A new tritylodontid from the Upper Jurassic of Xinjiang, China

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A new genus and species of Tritylodontidae, Yuanotherium minor, is described and compared with other known tritylodontids. The new taxon is represented by a partially preserved upper jaw with three postcanines, collected from the upper part of the Shishugou Formation (Oxfordian, Late Jurassic) in the Wucaiwan area of the Junggar Basin, northwestern Xinjiang, China. Like other tritylodontids its maxillary teeth have three rows of blade-like trenchant cusps separated by deep furrows. The new species differs from other tritylodontids mainly in having posteriormost two cusps of the median row on upper postcanines closely placed. The new tritylodontid may have been omnivorous rather than herbivorous, as previously suggested for tritylodontids in general.

Key words: Tritylodontidae, Cynodontia, Upper Jurassic, Xinjiang, China.

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Introduction

Tritylodontidae are a group of highly derived nonmammalian cynodonts living in the middle Mesozoic (Kemp 1982, 2005; Watabe et al. 2007). Fossil remains of definite tritylodontids have been found in terrestrial sediments of Early Jurassic to Early Cretaceous age from England, South Africa, Antarctica, North America, China, western Siberia, Japan, and Mongolia (Watabe et al. 2007; Hammer and Smith 2008). The family Tritylodontidae Cope, 1884 are characterized by an aberrant and stereotyped dentition that has enlarged incisors, no canine but a distinct diastema, and squarish postcanines with three rows of crescent cusps on upper teeth and two rows on the lowers. During mastication, leading edges on cusps of the lower postcanines moved posteriorly relative to opposing surfaces of the uppers, producing shearing action (Crompton 1972; Sues 1986a). The peculiar dental structures of tritylodontids are somewhat multituberculate-like and, to a less extent, rodent-like, and were presumably suitable for an herbivorous diet (Kemp 1982). Because tritylodontids possess some mammal-like dental, cranial and postcranial features, they were considered a group within mammals in early studies (see Simpson 1928 for a summary). The group was later removed from Mammalia because a mammalian jaw joint is lacking (Kühne 1956). Some workers recognize a close relationship between tritylodontids and mammals (Kemp 1982; Rowe 1988), whereas most studies of advanced synapsids favor the hypothesis that tritylodontids belong to a clade of largely herbivorous cynodonts, of which no branch led to mammals (Crompton and Ellenberger 1957; Hopson and Crompton 1969; Crompton 1972; Sues 1985a; Hopson 1991; Sidor and Hopson 1998; Hopson and Kitching 2001; Bonaparte et al. 2003, 2005). Regardless of their affinities, tritylodontids have a cosmopolitan distribution and are very abundant in terms of specimens in many Jurassic localities, indicating a degree of evolutionary success for the group in the middle Mesozoic.

Here we report a new genus and species of Tritylodontidae, represented by a partial left upper jaw with three postcanines. The specimen was collected from the Upper Jurassic part of the Shishugou Formation in the Wucaiwan area of the Junggar Basin in Xinjiang, northwestern China (Clark et al. 2006). Other tritylodontids, e.g., Bienotheroides zigongensis Sun, 1986, B. ultimus Maisch, Matzke, and Sun, 2004, and B. shartegensis Watabe, Tsubitomo, and Tsogbaatar, 2007, have been reported from the Middle and Upper Jurassic of the Junggar Basin (Sun and Cui 1989; Maisch et al. 2004) and neighboring southwestern Mongolia (Watabe et al. 2007).

Institutional abbreviation.—IVPP, Institute of Vertebrate Paleontology and Paleoanthropology, Chinese Academy of Sciences, Beijing, China.
Materials and methods

The fossil described in this paper is housed at the IVPP. Although the canines were absent in tritylodontids, we follow the convention of referring to cheek teeth of tritylodontids as postcanines. Cusps on the tooth crown are described based on their relative positions (buccal, median and lingual; anterior, middle and posterior). The photographs were taken using a Nikon digital camera mounted to Nikon SMZ-U microscope.

Systematic paleontology

Synapsida Osborn, 1903
Cynodontia Owen, 1861
Tritylodontidae Cope, 1884

Genus *Yuanotherium* nov.

**Etymology:** Yuan Fuli was a pioneer Chinese geologist and paleontologist who worked in Xinjiang early in the last century; *therium* (L.), beast.

**Type species:** *Yuanotherium minor* sp. nov.

**Diagnosis:**—The same as for the type and only species.

**Stratigraphic and geographic range.**—The upper part of the Shishugou Formation, Oxfordian of the Late Jurassic.

*Yuanotherium minor* sp. nov.

Figs. 1, 2.

**Etymology:** From Latin *minor*, small.

**Holotype:** IVPP V15335, a partial left upper jaw with anterior three postcanines (Figs. 1, 2).

**Type locality:** Wucaiwan area of Junggar Basin in northeastern Xinjiang, China.

**Type horizon:** The upper part of the Shishugou Formation, radiometrically dated as between 161.2±0.2 Ma and 158.7±0.3 Ma (Eberth et al. 2001, 2006; Clark et al. 2006), within the Oxfordian stage of the Late Jurassic.

**Diagnosis:**—Upper cheek tooth with a cusp formula 2:4:3 on the second and third postcanines. Differing from other tritylodontids in having posteriormost two cusps of the median row on upper postcanines closely placed; cusps high and slender (potentially owing to lack of wear), buccolingually compressed; posteriorobuccal cusp with a prominent posterior crest.

**Description:**—The specimen is preserved in matrix, with only the palatal side being exposed (Fig. 1), and represents the middle section of the left upper jaw, including much of the palatal portion of the highly reduced maxilla and palatine, a small portion of the premaxilla, the root of the zygomatic arch, and three anterior upper postcanines, denoted as PC1, PC2, and PC3. In ventral view, the maxilla comprises only a thin bone forming the alveoli of postcanines, as derived tritylodontids such as *Bienotheroides*. A narrow band of the maxilla forms the lingual margins of the alveoli and separates them from the premaxilla and palatine; the latter two elements contact each other along a transverse, interdigitating suture at a level medial to the anterior portion of PC2. Only a small portion of the premaxilla medial to the suture is preserved. The preserved portion of the palatine is a thin, slightly concave plate bearing two small foramina, one being about 1.5 mm medial to the middle lingual cusp of PC2 and the other 2.0 mm medial to the middle lingual cusp of PC3. Watabe et al. (2007) identified similar foramina on a specimen of *Bienotheroides sharTEGRensis* Watabe, Tsubamoto, and Tsogtbaatar, 2007 as the greater and lesser palatine foramina, respectively. Due to the damage of the premaxilla, the maxilla anterior and medial to PC1 is exposed ventrally. The medial edge of the bone does not contact its counterpart on the other side of the skull. It appears that the maxilla is reduced in size, but is not completely excluded from the secondary palate. Instead, the premaxilla ventrally overlaps the reduced palatal process of the maxilla and contacts the palatine. The stout zygomatic process of the maxilla forms the anterior root of the zygomatic arch laterodorsal to PC 2 and 3. The surface of the maxilla between the postcanines and the zygomatic arch is concave. A triangular but uneven facet on the ventral side of the maxilla root of the zygomatic arch is probably for the jugal.

Upper postcanines of *Yuanotherium* have a sub-quadrangular outline in occlusal view with rounded and convex buccal and, to a less extent, lingual margins (Figs. 1, 2). Measurements of these teeth are (length/width in mm): PC1, 2.63/2.76; PC2, 2.82/3.07; and PC3,/?/3.48, respectively. Each tooth has three anteroposterior rows of cusps, which are separated by two deep longitudinal furrows. Apices of cusps are knob-like (Fig. 2A, B). Cusps of the median row are nearly symmetrical relative to the longitudinal axis, and those of lingual and buccal rows are asymmetrical. All cusps are slightly compressed linguobuccally and most of them form crescents facing anteriorly (Fig. 2D). The posterior buccal cusp is the tallest and anteroposteriorly longest cusp on the crown.

In crown view, PC1 has a rounded anterior edge and a transversely straight posterior one. The PC1 cusp formula is 2:3:3. Three cusp rows are subequal in length although the anterior cusp on the median row is more anteriorly positioned than those of the other two rows. The anterior cusps of all three rows are small and similar in size. The buccal and lingual anterior cusps are somewhat crescentic and strongly asymmetrical in that the buccal cusp has a sharp lingual crest and a blunt buccal one, whereas the lingual one has the reverse condition. The median anterior cusp is nearly symmetrical but is not crescentic. There are four accessory cuspules along the anterior margin of the crown, two of which are at the anterior ends of the longitudinal furrows and are smaller than other cuspules. Within the buccal row, the posterior cusp is similarly asymmetrical to, but much taller than, the anterior one. Its lingual crest extends anteriorly to the base of the anterior cusp but does not embrace it. In buccal and lingual views, the cusp is triangular in outline, with the apex of the cusp being positioned almost at the transverse axis of the tooth. The buccal surface of the cusp is convex, contrasting the flat lingual one that forms most of the lateral wall of the buccal furrow. The
The cusp possesses a distinct posterior crest that extends from the apex to the posterobuccal corner of the tooth, forming the posterobuccal margin of the tooth crown. The middle and posterior cusps of the median row are similar in size and shape; each is slightly shorter than the posterior cusp on the buccal row. The middle median cusp has symmetric buccal and lingual crests that enclose a steep crescent surface anteriorly and form a convex posterior surface. The crests reach anteriorly to the base of the anterior median cusp and slightly embrace it. In buccal or lingual view each crest is steep near the apex of the cusp and gently sloped approaching the base of the preceding cusp. The posterior median cusp is somewhat asymmetrical due to wear, deeper on its buccal side than on the lingual. Its crests extend to the base of the preceding cusp but do not embrace it. The posterior surface of the cusp protrudes slightly posteriorly beyond the posterior edge of the tooth and partially overlaps the anteromedian cusp of PC2. The middle lingual cusp is strongly asymmetrical, somewhat crescentic, and slightly smaller than the posterior two cusps of the median row. Its apex levels with that of the posterior cusp on the buccal row and its buccal crest extends anteriorly to a point lingual to the base of the anterior cusp on the lingual row. The buccal and lingual furrows are deep, roughly V-shaped in transverse cross section, anteroposteriorly straight, and widened posteriorly. The buccal furrow is wider and deeper than the lingual one, probably owing to deeper wear. The crests of crescentic cusps do not reach the bottom of either furrow, nor were they eliminated by wear.

PC2 is about 10% longer and wider than PC1 and has the cusp formula 2:4:3. The anterior and posterior edges of its crown are nearly straight and parallel to each other. The tooth is similar to PC1 in general morphology. The most obvious difference is that its median row has four rather than three cusps, of which the two posterior cusps are closely packed so that they share a common base. PC2 also differs from PC1 in several detailed aspects: (i) the anterior cusp on the median row is at the anterior edge of the tooth and buttresses the corresponding cusp of PC1; (ii) the notch separating the posterolingual and mediodistal cusps is wider than that on PC1; and (iii) there are only two cuspules, instead of four, on the anterior edge of the tooth crown.

PC3 was broken at its posterior end. The preserved tooth is almost identical to PC2 in crown morphology, except for its slightly larger size. Trivial differences from PC2 include that the lingual crest of the anterior cusp on the buccal row almost reaches the anterior edge of the tooth and that the buccal crest of the middle lingual cusp embraces the anterolateral cusp.
IVPP V15335 probably belongs to a young adult individual because PC1–3 display some wear. All wear facets are limited to the anterior edges of crescents, suggesting that the crescents functioned as a cutting apparatus, as commonly seen in tritylodontids.

Stratigraphic and geographic range.—The upper part of the Shishugou Formation, Oxfordian of the Late Jurassic.

Comparison and discussion

As in Bienotheroides, Stereognathus, Dinnebidoon, and Bocatherium (Sun 1984; Clark and Hopson 1985; Sues 1986c; Watabe et al. 2007), the premaxilla and palatine of IVPP V15335 contact each other on the palate and the maxilla is highly reduced. IVPP V15335 further shows that the premaxilla ventrally overlapped the reduced maxilla, although the latter is not completely excluded from the secondary plate by the expanded premaxilla. The condition is unclear in the other taxa with reduced maxillae.

IVPP V15335 displays the typical tooth morphology of tritylodontids and unquestionably belongs to the family. *Yuanotherium minor* is one of the smallest tritylodontids. Its PC2 is comparable in size to that of *Oligokyphus minor* Kühne, 1956 and smaller than all other tritylodontids except for *Lufengia* and *Yunnanodon*. The presence of closely packed posterior cusps in the median row of PC2–3 (and probably in more distal teeth as well) is unique among tritylodontids. Judging from moderate tooth wear and small size gradient of teeth, the specimen was probably from a young adult and thus the packed posterior cusps on the median row are not juvenile features. These morphological differences warrant establishment of the new genus and species within Tritylodontidae.

The early Jurassic *Oligokyphus* has a wide distribution and is known by abundant fossil remains (Simpson 1928; Kühne 1956; Sues 1985b; Luo and Sun 1993). Given its basal position in tritylodontid phylogeny (Clark and Hopson 1985; Sues 1986b; Setoguchi et al. 1999; Watabe et al. 2007), *Oligokyphus* may be regarded as approximating the ancestral morphotype of tritylodontids. Overall, the upper postcanine of *Oligokyphus* is longer than wide, which is different from all other tritylodontids. *Oligokyphus* differs from *Yuanotherium* in many aspects. In *Oligokyphus*, the cusp formula of a typical upper postcanine (PC2–5) is 3:4:4; the mesial and distal edges of the tooth are convex instead of being truncated; the median cusp row is longer than other two; the buccal row is placed mesially relative to the lingual row; the posterior median cusp projects posteriorly well beyond the margin of the tooth crown; the cusps are low, with minor differences in height between neighboring cusps, and are not linguobuccally compressed; the crests of most cusps (except for the anterior cusps) embrace the bases of their respective preceding cusps. The anterior cusp on the median row is crescentic. A similarity between PCs of *Oligokyphus* and those of *Yuanotherium* is that their buccal and lingual margins are somewhat convex rather than straight.

The early Jurassic *Tritylodon* from Africa (Owen 1884; Simpson 1928) has the same PC cusp formula (2:4:3) as in *Yuanotherium*, but as in *Oligokyphus* the dental morphology of *Tritylodon* differs from *Yuanotherium* in having similar cusp shape, small height difference between cusps, crescentic shape of the anteromedian cusp, and anterior shifting of the buccal cusp row. *Tritylodon* resembles *Yuanotherium* in having straight anterior and posterior margins and convex lingual margins on upper postcanines. In addition, the posterior median cusp does not project posteriorly beyond the tooth margin.

A PC cusp formula of 2:3:3 exists in several tritylodontid genera, including *Bienotherium*, *Dianzhongia*, *Lufengia*, *Kayentatherium*, and *Bienotheroides*, of which *Bienotherium*, *Dianzhongia* and *Lufengia* are from the early Jurassic of Yunnan, China (Young 1940, 1947, 1974; Chow and Hu 1959; Chow 1962; Hopson 1965; Cui 1981; Luo and Wu 1994). In *Bienotherium* a small cuspile is present in front of each cusp row (Hopson 1965; Sun 1984; Luo and Wu 1994) so that the total cusp number of a typical PC can be as many as eleven (Sun 1984). As in *Oligokyphus* the upper tooth of *Bienotherium* is square-shaped and has low cusps and a short buccal cusp row that is more anterior than the lingual row. As in *Yuanotherium* the upper tooth cusps of *Bienotherium* have weak crests.

*Dianzhongia* and *Lufengia* are similar to each other in upper postcanine morphology but differ from each other in size. *Lufengia* is by far the smallest known tritylododontid, with a skull length only about 40 mm (Chow and Hu 1959; Cui 1981; Cui and Sun 1987; Luo and Wu 1994; see also Fig. 3). The buccal cusp row in these two genera is short but is not shifted anteriorly relative to the lingual row. In the two genera, the anterior edge of the tooth is transversely straight but the posterior edge is convex, due to the protruding of the posterior median cusp, and most cusps have well-developed crests. The two genera are similar to *Yuanotherium* in having a reduced posterolingual cusp but in *Lufengia* the reduced posterolingual cusp extends more anteriorly to its preceding cusp, a condition absent in *Dianzhongia* and *Yuanotherium*.

*Kayentatherium* Kermack, 1982 (including *Nearctylodon* Lewis, 1986, as a junior synonym; Sues 1986a, c; Sues and Jenkins 2006), is from the Lower Jurassic Kayenta Formation of southwestern North America, whereas *Bienotheroides*, with four named species, comes from the middle to late Jurassic of eastern and central Asia (Young 1982, Sun 1984, 1986; Sun and Li 1985; Sun and Cui 1989; Maisch et al. 2004; Watabe et al. 2007). Both genera have postcanine tooth cusps buccolingually compressed and trenchant with steep flanks, resembling the condition of *Yuanotherium*, but crests on the cusps are more conspicuous than in *Yuanotherium*. The tooth crowns of the two taxa are somewhat oval in occlusal view due to the rounded tooth corners, in contrast to a more angular appearance in *Yuanotherium*. The anterior and posterior edges
of the postcanines are straight in the upper postcanines similar to those of Bienotheroides ultimus: Watabe et al. (2007). However, the cusps with distinct and long crests extending from the lingual/buccal flanks of the preceding cusps, and any cusp on the lingual or buccal row having only a single crest.

Xenocretosuchus from the Lower Cretaceous of Siberia is similar to Stereoognathus in upper tooth cusp formula and morphology of lingual and buccal cusps (Tatarinov and Matchenko 1999). However, it has small cusps in front of the principal cusps, which are absent in Stereoognathus. An unnamed tritylodontid from the Lower Cretaceous of Japan has upper postcanines similar to those of Stereoognathus, although they probably differ in the development of cusps along the anterior edges of the teeth (Setoguchi et al. 1999: figs. 1, 3). Polistodon from the Middle Jurassic of Sichuan, China (He and Cai 1984) and Bocatherium from the Lower Jurassic of Mexico (Clark and Hopson 1985; Clark et al. 1994; Fastovsky et al. 2005) have the same cusp formula as Stereoognathus, on upper postcanines, but they also have a small cuspule in front of each cusp row, which is a condition more similar to Yuanotherium than to Stereoognathus. Polistodon is unique among tritylodontids in having thirteen upper postcanines, with each tooth being relatively wide and short compared to those of other tritylodontids, Yuanotherium included. Bocatherium is similar to Yuanotherium in having an oval coronal shape of the upper postcanine.

To sum up, the new specimen differs from those of previously known tritylodontids and represents a new genus and
species within Tritylodontidae. The interrelationships among
tritylodontid genera have been explored in several studies
(Clark and Hopson 1985; Sues 1986b; Setoguchi et al. 1999;
Watabe et al. 2007). Based primarily on dental and cranial
characters, these studies concluded that Oligokyphus was
probably the most basal member of the tritylodontid clade and
that more derived members of the clade evolved a relatively
short and broad snout with a highly reduced maxilla and upper
postcanines bearing fewer cusps in each row. Though uncertain-
ties remain on several aspects of the tritylodontid morphol-
ogy, such as the cusp homologies (Setoguchi et al. 1999;
Watabe et al. 2007), it is notable that tritylodontid postcanines
are highly conservative and variations among different taxa
are small, if not trivial.

In IVPP V15335 the first upper postcanine has a rounded
anterior margin decorated with minor cuspules, in contrast to
more posterior teeth whose anterior margin is truncated. Evi-
dence suggests that in tritylodontids the postcanines were not
replaced and that new teeth were added sequentially at the
posterior end of the tooth row, while anterior ones were shed
after severe wear (Crompton 1955; Kühne 1956; Sues 1986a;
Matsuoka and Setoguchi 2000). The morphology and the de-
gree of wear of the first preserved tooth (PC1) of IVPP
V15335 suggests that there has not been a tooth shed anterior
to PC1, and that PC1 is probably the first upper postcanine
this individual ever developed in life. PC1 of V15335 is only
slightly smaller than more posterior teeth, suggesting that the
animal probably grew to a substantial size before the first
cheek tooth erupted. This appears also the case for several
other tritylodontids with well-preserved upper dentitions,
such as Bocatherium, Bienotherium, Bienotheroides, Dian-
zhongia, Lufengia, Oligokyphus, Tritylodon, and Yunnano-
don. Timing of the first tooth eruption could be demonstrated
with fossils from earlier ontogenetic stages, which would
shed light on tritylodontid biology, such as parental care of
neonates.

Tritylodontids have been inferred to have been herbivo-
rous (Kühne 1956; Kemp 1982, 2005; Sues 1986a). The op-
opposing crescent cusps of upper and lower postcanines are
considered to be efficient for cutting vegetable fibers (Kühne
1956), and the cranial morphology is also consistent with an
herbivorous masticatory apparatus (Sues 1986a). However,
the postcanine morphology of Yunnatherium suggests some
deviation from a purely herbivorous diet. The cusps in
Yunnatherium are slender, with relatively weak crests, and
the posteriorlingual cusp being high and blade-like. These fea-
tures indicate more trenchant and probably more fragile
postcanines in Yunnatherium than in other tritylodontids.
The postcanines of Yunnatherium appear not well adapted
for processing tough plants but suitable for puncturing, tear-
ing and slicing soft food items, suggesting that this tritylo-
dontid may have been omnivorous rather than herbivorous.
This is consistent with the observation that some rodents and
other extant mammals with teeth seemingly adapted to plant
eating are actually omnivorous (Landry 1970; Nowak 1999
and references therein).

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