DINOSAURS OF THE GOBI: FOLLOWING IN THE FOOTSTEPS OF THE POLISH-MONGOLIAN EXPEDITIONS

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The Polish-Mongolian Palaeontological Expeditions collected many partial and complete dinosaur skeletons from the Nemegt Formation of Mongolia between 1964 and 1971. Under the leadership of Zofia Kielan-Jaworowska, the specific localities of fifty of these quarries were recorded on published maps. In recent years, more than half of these quarries have been relocated for the collection of additional data and even missing parts of some specimens. They have been included in a database that contains more than six times the original number of specimens. The larger, more precise database will ultimately be useful for identifying and interpreting the stratigraphic and geographic distributions of specific dinosaur taxa. However, at this stage it only confirms a preservational bias that favors the recovery of specimens of the tyrannosaurid *Tarbosaurus* with greater frequency than any herbivorous dinosaurs.

Key words: Dinosauria, Polish-Mongolian Palaeontological Expeditions, Upper Cretaceous, Nemegt Formation.

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INTRODUCTION

Some of the most famous and influential scientific expeditions were the central Asiatic expeditions (1922–1930) of the American Museum of Natural History (Andrews 1932). Under the leadership of Roy Chapman Andrews, the multidisciplinary team became best known for their palaeontological discoveries, including many important localities in the Gobi Desert of China and Mongolia, and spectacular fossils that included the first recognized dinosaur eggs plus now famous dinosaurs like *Alectrosaurus olseni*, *Oviraptor philoceratops*, *Protoceratops andrewsi*, *Psittacosaurus mongoliensis*, and *Velociraptor mongoliensis*. The expeditions, which ended in 1930, attracted worldwide attention, and inspired a series of large-scale expeditions from the Soviet Union (USSR) in 1946, 1948 and 1949 (Lavas 1993). In addition to collecting at some of the sites discovered by the AMNH expeditions, the Soviet expeditions discovered some spectacular Late Cretaceous sites farther to the West that have produced one of the richest dinosaur faunas known. They called one site the "Dragon's Tomb," and it yielded more than 60 tonnes of articulated dinosaur skeletons, including partially mummified remains of the hadrosaur *Saurolophus*, and skeletons of the tyrannosaur now known as *Tarbosaurus*. The accomplishments of both the American and Russian expeditions in Mongolia became well-known in Soviet Bloc countries in the years following the Second World War. An agreement between the Mongolian and Polish scientific academies put a youthful and energetic Zofia Kielan-Jaworowska in charge of setting up and leading a series of expeditions to the central Asian country (Kielan-Jaworowska 2013). The Polish-Mongolian Paleontological Expeditions (1964–1971) went on to become one of the greatest and most productive expeditions in the history of vertebrate palaeontology. They not only collected some of the best specimens that had been discovered in the Gobi Desert up to that time, but they kept good records of what, when, where, and how they collected specimens. The specimens were quickly prepared and within two years of starting the expeditions, the first scientific papers were released in international, peer-reviewed scientific journals. Their publications, both scientific and popular, were in English, which gave them the broadest audience and the greatest international attention. Although none of the scientists were well-known outside of their limited fields of research expertise in Europe, they quickly became internationally renowned for their work on Cretaceous vertebrates from Mongolia. This is especially true when it came to Zofia Kielan-Jaworowska's research on Cretaceous mammals, the research on Cretaceous dinosaurs by Halszka Osmólska and Teresa Maryańska, the stratigraphic/ sedimentological analyses by Ryszard Gradziński and Tomasz Jerzykiewicz, and the research of virtually everyone who was part of this incredible team of researchers. On the Mongolian side, Rinchen Barsbold also climbed to international fame as a dinosaur researcher. Long after their last expedition in 1971, their work endures through specimens (particularly the holotypes of many species) in Poland and Mongolia, through their pivotal research projects, and through the information they collected in the field. In spite of the fact that the world was not so technologically advanced when the PMPE were underway, they nevertheless established the gold standard for how expeditions should be run. The purpose of this article is to show how their attention to detail has allowed us to return to their dinosaur quarries and collect more data that will help us to better understand the palaeobiology of dinosaurs and the animals that lived with them.

A chance reading of "All About Dinosaurs" (Andrews 1953) was in fact the reason that I decided to become a vertebrate palaeontologist. Andrews, based on his experiences as the leader of the Central Asiatic Expeditions (Andrews 1932), described how they had found the first dinosaur fossils in the Gobi Desert of Mongolia. Not surprisingly, I was also fascinated by subsequent expeditions that collected dinosaurs in the Gobi (Rozhdestvenskii 1960, Colbert 1968, Kielan-Jaworowska 1969). Throughout my student years, I never thought it would be possible for me to go to the either China or Mongolia because of the international political conditions. However, when I started to collect dinosaurs as a professional in Alberta, Canada in 1976, it became evident that the Cretaceous dinosaurs of Alberta and Mongolia were inter-related. This increased my desire to study the Asian fossils and sites, and a few years later I had an opportunity to do an expedition to central Asia. Initially our team at the newly created Tyrrell Museum of Palaeontology tried to secure an agreement with Mongolia, and I contacted Zofia Kielan-Jaworowska for advice. We had met in 1981 at the Mesozoic Terrestrial Ecosystems Conference in Warsaw, where I remembered being pleasantly surprised by how much she looked and behaved like a younger version of my own grandmother (Ruth Brander, 1903–1983). When I contacted Zofia about the potential project in Mongolia in the summer of 1983, she was in Malcolm McKenna's field camp in Wyoming; I went there to speak with her directly. She was very happy to talk about the Polish-Mongolian Palaeontological Expeditions, and freely provided advice and contacts.

In the long run, we were unable to secure an agreement with Mongolia, but went instead to the Chinese Gobi Desert as the Canada-China Dinosaur Project, 1986–1990 (Currie 1991, Grady 1993). Ultimately, I was also able to work in Mongolia, as a member of “Dinosaurs of the Gobi” (Nomadic Expeditions, 1996–2007, 2011) and as part of the Korea-Mongolia International Dinosaur Project (2006–2010, 2012). One of the greatest thrills of my life was when Zofia joined us in 2002 with her husband Zbigniew Jaworowski and granddaughter Zofia (Zosia) Jaworowska (Kielan-Jaworowska 2013). In addition to our normal program of work, we visited Polish-Mongolian expedition sites with her at Hermiin-Tsav (I and II), Khulsan, and Nemegt (Central and Northern Sayrs, Red Monadnocks, Southern Monadnocks), and she helped to unravel the mysteries of some of the locality information. During the evenings, she would share stories of the Polish-Mongolian expeditions around the supper table.

For many years, I have led interdisciplinary field projects in which we search for new dinosaur specimens (isolated bones, skeletons, bonebeds) and sites, and document and collect what we find. During the dinosaur renaissance of the 1970s, I realized that arguments about the physiology and palaeoecology of dinosaurs depended to a large extent on the reliability of records of specimens that had been collected previously (Sternberg 1950), and whether or not preservational or collecting biases existed. For example, Bakker (1972) maintained that evidence existed in Dinosaur Provincial Park (Alberta, Canada) for dinosaurian predator/prey ratios, and that these ratios showed that carnivorous dinosaurs in the Late Cretaceous were warm-blooded. He reasoned that the predators made up less than 10% of the known specimens, and that there were collecting biases that favoured the collection of all theropod skeletons but not all specimens of the more common herbivorous dinosaurs. This would therefore suggest that the actual predator/prey ratio was as low as 5%. Other researchers countered that there were no collecting biases, and that every well-preserved dinosaur was excavated. Because of these insoluble debates, two other priorities were added into my field programs — all articulated/associated dinosaur skeletons were documented, regardless of whether or not they were collected. Furthermore, old dinosaur sites were identified and documented whenever we found them so that we could improve the geographic and stratigraphic resolution of the provenance data associated with the older finds. In this way, we have strongly increased the sample size of dinosaur occurrences in the Park while minimizing the biases, and have produced some interesting results (Currie and Russell 2005).

Virtually every major dinosaur-hunting expedition to the Mongolian part of the Gobi Desert (Lavas 1993) has collected in what is now referred to as the Nemegt Formation. The formation has yielded the most diverse Late Cretaceous dinosaur fauna known (Weishampel *et al.* 2004) with the exception of the Dinosaur Park Formation of Canada (Currie and Koppelhus 2005). The Nemegt sites are inherently interesting palaeoecologically because of the faunal similarities with the Late Cretaceous faunas of Alberta (Currie and Koppelhus 2005). A program of collecting and documentation similar to the approach in Dinosaur Provincial Park was adopted in the Nemegt Formation of Mongolia because of its richness. Furthermore, previous work in the Nemegt Formation had revealed what appeared to be an ecologically skewed predator/prey ratio, and it was necessary to investigate the possibility that this represented a collecting bias. Overall, individuals of the tyrannosaurid *Tarbosaurus* clearly outnumbered individuals of any genus of herbivorous dinosaur from the same formation (Osmólska 1980). Consequently every articulated specimen encountered in the field has been documented and/or collected, including specimens vandalized by poachers (Currie 2012), and historic dinosaur quarries have been relocated and incorporated into the database whenever possible (Currie 2009). Quarries in the Baruungoyot Formation were included in the study because this formation is found at most of the same localities as the Nemegt Formation (and therefore included on the same maps). Furthermore, the two formations were not initially considered separate, and it is not always clear which formation a given specimen came from. Finally, the Baruungoyot and Nemegt formations overlap in time, and their sediments inter-finger (Eberth *et al.* 2009; Fanti *et al.* 2012).

Of the dinosaurs excavated in Mongolia during the twentieth century, those of the Central Asiatic Expeditions are mostly from the Djadokhta Formation. The positions of Soviet/Russian sites (from 1946 to present) were not recorded on maps, and we have not been able to field-identify more than a few of their quarries because specific locality data and/or photographs are rarely included in their publications. Exceptions include the famous Dragon’s Tomb at Altan Uul II, and one Soviet site in Nemegt Central Sayr that was incidentally marked on the Polish-Mongolian maps (Fig. 1). Many Russian (Kurochkin and Barsbold 2000), Soviet and Mongolian quarries have been identified by the excavations with their associated quarry garbage (usually including tin cans and glass jars with Cyrillic stamps or labels) and/or bulldozer tracks. However, determining which dinosaur came from which excavation is currently not possible.

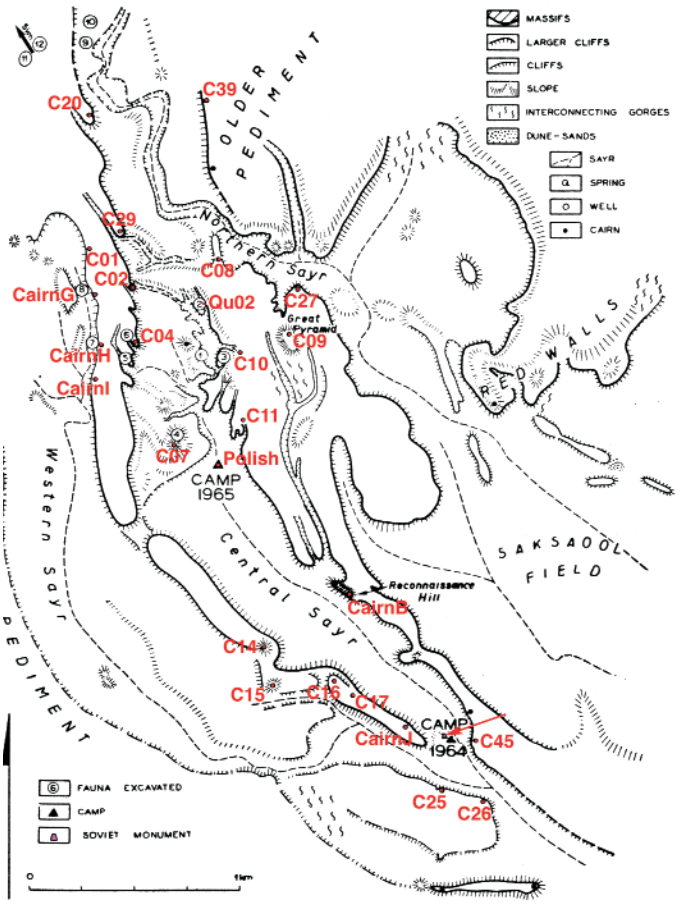

Fig. 1. Gradziński's map of the central and western part of Nemegt showing how the cairns used for triangulation were numbered as they were found and recorded by GPS. These data were used to modify the map slightly by adjusting the depiction of geography to better match GPS coordinates and by adding labels in red. Then the modified map was uploaded into a GIS program (initially it was Ozi Explorer, but more recently it has been MacGPS Pro) so that the expected coordinates could be calculated for all of the quarries that had not been found. Abbreviations: C, cairn; Qu02, quarry 2 of the PMPE plus an earlier Soviet excavation of a *Tarbosaurus* skeleton. Modified from original map by Gradziński *et al.* (1969, fig. 2).

The Polish-Mongolian Paleontological Expeditions were meticulous in recording where their specimens were collected. The topographic maps of Mongolia that were available to the expeditions (both then and now) were inadequate for meaningful documentation, and therefore the Polish geologists became proficient in producing maps of the primary collecting localities. These were essentially hand-drawn, although reference points were provided by constructing stone cairns (Fig. 2) for triangulation. The maps (Gradziński *et al.* 1969; Gradziński 1969; Gradziński and Jerzykiewicz 1974) drawn at the various Mongolian dinosaur localities have been the prime resource for finding and identifying original quarries. The Polish-Mongolian Expeditions collected more than 100 dinosaur skeletons between 1963 and 1971 (specimens and specimen records in ZPAL). By the definition adopted here, a skeleton may include as few as a half dozen bones provided they are from the same individual (for example, all specimens of *Elmisaurus rarus* Osmólska 1981), although some are virtually complete. Of these, 55 were recovered from the Baruungoyot and Nemegt formations, and most were included on the maps (Table 1).

Table 1. Abbreviations: AU2, Altan Uul 2; AU3, Altan Uul 3; AU4, Altan Uul 4; Khu, Khulsan; Nem, Nemegt; TsKh, Tsagan Khusuu.

Names	Specimen #	Quarry #	Collected	Discovered by
Saurolophus angustirostris	ZPAL MgD-I/087	AU2001		
Saurolophus angustirostris	ZPAL MgD-I/158	AU2001		
Saurolophus angustirostris	ZPAL MgD-I/166	AU2001		
Saurolophus angustirostris	ZPAL MgD-I/168	AU2001		
Tarbosaurus bataar	ZPAL MgD-I/005	AU3001	1965	Skarżyński
Deinocheirus mirificus	MPC-D100/018	AU3002	1965	Kielan-Jaworowska
Tarbosaurus bataar		AU3003	1965	Rachtan
Quadrupedal dinosaur		AU4001	1965	Kuczynski
Carnivorous dinosaur		AU4002		
Tarchia gigantea	ZPAL MgD-I/049	AU4003		

Names	Specimen	Quarry #	Collected	Discovered by
Opisthocoelicaudia skarzynskii	ZPAL MgD-I/048	AU4004	1965	Gradziński
Tarchia gigantea	ZPAL MgD-I/043	AU4005	1964	Walknowski
Tarbosaurus bataar	ZPAL MgD-I/044 and 45	AU4006	1964	
Tarchia gigantea	ZPAL MgD-I/042	AU4007	1965	Lefeld
Gallimimus bullatus		AU4008		
Tarbosaurus bataar	ZPAL MgD-I/031	AU4009	1964	
Tarchia gigantea		AU4010		
Tarbosaurus bataar		AU4011		
Tarbosaurus bataar	ZPAL MgD-I/046	AU4012		
Breviceratops kozlowskii	ZPAL MgD-I/118	Khu001		
Hulsanpes perlei (could also be Khu08)	ZPAL MgD-I/173	Khu002	1970	
Breviceratops kozlowskii	ZPAL MgD-I/116	Khu004		
Breviceratops kozlowskii	ZPAL MgD-I/117	Khu005		
Tarchia kielanae	ZPAL MgD-I/111	Khu006		
Small theropod		Khu008		
Tylocephale gilmorei	ZPAL MgD-I/105	Khu010		
Saichania chulsanensis	MPC-D100/151	Khu011	1971	found in 1970
Tarbosaurus bataar	ZPAL MgD-I/029?	Nem001	1964	
Tarbosaurus bataar		Nem001A	1964	Borsuk-Białynicka
Tarbosaurus bataar	ZPAL MgD-I/029?	Nem002	1965	Maryańska
Tarbosaurus bataar		Nem003	1965	Barsbold
Gallimimus bullatus	ZPAL MgD-I/010	Nem004		
Gallimimus bullatus	ZPAL MgD-I/007	Nem005		
Nemegtosaurus mongoliensis	ZPAL MgD-I/009	Nem006	1965	Kuczynski
Gallimimus bullatus	ZPAL MgD-I/011	Nem007		
Homalocephale calathocercos	MPC-D100/051	Nem008	1965	Kielan-Jaworowska
Gallimimus bullatus	ZPAL MgD-I/015	Nem009		
Tarbosaurus bataar		Nem010		
Gallimimus bullatus	ZPAL MgD-I/008	Nem011		
Tarbosaurus bataar	ZPAL MgD-I/004	Nem012	1965, 1970	Małecki
"Coeluroid"		Nem013		
Gallimimus bullatus	ZPAL MgD-I/094	Nem014	1970	
Prenocephale prenes	ZPAL MgD-I/104	Nem019	1970	Osmólska
Gallimimus bullatus		Nem020		
Gallimimus bullatus	ZPAL MgD-I/033	Nem021		
Barsboldia sicinskii	ZPAL MgD-I/110	Nem023	1970	
Tarbosaurus bataar	ZPAL MgD-I/178	Nem024	1970	
Gallimimus bullatus		Nem025		
Bagaratan ostromi	ZPAL MgD-I/108	Nem026	1970	Kielan-Jaworowska
Saurolophus angustirostris	MPC-D , ?ZPAL MgD-I/170	Nem027	1970	
Saurolophus angustirostris	ZPAL MgD-I/157	Nem028	1970	
Tarbosaurus bataar	ZPAL MgD-I/109	Nem029	1970	
Tarbosaurus bataar		Nem030		
Tarbosaurus bataar	ZPAL MgD-I/175?	Nem031	1970	
Gallimimus bullatus	ZPAL MgD-I/001	TsKh001	1964	Skarżyński
Tarbosaurus bataar	ZPAL MgD-I/003	TsKh002	1964	Gwidon Jakubowski
Gallimimus bullatus	MPC-D100/011	TsKh003	1964	Kielan-Jaworowska
Tarbosaurus bataar		TsKh004	1965	Gradziński and Skarżyński
Tarbosaurus bataar		TsKh005	1964	Dovchin
Gallimimus bullatus	ZPAL MgD-I/024	TsKh006		

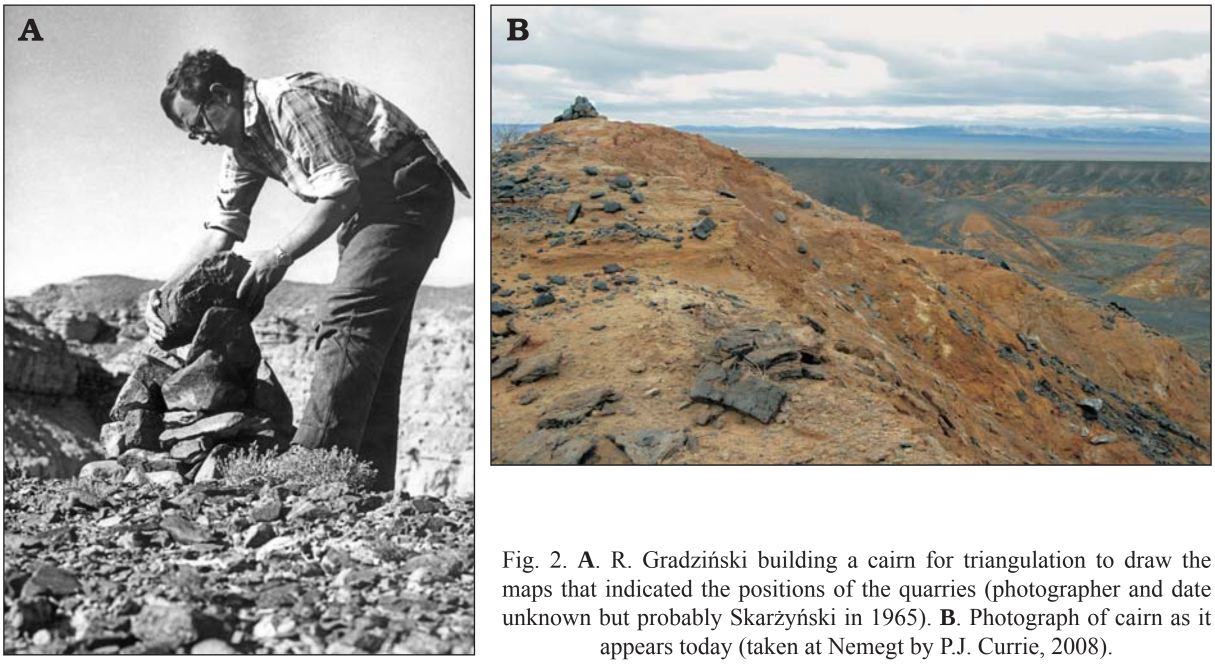

Fig. 2. **A**. R. Gradziński building a cairn for triangulation to draw the maps that indicated the positions of the quarries (photographer and date unknown but probably Skarżyński in 1965). **B**. Photograph of cairn as it appears today (taken at Nemegt by P.J. Currie, 2008).

The published maps of Baruungoyot/Nemegt dinosaur quarries include Altan Uul III (sketch map only, Gradziński *et al.* 1969, fig. 6), Altan Uul IV (Gradziński *et al.* 1969, fig. 4), Khulsan (Gradziński and Jerzykiewicz 1972, fig. 4), Nemegt Central Sayr (Gradziński *et al.* 1969, fig. 2), Nemegt/Khulsan (Gradziński and Jerzykiewicz 1974, fig. 1), Nemegt Northern Sayr (Gradziński and Jerzykiewicz 1972, fig. 1), the south-eastern part of Nemegt (Gradziński and Jerzykiewicz 1974, fig. 3), and Tsagaan Khushuu (sketch map only, Gradziński *et al.* 1969, fig. 8). There are variants of these maps in other publications related to the Polish-Mongolian expeditions. They were drawn with varying degrees of accuracy, and finding some of the quarries, even when field photographs supplement the maps, has not always been possible. The sketch map of Hermiin Tsav I and II (Gradziński and Jerzykiewicz 1972, fig. 6) does not show the positions of any quarries.

Abbreviations. — AMNH, American Museum of Natural History, New York, USA; AU, Altan Uul; HT, Hermiin Tsav; Khu, Khulsan; KID, Korea-Mongolia International Dinosaur Project; MPC, Paleontological Center of the Mongolian Academy of Sciences, Ulaan Baatar, Mongolia; Nem, Nemegt; PMPE, Polish-Mongolian Palaeontological Expeditions; Saurol, *Saurolophus*; Tarb, *Tarbosaurus*; TsKh, Tsagaan Khushuu; ZPAL, Institute of Paleobiology, Polish Academy of Sciences, Warsaw, Poland.

Acknowledgements. — Like so many others, I have nothing but the greatest respect for the role Zofia Kielan-Jaworowska played in making the PMPE such an incredible success. She proved herself to be not only a great scientist, but also a great leader who will inspire young scientists for generations to come. It was an honor and a pleasure to count her amongst my friends. In terms of the content of this article, she guided our expeditions to several of the sites in the Gobi Desert in 2002, provided me with unpublished information, and opened up her personal photograph collection so that I could find suitable images for re-locating some of the PMPE quarries. I am also indebted to Wojtek Skarżyński (Warsaw, Poland), who spent many hours going through the photographs with me in ZPAL, and Zofia's home. Magdalena Borsuk-Białynicka (ZPAL) and the late Halszka Osmólska were also very helpful in providing information on specific photographs and the expeditions. On numerous occasions, Tomasz Jerzykiewicz supplied information and field photographs from the 1971 expedition, and he also provided his mapping notes and sketches from Khulsan. Quarry AU4004 was only re-found when additional photographs and information were provided by the late Ryszard Gradziński. Jørn Hurum (University of Oslo, Norway) and Phil Bell (University of New England, Armidale, Australia) freely volunteered their time to sort through and duplicate photographs in Warsaw. My wife, Eva Koppelhus, provided constant assistance and support throughout this project. The manuscript benefited from two excellent, detailed reviews that were greatly appreciated. And finally, I would like to thank all the members of the PMPE who contributed to the collection of so many fine specimens, and to the members of the "Dinosaurs of the Gobi" and KID expeditions who spent hundreds of hours re-discovering those quarries.

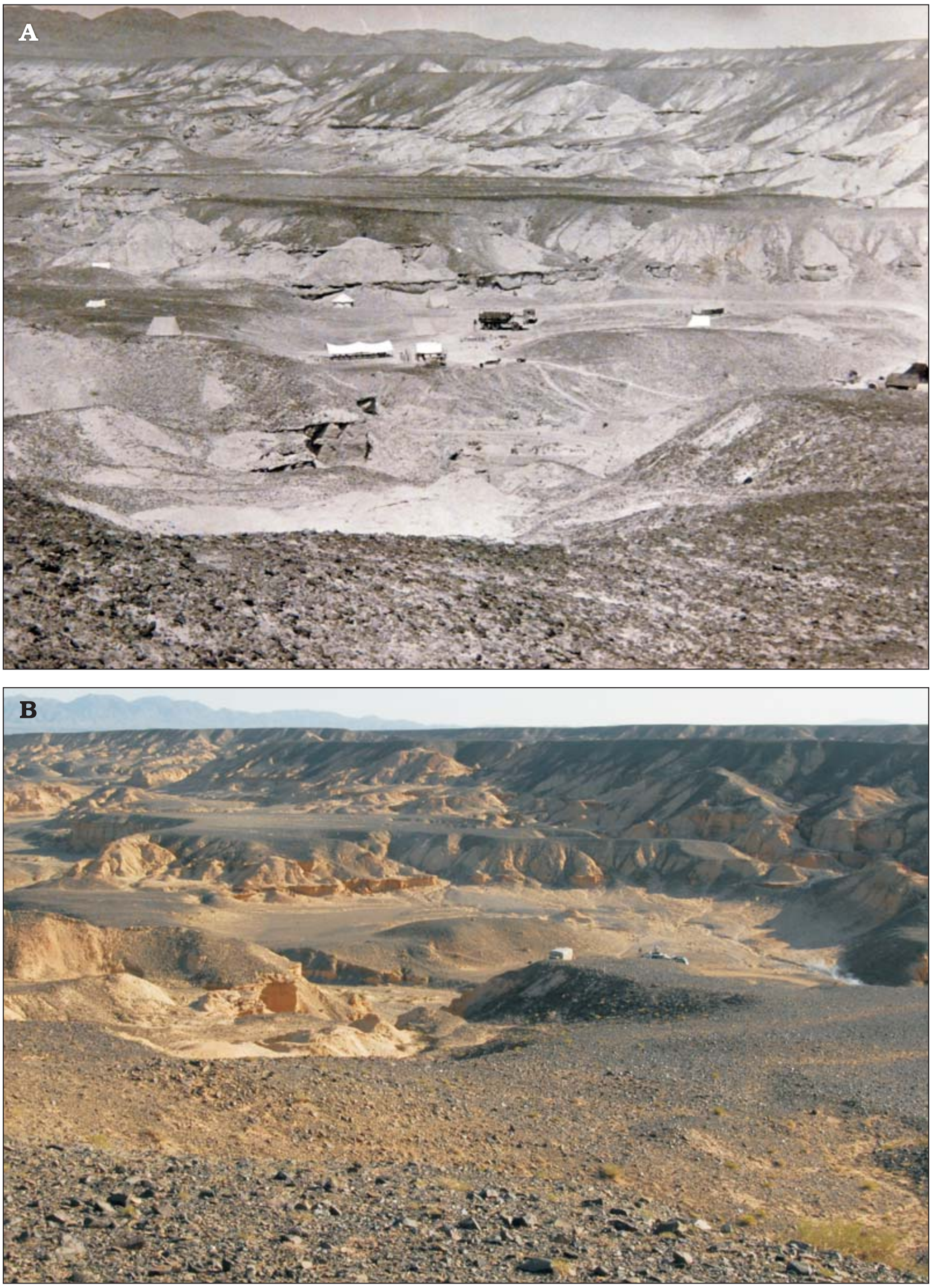

Fig. 3. **A**. View northeast across the Northern Sayr of Nemegt at the Polish-Mongolian camp in 1970. **B**. Same view in 2010. Photos by W. Maczek (A) and P.J. Currie (B).

MATERIAL AND METHODS

Initially quarries were located either fortuitously, or by hiking with a copy of the relevant map in hand. The project of relocating Nemegt Formation quarries started in 1999, and coordinates taken that year with a handheld GPS proved to be highly inaccurate (because of signal scrambling) and had to be checked and retaken in subsequent years. The identification of old camps (Fig. 3), cairns used for triangulation, graffiti (Fig. 4), and places where specimens were crated (Fig. 5) helped immensely in finding some quarries. Although some quarries were easily found because of their size and the presence of plaster, wood, nails, and

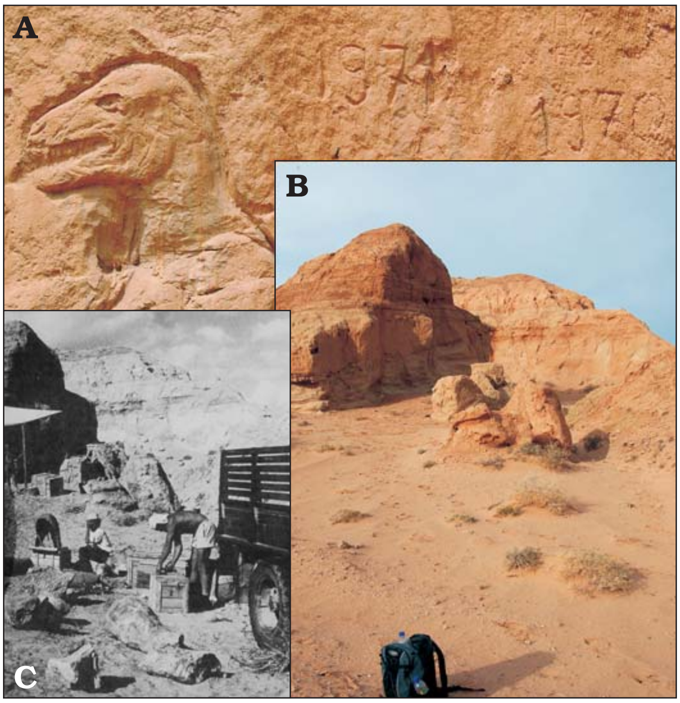

Fig. 4. "The Café" at Altan Uul IV, where the remains of *Opisthocoelocaudia* and other specimens were brought down from the upper level and crated. **A**. "The Café" was close to Polish-Mongolian camps in 1965, 1970 and 1971, and the walls are adorned with signatures, dates, and even bas-relief drawings like this *Tarbosaurus*. Note the dates 1971 and 1970 to the right of the *Tarbosaurus*. **B**. Dinosaur bones being crated (photo taken looking north by ?Gradziński, 1965). **C**. The same view in 2009, with the graffiti-covered wall in shadow. Photos A and C taken by P.J. Currie.

other paraphernalia (Fig. 6), others were only found after considerable effort. Copies of field photographs were obtained from the Institute of Paleobiology and the personal collection of Zofia Kielan-Jaworowska. Information on the backs of the photos was scanty, but was supplemented with information from Kielan-Jaworowska and Skarżyński. Copies of these photographs were taken into the field and used to identify some of the quarries. One quarry (AU4004, *Opisthocoelicaudia*), which should have been found easily because of its size, eluded us for several years, and was only found after Gradziński sent additional photographs of "the Café" (where the specimen was crated for transport, Fig. 5) and several points between AU4004 (Fig. 7) and "the Café".

For identifying specific quarries, the original map numbers have been retained, but a prefix has been added for each site: For example, "Nem001" is quarry 1 on the Nemegt map of Gradziński *et al.* (1969). The cairns marked on the maps were assigned numbers, and coordinates were taken for each cairn when it was found. Using MacGPS Pro 10.4 and Photoshop CS6, the coordinates of the cairns and known quarries were overlain on the hand-drawn maps. In some cases the points overlapped the maps perfectly when shrunk to the same scale. However, the maps tended to be less accurate toward the edges, where reference points were more dispersed. The maps were selectively distorted on a computer so that the reference points overlapped the known GPS points. Coordinates were then calculated for the quarries that had not been found yet. These were put into the handheld GPS, and used with varying degrees of success to try to find some of the missing quarries. In some cases this was possible, but most of the time the quarries still could not be located with certainty. Although not as accurate as those obtained for the field-checked quarries, the coordinates calculated from the maps (Table 2) are still useful.

The spellings of Mongolian geographic and stratigraphic names follow those of Benton *et al.* (2000), and the chronostratigraphic framework is from Jerzykiewicz and Russell (1991).

RESULTS

The positions of the Polish-Mongolian camps were identified by photographs (Fig. 3), the alignments of rocks that encircled tents and parking areas for the trucks, garbage pits that include jars, cans and broken porcelain from Poland, and sometimes by graffiti carved into the surrounding rocks. Finding the campsites (Table 2) was often the first step in confirming positions on the maps so that cairns and quarries could be identified. Furthermore, we often used the same campsites while we were in those areas.

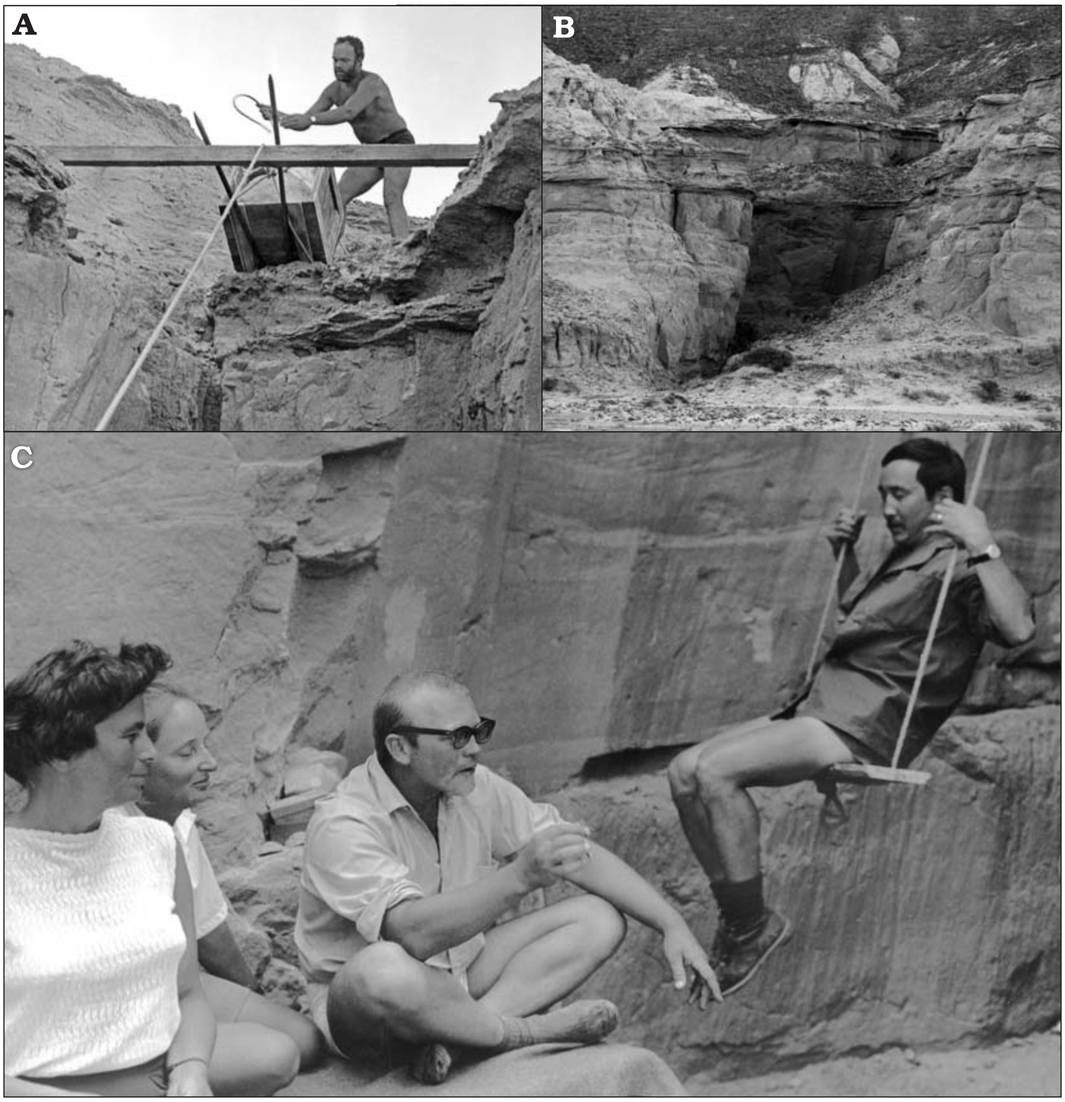

Fig. 5. "The Café 2" across the sayr from the 1970 and 1971 Nemegt camps of the PMPE. Specimens were lowered from a ledge above for crating inside the notch in the wall, which is shaded most of the day. **A**. Skarżyński preparing to lower a crate. **B**. "The Café" as it appeared in 2010. The patch of white that can be seen on the back wall of the quarry is a metal plaque placed there by Skarżyński in September 2008 when he was involved with a Polish wind-sailing expedition across the Gobi Desert. **C**. A historic meeting in "the Café" of the leaders of the Polish-Mongolian and Russian-Mongolian expeditions. This photograph shows Zofia Kielan-Jaworowska, Halszka Osmólska, V.I. Zhegallo and Rinchen Barsbold. Photos A and C taken by W. Maczek, and B was photographed by P.J. Currie.

Even though the first mapping cairns were built more than half a century ago, the majority of them are still standing. Each cairn is built where it can be seen from at least two other cairns, and most are high on the slopes close to the edges of canyons. They are generally less than a metre high, and are usually made of durable "Gobi stones" that are fist-sized or larger (Fig. 2). Khulsan proved to be an exception because hard stones are not as accessible, and it was necessary to use the field notes and sketches of Jerzykiewicz to sort out where many of the cairns were. Some of the cairns at each locality were undercut by erosion, and some have disappeared for no apparent reason (the stones may have been used for other purposes, for example). Another problem is that many additional cairns have been built over the years, often by poachers who are using them to mark specimens of interest.

Altan Uul I is the most eastern of the four sites on the south flank of the mountain known as Altan Uul. It was discovered by the Soviet expeditions in the 1940s, but received its present name from the Polish-Mongolian expeditions (Gradziński *et al.* 1969). Although Polish-Mongolian teams apparently visited the site in 1964, 1965 and 1971, no map was ever published to show the distribution of fossils, and the *Tarbosaurus* specimen (ZPAL MgD-I/038) collected there in 1964 is fragmentary and incomplete.

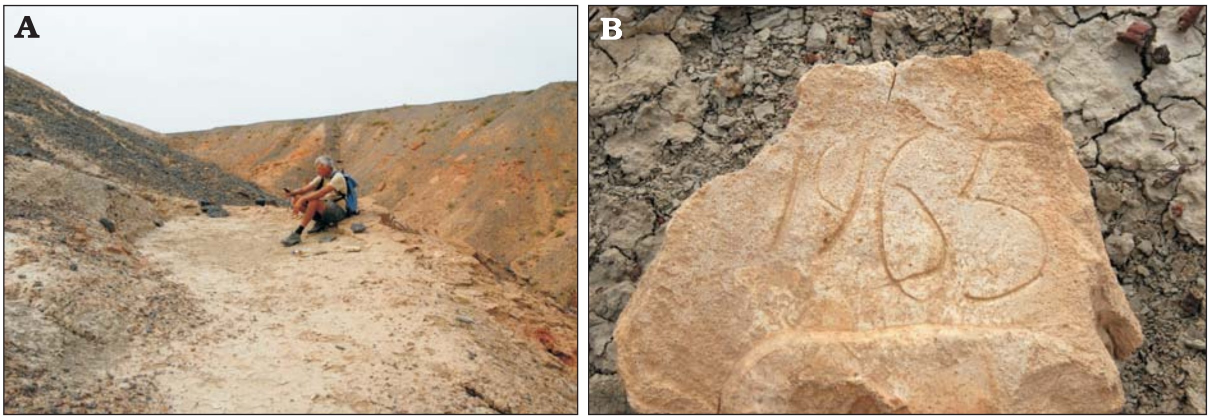

Fig. 6. Quarry AU4001 as it looked when it was re-located in 2010. Confirmation as to quarry identity came from a slab of plaster that, when turned over, revealed the date 1965. Pieces of lumber, plaster, and nails were found on the quarry floor, and a road went from the quarry up the hill toward the 1965 upper camp. Photo by E.B. Koppelhus (**A**) and by P.J. Currie (**B**).

Table 2. GPS coordinates (datum is WGS84) for Polish-Mongolian quarries and associated points of interest expressed in degrees and minutes. The first two columns were field-checked, whereas the third and fourth columns are calculations derived from the maps for Altan Uul4 and Nemegt. This could not be done for some maps because they were either too inaccurate, or not enough GPS points were taken to calibrate the maps. Note that AU4009, AU4010, AU4012 were field checked but there was no evidence (i.e. plaster, wood, nails, photographs, bone) to confirm that these quarries have been correctly identified. Nem011 (an ornithomimid tail and hind limbs) was never marked on the maps of Gradziński *et al.* (1969) and Gradziński and Jerzykiewicz (1972). See text for information on Saurol26, Saurol40, Tarb58 and Tarb68, all of which were marked on the Polish-Mongolian quarry maps even though they were not assigned quarry numbers. Abbreviations: AU2, Altan Uul 2; AU3, Altan Uul 3; AU4, Altan Uul4; calc, calculated; Khu, Khulsan; low, lower camp in 1965; Nem, Nemegt; Saurol, *Saurolophus*; Tarb, *Tarbosaurus*; TsKh, Tsagan Khusuu; up, upper camp in 1965.

	North actual	East actual	North calc	East calc
AU2001	43º36.192’	100º33.663’		
AU3001	43º34.358’	100º29.017’		
AU3002	43º33.987’	100º28.959’		
AU4001	43º35.263’	100º26.729’		
AU4002			43º35.469’	100º26.935’
AU4003			43º35.278’	100º26.762’
AU4004	43º36.157’	100º27.317’		
AU4005			43º34.932’	100º26.500’
AU4006			43º34.893’	100º26.484’
AU4007			43º35.200’	100º27.163’
AU4008	43º35.830’	100º27.426’		
AU4009	43º36.183’	100º27.364’		
AU4010	43º36.073’	100º27.162’		
AU4011			43º36.275’	100º27.355’
AU4012	43º36.087’	100º27.133’		
Khu011	43º30.419’	101º07.646’		
Khu013	43º29.607’	101º07.492’		
Nem001	43º30.157’	101º03.156’		
Nem001A	43º30.152’	101º03.154’		
Nem002	43º30.280’	101º03.152’		
Nem003	43º30.157’	101º03.218’		
Nem004			43º29.959’	101º03.062’
Nem005			43º30.149’	101º02.869’
Nem006			43º30.208’	101º02.871’
Nem007			43º30.190’	101º02.743’
Nem008			43º30.322’	101º02.706’
Nem009			43º30.939’	101º02.719’
Nem010			43º30.994’	101º02.736’
Nem012	43º31.089’	101º01.783’		

	North actual	East actual	North calc	East calc
Nem013			43º31.690’	101º02.613’
Nem014	43º31.744’	101º02.691’		
Nem019	43º32.366’	101º02.112’		
Nem020			43º32.290’	101º02.190’
Nem021			43º30.779’	101º02.752’
Nem023	43º31.799’	101º02.396’		
Nem024	43º31.743’	101º02.486’		
Nem025			43º32.375’	101º02.270’
Nem026			43º31.204’	101º02.991’
Nem027	43º31.485’	101º02.507’		
Nem028	43º31.513’	101º02.755’		
Nem029	43º31.689’	101º01.927’		
Nem030	43º31.233’	101º01.887’		
Nem031	43º31.591’	101º01.786’		
Saurol26	43º30.157’	101º03.037’		
Saurol40	43º30.202’	101º03.045’		
Tarb58	43º30.213’	101º03.063’		
Tarb68	43º30.283’	101º03.143’		
TsKh001	43º28.924’	100º21.640’		
TsKh002	43º28.911’	100º21.777’		
Café 1965	43º35.948’	100º27.430’		
Café 1970	43º30.803’	101º02.763’		
Camp Au4 1965up	43º34.968’	100º26.368’		
Camp Au4 1965low	43º35.718’	100º27.403’		
Camp Khu 1971	43º29.983’	101º07.482’		
Camp Nem 1964	43º29.202’	101º04.008’		
Camp Nem 1965	43º29.892’	101º03.218’		
Camp Nem 1970	43º30.853’	101º02.797’		
Camp TsKh 1964	43º29.022’	100º22.123’		

In 1948, a Soviet expedition discovered a spectacular site that they called the “Dragon’s Tomb”. They excavated seven skeletons of *Saurolophus*, and parts of at least three *Tarbosaurus* skeletons. Many of the hadrosaurs have associated skin impressions, sometimes covering the entire flank of the body (Bell 2012). Although the PMPE never did any major excavations at Altan Uul II, they apparently visited the site from time to time and collected several specimens that are now in Warsaw (Table 1). The “Dragon’s Tomb” still has many specimens of *Saurolophus* and *Tarbosaurus*, but has been heavily vandalized in recent years by poachers.

Altan Uul III was worked by the PMPE in 1964 and 1965 (Gradziński *et al.* 1969; Kielan-Jaworowska 1969). Their expeditions recovered two partial skeletons of *Tarbosaurus bataar* (one of which is ZPAL MgD-I/5 from AU3003), and the holotype of *Deinocheirus mirificus* (numbered initially as ZPAL MgD-I/6, but eventually transferred to Ulaan Baatar as MPC-D100/018). The latter was discovered by the Polish leader, Zofia Kielan-Jaworowska, and for a long time was one of the most enigmatic dinosaurs known because it consisted only of gigantic front limbs. The exact position of the shallow quarry had been forgotten over the years, even though it was marked on the sketch map of Altan Uul III (Gradziński *et al.* 1969, fig. 6). The published photographs (Kielan-Jaworowska and Dovchin, 1969) showed the bones in the quarry, but there were no clues about the surrounding terrain. However, I finally managed to get one photograph in Warsaw that showed some of the landscape (Fig. 8), and after years of looking for the quarry I found it during the 2008 KID Expedition. We picked up some additional fragments of vertebrae and gastralia of the *Deinocheirus*, but they were insufficient to resolve the relationships of this enigmatic dinosaur. However, interest in this dinosaur was so strong that word of the re-discovery of the quarry spread worldwide. The fallout was that I was notified of a poached specimen of *Deinocheirus* in Europe, which turned out to be the same individual as a damaged specimen we had collected at Bugeen Tsav in 2009. This in turn led to the recognition of another *Deinocheirus* specimen that we had collected at Altan Uul IV in 2007. After almost half a century, we finally knew that *Deinocheirus* was a large and unusual ornithomimosaur (Lee *et al.* 2014). I wrote to Zofia to let her know that there were finally several specimens of *Deinocheirus*, and that it was an even stranger

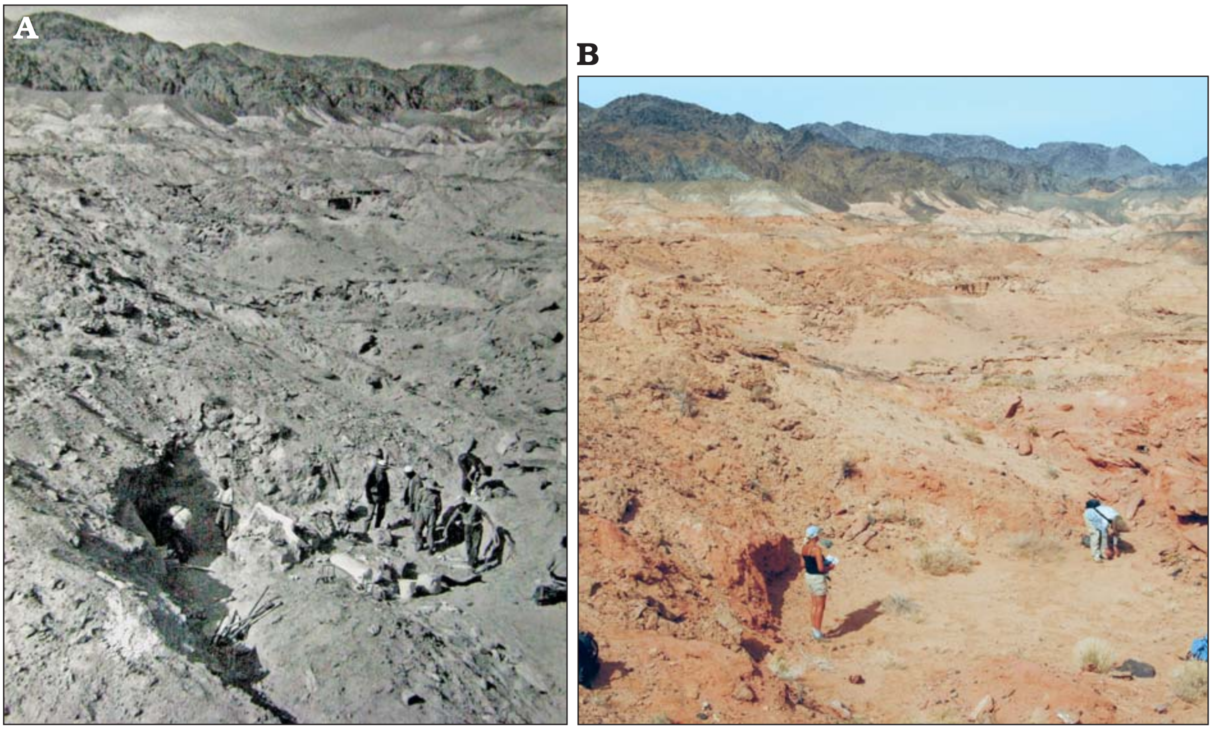

Fig. 7. Quarry AU4004 (IV on Altan Uul 4 map of Gradziński *et al.* 1969) where *Opisthocoelocaudia* was collected in 1965. Differences in the proportions of the photographs result from differences in the focal lengths of the camera lenses used. Upper photograph was taken by W. Skarżyński in 1965, whereas lower photograph was taken from North 43°36.150', East 100°27.305' by P.J. Currie in 2009.

animal than we had thought. Unfortunately she was not well by the time that the paper came out, and I never learned if she knew of the resolution of the mystery of the dinosaur she had discovered in 1965.

One other quarry was found at Altan Uul III (AU3001), but the excavation site of AU3003 remains unknown. Additional skeletons of an ankylosaur (ZPAL MgD-I/113), *Gallimimus* and *Tarbosaurus* were collected from AU3 in 1965 and 1971, but were never marked on any of the published maps.

Altan Uul IV was first explored by the Polish-Mongolian expedition of 1964 (Gradziński *et al.* 1969), although excavations were not undertaken until subsequent expeditions in 1965, 1970 and 1971. The material collected included the holotype of *Opisthocoelicaudia*, four ankylosaurs, one ornithomimid and five partial *Tarbosaurus.* Two of the Polish camps, half of the twelve quarries (Table 2), and many of the mapping cairns were rediscovered and pinpointed using GPS in 2006 and 2008.

One of the specimens excavated by the 2006 KID expedition was a large *Tarbosaurus* (Tarb32, MPC-KID022) from a place in Altan Uul IV that was impossible to access by vehicle. Consequently, the specimen had to be dragged out of the badlands using manpower. Interestingly, we discovered several years later that the Polish-Mongolian *Opisthocoelicaudia* quarry (AU4004) was nearby, and that they had similarly dragged that specimen down the same trail 41 years earlier. The spot where we loaded the specimen onto our truck was in fact the Café used by the PMPE to crate and load the sauropod skeleton.

Hermiin Tsav is a spectacularly beautiful site that yields dinosaur skeletons from both the Baruungoyot and Nemegt formations. It was originally discovered in 1969 by Barsbold, who worked there with the Joint Russian-Mongolian Palaeontological Expedition the following two years. The PMPE also worked at Hermiin Tsav in 1970 and 1971, but focused mostly on the Baruungoyot Formation. Although two distinct regions (Hermiin Tsav I, Hermiin Tsav II) are cited in the Polish literature (Gradziński and Jerzykiewicz 1972), they are lithologically similar and both include exposures of both formations. Unfortunately, the sketch map does not show the quarry locations. However, *Gobipteryx* eggs and embryos (Elżanowski 1981) were recovered from a single site at Hermiin Tsav I. One locality at the western end of the exposures (near a prominent natural feature called "the Gate") yielded abundant eggs of this animal and may have been the site where the embryos were found in 1971.

Khulsan was initially worked by the PMPE in 1970 and 1971 (Gradziński and Jerzykiewicz 1972), but has more recently been under heavy pressure from poachers. It has some of the best exposures of the

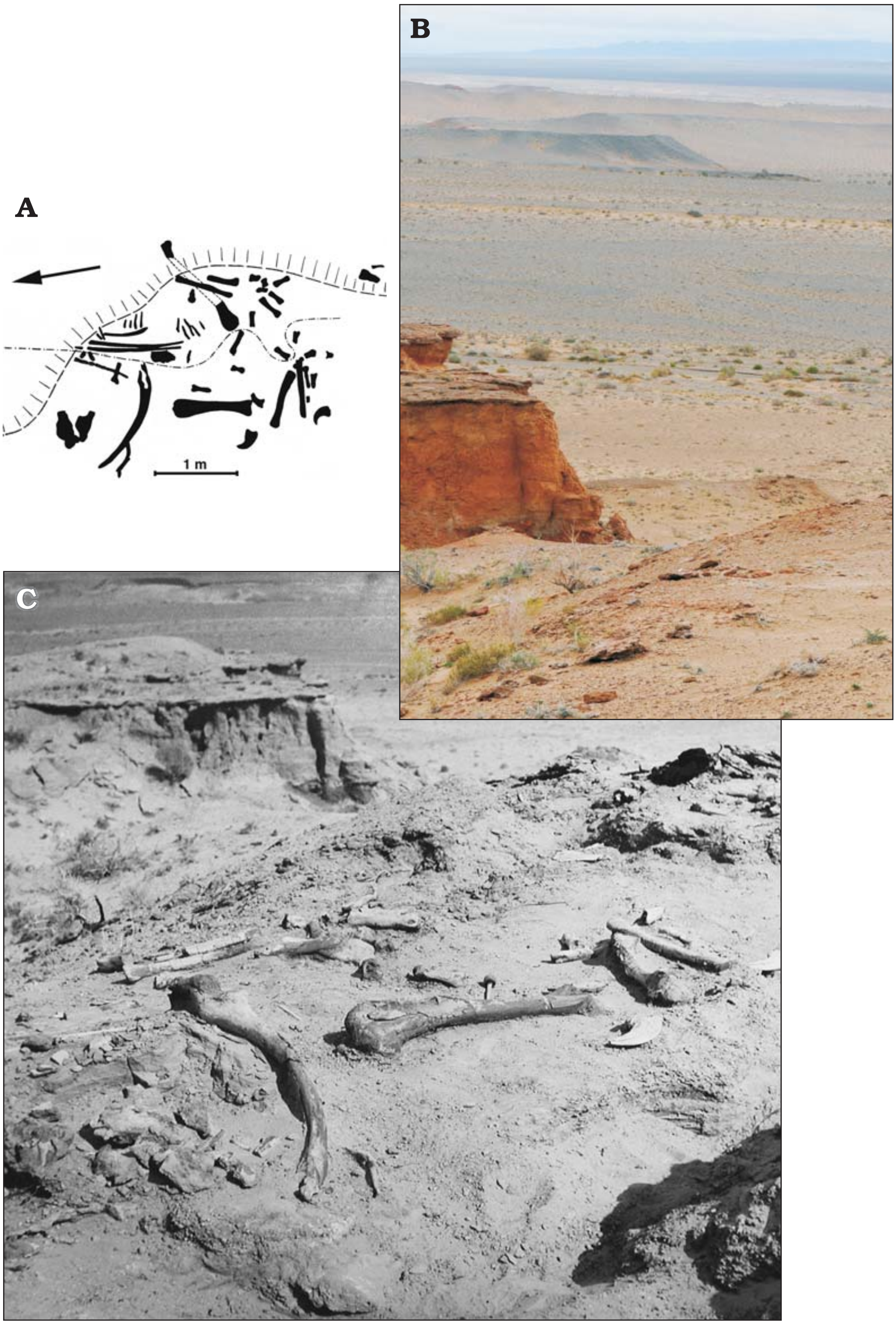

Fig. 8. Quarry AU3002 (II on Altan Uul 3 map of Gradziński *et al.* 1969) from which the holotype of *Deinocheirus mirificus* was recovered in 1965. **A**. Quarry map showing the distribution of bones (fig. 30 of Gradziński 1970). **B**. Photograph taken in 2008 by P.J. Currie from west side of quarry. **C**. Photograph taken by R. Gradziński in 1965 before the bones were removed from the quarry.

Baruungoyot Formation, which yielded two ankylosaurids, one pachycephalosaurid, three protoceratopsids, and one small theropod skeleton for the PMPE. In addition it yielded numerous, nicely preserved microvertebrates, including a spectacular concentration of mammal skulls that was referred to as Eldorado (Khu013). Presumably the *Gobipteryx* material described by Elżanowski (1974, 1977) also came from the same site, because we recovered *Gobipteryx* eggs from Eldorado in 2011. Generally speaking, the dinosaurs at Khulsan

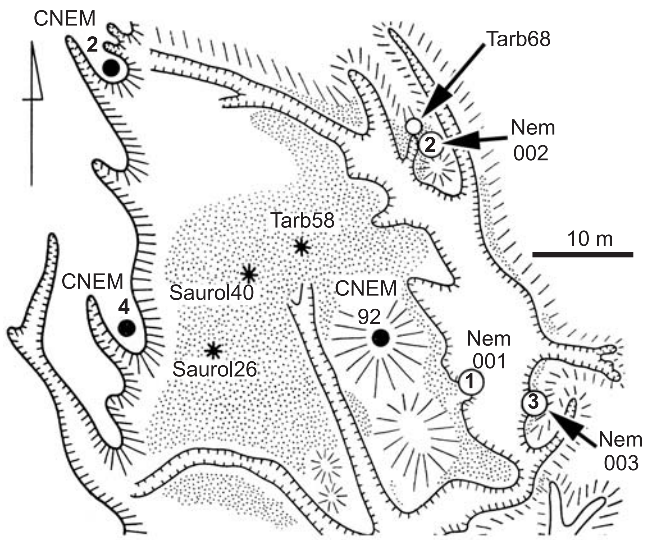

Fig. 9. Map of the northern part of Central Sayr of Nemegt Locality showing distribution of cairns (black dots), quarries (open circles) and weathered skeletons (asterisks). The quarry numbers have been modified by the addition of "Nem" to signify that they are from the Nemegt locality, and the cairns have been numbered and coordinates established with GPS. Abbreviations: CNEM, cairn from Nemegt locality; Nem, Nemegt locality; Saurol, *Saurolophus*; Tarb, *Tarbosaurus*. Modified from Gradziński (1970, fig. 33).

tend to be relatively small, and the soft sediments erode rapidly. The quarry that yielded the holotype of the ankylosaur *Saichania chulsanensis* (Khu011) is still easily seen, however.

The beds at Nemegt were originally found in 1946 by the Soviet Paleontological Expeditions, and were subsequently worked by the same group in 1948 and 1949. Polish-Mongolian expeditions to this locality started in 1964, and resulted in the production of the first maps of the complex badlands (Gradziński *et al.* 1969, Gradziński 1970). These are the most extensive badlands exposing the Nemegt Formation, and have also yielded the most numerous and diverse specimens. The transition with the Baruungoyot is also well exposed at Nemegt, and in recent years at least one taxon (*Nemegtomaia barsboldi*) has been identified in both formations (Fanti *et al.* 2012). The Polish-Mongolian quarries include four hadrosaurs (one of which is the apparently rare *Barsboldia*), two pachycephalosaurids, ten ornithomimids, one sauropod (the holotype of *Nemegtosaurus mongoliensis*), and ten *Tarbosaurus*. Nemegt quarries 1 and 2 on the Gradziński (1970, fig. 33) map are both double quarries. Nem001 and Nem001A can be identified in the photographs of the site, and show evidence of being quarried at the same time (there are nails on the floors of both excavated areas). It is possible that one of the two "quarries" was flattened out to prepare the crate for packing the specimen. Gradziński (1970) identified the quarry next to Polish quarry Nem002 (Fig. 9) as being one of the Soviet Paleontological Expedition excavations. Bone left behind in the quarry is clearly part of a vertebral column of a large *Tarbosaurus* that is designated as Tarb68 (Currie 2009). Also marked on the map were three weathered dinosaur skeletons, which were still visible in 1999 and were designated as Saurol26, Saurol40 and Tarb58 (Fig. 9). The last two specimens were partially excavated by poachers in 2003, and it seemed that Gradziński's assessment that they were weathered specimens was correct. However, we were very surprised when we returned in 2004 to find that the poachers had returned to Tarb58 to dig deeper. They found the skull underneath its body, encased it in a thin layer of plaster and burlap, and then attempted to turn it over. Unfortunately, they had done a poor job of jacketing the specimen and it collapsed. Rather than trying to fix the damage they had done, they simply hacked out all of the teeth and left the rest of the specimen in the hole. We salvaged large portions of the back of the skull and some of the forelimb elements. Nem003 is another small *Tarbosaurus* that was found by Barsbold in 1965. When the quarry was re-discovered in 2011, a 275 mm-long right jugal was recovered; because it would have been part of the original specimen that was excavated, it will assist in determining which of the *Tarbosaurus* specimens in Warsaw came from this quarry.

Nemegt is a huge area containing many quarries that are difficult to find. Of the 25 dinosaur quarries on the maps, a dozen still have not been found. These quarries mostly yielded small specimens (the holotypes of *Homalocephale calathocercos* and *Nemegtosaurus mongoliensis*, several specimens of *Gallimimus*, and an isolated vertebra of *Tarbosaurus* for example) that would not have required the excavation of large holes. Quarry Nem012 was a *Tarbosaurus baatar* found by Malecki in 1965, but only the leg was excavated that year. The balance of the skeleton was collected in 1970. When we visited the quarry in 2008, we were surprised to find that poachers had found and partially excavated another *Tarbosaurus* skeleton (Tarb49) only 15 m away at a slightly lower level. Quarry Nem024 (Fig. 10) was well-photographed, but nevertheless was difficult to find because of its position on a ledge above the valley floor. When Nem030 was re-found in

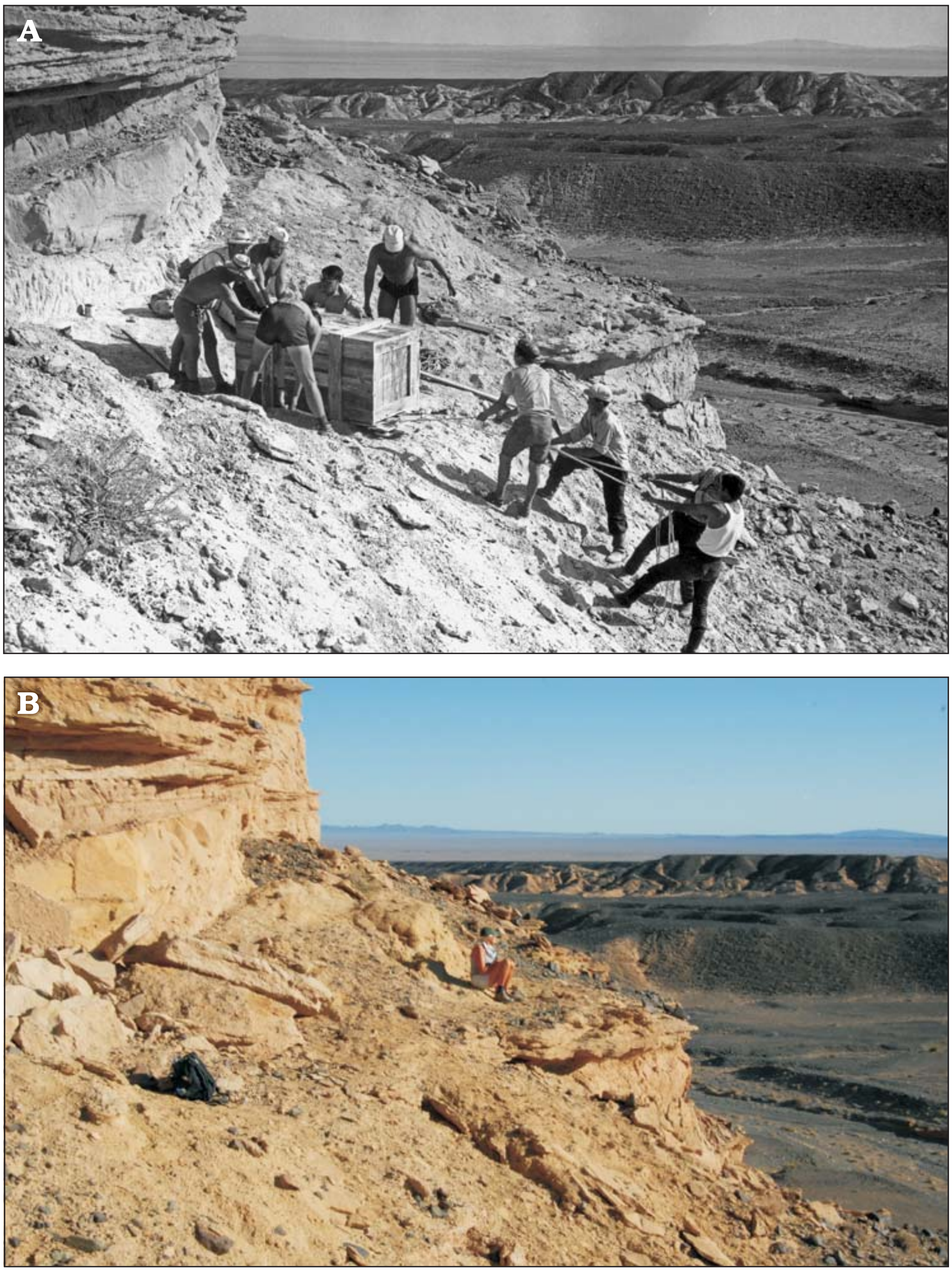

Fig. 10. Quarry Nem024, looking south down the Northern Sayr. **A**. Specimen being removed in 1970 (photo by W. Maczek). **B**. A similar view in 2010 (photo by P.J. Currie).

2009, there were bones of both *Tarbosaurus* and *Saurolophus* on the quarry floor, suggesting that parts of two individuals had been collected.

Tsagaan Khushuu is a much smaller area, but still gave the 1965 Polish-Mongolian Expedition a total of seven quarries, one of which was a concentration of turtles, whereas there were three quarries each of *Gallimimus* and *Tarbosaurus*. Two of the quarries (TsKh001) and (TsKh002) have been pinpointed.

DISCUSSION AND CONCLUSIONS

Precise locations (with GPS coordinates that can be returned to year after year) are now known for 32 of the PMPE quarries that were marked on maps of Altan Uul, Khulsan, Nemegt and Tsagaan Khushuu (Tables 1, 2). In spite of numerous attempts to find the rest of the sites in the Baruungoyot and Nemegt formations,

Table 3. Dinosaur faunal composition for the Nemegt Formation of Mongolia at the time of the PMPE compared with what is known at present. The PMPE numbers include specimens listed in Table 2, plus specimens in the ZPAL collections. The "present" numbers include the PMPE specimens and data/specimens collected by the Dinosaurs of the Gobi and KID expeditions, but almost none of the specimens collected by the AMNH, Japanese-Mongolian, Mongolian, Russian-Mongolian or Soviet-Mongolian expeditions.

Taxon	PMPE #s	PMPE %	Present #	Present %
Sauropoda	2	3.1	34	9.3
Ornithomimidae	18	28.1	105	28.9
Deinocheiridae	1	1.6	4	1.1
Tyrannosauridae	23	36.0	123	33.8
Other theropods	5	7.8	21	5.8
Ankylosauridae	8	12.5	26	7.1
Hadrosauridae	5	7.8	46	12.6
Pachycephalosauridae	2	3.1	5	1.4
Total	64	100	364	100

eighteen still have not been seen. Nevertheless, the approximate positions of these quarries can be determined from the maps (Table 2) and new clues may still lead to their discovery.

More precise documentation and additional work has not significantly changed the Nemegt Formation results of the PMPE of 1964, 1965, 1970, and 1971. The PMPE collected skeletons and partial skeletons of 64 dinosaurs from the Nemegt Formation (Table 3). The relative abundances of the families of dinosaurs have not changed appreciably (Table 3), most of older values falling within ±3% of those calculated from the larger sample that is available now. The numbers of hadrosaurids and sauropods have increased by more than 3% in the larger sample, whereas the number of ankylosaurs has decreased by more than 3%. The differences between the relative abundances of various dinosaur taxa found by the PMPE and what is now known are relatively trivial, and show that as far as dinosaurs were concerned, there were no collecting biases that favoured one type of dinosaur over any other.

Amongst the theropod dinosaurs, there are no changes in the order of abundance. Tyrannosaurids (*Tarbosaurus* makes up the vast majority of the tyrannosaurid numbers, and *Alioramus* continues to be rare) dominate over all other taxa, and compose almost a third of the dinosaurs found in the Nemegt Formation. Ornithomimids (mostly *Gallimimus*, but also *Anserimimus* and a possible new taxon under study) are almost as common. The ornithomimosaur *Deinocheirus* has quadrupled in numbers but remains one of the rarest elements of the fauna. *Therizinosaurus* was not recovered by the PMPE, and is represented by only a single claw in the enlarged sample of mapped specimens (and therefore was not included in Table 3). Other theropods (avimimids, dromaeosaurids, elmisaurids, oviraptorids, and troodontids) continue to be rare, and collectively make up less than 10% of the fauna.

Amongst the herbivores (ignoring the possibility that ornithomimosaurs and oviraptorids may have been at least facultative herbivores), the collections made by the PMPE would suggest that ankylosaurids are more common than hadrosaurids, and that sauropods are rare in the Nemegt fauna. Osmólska (1980) suggests that hadrosaurs were almost as common as *Tarbosaurus*. However, it is not clear from either the mapped or catalogued specimens where that statistic would have come from, and it is possible that it was a field observation. Regardless, the enlarged sample suggests that hadrosaur skeletons are less abundant than those of *Tarbosaurus*. The increased sample size (Table 3) also suggests that hadrosaurids (primarily *Saurolophus*) were the most common herbivores, that sauropods were almost as common, and that ankylosaurs were the third most abundant large herbivores. Pachycephalosaurids continue to be relatively rare. With the exception of Altan Uul 2 (where hadrosaurs clearly dominate in the Dragon's Tomb), the dominance of *Tarbosaurus* skeletons seems to be a common denominator in all sites where the Nemegt Formation is exposed.

The fact that *Tarbosaurus* continues to account for about a third of the dinosaur quarries is one of the most remarkable and puzzling aspects of the Nemegt Formation. It would be impossible to have a sustainable ecosystem that is dominated by such a large and clearly predatory dinosaur. In other ecosystems where tyrannosaurids were the top predator (for example, in Dinosaur Provincial Park, Currie and Russell, 2005), they normally comprise about 5% of the faunas. The suspicion that a preservational bias is at least partially responsible for the high incidence of *Tarbosaurus* in the Nemegt Formation is confirmed by comparison with a different preservational regime, the ichnite record. Dinosaur footprints are very common (numbering in the thousands) in the Nemegt Formation (Currie *et al.* 2003), and are usually recovered from specific levels at the tops of fining-upward sequences in which skeletons are common near the bases. The footprint and bone levels are interleaved throughout the formation. Footprints suggest that the most common dinosaurs were hadrosaurs, that sauropods were also relatively common, and that tyrannosaurids were rare. Less than 5% of the footprints belong to tyrannosaurids.

Much thought has been put into trying to account for the disproportionately high number of *Tarbosaurus* skeletons recovered from the Nemegt Formation (Young 2011). The more frequent recovery of skeletons in high energy deposits (sheet flooding), rather than in more typical fluvial deposits, may indicate that there were commonly recurring adverse weather conditions that may have affected populations of carnivores more than herbivores. Another possibility is that tyrannosaurids were so thorough in cleaning up the carcasses of other dinosaurs that hadrosaurs and many other herbivores are under-represented because there was nothing left of a carcass for preservation. A third possibility that has been suggested is that high sedimentation only occurred at a certain season when *Tarbosaurus* was concentrated in the area. These hypotheses unfortunately suffer from any lack of evidence to prove or refute them. More than a hundred sites (including those found by the PMPE) have been identified where *Tarbosaurus* skeletons have been found; the next step is to undertake a thorough taphonomic/sedimentologic study to look for common patterns in these quarries that might explain why this dinosaur is preferentially preserved over herbivorous forms.

Although the skeletons of another theropod group (the Ornithomimosauria) are almost as common as *Tarbosaurus*, *Gallimimus* and other ornithomimosaurs were presumably omnivorous (Lee *et al.* 2014) or herbivorous (Kobayashi *et al.* 1999), and so their abundance is easier to understand. Ornithomimid footprints have also been recovered, but other small theropods, ankylosaurids, pachycephalosaurids and other taxa still have not been identified in the ichnological record.

Although the new, more precise data acquired about the PMPE dinosaur quarries has not given any greater insight into the Nemegt fauna, sedimentologic/stratigraphic studies currently underway will benefit from the greater resolution. This in turn will give us a better understanding of the temporal distribution of dinosaurs that are found within the Nemegt Formation. Above all else, the results of the PMPE show the importance of documenting the information at a fossil site. And even though it is easier to take a GPS reading and take a digital photograph than it was for the geologists of the PMPE to hand draw a map, it is unfortunately still not something that is consistently done for every specimen.

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