Available online at www.sciencedirect.com
ScienceDirect
PALAEO
Palaeogeography, Palaeoclimatology, Palaeoecology 258 (2008) 59–70
www.elsevier.com/locate/palaeo

A reinterpretation of dinosaur footprints with internal ridges from the Upper Cretaceous Uhangri Formation, Korea

Koo-Geun Hwang [a,*], Martin G. Lockley [b], Min Huh [c], In Sung Paik [d]

[a] *Korea Dinosaur Research Center, Chonnam National University, Kwangju 500-757, Korea*
[b] *Dinosaur Tracks Museum, University of Colorado at Denver, Denver, CO 80217, USA*
[c] *Faculty of Earth Systems and Environmental Sciences & Korea Dinosaur Research Center, Chonnam National University, Kwangju 500-757, Korea*
[d] *Department of Environmental Geosciences, Pukyong National University, Pusan 608-737, Korea*

Received 29 April 2007; received in revised form 24 October 2007; accepted 30 October 2007

Abstract

Very unusual dinosaur footprints with radial internal ridges from the Late Cretaceous of southern Korea have been the subject of much controversy. All footprints are in black laminated mudstone/shale, and have gently curved cross-sections that show deformation of a flexible substrate by dinosaur footprint registration. These peculiar patterns have not been recorded at any other site in the world, although natural casts of such features have been reported from a few localities. Each footprint consists of several sectors or pockets partitioned by conspicuous radial ridges. These tracks were first interpreted as sauropod manus-only tracks, supporting Roland Bird's swimming sauropod hypothesis. However, our study casts serious doubt on this theory for two reasons. First, the footprints sometimes exhibit characteristic features such as ungual, 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.

Keywords: Cretaceous; Ornithopod; Footprint; Korea; Swimming; Internal ridge

1. Introduction

Unusual tracks with radial internal ridges were found in the Upper Cretaceous Uhangri Formation at Uhangri, South Jeolla Province, southwestern Korea (Fig. 1). Over a period of two years, these tracks were exposed by excavations at five locations (I, II, III-1, III-2 and VI) that resulted in the discovery of hundreds of dinosaur, pterosaur and bird footprints in three track layers exposed over a distance of about 2 km along the coastline (Hwang, 2001). The first (lowest) level (Fig. 1) is the only one on which bird, pterosaur, and non-avian dinosaur tracks occur on the same surface (Hwang et al., 2002). The bird footprints, *Uhangrichnus chuni* and *Hwangsanipes choughi*, were originally described as the oldest webbed-foot bird tracks in the fossil record (Yang et al., 1995), though older examples have since been reported from the Lower Cretaceous Haman Formation, South Gyeongsang Province, southeastern Korea (Kim et al., 2006). The pterosaur tracks, the largest pterosaur ichnites known and the first reported from Asia, were

* Corresponding author.
E-mail address: hwang-kg@hanmail.net (K.-G. Hwang).

0031-0182/$ - see front matter © 2007 Elsevier B.V. All rights reserved.
doi:10.1016/j.palaeo.2007.10.029

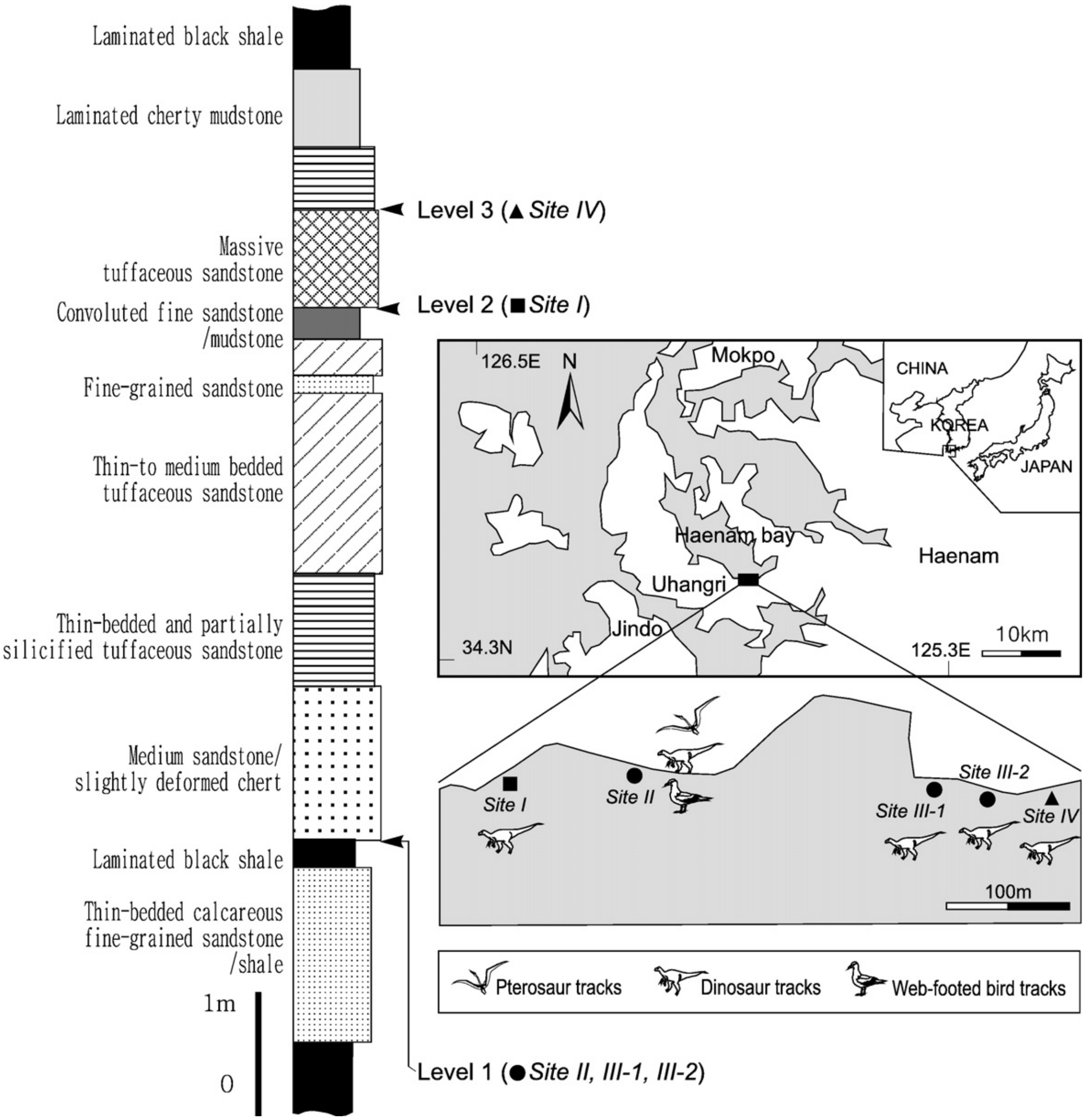

Fig. 1. Location of the Uhangri tracksite and stratigraphic section of the Upper Cretaceous Uhangri Formation. Dinosaur, pterosaur, and bird footprints have been found in three track layers. The dinosaur footprints with internal radial ridges were found in the lowest level, which contains pterosaur and bird footprints, at sites II, III-1 and III-2.

assigned to the novel ichnogenus *Haenamichnus* (Hwang et al., 2002). The longest pterosaur trackway in the world was also found at the same level and demonstrates that at least one clade of large, Late Cretaceous pterosaurs, probably azhdarchids, adopted a quadrupedal, plantigrade stance and gait, as seems to be the case for other pterodactyloid pterosaurs (Hwang et al., 2002).

Of special interest are 113 unusual, deep dinosaur footprints with internal radial ridges exposed on the first level. This unusual type (Figs. 1 and 2) had never previously been found at any other site (Hwang et al., 2002; Huh et al., 2003). Explanations of the formation of the ridges, as well as track maker identity, have been a matter of debate (Lee and Huh, 2002; Thulborn, 2004; Lee and Lee, 2006).

In this paper, we offer compelling arguments that the radial ridges are the result of the formation of radial cracks (sensu Lockley et al., 1989; Nadon, 1993) on the underside of a clastic, tuffaceous sandstone bed atop which large, bipedal dinosaurs had walked. All previous interpretations of the tracks as those of swimming sauropods, and the radial cracks as the results of either

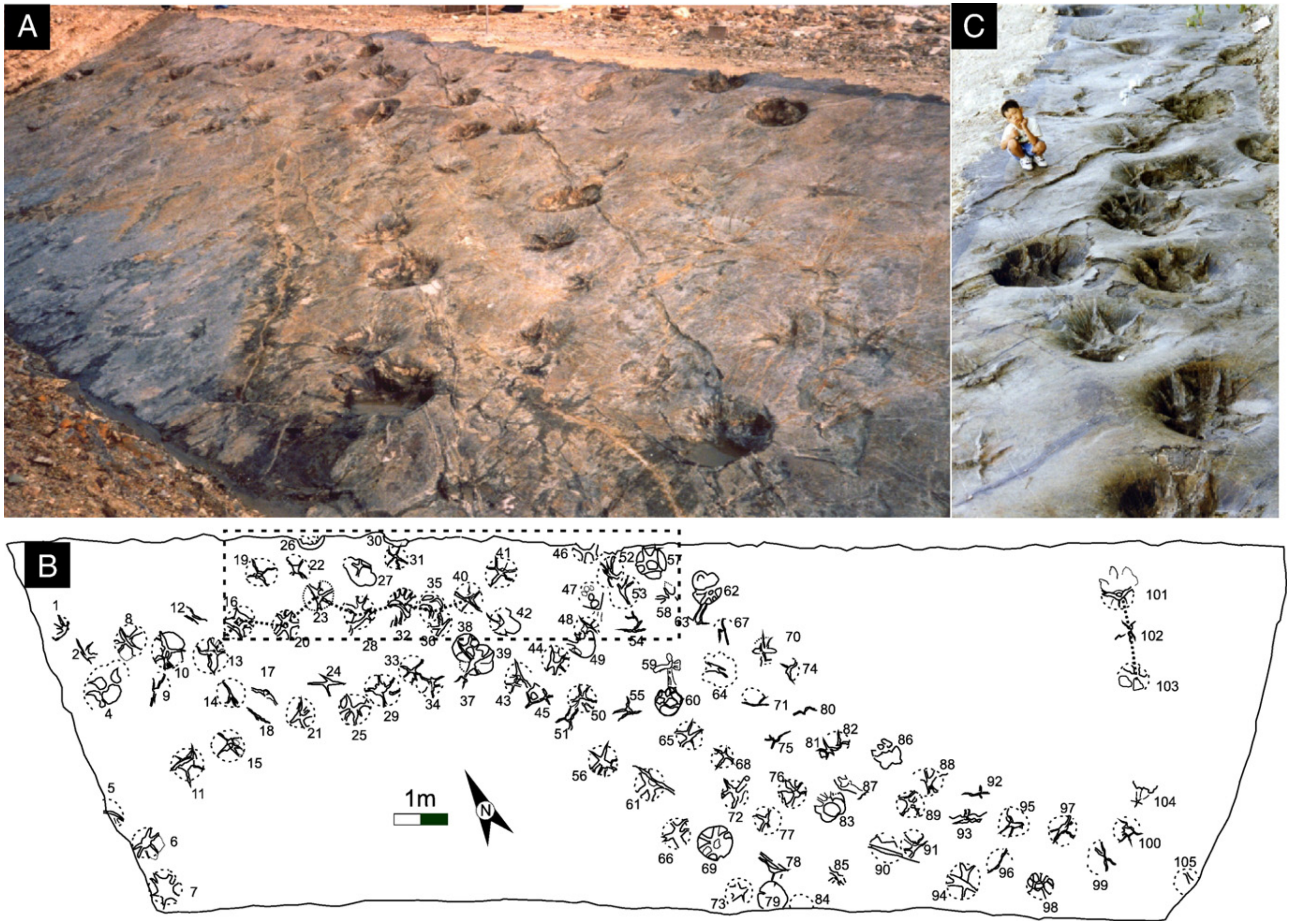

Fig. 2. Tracksite III-1 (A) and detailed map (B). (C) Photo showing the northern area of site III-1 at an early stage of excavation. There are two trackways here that proceed to northeast and east. Footprint numbers are listed on the detailed map (B).

suction or upwelling of fluids through a cracked surface, are essentially incorrect — these complex hypotheses do not satisfactorily explain several newly observed aspects of the Uhangri tracks.

2. Geological setting

The tracks discussed here occur in the Uhangri Formation, the middle unit of the Haenam Group in the Haenam Basin. The Haenam Basin is one of several isolated, non-marine Cretaceous basins distributed across the southern Korean peninsula. Haenam Basin contains four formations, in ascending order: an andesitic tuff with andesite intrusions and flows, the Uhangri Formation, the Hwangsan Tuff, and the Jindo Rhyolite (Lee and Lee, 1976). The Uhangri Formation comprises an epiclastic, fluvio-lacustrine sequence with intercalated volcaniclastics (Chun and Chough, 1995).

The upper part of the Uhangri Formation consists of tuffaceous sandstone with graded bedding, interbedded to interlaminated tuffaceous sandstone and mudstone, laminated cherty mudstone, and dark grey to black shale. The unusual footprints discussed herein occur in a black shale layer with a lustrous surface lacking mud cracks of the type often found at tracksites. The track-bearing layer was deposited by sheetflooding in a lake margin environment, and was excavated by removing an overlying, tuffaceous sandstone layer. By contrast to the occurrence of pedogenic features elsewhere in the Cretaceous dinosaur track-bearing deposits of Korea (Paik et al., 2001, 2006), the track-bearing deposit in the Uhangri Formation shows no indication of pedogenesis, suggesting a high sedimentation rate of the Uhangri Formation track deposits.

The tuff deposits, which overlie and underlie the Uhangri Formation, have been dated respectively at 82.8 ± 1.7 Ma and 94.1 ± 2 Ma by K–Ar methods (Moon et al., 1990). To refine the age of the tracks, Rb–Sr whole rock age measurements were obtained for the tuffs underlying and overlying the unusual track-bearing deposit (Kim et al., 2003). Lapilli andesitic tuff underlying the track deposit was dated as 96.0 ± 2.5 Ma, and felsic tuff overlying the track deposit was dated as 81.0 ± 2.0 Ma. The Hwangsan Tuff was dated as 77.9 ± 4.1 Ma. The track deposit is thus roughly between 96 and 81 Ma in age (mid-Cenomanian to Early Campanian based on Gradstein et al. (2004).

3. Description of tracks and previous interpretations

3.1. Description of tracks

Most non-avian dinosaur footprints from level 1 consist of deep rounded impressions partitioned into discreet pockets by 2–6 conspicuous radial ridges, and, in some cases, a circular pocket in the center (Figs. 2 and 3). Footprint, depth varies between 40 mm and 270 mm, and shows deformation of a flexible substrate by the impact of dinosaur feet. Most footprints have gently curved cross-sections rather than pronounced angular edges — i.e., few have vertical walls that intersect the sediment surface at ~90°. Only the deepest footprints (7% are deeper than 190 mm) possess angular edges. The ridges extend out from the center of each footprint, and the sizes and shapes of the internal compartments they encompass are variable (Fig. 3). Due to this peculiar pattern, even claw and digit impressions are easy to overlook and thus were not previously identified or described. Accordingly, even the direction of the track maker could not be determined. The size and age of the tracks imply a dinosaurian track maker, but in morphology the tracks could not be readily compared or assigned to any other type of dinosaur manus or pes prints (Lee and Huh, 2002; Thulborn, 2004; Lee and Lee, 2006). As the debate in the aforementioned papers demonstrated, in such circumstances it was difficult to understand the shapes of these footprints and the superimposed radial ridges only proved even more puzzling.

Even after a visit by an international delegation of paleontologists and ichnologists in 1997, when the Haenam Dinosaur theme park was first established, no one could identify the tracks or explain the preservation with any confidence. The tracks were initially interpreted as manus-only sauropod tracks based on their circular shapes, and it was suggested (Lee and Huh, 2002; Lee and Lee, 2006) that this track site supported a hypothesis of swimming sauropod ability and technique initially proposed by Bird (1944). However, Thulborn (2004) argued that the circular outlines of the large bowl-shaped impressions differ from the horseshoe shape typical of well-preserved prints of the sauropod manus, and that the Uhangri footprints do not obviously match the topography of the hand or foot of any known group of dinosaurs (Gillette and Lockley, 1989; Thulborn, 1990; Hwang et al., 2004). We agree and suggest therefore that they are underprints, not manufactured in a subaqueous setting.

3.2. Swimming scenario

In order for the ridged Uhangri tracks to have been registered by a swimming track maker (such as a sauropod) in the manner suggested by Lee and Huh (2002) or Lee and Lee (2006), then the tracks must necessarily represent actual tracks, not underprints. The exposed horizon would therefore represent the primary track surface and would be expected to exhibit other signs that

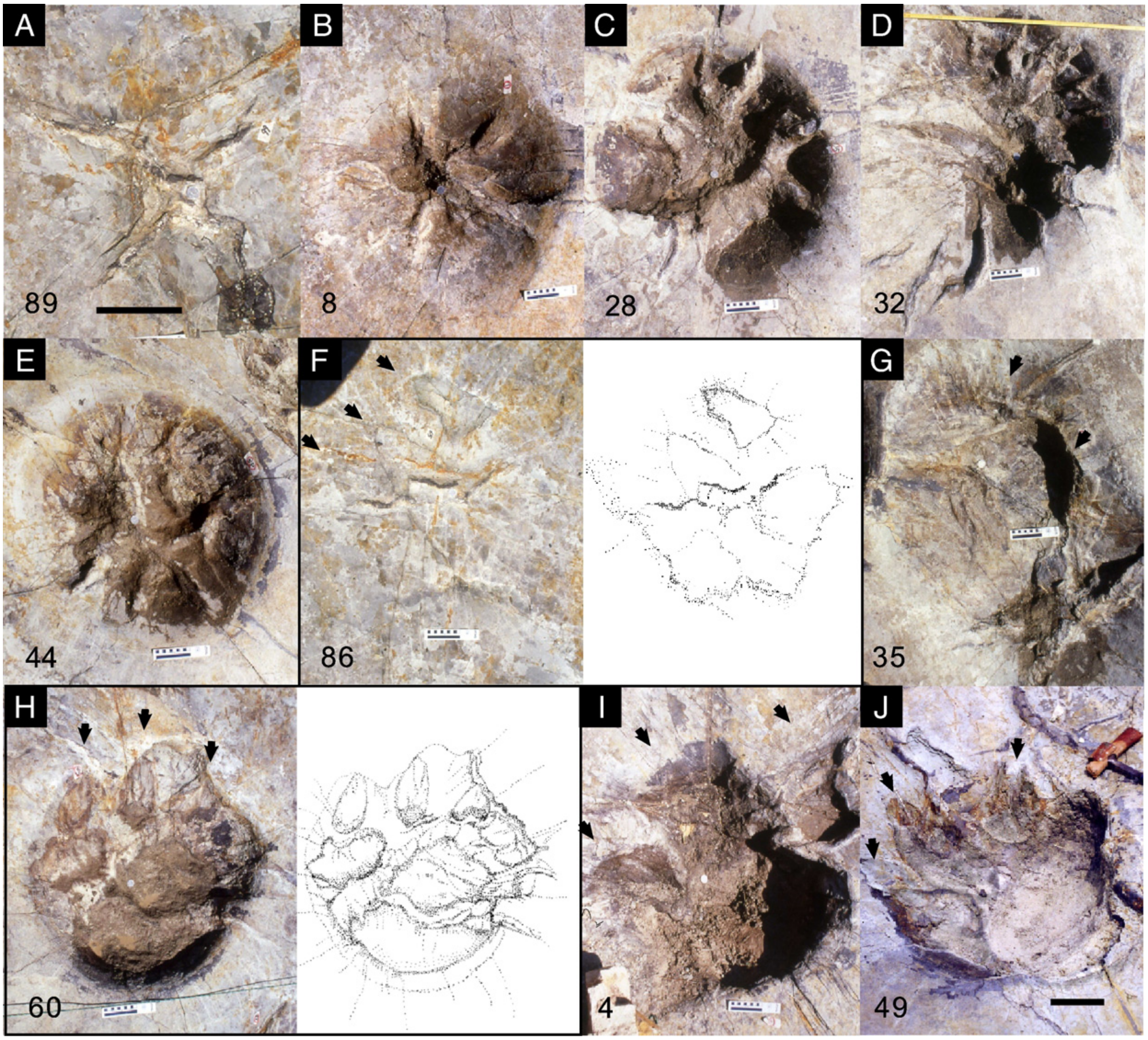

Fig. 3. Unusual dinosaur footprints with internal radial ridges at site III-1. Footprint numbers are noted in the lower left of each frame and probable ungual marks are shown by arrows on each applicable photo. (A–B) Shallow footprints. (C) Footprint with slide marks connected to internal ridges. Slide marks may have originated at the shale-tuffaceous sand interface as a result of the dinosaur foot impact on the sandy layer and sliding of coarse sandy sediment over the mudstone substrate. (D) Distinctive slide marks were left by foot or sediment — pushed by the foot sliding forward in the process of creating the cracks that generated the internal ridges. (E) Radial internal ridges. (F) A shallow print and schematic, showing three blunt ungual marks and a sinuous ridge on the anterior margin. A blunt ungual mark indicates an ornithopod track maker. (G) A circular footprint with blunt digits and a wide heel pad impression similar to *Caririchnium* described from level 2 (site I). The right digit impression has superimposed internal ridges from the footprint left by another dinosaur crossing the tracksite. (H) A deep print and schematic showing three blunt digit impressions and wide heel impressions, which are distinctive features typical of ornithopods. The left digit impression appears especially well-preserved. (I–J) A rare example of a footprint with sharp claw marks, possibly indicating a theropod track maker.

indicate a subaqueous paleoenvironment. As we argue herein, this is not the case. The unusual footprints occur at the lowest dinosaur track layer (level 1) presently exposed by excavation at any of the three sites (site II, III-1, III-2; Figs. 1, 2, 4A and 5C). This layer lacks mud cracks, indicating that the sediment held a quantity of water but was buried prior to dessication. Previous authors only described the dinosaur footprints from site III-1, where most of the unusual dinosaur footprints were found (Lee and Huh, 2002). However, site II also contains numerous bird and pterosaur, and three non-avian dinosaur footprints with radial ridges in the same layer (Figs. 1 and 4A). The small bird footprints are well-preserved around, as well as in, pterosaur tracks in the black shale (Fig. 4B; Hwang et al., 2002). One of three shallow dinosaur underprints in a trackway at site

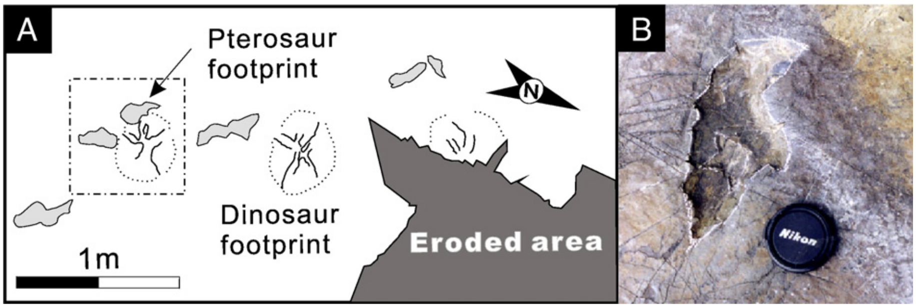

Fig. 4. Vertebrate footprints found at site II. (A) A pterosaur trackway intersecting a dinosaur trackway at site II. Box shows a pterosaur manus-pes print set overprinted by an unusual dinosaur footprint. (redrawn from Hwang et al., 2002). (B) A manus print of a pterosaur overprinted by a bird footprint at site II.

II apparently overprints a previously made pterosaur manus-pes print set (Fig. 4A). At the same site there are pterosaur footprints overprinted by bird footprints, and vice versa (Fig. 4B). That the small, light track-making birds and pterosaurs were not buoyant, i.e., making swim traces, and thus able to register typical walking

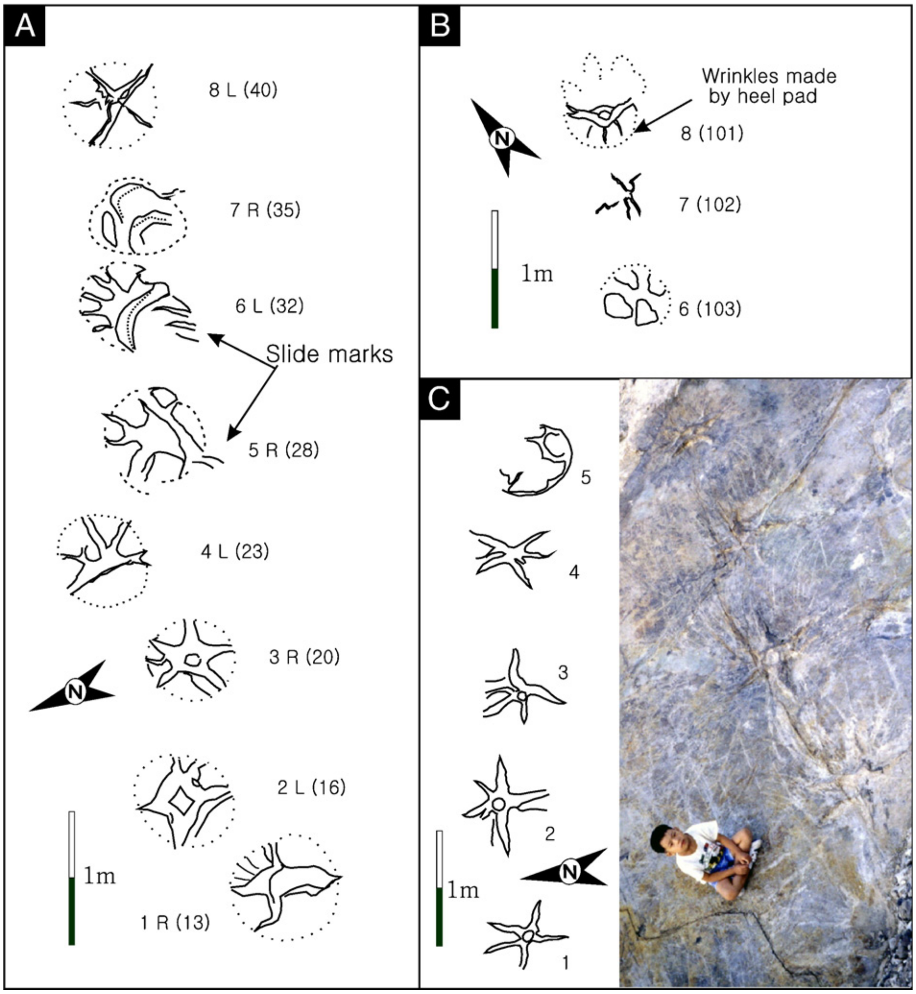

Fig. 5. Trackways from site III-1 (A, B) and III-2 (C) with regular short strides lengths and high pace angulations (146–180°), suggesting a bipedal track maker.

footprints demonstrate that any water, if present at all, could not have been more than a few centimeters deep. More likely, it suggests a short period of emergence and subsequent burial by sandy sediments before the substrate could dry out and crack (Fig. 6), and before dinosaur tracks were made in the sandy sediment that buried the shale, and served as the medium through which the dinosaur underprints were transmitted.

The presence of small prints at site II indicates that although the surface was wet enough to prevent mud cracking, the surface could not have been submerged enough for dinosaurs to swim at the time they were made. Thus, the dinosaur tracks could not be true 'swim' tracks as suggested by Lee and Huh (2002) and Lee and Lee (2006) unless some highly unparsimonious assumptions are made about changes in the water level and the preservation of small subaerial and deep subaqueous tracks on the same surface. We find that these tracks provide no support for the swimming sauropod scenario. Therefore, although this scenario is still hypothetically possible (Henderson, 2004), no true examples have been discovered as of now (Lockley and Rice, 1990; Lockley et al., 1994).

Although direct evidence of dinosaur swimming ability is scarce, non-avian theropod tracks from Lower Jurassic rocks at Rocky Hill, Connecticut (Coombs, 1980) and, more convincingly, Utah (Milner et al., 2006) support that some non-avian dinosaurs were capable of swimming and that such behavior produces highly distinct, easily recognizable traces. The *Characichnos* ichnofacies of Hunt and Lucas (2007) was defined by the presence of this ichnotaxon, based on 'swim' tracks described by Whyte and Romano (2001) from the Middle Jurassic of England. In addition to these swimming dinosaur tracks, swimming pterosaur tracks from the Cretaceous Dakota Group of Colorado (Lockley et al., 2007) and turtle tracks from the Jurassic Cerin Limestone of France (Gaillard et al., 2003) have been reported. No features remotely resembling these, made by any taxon, have been reported from the Uhangri Formation tracksites. Footprints registered by swimming track makers usually exhibit common features indicating that the track maker glided or floated between footfalls. Such evidence includes long strides and elongate claw scratches with small mounds of mud piled up at the posterior ends of the traces created by the digits displacing sediment. Such 'push up' ridges are not seen in any tracks at the Uhangri site.

Because the swimming non-avian dinosaur tracks mentioned above were made by theropods, the absence of these common features may not be absolute evidence that the ridged tracks were not made by swimming

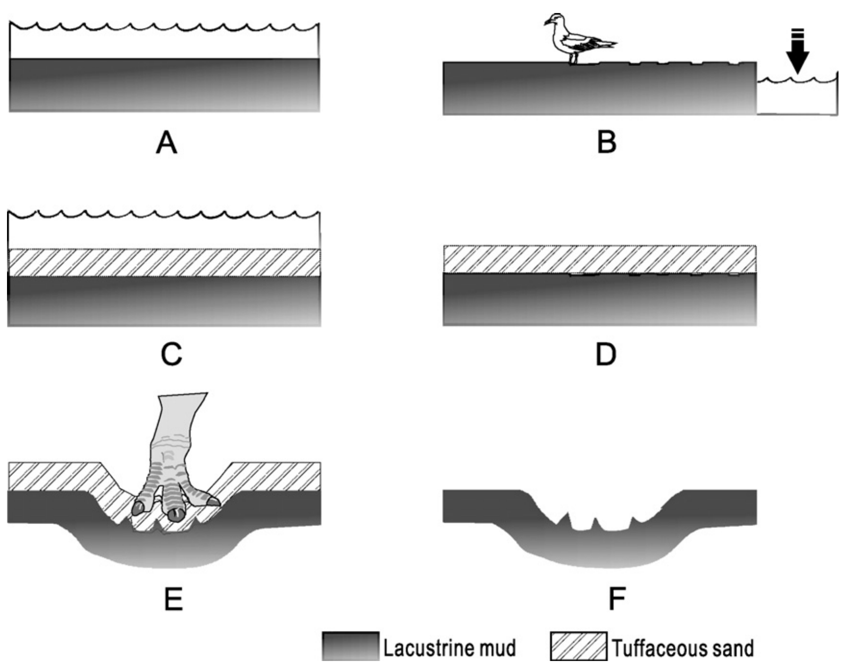

Fig. 6. Primary steps in the formation of the Uhangri dinosaur undertracks with radial ridges. (A) Subaqueous deposition of lacustrine mud (grey). (B) Emergence of mud and track making by birds and pterosaurs (C) Deposition of tuffaceous sand (diagonal lines). (D) Emergence of sand layer. (E) Formation of tracks in sand horizon and simultaneous undertracks with internal ridges in underlying mud layer, which are molds of radial cracks on the underside of the sand bed. (F) Exposure of raised radial mudstone ridges after sandstone is removed.

sauropods. However, since pterosaurs are now known to make swim tracks (Lockley et al., 2007), the absence of pterosaur swim tracks at this site suggests that the subaqueous environment at least could not have been deep enough to buoy a large sauropod.

Though they lack any of the swimming scenario indicators listed above, many of the ridged tracks have many small-scale concentric wrinkles near their rims (Fig. 3C, D, G and H). These wrinkles could have been formed by slight lateral pressure exerted when track makers were slipping forward or to the side. Additionally, all such wrinkles are connected to the enigmatic internal ridges (Fig. 3C, D and H) and appear to be related, i.e., formed at the same time as a result of pressure caused by the foot impact.

Four trackways (Figs. 4 and 5) from this layer also display regular, short steps that contrast with known swimming trackway patterns. The high pace angulations (146–180°) of these trackways are characteristic of the tracks of bipeds and cannot be explained as sauropod manus-trackways (Lockley and Rice, 1990; Lockley et al., 1994) which typically show pace angulations of about 100°.

3.3. Delamination scenario

As an alternative to the Swimming scenario discussed above, Thulborn (2004) proposed that the radial cracks are the result of delamination of the upper layers of the shale after the withdrawal of the dinosaur foot from the sediment. He proposed two possible mechanisms that "might" (Thulborn, 2004, p 295) have caused these features. 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 footprint impact, flowed back under the lifted laminae. 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.

We agree with Thulborn (2004) that the swimming scenario is not tenable, but we also argue that there is no evidence for either of the delamination scenarios. In the first mud-adherence scenario, the upper laminae would have to be stretched into a tent-like canopy, as the dinosaur foot lifted the mud laminae upwards before the laminae then fell back again. This would have required the sediment to move down, up and down again, whereas in normal track making the sediment is simply compacted downward. We found no evidence for separation of the upper laminae from lower ones. Moreover, we argue that the tracks are undertracks so the track-maker never had its foot in contact with ductile mud. By contrast the radial cracks scenario, outlined here, requires compression, not stretching, of the underlying mud as it was forced into cracks propagated from above.

The second, blister model also fails for several reasons. Thulborn (2004) incorrectly infers that the shallow tracks have superficial cracks, not radial ridges. Wet, ductile clay does not crack, as Thulborn correctly points out. It was the overlying sand that cracked radially, as a result of foot impact pressure, causing the ductile clay to mold into the cracks. As a result, similar radial ridges, not cracks, occur in both shallow and deep tracks. The claims that the radial ridges are higher in deep tracks (Lee and Huh, 2002) cannot be verified by our observations. Because little substrate deformation took place in the making of the shallow tracks (undertracks) little water could have been displaced from the shallow tracks to create a source that could flow back to create ridges of the same dimensions as those found in the deep tracks. In any event the undertracks were already covered by a layer of sand when made: thus the weight of this overburden would have prevented the upward blistering of the underlying shale. As discussed below a new and far less complex and conjectural model is required.

4. A new model

For many years, the authors have scrutinized the mysterious Uhangri footprints in some detail. As a result, we have developed an interpretation of the likely track makers and the process of track formation that created the internal ridges. This interpretation is not only consistent with all the major features seen at the site but also more parsimonious than previously-proposed hypotheses (Thulborn, 2004; Lee and Lee, 2006).

4.1. The track maker

Although many of the depressions and complex internal ridges are difficult to interpret, some prints appear to have recognizable ungual marks (e.g., footprint No. 86; Fig. 3F). In addition, the trackway pattern, with a much greater pace angulation than that of any known sauropod manus-only trackway, suggests a bipedal track maker. This interpretation renders the tracks and trackways easier to interpret on the basis of two criteria: 'footprint' shape, and trackway pattern.

A deep footprint (Footprint No. 35; Fig. 3G) seems to have three ridges on the left side. Such footprints, with No. 35 as an exemplar, could consist of left digit, center digit and heel pad impressions (probably disturbed or distorted on the right side by an intersecting trackway). Some footprints (Fig. 3H) have complex internal ridges near the anterior margin, a circular pocket in the center of the footprint, and a crescentic pocket at the posterior end. These anterior and center pockets could be interpreted as three thick digit impressions with thick ungual marks, and the posterior pocket as a heel pad impression. In this interpretation, we tentatively suggest that where the overlying (tuffaceous sand) layer was thinner, or the underlying mud softer, the foot of the track maker penetrated more deeply, leaving partially recognizable footprints with characteristic quadripartite morphology consistent with that typically seen in well-preserved footprints (Fig. 7C), such as those on the upper layer a few hundred meters to the west. The variability in track and trackway depth and the different character of the deeper tracks which, as noted, have steep vertical walls, indicate that the dinosaur feet penetrated more easily into the soft substrate in some areas than they did over most of the surface (Fig. 7).

Shallow tracks (depth 4 cm) mainly show radial ridges only (Fig. 3A and B). But as track depth increases (depth 11–16 cm), so does the number of new ridges that appear in the impressions (N=5–6; Fig. 3C). Where the track depth reaches 19.5–22 cm, elaborate tracks with a mosaic of features appear, and it is tempting to interpret some of these as digit and deep metatarsal–phalangeal pad impressions. In some tracks, large ridges appear to have formed between digits II and III, between digits III and IV, and/or between digit and heel pad impressions (Fig. 3G and H).

Thus, we tentatively identify the track makers based on those dinosaur footprints that have characteristic features of ungual, digit or heel pad impressions. Some well-preserved footprints from site III-1 show that they are tridactyl (Fig. 3F–J), and have the features of ornithopod prints, such as large, broad hind feet with blunt hoof and broad heel pad impressions between the ridges (Fig. 3F–H). This interpretation is supported by the fact that well-preserved, large, tridactyl ornithopod tracks occur on an overlying surface nearby.

The very obvious but misleading circular shape of these unusual dinosaur footprints only superficially resembles the reconstructed morphology of the sauropod manus of Farlow et al. (1989). In fact, this is not the first time there has been confusion between sauropod manus prints and ornithopod pes tracks (see Pittman, 1989, amended by Lockley et al., 1994; Pittman and Lockley, 1994). However, the manus prints of sauropods are more typically reniform (kidney shaped); in contrast, many ornithopod pes prints are overall sub-circular in shape and proportions (Leonardi, 1984; Farlow et al., 1989). Exemplar track No. 35 (Fig. 3G) from site III-1 particularly resembles the ornithopod footprints from site I, which occur at a level stratigraphically higher than site III (Huh et al., 2003; Fig. 1). Ornithopod body fossils are known from the Upper Cretaceous Neungju Group in the southeastern parts of the Korean peninsula (Huh

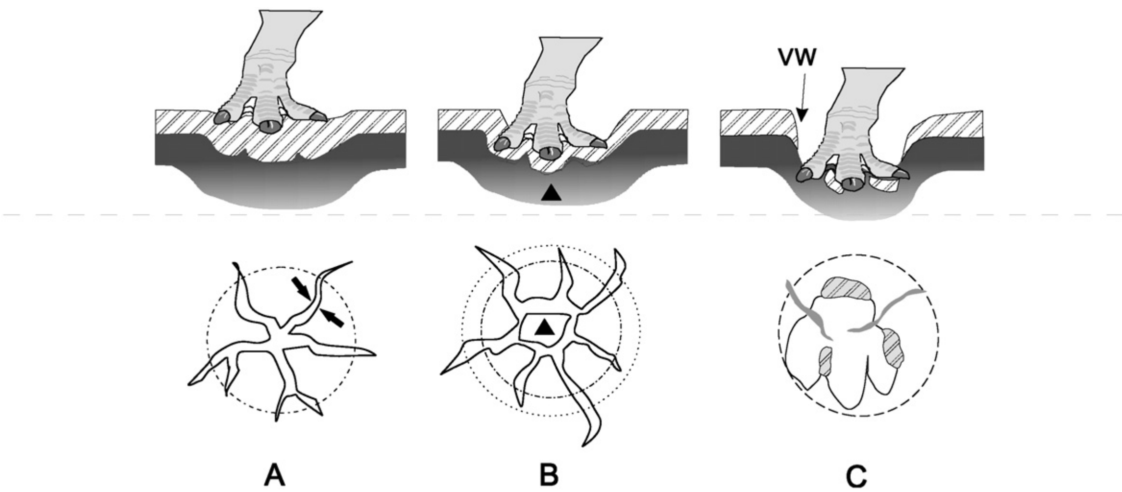

Fig. 7. Differential formation of undertracks with ridges depending on depth. (A) Relatively shallow undertracks lead to cracking of tuffaceous sand (diagonal lines) and molding of ridges in the underlying mud (grey). Arrows show that the angular change in direction of ridge margins is the same on both sides, supporting the evidence of cracking or 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 (▲). (C) Deepest penetration into the sand layer more completely creates true footprints, with interference caused by distorted fragments of the sand layer. VW = vertical wall seen in deep footprints.

et al., 2006) and many ornithopod tracks are known from the both the Neungju Group and Uhangri Formation (Huh et al., 2003). Therefore, one of the possible track making candidates is a large iguanodontoid, such as a hadrosaur, as was suggested by Huh et al. (2003).

However, several footprints found at site III-1 apparently have three sharp claw impressions (Fig. 3I and J). These also have the thick, broad digit impressions typical of ornithopods, but the sharp claw traces indicated that at least some of the track makers might have been theropods. The co-occurrence of ornithopod and theropod tracks is also inferred at site I as it is at many other tracksites globally, and neither track maker can be ruled out.

4.2. The internal ridges

These peculiar bipedal dinosaur footprints with gently curved cross-sections, which formed on a pliant, wet mud surface, are best explained as undertracks. In some cases, the sandy sediment from the overlying horizon still coats the ridges, having not been completely removed by excavation or weathering (Fig. 8B and C). Vertical striation of the shale comprising the ridges, created as sand grains slid through or over the underlying mud, shows that the presently exposed undertracks formed under the sandy layer (Lee and Lee, 2006). The substrate forming the ridges themselves is not different from the remainder of the exposed track surface (Fig. 3), indicating that its composing sediment was not emplaced from an overlying horizon. Moreover, because the ridges all connect to wrinkles at the rim, they all seem to have formed at the same time as the surface sediment was displaced. That is, as the foot of the track maker registered on the tuffaceous sand layer overlying the mud layer, undertracks with wrinkles and internal ridges were made at the interface between the tuffaceous sand and the mud layer (Fig. 7): the radial ridges seem to be the molds of radial cracks on the underside of the tuffaceous sand bed. If the underside of the sandy bed could be seen as the natural cast of these unusual footprint features, it would resemble the radial cracks described by Lockley et al. (1989). However, the tuffaceous sand weathers rather easily in comparison with the indurated black shale beneath, so no exposures of the underside can be excavated. This ‘radial cracks’ interpretation differs significantly from, and is far simpler than, the previously-proposed model of extrusion of the lower water-saturated mud upward through an overlying elastic layer (Lee and Huh, 2002) or the hypothesis of delamination of superficial layers of sediment on withdrawal of the track maker’s foot (Thulborn, 2004). It is also important to note that no radial crack features are associated with any of the undisturbed substrate between the underprints.

4.3. The trackways

Four trackways were recognized on the same surface at three sites (II, III-1, III-2; Figs. 4A and 5) and although many footprints were not interpreted as trackways at site III-1, most of the footprints are oriented in two major directions that are similar to those of the recognized trackways (i.e., both north–south and east–west) (Fig. 2). Poor preservation in some of the footprints that cannot be resolved into recognized trackways make identification difficult, but some individual footprints, such as No. 32, 35 and 101, do have distinct toe and heel impression that indicate that the directions of the two trackways are north and east (Figs. 2B, 3D, G and 5A–B) and the orientation of some isolated footprints (north), such as footprints

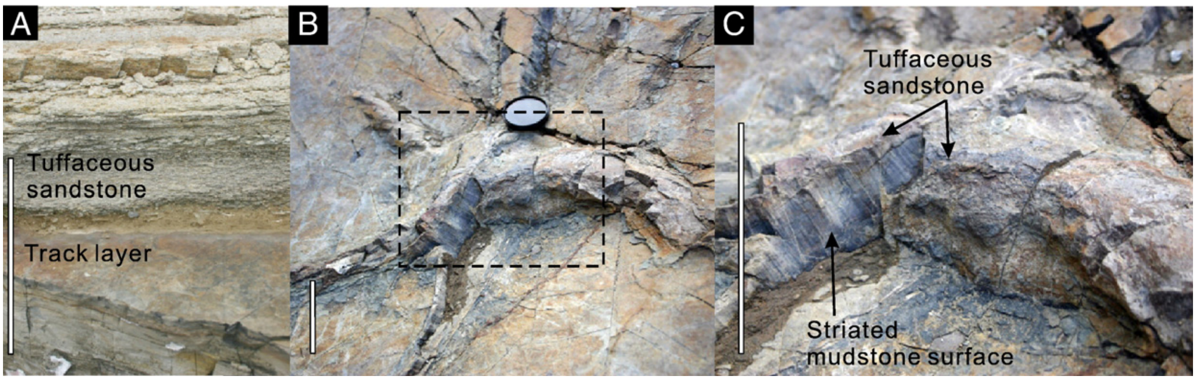

Fig. 8. (A) Tuffaceous sandstone covering the track layer. (B) An internal ridge coated with tuffaceous sandstone. (C) An enlarged photograph of rectangular area of photo B. The striated surface of mudstone indicates that the dinosaur walked on the upper sand layer. Sand grains pushed downward by the foot dragged through the underlying mud, creating the striations. Scale bar represents 10 cm.

No. 42, 49, 60, 83 and 86 match the trackway direction (Figs. 2 and 3H). Therefore, the main directions of the trackways were identified as north and east. The many unusual footprints at site III-1 were evidently left by dinosaurs crossing paths within a very short period of time, as indicated by the similar preservation (Figs. 2B and 3G).

Although average footprint diameter is about 77 cm, track size might have been exaggerated. In any event, underprints tend to be larger that the true prints – and the feet – that generated them. They are also harder to measure accurately because of their diffuse margins. Plausible foot lengths seem to be about 50 cm based on well-preserved foot impressions with well defined margins (such as No. 35; Fig. 3G) measured inside the footprint wall. Therefore, using the formulae of Thulborn (1990), the track making dinosaur is estimated to have been about 3 m high at the hip. The calculated velocities from two trackways are about 0.7 m/s with relative stride lengths (stride length/hip height) of 0.6 based on Alexander's (1976) formula. Because of the soft, pliable surface, dinosaur steps seem to have been rather short and the estimated velocities concomitantly low.

5. Conclusions

Many of the Cretaceous formations of southern Korean peninsula formed on emergent lake margins. The mud cracks usually found on most track layers in such environments have not been found at track site III (level 1). This means that while birds and pterosaurs left their tracks on a freshly emergent surface (that would become the black shale), the large dinosaurian track makers evidently did not walk on the same wet surface during the short exposure period as at other track sites. Instead, they walked later on a layer of overlying tuffaceous sand, creating the unusual, ridge-filled underprints (Fig. 6). If our interpretations are correct, the internal ridges of the dinosaur footprints from the Uhangri tracksite are molds of radial cracks on the underside of a tuffaceous sand bed on which large dinosaurs were walking (q.v., Lockley et al., 1989).

The shapes of both the deep and better preserved tridactyl footprints and trackway patterns, with regular spacing and high pace angulations, imply bipeds and not quadrupeds like sauropods. No evidence of swim tracks or a subaqueous environment is recognized, obviating the hypothesis that any track makers were buoyed by water. Likewise, we find no evidence for extrusion of mud, or delamination of superficial layers as various previous interpretations have suggested. The most parsimonious interpretation of the available evidence is that the unusual, ridged tracks are undertracks of tridactyl, bipedal dinosaurs made on a subaerially exposed tuffaceous sand that penetrated through to an underlying, previously tracked (by birds and pterosaurs) black mud.

Acknowledgements

This research was funded by a grant from the Korea Science and Engineering Foundation (KOSEF R01-2005-000-10060-0) and partly supported by Korea Research Foundation Grant (KRF-2004-015-C00590). We also thank Dr. Jerry Harris, Dixie State College for his helpful review.

References

Alexander, R.M., 1976. Estimates of the speeds of dinosaurs. Nature 261, 129–130.

Bird, R.T., 1944. Did *Brontosaurs* ever walk on land? Natural History 53, 60–67.

Chun, S.S., Chough, S.K., 1995. The Cretaceous Uhangri Formation, SW Korea: lacustrine margin facies. Sedimentology 42, 293–322.

Coombs Jr., W.P., 1980. Swimming ability of carnivorous dinosaurs. Science 207, 1198–1200.

Farlow, J.O., Pittman, J.G., Hawthorne, M., 1989. *Brontopodus birdi*, Lower Cretaceous sauropod footprints from the U.S. Gulf coastal plain. In: Gillette, D.D., Lockley, M.G. (Eds.), Dinosaur Tracks and Traces. Cambridge University Press, New York, pp. 371–394.

Gaillard, C., Bernier, P., Barale, G., Bourseau, J.-P., Buffetaut, E., Ezquerra, R., Gall, J.-C., de Broin, F., Renous, S., Wenz, S., 2003. A giant Upper Jurassic turtle revealed by its trackways. Lethaia 26, 315–322.

Gillette, D.D., Lockley, M.G. (Eds.), 1989. Dinosaur Tracks and Traces. Cambridge University Press, Cambridge. 454 pp.

Gradstein, F.M., Ogg, J.G., Smith, A., 2004. A Geologic Time Scale 2004. Cambridge University Press, Cambridge. 589 pp.

Henderson, D.M., 2004. Tipsy punters: sauropod dinosaur pneumaticity, buoyancy and aquatic habits. Proceedings of the Royal Society of London B 271 (suppl.), S180–S183.

Huh, M., Hwang, K.G., Paik, I.S., Chung, C.H., Kim, B.S., 2003. Dinosaur tracks from the Cretaceous of South Korea: distribution, occurrences and paleobiological significance. Island Arc 12, 132–144.

Huh, M., Lim, J.D., Paik, I.S., Hwang, K.G., Lee, Y.I., Paik, K.H., 2006. A research report on the Boseong dinosaur egg site, Korea. Korea Dinosaur Research Center, Gwangju. 229 p.

Hunt, A.P., Lucas, S.G., 2007. Tetrapod ichnofacies: a new paradigm. Ichnos 14, 59–68.

Hwang, K.G., 2001. Pterosaur and dinosaur tracks from the Late Cretaceous Uhangri Formation, Haenam, SW Korea. Ph.D. Dissertation, Chonnam National University, Gwangju, 182 p.

Hwang, K.G., Huh, M., Lockley, M., Unwin, D., Wright, J.L., 2002. New pterosaur tracks (Pteraichinidae) from the Late Cretaceous Uhangri Formation, SW Korea. Geological Magazine 139, 421–435.

Hwang, K.G., Huh, M., Paik, I.S., 2004. Sauropod trackways from the Cretaceous Jindong Formation at Docheon-ri, Changnyeon-geun, Gyeongsangnam-do, Korea. Journal of the Geological Society of Korea 40, 145–159 (in Korean, with English abstract).

Kim, C.B., Huh, M., Cheong, C.S., Lockley, M., Chang, H.W., 2003. Age of the pterosaur and web-footed bird tracks associated with dinosaur footprints from South Korea. Island Arc 12, 125–131.

Kim, J.Y., Kim, S.H., Kim, K.S., Lockley, M., 2006. The oldest record of webbed bird and pterosaur tracks from South Korea (Cretaceous Haman Formation, Changseon and Sinsu Islands): more evidence of high avian diversity in East Asia. Cretaceous Research 27, 56–69.

Lee, D.S., Lee, H.Y., 1976. Geological and geochemical study on the rock sequence containing oil materials in southwestern coast area of Korea. Korea Society of Economic and Environmental Geology 9, 45–74 (in Korean, with English abstract.).

Lee, Y.N., Huh, M., 2002. Manus-only sauropod tracks in the Uhangri Formation (Upper Cretaceous), Korea and their paleontological implications. Journal of Paleontology 76, 558–564.

Lee, Y.N., Lee, H.J., 2006. A sauropod trackway in Donghae-Myeon, Goseong County, South Gyeongsang Province, Korea and its paleobiological implications of Uhangri manus-only sauropod tracks. Journal of the Paleontological Society of Korea 22, 1–14.

Leonardi, G., 1984. Le impronte fossili di dinosauri. In: Bonaparte, J.F., Colbert, E.H., Currie, P.C., de Ricqlès, A., Kielan-Jaworowska, Z., Leonardi, G., Morello, N., Taquet, P. (Eds.), Sulle Orme dei Dinosauri. Erizzo Editrice, Venezia, pp. 161–186.

Lockley, M.G., Kukihara, R., Matsukawa, M., 2007. First report of pterosaur tracks from the Dakota Group (Cretaceous) of Colorado. Geological Society of America Abstracts with Programs 39 (5), 14.

Lockley, M.G., Matsukawa, M., Obata, I., 1989. Dinosaur tracks and radial cracks: unusual footprint features. Bulletin of the Natural Science Museum of Tokyo, Ser. C 15, 151–160.

Lockley, M.G., Pittman, J.G., Meyer, C.A., Santos, V.F., 1994. On the common occurrence of manus-dominated sauropod trackways in Mesozoic carbonates. Gaia 10, 119–124.

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

Milner, A.R.C., Lockley, M.G., Kirkland, J.I., 2006. A large collection of well-preserved theropod dinosaur swim tracks from the Lower Jurassic Moenave Formation, St. George, Utah. In: Harris, J.D., Lucas, S.G., Spielmann, J.A., Lockley, M.G., Milner, A.R.C., Kirkland, J.I. (Eds.), The Triassic–Jurassic Terrestrial Transition. New Mexico Museum of Natural History and Science Bulletin, vol. 37, pp. 315–328.

Moon, H.-S., Kim, Y.-H., Kim, J.-H., You, J.-H., 1990. K–Ar ages of alunite and sericite in altered rocks, and volcanic rocks around the Haenam area, southwest Korea. Journal of the Korean Institute of Mining Geology 23, 135–141.

Nadon, G., 1993. The association of anastamosed fluvial deposits and dinosaur tracks, eggs and nests: implications for the interpretation of floodplain environments and a possible survival strategy for ornithopods. Palaios 8, 31–44.

Paik, I.S., Kim, H.J., Lee, Y.I., 2001. Dinosaur track-bearing deposits in the Cretaceous Jindong Formation, Korea: occurrence, palaeoenvironments and preservation. Cretaceous Research 22, 79–92.

Paik, I.S., Huh, M., Park, K.H., Hwang, G.K., Kim, K.S., Kim, H.J., 2006. Yeosu dinosaur track sites of Korea: the youngest dinosaur track records in Asia. Journal of Asian Earth Sciences 28, 457–468.

Pittman, J.G., 1989. Stratigraphy, lithology, depositional environment and track type of dinosaur track-bearing beds of the Gulf Coastal Plain. In: Gillette, D.D., Lockley, M.G. (Eds.), Dinosaur Tracks and Traces. Cambridge University Press, Cambridge, pp. 136–153.

Pittman, J.G., Lockley, M.G., 1994. A review of sauropod dinosaur tracksites of the Gulf of Mexico Basin. Gaia 10, 95–108.

Thulborn, R.A., 1990. Dinosaur Tracks. Chapman & Hall, London. 410 p.

Thulborn, T., 2004. Extramorphological feature of sauropod dinosaur tracks in the Uhangri Formation (Cretaceous), Korea. Ichnos 11, 295–298.

Whyte, M.A., Romano, M., 2001. A dinosaur ichnocoenosis from the Middle Jurassic of Yorkshire, UK. Ichnos 8, 233–234.

Yang, S.-Y., Lockley, M.G., Greben, R., Erickson, B.R., Lim, S.-K., 1995. Flamingo and duck-like bird tracks from the Late Cretaceous and Early Tertiary: evidence and implications. Ichnos 4, 21–34.