

A new dinosaur tracksite from the Lower Cretaceous Sanbukdong Formation of Gunsan City, South Korea

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ABSTRACT

South Korea has become globally famous for various tetrapod footprints from Upper Cretaceous strata. Here we report the first Early Cretaceous “large” tracksite from the Sanbukdong Formation of an unnamed small basin in the west of Gunsan City, North Jeolla Province. The tracksite (720 m²) produced 425 tracks. Among them, eleven ornithopod and three theropod trackways (189 tracks) were measured and mapped in detail. Most of ornithopod tracks are large (32 cm–51 cm in length) and very similar to pes imprints of *Caririchnium lotus* from China in that the general track dimensions and large heel pad impressions are typically longer than wide. They are attributable to basal hadrosauroids based on their stratigraphic and palaeogeographic occurrence as well as skeletal evidence in Korea. Eleven ornithopod trackways show gregarious behaviour and two main directions of movements along a lake margin. One movement is that of a group that went back and forth along the lacustrine margin and the other movement showing dinosaurs that came to the lakeshore probably to drink water or any other purposes. One trackway consists of 39 consecutive tracks with the distance of 39 m, representing the longest Early Cretaceous ornithopod trackway ever found in Korea. Sanbukdong ornithopod tracks suggest that basal hadrosauroids had the same growth pattern as derived hadrosauroids such as a brief period where it was very rapid. They also support independently that the majority of Early Cretaceous basal hadrosauroids were smaller than Late Cretaceous hadrosauroids in body size. Two theropod trackways consist of large tracks (more than 40 cm in length) and closely resemble *Irenesauripus glenrosensis* from the Lower Cretaceous of Texas which was inferred to be of *Acrocantosaurius* origin. It is reasonable that they are attributable to carcharodontosaurids because their skeletal materials were already reported from the Lower Cretaceous strata in China and Korea. This new tracksite indicates that large ornithopod and theropod dinosaurs lived in the Early Cretaceous in Korea and strengthens previous hypotheses of their existence based on only isolated teeth.

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1. Introduction

South Korea is famous for Cretaceous tetrapod ichnocoenoses (Lockley et al., 2012). The Upper Cretaceous Jindong Formation of the Gyeongsang Basin, in particular, is known as the most prolific dinosaur track-producing formation in the world (Lee et al., 2000; Lockley et al., 2006). Within this basin, several formations of the

Sindong and Hayang groups have produced various vertebrate footprints such as turtles, lizards, pterosaurs, dinosaurs, birds, and mammals (Huh et al., 2003; Kim et al., 2006; Kim and Lockley, 2016; Kim et al., 2012b; Kim et al., 2017a,b; Lee et al., 2008; Lee et al., 2018). Besides the largest Gyeongsang Basin, there are over ten small Cretaceous subordinate basins in South Korea of which some basins produced dinosaur tracks (Lee et al., 2001; Huh et al., 2003). Among them, the most well-known sites are in the Uhangri Formation of the Haenam Basin (Uhangri site), the Jangdong Tuff of Neungju Basin (Hwasun site), and an unnamed formation of an unnamed basin (Yeosu site) of South Jeolla Province. The Uhangri Formation produced pterosaur, dinosaur, and bird footprints (Hwang et al., 2002; Lee and Huh, 2002; Kim et al., 2003). The

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Hwasun site is characterized by theropod trackways (Huh et al., 2006). The Yeosu site is known as the youngest dinosaur tracksite (81–65 Ma) in South Korea (Paik et al., 2006). These subordinate basins are the Upper Cretaceous and correlated to the youngest Yucheon Group of the Gyeongsang Supergroup stratigraphically (Paik et al., 2012). Along with these Upper Cretaceous basins, some dinosaur tracks were also found in the Lower Cretaceous Yeongdong Basin (Kim et al., 2016) and Tando Basin.

A new dinosaur tracksite was discovered by geological mappers of KIGAM (Korea Institute of Geoscience and Mineral Resources) at a construction site for building a new road nearby the Gunsan National Industrial Complex area, Gunsan City, North Jeolla Province in July, 2013 (Fig. 1, Choi and Hwang, 2013). After removing the overlying strata of track-bearing horizons, the Cultural Heritage Administration of Korean government designated this tracksite (720 m²) as the National Monument 548 in June, 2014. During excavation, some blocks near the road cut containing footprints were moved to a local museum in Gunsan City. This tracksite occurs in the Lower Cretaceous Sanbukdong Formation.

The discovery of this new dinosaur tracksite is somewhat unexpected because it was not only found in a small patch of outcrop surrounded by the large industrial complex of urban area and rice fields but it also shows a high density of tracks in a small exposed outcrop. From this site, eleven ornithopod trackways were mapped

to show gregarious behaviour and one of them consists of 39 consecutive tracks with the distance of 39 m. It is the longest Early Cretaceous ornithopod trackway ever found in Korea so far. In addition, large theropod tracks (over 46 cm in length) indicate that the large theropods lived in the Early Cretaceous in the Korean peninsula. Therefore, the purpose of this study is to report the largest Early Cretaceous dinosaur tracksite in South Korea and to investigate the palaeontological and palaeogeographical implications of possible trackmakers.

2. Geological setting

The western part of Gunsan City consists of Precambrian metamorphic rocks in the east, Jurassic and Cretaceous deposits in the center, and Jurassic granites in the west (Fig. 1). The Jurassic granites are unconformably overlain by the Cretaceous Nansan and Sanbukdong formations successively. They contact with unnamed Jurassic strata eastwards by a reverse fault. The outcrop of the Nansan and Sanbukdong formations is very limited due to the development of the Gunsan National Industrial Complex and rice fields.

The Nansan Formation consists mainly of reddish conglomerate, conglomeratic sandstone, and sandstone while the Sanbukdong Formation comprises predominantly dark grey mudstone and

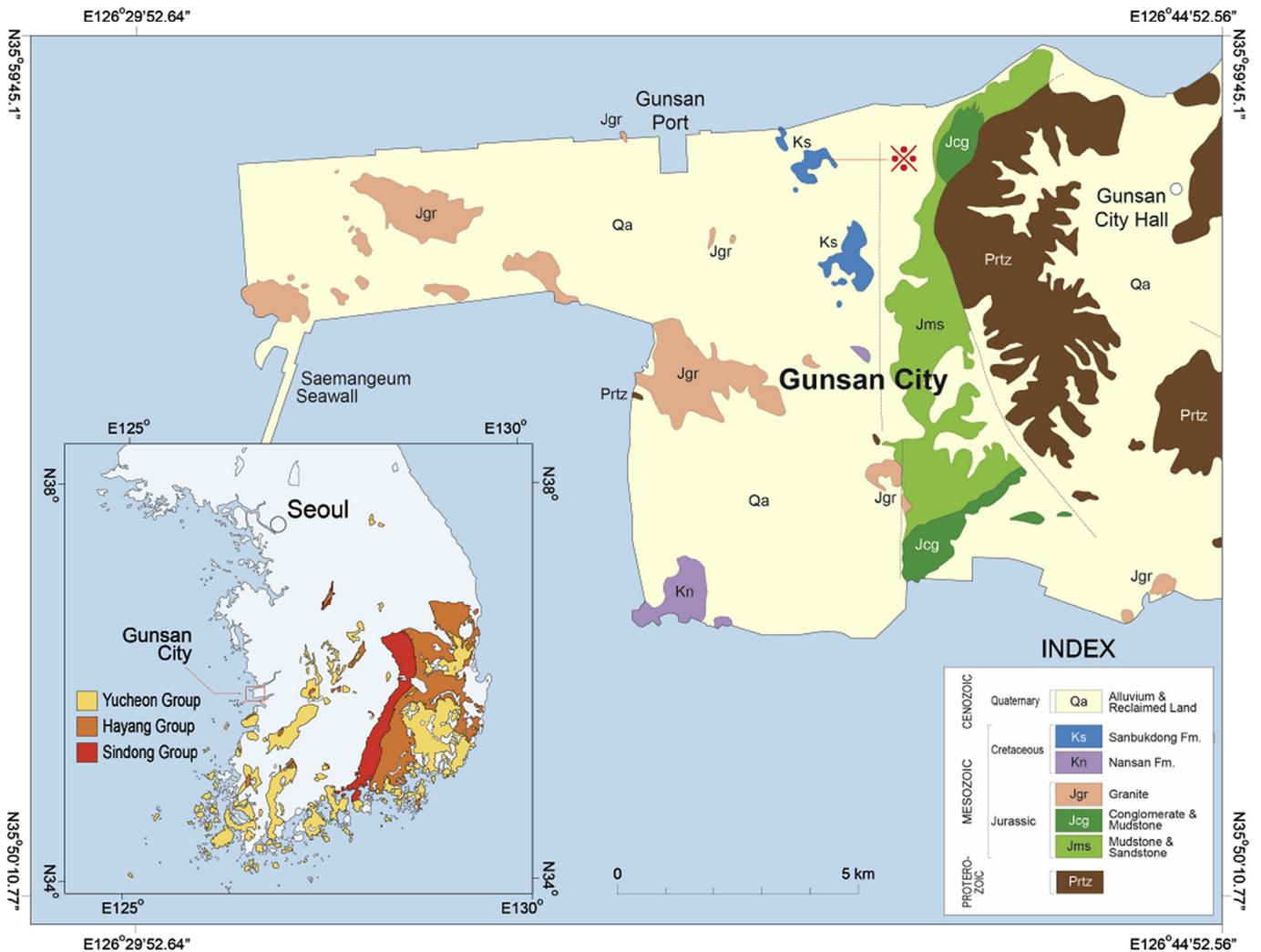


Fig. 1. Geological map of Gunsan City in the vicinity of Gunsan dinosaur tracksite, showing the Cretaceous basins including the Gyeongsang Supergroup.

siltstone locally interbedded with reddish and light grey sandstone. The Sanbukdong Formation contains various fossils and sedimentary structures such as lamination, ripple marks, rain drops, and mud cracks. Fossils are plants (*Pseudofrenelopsis* sp., cf. *P. parceramosa*, *Cupressinocladus* sp.), conchostracan *Esherites*, and dinosaur footprints. All plant fossils indicate that the Sanbukdong Formation is Early Cretaceous in age (Sun et al., 2011; Kim et al., 2012a).

The tracksite occurs in an isolated outcrop (16 m × 45 m) surrounded by rice fields and farmhouses of which the sedimentary strata dip towards the northeast at an angle of 20° (Fig. 2A). A total of 425 tracks including 14 trackways have been mapped in the three different horizons of this outcrop (Fig. 3). The number of tracks was likely much greater because most of trackways end at the edge of the outcrop. Five layers are exposed in this outcrop which were named A, B, C, D, and E consecutively from the top layer to the lower ones. The surface of B layer is the most widely exposed in the tracksite while the rest of layers are limited to the northwest and southeast corners. The dinosaur tracks were found on the surface of B, C, and E layers. The A layer (10 cm thick) partially exposed in the northwest area occurs as an alternation of dark grey mudstone and light grey siltstone at the millimeter scale but shows poor fissility. Mud cracks are observable on the surface. This layer was mostly removed to expose a track-bearing horizon of the underlying B layer. The B layer comprises 3 cm thick light grey silty mudstone, containing the main track-bearing horizon of this site. However, this silty mudstone is severely breaking with conchoidal fracture from the surface. Consequently, tracks themselves are being damaged by weathering. The vertical section of the C layer (10 cm thick) shows the flaser bedding in the lower part while in the upper part, siltstone grades upward to mudstone. The mud surface of C layer is less fractured with better preservation of tracks

than those of A and B layers. Besides dinosaur tracks, mud cracks and a few burrows are observed on the surface of the mudstone without any features of palaeosols. The D layer has a small exposure without tracks. The E layer consists mainly of silty mudstone that is covered with very thin mud lamination (2 mm thick). The dinosaur tracks are very shallowly impressed on the surface of this mudstone not enough to identify footprint morphologies. It implies that the tracks of E layer were generated in more dried condition than B and C layers.

The columnar section of this tracksite shows the alternation of thin sandstone layers containing ripple marks and mudstone layers containing mud cracks in general (Fig. 2B). Along with sedimentary structures mentioned above, the flaser bedding of C layer indicates that the tracksite was near the lake margin where the water level was frequently being changed. The association of tracks and mud cracks in the thin film of mudstone indicates that the lake margin was also exposed to the subaerial condition after the tracks was made. This site had probably repeated a depositional sequence seasonally to make multiple layers of tracks as follows: the water level went down to expose the mud surface after the mud had been deposited on each layer. And then, dinosaurs passed by partially dried mud flat and left their footprints. The track-bearing surface was sometimes getting more dried to form mud cracks after footprint generation (e.g., C layer) because mud cracks are nicely preserved inside tracks without distortion.

3. Description

The surface of B layer occupies over 80% of all exposed horizons and contains the largest number of footprints. A total of 387 footprints were mapped but only 183 tracks of 12 trackways were



Fig. 2. General view of Gunsan dinosaur tracksite. (A) Aerial view. (B) Vertical section of the tracksite on the right side. (C) Geological section of Figure B indicating the dinosaur track-bearing levels.

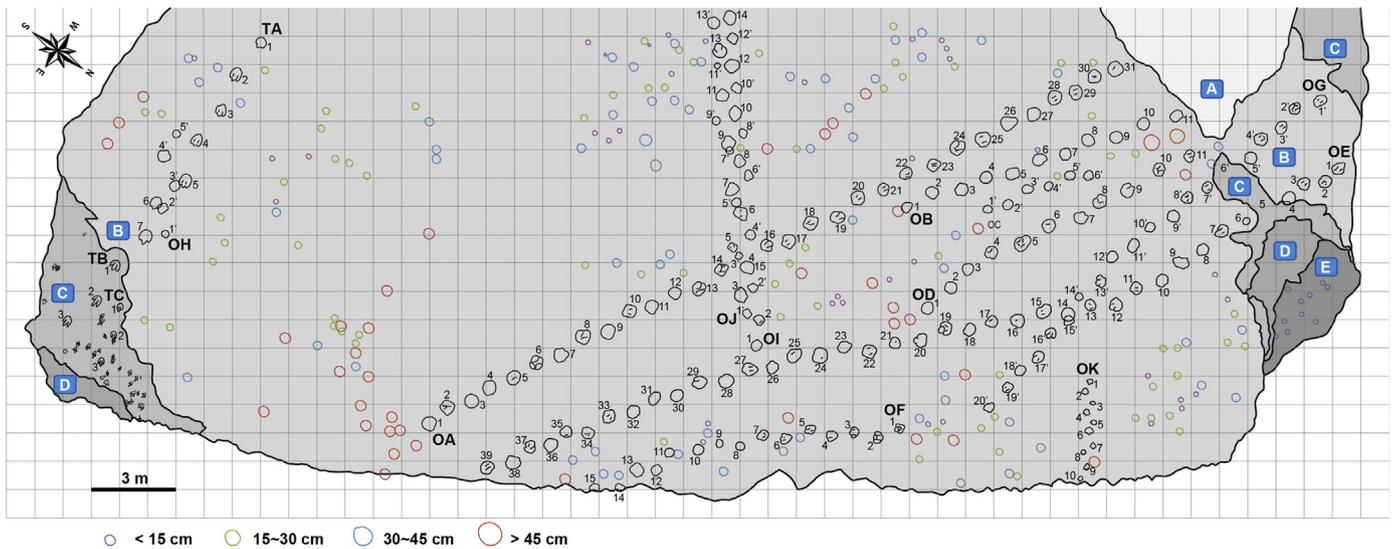


Fig. 3. Schematic map of Gusan dinosaur tracksite. A–E = exposed surface areas of different layers.

measured in detail. The rest of the tracks are not only well-preserved but it is also difficult to reveal the general trackway pattern. They appear to be round depressions with various sizes, that are probably underprints. According to sizes, there are divided into four groups: 33 tracks less than 15 cm, 70 tracks between 16 cm and 30 cm, 61 tracks between 31 cm and 45 cm, and 40 tracks over 45 cm in diameter (Fig. 3). Most of the trackways belong to ornithopod footprints except for one theropod trackway. Among 11 ornithopod trackways, the smallest footprints are average 20.47 cm in length of Trackway OK and the largest ones are average 50.99 cm in length of Trackway OA. The average footprint length of a theropod trackway (Trackway TA) is 48.13 cm which was made by a large theropod. The surface of C layer is more exposed in the southeast corner of the tracksite than in the northwest one (Fig. 3). This mudstone surface contains two theropod trackways and shallowly impressed 26 isolated theropod tracks which are less than 20 cm in length. The average footprint lengths are 41.56 cm and 30.90 cm in Trackway TB and TC, respectively. Ten isolated small depressions (less than 15 cm in diameter) are observed on the surface of E layer, but it is difficult to identify the footprint morphologies and trackways. Therefore, the description of footprints confines to ornithopod and theropod trackways in the B and C layers.

3.1. Ornithopod footprints

Most of the ornithopod tracks do not show detailed morphologies of footprints due to the surface of track-bearing horizon is being damaged both naturally and artificially. Nevertheless, there are no manus prints in all of the trackways. Pes prints are tridactyl and mesaxonic, which appear to be similar in craniocaudal and mediolateral dimensions showing wide digits with rounded ends (Fig. 4A and B). There are no distinct claw marks. The digit III imprint is 1.21 times longer than digit II and IV imprints. The heel pad impressions are large and oval in shape that are longer than wide. All tracks show a negative (inward) rotation. These features confirm that 11 trackways on the B layer belong to ornithopod tracks (Moreno et al., 2012). The lengths of digits II and IV are known to be nearly equal in ornithopod tracks which is generally concordant with the footprint measurements obtained from 11 trackways (Table 1, Supplementary Table 1). However, relative lengths of digits II and IV show some variation depending on the

depths of prints. For example, the digit II is more deeply impressed than the digit IV in some footprints (OG16, OE19) so that digit II impressions are longer than digit IV impressions in lengths as shown by photogrammetric images. The lengths of Sanbukdong ornithopod tracks are greater than their widths (the ratio is 1.18) as seen in *Caririchnium magnificum* (Leonardi, 1984) and *Caririchnium lotus* (Xing et al., 2007). The footprints being longer than wide is used as an ichnotaxonomical character in ornithopod tracks (Díaz-Martínez et al., 2015).

Sanbukdong ornithopod tracks can be attributed to the ichnogenus *Caririchnium* based on rounded large heel impression and short, wide digit impressions (Díaz-Martínez et al., 2015). Especially, they are very similar to pes prints of *Caririchnium lotus* reported from the Jiaguan Formation (Barremian–Albian), China in that large heel pad impressions are longer than wide (Xing et al., 2007). However, *Caririchnium lotus* has rectangular manus tracks which are not shown in Sanbukdong ornithopod tracks.

Trackway OA consists of 31 consecutive tracks (Fig. 5). The average footprint length is 50.99 cm, representing the largest track of this tracksite. The pace angulation ranges from 134° to 167° and the average stride is 184.63 cm. The trackway width is very narrow and the trackway is nearly straight without change of direction. Trackway OB consists of 11 consecutive tracks. The digital impressions are not well-preserved. The trackway is straight without change of direction and speed. Trackway OC consists of 6 consecutive tracks with poorly preserved digital impressions. Trackway OD consists of 11 consecutive tracks but the first three tracks are not well-preserved. Trackway OE consists of 39 consecutive tracks although the fifth track is missing, representing the longest trackway among 11 trackways. The trackway is curved to left in the first quarter but the rest is nearly straight. Both pace angulation and stride length decrease at the last several tracks of the trackway, indicating that the animal slowed the walking speed. Trackway OF consists of 15 consecutive tracks and the trackway width increases suddenly from the tenth track with change of direction to the left. Trackway OG consists of 20 consecutive tracks although the sixth track is missing. It changes the direction slightly to the left from the twelfth track. It is notable that tracks of the trackway OG have a higher ratio of footprint length to width (1.33) than others (1.17) because digit II is sometimes close to the digit III (Fig. 4B). Trackway OH consists of poorly preserved five consecutive tracks. Trackways OI consists of 14 consecutive poorly preserved tracks. Trackway OJ

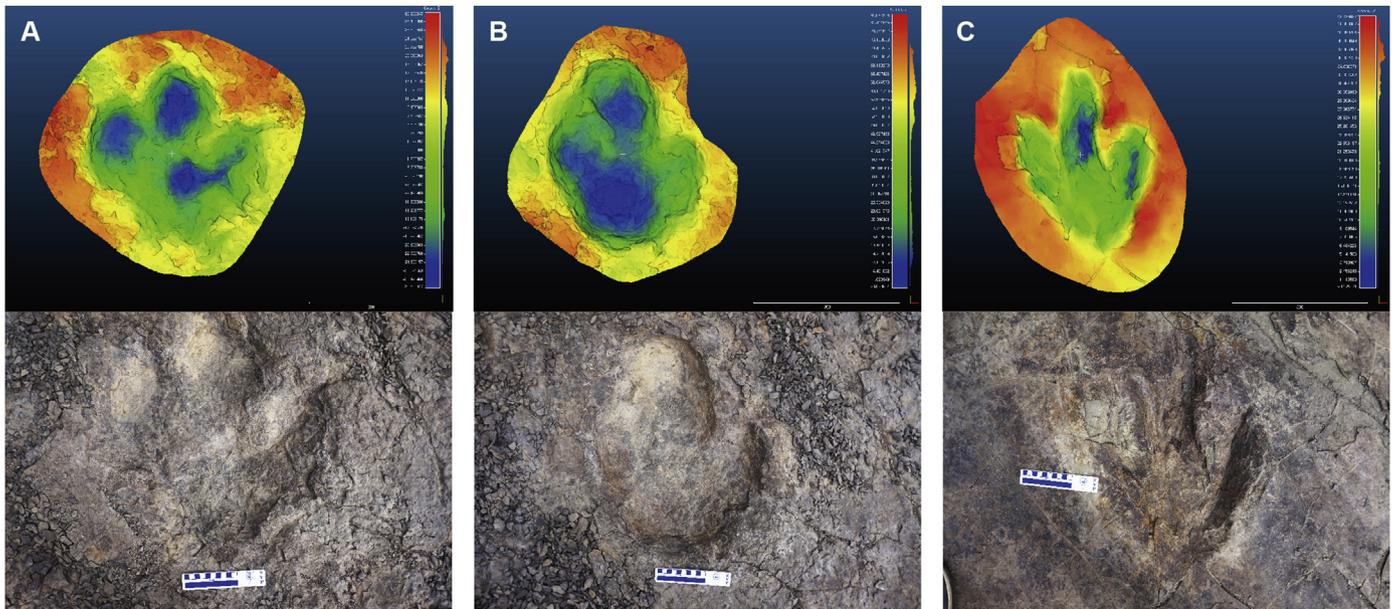


Fig. 4. 3D photogrammetric images (upper row) and real footprints (lower row). (A) The 19th ornithopod footprint of Trackway OE. (B) The 16th ornithopod footprint of Trackway OG. (C) The third theropod footprint of Trackway TB.

Table 1

The average value (in cm) of eleven ornithopod (OA–OK) and three theropod (TA–TC) trackways from the Gusan dinosaur tracksite. Abbreviations: Trackway # = trackway number in Figs. 3 and 5; L = footprint length; W = footprint width; L/W = ratio of footprint length and width; II = digital length of digit II; III = digital length of digit III; IV = digital length of digit IV; D (II–III) = divarication angle between digits II and III; D (III–IV) = divarication angle between digits III and IV; Stride = stride length; Pace = pace length; ANG = pace angulation.

Layer	Trackway #	L	W	L/W	II	III	IV	D(II–III)	D(III–IV)	Stride	Pace	ANG	Azimuth
B	OA	50.99	42.72	1.21	41.37	50.98	42.01	28.45	27.60	184.63	94.75	153.10	301.00
	OB	45.67	41.30	1.12	–	45.67	–	–	–	200.35	99.14	155.89	311.00
	OC	36.67	30.13	1.22	–	36.67	–	–	–	169.21	79.29	146.50	305.00
	OD	47.36	41.38	1.15	39.57	47.37	40.61	28.50	28.14	215.50	109.87	163.44	300.00
	OE	46.39	40.11	1.17	40.56	47.08	39.51	25.29	27.65	171.40	88.06	151.79	129.00
	OF	36.19	31.27	1.19	33.95	36.19	34.59	23.29	23.00	159.32	86.79	136.69	135.00
	OG	42.35	32.39	1.33	38.25	42.35	38.58	23.70	22.20	169.21	87.70	147.93	105.00
	OH	35.85	32.17	1.10	38.16	35.85	38.85	24.00	31.00	180.45	96.94	133.00	244.00
	OI	47.15	41.33	1.15	36.37	47.37	37.77	29.67	27.67	176.65	97.27	132.17	235.00
	OJ	32.80	28.96	1.14	30.19	32.80	31.96	25.25	24.80	176.74	106.74	108.73	233.00
	OK	20.47	16.76	1.24	19.13	20.47	17.96	26.11	26.00	77.06	44.97	116.50	57.00
C	TA	48.13	27.46	1.76	42.55	48.13	43.09	19.00	19.00	266.97	135.82	155.00	92.00
	TB	41.56	28.67	1.46	34.91	41.56	34.73	25.33	21.67	290.79	147.37	151.00	100.00
	TC	30.90	15.82	1.98	23.75	30.90	25.24	18.33	19.00	204.90	104.10	169.00	75.00

consists of 13 consecutive tracks which has wider trackway width, showing faster walking speed than others (Fig. 6A). Trackway OK consists of 10 consecutive tracks, representing the smallest track among 11 ornithopod trackways.

Eleven trackways plotted in a rose diagram show two main directions (Fig. 5). The orientation of seven trackways show a main mode trending NW–SE (Group A): the trackways OA, OB, OC, OD indicate that animals moved towards the northwest while the trackways OE, OF, OG show an opposite direction movement (to the southeast). Because the trackways OA, OB, OC, OD are not overlapped but paralleled each other, it is possible that animals moved together as a herd. On the other hand, the trackway OG crossed the trackway OE because the fifteenth track of the trackway OG overprinted on the fourteenth track of the trackway OE, indicating a short time interval between two formations. The orientation of Group B (the trackways OI, OJ, OH, OK) is nearly perpendicular to that of Group A. Two preferred orientations of all ornithopod trackways may suggest that there were two main pathways in this area. The palaeocurrent analysis based on ripple marks and cross-

beddings shown in a vertical section (Fig. 2) indicate that this tracksite was located in the southwest of a lacustrine sedimentary environment. If true, Group A (NW–SE) would be made by ornithopods that went back and forth along the lacustrine margin while Group B (NE–SW) came to the lakeshore perhaps engaged in activities such as drinking water. All ornithopods walked slower than theropods at this site. Among the ornithopod trackways, trackways OJ and OH walked relatively faster than others while trackways OA, OE, OI walked at very low speeds based on the ratio of footprint length and stride (Fig. 6A).

3.2. Theropod footprints

Although a theropod trackway occurs on the surface of the B layer (Trackway TA) along with 11 ornithopod trackways, it is difficult to see detailed morphologies of the tracks due to poor preservation. Trackway TA consists of seven consecutive tracks which show a much higher ratio of track length to width (1.76) than those of all ornithopod tracks. The average pace angulation (155°) is

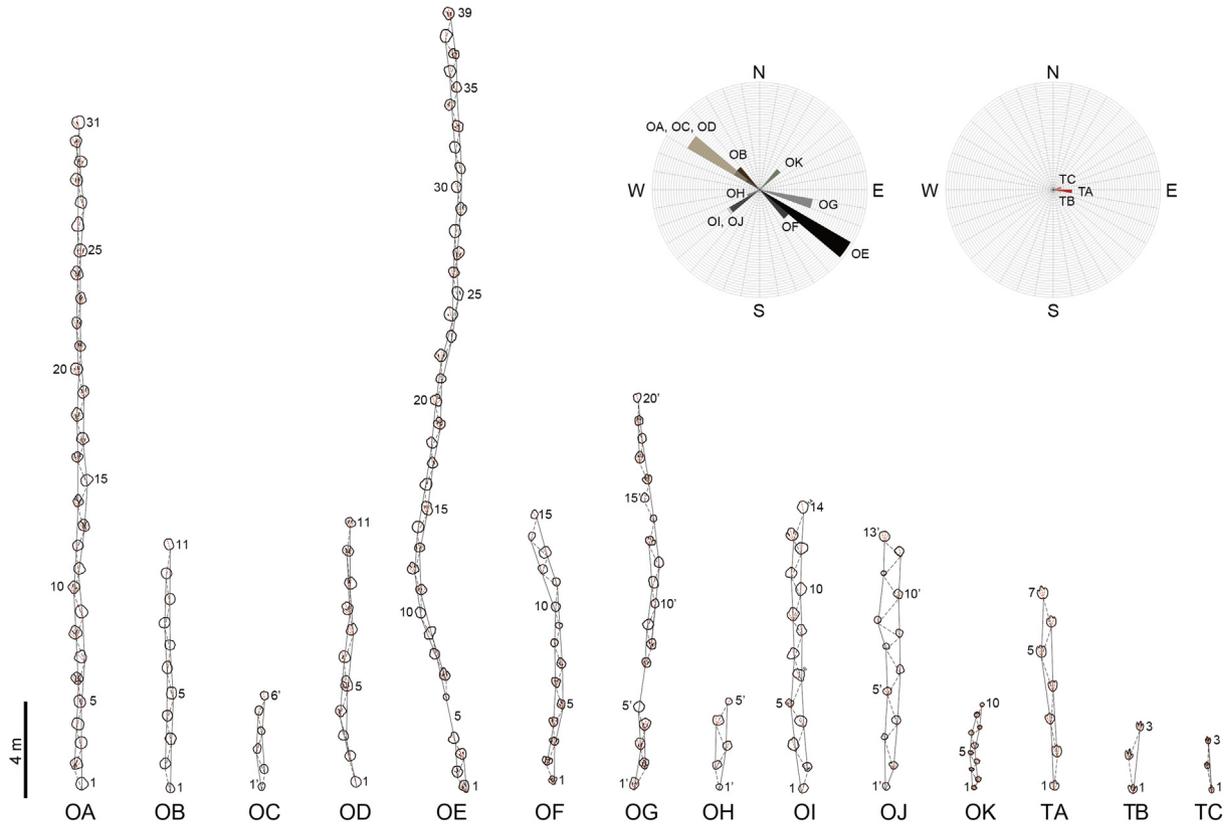


Fig. 5. Eleven ornithopod (OA–OK) and three theropod (TA–TC) trackways of the site with rose diagrams showing their orientations.

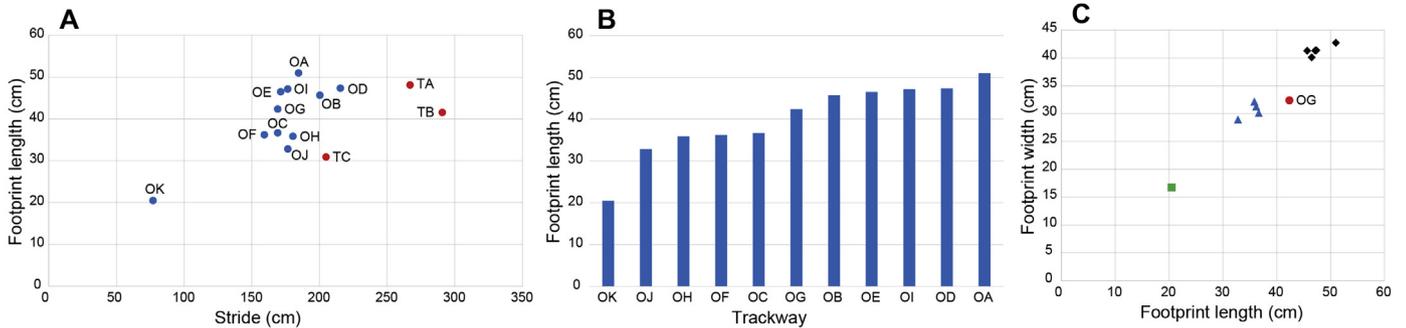


Fig. 6. Bivariate plots of various trackway measurements. (A) Bivariate plot of footprint length-stride measurements of each trackway. (B) Histogram of footprint lengths of all ornithopod trackways. (C) Bivariate plot of footprint length-width measurements of all ornithopod trackways.

also higher than those of ornithopod trackways. This trackway indicates that a large theropod moved eastwards alone. On the other hand, the C layer contains only theropod tracks which are well-preserved on the surface of thin mudstone. They include two trackway segments each with three consecutive footprints and more than twenty shallowly depressed isolated tracks. The mud cracks on the surface indicate that the surface had undergone subaerial exposure for some length of time. The tracks of trackways TB and TC are tridactyl and mesaxonic, having digit III much longer than digits II and IV of which digit ends are tapering with claw marks. Especially, the third track of the trackway TB shows a sharp claw mark at the end of digit II imprint (Fig. 4C). Three digital imprints are narrower than those of ornithopod tracks. The metatarsophalangeal pad is a reverse triangular in shape, tapering backwards. The photogrammetric image of the trackway TB 03 shows that digits III and IV are more deeply impressed than digit II,

which is opposite to ornithopod tracks in which the medial digit is more deeply impressed than the lateral digit.

The length and width of the trackway TB are 41.56 cm and 28.67 cm, respectively which is smaller than those of the trackway TA. However, the ratio of its stride (290.79 cm) and footprint length is the highest among all theropod trackways, representing the fastest walking trackway (Fig. 6A). The length and width of the trackway TC are 30.90 cm and 15.82 cm, respectively and the pace angulation is 169° which is the highest among all trackways at this tracksite. The azimuths of trackways TB and TC indicate that two theropods were both moving in the same direction (Fig. 5).

Several large theropod ichnogenera (footprint length more than 40 cm) are reported in the Jurassic and Cretaceous formations in the world. They are *Kayentapus* (Welles, 1971), *Eubrontes* (Hitchcock, 1845), *Megalosauripus* (Lockley et al., 1998), *Irenesauripus* (Sternberg, 1932), *Tyrannosauripus* (Lockley and Hunt, 1994),

and *Bellatoripes* (McCrea et al., 2014). *Kayentapus* is a gracile tri-dactyl track with slender digits that have less acute angles of divarication than those of either *Grallator* or *Eubrontes* (Milner et al., 2009). The spindle shaped impression of digit III is characteristic in *Eubrontes* while *Megalosauripus* has a parallel-side digit III impression with an elongated heel (Lockley et al., 1998). The morphological features above of these Jurassic ichnotaxa are not observed in Sanbukdong theropod tracks. The diagnoses of the Tyrannosauripodidae which includes *Tyrannosauripus* and *Bellatoripes* from the Late Cretaceous of North America are proximally thickened digit impressions, strongly tapering acuminate claw impressions, and craniomedially-directed hallux impression if any (McCrea et al., 2014). As the ichnofamily implies, these tracks were interpreted to being made by tyrannosaurids based on footprint size, overall morphology as well as stratigraphic and geographic occurrence. *Irenesauripus* is a large theropod ichnotaxon from the Early Cretaceous. This ichnogenus was reported from the Lower Cretaceous Gething Formation (Aptian), British Columbia, Canada (Sternberg, 1932). He described three ichnospecies, *I. mclearni*, *I. acutus*, and *I. occidentalis*, but later *I. occidentalis* was regarded as a synonym of *Amblydactylus* (Currie, 1983). *Eubrontes* (?) *glenrosensis* from the Glen Rose Formation (Albian), Texas, USA (Shuler, 1935) was renamed as *Irenesauripus glenrosensis* (Langston, 1974).

Sanbukdong theropod footprints resemble *I. mclearni* and *I. glenrosensis* more closely than *I. acutus*. The digits of *I. acutus* are more elongate and slender than those of other two ichnospecies with the divarication of digit III and IV typically greater than that of digits II and III, giving impressions an asymmetry inwards (Gangloff et al., 2004) although the differences between *I. mclearni* and *I. acutus* was ascribed to variations in substrate properties (McCrea, 2000). The divarication angles between digit II and IV of *I. mclearni* and *I. glenrosensis* are average 65° and 55°, respectively. The ratio of the metatarsophalangeal length (MPL) to footprint length (FL) is greater in *I. glenrosensis* (0.48) than *I. mclearni* (0.39). Based on the total divarication angle and ratio of MPL/FL, Sanbukdong theropod footprints show strong similarity to *I. glenrosensis*. The tracks of the trackway TC are smaller in size than those of the trackway TB (Table 1, Supplementary Table 1). However, their general foot morphology, total divarication, and ratio of MPL/FL are very similar to those of the trackway TB. Thus, it is possible that the trackway TC was made by a smaller individual of the same kind of theropod that left Trackway TB.

4. Discussion

The known large Early Cretaceous ornithopods from Asia are, an exceptionally giant basal styracosternan (*Lanzhousaurus*) from China and, basal hadrosauroids (*Jinzhousaurus*, *Penelopognathus*, *Jintasaurus*, *Equijubus*, *Gongpoquansaurus*, *Probactrosaurus*, *Altirhinus*, and *Fukuisaurus*) from China, Mongolia, and Japan (Ramírez-Velasco et al., 2012; Wu and Godefroit, 2012). An incomplete maxillary tooth is the only skeletal remain of large ornithopods from the Early Cretaceous of South Korea, which was interpreted as belonging to a non-hadrosaurid hadrosauroid tooth (Lee and Lee, 2007). Therefore, it is likely that Sanbukdong ornithopod tracks were made by basal hadrosauroids.

The ornithopod tracks on the B layer are most similar to *Caririchnium lotus*. The ichnogenus *Caririchnium* has been widely distributed in the Early Cretaceous of Asia, America, and Europe (Díaz-Martínez et al., 2015). In Asia, *Caririchnium lotus* from the Jiaguan Formation (Barremian-Albian), Chongqing, China is known as only ichnospecies for the large ornithopod tracks from the Early Cretaceous so far (Xing et al., 2007). *Hadrosauropodus kyoungsookimi* reported from the Upper Cretaceous Jindong Formation (Cenomanian–Santonian), South Korea is different from *Caririchnium*

in that it has a bilobed but not rounded heel impression (Lim et al., 2012). All ornithopod trackways seem to have been made by the same kind of ornithopods because they have a similar trackway pattern such as no manus prints as well as ichnomorphological features such as three wide digit imprints with round digital ends, a large heel pad impression longer than wide, and track dimensions (longer than wide). If true, they could be divided into four distinct ontogenetic age groups of individuals (Fig. 6B and C). The most common tracks (ten trackways) belong to stages 3 and 4 (between 32 cm and 41 cm, between 42 cm and 51 cm in length, respectively), followed by the smallest tracks of stage 1 (less than 21 cm in length, one trackway). Stage 2 (between 22 cm and 31 cm in length) individuals are absent. This frequency of each age of individuals is very similar to a hadrosaurid growth pattern reported in Denali National Park, Alaska (Fiorillo et al., 2014). They found that the growth pattern based on tracks is concordant with the skeletal growth curve. A similar growth pattern has been also found in hadrosaurid tracks in Mongolia (Nakajima et al., 2018). If true, Sanbukdong ornithopod tracks suggest that growth in young basal hadrosauroids (stage 2) had a brief period where it was very rapid, too. Interestingly, the main Alaskan and Mongolian hadrosaurid tracks range between 30 and 72 cm in length while Sanbukdong basal hadrosauroid tracks between 32 and 51 cm (Fig. 6B). The body size increased in the major non-avian dinosaurs through the Mesozoic including Ornithopoda (Carrano, 2006). These Sanbukdong ornithopod track data therefore support a disparity of the maximum body size between Early Cretaceous basal hadrosauroids in Asia (less than 7 m in body length) and the larger late Campanian and Maastrichtian hadrosaurids in Asia and North America.

Trackway TB consists of large theropod tracks (more than 40 cm in length). The tracks are morphologically similar to large Glen Rose theropod footprints, *Irenesauripus glenrosensis* from the Lower Cretaceous of Texas. This ichnospecies was inferred to be of *Acrocantiosaurus* origin (Farlow, 2001; Adams et al., 2010). Interestingly, cf. *Acrocantiosaurus* teeth had been discovered in the Hasandong Formation (Aptian–Albian), South Korea (Lee, 2007). Recently two carcharodontosaurid taxa, *Shaochilong* (Brusatte et al., 2009) and *Kelmaysaurus* (Brusatte et al., 2012) were reported in China with several teeth (Mo et al., 2014; Lü et al., 2016). Therefore, it is possible that the Sanbukdong theropod tracks were made by large carcharodontosaurid dinosaurs.

Many small Early Cretaceous theropod ichnofaunas such as *Grallator ssatoi*, *Velociraptorichnus*, *Minisauripus*, *Corpulentapus*, *Dromaosauripus*, and *Asianopodus* have been found in China (Lockley et al., 2013). Many of these ichnogenera also occur in South Korea, implying there were theropod ichnofaunal affinities between two countries in the Early Cretaceous (Kim et al., 2018). On the other hand, large Early Cretaceous theropod tracks are very rare in China. *Chapus lockleyi* from the Lower Cretaceous Jingchuan Formation in Inner Mongolia is only ichnotaxon in China for large (58.2 cm long) Early Cretaceous theropod tracks (Li et al., 2006) although it was provisionally regarded as valid (*sensu* Lockley et al., 2013). It is characterized by distinct phalangeal pad impressions, which are not shown in Sanbukdong theropod tracks. Although Xing et al. (2011) classified medium-sized theropod tracks with a hallux from “mid” Cretaceous Jiaguan Formation, Guizhou Province, China into cf. *Irenesauripus* isp., it does not appear to be the same as Sanbukdong tracks. Therefore, it is not certain yet whether large theropod ichnofaunal affinities existed between China and Korea as small theropod ichnofaunas in the Early Cretaceous.

5. Conclusions

- 1) Sanbukdong tracksite represents the largest Early Cretaceous dinosaur tracksite in the Korean peninsula.

- 2) All tracks indicate that large ornithopod and theropod dinosaurs lived in the Early Cretaceous and strengthen previous hypotheses of their existence in Korea based on only isolated teeth.
- 3) Sanbukdong ornithopod tracks closely resemble *Caririchnium lotus* from China, implying a possible ichnofaunal connection between Korea and China in the Early Cretaceous.
- 4) Sanbukdong theropod tracks are most similar to *Irenesauripus glenosensis* from the USA and they were possibly made by carcharodontosaurid dinosaurs.
- 5) Sanbukdong track data suggest that basal hadrosauroids had the same growth pattern as derived hadrosaurids.
- 6) Sanbukdong track data independently support that the majority of Early Cretaceous basal hadrosauroids were smaller than Late Cretaceous hadrosaurids in body size.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at <https://doi.org/10.1016/j.cretres.2018.06.003>.