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High-resolution UAV maps of the Gobi Desert provide new insights into the Upper Cretaceous of Mongolia

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A B S T R A C T

The Gobi Desert of southern Mongolia is home to an incredibly rich record of dinosaurs and other vertebrate fossils from the latest Cretaceous Period. Together, more than a dozen sites in several basins have produced one of the richest palaeofaunas known from this interval anywhere in the world. Most of this diversity has been recovered from the fluvial deposits of the Nemegt Formation. Despite historic and ongoing research in southern Mongolia, accurate maps and geological data for the main fossil sites are still lacking, limiting our ability to investigate how local palaeoecological dynamics influenced Nemegt taxa, their geographic distribution, and their evolutionary patterns. One of these sites, Guriliin Tsav, has produced more than a hundred significant fossil specimens to date, but still remains one of the lesser known Nemegt localities. In part this is because many expeditions have instead focused on the nearby Bügiin Tsav, one of the largest and richest localities for the Nemegt Formation. To address this gap, a project was initiated in 2018 to produce a high-resolution topographic map of Guriliin Tsav using Unmanned Aerial Vehicles (UAV), and consequently, to plot the geographic and stratigraphic distributions of palaeontological resources on this map. In so doing, we also collected stratigraphic and taphonomic data from the area, allowing for the first detailed palaeoecological interpretation of Guriliin Tsav and a comparison with other localities of southern Mongolia. Here we present the results of this project, and also discuss new topographic and stratigraphic data from Bügiin Tsav. This sheds new light into the temporal and geographic distribution of vertebrate taxa in the latest Cretaceous of Mongolia.

1. Introduction

Recent technological developments of Unmanned Aerial Systems (UAS), Unmanned Aerial Vehicles (UAV) and related processing technologies mean that these techniques are increasing in application, particularly in the fields of geology and vertebrate palaeontology (Breithaupt et al., 2004; Jennings and Hasiotis, 2006; Bramble et al., 2014; Fanti et al., 2018; Platt et al., 2018; Beelders and Dollman, 2021; Brown et al., 2021). This increase is primarily due to their capability of covering large areas in relatively short times and surveying remote or extreme exposures (i.e., near-vertical slopes), as well as the high-quality data produced (both in terms of image resolution and GIS precision), and their reduced costs. In 2016, a project was initiated, incorporating extensive UAV-based mapping of selected areas of the Gobi Desert of Mongolia, to generate high-resolution topographic and geological maps of fossil-bearing units in the Nemegt Basin (Fanti et al., 2018). Since their discovery in 1946 during reconnaissance expeditions of the Russian Academy of Sciences, the Upper Cretaceous fossil remains from this region, and in particular the rich and diverse dinosaur-dominated fauna, have attracted dozens of expeditions. However, decades after the advent of modern cartographic technologies, maps for the vast Nemegt Basin are still limited, and most are still based on field data acquired between 1964 and 1971 (Gradziński et al., 1968; Gradziński, 1970; Gradziński and Jerzykiewicz, 1974a, 1974b). These basic maps, designed to provide a preliminary reference for

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marking historical quarries and access routes in the vastness of the Gobi Desert, are inadequate for detailed stratigraphic and biostratigraphic analyses, which have accordingly remained largely unresolved. Although high-quality geological maps have been produced using other techniques for some other Mongolian localities, such as Bayan Zag (=Flaming Cliffs), and Ukhaa Tolgod (Dashzeveg et al., 2005; Dingus et al., 2008), applying UAV methodologies can extend mappable units into much larger contexts (in the range of 40–60 square km), without decreasing accuracy. For example, using data from a 2016 expedition, Fanti et al. (2018) provided the first high-resolution topographic and geological maps of the Nemegt Basin, with full coverage of the Nemegt and Khulsan localities. Partial maps of Altan Uul II and III, Tsagaan Khushuu, and Ulaan Khushuu localities were also collected during the field survey of 2016 (Bell et al., 2018; Fanti et al., 2018). These GIS-based datasets provide robust geographic frameworks and are easily integrated with field-collected data, such as geological sections, samples, historic data, GPS data points for active and poached fossil localities, and other applications.

In 2018, as part of a 14-day expedition in the northwestern part of the Nemegt Basin of southern Mongolia, two localities renowned for their remarkable fossil record, Guriliin Tsav and Bügiin Tsav, were targeted for the acquisition of new UAV-based maps (Fig. 1). Here we present data primarily on the easternmost locality, Guriliin Tsav, a relatively confined area of approximately 18 km^2 that has been only briefly mentioned in the literature, despite its rich geological and palaeontological records (see Watabe et al., 2010). Detailed cartography enables discussion of facies distribution and overall stratigraphic setting, and the placement of fossil sites into a reference stratigraphic column. Our study further recognizes distinct types of fluvial-aeolian interactions, including documentation of well-developed aeolian dunes within the upper deposits of the Nemegt Formation, historically considered as fluvio-paludal in origin. Furthermore, data presented here may shed new light on the dinosaur community composition of the Nemegt Basin area and clarify hypotheses regarding the true distinctiveness of the inferred Baruungoyot–Nemegt dinosaur faunas. Additionally, given the geographic proximity of our study area to the Bügiin Tsav locality, amongst the richest and least documented localities of southern Mongolia, we present an additional map with topographic and geological information crucial for correlating Bügiin Tsav to Guriliin Tsav, as well as detailed information on the palaeo-morphologies exposed at the site.

2. Location and geologic setting

Two stratigraphic units are of interest in this study: the Baruungoyot Formation, a series of red and red-brown eolian sandstones interbedded with fluvial and lacustrine mudstones and sandstones (Gradziński and Jerzykiewicz, 1974a); and the Nemegt Formation, characterized by fluvial, light-colored sandstones and mudstones (Eberth, 2018). Patches of the dinosaur-rich Baruungoyot and Nemegt successions are widely exposed in southern Mongolia. These formations were historically described from exposures clustered in four geographically confined areas, which still represent the densest concentrations of fossil sites (Fig. 1). From east to west, these are named Nemegt (including the Nemegt and Khulsan localities), Altan Uul (Altan Uul I-IV), Bügiin Tsav (the Bügiin Tsav and Guriliin Tsav localities), and Khermiin Tsav I-II. The geology of these areas have been discussed in a series of papers (Gradziński et al., 1968; Gradziński, 1970; Gradziński and Jerzykiewicz, 1974a, 1974b; Gradziński et al., 1977; Jerzykiewicz, 2003; Watabe et al., 2010; Eberth, 2018; Fanti et al., 2018; Jerzykiewicz et al., 2021). A comprehensive stratigraphy of Bügiin Tsav was recently published by Eberth (2018), who assigned exposed palaeochannel, paludal and lacustrine deposits to the middle and upper Nemegt Formation. No detailed stratigraphic data from Guriliin Tsav have yet been published at the time of writing, although exposures in the area are commonly considered laterally equivalent to those exposed at Bügiin Tsav (Watabe et al.,

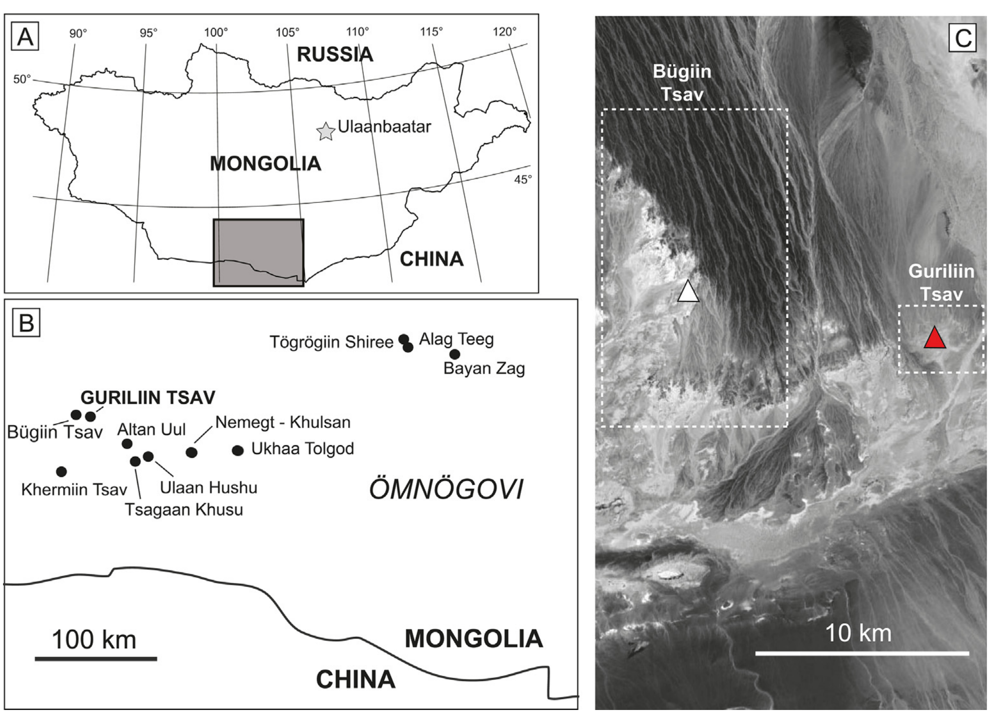

Fig. 1. Simplified map of the study area in southern Mongolia (A), and main historic Cretaceous fossil localities showing Guriliin Tsav and Bügiin Tsav, which are located in the northwestern margin of the area (B). C) Satellite photo showing the topography of the study area. Solid triangles indicate main camp locations during the 2018 expedition.

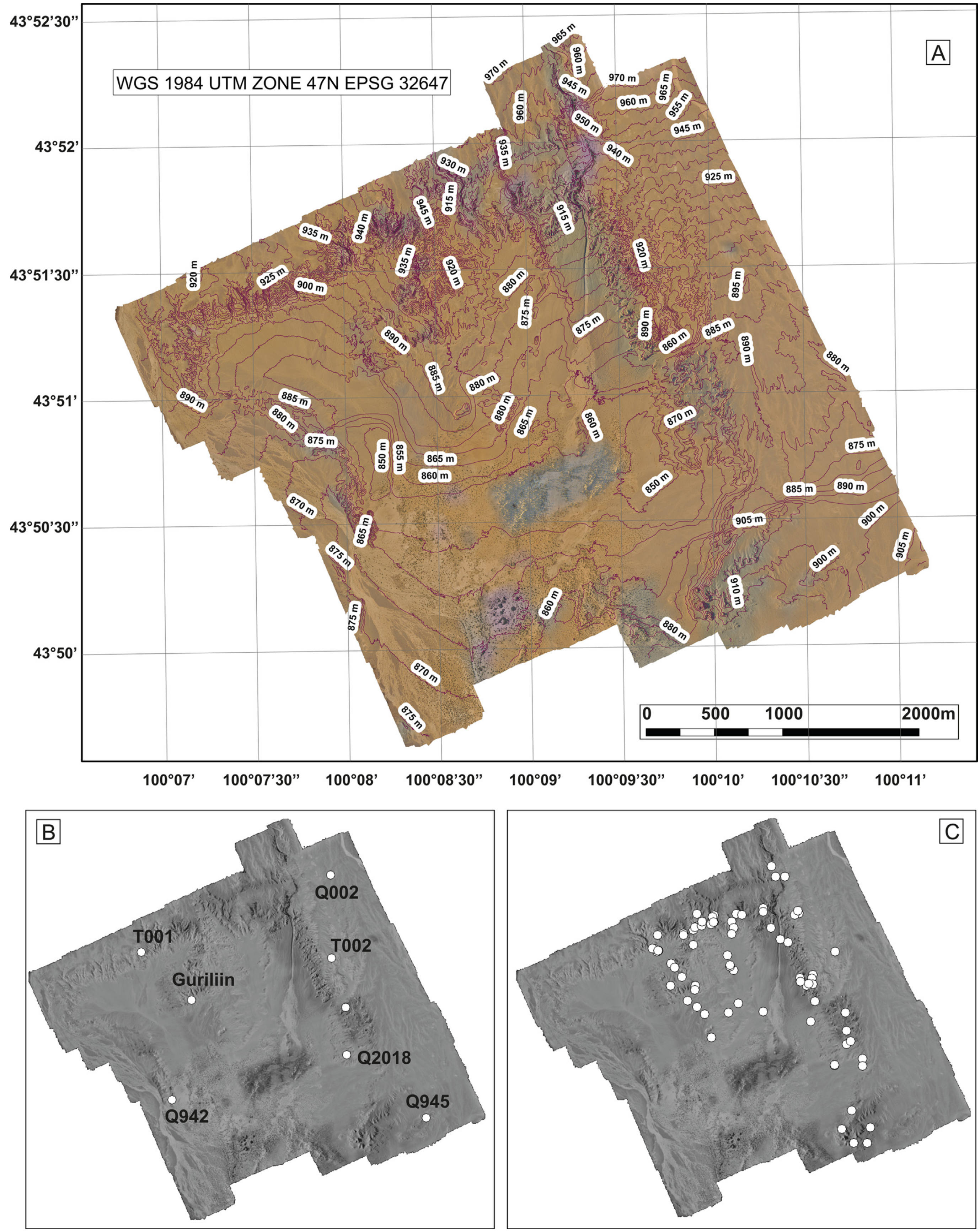

Fig. 2. A) New topographic map of Guriliin Tsav locality based on high resolution orthophotos. Contour lines are 5 m. B) Location of the Guriliin GNSS station and other GCPs used in this study (see also Table 1). C) Location of all quarries known from the Guriliin Tsav locality (Watabe et al., 2010, this study).

2010; Eberth, 2018; Jerzykiewicz et al., 2021). Conventionally, the age of Nemegt Formation fossil-bearing beds is regarded as early Maastrichtian, although direct evidence (biostratigraphic or radioisotopic data) to support this claim has never been provided, nor is there a robust stratigraphic correlation within the basin. For most Gobi fossil localities, geographic extension, facies distribution, reciprocal architecture, and age remain poorly understood, as these Upper Cretaceous sedimentary units accumulated in a series of fault-bounded grabens (Jerzykiewicz et al., 2021). One such basin is the Nemegt Basin, and another is the more westerly Ingeni Khovur Basin (Watabe et al., 2010) that includes the Guriliin Tsav and Bügiin Tsav localities. As the deposition of both the Baruungoyot and Nemegt successions reflect tectonics and climate factors, which result in asymmetrically distributed facies, high-resolution cartographic data coupled with geological sections are crucial for understanding uppermost Cretaceous stratigraphy and vertebrate faunal diversity in the Gobi (Jerzykiewicz et al., 2021). This has become of even greater importance in recent decades, because fossil sites in the Ingeni Khovur Basin have been targeted by poachers resulting in a severe impoverishment of fossil sites (Currie 2012, 2016; Fanti et al., 2018), enabled by the remoteness and vastness of these badland-like exposures,.

3. Materials and methods

A combination of high-resolution aerial photography, panoramic photographs, and ground control points were used to provide robust data for the construction of accurate digital 3D surface models (DSM). Subsequently, terrain data (location of quarries, historic and poached sites, access routes, and geological sections) were overlapped (Fig. 2) to visualize the distribution of important features. Methods for both steps are provided in more detail in this paper.

3.1. Photogrammetry data acquisition and processing

High-resolution photographs were acquired using a DJI Phantom 3 Professional Unmanned Aerial Vehicle (UAV) with a FC300X_36_4000X3000 (RGB) 4 K resolution camera. We used a Sony EXMOR 1/2.3″ sensor with 12.4 Megapixels, and stabilized the DJI UAV using a GPS/Glonass system. The final dataset used in this study includes 24,451 photographs (22,114 acquired at Guriliin Tsav, and 2337 at Bügiin Tsav). Each individual image was acquired with ±10 cm vertical accuracy and ±1 m horizontal accuracy during 46 flights. Photogrammetry data were processed using Pix 4D Desktop to obtain DSM, contour lines (5 m) and orthorectified photos.

3.2. Ground control points and global navigation satellite system

One of the most significant advances enabling UAS and UAV technologies to be applied to cartography and palaeontology is Global Navigation Satellite System (GNSS) techniques that use precise position of ground control points (GCPs) in the study area to refer collected data to regional and global reference frames. Professional real-time services available in several areas of the world provide GNSS surveys with centimeter–precision, as in the case of dense data networks in permanently monitored sites. However, as these real-time positioning services are not available at the remote Guriliin Tsav and Bügiin Tsav localities, GCP precision was improved by using reference ground control points (RGCPs). Two fixed GNSS stations were installed near each of the base camps at Guriliin Tsav and Bügiin Tsav, and these received GNSS data without interruption for seven and three days respectively. These data were used to test and calibrate the data collected from other GCPs across the survey area (Fig. 2, Table 1).

An approach for the post-processing workflow (Herring et al., 2018a) was adopted that requires overlapping the observation time span between GCPs and RGGPs (Table 1). The positions of the RGCPs and GCPs were estimated using post-processing procedures used to monitor landslide and subsidence areas (Cenni et al., 2021a, 2021b); specifically, GCP position coordinates were estimated using the Gamit/Globk scientific software (Herring et al., 2018a, 2018b). Data from the two RGCP sites were analyzed with available observations of the four scientific continuous GNSS sites (CGNSS) closest to the survey areas, for which position is always known with a precision of a few millimeters in the ITRF2014 reference frame (Altamini et al., 2016). Accordingly, position coordinates of RCGP sites (Table 1) were used to calibrate the estimation the GCP coordinates by including GCPs, CGNSS, and RCGPs. The CGNSS sites were adopted to introduce the coordinates in the ITRF2014 reference frame, and the RCGP sites closest to the GCPs were used to increase the precision of the GCPs reported in Table 1. It should be noted that the precision of the estimated coordinates depends on the observation time span. RCGP and GCP GNSS elevation data presented in this study are the geometric elevations above the reference ellipsoid (WGS84), called ellipsoidal heights (H-ell, Table 1). The orthometric heights were estimated using the geoid undulation provided by the ICGEM (International Centre for Global Earth Models) global gravitational models (Ince et al., 2019).

3.3. Palaeocommunity data collection

Palaeocommunity data was collected on-site during the 2018 expedition by prospecting the area and recording or collecting all

Table 1
Local geodetic position coordinates of the RCGPs (reference ground control points) and CGPs (ground control points) sites. From left to right: four characters site code; local geodetic position coordinates in the ITRF2014 reference frame. In particular: North: distance from the equator, East: distance from the Greenwich meridian and ellipsoidal height (H ell) in metres with respect to WGS84 coordinates system. Orthometric height (Ho) has been estimated using AIUB-GRACE01S geoid undulation provided to International Centre for Global Earth Models (ICGEM, Ince et al., 2019). The first two site are the RCGP stations located near the base camps, and the other 8 sites are located on the UAV survey areas, and they are used to refer the UAV observations on the ITRF2014 global reference frame (Altamimi et al., 2014). The uncertainties associated to the coordinates have been estimated using ones computed to GNSS software (Gamit Globk, Herring et al., 2018a, 2018b) and the geoid model (Ince et al., 2019).

Site	T (h)	North (m)	East (m)	H ell (m)	Ho (m)
GURILIIN	175.13	4881695.862 ± 0.004	8038449.051 ± 0.004	886.734 ± 0.008	943.98 ± 0.02
BUGIIN	37.50	4883149.573 ± 0.006	8026723.541 ± 0.006	903.310 ± 0.015	956.61 ± 0.03
Q2018	10.81	4880916.55 ± 0.01	8041652.04 ± 0.01	898.28 ± 0.02	941.8 ± 0.1
Q942	1.08	4880361.54 ± 0.01	8040146.44 ± 0.01	881.60 ± 0.07	927.0 ± 0.1
Q945	0.81	4880076.22 ± 0.01	8043447.07 ± 0.01	889.05 ± 0.04	934.8 ± 0.1
T001	0.43	4882288.2 ± 0.1	8037069.0 ± 0.1	925.9 ± 0.1	964.1 ± 0.1
Q002	0.39	4883264.22 ± 0.06	8038390.10 ± 0.06	932.3 ± 0.1	981.1 ± 0.1
T002	0.33	4882178.7 ± 0.1	8039929.2 ± 0.1	918.5 ± 0.1	960.9 ± 0.1
BUG1	1.46	4883402.37 ± 0.01	8026292.31 ± 0.01	908.76 ± 0.04	958.1 ± 0.1
BUG2	0.98	4883798.62 ± 0.01	8025917.08 ± 0.01	907.33 ± 0.03	962.3 ± 0.1

specimens that could reasonably be identified, to supplement existing data tabulated from literature sources. The main literature source was Funston et al. (2018b), which itself was compiled from a variety of literature sources and GPS data from past expeditions (see references therein). GPS data were collected for each site, except for two specimens that did not have these data recorded due to errors. Specimens were collected using a variety of techniques, including surface collection for small vertebrate elements or assemblages, and plaster and burlap strips for medium to large specimens. All specimens collected were entered into a catalogue in the field, and provisional field identities were reviewed by the team during cataloguing. All specimens are accessioned at the Institute of Paleontology (MPC), Ulaanbaatar, Mongolia. The full field catalogue of specimens is included in Table S1, and precise GPS locations for specimens collected in 2018 are available upon request. To tabulate abundances of different taxa, we followed the approach of Funston et al. (2018a, 2018b): each instance where a specimen of a taxon was collected was considered a separate occurrence of that taxon (i.e., contributing 1 to the abundance of that taxon), except where multiple individuals were collected together. In these cases, the minimum number of individuals based on overlapping elements were used to calculate abundance. In Funston et al. (2018a, 2018b), such instances were counted as a single occurrence to avoid inflation in calculating relative abundances of taxa. However, in this study we did not compute relative abundances within the palaeocommunity so it was more appropriate to compile all individuals. Abundance was not calculated for teleost fish because their vertebrae are common as clasts within sandstone horizons. However, associated fish skeletons have not been found, and it is difficult to adequately assess correspondence between number of vertebrae and number of individuals. Accordingly, their presence was noted but raw abundance counts were not compiled.

4. Guriliin Tsav locality

Exposures at Guriliin Tsav are located on the eastern margin of a large plateau that also hosts Bügiin Tsav. Guriliin Tsav is approximately 10 km to the east (Fig. 1) of Bügiin Tsav, and itself extends over approximately 12 km^2 between 43°52′26″ N to 43°49′36″ N latitude and 101°06′45″ E to 101°11′10″ E longitude, at an altitude of 880–950 m above sea level (Fig. 2). In the area, east-west and north-south oriented escarpments intersect, forming an L-shaped ridge bordered by low, badland-like hills, separating pediment deposits from the Cretaceous bedrock exposed primarily to the south and west. The sayr drainage system is oriented primarily north to south. Despite its proximity to Bügiin Tsav, as well as its continuous exposures and rich fossil sites, Guriliin Tsav is one of the less well documented fossil areas in southern Mongolia. Guriliin Tsav was probably discovered by a Mongolian-Russian expedition in 1964 when Bügiin Tsav was first explored. It was visited multiple times by the Soviet-Mongolian Palaeontological Expedition between 1971 and 1979 (Kurochkin and Barsbold, 2000), and was prospected by the 1993, 1994, 1998 and 2006 expeditions of the Hayashibara Museum of Natural Sciences and Mongolian Paleontological Center Joint Paleontological Expedition (HMNS-MPC; Watabe and Suzuki, 2000; Watabe et al., 2010). Various members of the Russian-Mongolian Palaeontological Expedition collected at Guriliin Tsav in 1994, 1997, and in other years (Currie, 2016). Some authors of the current paper spent time at Guriliin Tsav in 2006 and 2010 (as part of the Korea-Mongolia International Dinosaur Project), and in 2018 (as part of a National Geographic funded Expedition).

From a geological perspective, fluvial beds exposed at Guriliin Tsav have been referred to the Nemegt Formation, and informally divided into lower mud-dominated beds, and upper sand-dominated beds (Watabe et al., 2010), although no stratigraphic column has been provided until now (Fig. 3).

5. Stratigraphy

Overall, Guriliin Tsav records deposition in an alluvial setting with alternating thick successions of red-brown, calcareous palaeosol-rich interfluve deposits, and cross-bedded sandstones. Coarse, diamict deposits present on the main plateau and along canyon edges form the modern pediment. The Cretaceous beds are capped and frequently intermixed with those of Tertiary and Quaternary sediments, and the area is characterized by incised valleys up to 50 m deep and an ephemeral sayr network mobilizing sediments derived from the piedmont area. In this study, Quaternary deposits are referred to as Older and Younger pediment, corresponding to the alluvium and wash surfaces respectively, consistent with the terminology used in most geological papers related to southern Mongolia (Gradziński and Jerzykiewicz, 1972, 1974a, 1974b; Eberth et al., 2009; Eberth, 2018; Fanti et al., 2018).

Five lithostratigraphic sections were measured in the north-central and south-eastern cliffs of Guriliin Tsav to obtain composite sections of the most representative and fossil-rich exposures. In total, there are approximately 50 m of exposed section at this locality, comprised of fluvial (active channel, interfluvial) and aeolian deposits (Fig. 3).

Beds facing south, exposed in the northern escarpment, include a stacked succession of alluvial sheet sandstones, laminated red-brown to grey-green mudstones and fine-grained sandstones (Fig. 4). Soft sediment deformation is abundant, as are tubular invertebrate traces and evidence of loading, including features derived from dinosaur trampling. In-situ caliche nodules are common and suggest palaeosol development in a seasonally dry setting, whereas reworked caliches, which are commonly observed at the base of fining-up channel sequences in the Nemegt Formation, are rare (Fig. 4A, B). Palaeosol-dominated beds exposed in the north-western part of Guriliin Tsav testify to poor and infrequent input of sediment, probably related to seasonally dry intervals, resulting in reduced river discharge in the basin. Coarse-grained deposits, primarily located in the central northern escarpment in the proximity of the 2018 main camp area (Fig. 3A), include meter-thick trough cross-bedded granulitic sandstones that are rich in well-rounded quartz and feldspar granules. Inclined strata include decimeter- to meter-scale sets of crossbedding, capped by thick deposits of ripple laminae. They commonly lack vertical grading into finer components, suggesting rapid deposition under constant flow rates. Given their limited lateral extension, these sheet-like deposits are interpreted as fluvial splays and floods that developed – potentially from multiple sources – during episodes of increased runoff. These fluvial deposits include centimeter- to decimeter-sized rounded clasts, suggesting proximity to the sediment source area and high energy of palaeoflows (Fig. 4C, D).

Observed tracks and traces include rhizolites, both horizontal and vertical burrows most likely made by limnivores or other invertebrates, and large, deep dinosaur tracks (up to 90 cm in length and 45 cm in depth) preserved as concretions infilled by carbonate-cemented sandstones (Fig 4B and 5D).

A remarkable feature in the northern escarpments at Guriliin Tsav are three-dimensionally preserved aeolian sand dunes, each extending horizontally for 70 linear meters (Fig. 5). Differences in lithology with the adjacent mud- and silt-dominated fluvial beds result in differential erosion and prominent morphologies. Red-colored aeolian deposits exhibit tangential-planar and trough cross-stratification; these sharply overlie alluvial mudstone showing local bioturbation, and interfinger laterally with mud-dominated palaeosol successions (Fig. 5B, C). These dunes are

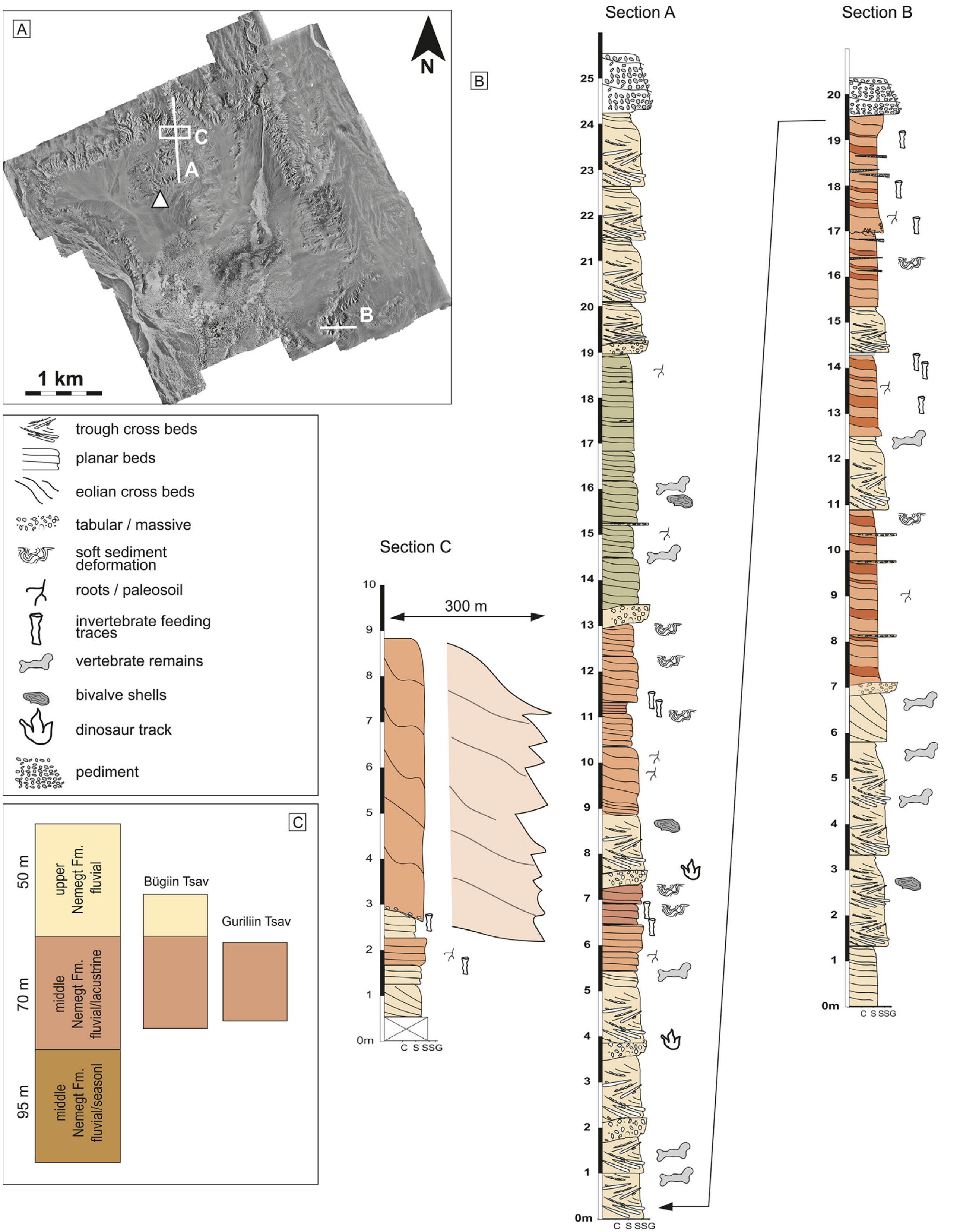

Fig. 3. A) Orthophotography of Guriliin Tsav showing the main camp area (solid white triangle) and the location of measured stratigraphic sections. B) Composite lithostratigraphic sectionsm, representative of approximately 45 m of Upper Cretaceous aeolian and fluvial deposits, exposed in the area. Section C shows the isolated aeolian dunes located to the north of the, main camp. C) Composite stratigraphy of the Nemegt Formation in the study area (after Eberth, 2018).

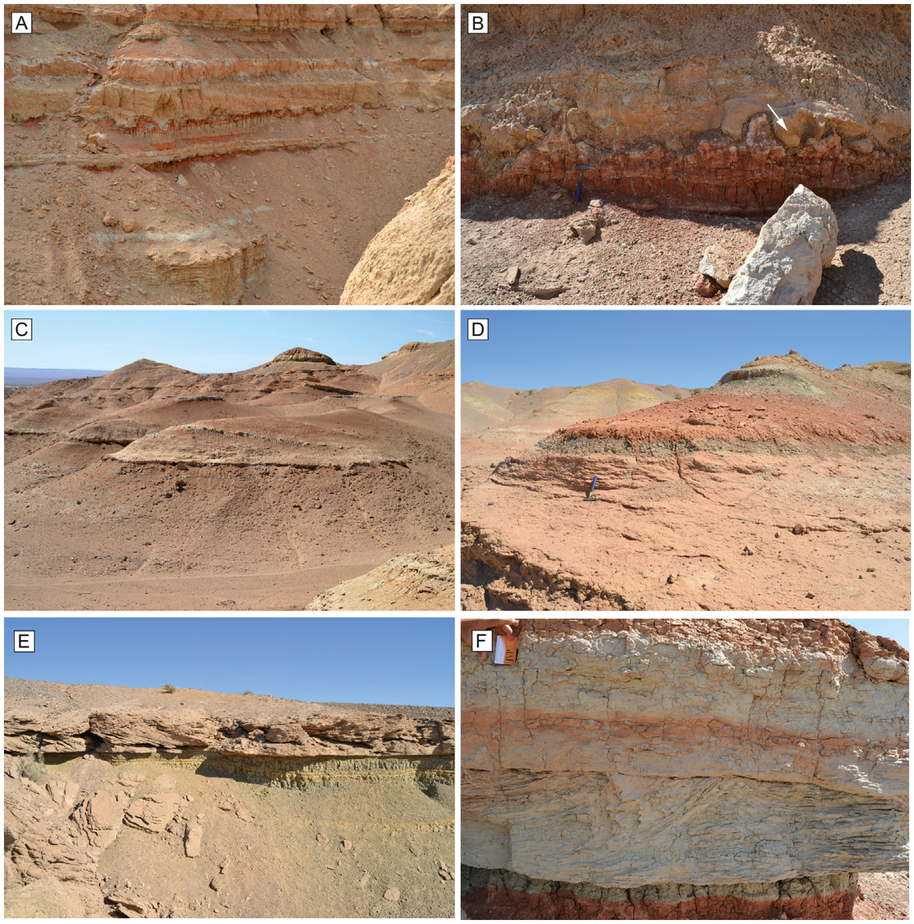

Fig. 4. Field photographs showing typical deposits exposed at the Guriliin Tsav locality. A) Stacked sheet sandstone and mudstone exhibiting color variegation associated with water table fluctuation. B) Load structures, including well-preserved dinosaur track (white arrow). C) Large-scale, laterally-accreted deposits capped by tabular, fine-grained beds. D) Fining-upward sequences showing rapid color variations. E) Planar-laminated green mudstones suggesting lacustrine/still water origin of sediments capped by coarse, cross-bedded sandstones. F). Fine grained, cross-bedded sandstones of fluvial origin on top of mud-dominated palaeosols.

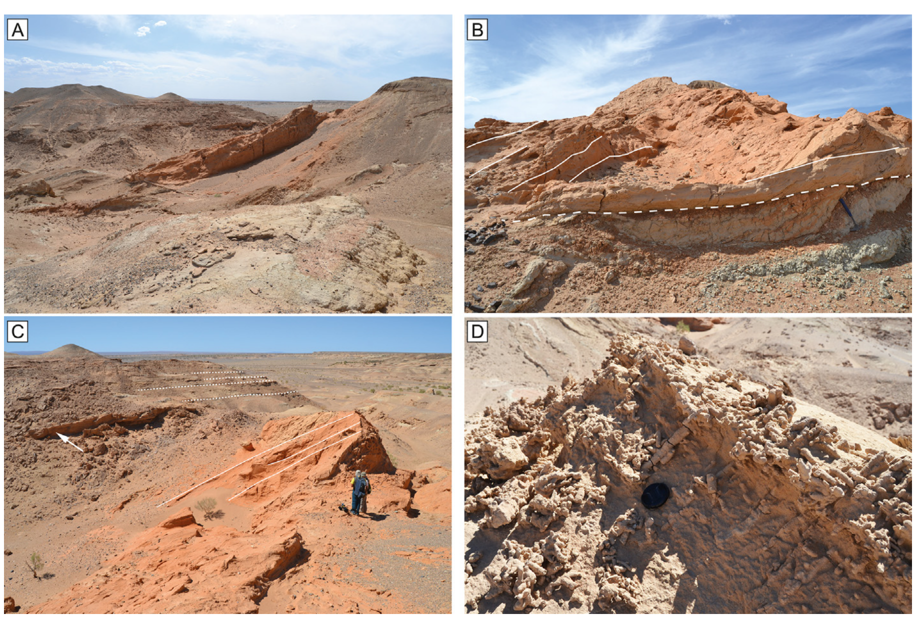

Fig. 5. A) Isolated aeolian dunes exposed within typical Nemegt fluvial deposits at Guriliin Tsav. B) Sharp lithologic contact at the base of the aeolian beds and overlying high-angled inclined strata. C) Panoramic photo from the top of the aeolian deposits showing the rapid, lateral variation into horizontally bedded alluvial beds typical of the Nemegt Formation in the area. D) Vertically developed invertebrate feeding traces that are common in the mud-dominated intervals.

buried within typical Nemegt alluvial successions that interfinger with (near the base), prograde, and conformably cap the aeolian beds. No evidence of fluvial incursion/erosion could be found, nor was there evidence of sediment reworking and redeposition in the surrounding alluvial deposits.

Although it is unclear whether aeolian deposits represent isolated or extensive areas of dunes, and their spatial occurrence within the basin is difficult to determine (i.e., proximal or distal to the sediment source), the overall vertical architecture observed in the field suggests a dune-field margin or isolated dunes that maintained a fixed position for protracted periods (see Al-Masrahy and Mountney, 2015; Mayoral et al., 2021). In desert regions, fluvial and aeolian processes do not operate independently, and have major impacts in resulting sedimentary successions. Aeolian deposits at Guriliin Tsav appear geographically confined and isolated, although erosion may limit estimates of their actual sizes. In terms of palaeoenvironmental hypotheses, this may indicate: 1) the presence of relict dunes progressively buried in fluvial deposits (thus multiple and major depositional hiatuses); or 2) local aeolian accumulation leading to stabilized dunes in a fluvial-dominated setting, determined by prevailing wind directions or local morphologies (although a source of sediment would have had to have been present in the vicinity). Aeolian dunes have not been previously reported in the Nemegt Formation, except for the basal interfingering Baruungoyot-Nemegt Formation transition at the Nemegt and Khermiin Tsav localities (Eberth, 2018; Jerzykiewicz et al., 2021 and references therein). The occurrence of aeolian dunes much higher in the Nemegt Formation at Guriliin Tsav challenges the previous consensus of exclusive fluvial deposition in this formation, and provides additional insights into the Cretaceous Gobi ecosystems (see the following discussion on the reciprocal stratigraphic position of Guriliin Tsav and Bügiin Tsav).

To the northeast of the study area, green-brown, planar laminated mudstones and finer grained deposits become predominant. Well-defined, continuous, horizontally laminated beds of alternating mudstone and siltstone suggest accumulation in low-energy, interfluve to paludal environments, similar to those described from Altan Uul and Bügiin Tsav and assigned to the middle Nemegt Formation (Eberth, 2018). Isolated channels showing lateral accretion occur in the area and are here interpreted as small-scale meandering channels, which most likely originated during run-off or seasonally-driven flooding events. In the uppermost part of the easternmost exposures, tabular, laterally continuous, cross-bedded sandstone deposits sharply overlie mud-dominated alluvial facies, suggesting rapid, high-energy run-off episodes within the basin (Fig. 4E, F).

Finer alluvial deposits (finer-grained sandstones, siltstones and mudstones), as well as evidence of lateral accretion, are primarily observed in the southeastern exposures, where the majority of well-preserved vertebrate remains have been collected. Overall, palaeocurrent measurements collected in channelized bodies showing trough-cross bedded strata indicate that flow was oriented generally southward, whereas measurements acquired in the splay-overbank deposits range from east to south-west.

Finally, Nemegt Formation deposits in the central area of the northern escarpment are complicated by sin-depositional normal faults, most likely related to an as-yet-undefined extensional fault system associated with the complex tectonic grabens that characterize the region (see Eberth, 2018; Jerzykiewicz et al., 2021).

6. Vertebrate diversity at Guriliin Tsav

A rich assemblage of vertebrates is known from Guriliin Tsav, although its vertebrate diversity has never been comprehensively tabulated or compared to other localities in the Nemegt Formation (but see Funston et al., 2018a, 2018b for a dinosaur-centric example). It is unclear when the first vertebrate fossils were collected from Guriliin Tsav: it was most likely visited by the Polish-Mongolian Palaeontological Expeditions, whereas accounts of the Soviet-Mongolian Palaeontological Expeditions indicate without further details that it was extensively worked at some point between 1970 and 1979 (Kurochkin and Barsbold, 2000). However, Soviet teams were in the vicinity as early as 1964, when introduced to Bügiin Tsav by Mongolian researchers (Kurochkin and Barsbold, 2000), who also worked the site later in 1987 (Tsogtbaatar and Chinzorig, 2007). In any case, the first mention of a significant fossil from the locality (under the alternate spelling "Gurlin Cav")

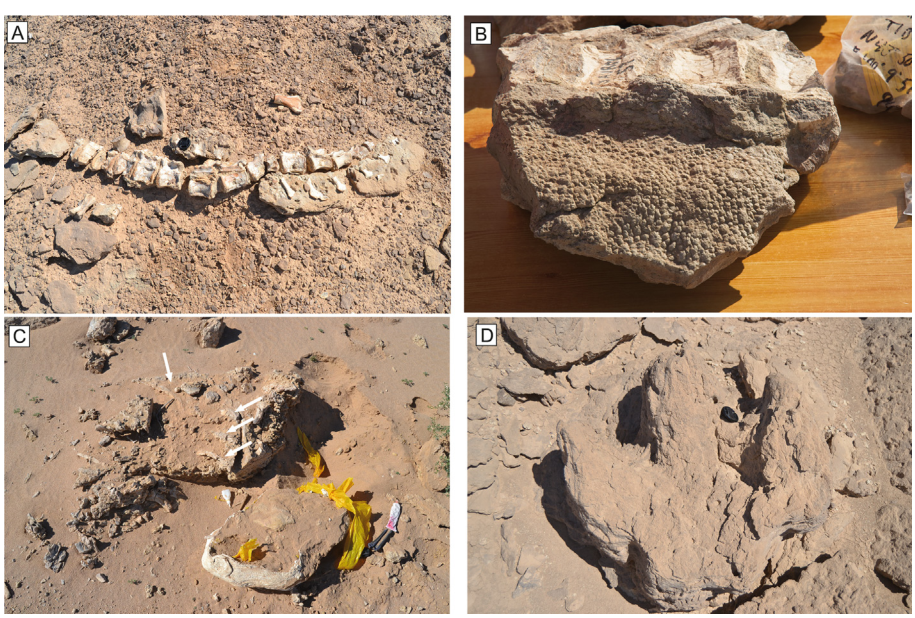

Fig. 6. A) Articulated *Tarbosaurus* skeleton. B) Skin patches associated with a *Saurolophus* skeleton. C) A poached ankylosaurid skeleton with still in situ rib cage. D) Large hadrosaur footprint.

was a deltatheroidan mammal skull ("the Guriliin Tsav Skull") in a 1983 brochure about the activities of the Soviet-Mongolian Palaeontological Expedition (Kielan-Jaworowska and Nessov, 1990). This particular skull, although it still remains undescribed, has since figured prominently in phylogenetic analyses of metatherian mammals (Rougier et al., 1998; Williamson et al., 2012, 2014; Beck, 2023). To our knowledge, no other mammalian fossils have been reported from Guriliin Tsav since then. However, the Report of the 2010 Japanese-Mongolian Paleontological Expedition (HMNS-MPC, Tsubamoto, 2010) mentions the discovery of some mammals in aeolian beds at a site further east, although the relationship of this site to the main Guriliin Tsav exposures is unknown (Watabe et al., 2010). It is possible that "the Guriliin Tsav Skull" was also collected in this area, but no detailed locality information is available for the specimen.

Despite extensive work in the area by the Soviet-Mongolian Palaeontological Expedition, none of the specimens collected appear to have made it into the literature. Brief explorations of the site by the HMNS-MPC Expedition in 1993, 1994, 1998, and 2006 (Ishii et al., 2000; Tsubamoto, 2010), alongside our 2018 expedition, revealed a vertebrate fauna relatively similar to other Nemegt Formation sites (Funston et al., 2018a): dinosaur remains are dominated by *Gallimimus*, *Saurolophus*, and *Tarbosaurus*. In 1987, a Mongolian team excavated a particularly large and complete *Saurolophus* postcranial skeleton (Tsogtbaatar and Chinzorig, 2007). Other skeletons in the northwest part of the locality preserve exceptional skin impressions (Fig. 6B), showing high-fidelity basement scales and feature scales. Several *Tarbosaurus* skeletons are known (PIN4216-1 in Moscow, and Tarb040, Tarb041 of Currie 2009, 2013), including cranial elements from multiple individuals discovered together by the 2018 expedition: at least two individuals are represented by parts of their braincases, nasals, and dentaries. Other components of the classic Nemegt fauna were detected by the 2018 expedition as well: ankylosaurs, dromaeosaurs, pachycephalosaurs, sauropods, and troodontids are known from relatively rare material (Tables 1 and 2). Notably, ankylosaur material known from the site includes an abandoned specimen left by poachers and rediscovered in 2018 (Fig. 6C). The forelimb of the specimen was jacketed by the poachers but left in the field, whereas the skull was presumably collected from where a sand-infilled void was found in this region of the quarry. Deinonychosaurian material is limited to small parts of the hindlimbs (a dromaeosaur tibia and a troodontid metatarsus), as well as to isolated teeth. Only one partial squamosal of a pachycephalosaur was collected by the HMNS-MPC Expedition in 1994 from the site (Evans et al., 2018). Multiple sauropod pelves are known, although most of these remain uncollected. Oviraptorids are particularly well-represented at Guriliin Tsav, especially in the south-eastern part of the locality. However, other oviraptorosaurs (avimimids and caenagnathids) are not yet known from the site, despite being known from nearby Nemegt Formation localities (i.e., Bügiin Tsav, Tsuihiji et al., 2017; Funston et al., 2018a). Two oviraptorid skeletons were collected at Guriliin Tsav in 1998 by the Japanese-Mongolian Joint Palaeontological Expedition team (Ishii et al., 2000), and in 2018 some partial hindlimb elements, a manual ungual and a bonebed of at least eight articulated skeletons with skulls were recovered. One of the 1998 specimens has now been referred to *Oksoko avarsan* (Funston et al., 2021; Funston 2024), and the manual ungual found in 2018 is from the same individual (MPC-D 102/12), discovered upon revisiting the quarry. The articulated skeletons collected in 2018 are likely representatives of *Conchoraptor gracilis*, based on preliminary preparation of one of the skulls (Funston, 2019). Similar collecting materials and techniques between the abandoned ankylosaur skeleton and the holotype of *Oksoko avarsan* (MPC-D 102/110) suggest that the latter specimen may also have been collected in this area (Funston 2024). This is supported by the presence of *Oksoko* in the area already (MPC-D 102/12), as well as by the taphonomically similar assemblage of multiple articulated skeletons of *Conchoraptor* found in 2018. Among dinosaurian clades known from the Baruungoyot or Nemegt beds in the Nemegt Basin (Funston et al., 2018a, 2018b), alvarezsaurs and therizinosaurians have not yet been found at Guriliin Tsav. In both cases, this is likely explicable by the small contributions of these groups to the overall community composition of the Nemegt ecosystems (Funston et al., 2018a, 2018b). Overall, the dinosaurian component of the fauna discovered at Guriliin Tsav is identical to better-sampled sites like Bügiin Tsav and Nemegt; there are no taxa known only from Guriliin Tsav, and the noted absences from the site are most likely attributable to sample size or sampling biases. However, azhdarchid pterosaur bones have not been recovered from other Nemegt sites (Tsuihiji et al., 2017), and relatively small taxa (including birds and lizards) seem to be more common at Guriliin Tsav (Table S1). Oviraptorids also appear to be more abundant here, at least in the south-east section of Guriliin Tsav, where the eight articulated skeletons were found in one quarry in 2018.

Prior to the 2018 expedition, avian remains had not been documented from Guriliin Tsav. However, isolated bird bones were collected in five separate instances in 2018, including two tarsometatarsi, and a *Gobipteryx* egg in the unusual aeolian zone in the northern part of the locality (see Section 5). Except for the *Gobipteryx* egg, the identities of these specimens have not been established, and so it is unclear how the local avifauna compares to that of other Nemegt sites or to other Late Cretaceous palaeoecosystems. Nevertheless, bird fossils tend to be more common in the Baruungoyot Formation, which has a stronger preservational bias towards small animals than the Nemegt Formation, and thus the presence of isolated bird bones in the Nemegt Formation beds at Guriliin Tsav is notable. Indeed, at least one multitaxic concentration of small-sized fossils, fitting the criteria for a microsite (Rogers et al., 2014), is known in the northeastern part of the locality, whereas these sites are generally absent at other Nemegt Formation localities.

With regards to non-dinosaurian sauropsids, turtles are known in relative abundance from Guriliin Tsav, and include examples with relatively complete skeletons. Turtles are also common at Bügiin Tsav, and in general seem to be relatively more frequent and complete in these two sites than in other parts of the Nemegt Basin, especially in sites further east such as Nemegt. *Mongolochelys* is the most common turtle at the site (Suzuki and Chinzorig, 2010), although occurrences of Lindholmemydidae were also reported (Tsubamoto, 2010). Crocodilian fossils are apparently known from the site (Tsubamoto, 2010), but none of them have been described or further documented. A lizard frontal was collected in 2018, but its identity has not been established.

No complete fish skeletons have been recorded from Guriliin Tsav, although just as in other Nemegt Basin sites, disarticulated fish vertebrae are common in the more concreted, coarser-grained strata. At present, there are no reported occurrences of amphibians from Guriliin Tsav.

Overall, the vertebrate fauna at Guriliin Tsav is similar to that of other Nemegt Formation sites (Fig. 6). Also, similar to other Nemegt Basin sites, a considerable portion of this fauna has been lost to illegal poaching activities. Multiple vandalized skeletons were encountered during the 2018 expedition, most remarkable of which is the abandoned ankylosaur (Fig. 6C). It is a testament to the richness of this and other Nemegt sites that the forelimb, which had already been fully pedestalled and jacketed, was apparently not worth returning to collect for whoever worked on this specimen. Poaching is particularly problematic for understudied sites such as Guriliin Tsav, which by no means are any less rich than nearby sites like Bügiin Tsav. Vandalization and removal of specimens disproportionately affects sampling efforts at these smaller sites, making it more difficult to understand their diversity and taphonomy. Because they are visited infrequently, it is also difficult to evaluate the severity and frequency of these illegal activities: the abandoned ankylosaur site could have been vandalized anytime between 2006 and 2018, a period during which there were no palaeontological expeditions to the site, or it could have been undetected by the HMNS-MPC Expedition team in 2006 during their brief three-day visit.

7. Correlation with beds exposed at Bügiin Tsav locality

Known since the 1964 Soviet-Mongolian Palaeontological Expeditions (Rozhdestvensky, 1969), Bügiin Tsav is a vast area of badlands-style topography resulting from eroding cliffs facing to the south and the west. Composite sections representative of Bügiin Tsav, and of the broader Ingeni Khovur Basin, were correlated by Eberth (2018) on a lithostratigraphic basis with the Nemegt Formation beds exposed at Altan Uul to the south-east (Nemegt Basin), although the depositional history, hiatuses, and chronology of these two basins has never been properly addressed. Overall, the Bügiin Tsav locality is dominated by low-relief, exhumed, three-dimensional, palaeochannel deposits (Weishampel et al., 2008; Eberth, 2018), and by a rich and diverse vertebrate fauna (Funston et al., 2018a, 2018b). The 2018 field survey aimed to provide more robust information to include the geographically-isolated beds exposed at Guriliin Tsav into a more complete stratigraphic framework, such as the one available for Bügiin Tsav (Eberth, 2018, and references therein), thus improving the mapping of sedimentary facies and fossil distribution. To accomplish this, an area at Bügiin Tsav was surveyed in addition to the work at Guriliin Tsav. The area surveyed for this purpose is among the central-southern exposures of Bügiin Tsav, close to where detailed geological sections have been acquired previously (Eberth, 2018; see also Funston et al., 2021). In this study, our observations and analyses use information from sections Bügiin Tsav '2a', 'Camp 2009', and 'Camp 2010' (Figure 9 in Eberth, 2018), and data collected during the 2018 field survey.

High-resolution data collected from selected GNNS-GCPs at Guriliin Tsav indicate an altitude between 880 m and 950 m.s.l.d., whereas GCPs from Bügiin Tsav – although geographically limited to a restricted area – indicate an elevation of 904 m.s.l.d. The two areas are separated by approximately 10 km, and no reliable marker bed enabling lateral correlation has been documented. From a lithostratigraphic perspective, deposits and facies associations exposed at Bügiin Tsav are similar to those documented at Guriliin Tsav, representing a range of alluvial environments, including meandering channels, palaeosol-rich interfluvial beds and possibly paludal deposits.

Based on available data, we interpret the beds exposed at Guriliin Tsav to be referable to the middle Nemegt Formation (*sensu* Eberth, 2018), a stratigraphic interval characterized by articulated dinosaur and turtle remains as well as tracks and trackways. With respect to published sections in Eberth (2018), the lower beds exposed at Guriliin Tsav are here considered as correlative to the lowermost beds exposed at Bügiin Tsav (lower 15 m in Eberth, 2018: Fig. 9). The light-colored, mud-dominated interval in the upper section of Guriliin Tsav is here considered as correlative to the lacustrine/paludal deposits from the upper stratigraphic levels at Bügiin Tsav (20–45 m interval in Eberth, 2018: Fig. 9). Remarkably, this correlation means that the aeolian dunes preserved at Guriliin Tsav are in the middle Nemegt Formation. This further indicates persistent local interaction between aeolian and fluvial environments during the deposition of the Nemegt Formation, much later in time than the basal, interfingering interval with the Baruungoyot Formation.

From a palaeontological perspective, the faunal assemblage at Guriliin Tsav is comparable to the one documented at Bügiin Tsav. The dinosaurian fauna is essentially the same, and several species are known from both sites: *Gallimimus bullatus*, *Oksoko avarsan*, *Saurolophus angustirostris*, and *Tarbosaurus bataar*. If the taxonomic identity of the supposed *Conchoraptor gracilis* specimens is confirmed, then this taxon would be shared between Guriliin Tsav, Khulsan, Khermiin Tsav, and Altan Uul III (under the assumption that *Gobiraptor minutus* is a junior synonym of *Conchoraptor gracilis* as suggested by Funston, 2019). Guriliin Tsav and Bügiin Tsav are more similar to each other in the composition of the non-dinosaurian component of the fauna than to any other Nemegt sites: the abundance of turtles, particularly *Mongolochelys*, is distinctive. Overall, both lithological and faunal lines of evidence support the idea that Guriliin Tsav and Bügiin Tsav represent similar parts of the Nemegt Formation succession.

8. Cretaceous meandering systems and associated taphonomy

The different depositional facies of the Nemegt Formation are the result of fluvial deposition related to autogenic processes inherent to meandering channels. Heterogeneous lithologies and depositional architecture reflect different parts of the depositional system (i.e., crevasse-splays, cutoffs, flood plains, natural levees, oxbows, point and counter-point bars, etc.), changes in the average water table (i.e., different soil development, ephemeral lakes, swamps, etc.), and dynamics reflecting the expansion and translation of the active channels (related primarily to the curvature of bends), with rapid and localized shifts from erosion to deposition. The detailed spatial and stratigraphic data collected at Guriliin Tsav and Bügiin Tsav presented here enable accurate discrimination of these different factors, and thus inferences concerning the genetic and taphonomic controls on the distribution of fossil remains.

Spatial distribution of fossils documented from Guriliin Tsav (Fig. 2) indicate higher concentrations in the central and southeastern escarpments, areas where sand-dominated fluvial splays and floods are the dominant deposits. Specimens in these areas are typically recovered as either disarticulated or associated remains (Table 2).

Table 2
Vertebrate diversity at Guriliin Tsav, including abundances.

Clade	Subclade	Species	Abundance
Actinopterygii	Teleosti *cf.* Hiodontidae	Indet.	–
Diapsida	Testudinata: Sichuanchelydidae	*Mongolochelys efremovi*	13
	Testudinata: Lindholmemydidae	Indet.	2
	Testudinata: Indet.	Indet.	2
Squamata	Indet.	Indet.	1
Archosauria	Crocodylia	Indet.	1
Dinosauria:	Sauropoda: Titanosauria	*cf. Nemegtosaurus*	4
	Ornithopoda: Hadrosauridae	*Saurolophus angustirostris*	7
	Thyreophora: Ankylosauridae	Indet.	2
	Theropoda: Ornithomimidae	*Gallimimus bullatus*	10
	Theropoda: Tyrannosauridae	*Tarbosaurus bataar*	10
	Theropoda: Oviraptoridae	*Oksoko avarsan*	2
		Conchoraptor gracilis	9
		Indet.	1
	Theropoda: Dromaeosauridae	Indet.	2
	Theropoda: Troodontidae	Indet.	1
	Theropoda: Aves	Indet.	5
Mammalia	Metatheria: Deltatheroidea	Indet.	1

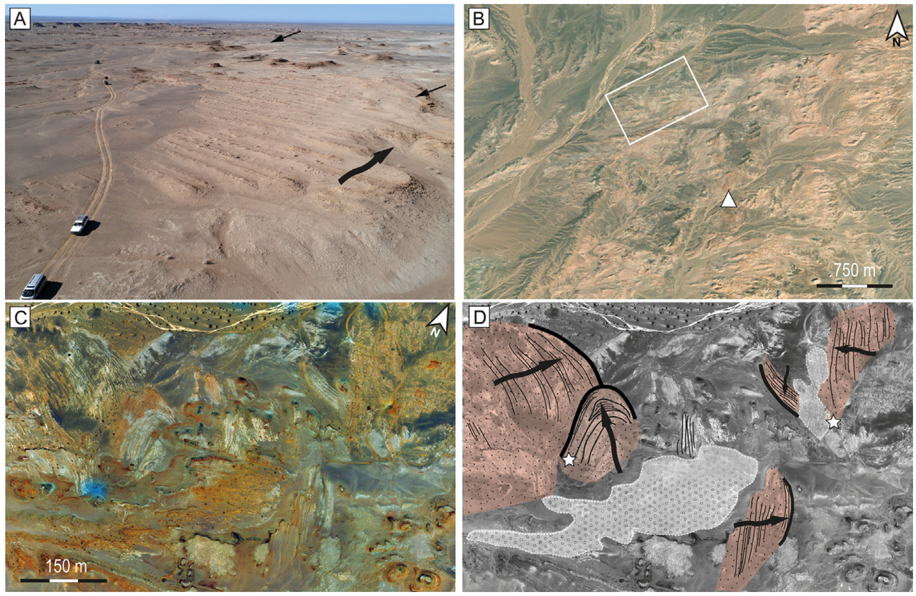

Fig. 7. A) UAV photograph from Bügiin Tsav showing exhumed lateral accretion deposits and the overlying topsets. B) Low-resolution satellite image of Bügiin Tsav showing the 2018 main camp (solid white triangle). The white box indicates where high-resolution images were used to map palaeo-meander deposits shown in C and D. C) High-resolution UAV-acquired photograph of a selected area Bügiin Tsav. D) Interpretive image showing meander lateral accretion deposits (highlighted in red), and topset and finer, tabular sediments (highlighted in white).

Bones with patches of associated skin (referred to *Saurolophus*) and skin impressions are also occasionally found, suggesting rapid burial and high sediment supply. Large, tridactyl hadrosaur footprints are abundant and preserved as deep sandstone infills. In contrast, fine-grained, palaeosol-dominated, tabular beds exposed in the north-western escarpment are virtually barren in vertebrate remains. The northeastern escarpment is dominated by greenish, laminated mudstones accumulated under low-energy and high-water table conditions. Here, vertebrate remains are limited to nicely preserved, articulated turtles and isolated dinosaur vertebral centra. Finally, to the south-east, sediments include finer components (silt and mud-dominated, fining-up splay deposits) and preserve fully articulated specimens (ankylosaurs, oviraptorids, etc.).

The taphonomy and spatial distribution of fossil remains from Guriliin Tsav can therefore be interpreted within the framework of detailed palaeo-morphological reconstruction of a meandering alluvial system. No evidence of a single, major palaeochannel is found in this locality, but rather a combination of fluvial splays and floodplain deposits with areas of extensive calcrete-bearing palaeosol development. However, the deposits also suggest periodically increased runoff. In addition, the co-occurrence of aeolian dunes and paludal areas clearly supports a complex, aeolian-fluvial system interaction. Beyond its taphonomic implications, this palaeoenvironmental setting highlights the complexity of the latest Cretaceous biota of the Nemegt Formation. Most critically, it provides further and particularly strong evidence supporting the hypothesized time-equivalency of part of the Nemegt and Baruungoyt formations — and consequently their vertebrate faunas.

Orthophotos collected at Bügiin Tsav (Fig. 7), and supported by field observations, clearly highlight three-dimensional, exhumed topsets of meandering palaeochannels and related point bar deposits. This allowed us to map the direction of expansion of point and scroll bars, based on cemented topsets of meandering palaeochannels, as well as the lithological boundaries between active channels and floodplains (i.e., topset, splays, etc.). Individual, sandstone-dominated lateral-accretion packages extend for more than 250 m normal to the palaeo-flow directions, with sharp rotation events, suggesting a relatively high-sinuosity system (Durkin et al., 2015; Sylvester et al., 2021). Field data collected in the Nemegt Formation across the basin (Eberth, 2018 and references therein) produced estimates of palaeochannel bankful widths from 75 to 150 m, with depths up to 15 m, as well as an increase in inferred channel size upsection in the Nemegt beds. Landforms observed in the 2018 study area discussed here include primarily point bars, abandoned channels, and fine-grained crevasse splays, whereas exposures further to the west are characterized by swamp and wetland deposits. Precise GPS data for fossil sites at Bügiin Tsav indicate that nearly all vertebrate remains are preserved in fine sandstone and silt-mud dominated flood plain deposits, with rare occurrences of fossils embedded in point bar deposits (which are dominated by large bivalves). This highlights that inferred information on palaeochannel hydrodynamics and related depositional settings are crucial for properly understanding the genetic and taphonomic nature of the remarkable fossils in these beds.

9. Conclusions

Jerzykiewicz et al. (2021) highlighted how faunal differences between the Baruungoyot and Nemegt formations of Mongolia should be discussed in light of physical, rather than temporal processes. Because proper tools to evaluate geographic and chronostratigraphic boundaries of these units are currently unavailable, data like those presented here are important contributions to building a solid framework for the genesis of the uppermost Cretaceous dinosaur sites of the Mongolian Gobi Desert. In particular, the integration of precise analysis of spatial facies distribution and their related taphonomic biases and fossil distribution is a crucial for improving our understanding of the Cretaceous Gobi and its fossil record.

This study contributes to this objective by describing Guriliin Tsav, one of the richest fossil localities within the Ingeni Khovur Basin, including the first high-resolution cartographic and geological descriptions. From a geological perspective, the area is characterized by fluvial splays and floodplain deposits of unconfined fluvial bodies interbedded with extensive areas of palaeosol development (both calcrete-dominated and waterlogged), typical of the Nemegt Formation. Remarkably, however, large aeolian dunes typical of the Baruungoyot Formation are also present, documenting their gradual dismantling and burial by fluvial processes. A comprehensive checklist of vertebrate diversity from this locality includes actinopterygians, testudines, squamates, crocodylians, pterosaurs, dinosaurs, aves, and mammalians (Table 2). GNNS-based topographic maps, as well as new lithostratigraphic and palaeontological data, support the referral of beds exposed at Guriliin Tsav to the middle Nemegt Formation (*sensu* Eberth, 2018).

High-resolution orthophotographs from Bügiin Tsav, despite covering only a restricted area of this vast fossil site, were a pivotal tool for identifying and mapping Cretaceous landforms with unprecedented accuracy. The combination of historic and newly acquired GIS and field data from major quarries and fossil sites allows these landforms to be linked with precise taphonomic biases related to changes in energy, sediment supply, and granulometry, as well as taxon size and distribution. Further analyses of this type will likely continue to shed new light on the long-discussed preservation patterns and biases related to fossil localities of the Nemegt and Ingeni Khovur basins.

In summary, lithostratigraphic data collected at Guriliin Tsav and Bügiin Tsav provide new insights into the Baruungoyot and Nemegt deposition and biota, supporting: 1) lateral shifts from fluvial to interdune/aeolian ecosystems; 2) major overlap in taxonomic diversity (primarily dinosaurs) across fossil sites in the Nemegt and Ingeni Khovur basins (both interpreted as partially exhumed asymmetric grabens); and 3) temporal overlap in discrete stratigraphic intervals, and therefore faunal components.

CRediT authorship contribution statement

F. Fanti: Validation, Resources, Data curation, Conceptualization. **L. Cantelli:** Methodology, Data curation, Conceptualization. **P.J. Currie:** Writing – original draft, Validation, Formal analysis, Conceptualization. **G.F. Funston:** Writing – original draft, Data curation, Conceptualization. **N. Cenni:** Methodology, Data curation. **S. Catellani:** Data curation. **T. Chinzorig:** Writing – original draft, Methodology, Data curation. **K.H. Tsogtbaatar:** Writing – review & editing, Conceptualization. **R. Barsbold:** Validation, Supervision, Investigation.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests. Federico Fanti reports financial support was provided by National Geographic Society. Gregory Funston reports financial support was provided by Dinosaur Research Institute. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cretres.2024.105916.