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A new, large tyrannosaurine theropod from the Upper Cretaceous of China

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A B S T R A C T

Tyrannosaurids are primarily gigantic, predatory theropod dinosaurs of the Cretaceous. Here we report a new member of the tyrannosaurid clade Tyrannosaurinae from the Upper Cretaceous Wangshi Group of Zhucheng, Shandong Province, China, based on a maxilla and associated dentary. The discovery of this animal, here named *Zhuchengtyrannus magnus* gen. et sp. nov., adds to the known diversity of tyrannosaurids in Asia. *Z. magnus* can be identified by a horizontal shelf on the lateral surface of the base of the ascending process, and a rounded notch in the anterior margin of the maxillary fenestra. Several additional features contribute to a unique combination of character states that serves to further distinguish *Z. magnus* from other taxa. Comparisons with other tyrannosaurids suggest that *Zhuchengtyrannus* was a very large theropod, comparable in size to both *Tarbosaurus* and *Tyrannosaurus*.

1. Introduction

The clade Tyrannosauroidea includes some of the largest of all theropod dinosaurs (Holtz, 2004), and continues to fascinate both researchers and the general public. Recent discoveries in Asia, including the new taxa *Raptorex kriegsteini* (Sereno et al., 2009), *Alioramus altai* (Brusatte et al., 2009), *Sinotyrannus kazuoensis* (Ji et al., 2009), and *Xiongguanlong baimoensis* (Li et al., 2009), have dramatically increased the number of tyrannosauroids known from this continent.

Another recent development has been the reopening of the quarry close to the city of Zhucheng, Shandong Province, eastern China that yielded the giant hadrosaurid *Shantungosaurus giganteus* (Hu, 1973). Excavations have also been carried out at several new nearby sites. Alongside his description of *Shantungosaurus*, Hu (1973) assigned four theropod teeth from the same quarry to the North American tyrannosaurid *Tyrannosaurus rex*, and subsequently (Hu et al., 2001) used these teeth and a single metatarsal as a basis for erecting the putative new *Tyrannosaurus* species *Tyrannosaurus zhuchengensis*. Prior to the recent excavations near Zhucheng, the specimens described by Hu (1973) and Hu et al. (2001) represented the only theropod material that had ever been reported from the area. However, the recent excavations have uncovered several new tyrannosaurid cranial and postcranial bones from the Zangjiazhuang site, a locality near the *Shantungosaurus* quarry that has also yielded numerous hadrosaurid bones and some ceratopsid material (Xu et al., 2010).

The various tyrannosaurid bones from the Zangjiazhuang site are largely separate from one another (though some are in association), making it difficult to determine how many individuals or even taxa are represented. However, in addition to a variety of postcranial bones, the material includes an associated dentary and maxilla (ZCDM V0031) that clearly belong to a tyrannosaurid distinct from all previously described members of this clade. Accordingly, these elements are designated in this paper as the holotype of a new taxon. A second dentary (ZCDM V0030) and second maxilla (ZCDM V0032) have also been recovered. Although these latter elements were not found in association, each is clearly different from its counterpart in other tyrannosaurids, including the taxon described in this paper. This implies the existence of at least one additional new tyrannosaurid from Zangjiazhuang. These elements, and other tyrannosaurid remains from Zhucheng, will be described in a later paper.

The associated maxilla and dentary described in the present contribution clearly represent a new giant tyrannosaurid from the Upper Cretaceous of the Zhucheng area. While similar in size and

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gross morphology to *Tarbosaurus*, the new tyrannosaurid can be distinguished from *Tarbosaurus* and other tyrannosaurids by a number of apomorphic characters.

1.1. Institutional abbreviations

AMNH, American Museum of Natural History, New York, USA; BYU, Brigham Young University, Provo, USA; CMN, Canadian Museum of Nature, Aylmer, Canada; FMNH, Field Museum of Natural History, Chicago, USA; GMC, Geological Museum of China, Beijing, China; IGM, Institute of Geology, Mongolian Academy of Sciences, Ulan Bator, Mongolia; IVPP, Institute of Vertebrate Paleontology & Palaeoanthropology, Beijing, China; LACM, Los Angeles County Museum, Los Angeles, USA; NMMNH, New Mexico Museum of Natural History and Science, Albuquerque, USA; PIN, Palaeontological Institute of the Russian Academy of Sciences, Moscow, Russia; TMP, Tyrrell Museum of Palaeontology, Drumheller, Canada; ZCDM, Zhucheng Dinosaur Museum, Zhucheng, China; ZPAL, Institute of Palaeobiology of the Polish Academy of Sciences, Warsaw, Poland.

Fig. 1. Map showing location of Zangjiazhuang quarry near Zhucheng, Shandong Province, China.

2. Systematic Palaeontology

Dinosauria Owen, 1842
Theropoda Marsh, 1881
Tyrannosauridae Osborn, 1906
Tyrannosaurinae Matthew and Brown, 1922
Zhuchengtyrannus gen. nov. *magnus* sp. nov.

2.1. Etymology

Generic name in honour of the city of Zhucheng, from which the material was recovered, with the suffix 'tyrannus' from the Latin for 'king' or 'tyrant'. Specific name 'magnus' from the Latin for 'great', in reference to the size of the animal.

2.2. Holotype

Zhucheng Dinosaur Museum (ZCDM) V0031, a nearly complete right maxilla and associated left dentary, both with teeth in situ. Casts of the maxilla and dentary are held at the Institute of Vertebrate Paleontology and Paleoanthropology as IVPP FV 1794.

2.3. Age & locality

Zangjiazhuang, Zhucheng City, Shandong Province (Fig. 1); Upper Cretaceous Wangshi Group (Hu et al., 2001). Within the fluvial sediments of the Wangshi Group, the abundant dinosaur material preserved in the Zhucheng quarries lies near the transition between the Xingezhuang Formation and the overlying Hongtuya Formation (Li et al., 2009). Basalt within the upper part of the Hongtuya Formation has been radiometrically dated to an age of 73.5 Ma (Campanian), which establishes a minimum bound on the age of the dinosaur deposits. Apart from the tyrannosaurid material, specimens so far recovered from the Zanjiazhuang quarry include hadrosaurids (probably *Shantungosaurus*), unidentified ankylosaurs, and a large-bodied ceratopsid (Xu et al., 2010).

2.4. Diagnosis

A large tyrannosaurine theropod dinosaur distinguished from other tyrannosaurine taxa by the following features of the maxilla: a horizontal shelf on the lateral surface of the base of the ascending process, and a rounded notch in the anterior margin of the maxillary fenestra. *Zhuchengtyrannus magnus* also possesses the following unique combination of characters: the ventral margin of the antorbital fenestra lies well above that of the ventral rim of the antorbital fossa, and the anteroposterior length of the maxillary fenestra is more than half the distance between the anterior margins of the antorbital fossa and fenestra.

Zhuchengtyrannus magnus can be distinguished from the contemporaneous Asian tyrannosaurine *Tarbosaurus bataar* by the absence of a subcutaneous flange on the posterodorsal part of the jugal ramus of the maxilla, and the absence of a ventrally convex palatal shelf that covers the bulges of the roots of the posterior teeth in medial view.

3. Description

The holotype material of *Zhuchengtyrannus* consists of a right maxilla (Fig. 2) and left dentary (Fig. 3), both of which are nearly complete. When discovered, the maxilla was in good condition, despite some damage to the ascending process and parts of the medial surface. Unfortunately the bone subsequently suffered severe additional damage during handling (Fig. 2A), although an excellent cast (Fig. 2C, D) and a photograph (Fig. 2B) record its condition prior to the accident. Seven partly to fully erupted teeth are present in the maxilla. The dentary is in good condition (though with some posterior damage), retaining eight teeth, and was found in association with the maxilla. The two bones were discovered approximately 30 cm away from each other and came from the same layer. The proportions of the bones and their respective dentitions suggest that they are indeed from the same individual. Both bones were lying with the lateral face uppermost, though unfortunately both were extracted from the quarry without their exact orientation and position being recorded. Neither bone appears to have suffered any taphonomic distortion.

The maxilla is a large, robust, roughly triangular element with two large posteriorly directed rami, a ventral one that reaches the jugal and a dorsal ascending process that extends towards the lacrimal. The ascending process is broken away close to its base. The two processes form the margins of the anterior part of the antorbital fenestra and fossa. As preserved, the maxilla is 64 cm long and 30 cm high. The anterior face is 34 cm tall, and the height of the maxilla below the maxillary fenestra is 19 cm (measured on the cast). In lateral view, the maxilla has a slightly convex anterior edge. The anterior part of the ventral edge has a much stronger convexity, whereas the jugal ramus tapers and curves ventrally to a pointed, downturned tip (now missing as a result of damage).

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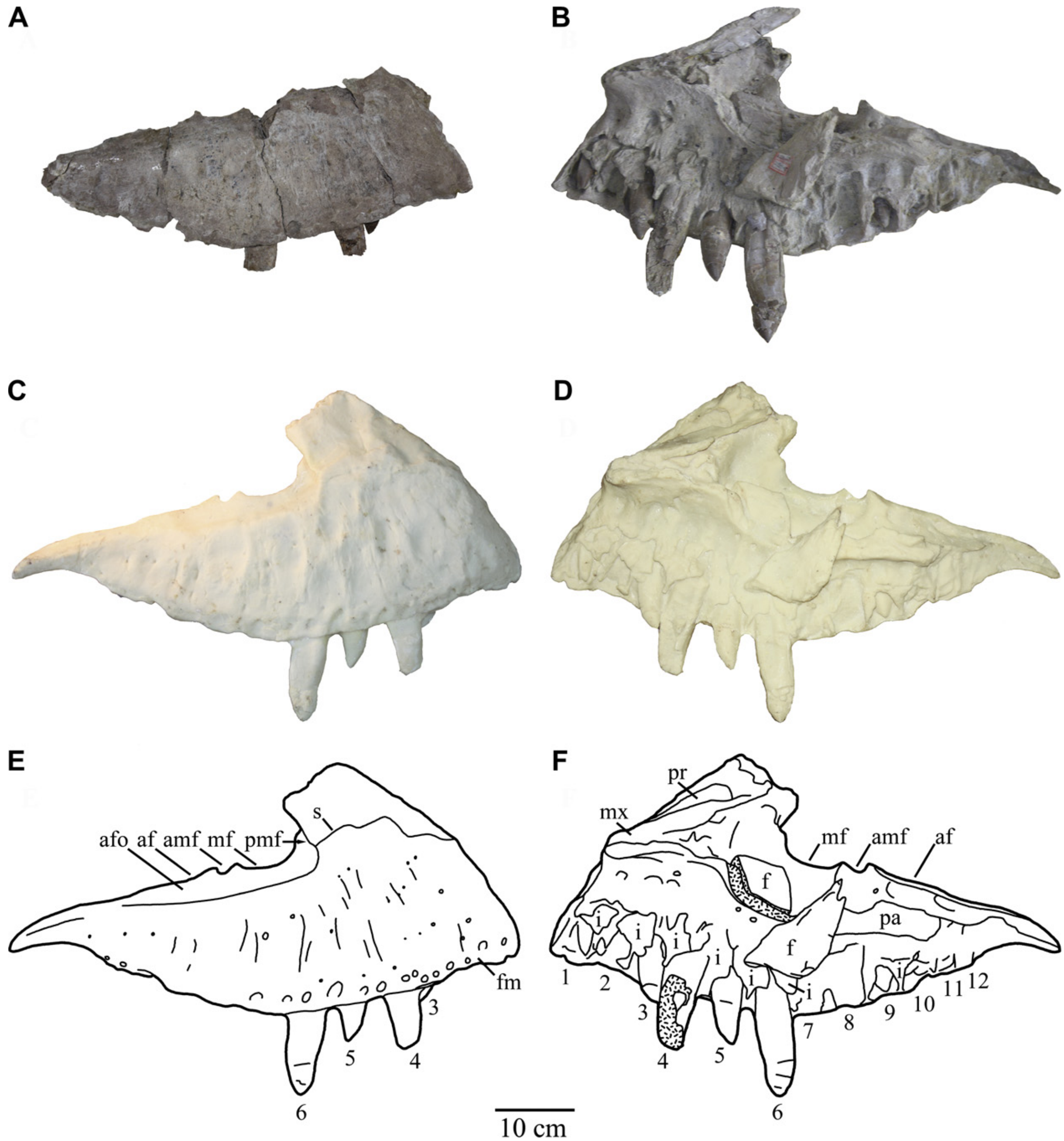

Fig. 2. Right maxilla of holotype specimen of *Zhuchengtyrannus magnus* (ZCDM V0031). A, Maxilla in lateral view, following specimen damage; distal part of 6th tooth, which remains intact despite being detached through breakage, not shown. B, Undamaged maxilla in medial view. C–F, Photos and line drawings of a cast of the slightly damaged maxilla. C and E in lateral view, D and F in medial view. Abbreviations: af, antorbital fenestra; afo, antorbital fossa; amf, accessory maxillary fenestra; f, displaced fragment of bone; fm, row of foramina; i, interdental plate; mf, maxillary fenestra; mx, articular surface for contralateral maxilla; pa, articular surface for palatine; pmf, promaxillary fenestra; pr, promaxillary recess; s, shelf on lateral surface of ascending process. Numerals indicate tooth positions. Hatching indicates a broken surface, stippling indicates matrix.

The lateral face bears numerous enlarged foramina in a row close to the ventral margin. The largest foramen measures around 16 mm by 7 mm, though most are subcircular and only around 6 mm in diameter. The surface as a whole is rugose, although there are faint flutes on the lateral surface of the maxilla, perpendicular to the ventral edge. The raised areas are aligned roughly with the spaces between successive tooth sockets, and separated from each other by subcircular depressions (Fig. 4). The ventral edge of the jugal ramus is not only ventrally concave but also crenulated with more subtle, alternating concavities and convexities, the former corresponding to the positions of the tooth sockets.

The jugal ramus bears a distinct shelf defining the ventral edge of the antorbital fossa, and forms the ventral margins of the maxillary fenestra, accessory maxillary fenestra and antorbital fenestra. Above the shelf, the medially recessed strip of bone belonging to the antorbital fossa is about 30 mm high throughout its length. The anterior end of this strip passes medial to the posterior edge of the ascending process, forming a small recess between the two structures at a level just dorsal to the ventral edge of the maxillary fenestra. Because of the damage to the specimen, there is no definite evidence that this recess contains a promaxillary fenestra as in some tyrannosaurids (Witmer, 1997). However,

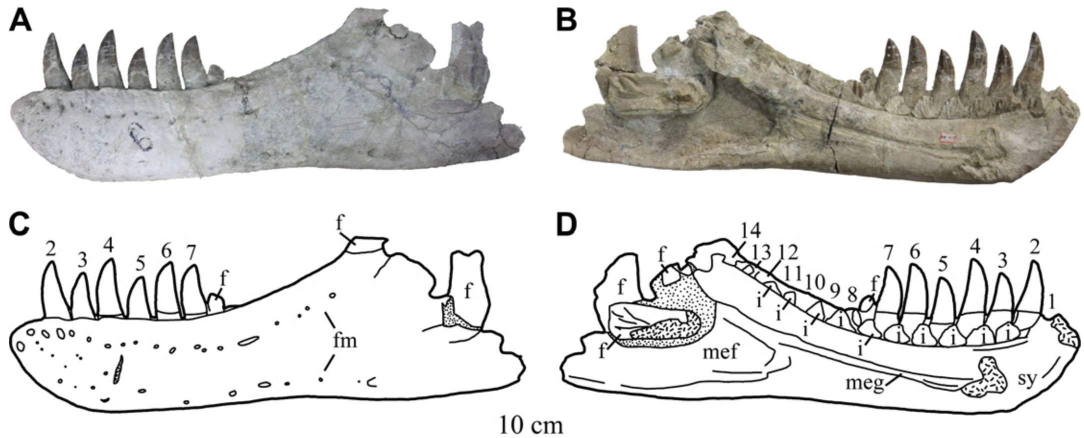

Fig. 3. Photos and line drawings of left dentary of holotype specimen of *Zhuchengtyrannus magnus* (ZCDM V0031). A and C in lateral view, B and D in medial view. Abbreviations: mef, Meckelian fossa; meg, Meckelian groove; sy, symphyseal region. Other abbreviations as in Fig. 1. Numerals indicate tooth positions.

the location of the recess corresponds to that of the promaxillary fenestra in *T. rex* (Brochu, 2003) and *Ta. bataar* (Hurum and Sabath, 2003), and there is no indication in *Zhuchengtyrannus* of a more posteriorly positioned promaxillary fenestra that would be visible in lateral view. Accordingly, the promaxillary fenestra was probably concealed by the ascending process. Slightly above the ventral margin of the antorbital fossa, the lateral surface of the maxilla forms a horizontal shelf separating the thin, poorly developed dorsal part of the ramus from the rest of the lateral face of the maxilla.

In anterior view the lateral border of the maxilla is slightly convex, such that the ascending process angles slightly dorsomedially. The lateral edge of the anterior face of the maxilla forms a slight but distinct rounded prominence at about the dorsoventral level of the anterior end of the lateral shelf on the ascending process. The smooth texture of this prominence suggests that it may have protruded between the praemaxilla and nasal to enter the margin of the external naris, but this is uncertain: it is also possible that slender processes of the maxilla and nasal came together in the vicinity of the prominence, excluding the maxilla from the naris as in typical tyrannosauroids (though some variation is seen in tyrannosaurids – Brochu, 2003). The smooth area of bone is slightly expanded medially, forming a surface that presumably represents part of the roof of the vestibular bulla and also contributes to the floor of the narial cavity. Further ventrally, a slight embayment in the lateral edge of the anterior surface of the maxilla may mark the position of a substantial narial foramen as in some other tyrannosaurids (Osborn, 1912; Brochu, 2003).

The medial surface of the maxilla bears a broad, deep and robust shelf, which begins midway up the anterior face and extends posterodorsally in line with the ascending process. This shelf is 220 mm long and about 70 mm broad at its rostroventral end, though it is broken posteriorly. Anterodorsal to the shelf is a furrow, representing the interior of the promaxillary recess, in the medial face of the bone. The furrow is about 110 mm long and 20 mm wide, and terminates close to the point of breakage of the ascending process.

The palatal shelf extends posteriorly from the anterior shelf at a level about 30 mm below the antorbital fenestra. The anterior confluence of the two shelves forms a sub-triangular mass of bone whose damaged medial surface would have formed a sutural area for the contralateral maxilla, dorsal to the overlapping vomer. The

Fig. 4. Low-angle photograph of lateral face of right maxilla of *Zhuchengtyrannus magnus* (ZCDM V0031). Note the pronounced sculpting of the surface.

Fig. 5. First right maxillary tooth of *Zhuchengtyrannus magnus* (ZCDM V0031) in lingual view. Note lingual twist of the mesial carina.

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preserved width of the palatal shelf in this region is about 30 mm. More posteriorly, the palatal shelf largely runs sub-parallel to the ventral border of the maxillary and antorbital fenestrae. The shelf is broken close to the posterior end of the jugal ramus, so it is not clear whether it maintained its width beyond this point or began to taper. However, it is clear that the posterior part of the shelf, which forms the contact with the palatine, is relatively straight and does not bulge downwards to obscure the roots of the posteriormost teeth in medial view as occurs in *Tyrannosaurus* (Osborn, 1912: Fig. 26; Brochu, 2003: Fig. 14B), *Albertosaurus* (Currie, 2003:Fig. 6B) and to some extent *Tarbosaurus* (Hurum and Sabath, 2003:Fig. 4C, D). Two substantial pieces of bone have also broken away from near the midpoint of the palatal shelf's length. This broken part would likely mark the expansion of the shelf that would form part of the internal naris and, further posteriorly, where the shelf would meet with the palatines (cf. Brochu, 2003: Fig. 4).

Large pentagonal interdental plates are present. They are clearly not fused either to the maxilla or to each other, as is evident from the fact that several have moved from their natural positions. Most have dorsoventrally aligned grooves running across their surfaces. The grooves are similar to, though less strongly developed than, those on the interdental plates of the dentary.

Although the ascending process is broken and the other bones of the skull are not present, the margins of the various fenestrae of the maxilla are partially preserved. As described above, a promaxillary fenestra is likely present medial to the posterior edge of the ascending process and above the ventral margin of the antorbital fossa. The curved ventral border of the maxillary fenestra is visible within the antorbital fossa. Judging by the ventral border, the fenestra would have been about 70 mm long and sub-oval in shape, though a slight, rounded, notch-like extension is present anteriorly. The extension appears genuine, and is unlikely to represent the result of a break or a casting error. Apart from this notch, the maxillary fenestra is entirely posterior to the edge of the ascending process, but occupies most of the area of the fossa anterior to the antorbital fenestra. The ventral edge of the maxillary fenestra is a short distance above the shelf that marks the ventral boundary of the antorbital fossa. Posterior to the ventral part of the maxillary fenestra lies a structure that we term an 'accessory maxillary fenestra', situated between the maxillary and antorbital fenestrae. The preserved part of the margin of this fenestra suggests that it was roughly circular when intact and about 30 mm in diameter. The shape of the antorbital fenestra is almost entirely uncertain, owing to the lack of an interfenestral strut and of cranial elements other than the maxilla.

Fig. 6. Second and third right dentary teeth of *Zhuchengtyrannus magnus* (ZCDM V0031) in lingual view. Note the lingual placement of the mesial carina. Abbreviation: c, mesial tooth carina. Numerals indicate tooth positions.

A total of 12 alveoli are present along the ventral margin of the maxilla, with the tooth row extending over a distance of around 520 mm (measured in a straight line). The posteriormost two alveoli are exposed medially, and contain traces of enamel showing that teeth were originally preserved even though the sockets are now empty. The largest alveolus is the 6th, which measures 43 mm long by 27 mm wide (though maxillary alveoli [hereafter, abbreviated to 'm'] 4–8 are of comparable size). Seven of the alveoli contain teeth. Of these, two (m1 and m9) were only beginning to erupt, and do not extend beyond the ventral margin of the maxilla. Two more (m3 and m5) are partially erupted, while the final two (m4 and m6) protrude out of their sockets to such a degree that their roots are partially visible in lingual view. The crowns of m4 and m6 have both suffered damage, which presumably was sustained post-mortem. In m4 the medial side of the crown has sheared off and the tip is missing, and the apical area of m6 is somewhat broken but still in place.

The tooth crowns are typical of large derived tyrannosaurids, being large, broad with relatively blunt tips, and sub-oval in cross-section. The distal edges of the teeth are approximately straight, whereas the mesial edges curve only close to the apex. Mesial and distal carinae are present, with the mesial carina being somewhat lingually positioned on m1 (Fig. 5). The crown of the largest preserved maxillary tooth, m4, is close to 100 mm in length. As the fourth alveolus is also the largest in the entire series, m4 is probably the largest tooth in the maxilla of *Zhuchengtyrannus*. The denticles are best preserved in the case of m1. In this tooth the mesial and distal denticles appear approximately equal in size, and become mesiodistally shorter towards the apex of the tooth but continue across it without a break in the series. In labial view the denticles appear subrectangular. Except near the apex, the mesiodistal length of the denticles exceeds their apicobasal width.

The dentary (Fig. 3) is a long, low bone that is well preserved, but damaged at the posterior end. As preserved it is 760 mm long, and 235 mm high at its highest point. The ventral margin of the dentary is 50 mm wide anteriorly, but narrows to just 5 mm posteriorly. The anterior end is strongly convex. The dentary is dorsoventrally shallowest midway along its length, the posterior end being slightly expanded ventrally and strongly expanded dorsally. The expansion of the posterior end is so modest that the ventral edge of the dentary has only a slight concave curvature. The anterior end of the dentary is relatively blunt and rounded, with the symphysis terminating posteroventrally below the third dentary tooth.

The lateral face of the dentary is slightly convex from dorsal to ventral. As in other tyrannosaurids, two distinct longitudinal rows of foramina are present on the lateral face, one near the dorsal margin and one near the ventral. Several additional foramina are scattered between the two rows anteriorly. The dorsal row contains about 20 foramina, which lie close to the alveolar margin of the mandible anteriorly. Beyond the fifth foramen, the row lies further ventrally, but approximately follows the curvature of the upper edge of the mandible. The foramina are somewhat variable in size, with an especially large and elongate foramen situated just posterior to the level of the last preserved dentary tooth.

The ventral row contains about 15 individual foramina, of which the posteriormost is the largest and deepest, and stops well short of the posterior end of the dentary. The anterior half of the row is actually situated along the ventral edge of the dentary and not readily visible in lateral view, but the more posterior foramina are fully on the lateral surface although close to the ventral margin. Neither the dorsal nor the ventral foramina have any obvious positional relationship to the spacing of the dentary teeth.

The medial face of the dentary bears a narrow Meckelian groove that seems to terminate just short of the anterior end of the bone. The anterior end of the groove is closer to the ventral edge of the dentary than to the dorsal edge, but the groove slopes dorsally as it passes posteriorly and ultimately enters the Meckelian fossa. The area around the anterior end of the Meckelian groove has suffered some damage. It is not clear whether or not a foramen intramandibularis oralis (see Brochu, 2003: Fig. 41) is present, although an approximately cylindrical structure within the damaged region may represent an infilling of the foramen. The bone of the dentary adjacent to the line of interdental plates is recessed to accommodate the supradentary, although there is no dorsally positioned groove to mark the position of the lower edge of the latter bone. The Meckelian fossa is broad, tapering to a blunt anterior end. The fossa is bounded ventrally by a low, narrow rim, and dorsally by a higher and more robust ridge that represents the posterior end of the dentary shelf. The anterior part of the ventral rim is wider than the posterior part, and bears a dorsally-facing rugose area for articulation with the splenial. This articular area continues into a small triangular depression adjacent to the anterior edge of the fossa.

The posterior end of the dentary is a broad, thin plate embayed by the external mandibular fenestra. The bone is damaged in this region, and overlapped both medially and laterally by what appear to be adhering fragments of postdentary bones. The most intact part of the posterior end of the dentary is the ventral process for the angular, a thin and broad structure terminating posteriorly in an undulating line. From here the posterior edge of the dentary slopes anterodorsally in an irregular manner towards the posterior end of the dentary shelf, and it is not clear how much of the edge formed part of the margin of the external mandibular fenestra. On the lateral face of the dorsal apex of the dentary is a robust, elongate piece of bone that might represent either a fragment of another bone or a slightly displaced intramandibular process sensu Currie (2003).

The teeth of the dentary are generally better preserved than those of the maxilla, and there are 15 dentary alveoli over a length of 540 mm (measured in a straight line; note that this distance is nearly identical to the length of the maxillary tooth row). The largest alveolus is the fifth (approximately 32 mm wide by 38 long, though this is hard to measure because of the in situ teeth). Alveolar size diminishes rapidly posterior to the tenth alveolus.

The anteriormost dentary alveoli (d1 and d2) are empty, but teeth d3–d8 are fully erupted with only slight, irregular variation in height (Fig. 6). Alveoli d9 and d14 contain tiny, partly erupted teeth, while d10-d13 and d15 are empty. Alveolus d1 is considerably smaller than the other anterior alveoli (13 mm long, compared to 32 mm for d2). Alveolus d1 is not well preserved, as a result of damage to the anterior end of the dentary, but it is clear that this alveolus is only minimally displaced posteriorly from the anteriormost point of the dentary. The posterior part of alveolus d1 may merge into the anterior end of alveolus d2. Tooth d3 is rounded in cross-section with the carinae mesiolingually and distiolabially positioned, but the more posterior teeth are more laterally compressed with carinae that are approximately mesial and distal in position. The mesial carinae shift slightly lingually as they descend from the apices of the teeth. The distal edge of tooth d3 is slightly concave, so that this tooth shows a modest degree of recurvature, but the other preserved dentary teeth are uniform in having straight distal edges. As in the maxillary teeth, the mesial and distal denticles of the dentary teeth are similar in mesiodistal length and closely approach, if not continue across, the tooth apices.

The anteriormost interdental plate is missing, but the series is otherwise intact apart from some damage to the posteriormost plates. The anterior plates are distinctly pentagonal and sculptured with vertical ridges that are stronger than those on the maxillary interdental plates, but posterior to tooth d7 the plates become triangular and lose their sculpturing. The plates posterior to teeth d4-d6 are the largest in the series, and towards the posterior end of the tooth row the plates are very small.

4. Systematic position of *Zhuchengtyrannus*

Although the morphological information available for *Zhuchengtyrannus* is limited to features of the maxilla and dentary, these bones provide enough data to support a precise and confident taxonomic assignment. The specimen can be diagnosed as a tyrannosauroid based on the presence of unfused interdental plates (Currie et al., 2003). It also has the tyrannosaurid characteristics of a relatively small first maxillary tooth and a convex alveolar margin of the maxilla (Carr and Williamson, 2004). The labiolingually broad maxillary teeth and the dorsoventrally expanded posterior part of the dentary (Holtz, 2004) further support referral of the specimen to Tyrannosauridae. The anterior edge of the maxillary fenestra also approaches the anterior margin of the antorbital fossa as seen in derived tyrannosaurines (Carr and Williamson, 2010). While hardly definitive, the Late Cretaceous age of the specimen, as well as its location in eastern Asia and large size, are also consistent with the identification of *Zhuchengtyrannus* as a tyrannosaurid.

At a more precise taxonomic level, the maxilla of *Zhuchengtyrannus* displays one key tyrannosaurine characteristic: the anteroposterior length of the maxillary fenestra is more than half the distance between the anterior margins of the antorbital fossa and fenestra (Carr, 1999; Currie et al., 2003). However, a second expected character state, a palatal shelf whose posterior part is deep and obscures the roots of the teeth from view, is absent (Carr, 1999; Carr et al., 2011).

While the ontogenetic stage of the specimen cannot be definitively evaluated without indicators such as vertebrae with fused neurocentral sutures, both the large size of the maxilla and dentary and the limited suite of ontogenetically variable features pertaining to these bones imply maturity. Accordingly, it is unlikely that any of the character states used to assess the taxonomic position of *Zhuchengtyrannus* reflect juvenile status. The maxilla and dentary are comparable in size to those of adult specimens of both *T. rex* and *Ta. bataar*, and larger than those of other adult tyrannosaurids (see below for details). Regarding the ontogenetic characters of tyrannosaurids investigated by Carr (1999), the thickness of the maxilla and the fact that it bears enlarged anteroventral foramina suggest adult status. The large angle (over 45°) between the anterior and ventral margins of the maxilla is also characteristic of adult tyrannosaurids (Carr and Williamson, 2004), as is the relatively large maxillary fenestra (Currie, 2003). Finally, young and basal tyrannosauroids tend to have dorsoventrally shallow lower jaws (Currie and Dong, 2001), so that the depth of the dentary increases allometrically through ontogeny (Carr and Williamson, 2004).

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Thus, the deep dentary of the *Zhuchengtyrannus* holotype represents another indication of adult status. Based on the size and structure of the maxilla and dentary, we are confident that the specimen represents an adult, or near-adult, individual.

5. Comparative material

Despite the high variability seen in some tyrannosaurid cranial characters (e.g. see Carr, 1999; Currie, 2003), a large number of characters are more stable and have greater taxonomic value. While caution must be exercised in erecting a new taxon based on fragmentary material, even highly incomplete specimens may nevertheless be diagnostic, and this appears to be the case for the holotype of *Zhuchengtyrannus*. As noted above, there is good reason to consider this an adult specimen and those features that vary within ontogeny are not, therefore, considered further.

Variation in the maxilla and dentary has been documented in *T. rex* (Carpenter, 1990a; Carr and Williamson, 2004; Larson, 2008), which as a tyrannosaurine provides some measure of the likely variation present in other members of the group. Carpenter (1990a: p. 141) recorded variation in "the depth of the maxilla, size and shape of the maxillary and antorbital fenestrae, position of the lacrimal processes, and the position and shape of the jugal process". Larson (2008) documented proportional changes in the gross shape of the maxilla of *Tyrannosaurus*, none of which relate to the features used here to define the new taxon.

Therefore, none of the characters noted by these authors raise any difficulties for the diagnosis of *Zhuchengtyrannus*. We are not aware of any previously described tyrannosaurids that possess either a shelf at the base of ascending process of the maxilla or a notch in the anterior margin of the maxillary fenestra. Both of these features can be readily interpreted as autapomorphies of *Zhuchengtyrannus*. Furthermore, various phylogenetic characters that have been used to analyse tyrannosaurid relationships show that *Zhuchengtyrannus* has a unique combination of character states. A series of maxillary characters defined and scored by Currie et al. (2003) have a unique pattern of expression in *Zhuchengtyrannus* (see Table 1), extending the diagnosis of this genus: the ventral margin of the antorbital fossa near the back of the tooth row is lower than the margin of the antorbital fenestra, and the anterior margin of the maxillary fenestra terminates posterior to the anterior margin of the antorbital fossa. Thus we conclude that the characters used here to diagnose *Zhuchengtyrannus* are likely of genuine phylogenetic significance and not simply products of the variation seen in tyrannosaurids (or indeed ontogenetic variation), reinforcing the conclusion that *Zhuchengtyrannus* is distinct from other tyrannosaurid taxa.

While numerous tyrannosauroids are now known from Asia, most need not be compared to *Zhuchengtyrannus* in detail as all of these taxa, with the possible exception of *Alectrosaurus olseni* (Holtz, 2004) fall outside the clade Tyrannosauridae. *Zhuchengtyrannus* is considerably larger and/or geologically younger than *Guanlong wucaii* (Xu et al., 2006), *Dilong paradoxus* (Xu et al., 2004), *S. kazuoensis* (Ji et al., 2009), *R. kriegsteini* (Sereno et al., 2009), and *A. olseni* (Gilmore, 1933; Mader and Bradley, 1989). Morphologically, *Zhuchengtyrannus* clearly lacks the very low longirostrine snout seen in three Asian tyrannosauroids, *A. altai* (Brusatte et al., 2009), *Alioramus remotus* (Kurzanov, 1976) and *X. baimoensis* (Li et al., 2010), and incidentally in the North American tyrannosauroid *Appalachiosaurus montgomeriensis* (Carr et al., 2005).

However, two comparisons are particularly important. First, the four teeth and one metatarsal that Hu (1973) and Hu et al. (2001) described and ultimately named *T. zhuchengensis* also come from the Zhucheng dinosaur quarries, and the possibility that they might represent the same taxon as the maxilla and dentary described in the present paper should be considered. Second, *Ta. bataar* is a large, Late Cretaceous Asian tyrannosaurine (Hurum and Sabath, 2003), so the possibility of synonymy between this taxon and *Z. magnus* is considered further.

The Geological Museum of China currently houses the teeth (GMC V286, V288, V1174 and V1773) and metatarsal (GMC V1777) assigned by Hu et al. (2001) to *T. zhuchengensis*. The specimens are on display in the galleries, along with a basal fragment of an additional tooth crown (GMC V287), and could not be removed from their case for detailed examination. However, it is evident that GMC V286, V287 and V1773 are all relatively large teeth with robust proportions, although V1773 is smaller than the others. Both V286 and V1773 are relatively intact crowns with minimal recurvature, but carinae are well preserved only on the latter specimen. The mesial carina and its series of denticles may reach the base of the crown, although this cannot be definitively ascertained because of slight damage to the tooth. The mesial carina shifts towards what

Table 1
A series of maxillary characters used by Currie et al. (2003) as part of a phylogenetic analysis of tyrannosaurids. *Zhuchengtyrannus* clearly has a unique combination of character states of the maxilla. *Bistahieversor* is coded from Carr and Williamson (2010), and *Teratophoneus* from (Carr et al., 2011); other codings as per Currie et al. (2003). ? denotes and unknown character state and X are differences attributable to immaturity. Abbreviations: Alb *Albertosaurus*, Alio *Alioramus*, Terat *Teratophoneus*, Dasp *Daspletosaurus*, Gorgo *Gorgosaurus*, Bista *Bistahieversor*, Nano *Nanotyrannus*, Tarbo *Tarbosaurus*, Tyrann *Tyrannosaurus*, Zhu *Zhuchengtyrannus*. All characters refer to the condition in adults.

Character	Alb	Alio	Terat	Dasp	Gorgo	Bista	Nano	Tarbo	Tyrann	Zhu
Antorbital fossa ventral margin near back of tooth row: 0 coincides with lower margin of antorbital fenestra, 1 lower than margin of antobital fenestra.	1	X	–	0	1	0	X	0	0	1
Maxillary fenestra anterior margin in adults: 0 terminates posterior to anterior margin of antorbital fossa, 1 terminates along anterior margin of antorbital fossa.	0	X	0	1	0	0	X	1	1	0
Maxillary fenestra anteroposterior length compared to the distance between anterior margins of antorbital fossa and fenestra: 0 less than half, 1 more than half.	0	X	0	1	0	0/1	X	1	1	1[a]
Palatal shelf suture for palatine: 0 relatively shallow, tooth roots forming bulge on lateral side of dorsal surface, 1 relatively deep, thereby obscuring positions of alveoli.	0	?	–	1	0	?	?	1	1	0
Palatal shelf: 0 contacts vomer for length one half or less of tooth row, 1 contacts vomer for greater than three quarters the length of the tooth row.	0	?	–	0	0	?	1	0	1	0
Maxilla promaxillary fenestra: 0 visible in lateral view, 1 obscured in lateral view by ascending ramus of jugal.	0	X	1	1	0	0	X	1	1	1

[a] The anteriorly positioned notch of the maxillary fenestra of *Zhuchengtyrannus* was not included in this measurement.

is presumably the lingual side of the tooth as it approaches the crown base, and its denticles are approximately equal in mesiodistal length to those of the distal carina. The fact that the mesial denticle series reaches or closely approaches the base of the crown is unusual among tyrannosaurids (Carr and Williamson, 2004; Smith, 2005) and does not occur in the available dentary teeth of *Z. magnus*, but the maxillary teeth known for *Zhuchengtyrannus* are too poorly preserved and/or incompletely erupted for the basal extent of the mesial denticles to be confidently assessed. Otherwise, the character states visible in V286, V287 and V1773 are typical of tyrannosaurid teeth, which are generally not diagnostic at a fine taxonomic level (Carr and Williamson, 2000).

Similarly, the two smallest teeth in the sample (V288 and V1174) are slender, more recurved crowns that could belong to a juvenile tyrannosaurid but lack conspicuous features that would rule out an assignment to *Zhuchengtyrannus* or support any alternative identification. In both cases the mesial carina becomes lingually displaced as it descends from the apex, bears denticles that are close in length to their distal counterparts, and comes relatively close to the base of the crown but may not reach it. The metatarsal is probably a left metatarsal II, and is a robust bone with a large medial facet for articulation with metatarsal III. The proximal surface is damaged on the flexor side, but is mediolaterally broad and forms a thick and prominent extensor lip. The metatarsal clearly belongs to an arctometatarsal pes and is large and very robust, comparable in its proportions to the equivalent element in tyrannosaurines. Again, however, there are no characters that would permit a more detailed referral.

Accordingly, *T. zhuchengensis* should be regarded as a nomen dubium because neither the teeth nor the metatarsal appear to have features that are diagnostic below the level of Tyrannosauridae, or at best Tyrannosaurinae. However, the specimens have historical importance in that they represent the first tyrannosaurid material reported from the Zhucheng quarries. They may represent the same taxon as *Zhuchengtyrannus*, and it is not impossible that a more detailed examination of the material would confirm or refute this possibility by revealing diagnostic features.

Despite the paucity of material for the new taxon, *Zhuchengtyrannus* and *Ta. bataar* can be reliably distinguished based on a suite of characters. *Ta. bataar* is characterised by the presence of a subcutaneous flange (Carr and Williamson, 2010) that rises dorsally from the jugal ramus of the maxilla such that it covers the ventral part of the antorbital fossa (Maleev, 1974; Carr and Williamson, 2010). This is seen in adult and juvenile *Ta. bataar* specimens (e.g. ZPALMgD I4) and is also present, in incipient form, in the sub-adult specimens of *Shanshanosaurus huoyanshanensis* (itself perhaps a juvenile *Ta. bataar* - Currie and Dong, 2001) and *A. altai* (Brusatte et al., 2009). It is not present in any form in *Zhuchengtyrannus*. Further characters separate the two taxa (Table 1), including the shape of the posterior part of the antorbital fossa, the position of the maxillary fenestra, and the shape of the palatal shelf.

6. Discussion

A phylogenetic analysis was not performed here due to the obvious paucity of character data. However, based on the size and age of the material, but more importantly the available characters in the bones and teeth, *Zhuchengtyrannus* can be identified as a tyrannosaurine closely related to *Ta. bataar* and *T. rex*.

As noted above, *Zhuchengtyrannus* appears to be one of at least two tyrannosaurid (and perhaps tyrannosaurine) taxa in the quarry. Counting the second, presently undescribed Zhucheng tyrannosaurid, a total of 13 tyrannosauroid species are now known from Asia, ranging in age from early Late Jurassic to latest Cretaceous (based on Holtz, 2004; Xu et al., 2004, 2006; Brusatte et al., 2009; Ji et al., 2009; Li et al., 2010; Sereno et al., 2009). More narrowly, it is now clear that at least three species of large-bodied predatory theropods (*Tarbosaurus*, *Zhuchengtyrannus* and the unnamed taxon at Zangjiazhuang) existed in eastern Asia during the Campanian (though this is a significant period of time), but this is hardly unique. For example, the Upper Jurassic Morrison Formation of North America has yielded *Ceratosaurus nasicornis*, *Torvosaurus tanneri*, *Allosaurus fragilis*, *Saurophaganax maximus* and others (Weishampel et al., 2004); Campanian deposits in North America contain the tyrannosaurids *Albertosaurus sarcophagus*, *Gorgosaurus libratus* and *Daspletosaurus torosus* and perhaps more (Holtz, 2004); and Upper Cretaceous Moroccan red beds in North Africa have yielded *Sigilmassasaurus brevicollis* and a large abelisaurid together with the tetanurans *Carcharodontosaurus saharicus* and *Spinosaurus aegyptiacus* (Weishampel et al., 2004). Thus, the presence of multiple large tyrannosaurids in the Campanian of eastern Asia should not be considered unusual, particularly given that a similar level of diversity is seen in North America at the same time. This is interesting given the previously documented similarities between the Campanian dinosaur faunas of the two continents (Holtz et al., 2004), and suggests that large numbers of large-bodied carnivores and even large numbers of tyrannosaurids might have

Table 2
Dimensions of the maxilla and dentary of *Zhuchengtyrannus* and other tyrannosaurids, showing that *Zhuchengtyrannus* is comparable in size to both *Tyrannosaurus* and *Tarbosaurus* but smaller than the largest individuals of either taxon. Measurements taken directly from specimens are highlighted in boldface. Sources of data are as follows: AMNH 5027, from a cast at the IVPP; FMNH PR 2081, from Brochu (2003); TMP 81.10.1 from Currie (2003); *Daspletosaurus*, from Carr et al., (2005); *Bistahieversor*, from Carr and Williamson (2010); *Teratophoneus* from Carr et al., 2011; ZPALMgD specimens, from photographs (but dentary of I4 from Hurum and Sabath, 2003); PIN specimens, from Carpenter (1990b); LACM 23844, from Carpenter (1990a).

Taxon	Specimen	Maxilla total length (ventral edge, cm)	Maxilla tooth row length (cm)	Dentary (anterodorsal to posteroventral length, cm)	Dentary tooth row length (cm)
Zhuchengtyrannus	**ZCDM V0031**	64	52	78[a]	61
Tyrannosaurus	**AMNH 5027**	65	55	64	49
	LACM 23844	66	–	89	–
	FMNH PR 2081	79	70	98	74
Tarbosaurus	**IGM 107/2**	62	54	78	50
	ZPALMgD I38	62[a]	–	–	–
	ZPALMgD I4	64	–	81	44
	ZPALMgD I3	49	39	–	–
	ZPALMgD I5	–	–	80	51
	PIN 551	73	–	–	–
Albertosaurus	TMP 81.10.1	51	40	–	–
Daspletosaurus	CMN 8506	61	–	–	–
Bistahieversor	NMMNH P-27469	63	–	77	–
Teratophoneus	BYU 826/9402	40[a]	34[a]	–	–

[a] Indicates the specimen is not entirely complete, though in all cases it is likely that only a small part is missing.

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been normal for Late Cretaceous terrestrial ecosystems. If *T. rex* is the sole large-bodied theropod in the very latest Cretaceous of North America, this would seem to represent the exception, not the rule (see also Carr and Williamson, 2004).

7. Size comparison

Zhuchengtyrannus is comparable in size to *Ta. bataar* and is thus one of the biggest carnivorous theropods known from Asia. *Ta. bataar* is the largest Asian tyrannosaurid, with some specimens reaching 12 m in length. One individual has been quoted as exceeding 15 m, but this has never been confirmed (Currie, 2000). The largest individual of the North American taxon *T. rex* (FMNH PR 2081) is estimated to have been some 13 m in length (Holtz, 2004), and is the largest known tyrannosaurid specimen. Clearly it is difficult to infer the overall size of *Zhuchengtyrannus* based only on a maxilla and dentary; however, the relatively conservative nature of the tyrannosaurine skull means that these bones can be compared to other specimens to determine the approximate size of the new animal.

The maxilla of *Zhuchengtyrannus* measures 64 cm in length. This figure is nearly identical to the length of the maxilla in the *T. rex* specimen AMNH 5027, a cast of which is held at the IVPP. The maxilla of FMNH PR 2081 (the largest *Tyrannosaurus* specimen known) is 79 cm in length and thus considerably larger than the holotype maxilla of *Zhuchengtyrannus*. Indeed, measurements for various individuals of *T. rex* given by Larson (2008) suggest that maxillae of this genus are typically larger than that of *Zhuchengtyrannus*, though the dentaries of the two taxa are closer in size. However, when compared to various specimens of *Ta. bataar*, the maxilla of *Zhuchengtyrannus* falls at the upper end of the size range (Table 2), and exceeds in size the maxillae of other large tyrannosaurines such as *D. torosus*. Similarly, comparisons of the dentary also show that *Zhuchengtyrannus*, while smaller than the larger specimens of *Tyrannosaurus*, was comparable in size to *Ta. bataar* and thus likely had a total length in the region of 10–12 m and may have been even larger.

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