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A new hadrosauroid dinosaur from the Late Cretaceous of Tianzhen, Shanxi Province, China

XU Shi-Chao[1] YOU Hai-Lu[2*] WANG Jia-Wei[3] WANG Suo-Zhu[1] YI Jian[1] JIA Lei[1,2]

(1 *Shanxi Museum of Geology* Taiyuan 030024, China)
(2 *Key Laboratory of Vertebrate Evolution and Human Origins of Chinese Academy of Sciences, Institute of Vertebrate Paleontology and Paleoanthropology, Chinese Academy of Sciences* Beijing 100044, China * Corresponding author: youhailu@ivpp.ac.cn)
(3 *Faculty of Geology, Lomonosov Moscow State University* Moscow 119991, Russian Federation)

Abstract A new non-hadrosaurid hadrosauroid dinosaur (*Datonglong tianzhenensis* gen. et sp. nov.) is reported. The new taxon is recovered from the Upper Cretaceous Huiquanpu Formation of Tianzhen County, Shanxi Province in northern China, and represented by an almost complete right dentary with dentition. Different from all other hadrosauroids, *Datonglong* possesses two functional teeth in each alveolus, and the pattern of ridge development on the lingual surface of its dentary crown shows a unique combination of character states (for example: distally offset primary ridge; well-developed secondary ridge; no additional ridge(s); slightly distally curved apical half of primary ridge). Comparative studies indicate advanced non-hadrosaurid hadrosauroids experienced a complex pattern in the evolution of their dentary, especially dentary dentition. Derived hadrosaurid features occurred frequently in these taxa, such as high height/width ratio of tooth crown in *Bactrosaurus*, one primary and one faint ridges in *Gilmoreosaurus*, median placed primary ridge in *Zhanghenglong*, rostrally inclined coronoid process in *Nanningosaurus*, and two functional teeth in each alveolus in *Datonglong*. This implies incredible diversities and attempts close to the origin of Hadrosauridae and difficulties to elucidate their phylogenetic relationships.

Key words Tianzhen, Shanxi; Late Cretaceous; dinosaur, hadrosauroid

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1 Introduction

The Huiquanpu Formation was established by the Regional Geological Survey Team of

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Hebei Province in 1959. It refers to the over 200 meter thick terrestrial deposits bounded by the pre-Cambrian rocks and the Miocene basalts, and is distributed in an area of about 150 km^2 around the boundary of Tianzhen County of Shanxi Province and Yangyuan County of Hebei Province in northern China, with an age assignment of Eocene. Liu (1983) and Chen et al. (1983) reassigned its age to Late Cretaceous based on discoveries of dinosaurs, especially Hadrosauridae dinosaurs. In 1989 and 1991–1994, Shijiazhuang Economic University of Hebei Province excavated over 2300 dinosaur specimens mainly in the Kangdailiang Quarry of Tianzhen County, Shanxi Province (Pang et al., 1996), and two new dinosaurs have been established, namely an ankylosaur *Tianzhenosaurus* youngi Pang & Cheng, 1998, and a sauropod *Huabeisaurus allocotus* Pang & Cheng, 2000. In 1998, another ankylosaur *Shanxia tianzhenensis* Barrett et al., 1998 was also reported from the Wujiashan Quarry of Tianzhen County, about 7 km northeast of the previous Kangdailiang Quarry. These two ankylosaurs may be distinct from each other (Upchurch and Barrett, 2000; Thompson et al., 2012), or represent the same taxon (Sullivan, 2000); while *Tianzhenosaurus* may be synonymous with *Saichania* (Sullivan, 1999). Recent restudy of *Huabeisaurus allocotus* shows this taxon is probably a member of the Cretaceous East Asian endemic clade of Euhelopodidae (D'Emic et al., 2013).

Pang et al. (1996) and Pang and Chen (2000, 2001) also mentioned the existence of theropod cf. *Szechuanosaurus campi* Young, 1942 and hadrosaurid cf. *Shantungosaurus* sp. in the Huiquanpu Formation. The former has been regarded as a nomen dubium (Carrano et al., 2012); while the assignment of fragmentary material to cf. *Shantungosaurus* sp. is based on observation of their tibia similarity (Pang and Cheng, 2000, 2001).

Here we report a new hadrosauroid specimen recovered from the Kangdailiang Quarry by the Shanxi Museum of Geological and Mineral Science and Technology (now Shanxi Museum of Geology, SXMG) in 2008 (Fig. 1). Although the specimen is represented only by

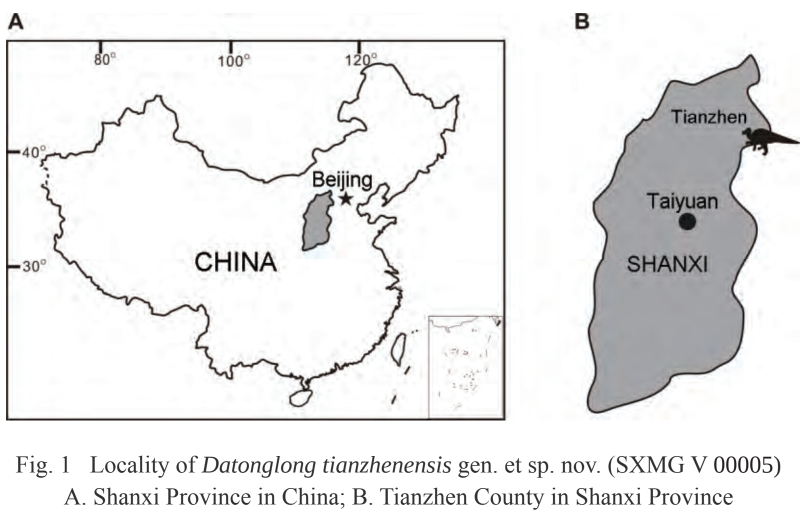

Fig. 1 Locality of *Datonglong tianzhenensis* gen. et sp. nov. (SXMG V 00005)
A. Shanxi Province in China; B. Tianzhen County in Shanxi Province

a right dentary with dentition, it provides numerous important anatomical features to depict its taxonomic status and systematic relationship. Based on our anatomical observation and taxonomic comparison, the new specimen is distinct from all previous known hadrosauroid dinosaurs, represents a new taxon (*Datonglong tianzhenensis* gen. et sp. nov.), and belongs to an advanced non-hadrosaurid hadrosauroid.

Institutional abbreviations AMNH, American Museum of Natural History (New York City, New York); LPM, Liaoning Paleontological Museum (Beipiao, Liaoning); NHMG, Natural History Museum of Guangxi Zhuang Autonomous Region (Nanning, Guangxi); SBDE, Sino-Belgium Dinosaur Expedition, Inner Mongolia Museum (Hohhot, Nei Mongol Autonomous Region); SXMG, Shanxi Museum of Geology (Taiyuan, Shanxi); XMDFEC, Xixia Museum of Dinosaur Fossil Eggs of China (Xixia, Henan).

2 Systematic paleontology

Dinosauria Owen, 1842

Ornithischia Seeley, 1887

Ornithopoda Marsh, 1881

Iguanodontia Dollo, 1888 sensu Sereno, 2005

Ankylopollexia Sereno, 1986 sensu Sereno, 2005

Styracosterna Sereno, 1986 sensu Sereno, 2005

Hadrosauriformes Sereno, 1997 sensu Sereno, 1998

Hadrosauroidea Sereno, 1986 sensu Sereno, 2005

***Datonglong* gen. nov.**

***Datonglong tianzhenensis* sp. nov.**

Holotype SXMG V 00005, almost complete right dentary with dentition.

Etymology The generic name “Datong” is after “Datong City”, and Tianzhen is a county belonging to it; “long” means “dragon” in Chinese. The specific name “Tianzhen” is after “Tianzhen County”, where the current material is discovered.

Locality and horizon Kangdailiang Quarry, Tianzhen County, Datong City, Shanxi Province, China. Huiquanpu Formation, Upper Cretaceous.

Differential diagnosis (for genus and species by monotypy) Advanced non-hadrosaurid hadrosauroid with one autapomorphy (two functional teeth in each alveolus along at least the mid- and caudal dentary occlusal plane) and the following unique combination of character states in the pattern of ridge development on the enameled lingual surface of dentary tooth crown: 1) distally offset primary ridge, 2) well-developed secondary ridge, 3) no additional ridge(s), 4) slightly distally curved apical half of primary ridge.

Description An almost complete 34 cm long right dentary is preserved, missing its rostral end including the rostral end of the tooth row (Fig. 2). The preserved ramus of the dentary is rectangular in lateral view, with roughly parallel dorsal and ventral margins, 14 cm high at the mid portion with the occlusal plane or 10.5 cm high without it (Fig. 2A). The tooth row (28 cm long) ends caudally right medial to the caudal margin of the coronoid process (Fig. 2B). The 8 cm high coronoid process is almost perpendicular and slightly caudodorsally-directed to the ramus, and the dentary height along it is 17 cm. Although the tip of the coronoid process is not preserved, its dorsal portion is expanded at least rostrally as evidenced by its broken contour, and its craniocaudal width at base is 4.8 cm. Its lateral surface bulges slightly, while the medial one is flat, bearing a faint vertical ridge limiting its caudal two fifths with further ridges on it. In dorsal view, the caudal half of the ramus curves laterally, with caudally increasing distance between the tooth row and the lateral surface of the ramus, ending in an about 3 cm wide horizontal shelf separating the coronoid process and the caudal end of the tooth row (Fig. 2C). In caudal view, a triangular fossa is bounded by the coronoid process (Fig. 2D). The fossa extends ventrally to the mandibular adductor fossa. Rostral to the adductor fossa, the Meckelian groove is deep and long, and progressively decreases its dimensions toward the preserved rostral end.

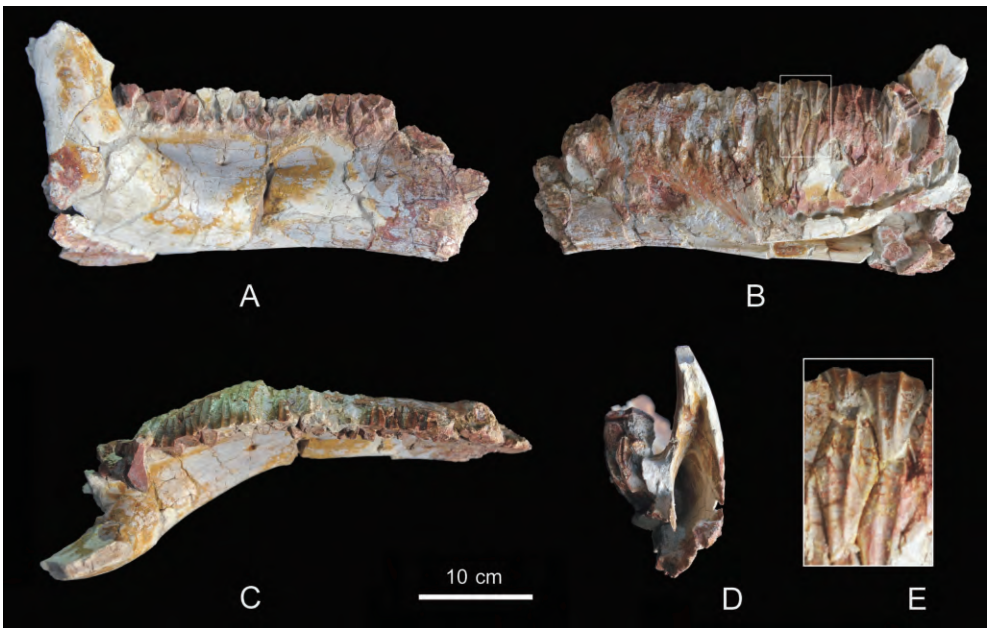

Fig. 2 Photos of right dentary of *Datonglong tianzhenensis* gen. et sp. nov. (SXMG V 00005)
A. lateral view; B: medial view. C: dorsal view; D. caudal view;
E. close-up of partial dentition in B; E is not in scale

The tooth row is largely preserved, with 17 alveoli full of teeth plus five successive most caudal alveoli bearing several scattered teeth. At least another five alveoli exist rostral to the above 22 alveoli judging by the preserved length and the existence of two broken teeth in this portion. Therefore, a total of at least 27 alveoli are expected for this animal; and the actual number is probably less than 30 based on the general alveolar contour, which reduces its depth rapidly rostrodorsally. In medial view, a row of neurovascular foramina slightly extends caudodorsally along the mid-caudal portion of the ramus, and in this portion about three quarters of the dorsoventral depth of the dentary ramus is occupied by the alveoli. The partial septum dividing the fourth and fifth most caudal alveoli is exposed, and it is straight and relatively thick (2 mm).

The teeth are best exposed in the mid-caudal portion of the tooth row. In medial view, two or three teeth are vertically aligned in each alveolus (Fig. 2B). In lateral view, each alveolus bears two functional teeth, of which the upper one is large and obviously the same as the uppermost one seen medially, while the lower one should be the remaining worn facet of the earlier functional tooth (Fig. 2A). Therefore, three or four teeth are held in each alveolus. Both worn surfaces in each alveolus are slightly concave, and in some alveoli the upper one is not continuous with the lower one, with the latter placed more medially.

The teeth are large, and their morphology can be best shown in the tenth functional and eleventh replacement positions counting from the caudal (Fig. 2E). A distally offset primary ridge exists on the enameled lingual side in teeth, and is accompanied by a well-developed secondary ridge in the mesial half of the crown. These two roughly parallel ridges divide the lingual crown surface into three zones, without evidence of any subsidiary ridges on it. The ventral halves of these two ridges are vertical, while the dorsal halves curve slightly caudodorsally. The unerupted tooth is diamond-shaped, with the height of 5.5 cm and maximum width of 2.0 cm, a ratio of 2.75. One scattered tooth attached to the third last alveolus exposes its mesial margin, where small mammillated papillae occur apically.

Comparison In the evolution from non-hadrosaurid hadrosauroids to hadrosaurids, their dentaries acquired several key innovations. In all hadrosaurids, the tooth row ends caudally to the caudal margin of the coronoid process (Xing et al., 2014: character 56) and the coronoid process inclines rostrally (Xing et al., 2014: character 48). In addition, the dentary dental battery bears more than 30 alveoli (Xing et al., 2014: character 1), and the unworn crown in the mid-tooth row is elongate lanceolate with a height/width ratio greater than 3.1 (Sues and Averianov, 2009). All these features are not present in *Datonglong*. Therefore, *Datonglong* does not belong to Hadrosauridae, and our comparison will focus on non-hadrosaurid hadrosauroids, especially those from the Late Cretaceous of China. Based on Wang et al. (2013), Xing et al. (2014), and Tsogtbaatar et al. (2014), 15 Late Cretaceous non-hadrosaurid hadrosauroid genera have been reported, with eight from China (*Tanius* Wiman, 1929; *Bactrosaurus* Gilmore, 1933; *Gilmoreosaurus* Brett-Surman, 1979; *Nanyangosaurus* Xu et al., 2000; *Shuangmiaosaurus* You et al., 2003; *Nanningosaurus* Mo et al., 2007; *Yunganglong* Wang et al., 2013; *Zhanghenglong* Xing et al., 2014), three from North America (*Claosaurus* Marsh, 1890 ; *Eolambia* Kirkland, 1998; *Protohadros* Head, 1998), two from Europe (*Telmatosaurus* Nopcsa, 1903; *Tethyshadros* Dalla Vecchia, 2009), one from Central Asia (*Levnesovia* Sues & Averianov, 2009), and one from Mongolia (*Plesiohadros*

Tsogtbaatar et al., 2014). Among these eight Chinese taxa, three (*Tanius, Nanyangosaurus,* and *Yunganglong*) do not preserve comparable parts with *Datonglong*.

Nanningosaurus, recovered from the Upper Cretaceous red beds of Guangxi in southern China, was originally reported as a lambeosaurine hadrosaurid (Mo et al., 2007). Recently, it was recovered as a non-hadrosaurid hadrosauroid (Xing et al., 2014). A left dentary and an isolated dentary tooth are included in the holotype (NHMG 8142). It has a high coronoid process that inclines slightly rostrally and ends slightly caudal to the coronoid process, definitely derived features typical for hadrosaurids and different from the conditions in *Datonglong*. However, two ridges are present on the lingual crown of dentary tooth as in *Datonglong*. The primary ridge is sinuous as seen in *Tsintaosaurus*.

An isolated left dentary (LPM 0166) is referred to *Shuangmiaosaurus gilmorei* (You et al., 2003a). In *Shuangmiaosaurus*, the coronoid process inclines caudodorsally and the tooth row ends in a position medial to the middle of the coronoid process. Moreover, the dorsal edge of the dentary ramus slightly bows dorsally and the 27 alveoli clearly incline caudodorsally. All these features are not present in similar-sized *Datonglong*.

Bactrosaurus was originally studied by Gilmore (1933) based on material from a bonebed in Quarry 141 (Johnson's Quarry) collected by Central Asiatic Expeditions of the American Museum of Natural History. AMNH 6553 is designated as the holotype, and it contains more than one individual including left and right dentaries. Based on Gilmore (1933), 12 dentaries have been collected in this bonebed, and more than half of them pertain to juveniles. However, Gilmore's description of dentary seems to be based on AMNH 6353 (a right dentary), with a drawing of its medial and dorsal views. The length of adult dentary is 222 mm, and the length of the longest tooth row is 152 mm with 23 alveoli. Each alveolus holds one replacement tooth, and at most two functional teeth. A large unworn tooth crown has a ratio of 3.3 (33/10 mm).

Prieto-Marquez (2011) studied the ontogeny of *Bactrosaurus*. He notices that in the adult dentary (AMNH 6553: 23 cm long) there are as many as three teeth per alveolus arranged dorsoventrally at mid-length of the dental battery with two functional teeth. The tooth crowns have a height/width ratio of 3.1–3.2 as in juvenile specimens; in contrast to 2.75 in *Datonglong* (55/20 mm). The position of the primary ridge is slightly or modestly offset from the midline.

Godefroit et al. (1998) studied *Bactrosaurus* from another bonebed excavated by SBDE in 1995, within 1 km to AMNH Quarry 141. It contains several hundred bones of at least four hadrosaur individuals, including a left dentary (SBDE 95E5/12). Godefroit also demonstrated that all hadrosauroids in Quarry 141 belong to *Bactrosaurus* as Gilmore originally suggested. SBDE 95E5/12 is about the same size as the holotype dentary (AMNH 6553), and bears 20 alveoli. In contrast, around 30 alveoli have been estimated for *Datonglong*; however, the length of dentary in *Datonglong* is about 1.5 times as that in adult *Bactrosaurus*. Godefroit et al. (1998) described that each alveolus is composed of one functional tooth and at least two replacement teeth. However, based on the illustration, two or three teeth can be seen medially, and two functional teeth are visible laterally in the preserved mid- and caudal portion of the tooth row. Here, based on our observation in *Datonglong*, the lower functional tooth should be from the earlier worn facet, but not from any tooth can be seen medially. Therefore, in both *Bactrosaurus* and *Datonglong*, at most two replacement and two functional teeth are present in one alveolus. However, two functional teeth seem to persist along the entire tooth tow in *Datonglong*, but not in the rostral portion of the tooth row in *Bactrosaurus* as shown in AMNH 6553. As in *Datonglong, Bactrosaurus* also has two ridges, one primary and one relatively well developed secondary ridge on the lingual tooth crown; however in *Bactrosaurus* there are evidence of other faint ridges in the adults, and a third caudal ridge appears in caudal most teeth. The primary ridges may curve slightly caudally in *Bactrosaurus* as in *Datonglong*.

Therefore, the crown ratio, the number of alveoli, and the condition of functional teeth in rostral portion of tooth row are different between *Bactrosaurus* and *Datonglong*. The details of ridge development pattern in the dentary tooth crown are also different.

Prieto-Marquez and Norell (2010) redescribed the second hadrosauroid *Gilmoreosaurus mongoliensis* from the Iren Dabasu Formation in Irenhot. This species is represented by at least four individuals from quarries 145 and 149. Among the material, only a partial right dentary (AMNH FARB 30654) and an isolated dentary tooth (AMNH FARB 30661) are preserved. The dentary mainly consists of the rostral and middle portion without the coronoid process and dentition (295 mm long and 71 mm high), and it is hard to tell definite diagnostic differences between it and *Datonglong*, although the latter seems to be more robust. In contrast, the worn half crown of an isolated dentary tooth possesses only one ridge that lies off center, different from the condition in *Datonglong*, which has two ridges. *Gilmoreosaurus* probably possesses one primary and one faint ridges on its dentary tooth crown (personal communication with Xing Hai).

Zhanghenglong is a recently described hadrosauroid from the Santonian Majiacun Formation of Xixia Basin, Henan Province in central China (Xing et al., 2014). Its holotype (XMDFEC V0013) preserves an incomplete, disarticulated cranium, including a right dentary with dentition. In *Zhanghenglong*, the tooth row bows dorsally and its long axis is nearly parallel to the lateral side of the dentary ramus, unlike the horizontal and diverged condition in *Datonglong*. The 26 alveoli bear one functional tooth at the rostral and caudal portions, two in the midsection, and even three in the 17^{th} tooth alveolus; while in *Datonglong*, two functional teeth seem to persist along the entire tooth row. In *Zhanghenglong*, the primary ridge is situated median (about 40%) or distally offset on the lingual crown of the dentary, a clear secondary ridge is on the mesial half, and additional faint ridge(s) may appear close to the mesial edge; in contrast in *Datonglong*, all primary ridges are placed in the distal halves, and no additional ridge(s) are evident besides the secondary one. The dentary tooth crown has an approximate height/width ratio of 2.36 in *Zhanghenglong*, and less than 2.75 as in

Datonglong.

The latest reported non-hadrosaurid hadrosauroid is *Plesiohadros djadokhtaensis* from the Campanian of Mongolia (Tsogtbaatar et al., 2014). *Plesiohadros* preserves a left dentary with dentition. The dentary is relatively slender with a straight ramus in occlusal view, while that of *Datonglong* is relatively robust with a laterally curved ramus. Besides the primary and mesial secondary ridges, a distal secondary ridge occurs in some teeth in *Plesiohadros*, while only two ridges exist in *Datonglong*.

3 Discussion

Several dentition features show that *Datonglong* is an advanced taxon among non-hadrosaurid hadrosauroids. The dentary teeth became miniaturized in the evolution of hadrosauroids. In relatively primitive ones, such as *Jinzhousaurus* Wang & Xu, 2001, *Equijubus* You et al., 2003, *Xuwulong* You et al., 2011, *Probactrosaurus* Rozhdestvensky, 1966, *Eolambia* Kirkland, 1998, *Protohadros* Head, 1998, and *Levnesovia* Sues & Averianov, 2009, the dentary teeth are large and shield-shaped relative to the alveolar trough (Norman, 2015: character 65). In contrary, in *Datonglong*, as well as in *Bactrosaurus, Gilmoreosaurus, Nanningosaurus, Zhanghenglong, Tethyshadros, Telmatosaurus*, and hadrosaurids, the dentary teeth are miniaturized, and the lateral alveolar walls of tooth grooves became narrow and parallel-sided, rather than shaped by successional dentary crowns (Norman, 2015: character 66). *Probactrosaurus* and *Levnesovia* possess both large and shield-shaped teeth and narrow and parallel-sided lateral alveolar walls. *Bactrosaurus* is unique in having a height/width ratio greater than 3.1 as in hadrosaurids, defining the dentary tooth crown in the mid-tooth row as an elongate lanceolate rather than diamond-shaped contour (Gilmore, 1933; Sues and Averianov, 2009; Prieto-Marquez, 2011).

The developments of ridges on the enameled lingual surface of the dentary tooth crown show various complex patterns and are characteristic for different taxa among hadrosauroids. The pattern in *Datonglong* shows a unique combination of character states. Generally, the positon of the primary ridge shifted from distal to median on the crown, and the number of ridges reduced from five or more to only one primary ridge. In all hadrosaurids, the primary ridge is median placed; in *Zhanghenglong*, the primary ridge is either median or slightly distally offset; while in *Datonglong* and all other known hadrosauroids, the primary ridge is distally offset (Xing et al., 2014: character 7). Therefore, *Datonglong* is probably more basal than *Zhanghenglong* based on the placement of the primary ridge.

One the other hand, *Datonglong* possesses two ridges as in *Telmatosaurus*, while many others including *Protohadros, Levnesovia, Bactrosaurus*, and *Tethyshadros* have three or more (Xing et al., 2014: character 6), and *Gilmoreosaurus, Eolambia* and *Claosaurus* have only one ridge (the primary ridge). Although both possess secondary ridge, it is strongly developed in *Datonglong*, in contrary to the faint one in *Telmatosaurus*. Therefore, *Datonglong* is probably more basal than *Gilmoreosaurus* but more advanced than *Bactrosaurus* based on the number of ridges on the dentary tooth crown.

The inclination of the coronoid process shifted from caudally-, vertically-, to rostrally inclined along the course of hadrosauroid evolution. In *Shuangmiaosaurus* it is caudally inclined, in *Datonglong* it is basically vertical, while in *Nanningosaurus* it is rostrally inclined. Therefore, *Datonglong* is probably more advanced than *Shuangmiaosaurus*, but less so than *Nanningosaurus* based on the nature of the coronoid process. It is possible that as a non-hadrosaurid hadrosauroid, *Nanningosaurus* convergently achieved a rostrally inclined coronoid process as in hadrosaurids.

Datonglong is unique in possessing two functional teeth in each alveolus at least along the mid- and caudal portion and probably along the entire occlusal plane. In primitive hadrosauroids, such as *Jinzhousaurus*, only one functional tooth exists in each alveolus. In more advanced non-hadrosaurid hadrosauroids, such as *Equijubus, Xuwulong, Probactrosaurus, Eolambia, Bactrosaurus, Gilmoreosaurus*, and *Tethyshadros*, a second functional tooth may occur in some alveoli in the middle portion of the dentary tooth row, in *Zhanghenglong* one mid-alveolus possesses a third functional tooth although its rostral and caudal portions still having one, while in *Telmatosaurus* (Norman, 2015: character 54) and hadrosaurids, a third functional tooth adds on at least in some alveoli (Xing et al., 2014: character 4). Therefore, *Datonglong* seems to represent an advanced non-hadrosaurid hadrosauroid based on the development and pattern of functional teeth.

The above discussion shows a complex pattern in the evolution of dentary, especially dentary dentition among advanced non-hadrosaurid hadrosauroids. Derived hadrosaurid features occurred earlier frequently in non-hadrosaurids, such as high height/width ratio of tooth crown in *Bactrosaurus*, one primary and one faint ridges in *Gilmoreosaurus*, median placed primary ridge in *Zhanghenglong*, rostrally inclined coronoid process in *Nanningosaurus*, and two functional teeth per alveolus along at least mid- and caudal portion of the tooth row in *Datonglong*. This implies incredible diversities and attempts close to the origin of Hadrosauridae and how difficult to elucidate their phylogenetic relationships.

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山西天镇晚白垩世一新鸭嘴龙超科恐龙

续世朝[1] 尤海鲁[2*] 王嘉玮[3] 王锁柱[1] 伊 剑[1] 贾 磊[1, 2]

(1 山西地质博物馆 太原 030024)

(2 中国科学院脊椎动物演化与人类起源重点实验室，中国科学院古脊椎动物与古人类研究所 北京 100044
＊通讯作者)

(3 俄罗斯罗蒙诺索夫莫斯科国立大学地质系 莫斯科 119991)

摘要：记述了山西天镇晚白垩世灰泉堡组发现的一鸭嘴龙超科恐龙新属种：天镇大同龙*Datonglong tianzhenensis* gen. et sp. nov.。标本为一保存较完好的右侧齿骨并带牙齿。与其他鸭嘴龙超科恐龙不同，大同龙每个齿槽有两个功能齿，而且舌面齿冠上嵴的发育也具有独特的特征组合(主嵴向远中方向偏移；次嵴发育；无其他附嵴；主嵴上半段略后弯)。对比研究发现，在较进步的非鸭嘴龙科鸭嘴龙超科类群中齿骨和牙齿的演化过程复杂，许多鸭嘴龙科的特征在这些类群中时而出现，如：巴克龙*Bactrosaurus*齿冠具有较大的高/宽比；吉尔摩龙*Gilmoreosaurus*齿冠上只有一个主嵴和纤弱的附嵴；张衡龙*Zhanghenglong*齿冠上主嵴中置；南宁龙*Nanningosaurus*下颌冠状突前倾；大同龙*Datonglong*每个齿槽有两个功能齿。这表明为了获得更有效的牙齿咀嚼方式，在鸭嘴龙科起源前它的姐妹群们曾进行过多种尝试；这也告诫我们，受大量趋同演化的影响，要厘清这些类群间的关系并非易事。

关键词：山西天镇，晚白垩世，恐龙，鸭嘴龙超科

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