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Lithographus, an Abundant Arthropod Trackway from the Cretaceous Haenam Tracksite of Korea

Nicholas J. Minter [a], Martin G. Lockley [b], Min Huh [c], Koo-Geun Hwang [c] & Jeong Yul Kim [d]

[a] Department of Geological Sciences, University of Saskatchewan, Saskatoon, Saskatchewan, Canada

[b] Dinosaur Tracks Museum, University of Colorado, Denver, Colorado, USA

[c] Faculty of Earth Systems and Environmental Sciences and Korea Dinosaur Research Center, Chonnam National University, Gwangju, Korea

[d] Department of Earth Science Education, Korea National University of Education, Cheongwon, Korea

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Nicholas J. Minter,[1] Martin G. Lockley,[2] Min Huh,[3] Koo-Geun Hwang,[3] and Jeong Yul Kim[4]

[1]*Department of Geological Sciences, University of Saskatchewan, Saskatoon, Saskatchewan, Canada*
[2]*Dinosaur Tracks Museum, University of Colorado, Denver, Colorado, USA*
[3]*Faculty of Earth Systems and Environmental Sciences and Korea Dinosaur Research Center, Chonnam National University, Gwangju, Korea*
[4]*Department of Earth Science Education, Korea National University of Education, Cheongwon, Korea*

Trackways ascribed to *Lithographus hieroglypichus* and attributed to pterygote insects are described from the Cretaceous Uhangri Formation of Korea. The locality is part of the Haenam Tracksite at the Uhangri Dinosaur Museum Complex, which is famous for dinosaur, pterosaur and bird tracks. This represents the first report of the arthropod trackway *Lithographus* from the Cretaceous of Korea. The trackways are preserved in cherty mudstones that formed in the margins of an alkaline lake in the vicinity of active volcanoes. Numerous trackways are preserved at a single horizon. This probably reflects a brief period of exposure of balanced-fill lake margin sediments, which provided a window of opportunity for the production and preservation of trackways of insects that inhabited the region rather than a sudden influx of insects into the area related to volcanism and a productivity bloom.

Keywords Arthropod, Continental, Ichnology, Insect, Lake margin, Trackway

INTRODUCTION

The tracksite locality at the Uhangri Dinosaur Museum Complex in Haenam-gun County (Figs. 1A–C), situated in the Haenam Basin, is one of the most interesting vertebrate tracksites in Asia. In 1998 it was designated as Haenam Tracksite Natural Monument No. 394. The track-bearing units, occurring at several levels in the Uhangri Formation, have been intensively studied and have produced abundant tracks of dinosaurs, pterosaurs and birds. Most dinosaur tracks have been attributed to the ichnogenus *Caririchnium* (Hwang, 2001). There has also been heated debate about some unusual footprints first considered to be those of swimming sauropods (Lee and Huh, 2002; Thulborn, 2004; Lee and Lee, 2006) but later reinterpreted as large ornithopod undertracks caused by progression over unusual substrates (Hwang et al., 2008; Song, 2010). The site has also produced the world's largest pterosaur tracks, assigned to the ichnogenus *Haenamichnus* (Lockley et al., 1997; Hwang et al., 2002) and trackways (*Uhangrichnus chuni* and *Hwangsanipes choughi*) attributed to birds with webbed feet (Yang et al., 1995).

In addition, the site reveals a single horizon with a high density of arthropod trackways. This material has previously only been illustrated briefly and without detailed comment. The first reports and illustrations of the material appeared in an unpublished research report (Huh et al., 1998) compiled at the time the site was being excavated prior to construction of the Uhangri Dinosaur Museum Complex. Subsequently, Hwang et al. (2002, fig. 3) published a photograph of one of these trackways but did not assign it to any ichnotaxon. No other description of these trackways exists, and they have not been assigned to an appropriate ichnotaxon. Herein, we provide the first detailed description of these trackways and discuss their paleoecological significance.

GEOLOGICAL SETTING

The Haenam tracksite locality occurs within the Uhangri Formation, which is the middle unit of the Haenam Group in the Haenam Basin of Korea. The Uhangri Formation is underlain by an andesitic tuff with andesite intrusions and flows and is overlain by the Hwangsan Tuff and Jindo Rhyolite (Lee and Lee, 1976; Chun and Chough, 1995; Hwang et al., 2008). Radiometric dating of tuffs above and below the Uhangri Formation places age constraints of 96 to 81 Ma (mid-Cenomanian to Early Campanian) on the trace fossil-bearing sequence (Moon et al., 1990; Kim et al., 2003).

Address correspondence to Nicholas J. Minter, Department of Geological Sciences, University of Saskatchewan, 114 Science Place, Saskatoon, Saskatchewan, S7N 5E2, Canada. E-mail: nic.minter@usask.ca

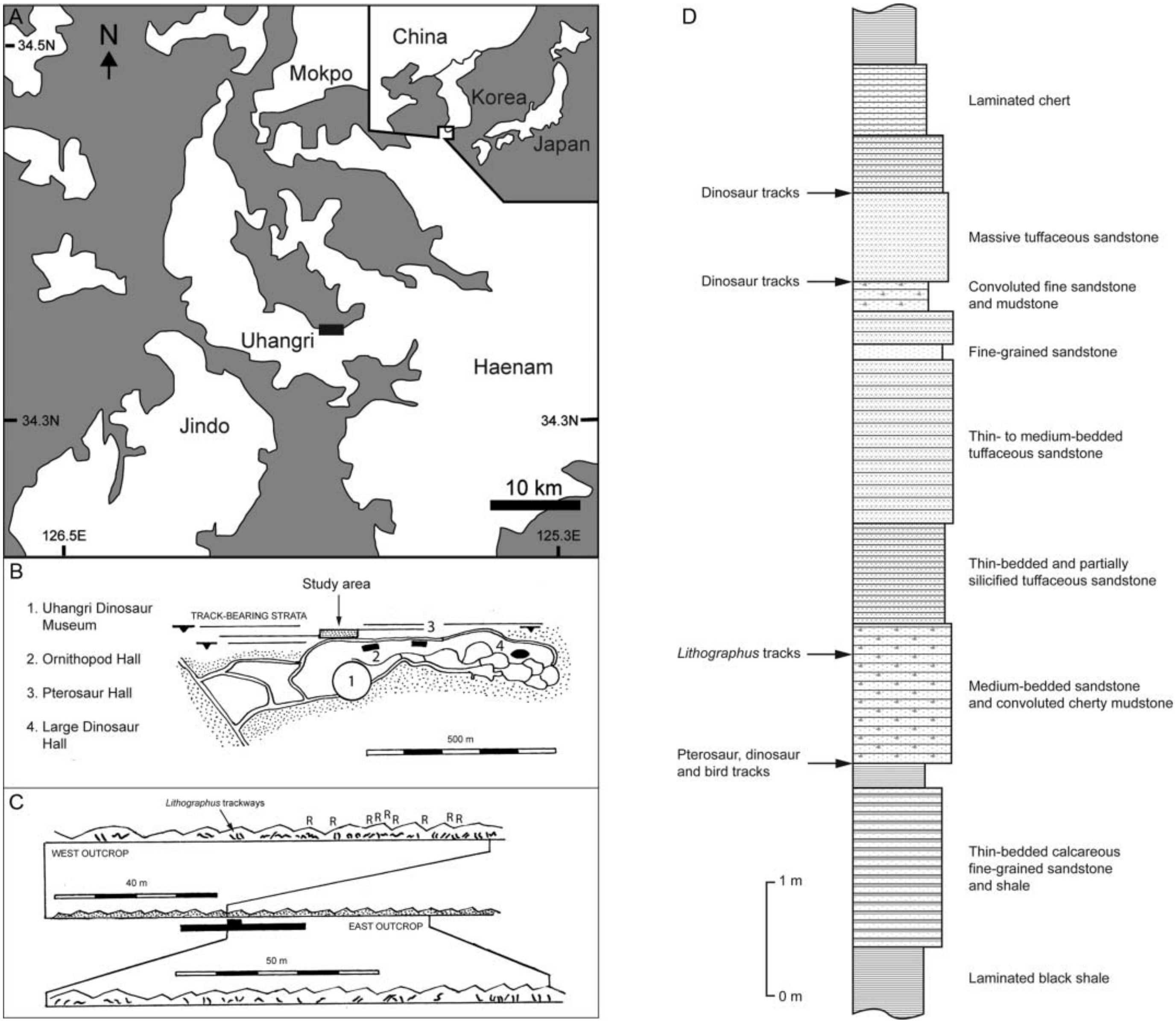

FIG. 1. **A:** Location of the Haenam tracksite at the Uhangri Dinosaur Museum Complex (black rectangle). **B:** Map of the study locality at the Uhangri Dinosaur Museum Complex. **C:** Linear outcrop of the *Lithographus*-bearing layer (stippled, at half scale) parallel to interpretative trail boardwalk and viewing platform (in black). Details of west and east outcrops are also shown with locations of approximately 80 conspicuous *Lithographus* trackways and those from which replicas (R) were obtained through molding. **D:** Schematic stratigraphic section of the Upper Cretaceous Uhangri Formation. *Lithographus* trackways occur at a single horizon and dinosaur, pterosaur, and bird tracks have been found in three layers. **A** and **D** redrawn after Hwang et al. (2002).

The sedimentology of the Uhangri Formation was described in detail by Chun and Chough (1995). It consists mainly of an epiclastic sequence of conglomerates, sandstones, cherty mudstones, black shales and volcaniclastics. The upper part consists of laminated dark gray to black shale, crudely stratified sandstone, convoluted sandstone/cherty mudstone and massive sandstone (Chun and Chough, 1995). Tuffaceous sandstones also occur within the study section at the Uhangri Dinosaur Museum Complex (Fig. 1D).

Vertebrate tracks occur at three horizons in the study section. The most abundant vertebrate tracks occur in the lowermost of these horizons (Figs. 1D, 2A), which consists of laminated black shales with plants and nonmarine ostracods. This is overlain by a unit of convoluted sandstones/cherty mudstones (Figs. 1D, 2; facies S/M2 of Chun and Chough, 1995). This facies consists of couplets of sandstone and cherty mudstone with transitional boundaries between the sandstone and base of the cherty mudstone and sharp upper boundaries (Fig. 2B).

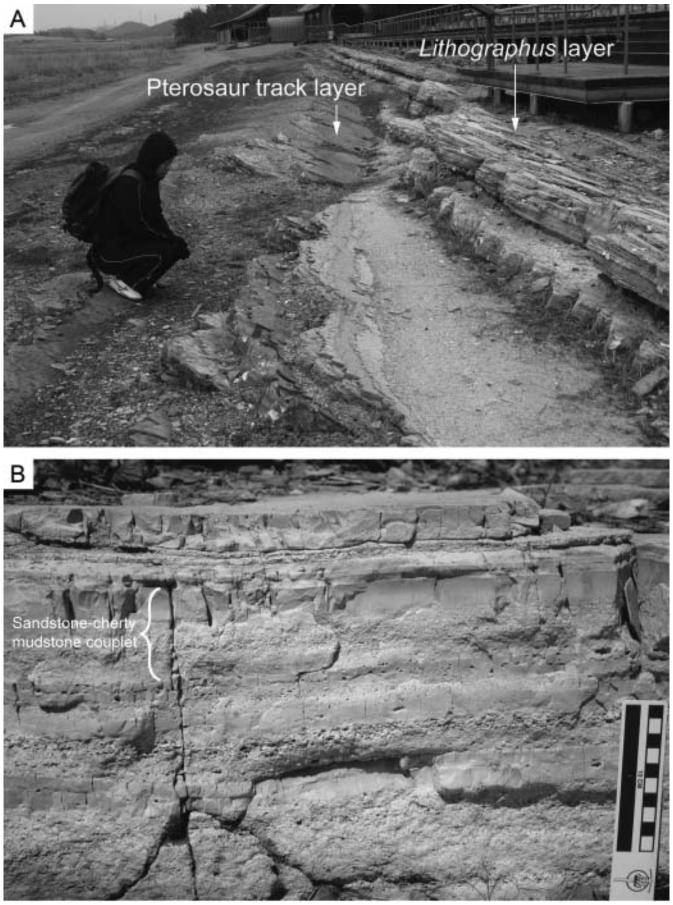

FIG. 2. **A:** Study locality along the northern margin of the Uhangri Dinosaur Museum Complex showing the position of the *Lithographus* trackway layer and vertebrate track layer. **B:** *Lithographus*-bearing lithology. Couplets of sandstone and convoluted cherty mudstone. *Lithographus* trackways occur at the top of one of the cherty mudstones beds. (See Color Plate XII.)

Symmetrical ripples are present on the surfaces of the sandstones (Chun and Chough, 1995). Within this unit, the arthropod trackways are preserved on a single horizon of the cherty mudstone that stretches along strike for 90 m but is only exposed down dip for 0.3–0.4 m (Figs. 1C, 2A). The trackway surface therefore represents an area of approximately 30 m^2. *Planolites* and *Skolithos* have also been reported from the arthropod trackway-bearing unit (Hwang et al., 2002).

PALEOENVIRONMENTAL INTERPRETATION

The arthropod trackway-bearing unit is interpreted to have been deposited in a lake margin setting (Chun and Chough, 1995), which was probably a balanced-fill lake. In balanced-fill lakes, the rate of sediment and water supply is approximately equal with that of potential accommodation. As such, balanced-fill lakes are subject to climatically driven fluctuations in lake level, whereas such fluctuations are minimal in overfilled lakes and underfilled lakes show greater evidence of desiccation (Bohacs et al., 2000). Balanced-fill and underfilled lakes are commonly alkaline or saline and chemically stratified (Bohacs et al., 2000), and the lake waters at the time of deposition of the Haenam arthropod trackway-bearing unit are inferred to have been alkaline and saturated with dissolved silica from the nearby volcanism (Chun and Chough, 1995). The sandstones in the sandstone/cherty mudstone couplets are interpreted to have been deposited by density flows, and such perturbations are suggested to have disrupted the chemical balance of the lake water, which resulted the precipitation of silica in the cherty mudstones (Chun and Chough, 1995). Associated symmetrical ripple marks indicate wave action and that the water was shallow. The single horizon with arthropod trackways suggests that emplacement of the trackways was enabled by temporary exposure of the lake margin sediment. The lack of desiccation features indicates that exposure was probably only brief and is consistent with a balanced-fill lake.

SYSTEMATIC ICHNOLOGY

The trackway terminology used herein follows that of Trewin (1994), Braddy (2001) and Minter et al. (2007a).

Ichnogenus *Lithographus* Hitchcock, 1858

Type ichnospecies: *Lithographus hieroglyphicus* Hitchcock, 1858.

Lithographus hieroglyphicus Hitchcock, 1858
Figure 3

***Diagnosis*:** Trackways consisting of staggered to alternating series of up to three tracks, at least one of which is linear to curvilinear, whereas they may also be ovoid or crook shaped. The tracks in a series have different orientations. The longest track is parallel to postero-lateral to the mid-line of the trackway and is either the middle or the inner track. The shortest track is oriented antero-laterally, or parallel, to the mid-line and is either the inner or the middle track. The intermediate-sized track is generally oriented perpendicular to the mid-line but can also be oriented postero-laterally or antero-laterally. Straight or sinusoidal single or paired medial impressions may also be present (after Minter and Braddy, 2009).

***Material*:** Approximately 80 trackways ranging from 0.1 to 1.0 m in length and of variable orientation are preserved *in situ* at the Uhangri Dinosaur Museum Complex (Fig. 1C). Latex molds and the corresponding plaster replicas of six of these trackway segments are reposited at the University of Colorado Denver Dinosaur Tracks Museum (CU 214.207-214.212). The four *in situ* trackways figured correspond to CU 214.208, CU 214.209, CU 214.211 and CU 214.212 (Fig. 3).

***Description*:** Trackways comprise staggered to alternating series of two to three linear tracks with differing orientations. The two most commonly observed tracks are those oriented parallel to postero-laterally to the mid-line of the trackway and those oriented perpendicular to postero- or antero-laterally to

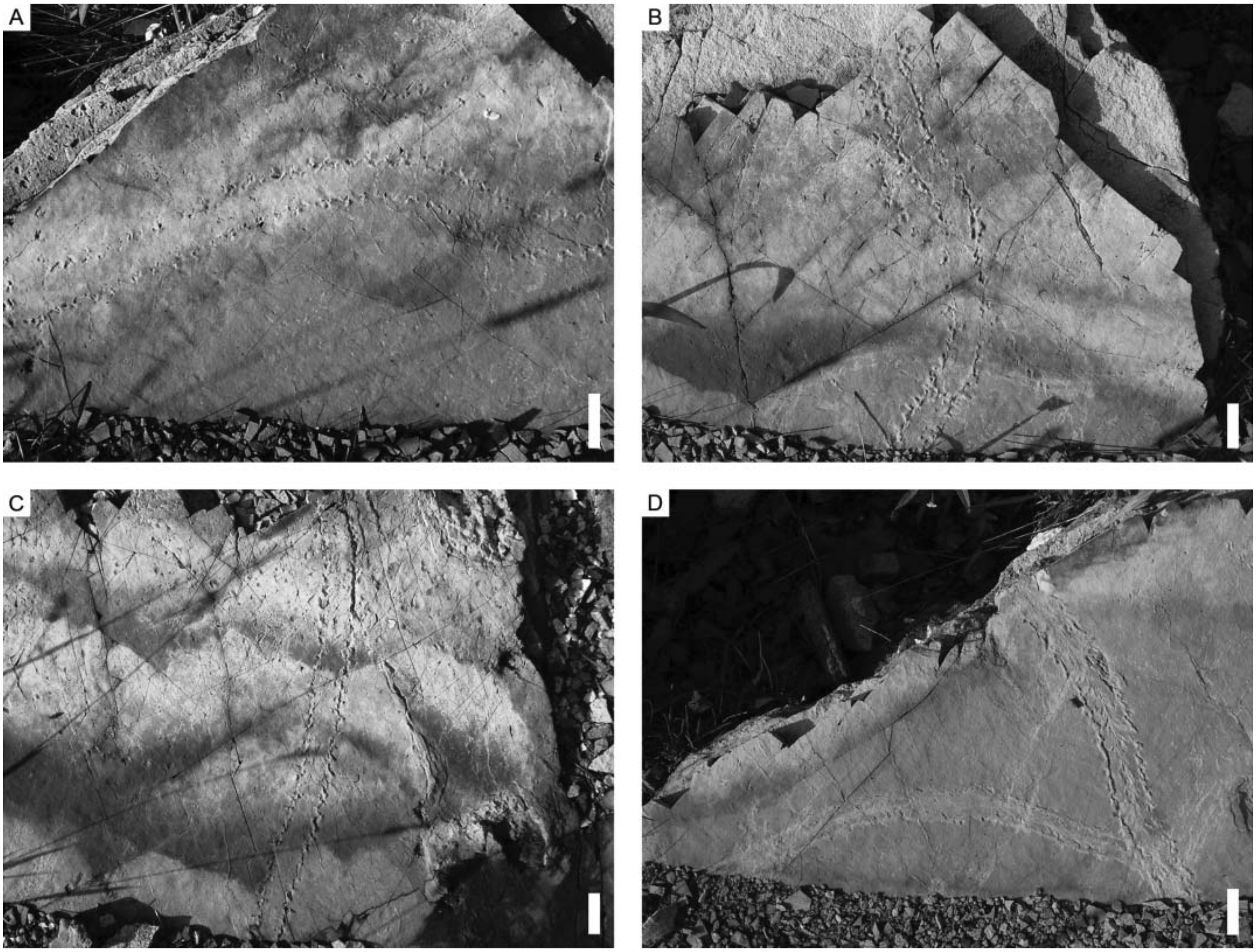

FIG. 3. Field photographs of *Lithographus* trackways from which replicas were made. **A:** Trackways showing well-spaced series of tracks (replica, CU 214.209). **B:** Trackway showing closely spaced series of tracks (replica, CU 214.212). **C:** Trackway showing closely spaced series of tracks (replica, CU 214.208). **D:** One trackway with a chevroned medial region and another where the track series have merged into two parallel track rows (replica, CU 214.211). Scale bars are 40 mm. (See Color Plate XIII.)

the mid-line. The latter are situated more laterally, whereas a third track situated medial to the other two is only rarely observed. The external widths of the majority of trackways range from 32–42 mm; however, smaller and more poorly preserved trackways with external widths of 22–27 mm are also present. Stride varies from 10–20 mm, and this results in some trackways having well-spaced series (Fig. 3A) and others where series are beginning to merge (Figs. 3B–C). The middle tracks oriented parallel to postero-laterally to the mid-line of the trackway tend to be longest, from 5–9 mm in length, whereas the outer tracks that are oriented perpendicular to postero- or antero-laterally are 3–7 mm long. The inner tracks are the shortest, from 2–5 mm in length. Bifurcated distal terminations are observed in some tracks. The series of some of the smaller trackways have merged into two parallel lines, and a chevroned medial region is also present in some examples (Fig. 3D).

***Remarks*:** The presence of staggered to alternating series of up to three linear tracks with differing orientations is characteristic of *Lithographus*. This ichnogenus was first described by Hitchcock (1858) with several other similar ichnotaxa including *Hexapodichnus* and *Copeza*. *Permichnium* is a further similar ichnogenus that was erected by Güthorl (1934) for trackways with alternating series of two "V-forming" tracks. The ichnotaxonomy of these ichnogenera was reviewed recently by Minter and Braddy (2009) based on material from the Permian of Germany and the southwest United States. Ichnospecies of *Lithographus*, *Hexapodichnus*, *Copeza* and *Permichnium* were observed to intergrade with one another and/or ultimately with the type ichnospecies *Lithographus hieroglyphicus* based on the positions of the individual tracks within a series or the loss of tracks, resulting in just two "V-forming" tracks. Such ichnotaxa were therefore considered to be junior synonyms of *Lithographus hieroglyphicus*. *Copeza triremis* was retained as a distinct ichnogenus and ichnospecies. Hitchcock (1858) also described various other ichnotaxa that probably represent undertracks of *Lithographus*. Some of the names have priority but may be considered as a *nomina dubia* because they are based on incomplete material.

DISCUSSION

The features of *Lithographus*, with alternating series of three linear tracks with differing orientations are indicative of a hexapodal animal with linear distal tarsi. *Lithographus* is generally attributed to pterygote insects and has been reproduced experimentally by cockroaches (Davis et al., 2007). It can also be produced by a variety of other insects, including beetles. Within a series, the longer middle tracks that are oriented parallel to postero-laterally to the mid-line of the trackway correspond to the hind-limbs; the outer intermediate length tracks that are oriented perpendicular to postero- or antero-laterally to the mid-line correspond to the middle limbs; and the shorter inner tracks that are oriented antero-laterally to the mid-line are produced by the fore-limbs. Distal bifurcations are also observed in some tracks and correspond with the bifurcated linear distal tarsi of pterygote insects. Apterygote insects have pointed distal tarsi and tend to produce trackways such as *Stiaria*, with alternating series of three circular tracks (Minter and Braddy, 2006, 2009).

Trackways attributable to *Lithographus* have been reported from the Carboniferous of Canada (Keighley and Pickerill, 1998), the Permian of the United States (Lucas et al., 2005; Minter et al., 2007b; Minter and Braddy, 2009), Germany (Schmidtgen, 1928; Güthorl, 1934; Boy, 1976; Walter, 1983; Minter et al., 2007c) and Russia (Holub and Kozur, 1981), the Triassic of the United States (Hitchcock, 1858), the Jurassic of Argentina (de Valais et al., 2003) and the Cretaceous of the United States (Lockley et al., 2002). Trackways of the same form are also produced by modern insects (Davis et al., 2007). This is the first report of *Lithographus* from the Cretaceous of Korea. The Cretaceous Jinju Formation of Korea preserves the arthropod trackway *Diplichnites* together with invertebrate burrows, trails and sauropod tracks in a similar lake margin setting (Kim et al., 2005).

The trackways are preserved on an upper bedding plane surface, but many of the features are preserved in positive relief (Fig. 3). This suggests that the substrate was "sticky" at the time of trackway production. Chun and Chough (1995) note the presence of convoluted structures in the cherty mudstones of the Uhangri Formation and suggested that they formed when the inorganically precipitated silica was in a semi-consolidated, gel-like state. Such substrate conditions could explain the slightly unusual form and preservation of the arthropod trackways. In some trackways, the stride length is short relative to the external width of the trackways, and this results in the series beginning to merge (Figs. 3B–C), whereas in others the series are clearly separated and distinct (Fig. 3A). Similar phenomena have been observed in *Lithographus* trackways from the Permian of New Mexico (Minter and Braddy, 2009, text-fig. 17) and are considered to represent a change in the moisture content and consolidation of the substrate with the less consolidated substrate making progression more difficult, and so the series are more closely spaced. Chevroned medial regions and track series merging into parallel track rows are also present in some examples (Fig. 3D), suggesting that the sediment was soft at their particular time of production.

The occurrence of multiple trackways at a single horizon could be related to a window of opportunity and enhanced preservation potential or a sudden influx of insects into the overall environment. The sediments preserving the trackways were deposited subaqueously in a lake margin setting, although the trackways were made by terrestrial insects and must have been emplaced at a time of subaerial exposure or while there was a thin film of water covering the sediment. The lack of desiccation features suggests that any period of exposure was short. Trace fossils have been described in association with volcaniclastics in lake margin settings from the Carboniferous of Germany and the Czech Republic (Walter, 1982; Turek, 1989; Mikulas, 1999) and from standing water bodies on floodplains from the Silurian of the United Kingdom (Marriott et al., 2009). In the latter case, trace fossil diversity was found to be greater in the tuffs compared to the surrounding fluvial sediments, and it was suggested that this could be due to enhanced preservation potential or opportunistic colonization related to phytoplankton blooms associated with volcanic events. Tuffaceous units occur within the Uhangri Formation; however, they are above the arthropod trackway-bearing horizon. Therefore, rather than an influx of insects into the environment related to a productivity bloom due to volcanic ash, the occurrence of the single horizon with multiple arthropod trackways probably signifies a window of opportunity for the emplacement of trackways and their enhanced preservation potential due to the cherty nature of the mudstones.

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