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The first record of a dinosaur from Bulgaria

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A portion of a left humerus from the Upper Maastrichtian of Vratsa district (NW Bulgaria) is shown to be from a non-avian theropod dinosaur: this is the first record of a dinosaur from Bulgaria. We describe this bone, suggest that it most likely pertains to an ornithomimosaur, and discuss the fossil record of other similar taxa of Late Cretaceous age that have been reported from Europe. To investigate the taphonomy of this fossil, rare earth element (REE) analysis is combined with strontium (Sr) isotope data to confirm that this Bulgarian dinosaur bone was initially fossilized in a terrestrial environment, then later re-worked into late Maastrichtian marine sediments. □ *Bulgaria*, *Dinosauria*, *Late Cretaceous*, *Ornithomimosauria*, *rare earth elements*, *Sr isotopes*, *taphonomy*, *Theropoda*.

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The fossil record of Cretaceous vertebrates from Bulgaria is extremely sparse (Tzankov 1939; Tzankov & Datchev 1966; Datchev 1973, Nikolov & Westphal 1976; Jagt *et al.* 2006). Here, we report on a fragmentary theropod dinosaur bone that was surface collected from Kajlâka Formation limestones (Upper Maastrichtian) between the villages of Drashan and Breste, south-west of the town of Cherven Briag (Vratsa district, north-western Bulgaria) (Fig. 1). This fossil was found by the speleologist Zdravkro Iliev some 200 m east of the Labirinta cave – formed within the limestones of the Kajlâka Formation – from where mosasaurs have also been recently reported (Jagt *et al.* 2006). The bone (Fig. 2) was brought to one of us (P.I.) in August 2005 and was subsequently deposited in the National Museum of Natural History, Sofia (NMNHS). Because this unique fossil proves to be the first record of a non-avian dinosaur from Bulgaria, we describe its anatomy, present arguments for a taxonomic placement and investigate its taphonomy using chemical analyses. Because the bone was found in marine sediments, it is important to determine whether (or not) this Bulgarian dinosaur actually lived in a coastal environment or whether the fossil was subsequently re-worked from a more terrestrial sedimentary setting.

Background: geology and provenance

The Bulgarian dinosaur bone (NMNHS F-31436; Fig. 2) was surface collected from within marine limestones in a sinkhole (called 'the dinosaur') between the villages of Drashan and Breste, south-west of the town of Cherven Briag (NW Bulgaria) (Fig. 1). This flat area is covered by a field and is underlain by the limestones of the Kajlâka Formation. The formation outcrops in this region as the uppermost Cretaceous unit, spread widely across the Fore-Balkan and Moesian Platforms of northern Bulgaria. Because the Kajlâka Formation mostly comprises organodetritic limestones (Jolkičev 1986, 1989), this area is karstified and numerous sinkholes and erosion surfaces are developed along sub-parallel faults covered by vegetation. The sinkholes are thus easily recognized in the field by concentrations of bushes: underneath the vegetation, cracks spread out into the fossiliferous sequence (Jagt *et al.* 2006).

The geological and stratigraphical setting of this area was described by Jagt *et al.* (2006) who presented preliminary descriptions of a collection of more than 60 fragmentary bones collected some 200 m west from the 'the dinosaur' sinkhole. Jagt *et al.* (2006) identified

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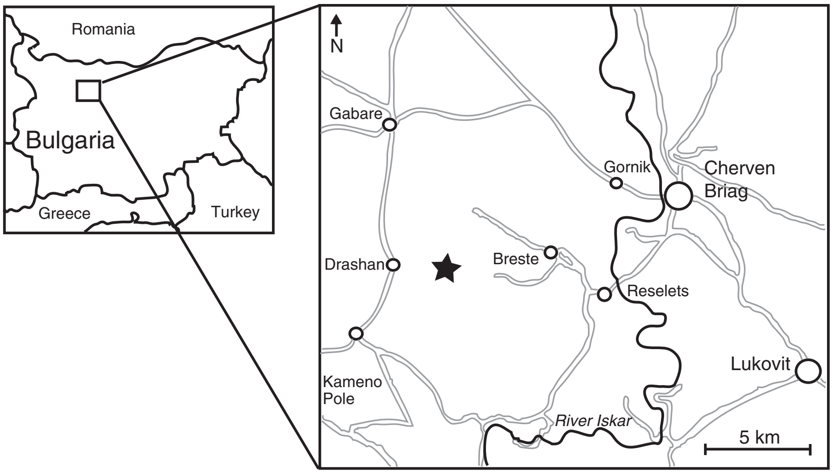

Fig. 1. Locality map of the study area in Vratsa district, NW Bulgaria; the star denotes the location of the dinosaur locality, between the villages of Drashan and Breste.

Mosasaurus cf. *hoffmanni* Mantell, 1829, and mentioned the presence of other putative marine reptiles, two isolated teeth from lamniform sharks (*Squalicorax pristodontus* [Agassiz, 1843] and *Anomotodon* sp.) and a phragmocone of *Hoploscaphites constrictus* (Sowerby, 1817). Some of the fragmentary bones from the Labirinta cave were recently re-examined and the presence of dinosaurs among them was suggested (P. Godefroit, J. Jagt and A. Schulp, personal communication). The age of the Kajlâka Formation has been determined based on ammonite and echinoid occurrences as late Maastrichtian: the ammonite *H. constrictus* from the Labirinta cave confirms this Maastichtian age determination and the occurrence of *S. pristodontus* narrows it further to late Maastrichtian. In addition, the presence of the pachydiscid ammonite, *Anapachydiscus* [*Menuites*] cf. *terminus* Ward & Kennedy, 1993, from correlative sediments in the 'quarry type' limestones of the Kajlâka Formation at the nearby village of Varbeshnitsa (see Jolkičev 2006, pl. 1, fig. 3) allows to date this level of the formation even more precisely to the upper part of the late Maastrichtian (Jagt *et al.* 2006). This age is further independently verified by our isotopic analysis (see below): strontium (Sr) isotopes delimit an age for these sediments between 66 and 63 Ma.

This age estimate, however, is unlikely to pertain to the Bulgarian dinosaur bone. As there is no doubt that the limestones in which this bone was found are both late Maastrichtian in age and marine in origin, the occurrence of a terrestrial reptile bone with continental sediment stuck to it is incongruous and suggests re-working. Therefore, independently from the taxonomic work, we conducted geochemical analyses (REE and Sr isotopes) to provide more data regarding the likely age and origin of this bone. The geochemical studies are part of a broader project (still in progress) also involving findings of marine reptiles and possible other dinosaurs in the Labirinta cave. Consequently, and to further address the taxonomic placement of this fossil, we conducted histological analyses.

The sediment stuck to the described bone, is a sandy limestone (60% carbonate, 40% clastic grains and clay minerals), the matrix is represented by micritic calcite. The clastic grain framework is composed by quartz (80%), feldspar (10–15%), mica (5%) and siltstone rock fragments. The detrital grains are angular to sub-angular, poorly sorted with grain size ranging from very fine to medium grained suggesting short transport before deposition. The cement is drusy mosaic calcite filling leached parts from the micritic matrix or depositional voids. Most likely this drusy mosaic cement has a meteoric phreatic origin; as discussed below this sediment suggests deposition and original burying of the bone on the continent but in a near costal zone.

Materials and methods

For histological analyses, a polished section of compact bone was prepared and examined under a microscope with normal light. The polished section was then further processed to make a thin section and pictures were taken under both normal and polarized light.

Isotopic Sr and trace-element REE analyses were conducted in the Department of Geological Sciences, University of Florida, where bone and limestone samples were processed with 'Optima' grade reagents in a clean laboratory environment. Elemental concentrations and Sr isotopic analyses were conducted following the methods outlined by Kamenov *et al.* (2008).

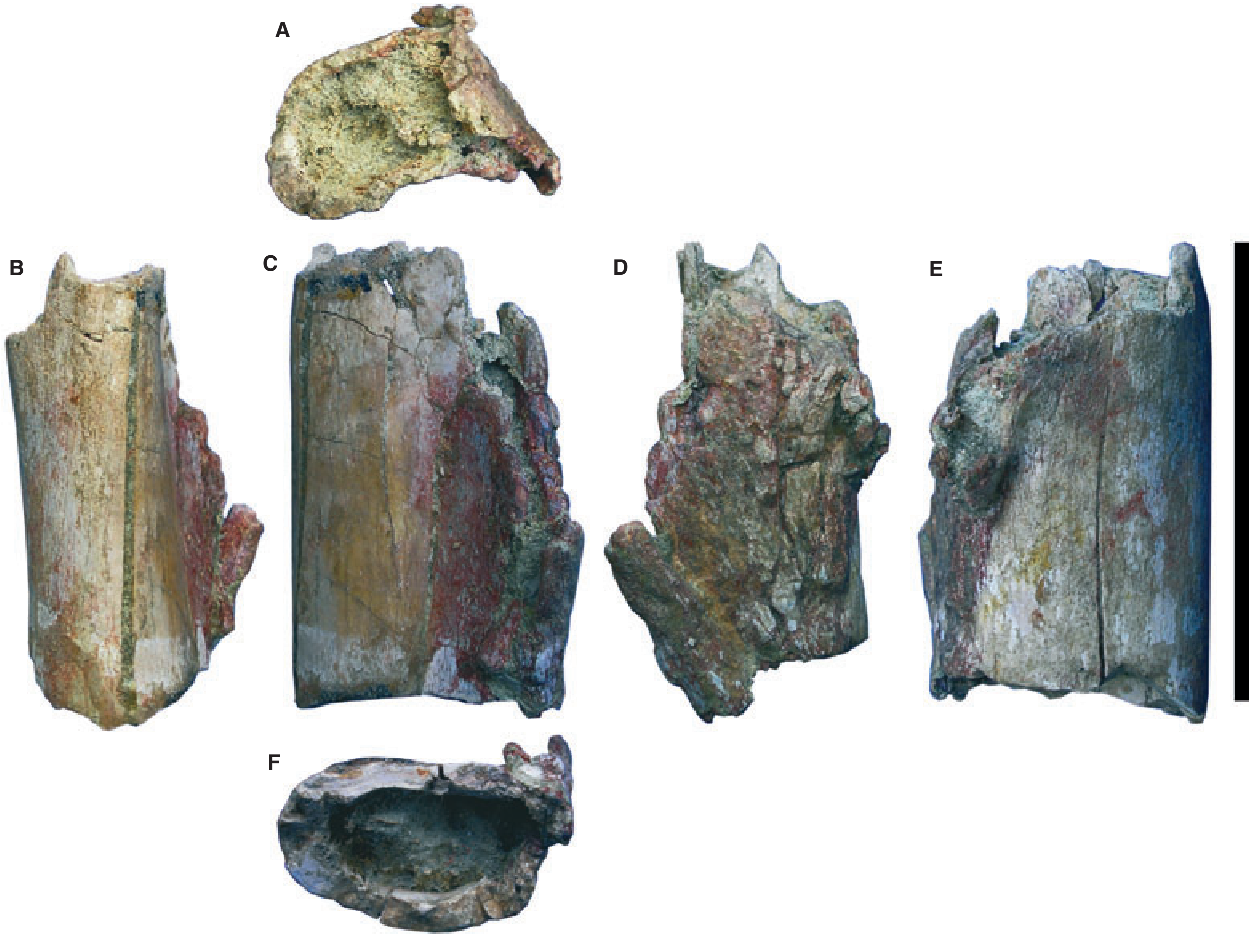

Fig. 2. Ornithomimosaur theropod: part of left humerus (NMNHS F-31436) in A, proximal; B, medial; C, anterior; D, lateral; E, posterior; and F, distal views. Scale bar: 10 cm.

For our analyses samples from 1 to 7 (Table 1) are from 'the dinosaur' sinkhole locality, some 200 m east of the Labirinta cave (Fig. 1; Jagt *et al.* 2006). Samples 1–3 were taken from compact bone (NMNHS F-31436), while sample 4 was extracted from the sediment infilling the medullary cavity (i.e. the hollow part of the limb bone present in all theropods which lacks bone structure). Sample 5 was taken from the surrounding limestone, attached externally to the dinosaur bone. Sample 6 is a late Maastrichtian limestone from the Kajlâka Formation, on which the dinosaur bone was found lying free. Sample 7 is also a late Maastrichtian limestone from the Kajlâka Formation but taken from a 20- to 30-cm higher level than sample 6. Samples 8 and 9 are from the Labirinta cave (Jagt *et al.* 2006), some 200 m west of the 'the dinosaur' sinkhole. Sample 8 was taken for comparison from a problematic bone (reptile?) (NMNHS F-31438) that was also found inside the cave, while sample 9 is from the Upper Maastrichtian limestone of the Kajlâka Formation, also from inside the cave.

A theropod dinosaur from Bulgaria: description and bone histology

We identify the partial Bulgarian dinosaur bone (NMNHS F-31436) as a diaphysial fragment of a left humerus, incorporating the diaphysis and part of the deltopectoral crest (Fig. 2). The bone is 94 mm long, preserving a diaphysis that is ellipsoid in cross-section and expanded transversely (54 mm wide versus 44 mm antero-posteriorly). The bone is hollow with a free medullary cavity bordered by a bone wall of 4–7 mm in thickness.

The presence of a free medullary cavity is informative: while this space is present in several reptile groups, a cavity of this size is seen only in mammals, pterosaurs and theropod dinosaurs, including birds (O'Connor 2006). Thus, the size and proportions of this cavity combined with the absence of internal bridges as in pterosaurs allows us to designate the Bulgarian bone as a theropod dinosaur.

Table 1. Rb, Sr, and rare earth element concentrations (in p.p.m.) and Sr isotopic data for the studied samples.

Sample no.	1	2	3	4	5	6	7	8	9
Type	Dinosaurian bone	Dinosaurian bone	Dinosaurian bone	Sediment mixed with bone	Limestone	Limestone	Limestone	Problematic bone (reptile?)	Limestone
Rb	0.9	7.7	1.5	113	59.9	4.0	2.5	0.04	2.1
Sr	1353	1209	1158	397	205	350	307	2170	227
La	69.05	108.63	210.45	22.84	19.24	5.54	3.08	52.48	1.88
Ce	93.52	147.38	172.02	31.97	33.21	8.72	3.78	40.77	2.18
Pr	9.11	11.70	13.57	3.35	3.68	1.16	0.61	7.11	0.37
Nd	34.02	42.39	49.08	12.14	12.99	4.32	2.38	28.70	1.44
Sm	5.90	7.74	8.72	2.39	2.43	0.79	0.47	5.31	0.29
Eu	2.03	2.42	2.44	0.67	0.62	0.14	0.10	1.23	0.06
Gd	6.16	7.61	8.94	2.17	2.31	0.69	0.45	6.17	0.27
Tb	1.05	1.22	1.49	0.31	0.33	0.11	0.08	1.03	0.04
Dy	6.27	6.87	8.51	1.65	1.85	0.58	0.45	6.46	0.25
Ho	1.43	1.40	2.09	0.32	0.37	0.10	0.09	1.46	0.05
Er	4.18	3.89	6.24	0.86	1.06	0.28	0.26	4.26	0.15
Tm	0.55	0.53	0.81	0.12	0.15	0.04	0.03	0.55	0.02
Yb	3.28	3.20	4.97	0.73	0.92	0.23	0.21	3.01	0.13
Lu	0.49	0.47	0.76	0.10	0.13	0.03	0.03	0.43	0.02
Pb	91.2	97.1	103	39.7	22.7	0.9	1.1	33.5	1.6
Th	2.8	12.3	3.3	7.6	7.0	1.3	0.3	0.6	0.3
U	411	302	731	63.3	2.9	0.9	0.6	113	0.7
$^{87}Sr/^{86}Sr$	0.70971	–	0.70961	0.71068	0.71002	0.70783	0.70782	0.70835	–

Within theropods, most taxa have a sigmoid diaphysis but in one group – ornithomimosaurs – the humerus is straight and slender in all taxa, as in NMNHS F-31436. The lateral side of the deltopectoral crest is also very rugose in all known specimens within this lineage (surfaces for muscle attachments) and has a transversely curved and concave anterior margin because of the weakly developed deltopectoral crest (Fig. 2). In addition, although this combination of derived character states is seen in some Gondwana theropods (e.g. *Masiakasaurus* known from Madagascar and the North African *Deltadromeus*; Carrano *et al.* 2002), and one or other of the two characters used here are seen in some other taxa (e.g. the laterally straight humerus of some tyrannosaurs, the flattened humeral shaft of *Erlikosaurus*), the presence of a weakly developed deltopectoral crest has nevertheless been optimized by recent phylogenetic analyses as an unambiguous synapomorphy for clade Ornithomimosauria (Makovicky *et al.* 2004; Kobayashi 2004). Similarly a slim humerus has been optimized as a synapomorphy for *Dromiceiomimus* spp. (cf. *Struthiomimus*) + *Ornithomimus* spp. (character 68 of Kobayashi 2004). Although this character cannot be observed for certain due to the incompleteness of the specimen, the plesiomorphic character condition is present. Thus, and even though it is very fragmentary, we advance the working hypothesis that this Bulgarian dinosaur bone can be tentatively ascribed to ornithomimosaurs within theropod dinosaurs. The discovery of additional material will be required to confirm this conclusion.

The histology of this bone also indicates that it comes from an adult. This is evidenced by the fibrolamellar structure, mainly in the outer surface and by the secondary bone tissue, mainly on the internal side. Lines of arrested growth (LAGs) cannot be observed. Work in progress on the histology may confirm the data given by the osteology.

Discussion

Taphonomic implications

Most parts of the present north Bulgarian territory during the Late Cretaceous were occupied by epicontinental sea (Jolkičev 1989) along the northerly margins of the Tethyan Ocean. The occurrence of a bone from a terrestrial animal in marine strata denoting a relatively shallow epicontinental sea should not be regarded as unusual. There could have been smaller or larger islands in this sea. Southern of the described locality was the landmass separating the Tethyan Ocean and the North European epicontinental sea. It is quite probable that dinosaurs and other terrestrial animals inhabited such landmasses. After death their carcasses could be easily transported to floodplains, deltas, lake beds, stream bottoms.

Although they are regularly found as fossils in intertidal habitats, most dinosaurs were terrestrial animals. However, because NMNHS F-31436 was found on top of a marine limestone, REE and Sr isotope analyses were conducted to investigate its age as well as

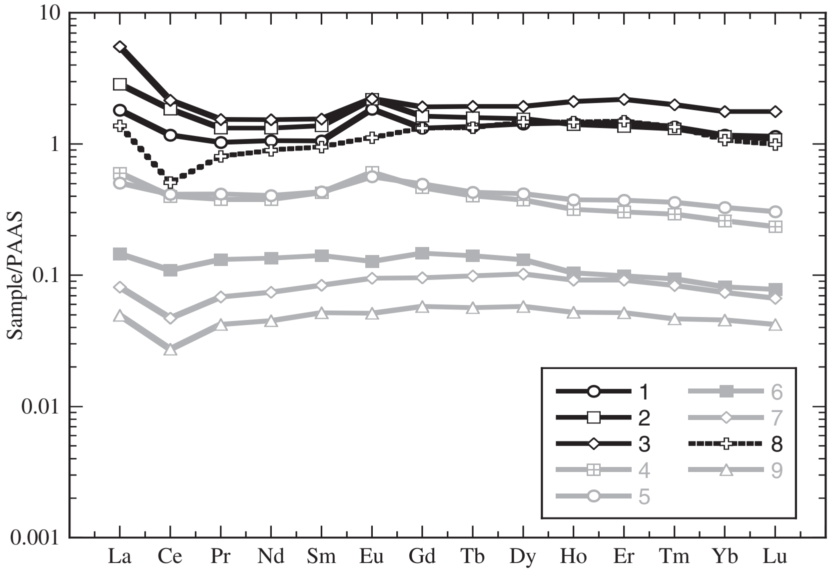

Fig. 3. Rare earth element (REE) data for the bone and limestone samples normalized to post-Archaean Australian Shale (McLennan 1989). Note the similar REE patterns for samples 1–5, distinct from the patterns in samples 6–9 (for more discussion see text).

taphonomy and bone diagenesis. We know that REE concentrations are very low in living skeletal tissues but are rapidly (0–30 kyr) absorbed by bone apatite during diagenesis (Trueman *et al.* 2004). Thus, the REE patterns of fossil bones reflect their diagenetic environments: studies have shown that bones fossilized in different geochemical environments can be distinguished based on their REE patterns (e.g. MacFadden *et al.* 2007). Results of our analyses are shown in Figure 3.

The bone samples taken from NMNHS F-31436 (samples 1–3) exhibit very similar REE patterns and are characterized by enrichment of light REEs and a positive Eu anomaly (Fig. 3). Samples 4 and 5 also show a pattern similar to NMNHS F-31436, although their overall REE concentrations are lower – these two samples probably contain some dinosaur bone, as sample 4 is from the sediment infilling the bone and sample 5 is from the sediment encrusted onto its external surface. Sample 8, the problematic bone (reptile?) (NMNHS F-31438) found *in situ* in the Labirinta cave, shows a distinct REE pattern with a bell-shaped mid-heavy REE and a negative Ce anomaly – this bone was found in the limestone of Kajlâka Fm represented by sample 9.

The comparative limestone samples 6, 7 and 9 exhibit REE patterns similar to each other and to sample 8 suggesting that the problematic bone (reptile?) (NMNHS F-31438) included for analysis was probably fossilized in these marine carbonates. The fact that the dinosaur samples 1–5 have distinct REE patterns when compared with samples 6–9 suggests that the former was not fossilized in the same environment as sample 8. Further evidence for this conclusion is provided by the Sr isotopic compositions of the samples: the $^{87}Sr/^{86}Sr$ ratio in samples 1–5 (Table 1) varies between 0.70961 and 0.71068, way above the expected values for Cretaceous sea water (McArthur & Howarth 2004). On the other hand, Rb–Sr ratios for the dinosaur bone samples are not high enough to explain the observed isotopic compositions via *in situ* Rb decay (Table 1), thus indicating that the observed $^{87}Sr/^{86}Sr$ ratio was either acquired during fossilization or *in vivo*, perhaps as a result of dietary Sr intake by the animal. This relatively radiogenic Sr isotopic signature suggests that if Sr was acquired during diagenesis, the bone was fossilized in an environment dominated by continental sediments.

Evidence for a continental origin for NMNHS F-31436 is also supported by the REE patterns for samples 1–5, distinct from the marine limestones in the region and from sample 8 (Table 1; Fig. 3). Thus, even if we speculate that the Sr isotopic ratios were acquired *in vivo*, the fact that the ratios are higher than Cretaceous or even present-day sea water values (0.70917), these data indicate that the Bulgarian dinosaur did not reside in a marine environment, or feed exclusively on a marine diet. Furthermore, the Sr isotopic compositions in the bone are much higher than would be expected for juvenile volcano-magmatic rocks (e.g. island arc settings). This latter observation provides a further constraint on our palaeoenvironmental interpretation, suggesting that the dinosaur lived, perished and was fossilized in an environment dominated by continental crustal rocks (e.g. granitoids and/or metamorphic rocks, and/or sediments rich in continental detritus).

Finally, because the Sr isotopic compositions of limestone samples 6 and 7 have values consistent with Late Cretaceous sea water, we can use them to further corroborate the age of these sediments: from McArthur & Howarth (2004), we calculate an age between 66 and 63 Ma for these samples. Bone sample 8, however, exhibits an elevated $^{87}Sr/^{86}Sr$ ratio (0.70835) compared with the local limestone samples. This is clear evidence for re-working of the bone into the limestones: this ratio gives an age of 22 Ma, much younger than expected based on its geological occurrence. Further, because sample 8 has very low Rb and very high Sr concentrations (Table 1), *in situ* Rb decay cannot explain the observed isotopic composition. One possible explanation for this could be that due to its very high Sr content, the bone sample did not completely equilibrate with the host marine carbonates during diagenesis. As a result, the elevated $^{87}Sr/^{86}Sr$ signal in sample 8 may suggest that this animal either did not have an exclusively marine diet or that the bone is from a terrestrial animal that lived near by the ancient marine basin. Overall, the distinct REE patterns and Sr isotopic compositions provide evidence that the dinosaur bone (NMNHS F-31436) was not fossilized *in situ* with sample 8 (NMNHS F-31438). Most probably the dinosaur bone was fossilized in a terrestrial environment and later was re-deposited in the late Maastrichtian marine sediments that contain sample 8. This indicates that the dinosaur bone can be either late Maastrichtian or older.

Ornithomimosaurs across Europe? – biogeographical patterns

Despite an excellent European fossil record for most groups of derived theropod dinosaurs, ornithomimosaurs are extremely rare. Should the Bulgarian taxon prove to be a certain member of this clade, then this record is very important. One well-preserved taxon (*Pelecanimimus*) from the Lower Cretaceous (Barremian) of Spain (Peréz-Moreno *et al.* 1994) has been placed in an early-diverging position within the clade (Qiang *et al.* 2003; Kobayashi 2004), but otherwise the European record is poor and in some cases questionable – for example, some partial bones held currently in a UK private collection were referred to this lineage by Martill *et al.* (2006). Thus, a valid record of these dinosaurs from the Bulgarian Late Cretaceous is of particular importance.

We contend that NMNHS F-31436 probably does represent the first valid occurrence of an ornithomimosaur from the European Late Cretaceous. There have been two earlier reports, but these are problematic. First, Dollo (1883) described a proximally incomplete theropod manual ungual phalanx from the Late Cretaceous of Lonzée, Belgium. The ungual phalanges of these dinosaurs are characteristic in having a well developed and distally placed flexor tubercle on the ventral rim of the proximal third of the claw – this tubercle is present on the specimen described by Dollo (1883). Second, the nomen dubium theropod taxon *Megalosaurus bredai* Seeley 1883, which was created for a right femur from the Maastrichtian of Maastricht (Jagt *et al.* 2003), has been interpreted by some workers as either an ornithomimid (see Russell 1972) or as a ceratosauroid (possibly an abelisaurid; Le Loeuff 1992). There is no anatomical evidence for either of these identifications.

According to Makovicky *et al.* (2004), the valid taxa of ornithomimosaurs known from the Late Cretaceous are *Garudimimus* Barsbold, 1981 (Cenomanian–Santonian of Mongolia), *Ornithomimus* Marsh, 1890 and *Struthiomimus* Osborn, 1917 (both in the Campanian–Maastrichtian or North America), *Archaeornithomimus* Russell 1972 (?Campanian of China), *Deinocheirus* Osmólska & Roniewicz, 1970, *Anserimimus* Barsbold, 1988 and *Gallimimus* Osmólska, Roniewicz & Barsbold, 1972 from the Maastrichtian of Mongolia.

The single well-represented European record of these dinosaurs – *Pelecanimimus* – has been hypothesized to occupy a basal position with the phylogeny of this group (Kobayashi 2004); because this taxon is also somewhat older than its Asian and North American counterparts, this may indicate that a later radiation of ornithomimosaurs occurred outside of Europe. Optimization of Cretaceous continent-scale distributions onto this phylogeny, however, has led to the alternative suggestion that the early evolution of ornithomimosaurs occurred in Asia (Makovicky *et al.* 2004). Nevertheless, the new Bulgarian record for these dinosaurs presented in this paper adds weight to biogeographical hypotheses for the radiation of ornithomimosaurs: it is intriguing that several other lineages of non-avian dinosaurs that have a predominantly Asian-North American fossil record seem to have had basal representatives in the Cretaceous of Europe (Sereno 1999). Certainly, countries such as Bulgaria, currently little explored in the search for Cretaceous vertebrates, should continue to yield critical information to develop our understanding of dinosaur evolution and biogeography.

Conclusions

In summary, here we report the occurrence of the first dinosaur of Bulgaria, a possible ornithomimosaur theropod from sediments of the end of the Cretaceous (66–65.5 Ma, although because of the bone redeposition it may be of an older age), which may confirm the existence of ornithomimosaur dinosaurs in the Late Cretaceous of Europe (potentially also validated by an ungual phalanx from Belgium). The fact that the dinosaur was found in marine limestones indicates that it was most likely reworked. REE analyses conducted on the bone sample show distinct patterns from a found nearby fossil bone and local marine limestones, confirming that the bone was re-deposited in the marine environment. The relatively radiogenic Sr isotopic data confirm that the studied bone was terrestrial and also indicate that the animal palaeohabitat was dominated by rock formations typical of the upper continental crust.

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