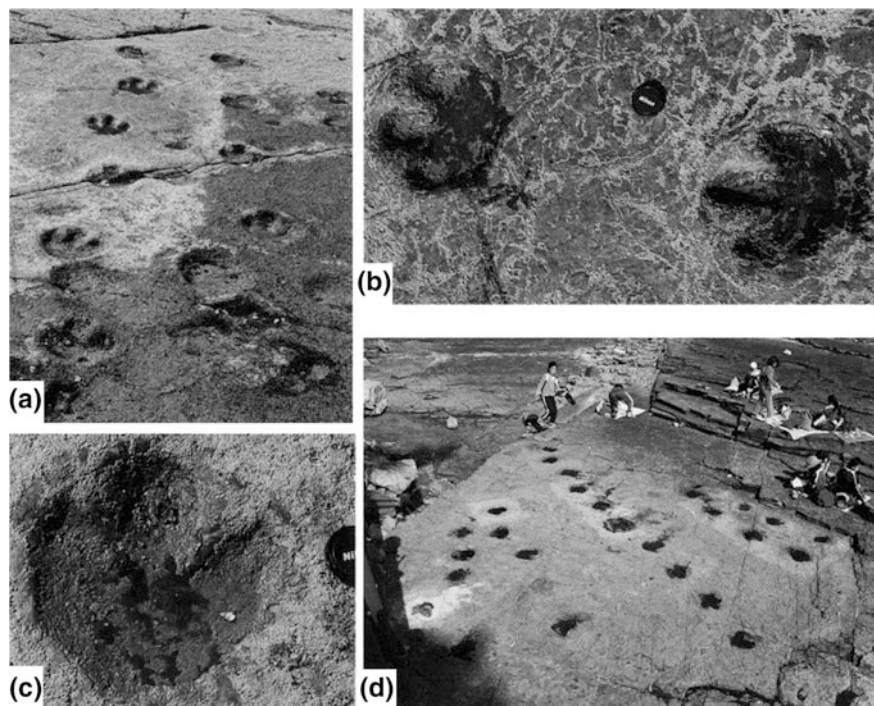


Fig. 2.3 Photographs of ornithopod trackways from the Sangjok section, Goseong area. *Notes a* Parallel ornithopod trackways (after Lockley 1989); compare with two trackways at right side of map in Fig. 2.2a. *b* and *c* details from same trackways as A. *d* trackways corresponding to map in Fig. 2.2c. *Source* Lockley et al. (2006)

wider than it is long (l/w ratio = 0.91), with positive (inward) rotation. The toe prints are very thick, broad and U-shaped, resulting in a trefoil outline with a smoothly rounded hind margin. Digit III is short and projects anteriorly much less than digit II and IV (weak mesaxony). Divarication of digits II–IV is about 70° with an interdigital angle II–III larger than III–IV. The trackway width is narrow and the stride length/track length ratio is 4.2–4.6 (Table 2.2).

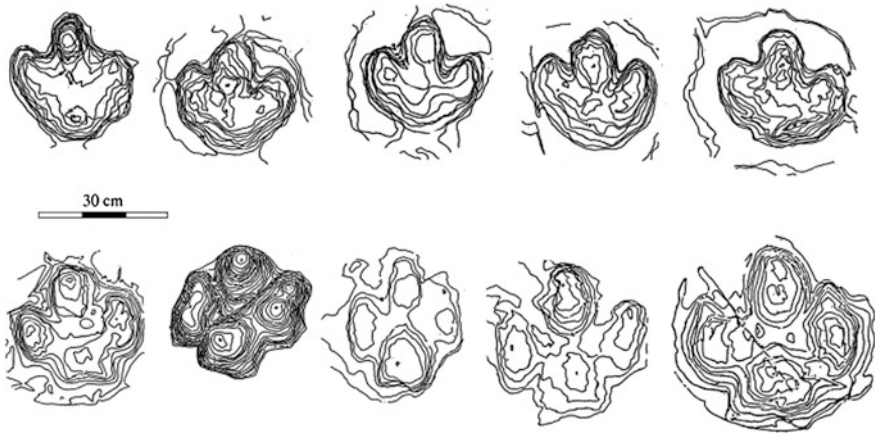


Fig. 2.4 Contour maps of ornithopod tracks from the Jindong Formation at the Goseong dinosaur track site. Source Lockley et al. (2006)

The parallel to subparallel orientation of the *Ornithopodichnus* trackways evidently represents gregarious blunt-toed *Iguanodon*-like bipedal ornithopods, although poorly preserved manus traces are discerned in a few trackways (Figs. 2.7 and 2.8). *Ornithopodichnus* is distinct from other well-known iguanodontid tracks that display much stronger mesaxony and indicates a polarity in ornithopod foot morphology that can be verified by reference to known foot skeletons (Kim et al. 2009, Fig. 2.9).

Subsequently, the ichnogenus *Ornithopodichnus* was also reported at the Lower Cretaceous Tianjialow Formation, Shandong, China (Lockley 2009), the Upper Cretaceous Jangdong Tuff, Hwasun, Korea (Lockley et al. 2012b), the Lower Cretaceous Feitianshan Formation, Sichuan, China (Xing and Lockley 2014), and the Lower Cretaceous Jiguan Formation, Sichuan, China (Xing et al. 2015).

Ornithopodichnus trackways evidently represent gregarious blunt-toed *Iguanodon*-like bipedal ornithopods (Kim et al. 2009, Fig. 2.7). To date, the ichnogenus *Ornithopodichnus* has only been recorded from the Cretaceous Period in Korea and China, and thus appears to be related to ecological and biogeographical peculiarities (Xing and Lockley 2014). Small ornithopod tracks (approximately 12 cm in length and 15 cm in width) assigned to ichnogenus *Ornithopodichnus* from the Cretaceous Jangdong Tuff, Hwasun area (Lockley et al. 2012b) are shown in Fig. 2.10.

The ichnogenus *Caririchnium* is a quadrupedal trackway with a subsymmetric pes trace with quadripartite morphology, and the manus trace is irregular in size and shape (Leonardi 1984). Four ichnospecies of *Caririchnium* are known to be valid ichnotaxa (Lockley et al. 2014): *Caririchnium magnificum* (Leonardi 1984), *Caririchnium leonardi* (Lockley 1987), *Caririchnium protohadrosaurichnus* (Lee 1997), and *Caririchnium lotus* (Xing et al. 2007). Many ornithopod tracks and trackways from the Cretaceous Period in Korea have been simply labeled as

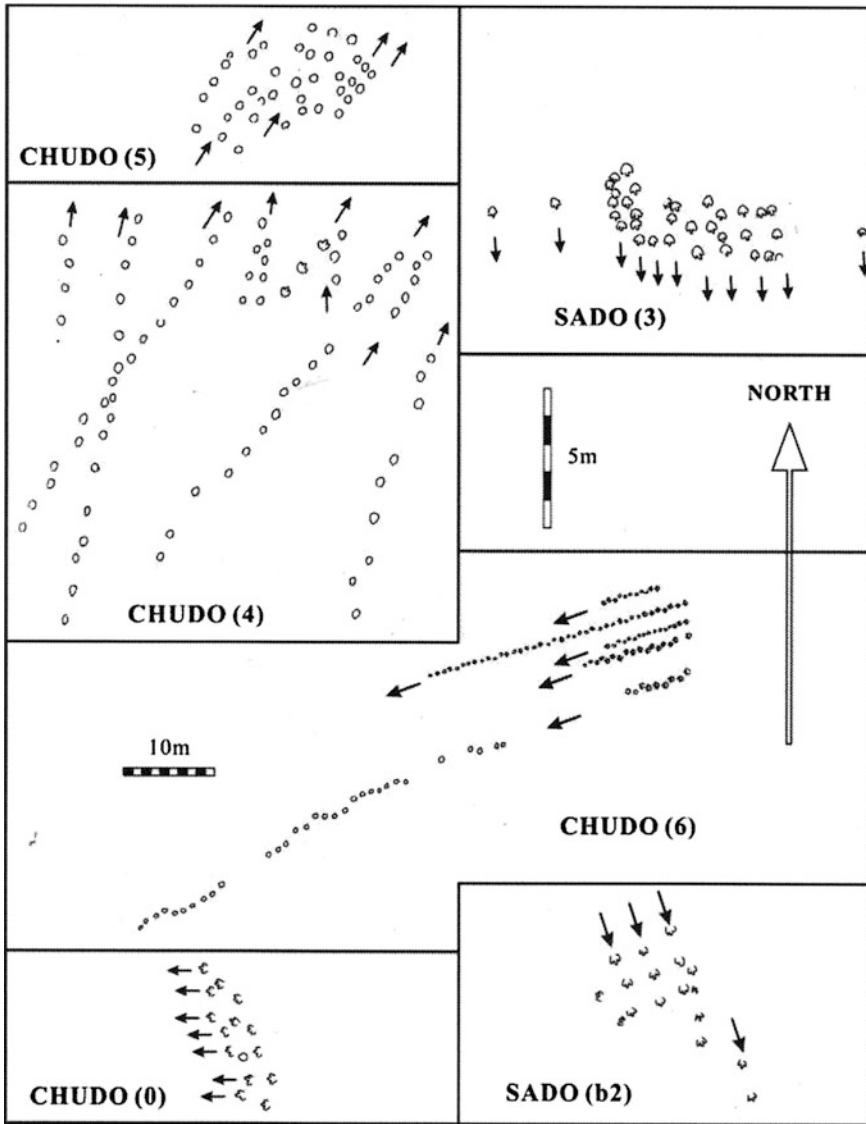


Fig. 2.5 Maps showing the main sites with parallel ornithomimid trackways on Chudo and Sado, Yeosu area. *Note* The 84 m trackway from the Chudo 6 site is the world's longest known ornithomimid trackway. *Source* Lockley et al. (2012c)

Iguanodon-like tracks or *Caririchnium* without systematic ichnotaxonomical study (e.g., Huh et al. 1997, 2001a; Hwang et al. 2002b, 2004; Lockley et al. 2006). Furthermore, abundant ornithomimid tracks occurred in the Cretaceous Period in Korea that have been regarded as having been formed by bipedal ornithomimids.



Fig. 2.6 Outcrop view of the 84 m trackway of ornithopod tracks at the Chudo site, Yeosu area

However, recent discovery of quadrupedal ornithopod trackways including *Caririchnium kyoungsookimi* (Lim et al. 2012) and *C. yeongdongensis* (Kim et al. 2016) may stimulate the reviewing of trackways previously considered as bipedal ornithopod trackways. Twenty years ago, Leonard (1997) suggested that many trackways of bipedal ornithopod dinosaurs may belong to facultative or obligate quadrupedal track makers. He suspected that all large ornithopods were quadrupedal, at least facultatively, and that they would produce very shallow and small manus tracks that would be highly susceptible to preservation bias, weathering and erosion after exposure, or oversight.

C. kyoungsookimi was first described at the Cretaceous Jindong Formation, Duhori, Goseong County (Lim et al. 2012). *C. kyoungsookimi* represents the first trackway of a quadrupedal ornithopod in Korea and consists of a tridactyl mesaxononic pes of quadripartite morphology and an elongatedly arcuate to gently subcrescentic manus. The pes impressions are approximately 40 cm in length and 32–35 cm in width (Lim et al. 2012, Fig. 2.11).

Recently, Kim et al. (2016) described new ornithopod tracks as *C. yeongdongensis* at the Lower Cretaceous Saniri Formation, Yeongdong area, central Korea. *C. yeongdongensis* is very unusual in having a large (approximately 15 cm in length and 15 cm in width) trefoil manus track situated anteromedial to the pes track with atypical negative (inward) rotation of 45° (Fig. 2.12). Ornithopod pes tracks are quadripartite with three separated, elongate-oval, nearly parallel sided,

Table 2.2 Measurement of *Ornithopodichnus* trackways from the Cretaceous Jindong Formation, Masan City

Trackway no.	Track no.	Length (cm)	Width (cm)	Pace (cm)	Stride (cm)	Pace angle (°)
TW 4'	R1	34	34			
	R2	36	32	70	160	
	L2	36	36		161	
	L3	37	40			
TW 4	R1	34	39	75		
	L1	36	38	82	153	164
	R2	38	40	80	159	173
	L2	37	41	82	161	173
	R3	36	38	84	166	175
	L3	37	42			
TW 2	L1	40	46	97		
	R1	44	52	100	230	170
	L2	44	48	94	197	174
	R2	44	47	92	183	170
	L3	40	49	97	183	168
	R3	44	49	92	187	170
	L4	44	47	96	186	167
	R4	42	44			
TW 3	R1	44	35	93		
	L1	45	38	91	182	164
	R2	41	36	91	183	166
	L2	41	35	91	180	165
	R3	45	38			
TW 5	R1	48	60	88		
	L1	40	58	92	177	160
	R2	42	51	92	179	158
	L2	37	58	92	177	165
	R3	44	55			
TW 1	L1	30	54	77		
	R1	(32)	(54)	77	151	155
	L2	39	63	78	153	160
	R2	36	51	82	153	150
	L3	36	55	83	162	155
	R3	38	60	85	165	147
	L4	40	55			

Source Kim et al. (2009)

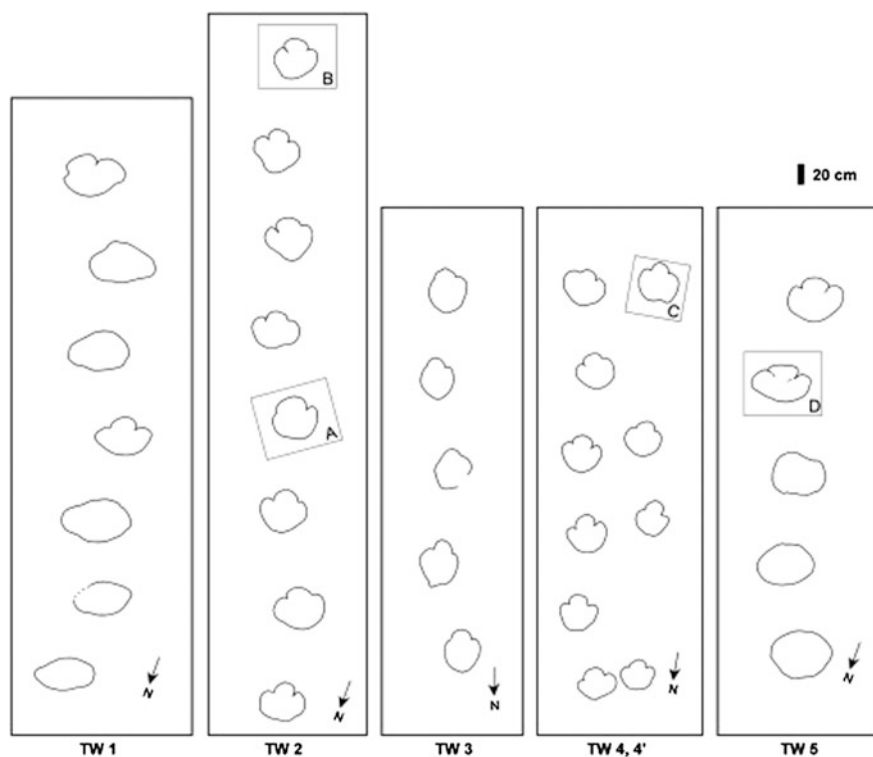


Fig. 2.7 Line drawings of ornithopod trackways from the Jindong Formation, Masan area. *Note* a–d in trackways 2, 4', and 5 correspond to individual tracks shown in II-8. These trackway sections are on display at the Natural Heritage Center, Daejeon. *Source* Kim et al. (2009)

wide digit impressions and a separate suboval heel impression (mean length and width about 41 and 36 cm, respectively: l/w ratio 1.13). Manus track morphotypes have a trefoil configuration, representing digits II–IV, in a triangular configuration and registered just in front of (anteromedial to) pes track digits II and III. The pes morphotype is typical of *Caririchnium*, but the manus morphotype is quite distinct from previously described ichnotaxa, thus justifying a new ichnotaxon (Kim et al. 2016). *C. yeongdongensis* is the sixth ichnospecies of *Caririchnium* and probably represents a facultatively quadrupedal *Iguanodon*-like ornithopod (Fig. 2.13).

Recently, Xing et al. (2016a) described a new ichnospecies of *Caririchnium*, *Caririchnium liucixini*, from the lower Cretaceous Jiguan Formation, Sichun, China. *C. liucixini* shows medium-sized, pes only *Caririchnium* tracks with quadripartite morphology including three digits with blunt claw or ungula marks and a triangular heel impressions (Xing et al. 2016a).

Measured data for the comparison of *Caririchnium* ichnospecies are shown in Table 2.3. Line drawings for the comparison of *Caririchnium* ichnospecies from the Cretaceous are shown in Fig. 2.14.

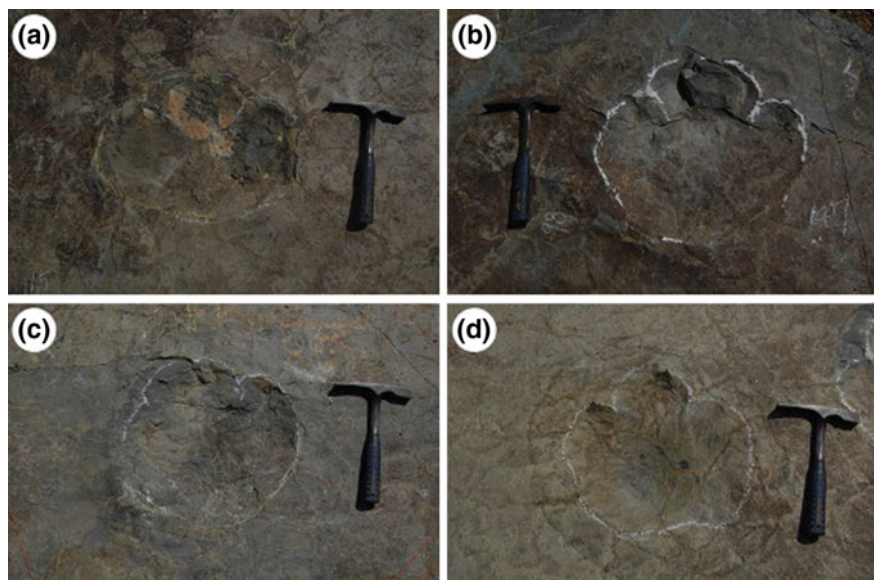


Fig. 2.8 Examples of individual tracks of *Ornithopodichnus masanensis* at the Jindong Formation, Masan area. *Notes* **a** R2 of trackway 2; **b** R4 of trackway 2; **c** L3 of trackway 4; **d** L2 of trackway 5. *Source* Kim et al. (2009)

2.1.2 Theropod Tracks

In comparison with tracks of herbivorous ornithopods and sauropods, theropod tracks were not abundantly recorded from the Cretaceous Period in Korea. In Goseong County, which has been known as one of the world's richest dinosaur track sites, containing 410 mapped trackways, only 5% (16 trackways) are attributed to theropods (Lee et al. 2000b). However, ichnotaxonomy based on a systematic description of theropod tracks from the Cretaceous Period in Korea has rarely been carried out, except for some theropod tracks and trackways assigned to *Minisauripus* (Lockley et al. 2008; Kim et al. 2012), *Dromaeosauripus hamanensis* (Kim et al. 2008a, b), and *Dromaeosauripus jinjuensis* (Kim et al. 2012b).

Examples of theropod tracks from the Jindong Formation, Goseong area, are shown in Fig. 2.15 (Lim 1990). The theropod tracks shown in Fig. 2.15 are tri-dactyl and mesaxonic. The three-digit impressions are relatively thick and tapered toward distal end. Digital pad impressions and sharp claw marks can be observed. Divarication between digits II and IV ranges between 60° and 80° (mostly

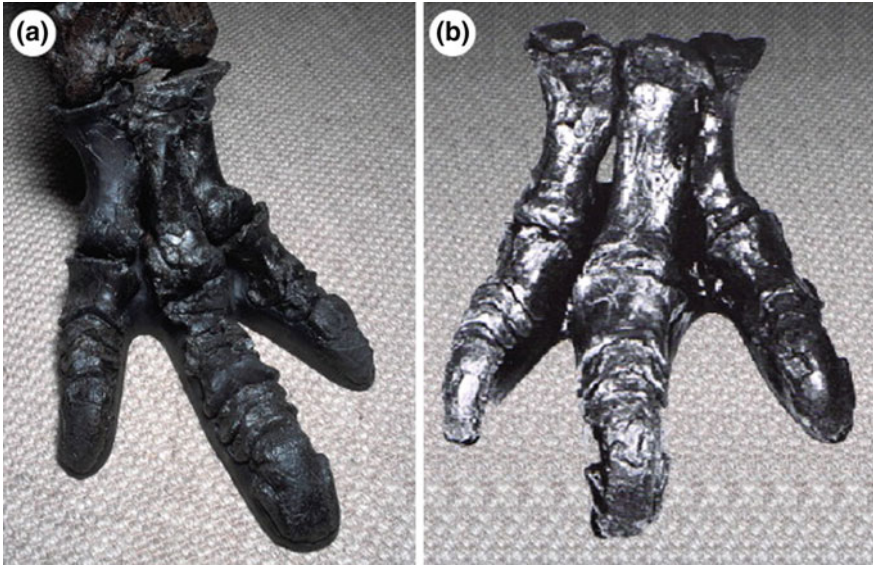


Fig. 2.9 Photographs of the feet of *Iguanodon atherfieldensis* (a) and *Iguanodon bernissartensis* (b). *Note* These images show the polarity between robust, weakly-mesaxonic and gracile, strongly mesaxonic morphologies, respectively. Photographs courtesy of Pascal Godefroit and Casier (1978). *Source* Kim et al. (2009)

approximately 70°). Heel margin impressions are generally V-shaped. Tracks are 15–30 cm in length.

Kwak et al. (2007) synthesized theropod tracks from the Cretaceous Period at the Hwasun, Yeosu, Goseong, and Changnyeong track sites. They showed 96 identified trackways of theropods, which are mostly tridactyl and mesaxonic with slender, straight, and tapered digit impressions. Claw marks are commonly observed. Most theropod tracks are less than 25 cm in length, with a few large tracks up to 33 cm in length (Kwak et al. 2007). Divarication between digits II and IV appears to range from 60° to 90° .

However, theropod tracks uniquely dominate the Hwasun track site; more than 1500 dinosaur tracks were found here at five levels (Huh et al. 2001b, 2006a). Of these, theropod tracks comprise 87% of the total number of footprints. Theropod tracks are mostly small (15–30 cm in length), but a few tracks are large (up to over 50 cm in length). Diverse shapes of small and large theropod tracks and trackways from the LI level of the Hwasun track site are shown in Fig. 2.16 (Huh et al. 2006a). Figure 2.17 shows the distribution of seven small theropod trackways, and one large theropod trackway (H). Trackways indicate movement toward the northeast (trackways C–G), west (trackway B), and southwest (trackway A). A striking characteristic of trackway D, which is composed of six consecutive tracks with a length of 56 cm, is the alternation of long (L–R) and short (R–L) steps, suggesting an example of a limping dinosaur (Huh et al. 2006a).

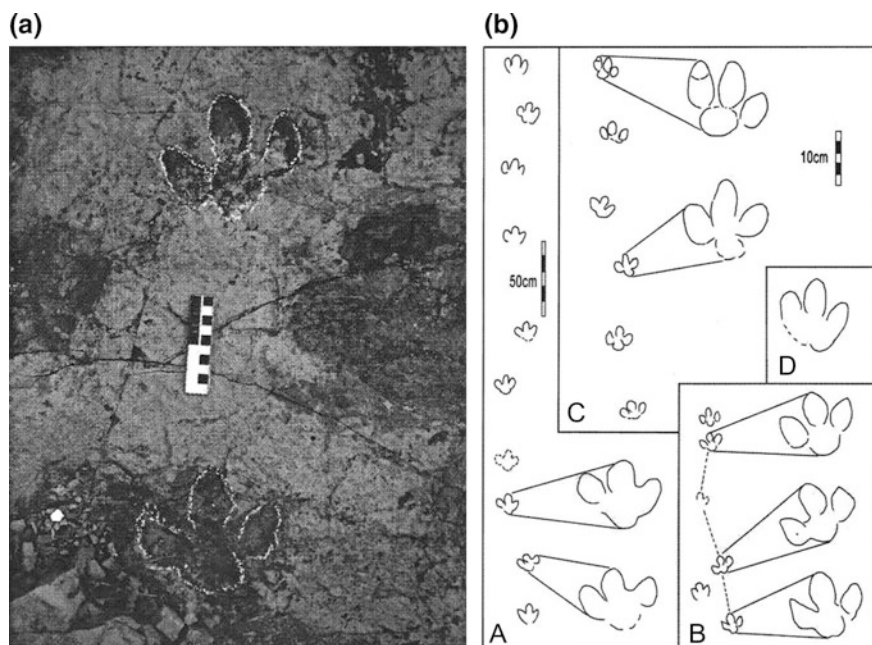


Fig. 2.10 *Ornithopodichnus*, Hwasun area. **Notes** **a** Photograph of small *Ornithopodichnus* tracks from level 2 at the Hwasun track site. Compare with sketch map on right. Scale bar = 10 cm. (Lockley et al. 2012b). **b** Sketch of small ornithopod trackways (*Ornithopodichnus*) from level 2. **a** O1 (with tracks inferred to be O1.t3 through O1.t13, but O1.t9 missing), **b** O2, **c** O5, **d** O6. All trackways are to the same scale with enlargements also drawn to same expanded scale. Note the reduced mesaxony in all tracks. (Lockley et al. 2012b)

Three types of theropod tracks were known from the Hwasun track sites (Huh et al. 2006a, Fig. 2.18). The first type, characterized by its small size, wide digit divarication, and thin digits, is comparable to *Magnoavipes* (Lee 1997). The second track type shows thick digits and relatively narrow divarication, and is similar to the tracks of *Ornithomimipus* and *Xianxipus*. The third type of track, characterized by its distinctive impressions of sharp claws, is larger, longer than 40 cm, with narrow digit divarication, and has been tentatively compared with theropod tracks from Canada and Japan (Huh et al. 2006a).

Minisauripus, originally regarded as an ornithopod track (Zhen et al. 1994), but later unequivocally recognized as a theropod track (Lockley et al. 2008), is the smallest known non-avian theropod ichnogenus. *Minisauripus* has been recorded only from the Lower Cretaceous Period in China and Korea (Zhen et al. 1994; Lockley et al. 2008; Kim et al. 2012; Xing et al. 2016b). All identified *Minisauripus* tracks from China (three sites) and Korea (five sites) are approximately 1.0–6.1 cm in length. The makers of these *Minisauripus* tracks have been interpreted to be approximately 5.0–23.0 cm high at the hip and to have bodies approximately 12.0–72.0 cm long (Xing et al. 2016b).

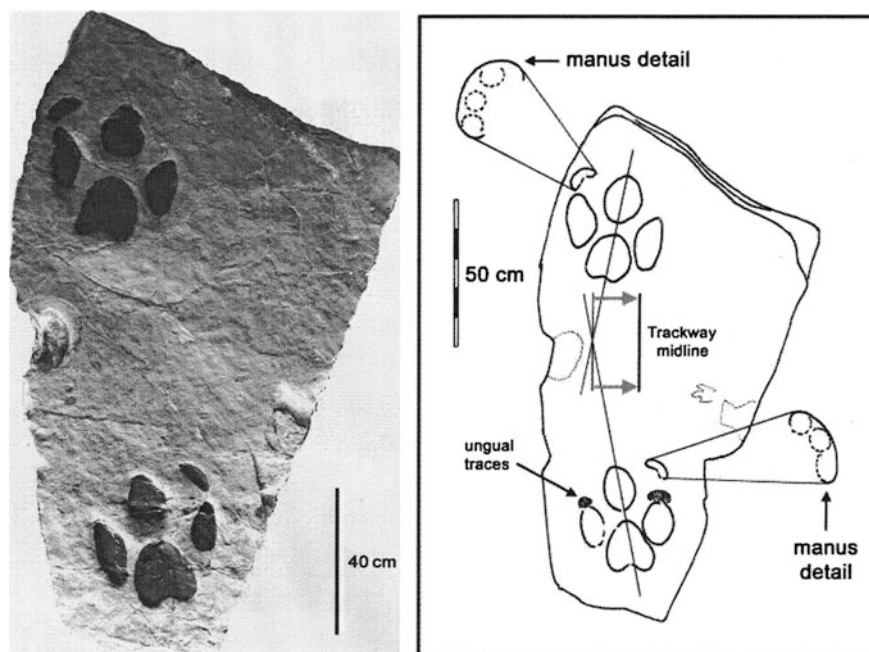


Fig. 2.11 Photograph and sketch of specimen NHCG 10194 of *Caririchnium kyoungsookimi* showing details of manus impression. *Source* Lim et al. (2012)

Examples of *Minisauripus* tracks from the Cretaceous Haman Formation, Changseon and Sinsu island, are shown in Figs. 2.19 and 2.20 (Lockley et al. 2008; Kim et al. 2012).

As shown in Figs. 2.19 and 2.20, *Minisauripus* from the Early Cretaceous Haman Formation, Changseon Island, is very small, ranging from 1.1 to 1.8 cm in length. The maker of the *Minisauripus* track, which is the smallest theropod track ever known, appears to have been a theropod dinosaur the size of a chicken or a dove, with an estimated height at the hip of 5–8 cm high at the hip.

Most tracks of bipedal dinosaurs are tridactyl and didactyl; other reptiles are rare except for a few ichnogenera including *Velociraptorichnus* (Zhen et al. 1994), *Dromaeopodus* (Li et al. 2007), *Dromaeosauripus* (Kim et al. 2008a, b), and *Menglongipus* (Xing et al. 2009) (Table 2.4).

Dromaeosauripus hamanesis, first described from the Lower Cretaceous Haman Formation, Namhae area, shows didactyl theropod tracks approximately 15 cm in length and 9 cm in width, and consists only of impressions of digits III and IV, which show well-developed pad impressions (Table 2.5). Digit impressions are narrow (about 2 cm) and terminate in sharp claw traces. The trackway width is very narrow, about 10 cm, and four consecutive tracks are almost in a straight line. The tracks are thought to have been made by a dromaeosaurid characterized by a strongly recurved, pes digit II that did not register on the substrate. The

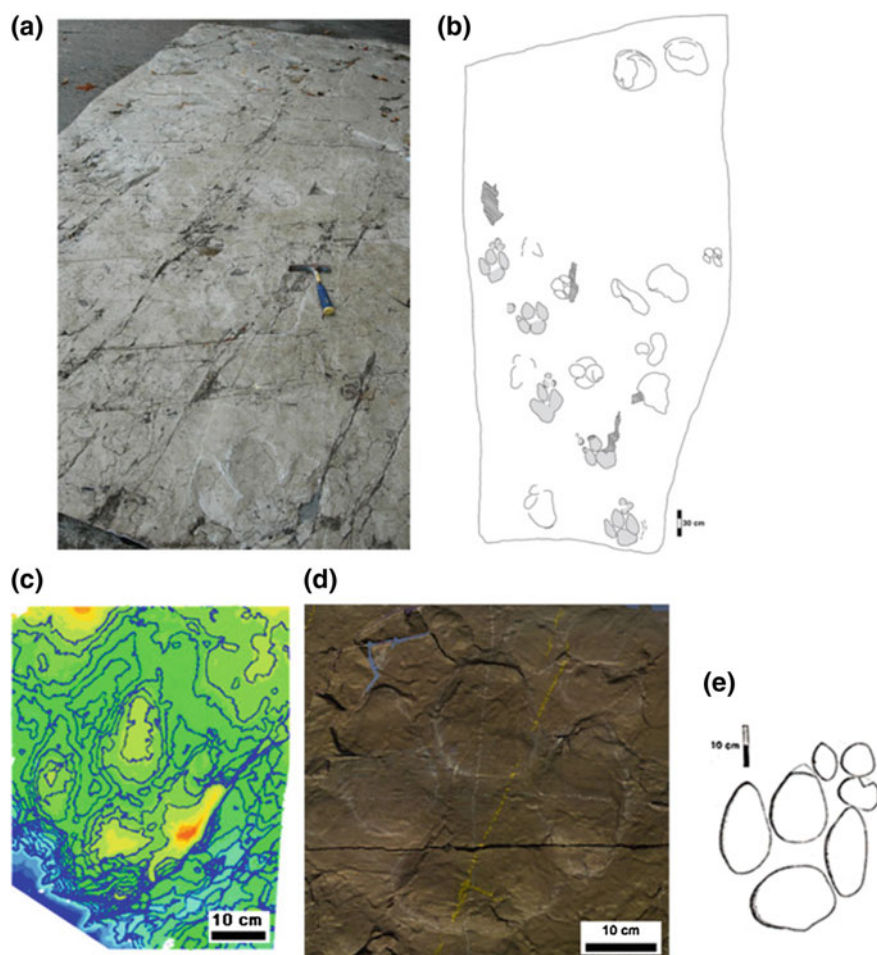


Fig. 2.12 *Caririchnium yeongdongensis* from the Lower Cretaceous Period, Yeongdong area
Notes: Photograph (a) and sketch (b) of trackway, 3D color contour map of right first (R1) track (c), 3D mesh image (d) and sketch (e) of left third (L3) track. *Source* Kim et al. (2016)

D. hamanensis trackway is attributed to a small Dromaeosaurid (Deinonychosauria) running bipedally at a speed of 17.5 km/h on a lake margin environment (Kim et al. 2008a, b, Fig. 2.21). The second ichnospecies of *Dromaeosauripus* was described as *D. jinjuensis* at the Jinju Formation, Namhae area, Korea (Kim et al. 2012b). *D. jinjuensis* is a small didactyl track (9.3 cm in length and 6.8 cm in width) characterized by slender impressions of digits III and IV, distinct digital pad impressions, very narrow divarication between digits III and IV, digit III slightly longer than digit IV, and sharp claw impressions (Table 2.6).

D. jinjuensis represents the oldest theropod dinosaur track described from the Cretaceous Period in Korea. *Dromaeosauripus* tracks suggest more diversity and a

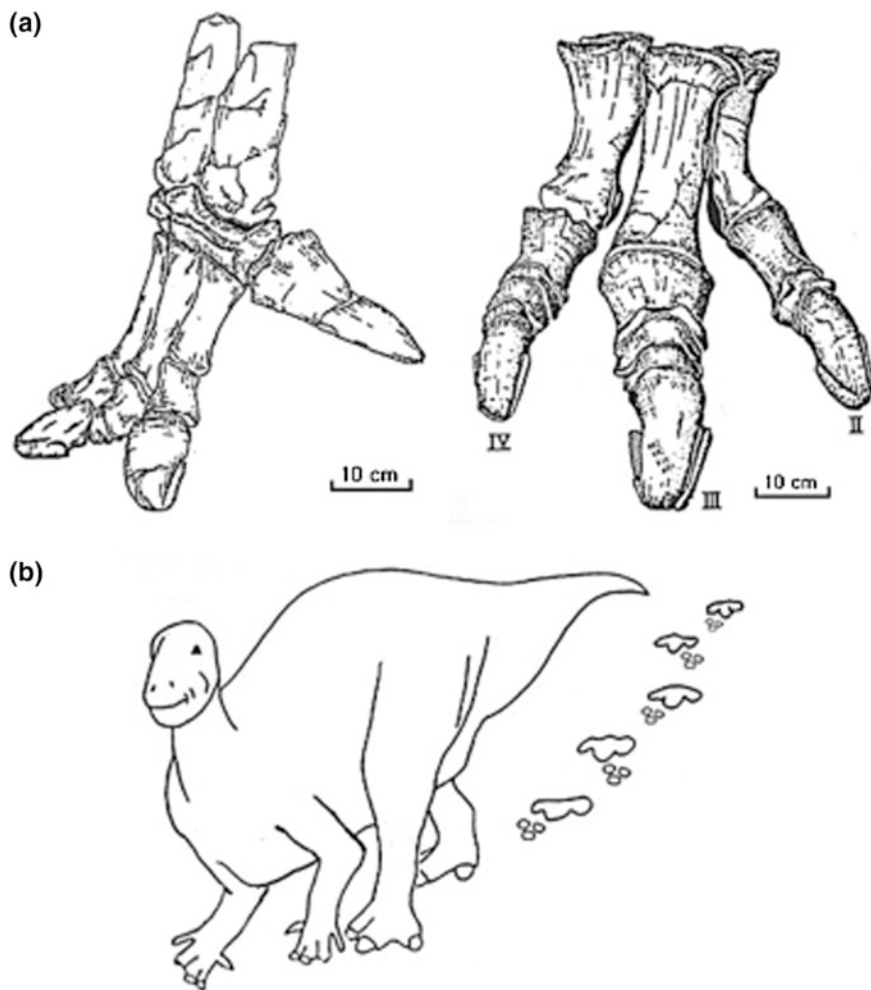


Fig. 2.13 Manus in weight-bearing position and pes of *Iguanodon bernissartensis*. Note The *Iguanodon bernissartensis* is regarded to be one of the most likely track makers for *Caririchnium yeongdongensis*. Figure 2.13b is a reconstruction (Kim et al. 2016). Sources Fig. 2.13a, Norman (1980); Fig. 2.13b, Kim et al. (2016)

wider stratigraphic and paleogeographic distribution of dromaeosaurids. The track morphology of *Dromaeosauripus* may also indicate a more digitigrade gait (Kim et al. 2012b). A trackway about 4.3 m long composed of 12 consecutive tracks of *D. jinjuensis* is shown in Figs. 2.22 and 2.23 shows the line drawings of *D. hamanensis* and *D. jinjuensis* (Kim et al. 2012b). Recently, *Dromaeosauripus* tracks have been also reported at the Lower Cretaceous, Shandong Province, China (Xing et al. 2013). Table 2.7 shows measured data for comparison of *Dromaeosauripus* from Korea and *Velociraptorichnus* and didactyl tracks from

Table 2.3 Measured data for comparison of *Caririchnium* ichnospecies

<i>Caririchnium</i> ichnospecies	L/W	AL/ W	RMPD	H	M _s	M _p	P _s	II/IV	H _s	H _m	References
<i>Caririchnium magnificum</i>	1.15 ^a	0.31 ^b	1.19 ^a	1:3.7 ^b	I	A-AM ^a	Q	35° -50°	ST	R	Leonardi (1984)
<i>Caririchnium leonardi</i>	1.12 ^a	0.46 ^b	1.12 ^a	1:8.1 ^b	I	AL ^a	T	90°	?	SA	Currie et al. (1991)
<i>Caririchnium protohadrosaurichnos</i>	1.10 ^a	0.39 ^b	0.83 ^a	1:14.6 ^b	E	AL ^a	T	56°	?	L	Lee (1997)
<i>Caririchnium lotus</i>	1.10 ^b	0.29 ^b	0.80 ^b	1:6.1 ^b	SO-S	AL ^a	Q	57° ^b	SC	SR	Xing et al. (2007, 2015)
<i>Caririchnium kyoungsookimi</i>	1.16 ^a	0.45 ^a	0.59 ^a	1:42.6 ^a	C	AL ^a	Q	15°	ST	B	Lim et al. (2012)
<i>Caririchnium yeongdongensis</i>	1.13 ^a	0.32 ^a	0.73 ^a	1:6.7 ^a	CL	AM ^a	Q	0°	SO	SR	Kim et al. (2016)

Source Kim et al. (2016)

Abbreviations L/W: ratio of length and width of pes track; AL/W: ratio of length and width of anterior triangle of pes track; RMPD: relative manus-pes distance, ratio of manus-pes distance and pes track length; H: heteropody, ratio of manus track size and pes track size; Mp: positioning of manus track in relation to pes track; Ps: shape of pes track; Ms: shape of manus; II/IV: angle between digits II and IV; Hs: shape of heel impression; Hm: shape of heel margin impression; I: irregular; E: elongated; SO-S: suboval-semicircular; C: crescentic; CL: trefoil; A: anterior; AL: anterolateral; AM: anteromedial; Q: quadrupartite; T: tripartite; ST: subtriangular; SC: subcircular; SO: suboval; R: rounded; SA: subangular; SR: subrounded; BL: bilobate

^aData calculated by present authors on the basis of corresponding papers

^bData from Xing et al. (2015)

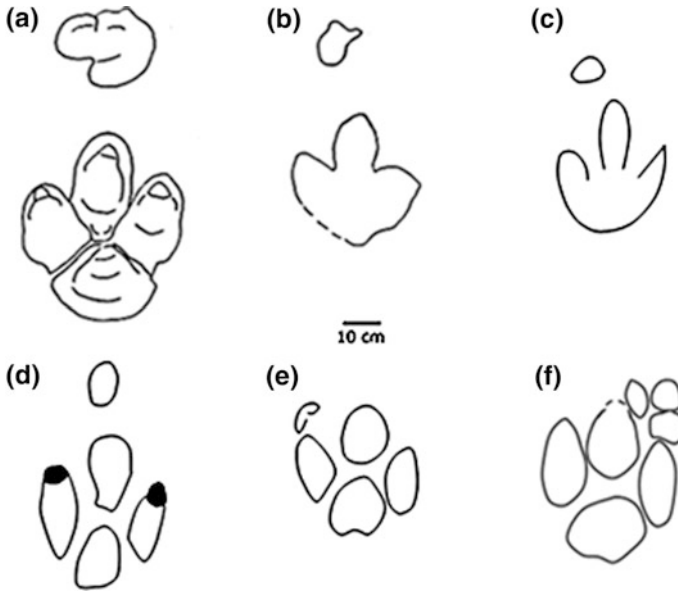


Fig. 2.14 Scale line drawings of left manus-pes track set of *Caririchnium* ichnospecies. *Notes* **a** *Caririchnium magnificum* (Leonardi 1984); **b** *C. leonardi* (Currie et al. 1991); **c** *C. protohadrosaurichnos* (Lee 1997); **d** *C. lotus* (Xing et al. 2007, 2015); **e** *C. kyoungsookimi* (Lim et al. 2012); **f** *C. yeongdongensis* (Kim et al. 2016) (modified after Lockley et al. 2014). These illustrations have been drawn to the same scale



Fig. 2.15 Theropod tracks from the Jindong Formation, Goseong area, arranged in order of increasing size. *Notes* From left to right, the specimens correspond to Figs. 18.25, 18.30, 18.24, 18.23, and 18.26 in Lim (1990), from the Sangjok, Bongwhagol, Sangjok, Sangjok and Dukmyeongri sections, respectively. *Source* Lockley et al. (2006)

China (Kim et al. 2012b). As shown in Table 2.7, *Dromaeosuripus* is distinguished from other didactyl tracks recorded in the morphology of footprint, the length/width ratio, divarication between digits III and IV, and the stride/track length ratio.

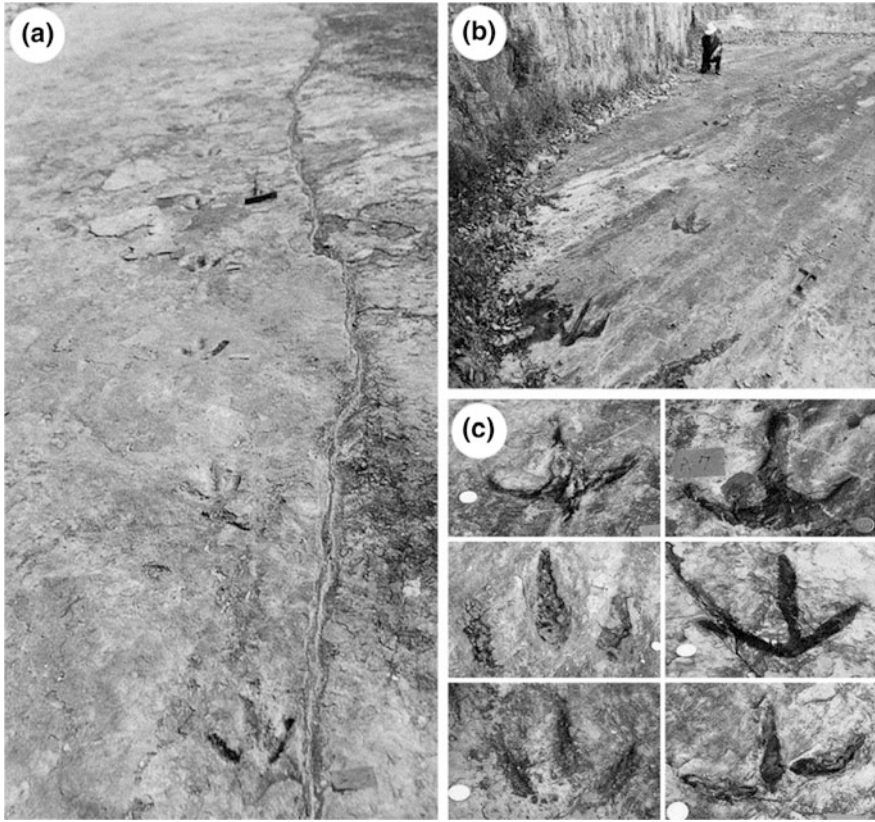


Fig. 2.16 Photographs of theropod dinosaur tracks and trackways from level L1 at the Hwasun track site. *Notes* **a** Well-preserved, long theropod trackway from the Hwasun track site; **b** trackway of large-sized theropod; **c** diverse shapes of small theropod tracks. *Source* Huh et al. (2006a)

2.1.3 Sauropod Tracks

Tracks of *Brontosaurus* (thunder lizards) are the largest among the most distinctive dinosaur tracks known. Despite a number of short reports in which various names have been assigned to sauropod ichnites, the general approach to sauropod ichnology has been almost entirely haphazard (Lockley et al. 1994). Therefore, a large number of existing sauropod ichnospecies including *Goseongosauripus kimi* (Kim 1986) and ornithopod tracks named *Koreanosauripus cheongi* (Kim 1986) are *nomen dubia* (Lockley et al. 1994). In addition, Kim and Seo (1992) and Kim (1993) described sauropod tracks named *Hamanosauripus ovalis*, *Ultrasauripus ungulatus*, and *Elephantosauripus metacarpus*, as well as *Caririchnium*-like ornithopod tracks named *Koseongosauripus onychion*, and theropod tracks named *Megalosauripus koreanensis* from the Cretaceous of the Gyeongsang Basin.

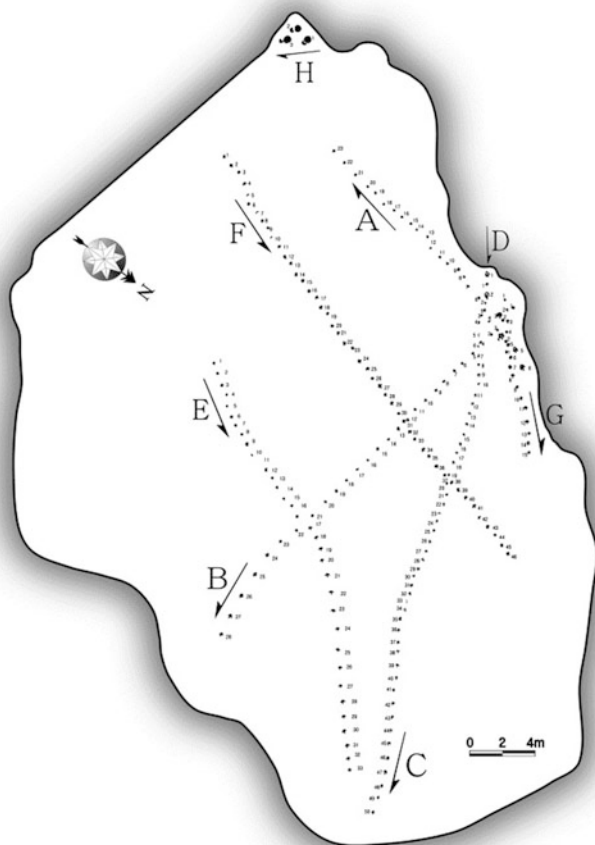


Fig. 2.17 Map showing distribution of eight dinosaur trackways (A–H) at level L1 at the Hwasun track site. Source Huh et al. (2006a)

However, Kim and Seo (1992) and Kim (1993) did not show holotype, systematic description and ichnotaxonomic comparison. Their papers were published in a report instead of a peer-reviewed journal. Therefore, these ichnotaxa are regarded to be invalid.

Lockley et al. (1994) documented that trackway width, heteropody (manus/pes area ratios), and the morphology of pes claw impressions are useful for distinguishing the ichnotaxa of sauropod tracks. To date, *Brontopodus birdi* (Farlow et al. 1989), *Brontopodus pentadactylus* (Kim and Lockley 2012), and *Parabrontopodus mcintoshii* (Lockley et al. 1994) have been named as sauropod tracks.

Following the most abundant ornithopod tracks, sauropod tracks have been also abundantly recorded in the Cretaceous of many track sites, including the Goseong,

Fig. 2.18 Three types of theropod footprints from the Hwasun track site. *Notes* Scale bar represents 1 m
a Small bird-like footprints with narrow digits and wide divarication; **b** medium-sized footprints with thick digits and a narrow toe impression; **c** large theropod footprints with distinct and sharp claw impressions. *Source* Huh et al. (2006a)



Hwasun, and Yeosu track sites. From the track sites of Goseong County, 139 identified trackways (34%) of a total of 410 dinosaur trackways are attributed to sauropods (Lee et al. 2000b). A sauropod trackway, one of the most familiar dinosaur trackways from the Goseong area, is shown in Fig. 2.24.

Sauropod tracks from the Jindong Formation, Goseong County, range from very small (9 cm in pes length) to very large (up to 105 cm in pes length) and the length of the pes track is predominately 20–40 cm (Lockley 1994; Lee et al. 2000b). Examples of sauropod trackways from the Jindong Formation, Goseong County, are shown in Fig. 2.25 (Lim 1990; Lockley et al. 1992, 2006; Lim et al. 1994; Lee et al. 2000b). Figures 2.25a, i show the smallest known sauropod trackway from the Hoehwa District (Lee et al. 2000b). The trackway consists of 30 consecutive tracks (13 manus and 17 pes impressions). The manus and pes tracks are 3 and 9 cm in length, respectively, which results in pronounced heteropody. The pes track is longer than it is wide, with a long axis slightly rotated outward. No pes claw impressions are observed (Lee et al. 2000b). Figure 2.25d–h show sauropod trackways with a wide gauge, which were described as *Brontopodus* ichnosp. (Lockley et al. 2006). Figure 2.25h shows the large sauropod trackway

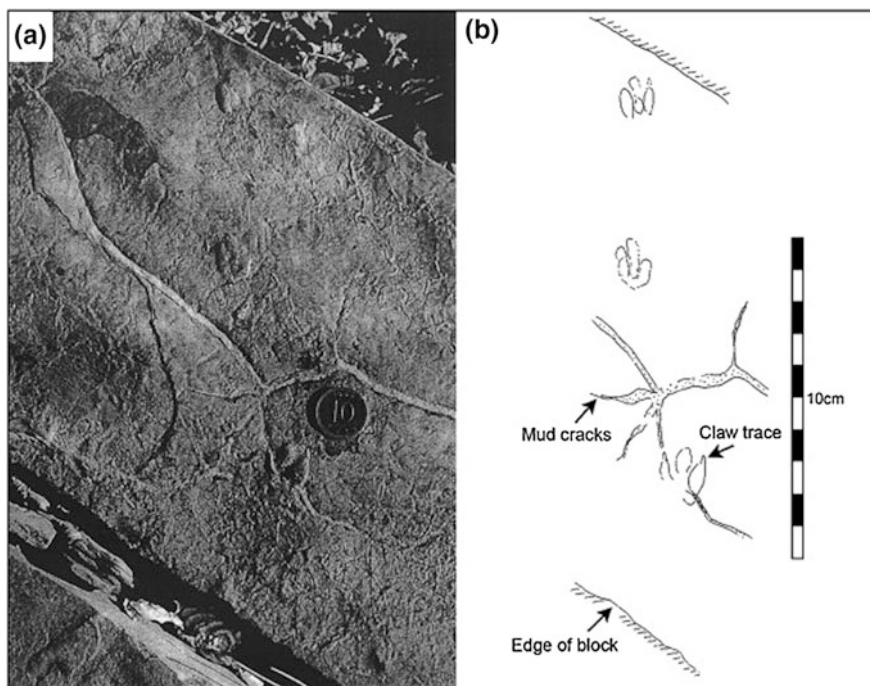


Fig. 2.19 Photograph and drawing of first South Korean *Minisauripus* trackway discovered at the KML2 site, Haman Formation, Sinsu Island. *Source* Lockley et al. (2008)

Fig. 2.20 Photograph of replica of CUE 08 1001 (=CU 214.190) showing two consecutive *Minisauripus* tracks. *Notes* These tracks are 1.2–1.3 cm long, with a step of 7.1 cm. Note the raindrop imprints; specimen from Buyun, Changseon Island, Korea. *Source* Kim et al. (2012)



Table 2.4 Record of Mesozoic didactyl dinosaur tracks described from literature

Geological era	Formation	Location	Name	Track maker	Authors
Late Cretaceous (Maastrichtian)		Mlynarka Mt. Poland	<i>Velociraptorichnus</i> sp.	Dromaeosaurid	Gierlinski (2007)
Early Cretaceous	Jiaguan Formation	Sichuan, China	<i>Velociraptorichnus sichuanensis</i>	<i>Velociraptor</i>	Zhen et al. (1994)
Early Cretaceous	Cedar Mt. Formation	Arches National Park, Utah	Didactyl tracks	<i>Utahraptor</i> -like dromaeosaurid	Lockley et al. (2004)
Early Cretaceous	Cedar Mt. Formation	Arches National Park, Utah	Didactyl tracks	<i>Utahraptor</i> -like dromaeosaurid	Cowan et al. (2010)
Early Cretaceous	Hekou Group	Gansu, China	Didactyl tracks	<i>Velociraptor</i>	Li et al. (2006), Xing et al. (2013)
Early Cretaceous (Barremian-Aptian)	Tianjialou Formation	Shandong, China	<i>Dromaeopodus shandongensis</i>	Deinonychosaur	Li et al. (2005, 2007)
Early Cretaceous	Haman Formation	Namhae, Korea	<i>Dromaeosauiripus hamanensis</i>	Dromaeosaurid	Kim et al. (2008a, b)
Early Cretaceous	Buckeberg Formation	Obernkirchen, Germany	Didactyl tracks	Troodontid	Lubbe et al. (2009)
Early Cretaceous	Jinju Formation	Namhae, Korea	<i>Dromaeosauiripus jinjuensis</i>	Dromaeosaurid	Kim et al. (2012b)
Jurassic-Cretaceous	Tuchenzi Formation	Hebei, China	<i>Menglongipus sinensis</i>	Deinonychosaur	Xing et al. (2009)
Late Triassic	Chinle Group	Gateway, Colorado	<i>Pseudotetrassauropus</i> -like “didactyl” tracks	Saurischian archosaurs	Gaston et al. (2003)
Late Triassic	Chinle Group	Gateway, Colorado	<i>Evazoum</i> -like “didactyl” tracks	Saurischian archosaurs	Lockley et al. (2006)

Note Not all tracks can be attributed to deinonychosaurs (*Dromaeosaurs* or Troodontids) (Kim et al. 2012b)

Table 2.5 Measurement of trackway of *Dromaeosauripus hamanensis* at the early Cretaceous Haman Formation, Namhae area, Korea

Track no.	L (cm)	W (cm)	L _{III} (cm)	L _{IV} (cm)	P (cm)	S (cm)	PA (°)	III/IV (°)	Or
R1	(11.7)	7.1	11.7	9.2	102			10	N85° W
L1	15.5	7.1	11.7	9.2	102	204	180	13	
R2	15.5	8.4	11.7	9.7	103	205	180	13	
L2	15.5	8.4	11.4	9.7	102	204	180	15	
R3	15.5		11.6						

Note Values in parenthesis are length of track without distal pad impression
Source Kim et al. (2008a, b)

composed of crescent-shaped manus tracks overprinted with large pes tracks, which is unusual in the sauropod trackways currently known.

The Jeori dinosaur track site, Uiseong County, first discovered in 1990 by Kim, was designated as the first Natural Monument (No. 373) related to dinosaur tracks in 1993. Compared with the Goseong track site located at the southern coastal area of Goseong County, where much more abundant and diverse dinosaur tracks are well-preserved, the Jeori track site, located inland, reveals dinosaur tracks that are relatively not well-preserved. Kim and Seo (1992) described the Jeori dinosaur tracks and assigned sauropod tracks to be *U. ungulatus*, and *E. metacarpus*. In addition, Kim (1993) assigned sauropod tracks from the Yongbawi site, Haman County, as *H. ovalis*. Figure 2.26 shows the outcrop view of the Jeori dinosaur track site and the sauropod tracks and trackways named *H. ovalis*, *U. ungulatus* and *E. metacarpus* (Kim and Seo 1992).

On the basis of brief description and measured data (Table 2.8) provided by Kim and Seo (1992) and Kim (1993), the narrow-gauge sauropod tracks named *U. ungulatus* and *E. metacarpus* appear to resemble *Parabrontopodus* (Farlow et al. 1989) and the wide-gauge sauropod tracks named *H. ovalis* seem to be *Brontopodus* (Lockley et al. 1994).

Although Kim (1986) already reported sauropod tracks tentatively named *H. ungulatus* and *K. cheongi* at the Lower Cretaceous, the Gyeongsang Basin, unfortunately *H. ovalis*, *U. ungulatus*, and *E. metacarpus* were not ichnotaxonically compared even with his sauropod ichnotaxa. Despite the ichnotaxonomic problems, dinosaur tracks of the Jeori track site, which represent the first named Natural Monument (No. 373) for a dinosaur track site in Korea, are important for the understanding of dinosaur ichnology. Unfortunately, however, further research on the Jeori dinosaur tracks has not yet been carried out. It is very necessary to undertake systematic research on these tracks because the Jeori tracks have been seriously damaged due to weathering.

Following the Goseong track site, where dinosaur tracks were discovered for the first time in 1982, and the Jeori track site, the first natural monument designated for dinosaur tracks in 1993, the Uhangri track site, Haenam County, was first reported in 1997 by Huh et al. (1997) reported approximately 200 dinosaur tracks composed

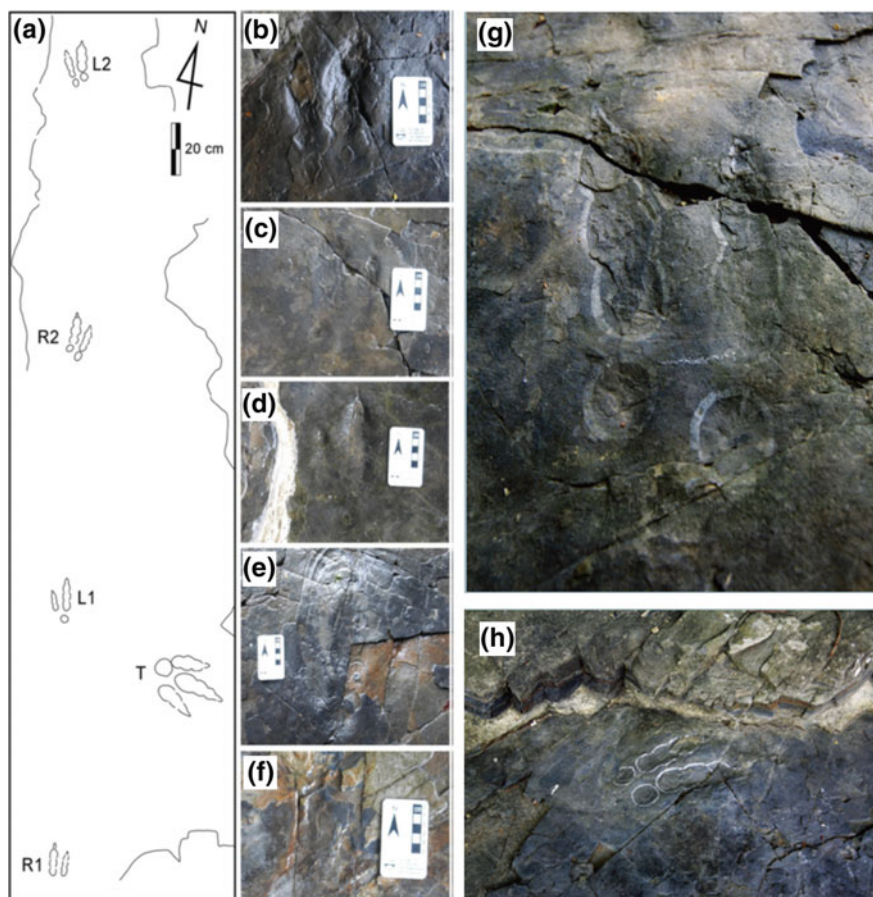


Fig. 2.21 *Dromaeosauripus hamanensis* and a theropod track from the Lower Cretaceous Haman Formation, Namhae area. Notes **a** Sketch of trackway composed of consecutive *Dromaeosauripus* tracks R1, L1, R2, and L2, and theropod track T; **b** photograph of track L2; **c** photograph of track R2; **d** photograph of track L1; **e** photograph of a tridactyl theropod track T; **f** photograph of track R1, R3 is only partly preserved and not figured; **g** detail of R2; **h** detail of L2. Source Kim et al. (2008a, b)

of about 180 ornithopod tracks and a few sauropod trackways from the Upper Cretaceous Uhangri Formation.

Among the ornithopod tracks, a well-preserved track resembling *Caririchnium* is regarded to be the first record of a quadrupedal ornithopod track with strong heteropody, though the authors probably did not recognize it (Huh et al. 1997, Fig. 3). An identified sauropod trackway in a state of relatively good preservation was shown by Huh et al. (1997, Fig. 6). As shown in Fig. 2.27, the sauropod trackway was composed of three consecutive manus and pes tracks. The manus tracks are 21 cm in length and 65 cm in width. The pes impressions are large, up to 101 cm in

Table 2.6 Measurement of trackway, *Dromaeosuripus jinjuensis* at the early Cretaceous Jinju Formation of Bito Island, Namhae area

Track no.	Length L (cm)	Width W (cm)	Length of digit III	Length of digit IV	Angle III–IV (°)	Pace (P; cm)	Stride (S; cm)	Pace angle (PA; °)
R1	8.7	7	7.6	8	12	–		
L1	11	7	11.5	10	10	40	78	180
R2	10.2	7	9.3	9.3	9	38	78	175
L2	9.8	7	7.6	8	8	42	76	180
R3	9	6.7	8.9	7.3	10	36	76	168
L3	10.5	6.7	8.2	9	10	36	73	177
R4	9.2	7	9.2	7.7	10	35	71	166
L4	9	6	7.5	5.5	13	35	76	166
R5	–	–	7.9	–	–	44	105	180
L5	7	7.2	6.7	5.9	14	60	100	175
R6	8.2	7	7.5	8	10	40	71	180
L6	–	5.7	–	–	12	35		
Mean	9.26	6.75	8.35	7.87	10.45	40.09	80.4	174.7

Source Kim et al. (2012b)

length and 74 cm in width, and the pace, stride, and pace angulation are 220 cm, 338 cm, and 114°, respectively. The manus tracks are elongated, generally shaped like a Fig. 2.28, and placed closely in front of the pes tracks. The pes tracks are longer than they are wide, subtriangular to subquadrangular, and outwardly (positively) rotated with angles of up to 45°. Digit impressions of pes tracks are not clearly observed, but the second pes track shows three short and thick digit impressions. The external trackway width is about 220 cm, and the trackway is narrow-gauged. Although the digit impressions are not clearly recognized and an ichnotaxonomic study on this trackway was not carried out (Huh et al. 1997), the overall features of this sauropod trackway resemble those of *Parabrontopodus* (Lockley et al. 1994).

In 1998, over 1300 dinosaur tracks and 132 identified trackways were reported from the new dinosaur track sites at Donghae District, southeast of Goseong County (Baek and Seo 1998). Of the 132 trackways, 98 trackways are bipedal (probably mostly ornithopod trackways) and 34 trackways are quadrupedal (probably mostly sauropod trackways). As shown in Fig. 2.28, most sauropod tracks are densely distributed and thus in many cases identified trackways are difficult to recognize.

In addition, most sauropod tracks are generally circular in outline without showing clear digit impressions. If they have a strong heteropody, sauropod trackways may appear to be bipedal because relatively small and shallow manus tracks may be overlooked or unrecognized. Furthermore, if they are overprinted or have very weak heteropody, some sauropod trackways may be regarded as bipedal because relatively similar sized manus tracks may be regarded as pes tracks. For example, Fig. 2.24 shows a symbolic and well-known dinosaur trackway in

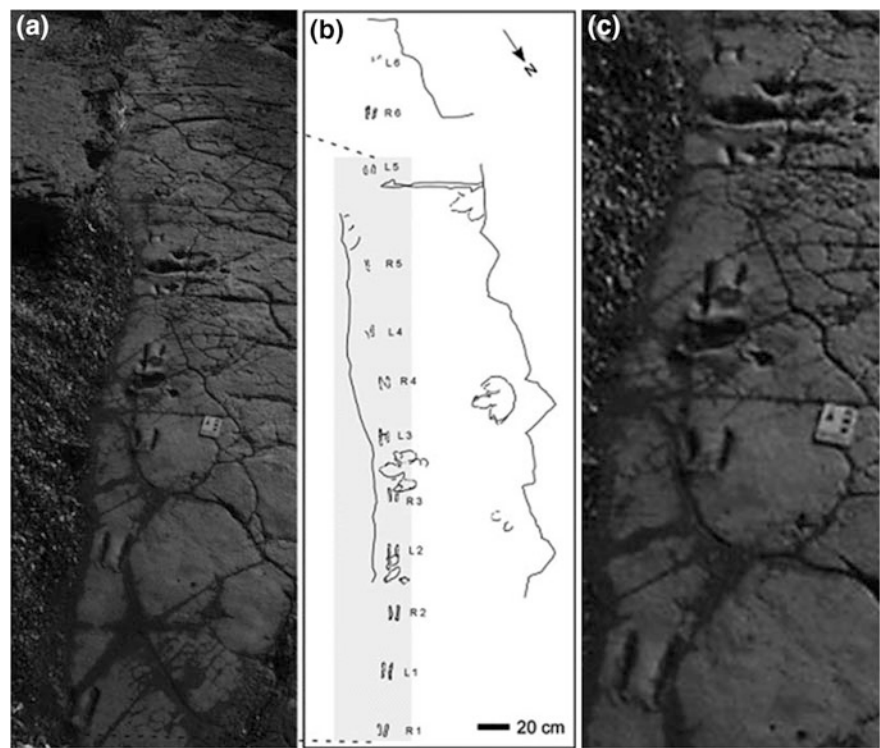


Fig. 2.22 Photograph (a) and drawing (b) of didactyl theropod trackway of *Dromaeosauripus jinjuensis* from the Jinju Formation, Namhae area. *Notes* The scale bars in photographs a and c are 8 cm long; c detail of trackway composed of consecutive tracks (L1, R2, L2, and R3) crossing two ornithomimid tracks. *Source* Kim et al. (2012b)

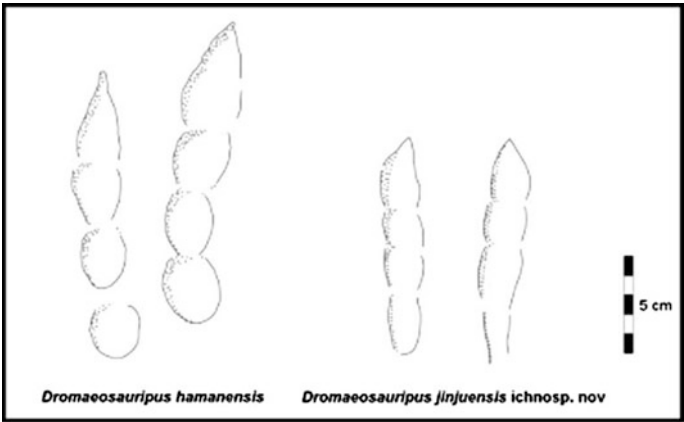


Fig. 2.23 Line drawings of *Dromaeosauripus hamanensis* and *Dromaeosauripus jinjuensis* tracks. *Sources* The line drawing of the *Dromaeosauripus hamanensis* track is from Kim et al. (2008a, b) and that of *Dromaeosauripus jinjuensis* (L1 in Fig. 2.21) is from Kim et al. (2012b)

Table 2.7 Comparison of *Dromaeosaurus* from Korea and *Velociraptorichnus* and didactyl tracks from China

Types of tracks	L (cm)	W (cm)	L/W	L _{III}	L _{IV}	W _{III}	W _{IV}	III–IV (°)	P (cm)	S (cm)	PA (°)	P/L	S/L	V (km/h)	Authors
<i>Velociraptorichnus</i>	10.7– 11.5	6.0–6.3	(1.8)	9– 10.3	9.3– 10	3– 3.7	2.3– 2.4	21–28	49			4.4			Zhen et al. (1994)
Didactyl tracks	13.5– 15.3	5.3–8.2	(2.1)						(20– 39)	(48– 68)	(115– 160)	2.7		(1.9)	Li et al. (2006)
<i>Dromaeosaurus</i>	15.5	8.4	1.91	11.7	9.2– 9.7	3.6	2.4	10–15	102	204	180	6.6	13.2	(17.5)	Kim et al. (2008a, b)
Shandong <i>Velociraptorichnus</i>	10.0	4.5	2.22	6.5	5.5	1.5	1.0	20	55.5	111	–	5.55	11.0	–	Li et al. (2007)
Large Shandong track	28.5	12.5	2.28	16.0	16.0	3.5	3.5	–5	92– 103	186– 206	180	3.6	7.2	(5.9)	Li et al. (2007)

Note Values in parenthesis are estimated and measured by authors from the figures of Zhen et al. (1994) and Li et al. (2006) who did not show these data in their papers
Source Kim et al. (2008a, b)



Fig. 2.24 Sauropod trackway from the Jindong Formation, Goseong dinosaur track site

Goseong County. However, it is difficult to know whether this track is attributable to bipedal or quadrupedal sauropods, even whether individual tracks are manus or pes impressions. Furthermore, it is difficult to tell in which direction the sauropod track maker was moving.

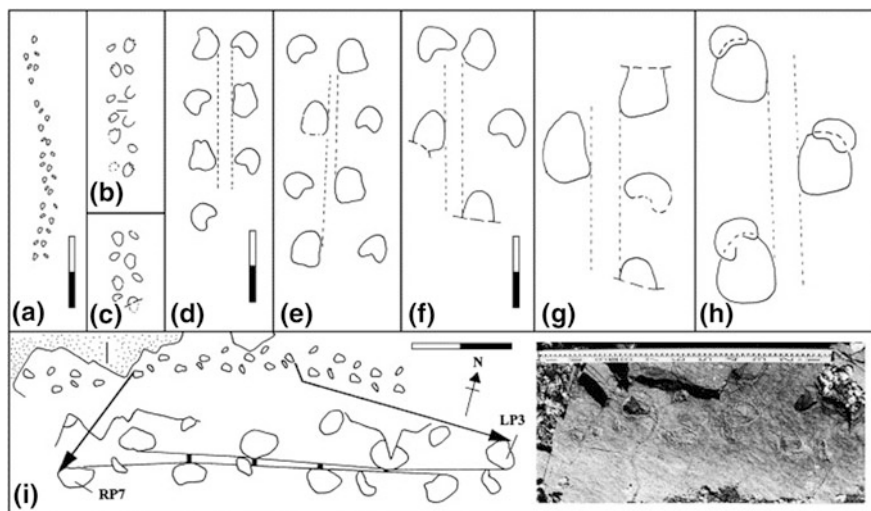


Fig. 2.25 Sauropod tracks from the Jindong Formation, Goseong area. *Notes* Observe that all the larger examples (**d–g**) are wide gauge, as shown by dotted lines that indicate the inner, inter-pes trackway width (after Lim 1990, with his numerical designations). **a** smallest known sauropod trackway at Hoewha District, Goseong County (after Lee et al. 2000b, Fig. 8A; Yang et al. 2003, pl. 89); **b–g** tracks at the Samcheonpo track site, Hai District, Goseong County; **b** tracks at the Dukmyeongri section after Lim et al. (1994, Fig. 2); **c** tracks at the Dukmyeongri section after Lockley et al. (1992); **d** trackway 2-6-1 at the Sangjok section; **e** trackway 10-22-1 at the Silbawi section; **f** trackway 2-3-1 at Sangjok 2 section; **g** trackway 8-1-1 at the Dukmyeongri section; **h** trackway 8-9-1 at the Dukmyeongri section; **i** detail of small sauropod trackway shown in Fig. 25A (after Yang et al. 2003, pl. 89) with detail (enlarged $\times 3$) of middle section showing left pes 3 (LP3) to right pes 7 (RP7), and margin of outcrop. Midlines and transverse black bars show variable trackway width. All scale bars represent 1 m (Lockley et al. 2006)

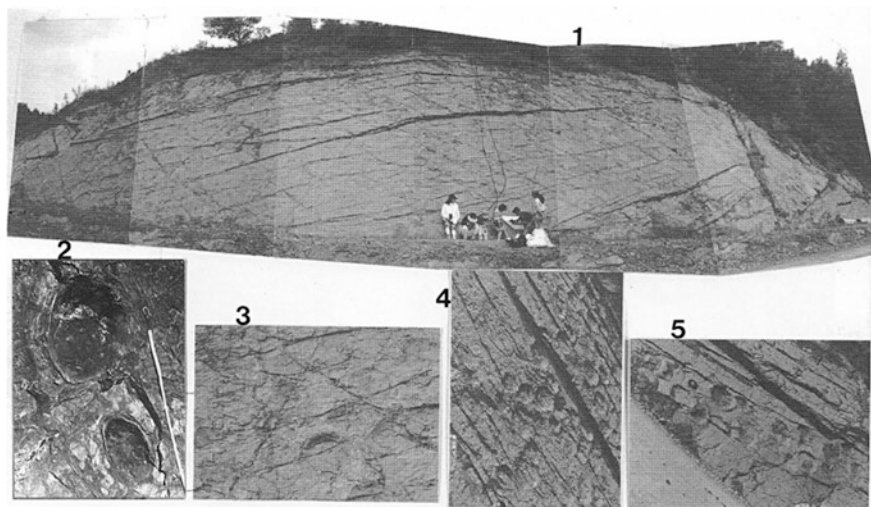


Fig. 2.26 Jeori dinosaur track site, Uiseong County. *Notes* (1) Outcrop view of the track site; (2) sauropod tracks and trackways named *Hamanosauripus ovalis*; (3–4) *Ultrasauripus unguilates*; (5) *Elephantosauripus metacarpus*. Source Kim and Seo (1992)

Table 2.8 Measurement of sauropod and ornithopod ichnotaxa named by Kim and Seo (1992) and Kim (1986, 1993)

Ichnotaxa	Track length (Manus/ Pes) (mm)	Track width (Manus/ Pes) (mm)	Pace (Manus/ Pes) (mm)	Stride (Manus/ Pes) (mm)	Pace angle (Manus/ Pes)	Trackway width (mm)	Remarks
<i>Hamanosauripus ovalis</i> , Kim and Seo, (1992), Kim (1993)	260/330	190/260	1010–670	930–1200	70°/95°	950–180	
<i>Elephantosauripus metacarpus</i> , Kim and Seo (1992)	110/530	360/470	1080/1010	1750/1700	100°/120°	1010/960	One trackway from Uiseong and another trackway from Gyeongsan, subcircular manus and elephant-like pes (Kim and Seo 1992)
<i>Ultrasauroipus unguilatus</i> , Kim and Seo (1992), Kim (1993)	230/805	450/805	1760/1840	980/870	107°/93°	1450/1430	One trackway, from Haman area, track maker is <i>Ultrasauroipus</i> (Kim 1993)
<i>Koseongosauripus onychion</i> , Kim (1993)	340	300	800	1600	180°	320	11 trackways from Goseong area, tridactyl tracks, claw marks, no figure (Kim 1993)
<i>Hamanosauripus unguilatus</i> , Kim (1986)							Track maker is Iguanodont, no figure, no description and no diagnosis (Kim 1986)
<i>Koreanosauripus cheongi</i> , Kim (1986)							Track maker is sauropod, no figure, no description and no diagnosis (Kim 1986)
<i>Goseongosauripus kimi</i> , Kim (1986)							Track maker is elephantine sauropod, no figure, no description and no diagnosis (Kim 1986)

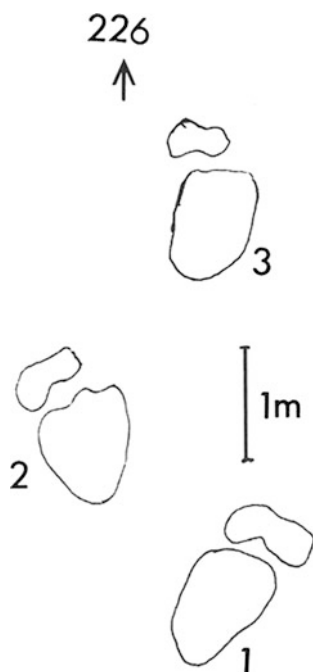


Fig. 2.27 A sauropod trackway from the Upper Cretaceous Uhangri Formation, Haenam County.
Source Huh et al. (1997)



Fig. 2.28 Dense sauropod tracks from the Cretaceous Jindong Formation, Donghae District, Goseong County. *Photo* by author

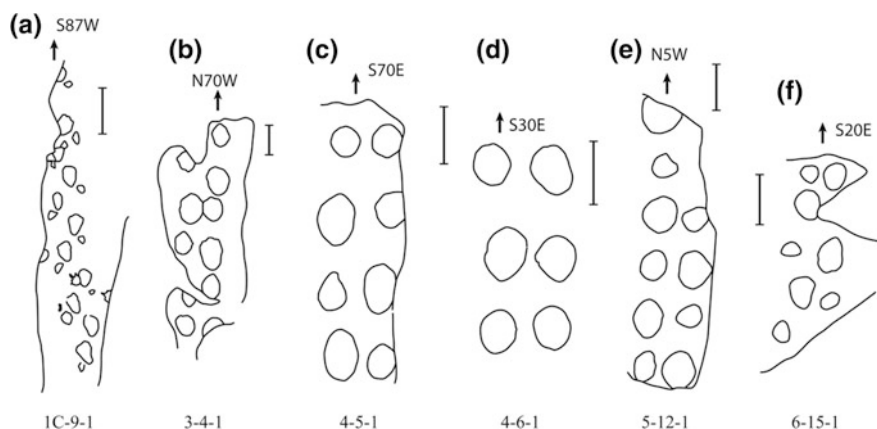


Fig. 2.29 Sketch of quadrupedal sauropod trackways from the Cretaceous Jindong Formation, Donghae District, southeast of Goseong County. *Note* Scale bar = 1 m. *Source* After Baek and Seo (1998), Fig. 6

Nevertheless, Baek and Seo (1998) reported 34 quadrupedal (probably sauropod) trackways at the Donghae District. Six examples of relatively well-defined quadrupedal sauropod trackways are shown in Fig. 2.29.

The trackway IC-9-1 is a narrow-gauge, very large sauropod trackway composed of small elongated subtriangular manus tracks and elongated subtriangular to subcircular pes tracks. Digit impressions of pes tracks are not clearly observed; the manus tracks are 29 cm in length and the pes tracks are 44 cm in length. Sauropod trackway 3-4-1 is also narrow-gauge, and is composed of relatively large subcircular manus tracks and relatively large, elliptical to subcircular pes tracks. The manus impressions are approximately 80 cm in length and the pes tracks are 110–120 cm in length. The digit impressions of the pes tracks are not clearly recognized. Trackways 4-5-1 and 4-6-1 are medium- to wide-gauge, large quadrupedal sauropod trackways. The manus tracks are relatively large (60–65 cm in length) and subcircular, and the pes tracks are elliptical to subcircular and 75–85 cm in length, which results in very weak heteropody. Digit impressions and claw marks are not observed in the pes tracks.

Trackway 5-12-1 is a medium-gauge, quadrupedal sauropod trackway composed of regularly spaced consecutive manus and pes tracks. The manus tracks are relatively large and generally oval, and the long axis of the manus impressions is nearly perpendicular to the midline of the trackway. The pes tracks are subcircular to elliptical. The lengths of the manus and pes tracks are 56 and 72 cm, respectively, resulting in weak heteropody. The pace, stride, and pace angle of the pes tracks are 128 cm, 196 cm, and 80°, respectively. Trackway 6-15-1 is a partial narrow-gauge, quadrupedal sauropod trackway. The manus tracks are relatively small (22 cm long and 11 cm wide), and oval, subtriangular, and subcircular in outline. The pes tracks are 30 cm in length and 28 cm in width, and elliptical and subcircular in shape (Baek and Seo 1998).

In summary, sauropod trackways from the Cretaceous Jindong Formation in the Donghae District, Goseong County, are narrow-gauge like *Parabrontopodus* or wide-gauge like *Brontopodus* and are highly variable in size, ranging between 30 and 115 cm in length. In addition, dense parallel to subparallel trackways at several localities strongly suggest a gregarious herding behavior in the sauropods that made the tracks.

Seven small sauropod trackways composed of 105 tracks were discovered at the Cretaceous Jindong Formation of the Hogyeri track site of Masan City (Hwang et al. 2002b). As shown in Fig. 2.30, all trackways are narrow-gauge like *Parabrontopodus* (Lockley et al. 1994), and generally composed of small crescent-shaped manus and relatively large elliptical to subcircular pes tracks. Although the digit impressions of the pes tracks are not clear for the most part, a few pes tracks show four thick digit impressions (Fig. 2.30b). Some tracks of trackways B and C show that manus tracks were partly overprinted by pes tracks. Almost all the manus and pes tracks are outwardly (positive) rotated, but the manus tracks of trackways B and G are inwardly rotated. It is difficult to identify the manus and pes tracks in the trackway shown in Fig. 2.30e due to the absence of recognized digit impressions in pes tracks and due to the similarity in the size and shape of individual tracks with low mesaxony. Parallel to subparallel trackways suggest these sauropods exhibited gregarious behavior.

As shown in Table 2.9, the length of the manus track is 9.4–20 cm and that of the pes track is 19–57 cm. The Hogyeri tracks were attributed to small sauropods with an estimated hip height of approximately 2 m that walked slowly at a speed of 0.16–1.89 m/s on the lake margin environment in relatively dry conditions (Hwang et al. 2002b).

Two years later, Hwang et al. (2004) reported a new track site at Docheonri, Changnyeong County, where ten well-defined sauropod trackways composed of over 550 tracks are distributed. The Dochenri track site is exposed on an inclined area approximately 57 m in length and 25 m in height (Fig. 2.31). Ten trackways are parallel to subparallel in a N18°W–N37°W orientation, and are very narrow-gauged like *Parabrontopodus* (Lockley et al. 1994). The manus tracks range in shape from a crescent to a fan, and range in length from approximately 20 to 29 cm in length. The pes tracks are longer than they are wide and range from approximately 30 to 38 cm in length (Table 2.10).

Of the ten trackways, trackway E is the most well-preserved; it is 32.7 m in length and composed of approximately 100 consecutive tracks. The manus tracks are about 24 cm in length and the pes traces are about 34 cm in length, resulting in weak heteropody. The manus tracks show digits II, III, and IV impressions outwardly rotated (nearly perpendicular to the midline of the trackway) and digit I impressions inwardly (medially) rotated (Fig. 2.32).

It is generally known that manus tracks of sauropods are semicircular or horseshoe-shaped (convex forward) and, usually, they show no indication of separate digit impressions (Thulborn 1990). In this regard, the Docheonri sauropod trackways represent an unusual example as they show sauropod manus tracks with separate digit traces. Although Hwang et al. (2004) regarded four (I–IV) digit

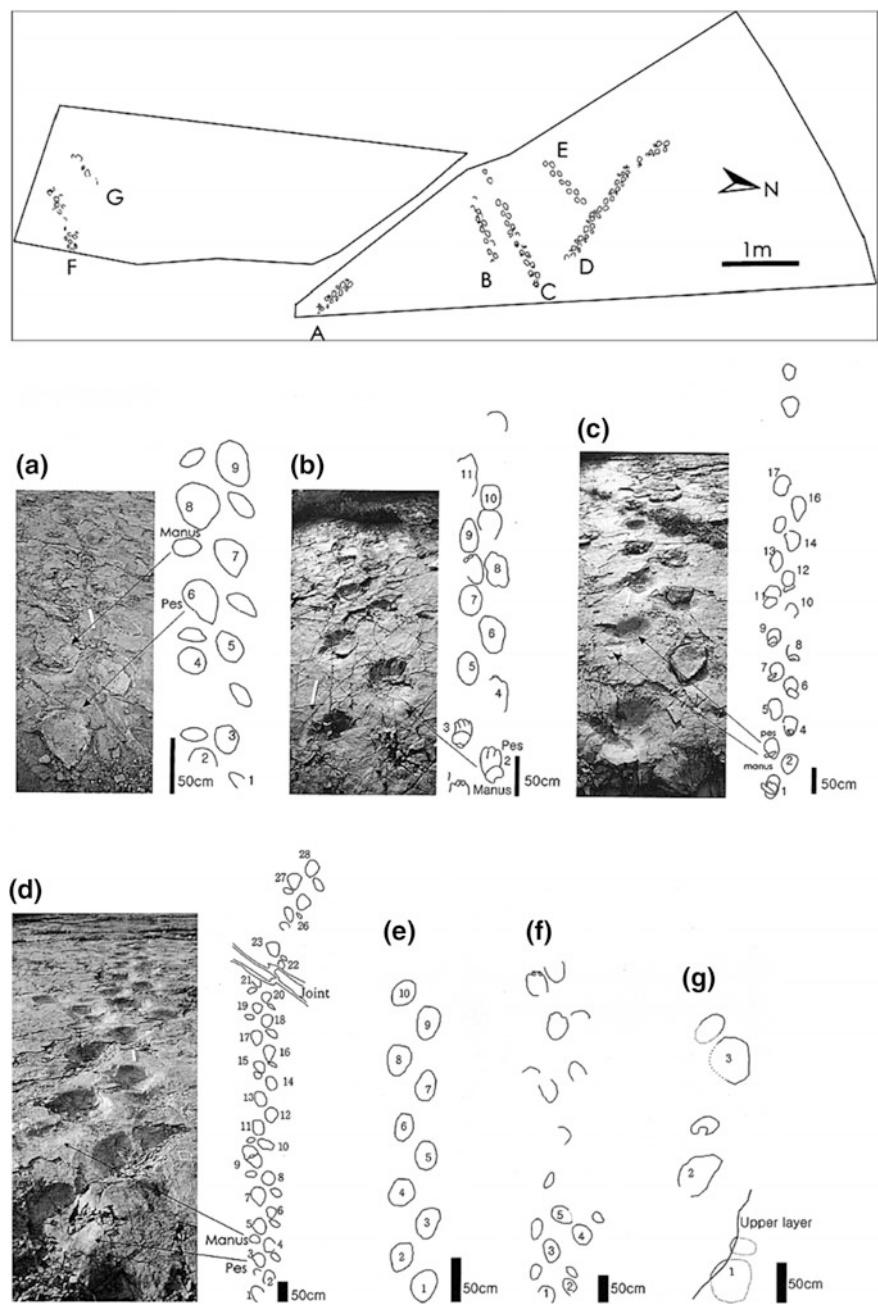


Fig. 2.30 Map showing distribution of sauropod trackways at the Hogyeri track site, Masan City (top), and photographs and line drawings of sauropod trackways (middle and bottom). *Source* Hwang et al. (2002b)

Table 2.9 Measurement of sauropod trackways from the Cretaceous Jindong Formation of Hogyeri, Masan City

Track way	Manus/pes	Trackway orientation	Track way width (cm)	Pace length	Stride length	Pace angulation	Track length	Track width	Track depth
A	Manus	N50W	35.7	68.3	91.0	107.9	13.6	27.6	2.0
	Pes			38.7	50.0	106.4	37.0	20.6	3.4
B	Manus	S68W	36.0	65.7			11.0	16.0	5.4
	Pes			58.7	92.0	104.5	45.3	25.9	3.7
C	Manus	S62W	38.7	63.5	82.5	107.5	10.5	21.4	5.9
	Pes			60.8	87.3	101.5	38.6	25.9	5.1
D	Manus	N64W	33.8	69.2	96.8	77.5	18.7	29.2	1.3
	Pes	N38W		56.0	95.4	111.5	42.3	30.6	4.7
E		S50W	33.4	54.2	90.2	107.9	43.5	28.2	
F	Manus	S60W	42.5			51.7			2.5
	Pes			75.8	90.5		27.0	28.2	2.9
G	Manus	S32W	29.0	120.5	272.6		31.0	32.0	2.6
	Pes			140.1	283.5	145.0	52.0	37.0	4.3

Source Hwang et al. (2002b)

traces, the manus tracks appear to have five (I–V) digit impressions (Fig. 2.32). Recently, sauropod tracks assigned to *B. pentadactylus* characterized by five digit impressions of manus track (Kim and Lockley 2012) have been clearly distinguished in the Docheonri sauropod tracks in the morphology of manus tracks. The pes tracks of the Docheonri sauropod trackway E are elliptical to subcircular and composed of four digits I–IV impressions with claw marks and rounded heel margin impressions. However, the other trackways of the Docheonri track site are relatively poorly preserved and do not clearly show digit impressions.

It may be noteworthy that smaller manus tracks are deeper than those of the larger pes tracks of the Docheonri sauropod trackways A, D, F, and J (Hwang et al. 2004) and the Hogyeri sauropod trackways B and C (Hwang et al. 2002b). As shown in Tables 2.9 and 2.10, the difference between the depth of manus and pes tracks may not be related to the size (length) of a manus and pes track, heteropody, and the shape of the manus impressions. It is generally known that the depth of tracks is related to the substrate conditions, such as moisture content and the texture of sediments, and also to the variations in pressure in the fore and hind limbs of the track makers. In addition, it is generally known that the tracks of relatively larger hind feet are deeper than those of relatively smaller forefeet.

Nevertheless, the reason why smaller manus tracks are deeper than relatively larger pes tracks in some sauropod trackways from the Hogyeri and Docheonri track sites remains to be explained. It is clear that substrate conditions do not offer a reasonable explanation, because the trackways occur densely in a limited area and there is no distinct trend in the difference of track depth between the parallel to subparallel trackways. So, the difference in body weight pressure between manus

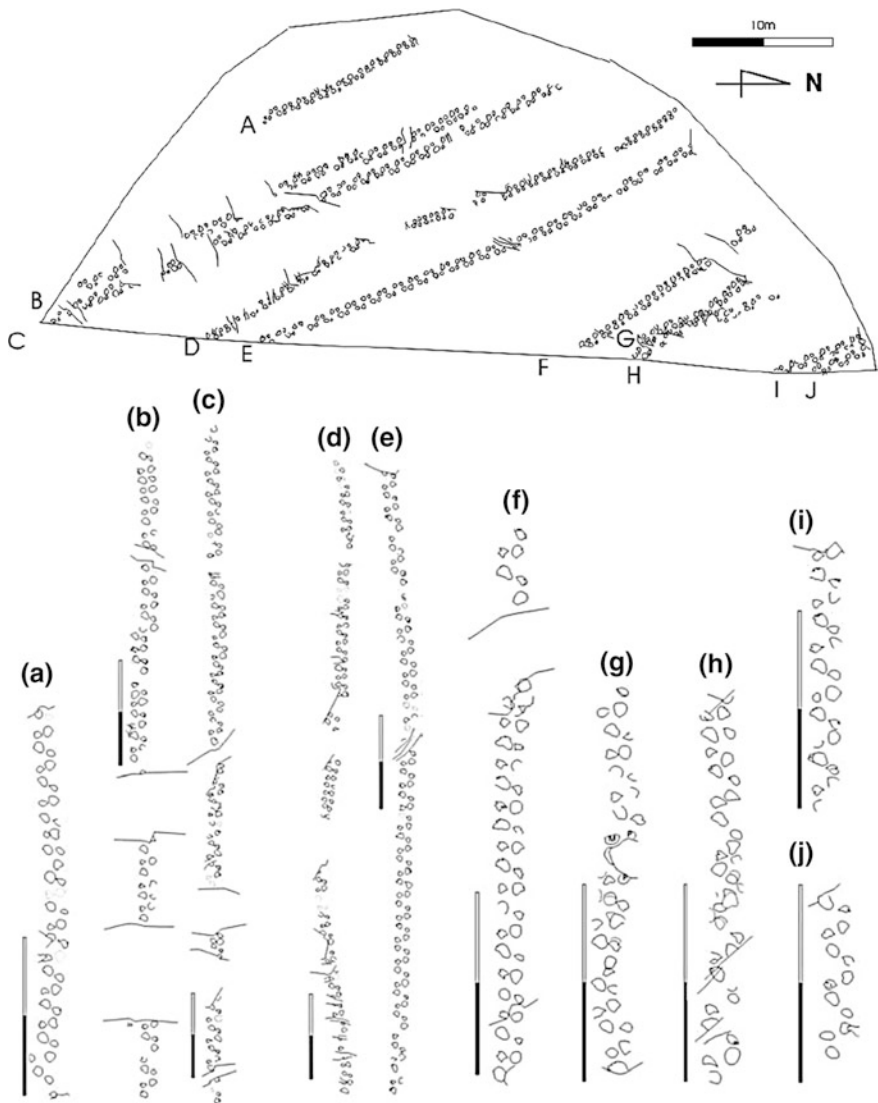


Fig. 2.31 Map showing distribution of sauropod trackways from the Cretaceous Jindong Formation, Docheonri, Changnyeong County (top), and line drawing of sauropod trackways (bottom). *Source* Hwang et al. (2004)

and pes during locomotion of the track making individuals and species may be a possible explication for this. Another possibility may be the amount of time that a foot remains on the ground (Thulborn 1990), though it is known to be roughly equal for the forefeet and hindfeet in quadrupedal mammals (Alexander and Jayes 1983).

Table 2.10 Measurement of sauropod trackways from the Cretaceous Jindong Formation of Docheonri, Changnyeong City (Hwang et al. 2004)

Track-way	Pes/ manus	Pace length	Stride length	Trackway width	Pace angulation	Track length	Track width	Track depth
A	Pes	83.0	111.2		88.1	29.9	31.0	25.4
	Manus	80.6	111.6		88.2	28.9	30.9	27.5
B	Pes	82.7	115.4	12.0	89.7	35.1	30.0	31.9
	Manus	78.0	113.0		93.1	22.9	30.4	20.1
C	Pes	70.4	119.6	8.0	100.0	35.7	29.8	27.4
	Manus	78.8	118.1		94.9	22.1	33.5	24.4
D	Pes	56.9	101.0		95.9	31.0	26.9	13.8
	Manus	62.0	101.6		105.4	20.1	27.4	17.8
E	Pes	69.6	125.3	11.0	95.8	33.5	30.1	30.8
	Manus	77.2	123.7		95.4	23.8	30.1	30.0
F	Pes	71.2	111.5	9.0	88.8	97.6	30.9	18.8
	Manus	79.3	115.4		91.8	24.0	27.1	19.2
G	Pes	65.1	108.7		101.3	35.6	29.9	19.8
	Manus	78.6	110.1		87.1	22.7	31.4	16.3
H	Pes	75.5	115.0		98.8	35.2	30.5	17.3
	Manus	79.9	126.4		97.8	19.8	31.1	13.8
I	Pes	68.3	116.0		116.6	38.2	32.0	25.8
	Manus	76.8	117.4		102.7	21.4	28.9	20.1
J	Pes	74.7	128.4	8.0	112.2	33.7	27.6	13.5
	Manus	78.9	131.7		105.0	20.2	31.5	18.2

Recently, a pes only sauropod trackway associated with ornithopod and theropod trackways was described at the Cretaceous Jangdong Tuff at the Hwasun track site (Lockley et al. 2012b). The sauropod trackway segment identified shows four consecutive pes tracks oriented towards the east. The trackway (Fig. 2.33) is distinctive because it shows no sign of manus tracks. Nevertheless, individual pes tracks are outwardly rotated, and well-preserved, with sediment rims and claw traces. The mean pes length and width is 72 and 52 cm, respectively ($N = 4$). The mean step is 135 cm ($N = 3$), and the mean stride is 217 cm ($N = 2$). The pace angulation is 108° , and the inner trackway width is approximately 30 cm. The lack of manus tracks suggests that they were overprinted by the pes. At least four isolated, crescent- to horseshoe-shaped (convex forward) manus tracks (M1–M4 in Fig. 2.32) are found scattered across the site at level 4. Their random distribution, without associated pes tracks, is difficult to interpret. It is tentatively inferred that they represent transmitted prints, or actual prints that penetrated randomly from a higher level as a result of differential substrate consistency (Lockely et al. 2012b).

A medium-gauge large sauropod trackway at the Haman Formation at the Gain track site, Namhae area, was first described as *B. birdi* (Kim et al. 2012a). The pes tracks, approximately 75 cm in length and 60 cm in width are composed of

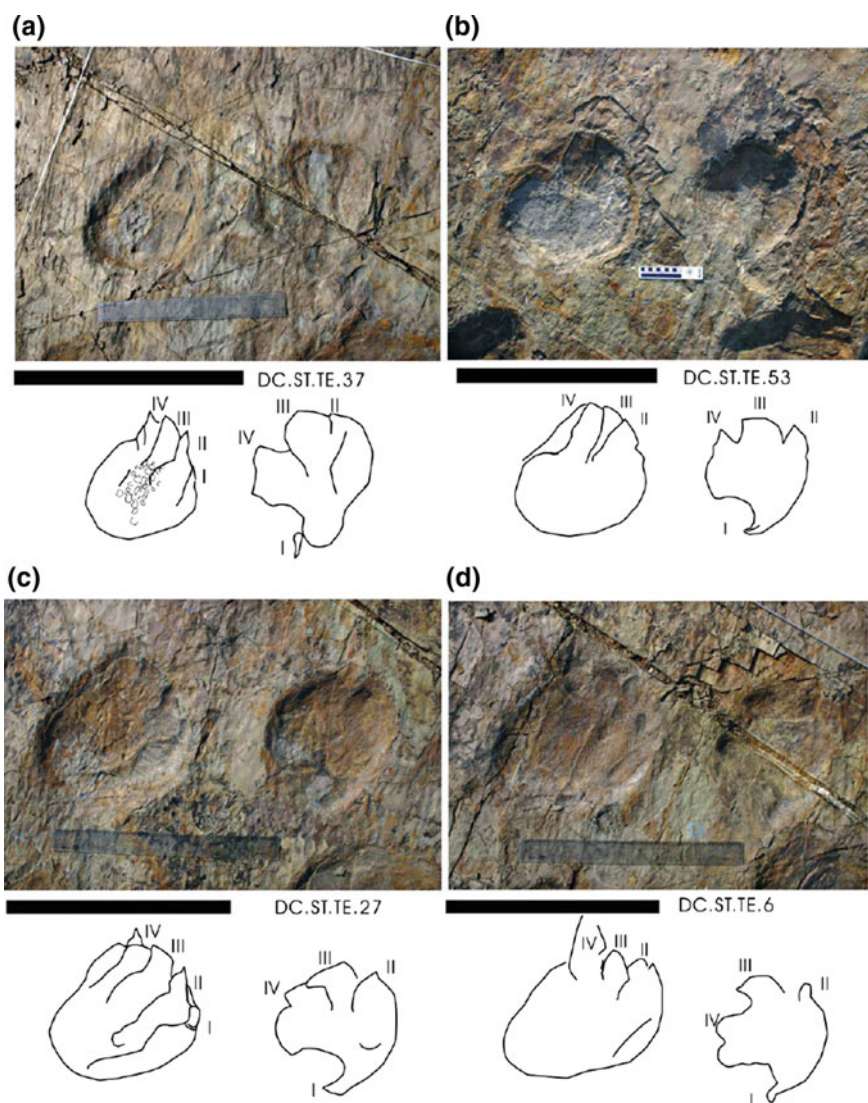


Fig. 2.32 Photographs and line drawings of well-preserved manus-pes sets at the Docheonri sauropod trackway E. *Notes a–d* Show the 27th set, 37th set, 53th set, and 6th set, respectively. *Source* Hwang et al. (2004)

outwardly rotated pedal claw I, II, and III impressions. The digit impressions are outwardly curved. Digit I is about 18 cm long and 9 cm wide, digit II is 11 cm long and 8 cm wide, and digit III has only a faint impression. The manus tracks are nearly circular with diameters of about 55 cm. The heteropody, the ratio between the manus and pes area, ranges from 1: 1.5 to 1:2 (i.e., no pronounced heteropody).

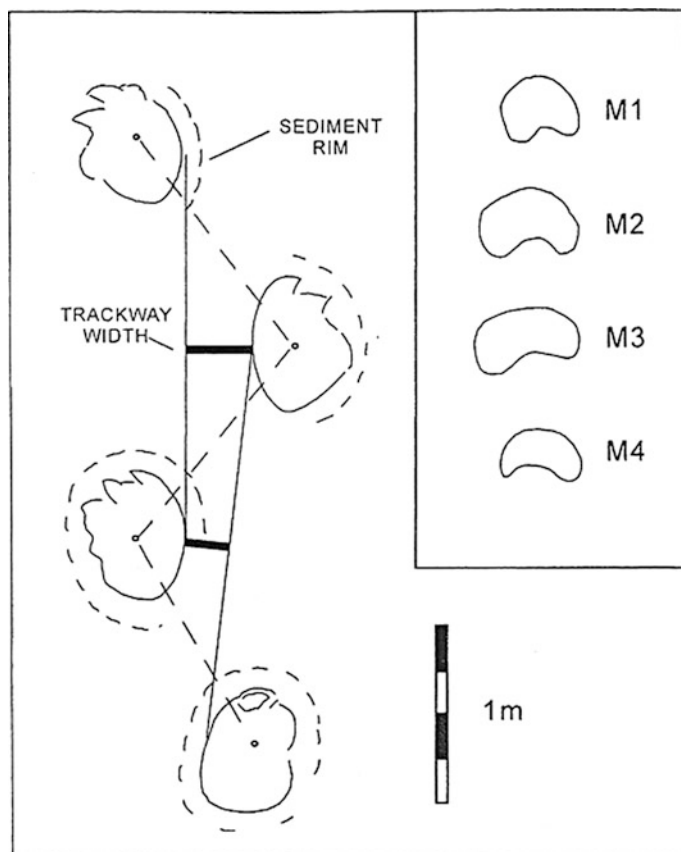


Fig. 2.33 Pes only sauropod trackway from the Cretaceous Jangdong Tuff, Hwasun track site. Notes Inset (top right) shows isolated manus tracks. Source Lockely et al. (2012b)

The speed of the sauropod was estimated to be 0.87 m/s (approximately 3 km/h), indicative of slow walking. The Gain trackway closely resembles *B. birdi* described at the Lower Cretaceous, Texas (Farlow et al. 1989). The manus-pes area ratio of the Gain sauropod track is nearly identical (about 0.5) to that of the Texas *B. birdi* (Kim et al. 2012a, Fig. 2.34). The Gain sauropod tracks assigned to *B. birdi* represent the first record of this ichnospecies from the Cretaceous in Asia (Kim et al. 2012a).

Wide-gauged sauropod trackways with wide pentadactyl manus tracks revealing hitherto unreported morphology were first described as *B. pentadactylus* at the Lower Cretaceous Haman Formation, Jinju area (Kim and Lockley 2012). Sauropod trackway 1 is about 6 m long and composed of five left manus and five left pes tracks, and three right manus and three pes tracks. The manus tracks are wider than they are long, 31 cm long and 36.5 cm wide on average. They are typically composed of three to five blunt short digit impressions, and appear to

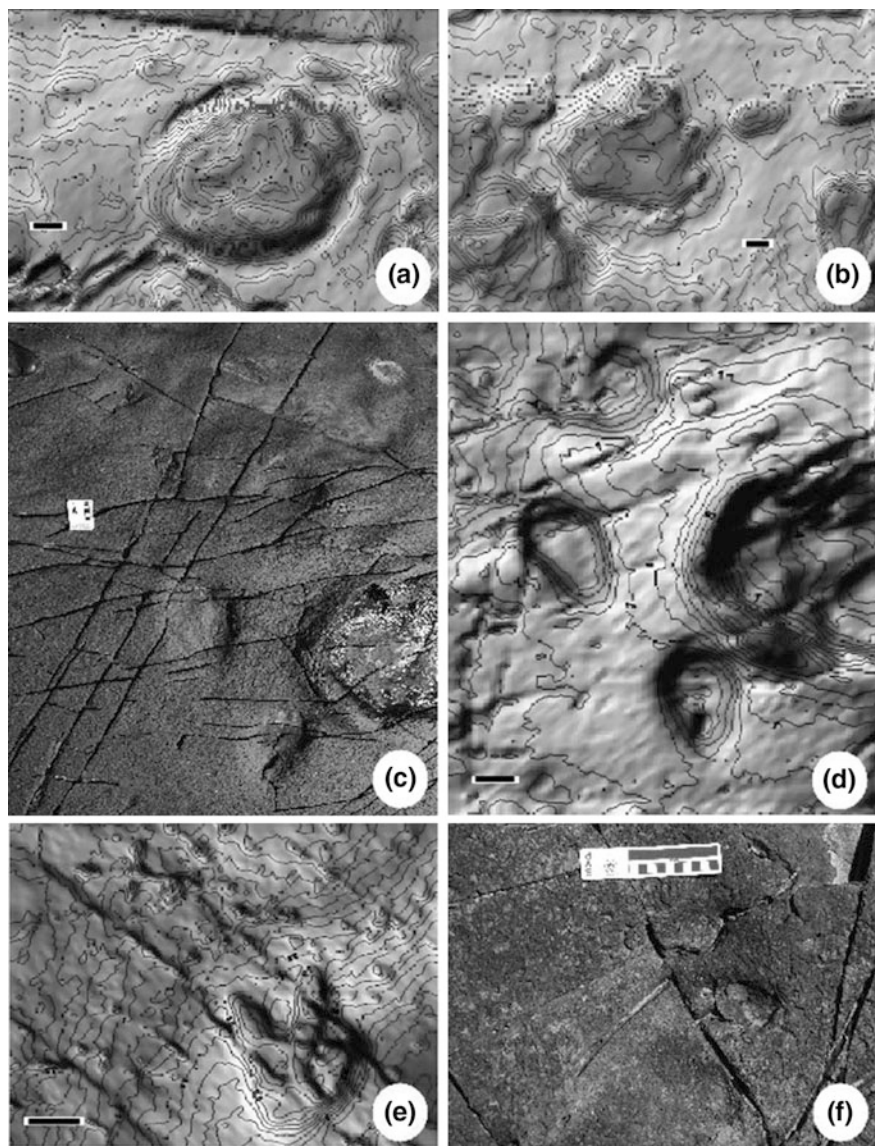


Fig. 2.34 3D scanning images showing the contours of tracks (**a**, **b**, **d**, **e**) and photographs of tracks (**c**, **f**) from the Haman Formation at the Gain track site. *Notes* **a** Left pes of a sauropod track with outwardly pointed digit impressions and a pterosaur trackway with five consecutive tracks (in upper part); **b** pterosaur trackway P1 and a sauropod pes showing outwardly curved digit impressions (note that the former is superimposed on the latter); **c**, **d** manus of a sauropod and pterosaur trackway P2; **e** a theropod track; **f** an ornithopod track from ornithopod trackway O1. Scale bars in **a**, **b**, **d** and **e** are 10 cm. *Source* Kim et al. (2012a)

rotate outward, with the axis of digit IV nearly at right angles to the midline of a trackway. The pes tracks are longer than they are wide, 50 cm long and 40 cm wide on average, and are outwardly rotated at about 35° . Digits I, II, and III have well-defined sharp claw traces (Figs. 2.35, 2.36 and 2.37; Table 2.11).

Trackway 2 is composed of ten consecutive manus and pes tracks. The manus tracks are wider than they are long, about 30 cm in length and 35 cm in width. The five-digit impressions of the manus track are blunt and show rounded terminations without claw impressions. The manus tracks are outwardly rotated at angles of 35° – 40° . The pes tracks are longer than they are wide, about 40 cm in length and 30 cm in width. The four-digit impressions of pes tracks are short and blunt, and show rounded terminations without claw marks. The pes tracks are outwardly rotated at angles of 40° – 50° (Figs. 2.35, 2.36 and 2.37).

All previously reported, well-preserved sauropod manus tracks have had a single semicircular outline. In most cases, discrete manus digit traces are not registered, although in some cases (e.g., type *Brontopodus*) impressions of digits I and V are visible, respectively, at the postero-medial and postero-lateral “corners” of the track’s semicircular outline (Kim and Lockley 2012). Therefore, *B. pentadactylus* from the Gajin track site, Jinju area, provided new insight into the morphology of the fleshed-out manus of sauropods, unlike the sauropod tracks currently known. In

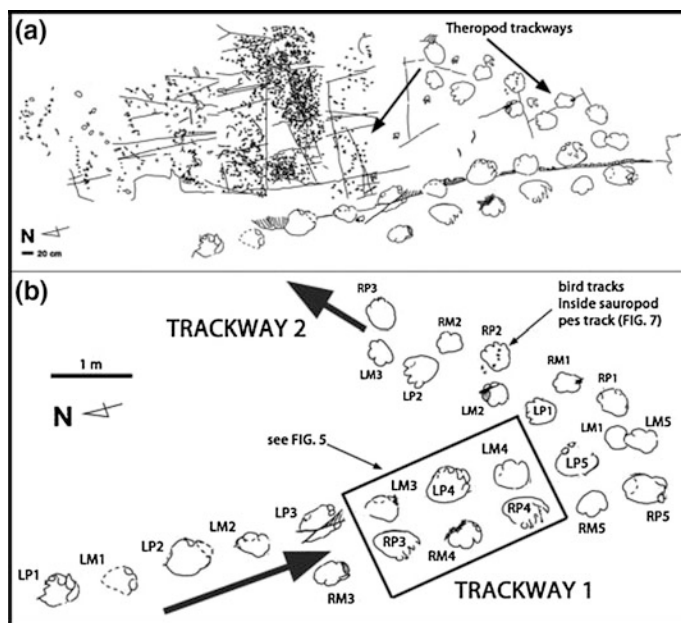
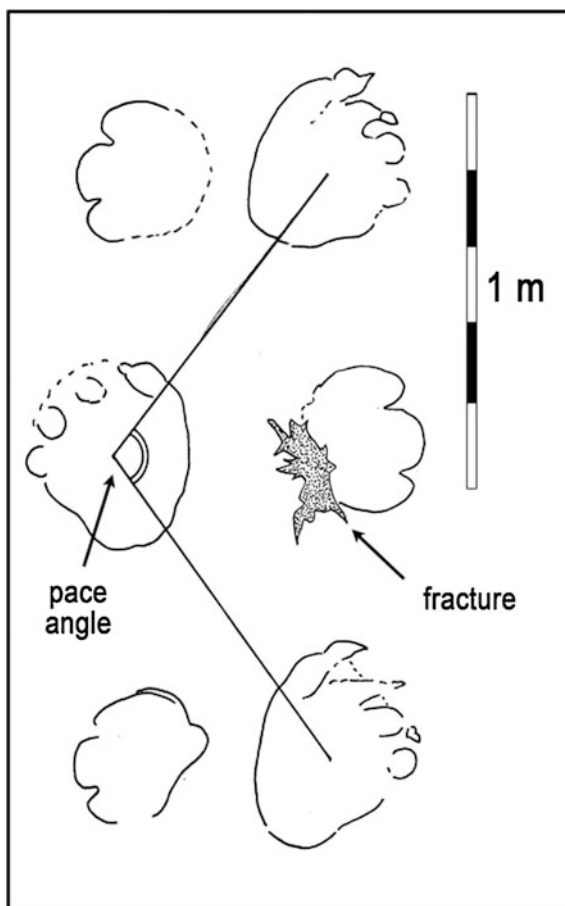


Fig. 2.35 Distribution of dinosaur and bird tracks at the Gajin track site, Jinju area. *Notes* **a** Map of dinosaur and bird tracks preserved at Heritage Hall I in the Gajin track site, showing two theropod trackways; **b** detail of sauropod trackways 1, with key to details shown in Figs. 2.36 and 2.37. *Source* Kim and Lockley (2012)

Fig. 2.36 Detail of manus-pes sets of sauropod trackway 1 from the Gajin track site. *Notes* Compare with Figs. 2.35, 2.37 and 2.38. Note the difference between the pentadactyl manus track (bottom left) and the tridactyl manus tracks (right and top left). *Source* Kim and Lockley (2012)



addition, *B. pentadactylus* tracks are associated with thousands of diverse bird footprints in a lakeshore paleoenvironment (Fig. 2.38). *B. pentadactylus* from the Gajin track site represents the second ichnospecies of *Brontopodus* following *B. birdi*, which was described at the Glen Rose Limestone (Lower Cretaceous) and equivalents of Texas and Arkansas (Farlow et al. 1989).

2.1.4 Unusual Dinosaur Tracks with Internal Ridges

Very unusual dinosaur tracks with radial internal ridges at the upper Cretaceous Uhangri Formation, Haenam area, Korea, have been the subject of much controversy (Hwang et al. 2008). A total of 105 tracks with radial ridges were excavated in a 270 m² area (Lee and Huh 2002). The outlines of the tracks are circular in shape and

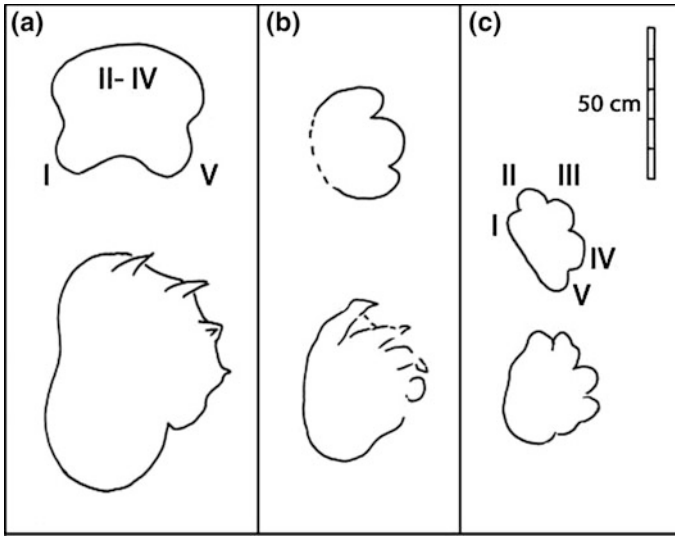


Fig. 2.37 Comparison between *Brontopodus birdi* and Gajin trackways 1 and 2. *Notes* *Brontopodus birdi* (a), after Farlow et al. (1989); Gajin trackways 1 and 2 (b and c, respectively) at the same scale. Note the difference in shape, orientation of manus tracks, and digit designations between a and c. Compare b with Fig. 2.38. *Source* Kim and Lockley (2012)

range from approximately 73 to 83 cm in diameter. The tracks are large bowl-shaped impressions with depths ranging from 40 to 270 mm (Hwang et al. 2008, Fig. 2.39). The six radial internal ridges extend out from the counter of each footprint. The size and age of these tracks imply a dinosaurian track maker, but in morphology these peculiar tracks could not be readily compared or assigned to any other type of dinosaur track (Lee and Huh 2002; Thulborn 2004; Lee and Lee 2006). Accordingly, it has not yet been possible to determine clearly the type of track, type of track maker, or the direction of movement. To date, three possible scenarios or models have been reported for the interpretation of unusual dinosaur tracks with internal ridges (Lee and Huh 2002; Thulborn 2004; Hwang et al. 2008).

Lee and Huh (2002) first interpreted the peculiar tracks with radiating ridges as manus only sauropod tracks attributed to swimming sauropods (Fig. 2.40). However, the swimming scenario has been challenged by subsequent authors (Thulborn 2004; Hwang et al. 2008). Thulborn (2004) argued that the circular outlines of the large bowl-shaped impressions differ from the horseshoe shape typical of well-preserved manus sauropod tracks, and that the Uhangri tracks do not obviously match the hand or foot of any known group of dinosaurs (Thulborn 1990). Furthermore, Hwang et al. (2008) documented that no indicators of the swimming scenario such as “push up” ridges could be found at the Uhangri track site.

As an alternative to the swimming scenario, Thulborn (2004) proposed that the radial cracks are the result of the deformation of the upper layers of shale after the

Table 2.11 Measurement of sauropod trackways 1 and 2 from the Gain track site

Track No.	Length (cm)	Width (cm)	Pace (cm)	Stride (cm)	Pace angulation (°)	Rotation angle (°)	Relative stride length (SL/h)	Hip height (m)	Speed (m/s)
Trackway 1									
LM1	30	38	—	—	—	90	Manus 1.21 Pes 0.78	Manus 1.24 Pes 1.89	Manus 1.21 Pes 0.72
LP1	45	38	—	—	—	—	—	—	—
RM1	—	—	—	—	—	90	—	—	—
RP1	—	—	—	—	—	—	—	—	—
LM2	32	36	—	155	—	90	—	—	—
LP2	48	42.7	—	151	—	—	—	—	—
RM2	—	—	—	—	—	—	—	—	—
RP2	48	43	—	—	—	—	—	—	—
LM3	33	35	96	147	107	90	—	—	—
LP3	—	36	—	152	—	37	—	—	—
RM3	30	39	93	—	105	90	—	—	—
RP3	48	36	91	—	—	35	—	—	—
LM4	35	38	86	147	104	90	—	—	—
LP4	49	42	95	150	—	35	—	—	—
RM4	32	37	97	154	104	90	—	—	—
RP4	45	40	93	153	114	38	—	—	—
LM5	26	35	92	153	—	90	—	—	—
LP5	46	39	85	149	110	37	—	—	—
RM5	30	34	98	148	102	90	—	—	—
RP5	49	33	83	135	—	35	—	—	—
Trackway 2									
LM1	24	27	—	—	—	—	Manus 1.39 Pes 1.03	Manus 1.06 Pes 1.46	Manus 1.4 Pes 0.99
RP1	36	29	—	—	—	—	—	—	—
RM1	22	30	85	—	125	—	—	—	—

(continued)

Table 2.11 (continued)

Track No.	Length (cm)	Width (cm)	Pace (cm)	Stride (cm)	Pace angulation (°)	Rotation angle (°)	Relative stride length (SL/h)	Hip height (m)	Speed (m/s)
LP1	33	26	78		135	28			
LM2	24	30	84	148	125				
RP2	35	28	89	147	135	28			
RM2	24	29	84	149	127				
LP2	37	31	89	156	135	30			
LM3	23	30	80	146					
RP3	41	28	83	148		32			

Source Kim and Lockley (2012)



Fig. 2.38 Photograph and sketch of bird tracks (*Koreanaornis hamanensis*) in the sauropod pes track (*Brontopodus pentadactylus*) from the Gain track site. Source Kim and Lockley (2012)

withdrawal of the dinosaur foot from the sediment. He proposed two possible mechanisms that might have caused the peculiar tracks with radial ridges. The first one was the adherence of mud to the dinosaur foot during withdrawal; the second was the formation of a blister-like dome as water, just displaced by the impact of the footfall, flowed back under the lifted laminae. The two models proposed by Thulborn (2004) for dinosaur tracks with internal ridges are shown in Fig. 2.41. Although he suggested that the two mechanisms could work in conjunction, the first requires very sticky, ductile mud to be directly impacted by the foot, whereas the second requires more cohesive laminae to lift up as a canopy (Hwang et al. 2008). However, there is no evidence supporting the delamination scenario of Thulborn (2004) at the track site at Uhangri (Hwang et al. 2008).

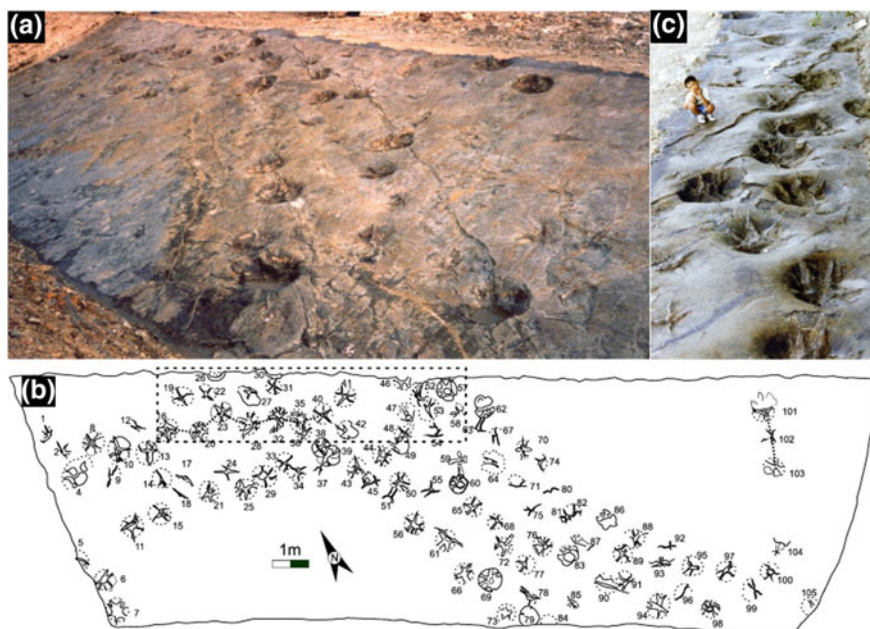


Fig. 2.39 Track site III-1 (a) and detailed map (b) of the unusual dinosaur tracks with internal ridges at the Uhangri track site; photograph (c) shows the northern area of site III-1 at an early stage of excavation at the Uhangri track site. *Notes* There are two trackways here that proceed to northeast and east. Footprint numbers are listed on the detailed map (b). *Source* Hwang et al. (2008)



Fig. 2.40 Reconstruction of a floating sauropod conjectured from the Uhangri sauropod manus tracks (after Lee and Huh 2002)

Hwang et al. (2008) proposed another new model for the interpretation of unusual tracks with internal ridges on the basis of tracks occurring at the Uhangri track site, Haenam area. They reviewed the swimming scenario (Lee and Huh 2002) and the delamination scenario (Thulborn 2004). Two important features newly observed at the track site are that, first, the footprints sometimes exhibit

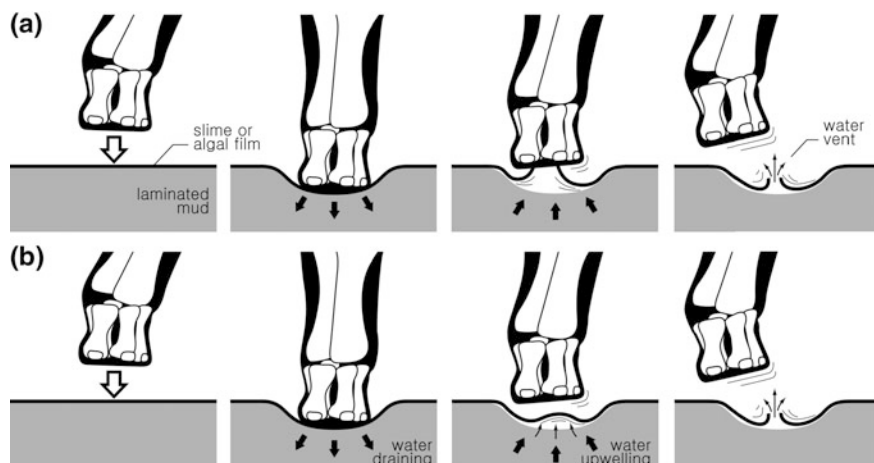


Fig. 2.41 Two models proposed by Thulborn (2004) for Uhangri manus only tracks. *Notes* a “Milk skin” model; b “blister” model. *Source* Lee and Lee (2006)

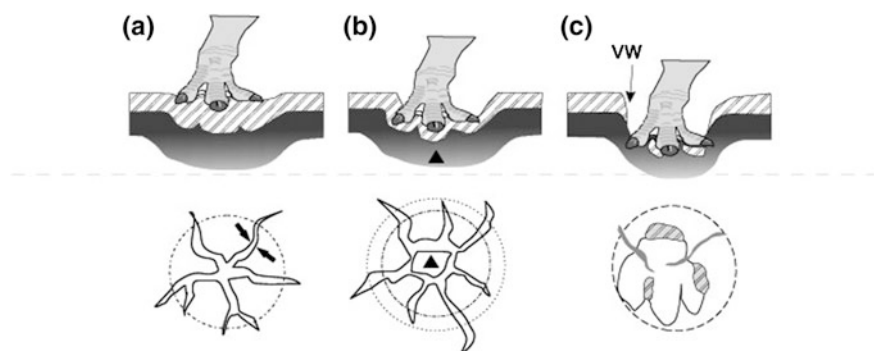


Fig. 2.42 Differential formation of undertracks with ridges depending on depth. *Notes* a Relatively shallow undertracks lead to cracking of tuffaceous sand (diagonal lines) and molding of ridges in the underlying mud (grey). Arrows show that the angular change in the direction of the ridge margins is the same on both sides, supporting the evidence of cracking or a brittle fracture; b deeper impact, causing the sand layer to be more deeply impressed, especially in the center near the point of maximal impact force (filled triangle); c deepest penetration into the sand layer creates more complete, true footprints, with interference caused by distorted fragments of the sand layer. VW = vertical wall seen in deep footprints. *Source* Hwang et al. (2008)

characteristic features such as ungula, digit or heel impressions, suggesting that the mysterious traces are those of a tridactyl, bipedal dinosaur. Second, the unusual tracks are underprints, and the internal ridges are molds of radial cracks on the underside of a sand bed on which large bipeds were walking (Hwang et al. 2008). The formation of the unusual dinosaur tracks with radial ridges is shown in Fig. 2.42.

2.1.5 Dinosaur Tracks of North Korea

Dinosaur tracks were also discovered at the Upper Cretaceous Ponghwasan Series of Ryonggungri, Phyongsan County, North Hwanghae Province (Pak and Kim 1996). The Ryonggungri dinosaur tracks discovered in 1989 were designated as Natural Monument No. 466 in North Korea in 1990. The Ryonggungri tracks are displayed at the Natural Museum of Kim Il Sung University, Pyongyang, North Korea (Pak and Kim 1996).

Unfortunately, a systematic description with measurement data of the dinosaur tracks was not provided. Only three photographs (unscaled) are shown in the book *Geology of Korea* (Paek et al. 1996), and these are presented in Fig. 2.43. Although the three trackways are shown as Anchisauripodidae (?), Tyrannosauridae, and Iguanodontidae, respectively, it is very difficult to recognize these in the photographs. However, their identification seems to be totally wrong, though they are ichnologically very important if they are proved to be ichnotaxonomically valid. Reexamination with careful observation, measurement, description, and comparison of dinosaur tracks from the Upper Cretaceous at Ryonggungri, Phyongsan County, North Korea, is necessary and should hopefully be undertaken in the future.

2.2 Dinosaur Bones

Compared with dinosaur tracks, skeletal dinosaur remains have rarely been reported from the Mesozoic in Korea. The first dinosaur skeletal remains were reported at the Gugyedong Formation of Tabri, Uiseong County, South Gyeongsang Province (Kim 1981). The dinosaur fossils were originally identified as a proximal end of right ulna belonging to the family Brachiosauridae (Kim 1981), and a part of sauropod femur or tibia (Chang et al. 1982). Kim (1983) described this dinosaur fossil as *Ultrasaurus tabriensis* based mainly on its supposed huge size by simple comparisons with the ulna of *Supersaurus*.

However, Lee et al. (1997) reexamined the fossil specimen and described it as a proximal part of the left humerus of a sauropod, instead of a portion of the right ulna. This dinosaur fossil specimen deposited at the Department of Geology, Kyungbuk National University, Daegu, represents the first sauropod dinosaur fossil found in Korea (Fig. 2.44). A skeletal dinosaur remain discovered at the Tabri site, Uiseong area, was originally described as a hadrosaur femur (Kim 1983). However, the fossil was reexamined and redescribed as the left femur of a dinosaur belonging to a non-avian maniraptoran theropod of possible dromaeosaurid affinity (Kim et al. 2005). This fossil, which is housed at the Natural Heritage Center, National Research Institute of Cultural Properties in Taejeon, represents the second skeletal dinosaur fossil and the first non-avian theropod described in Korea.

In 2001, skeletal sauropod remains were described at the Hasandong Formation, Hadong County (Dong et al. 2001). The material is a fragmentary skeleton including seven incomplete cervical vertebrae, one dorsal vertebrae, one partial

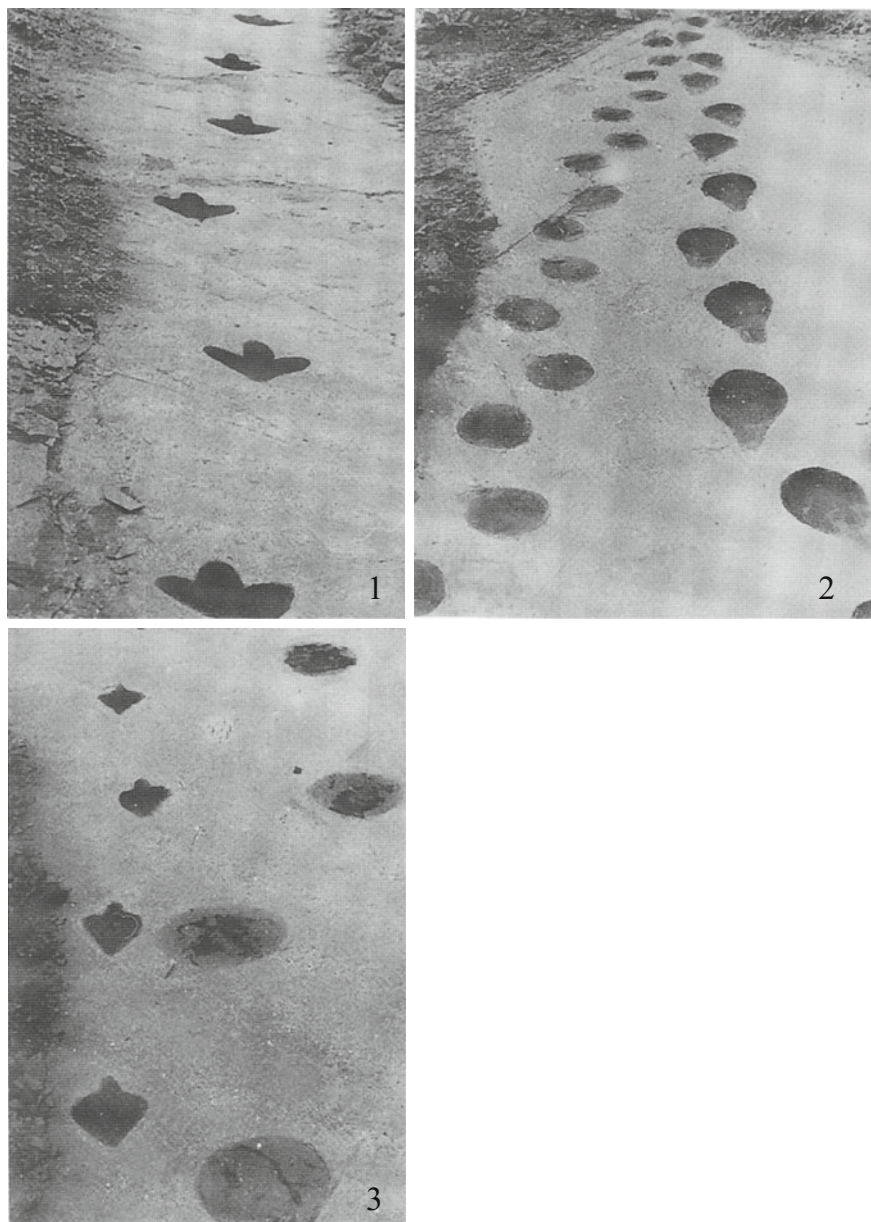


Fig. 2.43 Dinosaur footprints from the Upper Cretaceous Ponghwasan Series, Ryonggungri, Phyongsan County, North Korea. *Notes* Tracks were originally regarded to be attributable to: (1) Anchisauripodidae (?); (2) Tyrannosauridae; (3) Iguanodontidae. The quality of the original figure is not good. *Source* Pak and Kim (1996)



Fig. 2.44 The first dinosaur specimen discovered at the Cretaceous Gugyedong Formation at Tabri, Uiseong County. *Note* Length of specimen is 43 cm. *Sources* Chang et al. (1982); Kim (1983)

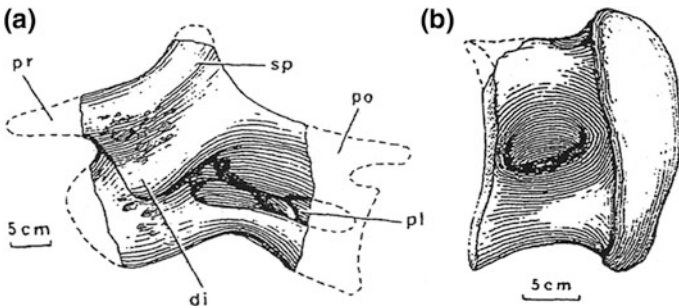


Fig. 2.45 Skeletal remains assigned to *Pukyongosaurus millenniumi*. *Notes* **a** Cervical vertebra in lateral view; **b** lateral view of a dorsal vertebra. *Source* Dong et al. (2001)

clavicle (?), one chevron, and isolated bones. Although the skeletal remains are only fragmentary and incomplete, these fossils were named *Pukyongosaurus millenniumi* as the first named dinosaur, mainly on the basis of the cervical and dorsal vertebrae (Fig. 2.45). However, Upchurch et al. (2004) regarded it to be *nomen dubia* due to incomplete material.

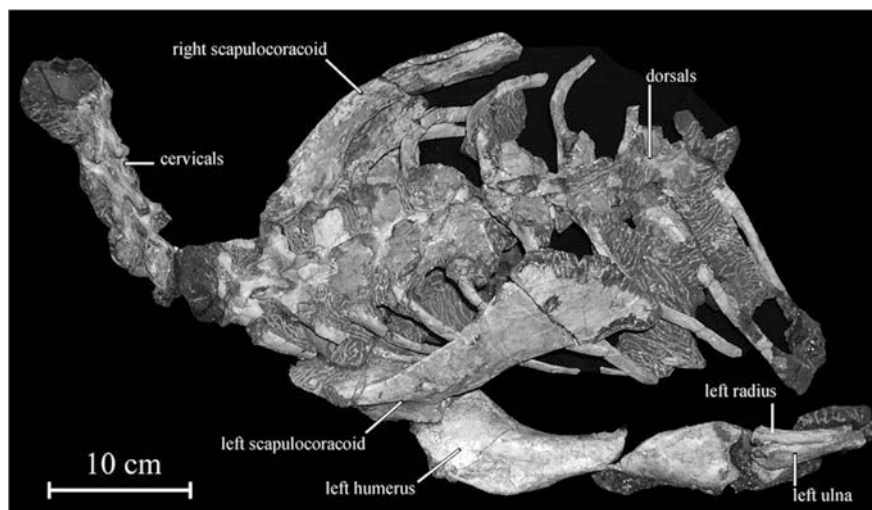


Fig. 2.46 Holotype of *Koreanosaurus boseongensis* (KDRC-BB2) in dorsolateral view. Source Huh et al. (2010)

New basal ornithopod dinosaur fossil remains were first described at the Upper Cretaceous Seonso Conglomerate, Boseong County, where about 200 dinosaur eggshells were discovered (Huh et al. 2010). They are well-preserved and assigned to a new ornithopod taxon named *Koreanosaurus boseongensis*. This dinosaur is characterized by elongated neck vertebrae, very long and massive scapulocoracoid and humerus bones, proportionally short hindlimbs with a low hindlimb ratio for tibia/femur, and an anteroposteriorly elongated femoral shaft. According to the morphological, phylogenetic, sedimentological, and taphonomic data at hand, it was a burrowing dinosaur, like *Oryctodromeus* (Huh et al. 2010, Fig. 2.46).

Subsequently, a new basal neoceratopsian was first described at the Lower Cretaceous Tando Formation at the Sihwa site, Hwaseong County, where rich deposits of dinosaur eggshells were found (Lee et al. 2011). It represents the first ceratopsian dinosaur in the Korea Peninsula and was assigned to *Koreaceratops hwaseongensis*, which is characterized by very long caudal neural spines and a unique astragalus divided into two fossae by a prominent craniocaudal ridge on the proximal surface (Lee et al. 2011, Fig. 2.47). A phylogenetic analysis indicated that the *Koreaceratops* is positioned between *Archaeoceratops* and all derived neoceratopsians, and that the very tall caudal neural spines appear to be homoplasious, suggesting an independent adaptation, possibly for swimming (Lee et al. 2011).

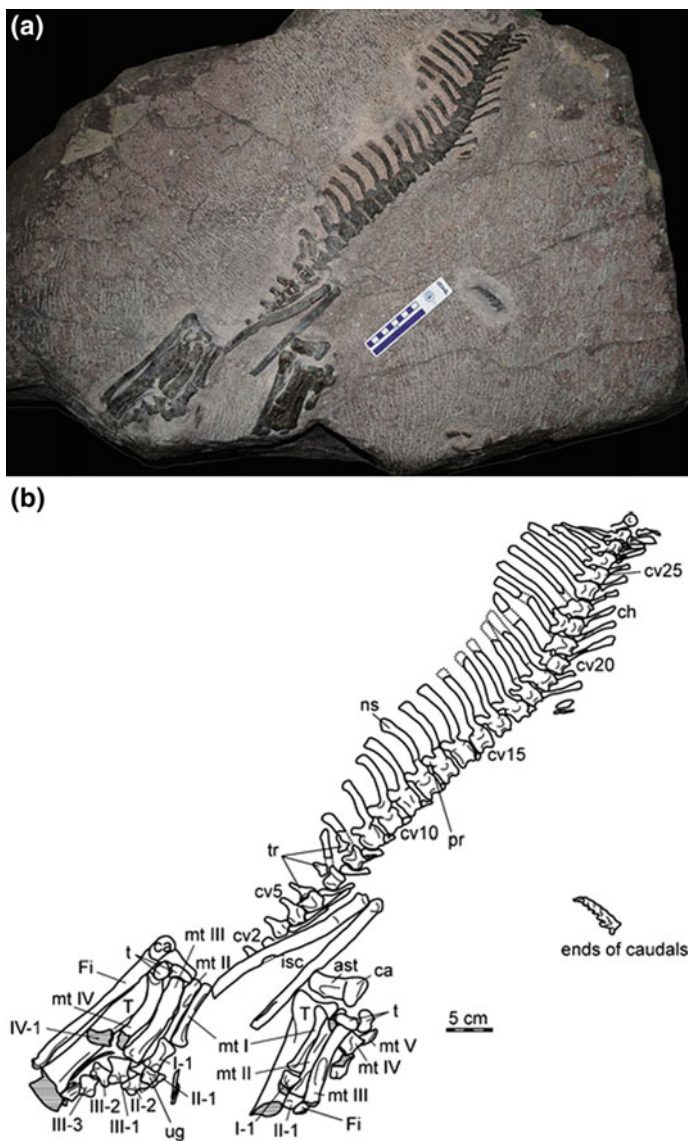


Fig. 2.47 *Koreaceratops hwaseongensis* from the Hwaseong area. **Notes** **a** Photograph of *Koreaceratops hwaseongensis* from the Tando beds (Albian) of Tando Basin in South Korea (KIGAM VP 200801, holotype) in ventral view. The proximal tibiae and fibulae are sharply cut off at the edge of the block. **b** Illustration of *K. hwaseongensis* with anatomical abbreviations: *ast* astragalus, *ca* calcaneum, *cv* caudal vertebra, *Fi* fibula, *isc* ischium, *mt* metatarsal, *ns* neural spine, *pr* prezygapophysis, *T* tibia, *t* tarsal, *tr* transverse process, *ug* ungula. The cross-hatch pattern indicates the broken edge of the bone, and the partial restoration of neural spines is shown with dotted lines. *Source* Lee et al. (2011)

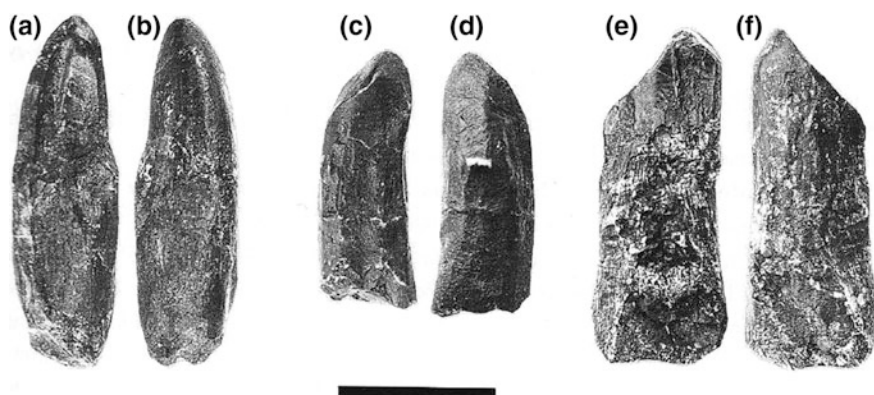


Fig. 2.48 Holotype of *Chiayüsauros asianensis* (KPE 8001) in lingual view (a) and labial view (b). Titanosaurid (?) tooth (KPE 8002) in lingual view (c) and labial view (d). Camarasaurid (?) tooth (KPE 8003) in lingual view (e) and labial view (f). Note Scale bar equals 2 cm. Source Lee et al. (1997)

2.3 Dinosaur Teeth

Dinosaur teeth were first described at the Lower Cretaceous Hasandong Formation at the Yusuri site, Jinju area (Lee et al. 1997). Three types of sauropod teeth were assigned to *Chiayüsauros asianensis*, *Titanosauridae* (?), and *Camarasauridae* (?) (Fig. 2.48). The tooth assigned to *Chiayüsauros asianensis* (Fig. 2.48a, b) is 46 mm in height as preserved. The root of the tooth is not preserved. The apical portion of the crown is slightly inclined lingually and distally. In lingual view, the slightly convex basal portion is high, occupying the proximal half of the height. The distal half is prominently concave in both vertical and horizontal directions. A narrow internal ridge runs in the middle part of the concavity from the apex. It bisects the spatulate depression asymmetrically, forming a smaller mesial portion than the distal. The well-developed wear surfaces produce a flat almost vertical facet cutting off the tip and extending downwards. It extends lingually to the half of the basal portion along the mesial margin, but does not reach the basal in the distal, forming a basally opening U-shaped border. Therefore, the border of the crown is entirely surrounded by the wear facet (1.8 mm in width) lingually. The labial side of the crown is uniformly convex without wear surfaces. There is a lateral groove on the mesio-labial side (Lee et al. 1997). Lee et al. (1997) regarded *Chiayüsauros asianensis* as the first named dinosaurian fauna described from the Cretaceous in Korea. Park et al. (2000) also described dinosaur teeth but, however, regarded that *Chiayüsauros asianensis* (Lee et al. 1997) should be considered as a *nomen dubium*.

Subsequently, a brachiosaurid tooth and megalosaurid tooth were first described at the Jinju and Hasandong formations, respectively (Lim et al. 2001, 2002). Yun et al. (2007) described theropod and sauropod teeth including specimens described by Lim et al. (2001, 2002) at the Lower Cretaceous Hasandong and Jinju formations. Of these, the tooth from the Hasandong Formation at Hapgari, Goryeong

County, was tentatively assigned to a tyrannosaurid tooth, which is characterized by well-developed multiple serrations (Figs. 2.49, 2.50 and 2.51).

Three new theropod teeth were discovered on Juji Island (Hasandong Formation), Daedori, Hadong County (Lee 2007). The crown height of one tooth is 81 mm, which is the largest theropod tooth ever found in Korea. The teeth are very similar to *Acrocanthosaurus* (Lee 2007). A tyrannosauroid premaxillary tooth was also described at the Hasandong Formation of the coastal area of Naeguri, Sacheon County (Lee 2008). Dinosaur teeth reported from the Cretaceous in Korea strongly indicate that a variety of theropod and sauropod dinosaurs, including tyrannosauroids, lived in the Korean Peninsula during the Cretaceous Period.

Interestingly, diverse theropod tooth marks were described on the caudal vertebra of an adult sauropod bone (*Pukyongosaurus*) from the Early Cretaceous (Paik et al. 2011). There, tooth marks provided new insight into the feeding behavior of theropods that scavenged the bodies of large sauropods.

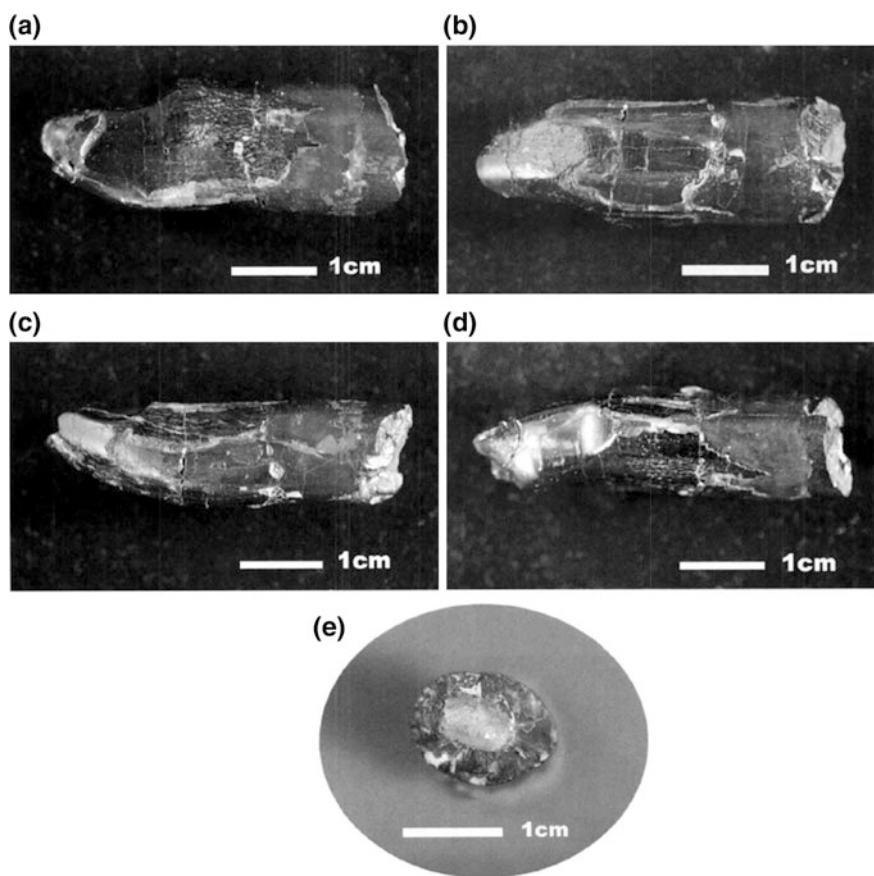


Fig. 2.49 Sauropod (Brachiosauridae) teeth, KS7002 from the Jinju Formation, Sacheon area. Notes **a** Lingual view, **b** labial view, **c** anterior view, **d** posterior view, **e** elliptical cross section at base. Source Yun et al. (2007)

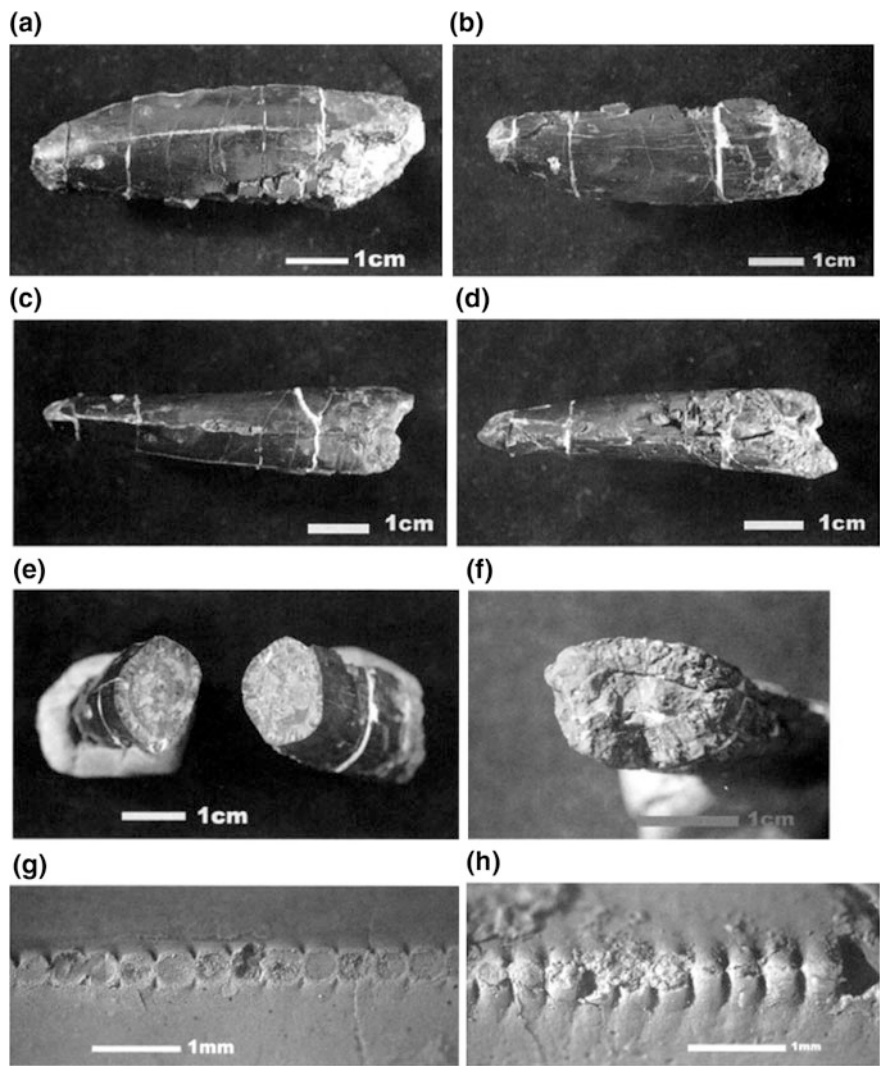
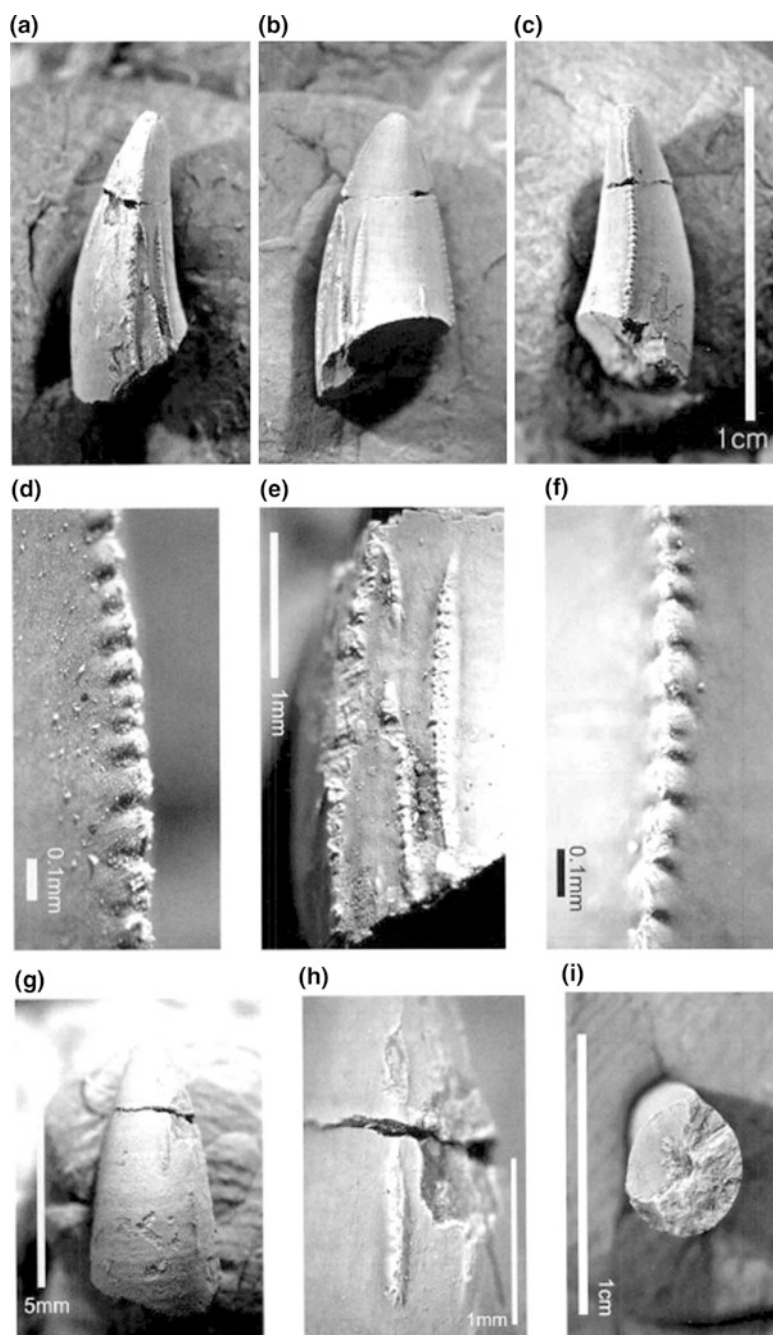


Fig. 2.50 Theropod tooth, Megalosauridae, KS7001 from the Hasandong Formation, Hadong area. *Notes* **a** Labial view; **b** lingual view; **c** anterior view; **d** posterior view; **e** cross section at the middle part of the teeth; **f** eroded cross section at base; **g** anterior view of serrations, crown eroded out; **h** posterior view of serrations. *Source* Yun et al. (2007)

2.4 Dinosaur Eggs

Dinosaur egg fossils were first described at the Lower Cretaceous of the Hasandong Formation at the Sumunri site, Hadong County (Yun and Yang 1997, Fig. 2.52). On the basis of the microstructure of the eggshells, Sumunri dinosaur eggs are



◀**Fig. 2.51** Theropod tooth, Tyrannosauridae, YCS2002 from the Hasandong Formation, Goryeong area. *Notes* **a** Anterior view, **b** lingual view, **c** posterior view, **d** lingual view of serrations, **e** lingual view of multiple serrations, **f** posterior serrations, **g** labial view, **h** serrations on labial surface, about 1 mm, **i** elliptical cross section at base. *Source* Yun et al. (2007)

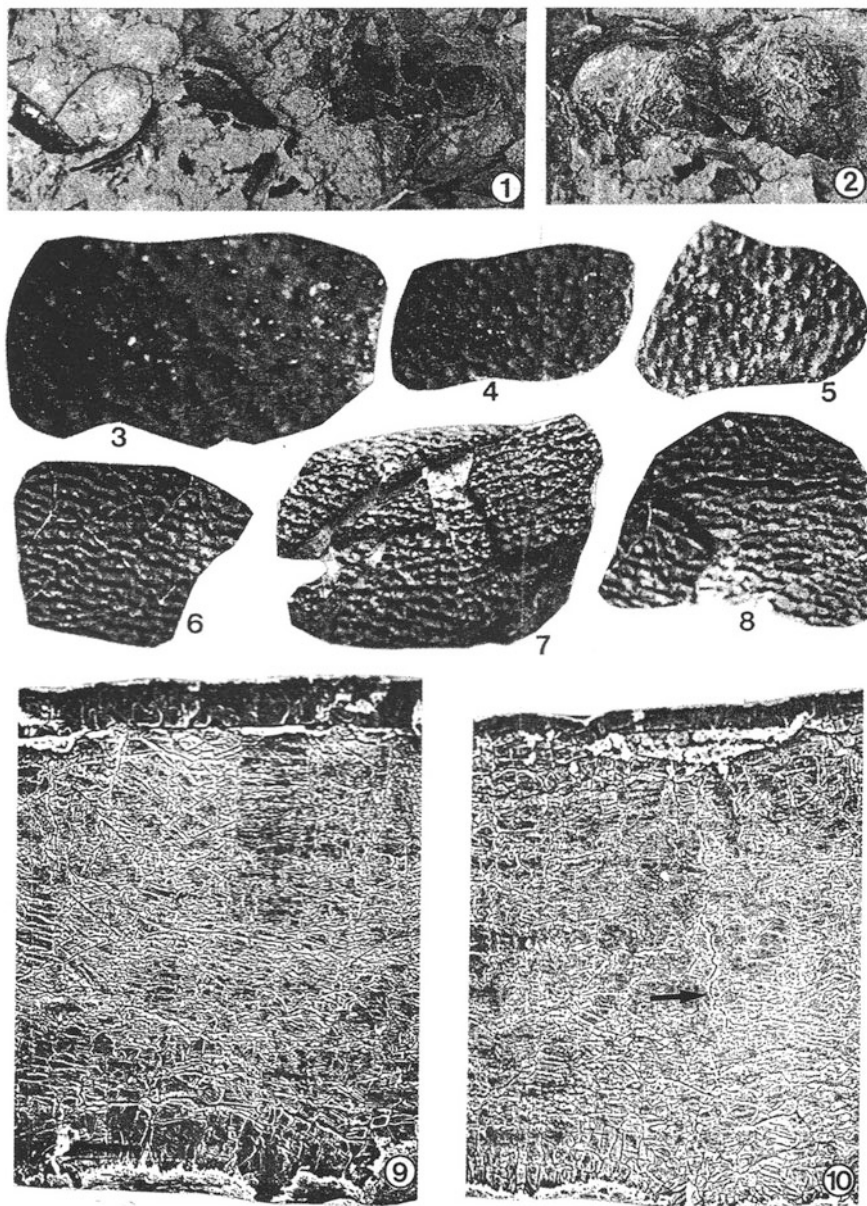


Fig. 2.52 Dinosaur eggshells from the Hasandong Formation, Hadong area. *Notes* (1, 2) outcrop view, 3-8: surface ornamentation, 9-10: microscopic view. *Source* Yun and Yang (1997)

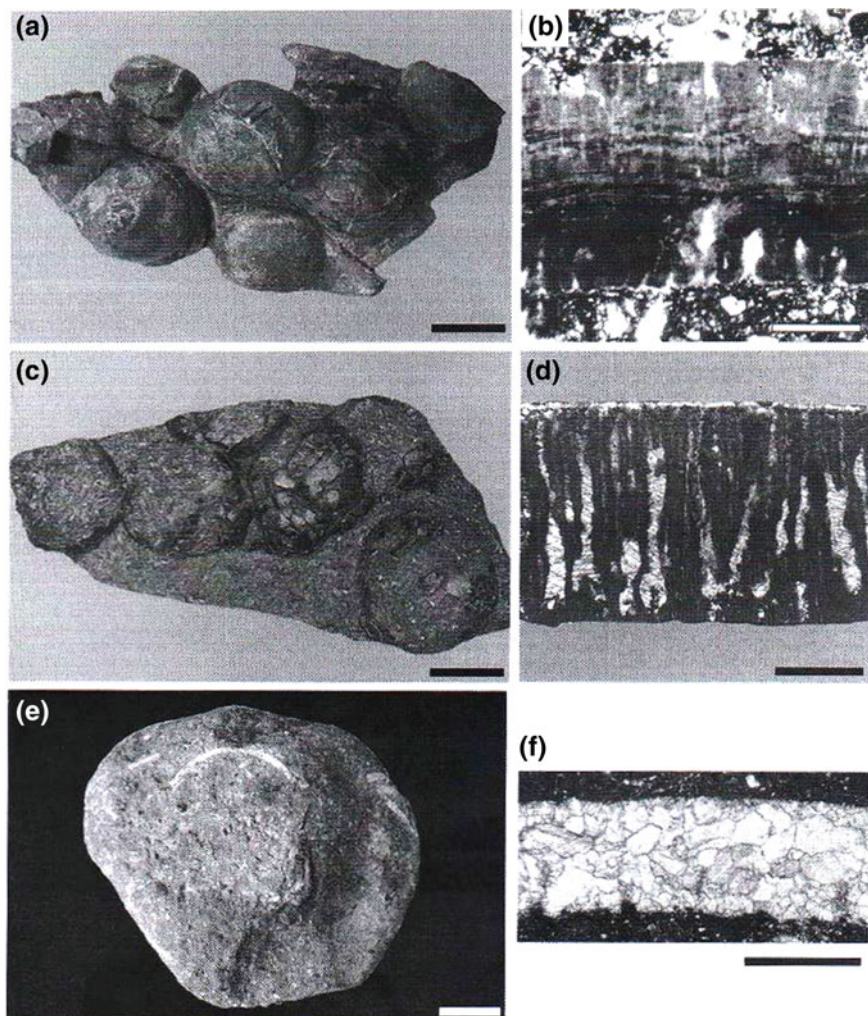


Fig. 2.53 Dinosaur eggs from the Boseong dinosaur egg site. *Notes* **a** Top view of unhatched *Spherooolithus* egg clutch (DRCC-B106) from the Boseong dinosaur egg site; scale bar equals 5 cm. **b** radial thin section of eggshell from **a**; scale bar equals 1 mm. **c** top view of hatched *Faveoololithus* egg clutch (cast, DRCC-B110); scale bar equals 10 cm. **d** radial thin section of eggshell from **c**; scale bar equals 1 mm. **e** partial fossil egg, possibly testudinate; scale bar equals 1 cm. **f** radial thin section of eggshell from **e**; scale bar equals 1 mm. *Source* Huh and Zelenisky (2002)

similar to those described as *Ovaloolithus laminadermus* and *Paraspherooolithus irenensis* from the Cretaceous in China (Yun and Yang 1997). Although the eggshells are poorly preserved, the Sumunri dinosaur eggs represent the first record of dinosaur egg fossils in Korea.

The second occurrence of dinosaur eggs was reported at the Seonso Conglomerate, Boseong site (Huh et al. 1999). Huh and Zelenitsky (2002) first described dinosaur eggshells as *Spheroolithus* sp. and *Faveoololithus* sp. from the Boseong dinosaur egg site (Fig. 2.53). At the Boseong site, a total of 21 dinosaur clutches containing 195 eggs has been discovered (Huh et al. 2006b).

The eggs in both clutches assigned to *Spheroolithus* sp. are well-preserved and several have maintained their spherical shape. One clutch (DRCC-B106) contains four complete and four partial eggs; these eggs appear to be unhatched (Fig. 2.53a). A second clutch consists of six to eight eggs with their upper portions eroded. The eggs are tightly grouped in both clutches and occur randomly in a single layer. A vertical separation of 10–30 mm is visible among adjacent eggs in DRCC-B106.

Well-preserved eggs range from 75 to 84 mm ($N = 5$) in diameter. The eggshell has a smooth outer surface and ranges in thickness from 1.83 to 2.52 mm ($N = 25$). Examination of five thin sections indicates that the shell units are columnar to fan-shaped and tightly abutting (Fig. 2.53b). The units display a sweeping extinction pattern typical of the spherulitic morphotype. These eggs are similar in form and structure to spheroolithids described in Mongolia (Mikhailov 1994) and China (Zhao and Jiang 1974).

Faveoololithus sp. is a partial clutch (DRCC-B110) collected from a block detached from a cliff face. This clutch contains six compressed eggs, three of which are complete and three of which are partial (Fig. 2.53c). Eggs within the clutch occur randomly in a single layer. The central portions of the upper halves of the eggs are missing, indicating that the eggs hatched prior to burial.

The clutched eggs range from 150 to 200 mm in diameter. The eggshell has a smooth outer surface and ranges in thickness from 1.33 to 2.10 mm ($N = 22$). Examination of six thin sections indicates that the eggshell is somewhat recrystallized. In some thin sections, individual shell units are visible and contain pore canals (Fig. 2.53d). Pore canals are numerous, branching, and filled with secondary calcite. The porosity of the eggshell is high (25–30%), which is indicative of underground incubation. This porosity, however, may have been augmented somewhat by diagenesis. The egg morphology and eggshell structure are similar to those of *Faveoololithid* eggs in China (Zhao and Ding 1976) and Mongolia (Mikhailov 1994). The *Faveoololithid* eggs in Mongolia have been attributed to sauropod dinosaurs on the basis of their stratigraphic association with sauropod skeletal remains (Mikhailov 1994).

The third dinosaur egg site was discovered in the Sihwa area of Hwaseong County (Lee et al. 2000a, Fig. 2.54). Dinosaur eggshells were assigned to *Faveoololithids*, *Dendroolithids*, and *Elongatoolithids* (Lee et al. 2000a; Lee 2004). At the Sihwa egg site, more than 20 clutches and 140 dinosaur eggs were found (Lee 2004).

A new dinosaur egg site was discovered in Tongyeong City, where at least six clutches including over 55 dinosaur eggs were found at the Upper Cretaceous Goseong Formation (Kim et al. 2011). Dinosaur eggs from the Tongyeong site were



Fig. 2.54 Dinosaur eggshells from the Cretaceous Tando Formation at the Sihwa dinosaur egg site, Hwaseong area

first described as a new species, *Macroelongatoolithus goseongensis* and *Dictyoolithus neixiangensis* (Kim et al. 2011). The eggshells of *M. goseongensis* are large (39 cm in length) and elongated. The elongation index is 3.4 and the shell thickness is 2.3–3.1 mm. The continuous layer to mammillary layer ratio ranges up to 4.8:1 (Fig. 2.55). *M. goseongensis* differs from previously known oospecies of *Macroelongatoolithus*, *M. xixiaensis* and *M. zhang*i in China and *M. carlylei* in Utah in microscopic features (Kim et al. 2011). The occurrence of *M. goseongensis* suggests an oviraptorosaur or oviraptorosaur-like theropod, a possible maker of *M. goseongensis*, who lived in the Gyeongsang Basin during the Cretaceous Period.

D. neixiangensis is a spherical egg with a diameter of about 120 mm and a shell thickness of 1.5–1.7 mm. The outer surface of the egg is smooth with a grainy texture. It is characterized by the basic microstructure of an eggshell which displays irregular reticulate composed of two or three superimposed eggshell units

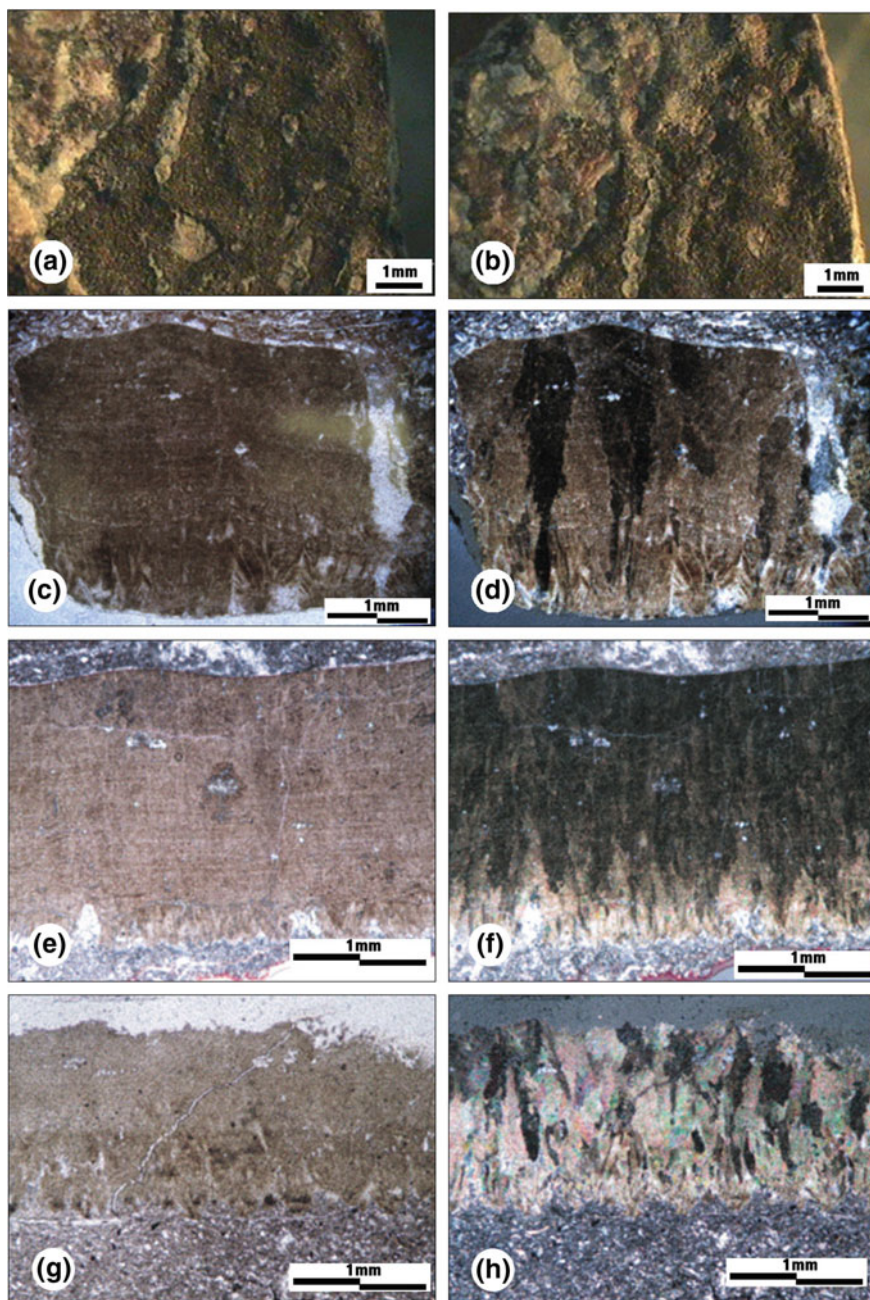


Fig. 2.55 Microscopic features of giant theropod dinosaur eggs from the Goseong Formation, Tongyeong area. *Notes* **a, b** Outer surface of shell, **c–h** thin section view, **c, e, g** open nicol, **d, f, h** cross nicol. *Source* Kim et al. (2011)

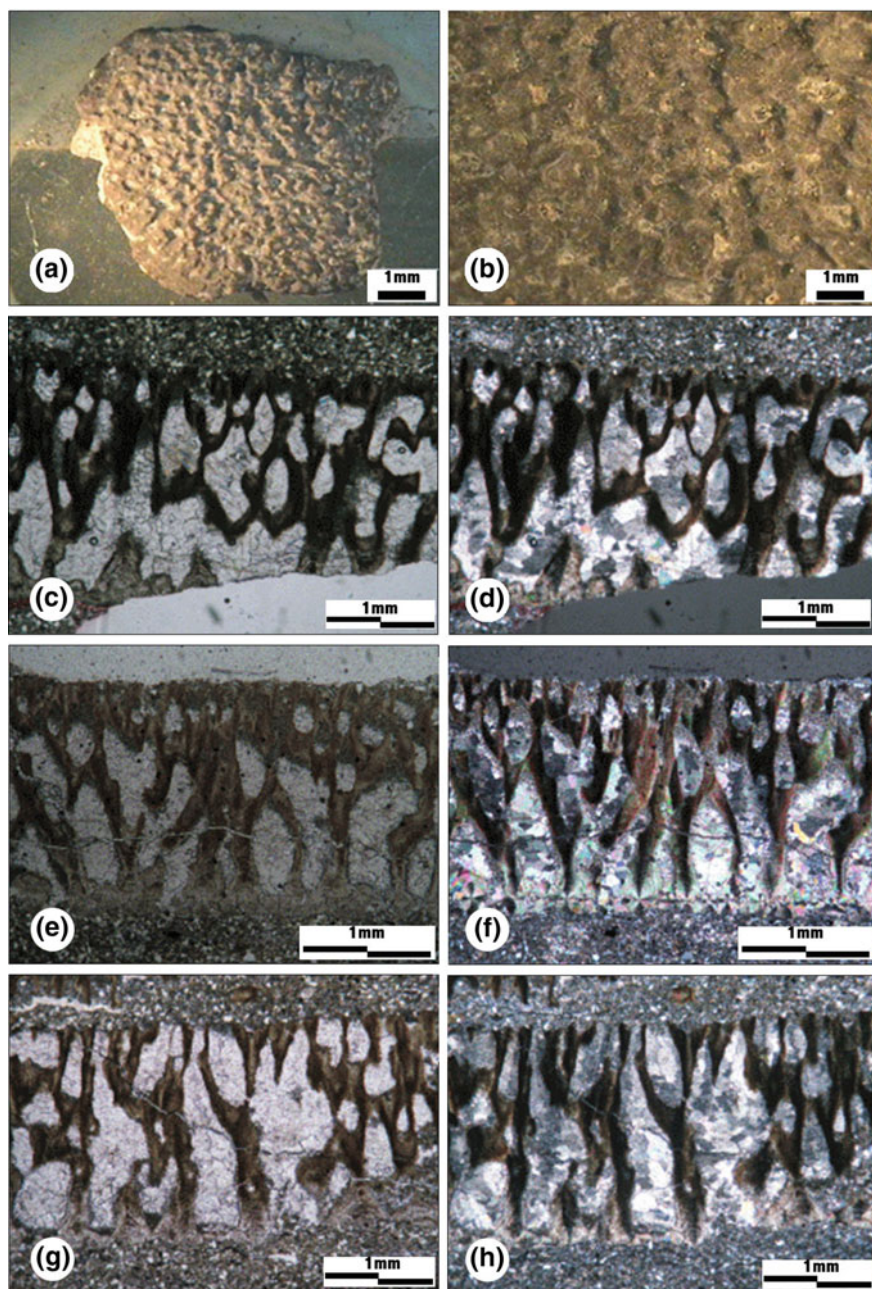


Fig. 2.56 Microscopic features of sauropod dinosaur eggs from the Goseong Formation, Tongyeong area. *Notes* **a, b** Outer surface of shell; **c–h** thin section view; **c, e, g** open nicol; **d, f, h** cross nicol. *Source* Kim et al. (2011)

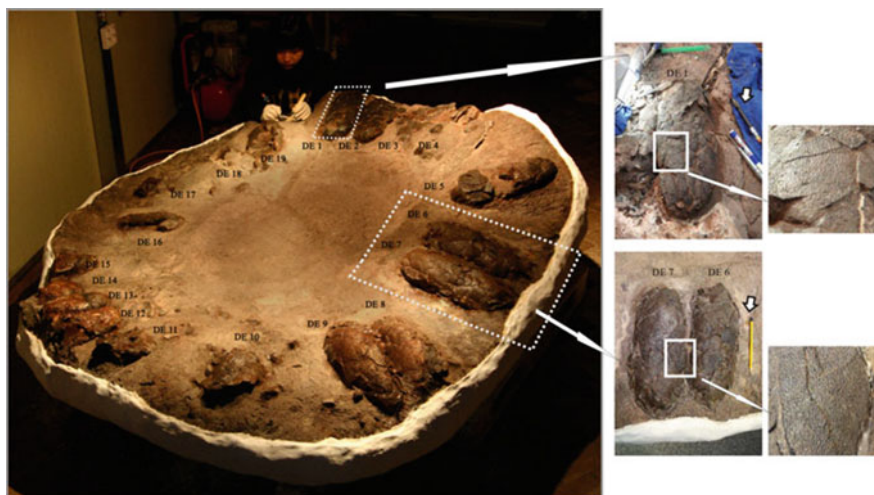


Fig. 2.57 Aphae-do *Macroelongatoolithus xixiaensis* clutch, MNHN-nat201153. *Notes* Sets of well-preserved eggs indicating typical elongatoolithid ornamentation grading from ramotuberculate to lineartuberculate. *Source* Huh et al. (2014)

(Kim et al. 2011, Fig. 2.56). The occurrence of *D. neixiangensis* at the Upper Cretaceous Goseong Formation represents the first record of *Dictyoolithus* outside its typical location, Henan, China. It also provides evidence for widening the stratigraphic range from the Early Cretaceous Period to the Late Cretaceous Period, and its paleogeographic distribution from southeast China to Korea (Kim et al. 2011).

Recently, a complete giant theropod egg clutch was reported at the Upper Cretaceous of Aphaedo Island, Shinan County, southwest of Korea (Huh et al. 2014). The clutch of 19 dinosaur eggs is characterized by large, elongated, symmetrical eggs arranged in a single-layered ring-shaped clutch (Fig. 2.57). The eggs are inclined towards the center of the clutch which is 23 m in diameter, and an average of 41.2 cm long and 15.6 cm wide. The giant theropod eggshells were assigned to *Macroelongatoolithus xixiaensis* (Huh et al. 2014).

2.5 Dinosaur Skin Impressions and Tail Traces

Only fossilized skin impressions can provide tangible evidence to show what dinosaur integument and skin texture looked like in life (Horner 1984; Czerkas 1994). Although the first discovery of dinosaur skin impressions was made by Beckles in 1852, skin impressions of dinosaurs are rarely reported and have mostly been reported since the late 1990s. To date, no useful synthesis of the scattered

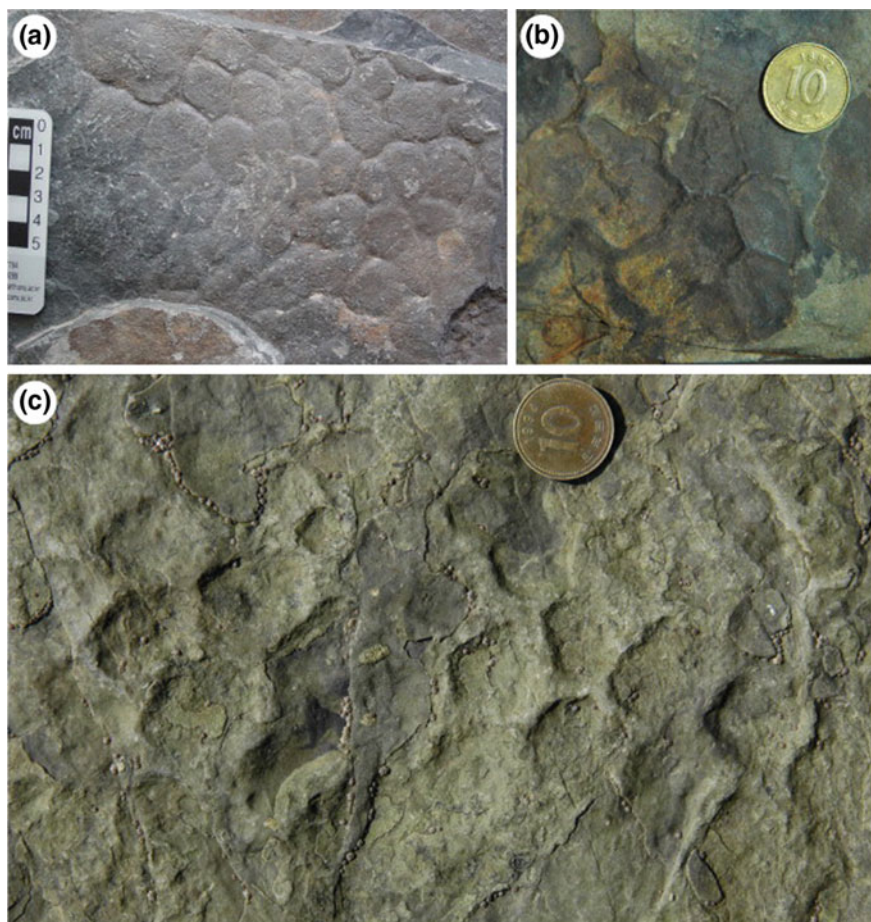


Fig. 2.58 Skin impressions of dinosaurs from the Jindong and Haman formations. *Notes* **a** Jindong Formation, Dukmyeongri area; **b** Haman Formation, Gainri area; **c** Haman Formation, Sinsu Island. Coins in **b** and **c** are approximately 22.9 mm in diameter. *Source* Kim et al. (2010)

reports and specimens of dinosaur skin impressions is yet available (Kim et al. 2010).

Kim et al. (2010) first described dinosaur skin impressions at the Cretaceous Jindong and Haman formations in the Goseong and Namhae areas. Two specimens from the Haman Formation at Gainri and Sinsu Island reveal large polygonal to heptagonal scale impressions (2.0–2.5 cm). Another specimen from the Jindong Formation at Dukmyeongri, Goseong area, is an extremely well-preserved, honeycomb-like pattern of hexagonal scale impressions (Fig. 2.58). Kim et al. (2010) also provided criteria useful for distinguishing dinosaur skin impressions from the similar-shaped invertebrate trace fossils, such as glypogryptids, and

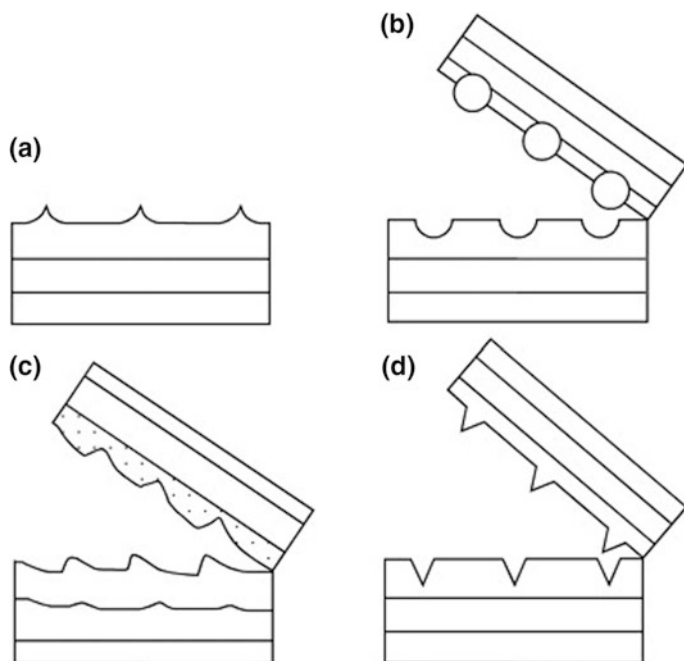


Fig. 2.59 Schematic diagram for comparison of skin impressions (a), glyptogryptids (b), load casts (c), and desiccation cracks (d). *Source* Kim et al. (2010)

inorganic sedimentary structures, such as load casts and desiccation cracks (Fig. 2.59).

In the same year, two specimens of dinosaur skin impressions were described from the Haman Formation, Sacheon area (Paik et al. 2010). The state of preservation of the Haman skin fossils suggests that sheet flood deposits on a floodplain to mudflat environment under only climatic conditions are potential candidates for dinosaur skin impressions to be found (Paik et al. 2010, Fig. 2.60).

Most dinosaurs seem to have walked with the tail lifted well clear of the ground; therefore, traces of a dragged tail are relatively uncommon (Bakker 1971, 1975; Thulborn 1990; Lockley 1991). Although more than 150 years have passed since Hitchcock first reported dinosaur tail traces from the Jurassic in Massachusetts (Hitchcock 1858) and subsequent discussion of the tail-dragging concept in relation to sauropods by Bird (1941, 1944), Bakker (1971), and others, dinosaur tail traces have rarely been reported (Irby and Albright 2002), and they are poorly understood (Platt and Hasiotis 2008), as are their functions. Tails of some dinosaurs, such as *Ankylosaurus* and *Euoplocephalus*, may have served as powerful weapons (Thulborn 1993). In other cases, dynamic stabilizing (Gauthier 1986) and counterbalancing (Ostrom 1969; Dixon 1989; Clark and Lindsay 2003; Norman 2005) functions have been proposed, especially for many dinosaurs with long necks and tails, and those with robust tail ligaments. Kim and Lockley (2013) reviewed 38

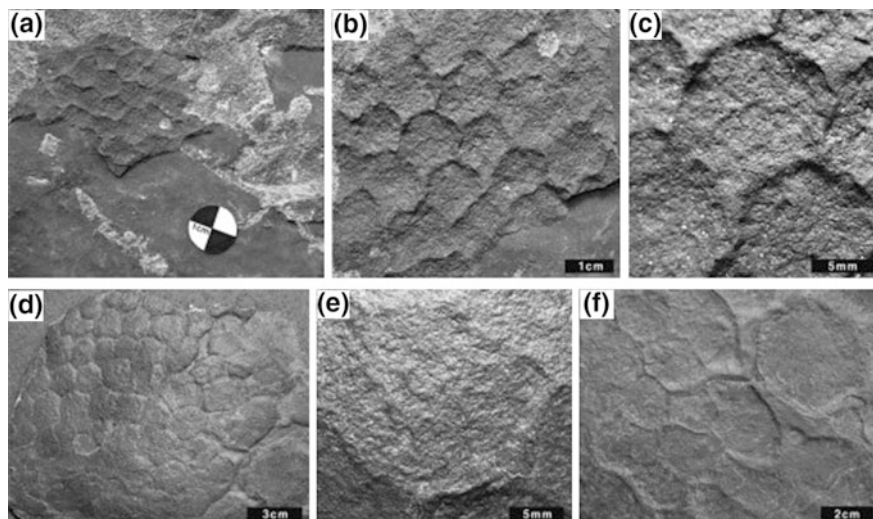


Fig. 2.60 Dinosaur skin fossils from the Cretaceous floodplain (a–c) and lake margin (d–e) deposits. *Notes* **a** Skin impression on sandy mudstone with interlocking polygons (mostly hexagonal) in a honeycomb-like pattern. Invertebrate traces are associated; **b** closer view of (a). Diamond-shaped micropolygons are observed within the hexagonal polygons; **c** closer view of (b); **d** skin impression in positive relief on mudstone with interlocking hexagonal polygons; **e** closer view of (d). Micropolygonal texture is also observed within the polygons; **f** counterpart of (d). *Source* Paik et al. (2010)

previously reported records of dinosaur tail traces associated with tracks, to assess their geographic, stratigraphic, and taxonomic significance.

Recently, a theropod trackway with tail traces was described for the first time at the Lower Cretaceous Saniri Formation, Yeongdong area, central Korea (Kim et al. 2016). Theropod tracks are composed of three tapered pes digit impressions with narrow interdigital angles between digits II and IV (45°). The length and width of tracks are 22.8 and 15.5 cm, respectively. Theropod tracks are characteristically associated with a nearly continuous tail track, which is up to 360 cm in length, 4.5–6 cm in width, and a broad “U” shape in cross section (Kim et al. 2016, Fig. 2.61). The Yeongdong theropod tail traces represent the second instance of theropod tail traces from the Cretaceous Period to be found anywhere in the world (Kim and Lockley, 2013; Kim et al. 2016).

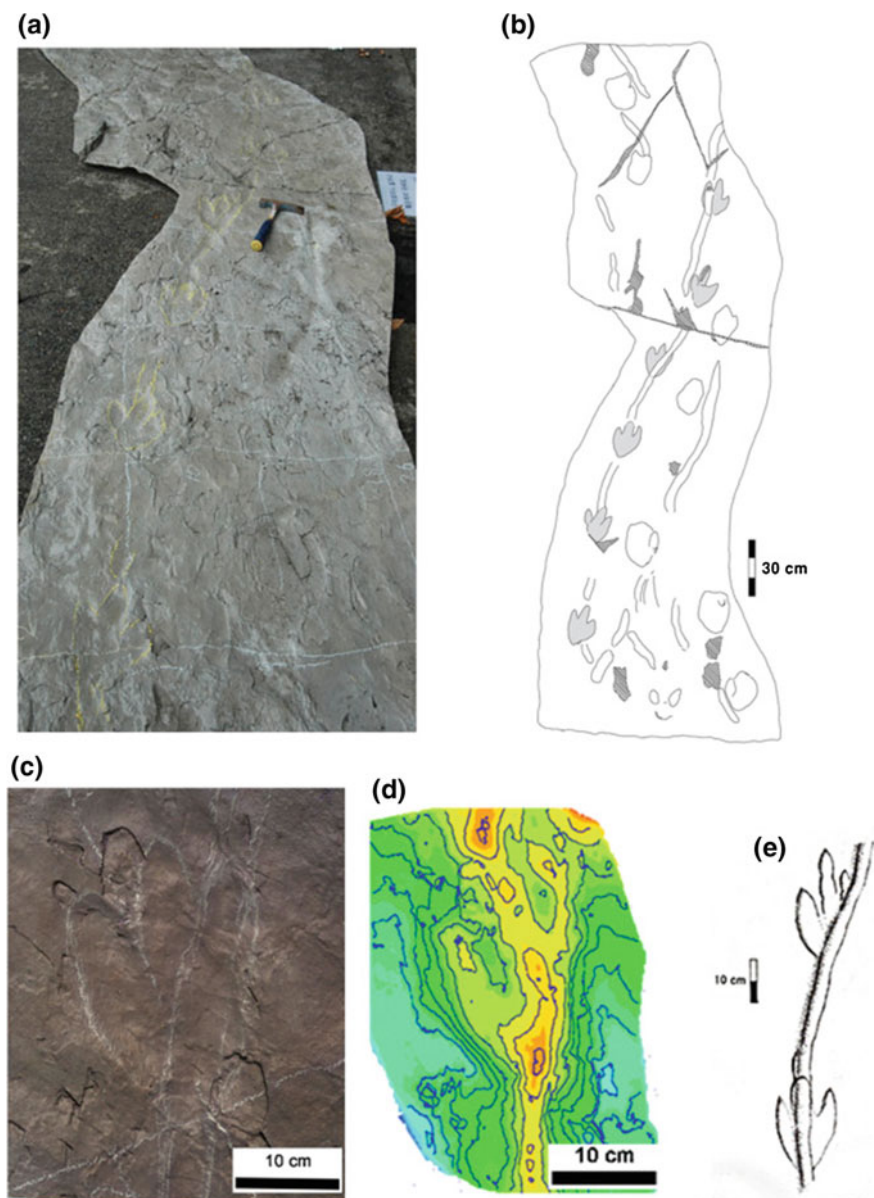


Fig. 2.61 Theropod trackway with tail traces from the Lower Cretaceous Period, Yeongdong area. *Notes* Photograph (a) and sketch (b) of trackway. 3D mesh image (c) and 3D color contour map (d) of right second (R2) track. Sketch of two consequent tracks (R2 and L2) crossed by continuous tail drag impression (e). *Source* Kim et al. (2016)

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