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Tetrapod burrows from the Triassic Ermaying Formation of Shaanxi, China

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Abstract Tetrapod burrow records are rare in the pre-Cenozoic strata of China. Here we report three casts of vertebrate burrows from the Ermaying Formation at Xizhen, Jiaxian, Shaanxi, China. They represent the first record of casts of the tetrapod burrows from the Chinese Triassic strata. One large burrow cast is underlain by two small burrow casts, and the small burrows were likely constructed after the infilling of the larger, upper burrow. The large burrow cast is elongated and inclined, with a very gently curved morphology. The surface of the large burrow cast is covered by grooves that resemble the apparent "scratch marks" described in previous publications. The large burrow is comparable to those produced by *Reniformichnus katikatii*, but it is at least twice the size of the holotype. The small burrow casts are preserved as terminal chambers with entry ramps, and no distinct scratch marks are present on the surface. It is difficult to compare them to the currently described ichnotaxa. The maker of the large burrow might be a juvenile of *Sinokannemeyeria* or *Parakannemeyeria*, while the small burrows may have been made by a member of *Sinognathus* or a procolophonid.

Key words Jiaxian, Shaanxi, China; Anisian, Middle Triassic; Ermaying Formation; vertebrate burrow

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1 Introduction

Burrowing is a common behavior for certain animals and other groups such as insects and fishes. Burrows are used for shelter, feeding, breeding, and other basic needs (Benton, 1988; Reichman and Smith, 1990). This behavior is common among extant tetrapods such as mammals and reptiles. Many extinct species are supposed to have displayed a burrowing behavior, and some fossil burrow casts were recorded in association with the fossils of the

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animals that might have inhabited these burrows (e.g., Damiani et al., 2003; Fernandez et al., 2013; Varricchio et al., 2007).

Many pre-Cenozoic terrestrial tetrapod burrows have been reported all over the world (Csiki-Sava et al., 2016; Damiani et al., 2003; Groenewald, 1991; Groenewald et al., 2001; Liu and Li, 2013; Sidor et al., 2008; Varricchio et al., 2007; Voigt et al., 2011). The majority of these burrows is Early Triassic in age, although burrows from other ages have also been reported. However, only a few pre-Cenozoic tetrapod burrow casts were known in China. The first Permian tetrapod burrow casts were discovered from the Naobaogou Formation of Nei Mongol (Inner Mongolia), China, and the burrow-maker was assumed to be a therapsid (Liu and Li, 2013). Recently, a Jurassic tetrapod burrow cast was reported from the Xiashaximiao Formation of Zigong, Sichuan Province, China, and a tritylodontid cynodont was listed as a likely candidate for the tracemaker (Xing et al., 2016).

Here we report tetrapod burrow casts from the lower part of the upper member of the Ermaying Formation of Jiaxian, Shaanxi, China. The Ermaying Formation and the lower part of the Tongchuang Formation produced a relatively diverse *Sinokannemeyeria-Shansisuchus* assemblage that includes *Sinokannemeyeria*, *Parakannemeyeria*, *Ordosia*, *Sinognathus*, *Shansisuchus*, *Neoprocolophon* and several small archosaur taxa (Li et al., 2008; Liu, 2015; Liu and Abdala, 2015; Liu and Sullivan, 2017).

Institutional abbreviations BP, Evolutionary Studies Institute, University of the Witwatersrand, Johannesburg, South Africa; NMQR, National Museum Bloemfontein, Bloemfontein, South Africa; SXMG, Shanxi Museum of Geology, Taiyuan, China; UWBM**,** Burke Museum of Natural History and Culture, Seattle, USA.

2 Geological settings

The Ermaying Formation, in which the casts were discovered, comprises rocks of fluvial and lacustrine origins. Averaging as thick as 400 m or more, the formation is composed of red mudstones interbedded with yellow to green sandstone. The Ermaying Formation is usually divided into the lower and upper members. The lower member is mostly sandstone, while the upper one has relatively more mudstone components (Yang et al., 2000). Several volcanic tuff layers within the Ermaying Formation have been sampled for geochronological studies (Liu and Li, 2013; Liu et al., 2018). Traditionally the Ermaying Formation was assigned an age of late Early Triassic to early Middle Triassic, or early Middle Triassic based on various paleontological evidence (Yang et al., 2000). Recently, it was assigned an Anisian age by zircon dating (Liu et al., 2018).

The burrow casts were discovered in the lower part of the upper member of the Ermaying Formation (Fig. 1). The rocks of the section in which the casts were discovered are mainly alterations of thickly or very thickly bedded greenish yellow medium to coarse arkosic sandstone and medium to thickly bedded dark purplish red sandy mudstone with bedding planes. The majority of the preserved portion of the burrow casts is in the thickly bedded

dark purplish red sandy mudstone, while the lower end of the preserved large cast penetrated the underlain sandstone bed and extended into the mudstone bed located further below. The entrances of the original burrows are not preserved, and the preserved upper end of the upper cast is approximately 10 cm below a medium-grained, well-bedded greenish grey siltstone layer. A very thickly bedded yellowish green sandstone overlays the siltstone bed. The burrow infilling consists of medium-grained arkosic sandstone, suggesting the original entrance of the burrow would probably have extended into the overlaid sandstone bed.

Fig. 1 Photo and sketch of the burrow casts from the Ermaying Formation, Jiaxian, Shaanxi, China

3 Description

The burrow casts were discovered along a horizontal roadcut near the west bank of the Yellow River. They were exposed at a locality near Xizhen, Jiaxian, Shaanxi (N 37°43′49.6″, E 110°42′34.2″). Most of the exposed portion was collected and housed in Shanxi Museum

of Geology (specimen number: SXMG T0002). The casts in the collected materials clearly include three pieces, two lower ones (L1, L2) and an upper one (U), and they appear to have been excavated by animals of different sizes (Fig. 2). The lower casts are terminal chambers. The scientific collection of the terminal chamber of the upper burrow cast was prevented due to the disturbance of nearby villagers and the following destruction by erosion.

SXMG T0002U Burrow cast SXMG T0002U lies above two lower casts, and there are clear surfaces separating the casts (Figs. 1–3). The preserved part of this cast measures approximately 2 m, but only the upper end (~1 m) was collected (Fig. 2).

In the field, the burrow cast was oriented obliquely, with a ~17° angle relative to the bedding plane, and positioned approximately 30 cm below a sandstone layer. The cast is similar in composition to that of the overlain sandstone, and therefore likely to be continuous to the base of the sandstone layer. We estimate the length of the original burrow cast to have been longer than 3 m.

The shaft of the burrow measures 13 cm in height and 30 cm in width. On the proximal side, two sides of the burrow shaft are slightly convex laterally with distinct vertical components. The floor bears two lateral concave troughs, which reflect the morphology of the roofs of the underlying casts. Although it was filled by mud, the middle of the floor is also a

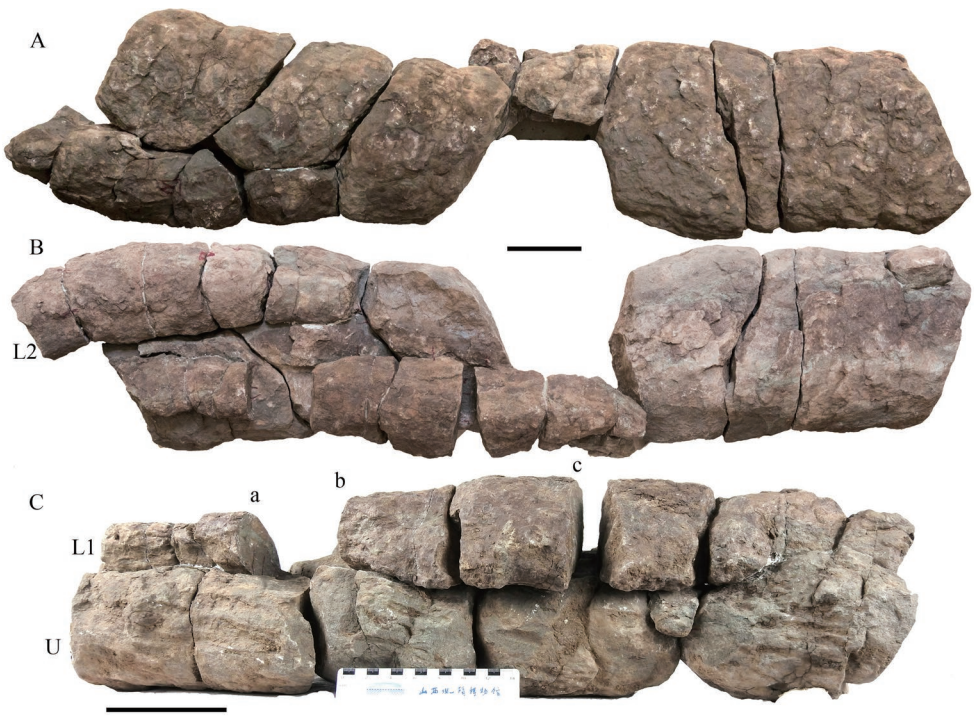

Fig. 2 Collected burrow casts (SXMG T0002: U, L1, L2) from the Ermaying Formation, Jiaxian, Shaanxi
A. dorsal view; B. ventral view; C. proximal portion in lateral view; entrance side on left
Note the scratch marks on the surface. The letters a–c marked the position of transverse sections in Fig. 4
Scale bars equal 10 cm

trough, as can be viewed from the underside of the casts. Distally, the floor bears a gentle ridge running along its midline, although the trough of the cast was filled by mud, giving it an oval configuration in cross-section (Figs. 2B, 3). In lateral view, the dorsal and ventral surfaces of the cast are roughly parallel (Figs. 1, 2). In dorsal view, the burrow is slightly curved, forming an elongated 'S' shape.

Ridges and furrows can clearly be seen on the surface of the cast (Figs. 1, 2). Most marks are oriented at an angle of ~20° with the proximodistal axis of the shaft, while a smaller portion is positioned at ~5° with the longitudinal axis of the shaft. The ridges are nearly 1 cm in width, and the distance between most ridges is 1.5–2 cm. The marks, which we interpret as scratch marks, are most prominent on the lateral portion of the cast, and rarely seen on the roof or floor of the burrow cast. The distal end of the burrow expands into a chamber roughly 0.5 m in diameter.

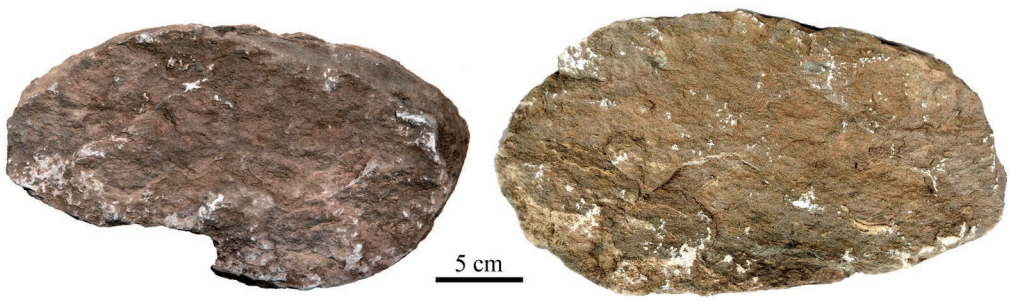

Fig. 3 Two cross sections of the upper cast from the Ermaying Formation, Jiaxian, Shaanxi
The ventral trough is filled by mud and is indistinct

SXMG T0002L The outer cast (L1) is a terminal chamber with a short (~30 cm) shaft, while the inner cast (L2) has only the terminal chamber preserved (Fig. 2). In ventral view, L1 is nearly straight, and L2 is slightly curved. They are also gently inclined with an approximately 17° angle with the bedding plane.

The shaft of the burrow of L1 is elliptical in cross section with a nearly flat floor, measuring 8 cm in diameter and 4 cm in height (Fig. 4A). The shaft gradually enlarges distally to the chamber. The entrance of the terminal chamber was lost during the collection, but can be seen on the in situ photo (Fig. 1). The chamber is flattened dorsoventrally (Figs. 2, 4). It reaches a maximum width of 13 cm and 8 cm height at the middle section then both the height and width diminish distally. There is a shallow depression on the dorsal surface, while the ventral surface is convex, which is quite different from casts collected from Antarctica (UWBM 88599, 88617) and South Africa (BP/1/5905) (Damiani et al., 2003; Sidor et al., 2008). The lower end turns dorsally for a length of 4 cm and decreases in width from ~6 to 4 cm. The preserved lower end is nearly square in cross-section, and a short and sharp tip terminates the burrow cast at this position. This termination is interpreted as the last attempt by the burrower to excavate deeper and the eventual abandonment of the digging attempt. A few narrow ridges are observed on the lateral side of the shaft. No fossil bones were observed within the cast.

The inner cast is nearly 45 cm in preserved length. The preserved proximal side measures 10.5 cm in width. The cast increases in width to 13 cm for the proximal 1/3 length, and then decreases to 5.5 cm at the preserved distal end. Based on the impression on the upper cast, the distal end should be ~10 cm or more in length.

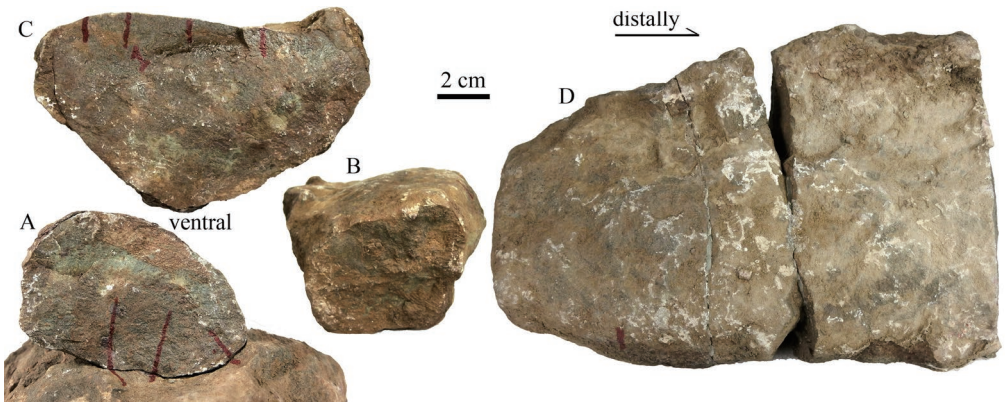

Fig. 4 Outer lower cast (SXMG T0002L1) from the Ermaying Formation, Jiaxian, Shaanxi
Transverse section of posterior shaft (A), proximal portion (B) and middle portion (C) of terminal chamber; dorsal view of proximal side of terminal chamber (D); upper is ventral in A, dorsal in C and D

4 Discussion

The upper and lower burrows could not have existed concurrently, and the lower two must have been constructed after sand had filled the upper one. On the proximal side, the floor of the larger upper cast was modified by the underlying burrows, so its shape is different from that of the distal side. The reuse of the same area indicates that the suitable burrowing area was limited and/or the burrowing animals were abundant during the time of burrow construction. This agrees with the observation of Groenewald et al (2001) that burrowing animals tend to collate in colonies, which was made based on many examples found in present and ancient burrow sites. The inhabiting animal perhaps abraded most of the scratch marks on the small burrows during the normal course of burrow use.

Middle Triassic tetrapod burrows were reported from the Lashly Formation of Antarctica and the Tarjados Formation of Argentina (Krapovickas et al., 2013; Sidor et al., 2008). The size of the small burrows (SXMG T0002L) is similar to that of burrows from Lashly Formation, but the shape of ventral surface is quite different: convex in SXMG T0002L, bilobate in Antarctic materials (Sidor, 2008). The height of the large burrow (SXMG T0002B) is similar to the burrows from the Tarjados Formation, but SXMG T0002U is bigger, longer and less inclined.

Recently, *Reniformichnus katikatii* was named as the maker for the inclined, burrow casts with bilobate base and reniform cross-section collected from the Karoo Basin (Krummeck and Bordy, 2017). The upper burrow cast has all the diagnostic features of this ichnotaxon, however its bilobate base is partially modified or filled by mud and is not clearly preserved. It

is also at least twice the size of the holotype. For this publication, the burrow cast is equated with *Reniformichnus katikatii*, and extends its distribution to Anisian. The lower burrows cannot be placed in any existing ichnotaxa genus with certainty, and more work is needed to confirm the observation and presence of details.

4.1 Identification of maker of large upper burrow

This burrow (Figs. 1–3) is a single burrow 27 cm in diameter, ~3 m long, ramp angle ~17°, also characterized by terminal chamber present, sandstone fill in mudstone host rock, and grooves and ridges well defined on sides. This is similar but slightly different from type 1b and type 2 in table 2 of Groenewald (1991). Groenewald (1991) referred to the generic classification of the traces according to Seilacher presenting only speculation on the possible tracemakers. The tracemaker of a relatively straight, subhorizontal burrow cast (inclined 12°) (NMQR 3606), which is a dorsoventrally compressed tube consisting of an entry ramp and living chamber, from the lowermost portion of the *Lystrosaurus* Assemblage Zone of South Africa is hypothesized to be a carnivorous tetrapod, i.e., akidnognathid theriodonts, even though a *Lystrosaurus* skeleton is preserved within the cast (Modesto and Botha-Brink, 2010). However, Botha-Brink (2017) recently provided the first evidence of burrowing in *Lystrosaurus*, and she suggested that *Lystrosaurus* should be the tracemaker of NMQR 3606. Cynodonts such as *Andescynodon* were interpreted as the makers of slightly smaller burrows from the Tarjados Formation (Krapovickas et al., 2013).

The large size of the burrow indicated a large tracemaker, and its skull width should be greater than 10 cm. Triassic tetrapods, procolophonids, cynodonts, therocephalians, and dicynodonts were potentially fossorial. Procolophonids are too small to be a maker of this gigantic burrow. The only known cynodont, *Sinognathus*, belongs to the herbivorous Trirachodontidae, however *Trirachodon* made complex burrows, which are not simple inclined burrows (Groenewald et al., 2001), so cynodonts may not be the burrow maker. The largest known therocephalian skull from the Ermaying Formation is ~13 cm in width, and its size could fit the burrow. However, dicynodonts are more likely the burrow-maker based on the morphology of the scratch markers. The postcranial features of *Sinokannemeyria* and *Parakannemeyria,* but not *Shansiodon,* are similar to *Lystrosaurus* (Sun, 1963; Yeh, 1959), which adapted for a burrowing lifestyle and was suggested as the burrow-maker for many Triassic burrows (Botha-Brink, 2017; Groenewald, 1991; Ray, 2006). However, the adults of *Sinokannemeyria* and *Parakannemeyria* are too big in size and only their juveniles could be the burrow-makers.

Similar to Antarctic burrows studied by Sidor et al. (2008), these burrow casts might have been somewhat flattened diagenetically, although their general shape has probably not been significantly altered. The large burrow is 27 cm in diameter, 15 cm in height, and the cross-sectional area is ~ 300 cm^2. Accordingly, the body mass of the tracemaker is calculated to be ~4 kg from the equation $A_b=1.34M^{0.65}$ (White, 2005). However, this is a conservative estimate and a more accurate estimate must account for the diagenesis.

4.2 Identification of makers of small lower burrows

Because two lower casts are similar in shape and size, their producers could be the same kind of animal. Two similar terminal chambers lie so closely associated that it could be indicative of a group association in the social behavior of the animals. Furthermore, the two chambers could belong to the same burrow network complex as in the case of *Trirachodon* (Groenewald et al., 2001).

The shaft of the small burrow is straight, gently inclined, with a diameter of 8 cm, and width/height ratio of 2. The sand-filled cast extends into the mudstone at least 30 cm beneath crevasse splay sandstone. It can be compared with type G burrow of Miller et al. (2001). Two terminal chambers are close to the size of UWBM 88617, but the lower surface is rounded rather than bilobed as in the latter (Sidor et al., 2008). The distal end of the terminal chamber is wide and square in dorsal view comparable to burrows assigned to *Diictodon* and *Thrinaxodon* (Damiani et al., 2003; Smith, 1987), while it is wedge-shaped and narrow in *Trirachodon* (Groenewald et al., 2001). The new casts are similar to the terminal chamber of *Trirachodon* in having a wedge-shaped, narrow tip and a concave dorsal surface. Because of these similarities, one possibility is that *Sinognathus,* a trirachodontid cynodont, was the burrow-maker. The adult size of *Sinognathus* (10 cm for skull width) is too big for these burrows, but its juvenile is postulated as having an appropriate size. Although the terminal chambers are unique in their shape for known Permian and Triassic burrows, they could represent burrow casts of other groups, such as procolophonid. Procolophonids were interpreted to have a burrowing lifestyle (deBraga, 2003; Groenewald, 1991), they fit the size of the burrow, and they were reported from the Ermaying Formation of this area. The morphology of the claws of *Sinognathus* or even trirachodontids is unknown, but the procolophonid claws are sharp and could made the observed narrow scratch marks (Li, 1989). For now, the maker of the small burrows is unsure, but they are probably associated with juvenile *Sinognathus* or procolophonids. We are presently still debating the identity of the burrow-makers for both casts of the smaller burrows beyond classifying them as tetrapods. This is partially due to the absence of definite comparative materials and the issue eagerly awaits more published information on the morphology of tetrapods and possible associated burrowing behavior.

These burrows were constructed on a floodplain within the Ordos Basin. The area is reconstructed to have been semiarid-arid with hot summers, possibly with marked seasonality, as indicated by red beds and modeling (Sellwood and Valdes, 2006). The construction and use of burrows possibly protected these tetrapods and may have enhanced their survivorship in the hot and dry conditions and greatly fluctuating temperatures, which have been reconstructed for the continental Middle Triassic of China, and has been proposed for Triassic Gondwanan tetrapods elsewhere.

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陕西二马营组新发现的四足动物潜穴

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摘要：记述了陕西佳县螅镇乡二马营组下段上部产出的三个潜穴。这是我国报道的首例三叠纪的四足动物潜穴。大潜穴叠覆在两个小潜穴之上，推测小潜穴应该是在大潜穴被充填之后挖掘形成。大潜穴简单，长, 轻微弯曲，两侧密布抓痕；小潜穴保存了部分通道以及居住室，表面抓痕不明显。大潜穴可以归入遗迹种：*Reniformichnus katikatii*, 并将其时代延续到中三叠世安尼期。小潜穴则无法归入已知的遗迹属种。大潜穴的造迹者则可能是肯氏兽类的幼体，小潜穴的造迹者推测是中国颌兽或者前棱蜥类。

关键词：陕西佳县，中三叠世，安尼期，二马营组，潜穴

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