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A giant sauropod footprint from the Nemegt Formation (Upper Cretaceous) of Mongolia

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ABSTRACT

An expedition to the Nemegt Formation in 2007 discovered new footprint sites at the Nemegt Locality. The sites contained natural-cast tracks identifiable as those of hadrosaurs, tyrannosaurs, and sauropods. Among the sauropod tracks was the best-preserved pes print yet described from the Late Cretaceous of Mongolia. The footprint is referred to *Brontopodus* sp. on the basis of footprint morphology, age, and potential trackmakers from the same formation. Size estimations based on the track indicate the trackmaker had an acetabular height of approximately 3.0–3.5 m. As such, the size of the trackmaker exceeds that of any Mongolian dinosaur yet reported from skeletal material.

1. Introduction

1.1. The Nemegt track record

The Nemegt Formation of Mongolia is notable for its diverse assemblage of both dinosaur body fossils and footprints (Currie et al., 2003; Currie, 2016; Chinzorig et al., 2017, this volume; Eberth, 2017, this volume; Evans et al., 2017, this volume; Fanti et al., 2017, this volume; Nakajima et al., 2017, this volume; Ishigaki et al., 2010). The majority of ichnites reported from the Nemegt Formation are thought to result from sand or silt that infilled footprints originally made in mud. Because the lithified sand infillings are more resistant to erosion, than the underlying mudstone, the track casts (convex hyporeliefs) weather out easily. As a result, the tracks are typically found as unassociated casts (Currie et al., 2003; Ishigaki et al., 2010). Although rare, some trackway-bearing surfaces tentatively assigned to the Nemegt Formation have been reported (Ishigaki et al., 2010). The dinosaurian tracks belong overwhelmingly to ornithopods and next most commonly to theropods. Footprints attributed to ankylosaurs and sauropods have also been reported, although these are significantly less common.

Currie et al. (2003) described two sauropod pes footprints. Both were sandstone casts and included digit impressions for the first four toes (Currie et al., 2003: their Fig. 6). The better preserved of these two ichnites is a right pes print with vertical margins along the anterior, medial, and lateral surfaces. These vertical margins reflect the depth of the track: i.e., the height of the track wall. The posterior surface was not particularly distinct, and the ventral surface was damaged. This footprint is longer than wide and bears clear impressions of scales above the claw marks. The second ichnite described by Currie et al. (2003) consists of only the anterior portion of a left pes print. It bears three definite digits, and a possible fourth. Claw impressions are clear for digits I–III, and digit pads are present on digits I and II. Currie et al. (2003) referred the tracks to the titanosaur *Opisthocoelicaudia*.

Ishigaki et al. (2010) reported additional sauropod ichnite casts from the Nemegt Formation. These large tracks possess four distinct claw marks and four distinct digit impressions, with a vaguer fifth digit impression usually discernible (Ishigaki et al., 2010). In the case of two of these tracks, slipping traces were present for all five digits, identified as such by the outward lateral (as opposed to vertical) incline of the traces, relative to the top surface of the cast (Lockley, 2007; Ishigaki et al., 2010). The general outlines of the tracks were described as either elliptical or triangular, and the triangular tracks were referred to as *Brontopodus*-type (no similar taxonomic assignment was offered for the elliptical tracks) (Ishigaki et al., 2010). Nakajima et al. (2017, this volume) described four additional sauropod pes tracks and the first sauropod manus print from the Nemegt Formation.

1.2. Sauropod pes osteology

Osteologically, the sauropod tarsus is composed of an astragalus and calcaneum, and the five metatarsals form a broad, shallow arch. The pes is oriented in a semi-plantigrade fashion, with the metatarsus typically reconstructed as angled somewhere between forty-five and fifty degrees relative to the horizontal. Tracks show that a large cushioning heel pad, similar to that of elephants, supported the metatarsus (Bonnan, 2005; Wright, 2005). Expanded articular facets indicate the pedal phalanges

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were much more capable of flexion, particularly dorsoventral flexion, than were the phalanges on the manus (Bonnan, 2005; Gonzalez Riga and Calvo, 2009). The asymmetry so characteristic of the sauropod pes is caused by differences in the length and robustness of each individual metatarsal, and in the lengths and orientations of the phalanges. Bonnan (2005) suggests this asymmetry may have evolved to either retain the use of the plantar flexors or as a more effective structure for distributing weight. The semi-plantigrade orientation of the pes is due to reorientation of the astragalus in relation to the tibia (Bonnan, 2005). The sauropod pes is also characterised by a strong lateral orientation, which results in trackways where the digits and long axis of each pes are rotated outward (relative to the trackway midline) (Lockley, 2007).

2. Lithology and depositional environment

The Nemegt Formation is the youngest of the Cretaceous formations present in the Gobi Desert (Upper Campanian-Lower Maastrichtian) (Gradziński et al., 1977; Eberth et al., 2009; Eberth, 2017, this volume; Fanti et al., 2017, this volume). Unlike the red beds of the older Djadokhta Formation (as well as the Baruungoyot Formation), the sandstones of the Nemegt Formation are composed predominantly of light, poorly cemented sands that typically vary from yellow to grey-brown (Eberth et al., 2009; 2017, this volume; Fanti et al., 2017, this volume). The sediments of the Nemegt Formation are indicative of a fluviolacustrine depositional setting. Fossil-rich deposits within the Nemegt Formation predominantly belong to channels, with overbank and ephemeral lake deposits being less common but still prevalent (Eberth et al., 2009, Eberth, 2017, this volume; Fanti et al., 2012).

The Nemegt locality is a particular series of Nemegt Formation outcrops on the northern rim of the Nemegt Basin (Currie et al., 2003; Fanti et al., 2017, this volume). At the Nemegt locality, footprints are normally found in strata composed of sand or silt-sized sediments, typically deposited as either point or channel bars. Siltstones, often intercalated with fine-grained sands, are indicative of overbank deposits, and localized mudstones are believed to have originated from the deposition of suspended particles in ephemeral lakes or abandoned channels (Currie et al., 2003; Nakajima et al., 2017, this volume). The footprint-bearing horizons often contain numerous sedimentary structures, including scoured surfaces, fining-upward sequences, trough cross-stratification, and climbing ripples (Currie et al., 2003; Eberth, 2017, this volume).

Unfortunately, the Nemegt locality footprints are exposed by the erosion of vertical sandstone cliff faces (Fig. 1), and are commonly found after having fallen to down-slope talus piles. The tracks are frequently badly damaged from their falls. Given the sheer volume of footprints present at the locality, it seems likely that many of the tracks were originally part of still-buried trackways, which cannot be observed because the erosional circumstances lead to only the gradual exposure of individual tracks (rather than large planar surfaces).

3. Description

In 2007, a 'Dinosaurs of the Gobi' (Nomadic Expeditions) field team discovered numerous dinosaur-footprint-bearing sites at the Nemegt Locality. Among the eroded tracks are numerous large tridactyl footprints (Fig. 2) and over a dozen sauropod footprints. Most of the tridactyl footprints have a form consistent with those of large ornithopods (relatively short digits with wide interdigital angles and blunt ungual traces). Presumably, these tracks were made by hadrosaurs (Nakajima et al., 2017, this volume). However, no definitive hadrosaur manus tracks have been identified, and it should be noted that the rare Nemegt theropod *Deinocheirus* is now understood to have had a pes morphology strikingly similar to that of hadrosaurs (Lee et al., 2014), such that *Deinocheirus* and hadrosaur tracks might be expected to be indistinguishable in most regards. Less common are large (total track length > 55 cm) tridactyl tracks with narrow digits, small interdigital angles, and more pointed claws. These tracks are definitively those of large non-deinocheirid and non-therizinosaur theropods, and the only such theropods known from Nemegt are tyrannosaurs (*Alioramus* and *Tarbosaurus*).

The single best preserved sauropod footprint yet described from the Nemegt Formation was discovered at Footprint Site 40 (FS40) (Fig. 3, and see also Nakajima et al., 2017, this volume). The site is located at 43° 29′ 58.5″ N, 101° 3′ 40.6″ E, is approximately 1502 m in elevation, and lies within the lower Nemegt Formation (Eberth, 2017, this volume; Fanti et al., 2017, this volume). It differs from other footprint sites in that the original track impressions appear to have been made in sediments composed of fine grained sands and silts, very similar to the sediments that make up the natural casts themselves. FS40 is interpreted as having formed in or near a channel that was abandoned long enough for trackways to be made before sedimentation was reactivated. This interpretation is based on the similarity of the sediments forming the natural casts and the surrounding substrate.

The FS40 sauropod cast is of a right pes print, and is similar in basic morphology to other published sauropod footprints from the Late Cretaceous of Mongolia and elsewhere in Asia (see the preceding discussion of taxonomy). It is longer than wide (760 × 620 cm), with a large and distinct heel pad impression, a feature that is common to sauropod footprints (Farlow et al., 1989) but undescribed in any previous Mongolian sauropod track (Currie et al., 2003; Ishigaki et al., 2010). The depth of the track (17.5 cm) is relatively shallow, suggesting that the substrate was resistant to vertical compression. The three-dimensional forms of the digital pads and claws are preserved in the mold. However, the quality of the cast has been subsequently diminished by erosion. Impressions of digit pads are clearly present on digits I–III. A slightly eroded pad impression is also present on (Farlow, 1992)

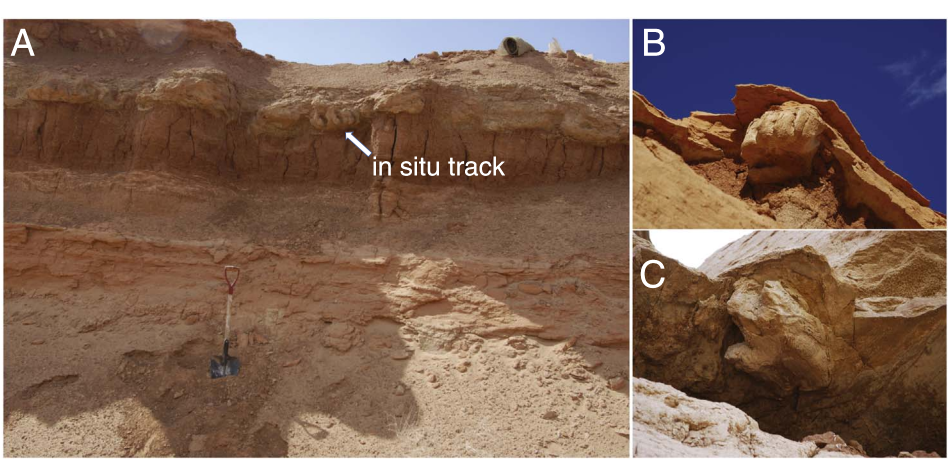

Fig. 1. In situ tracks at Nemegt are exposed on the undersurface of a sandstone layer, as the below cliff face erodes vertically. Tracks observed in situ include sauropod pes tracks at FS06 (A) and FS30 (B) and large tridactyl tracks at FS30 (C), which are presumed to be those of hadrosaurs.