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Dinosaur habitats from Upper Cretaceous eolian deposits in the Gobi desert, Mongolia

Mototaka Saneyoshi[1], Khishigjav Tsogtbaatar[2], Rinchen Barsbold[2], Tsogtbaatar Chinzorig[2], Buuvei Mainbayar[2], Hirotsugu Nishido[1], Shinobu Ishigaki[1]

[1]Faculty of Biosphere – Geosphere Science, Okayama University of Science, 1-1 Ridai-cho, Kita-ku, Okayama, 700-0005, Japan
[2]Institute of Paleontology, Mongolian Academy of Sciences, P.O.B 46/650, S. Danzan Street 3/1, 4th khoroo, Chingeltei district, Ulaanbaatar – 15160, Mongolia

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Author for correspondence:
Mototaka Saneyoshi
e-mail: saneyoshi@big.ous.ac.jp

INSTITUTE OF PALEONTOLOGY
Mongolian Academy of Sciences

The Upper Cretaceous eolian sediments in the Gobi Desert Mongolia yield a large number of dinosaur fossils with good preservation, well known as one of most important dinosaur localities in the world. Furthermore, vertebrate fossils have been extensively found from the Djadokhta Formation in these areas, where any of tephra and micro-fossils for a key of geochronological examination has not been confirmed so far. Therefore, a stratigraphic assignment of the eolian sediments should be indispensable in advancing paleontological investigations on the evolution of the dinosaurs by comparison with those reported elsewhere in the world as well as geological study in these areas.

INTRODUCTION

Dinosaur habitats in fluvial environments are well-known (e.g., Horner, 1984; Fiorillo, et al., 2010); by contrast, their habitats in other terrestrial setting are not as well understood. In recent years, however, our knowledge of dinosaur habitats in eolian environments has been increased by studies of dinosaur nests and their paleoenvironmental setting in the Upper Cretaceous Djadokhta Formation, central Gobi Desert, Mongolia (e.g., Eberth, 1993; Fastovsky et al., 1997; Loope et al., 1998; Jerzykiewicz, 2000). The Djadokhta Formation (e.g., Barkey and Moriss, 1927; Lefield, 1971; Barsbold, 1997; Jerzykiewicz et al., 1993; Dashzeveg et al., 1995; 2005) is widely distributed throughout the Gobi Desert (Figure 1), and is dominated by eolian deposits (e.g., Jerzykiewicz and Russell, 1991; Fastovsky et al., 1997). Spectacular, articulated dinosaur fossils such as the famous "fighting dinosaurs" (*Velociraptor* and *Protoceratops*; Kielan − Jaworoska and Barsbold, 1972; Kielan − Jaworoska, 1975), and more recently, in situ *Protoceratops* nests (Mongolian Paleontological Center MPC-D 100/530; Fastovsky et al., 2011), come from the formation.

It has become clear that a rich, complex invertebrate and vertebrate ecosystem (including dinosaur) colonized the eolian environments of the Djadokhta Formation (e.g., Dashzeveg et al., 1995; Fastovsky et al., 1997; Seike et al., 2010). However, a detailed analysis of dinosaur habitats in these Upper Cretaceous eolian environments has heretofore not been performed. To develop a better understanding of dinosaur habitats in eolian dune fields of the Djadokhta Formation, we undertook further study of the fossils and sediments of Tugrikin Shireh (44° 13 N; 103° 16) central Gobi Desert, Mongolia (Fastovsky et al., 1997; Jerzykiewicz, 1997). Excellent outcrops and thick eolian dune-derived, weakly lithified outcrops of Djadokhta Formation with well-preserved dinosaur fossils are well exposed at there. The present study focuses on the sedimentary characteristics of the eolian deposits as well as the stratigraphic distribution of fossils of the ornithischian dinosaur *Protoceratops* at Tugrikin Shireh. The work described here was carried out during the course of the Japanese-Mongolian Joint Paleontological Expeditions of 1993, 1994, 1995, and 2007 (Watabe and Suzuki, 2000a; 2000b; Suzuki and Watabe, 2000; Saneyoshi et al., 2010).

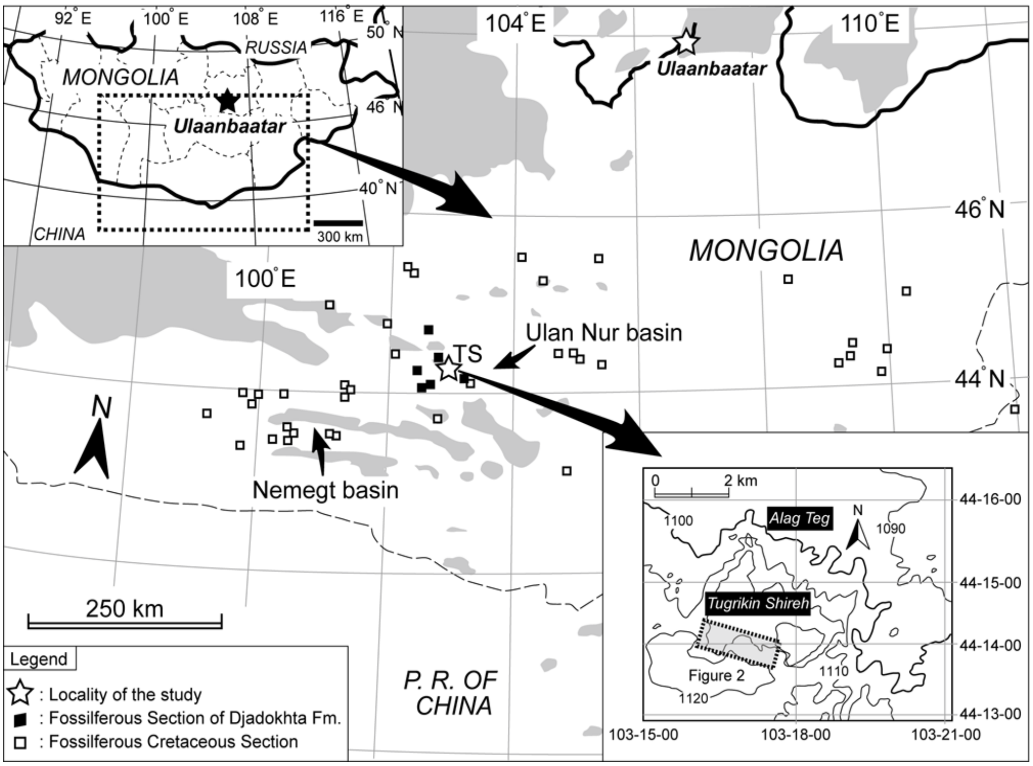

Figure 1. Map showing the location of the fossiliferous Cretaceous localities, fossiliferous localities of Djadokhta Formation, and Tugrikin Shireh (modified from Jerzykiewicz, 2000; Watabe and Suzuki, 2000c; Watabe et al., 2010). TS: Tugrikin Shireh.

DESCRIPTION

The Djadokhta Formation at the Tugrikin Shireh exposed in south- and west-facing outcrops, extending about 2.5 km laterally (Figure 2). The outcrops are carved out of a gravel-topped pediment extending several square kilometers. Two detailed stratigraphic sections were measured for this study (Figure 2C). These sections are about 25 m in thickness, and consist of medium- to fine-sand beds. Unconsolidated gravels of Pleistocene age (Fastovsky et al., 1997) cap the sections. The contact between these and the dinosaur-bearing Cretaceous sandstone beds beneath is characterized by concave-up surfaces, suggesting erosion of the Cretaceous deposits during the deposition of gravels. The entire deposits are flat-lying and undeformed.

As noted above, the fine grained sandstone beds at the locality gave proven to be a particularly rich source of vertebrate fossils, including non-avian dinosaurs (e.g., Fastovsky et al., 1997; Watabe and Suzuki, 2000a; 2000b), Aves (Chiappe et al., 2007), dinosaur eggshells (Watabe et al., 2010), nests of *Protoceratops* (Fastovsky et al., 2011), footprint (Saneyoshi and Watabe, 2008a), and Mesozoic mammals (Kielan-Jaworowska et al., 2004). Based upon vertebrate biostratigraphy, the age of the Djadokhta Formation at Tugrikin Shireh is estimated Middle Campanian (Fox, 1978; Jerzykiewicz and Russell, 1991; Jerzykiewicz, 2000). Fastovsky et al. (1997) provided general facies descriptions, and interpreted the locality as representing a sequence organically productive eolian erg deposits. Here, we recognized three units exposed in the outcrops (1 – 3 in ascending order), and describe differences among facies, correlating dinosaur fossils with occurrences (Figure, 2B).

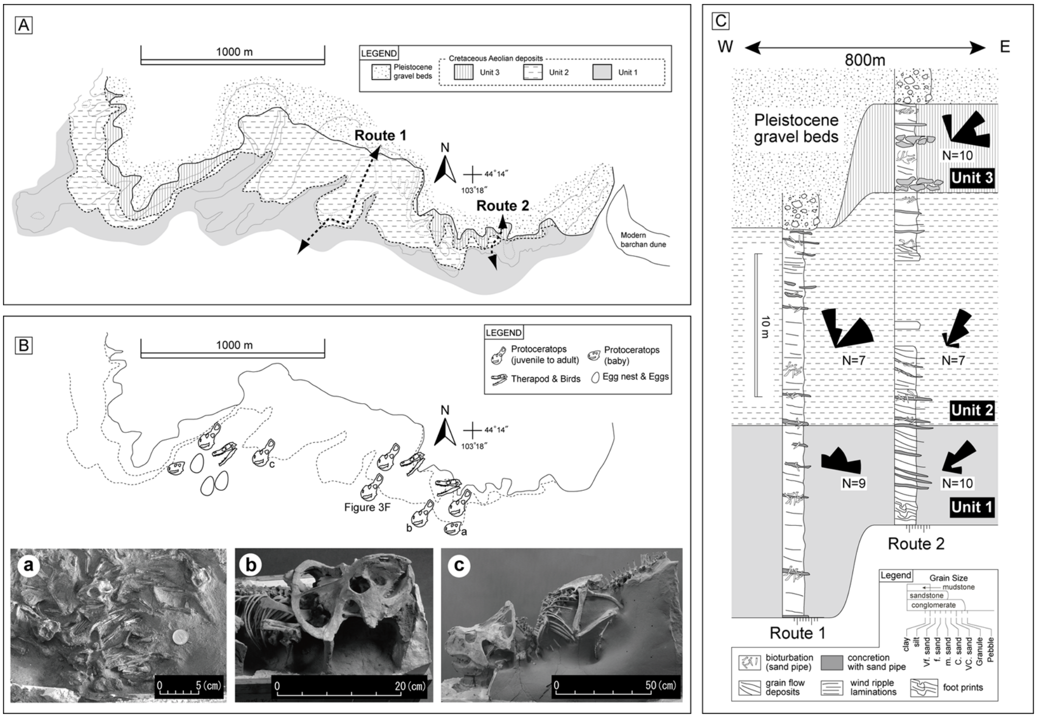

Figure 2. A) Geological map of eolian deposits in the Tugrikin Shireh. Routes show the location of columnar sections in C. B) Quarry sites of dinosaur fossils in the locality by Japan-Mongolian Paleontological Joint Expedition in 1993, 1994, 1995, and 2007. Lines show the boundary of each eolian unit. Dinosaur specimens have been founded from near eolian boundaries (see in text). Photographs of an specimens showing dinosaur fossils after preparation works; a) nest with babies of Protoceratops (MPC MPC-D 100/530), b) juvenile of Protoceratops (MPC-D 100/534), c) adult of Protoceratops (MPC-D 100/533). C) Columnar cross-sections of the Tugrikin Shireh. Rose diagrams show the paleocurrents of wind directions (up=north).

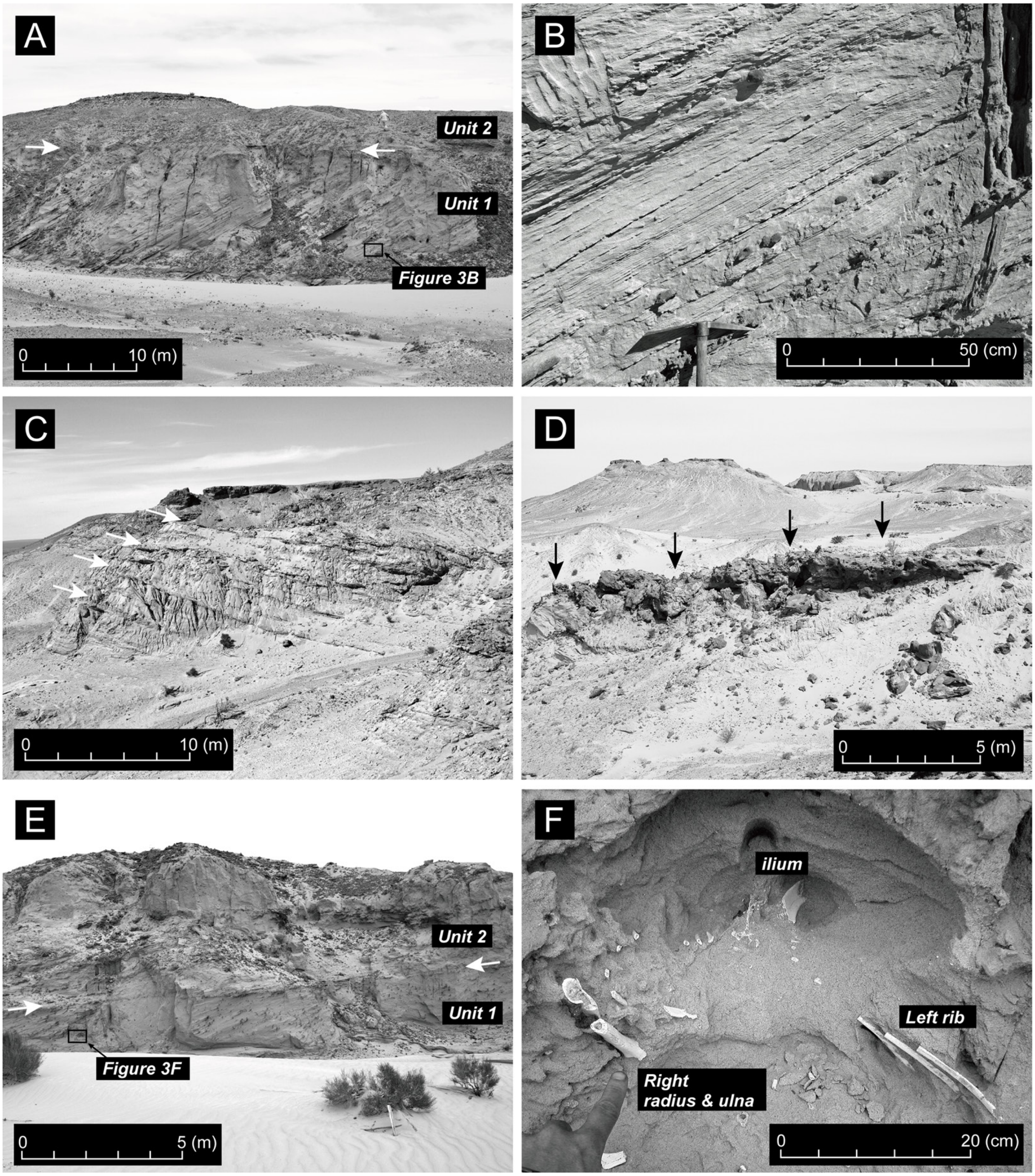

Figure 3. Photographic of outcrop of eolian deposits in the Tugrikin Shireh, central part of Gobi desert. A) Large-scale cross-stratification in the Unit 1. A disconformity marks the contact between the top of Unit 1 and the base of Unit 2. B) Wind ripple laminations accumulate on slip face of large-scale cross-stratification (Unit 1). C) Development of iron-oxide-cemented trace fossils (white arrows) along slip faces of ancient eolian dunes in Unit 2 (modified from Saneyoshi and Watabe, 2008b). D) Mega-concretion in Unit 3. These concretions have been interpreted to concentration of trace fossils. E) Stratigraphic position of young adult Protoceratops quarry which located at near disconformity between Unit 1 and Unit 2 (white arrows). F) The quarry of young adult Protoceratops in Figure 3E.

The sandstone beds of Unit 1 are typically white to light gray color, and are mainly well-sorted medium- to fine-grained. This Unit exhibits very large-scale cross-stratification (Figure 3A), which dips east-northeast (Figure 2C). All large-scale cross-stratification contains 0.1-5.0 cm thick wave ripple lamination (Figure 3B; Saneyoshi and Watabe, 2008b). Iron-oxide-cemented burrows are present along the foresets (Fastovsky et al., 1997; Saneyoshi and Watabe, 2008a; Seike et al., 2010). The thickness of Unit

1 is 7.0-15.0 m (Figure 2C). A disconformity marks the contact between the top of

Unit 1 and the base of Unit 2 (Figure 3A). Unit 2 is 10.0-20.0 m thick (Figure 2C), and comprises the middle to upper part of the locality (Figure 2A). Sandstone beds of this unit are light yellow to pale orange color, well-sorted, and medium- to fine-grained. Large-scale cross-stratification is pervasive and dips north-northeast (Figure 2C). Wind ripple laminations are exposed on the large-scale cross-stratifications. Trace fossils are extensively developed along the foresets (Figure 3C; Saneyoshi and Watabe, 2008a, B; Seike et al., 2010). A disconformity marks to the tops of this unit as well. In central part of Tugrikin Shireh, Pleistocene gravel beds unconformably overlie Unit 2 (Figures 2A and 2C), whereas in the eastern and western exposures of the outcrops, it is disconformably overlain by Unit 3 (Figure 2A).

Unit 3 is crops out on eastern and western parts of the outcrops at the locality (Figure 2A). Sandstone beds in this unit are well-sorted, fine- to medium-grained, and typically pale yellow to bright yellowish brown in color. Here, too, large-scale cross-stratification, east-northeast-dipping, dominates the exposures (Figure 2C). Trace fossils are well-developed in the western part of the locality. By contrast, the eastern part of Unit 3 contains several horizontal mega-concretions with burrows (Figure 3D). Unit 3 is unconformably overlain by Pleistocene gravels. Tugrikin Shireh has yielded a rich dinosaur assemblage, including Velociraptor (a dromaeosaurid), a troodontid, *Pinacosaurus* (an ankylosaurid), juveniles and adults of *Protoceratops* (a primitive neoceratopsian), and ornithopod juveniles (Watabe and Suzuki, 2000a; 2000b; Suzuki and Watabe, 2000; Saneyoshi et al., 2010; Watabe et al., 2010; Figure 2B and 3E). Strikingly, most of the specimens were obtained near the two disconformities between the three units (Figures 2B, 3E, and 3F).

DISCUSSION

Paleoenvironments of the Tugrikin Shireh locality have been reliably characterized as eolian (Fastovsky et al., 1997; Watabe et al., 2010). Fastovsky et al. (1997) reconstructed an extensive eolian erg with transverse dunes, and also note that all sandstone beds at Tugrikin Shireh have comparable petrographic (textural and compositional) qualities. Dipping of large-scale cross-stratification in three units shows similar directions of east-northeast (Figure 2C). This can be explained by stable eolian and climatic systems throughout depositional timeframe of the locality. Two models have been proposed to explain the processes of burial in the Djadokhta Formation: (1) burial by sediment gravity flows in alluvial fan environments due to heavy rainfall from episodic storms (Loope et al., 1998); and (2) catastrophic inundation by dune migration during desert windstorms (Jerzykiewicz et al., 1993; Fastovsky et al., 1997). In the sediment gravity-flow model, developed from work done at the southwestern Gobi locality of Ukhaa Tolgod, the fossils are encased in structureless sandy deposits (Loope et al., 1998) resulting from depositional processes not acting in traction transport. In addition, Loope et al. (1998) proposed that some dinosaur carcasses could have been buried by small migrating dunes on the alluvial fan. This contrasts markedly with the preservation dinosaur specimens at Tugrikin Shireh, which, as we have seen, are consistently found at the Unit boundaries, adjacent to large-scale cross-stratification (Figures 3E and 3F). These observations suggest that the dinosaur fossils at Tugrikin Shireh were deposited by means other than by sediment gravity flows; moreover, no facies suggestive of alluvial fan deposition are preserved at Tugrikin Shireh (Fastovsky et al., 2011). Moreover, catastrophic desert storms could account for the arched position of many of the *Protoceratops* specimens recovered from the locality, for fossilized specimen behaviors such as the "fighting dinosaurs" specimen, and for the specimen of *Protoceratops* juveniles preserved in their nest (Fastovsky et al., 2011). The idea that episodically migrating eolian dunes overran the organisms at Tugrikin Shireh is therefore still the most plausible explanation (Fastovsky et al., 1997; Fastovsky et al., 2011). These results affirm the idea that the modes of burial of dinosaur specimens in eolian deposits of Mongolia differ for each locality; the causes of death and mode of burial should therefore be considered on a case-by-case basis in these eolian sedimentary rocks.

The nests and babies of *Protoceratops*, including eggshells (Watabe et al., 2010) and nests with babies (Barsbold et al., 2008; Fastovsky et al., 2011; Figure 2B), are known from Upper Cretaceous eolian deposits, all referred to the Djadokhta Formation, of the Gobi Desert. A number of authors have suggested that these dinosaurs all lived in these ergs, as opposed to merely passing through them (e.g., Jerzykiewicz and Russell, 1991; Fastovsky et al., 1997; Jerzykiewicz, 2000). Indeed, the presence of eggshells, nests, and *Protoceratops* specimens of varying degrees of ontogenetic development from the Tugrikin Shireh (Watabe and Suzuki, 2000a; 2000b; Suzuki and Watabe, 2000) are good indicators that *Protoceratops,* at least continuously habituated erg environments throughout its entire life. Within the past 30 years, on the basis of comparative osteology, the phylogenetic propinquity of non-avian dinosaurs and Aves has become manifest (e.g., Gauthier, 1986; Dingus and Rowe, 1997; Shipman, 1998; Paul, 2001; Turner, et al., 2007; Fastovsky and Weishampel, 2009), leading some authors to propose that non-avian dinosaurs and birds might share similarities of ecology and behavior (Horner, 1984; Varricchio, et al., 1997; Grellet-Tinner et al., 2006). However, modern birds that inhabit arid environments, such as savannahs, nest in different locations from their normal living ranges (Crook, 1965). By contrast, the work presented here and elsewhere suggests that the nesting place and living habitats of *Protoceratops* were largely (and narrowly) restricted to eolian environments. Birds, of course, can fly significant distances; the migratory abilities of dinosaurs are unknown, but it is reasonable to suppose that smaller dinosaurs such as *Protoceratops* had limited options for long-range mobility. Our work suggests, then, that important limitations should be in force when comparing bird and dinosaur behavior. This is certainly true when it comes to the nesting habitats of non-avian dinosaurs in eolian environments.

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