Sauropod Teeth from the Lower Cretaceous Luohandong Formation of Ordos Basin, Inner Mongolia

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Abstract: The Early Cretaceous Zhidan Group in the northern Ordos Basin, Inner Mongolia, yielded a large number of tetrapods, including turtles, choristoderes, crocodyliforms, psittacosaurs, stegosaurs, theropods and birds. Well-preserved sauropod teeth have been found in the Luohandong Formation, a middle-upper unit of the Zhidan Group. The large V-shaped wear facet, low slenderness index value, labial grooves, lingual ridge and concavity on the tooth crown suggest that these teeth are from titanosauriforms. Moreover, the presence of the prominent bosses on the lingual side of the tooth crown indicates these teeth should be identified as *Euhelopus* teeth further. The existence of *Euhelopus* in Ordos Basin (Inner Mongolia), Shandong Province and western Liaoning Province shows some connections about vertebrate faunas during Early Cretaceous in these areas. Other tetrapod groups such as turtles (*Sinemys*, *Ordosemys*), choristoderes (*Ikechosaurus*), psittacosaurs (*Psittacosaurus*) and birds (*Cathayornis*) provide more evidences for this viewpoint.

Key words: Lower Cretaceous, Luohandong Formation, Ordos Basin, Sauropoda, *Euhelopus*

1 Introduction

The Early Cretaceous terrestrial deposits are widely exposed in North China where several dinosaur faunas have been known. One of the important sedimentary strata is the Zhidan Group which has yielded a rich and diverse assemblage of the invertebrates, vertebrates and plants. The Zhidan Group can be divided into six formations from the top to bottom: Dongsheng Formation, Jingchuan Formation, Luohandong Formation, Huanhe Formation, Luohe Formation, and Yijun Formation (Inner Mongolia Bureau of Geology and Minerals, 1996). Various terrestrial tetrapods were found by the Sino-Canadian Dinosaur Project from the Lower Cretaceous Luohandong and Jingchuan Formations in the northern Ordos Basin, Inner Mongolia, China, in the late 1980s during the Sino-Canadian Dinosaur Project. Subsequent studies supplemented new genera and species. These findings demonstrated turtles, choristoderes, crocodyliforms, psittacosaurs, stegosaurs, theropods and birds were important components of the ecosystem in Early Cretaceous (Dong, 1993a). These specimens include turtles, i.e, *Ordosemys leios* (Brinkman and Peng, 1993a), *Sinemys gamera* (Brinkman and Peng, 1993b) and *Sinemys brevispinus* (Tong and Brinkman, 2013), choristoderes, i.e, *Ikechosaurus sunailinae* (Sigogneau-Russell, 1981; Brinkman and Dong, 1993), crocodyliforms, i.e, *Shantungosuchus hangjinensis* (Wu et al., 1994), cf. *Theriosuchus* sp. (Wu et al., 1996), psittacosaurs, i.e, *Psittacosaurus neimongoliensis*, and *Psittacosaurus ordosensis* (Russell and Zhao, 1996), stegosaurs, i.e, *Wuerhosaurus ordosensis* (Dong, 1993b), theropods, i.e, *Sinornithoides youngi* (Russell and Dong, 1993; Currie and Dong, 2001), enantiornithines, i.e, *Otogornis genhisi* (Dong, 1993c; Hou Lianhai, 1994), and *Cathayornis chabuensis* (Li Jianjun et al., 2008).

Sauropod materials in this region was only mentioned by the Sino-Canadian Dinosaur Project (e.g., Dong, 1993a), and at least two groups, Diplodocidae indet. and Brachiosauridae indet., were identified. But no description and figures have been published until now. Recently, we collected some sauropod teeth from the Early Cretaceous Luohandong Formation at Laolonghuozi site and adjacent regions in Hanggin Qi, Ordos Basin, Inner Mongolia (Fig.

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1). Luohandong Formation, a middle–upper unit of the Zhidan Group, reaches a thickness of up to 107–218 m. This formation comprises a lower part of red, purplish to bluish mudstones and sandstones, an upper part of grayish-green to reddish-orange cross-bedded sandstones and siltstones. In this paper, we describe a few sauropod teeth from the Ordos Basin, which represents the first convincing finding of sauropod dinosaurs in this region.

2 Terminology

The important terms to describe the sauropod teeth are after Barrett and Wang (2007). Several features are used for the morphology of sauropod teeth: (1) b-buttress on the lingual surface; (2) d-denticles developed along distal and mesial margins of the crown; (3) h-height of the tooth crown; (4) l.c.-lingual concavity; (5) l.g.-labial groove; (6) l.r.-lingual ridge; (7)s.cs.-shape of cross section at mid-crown; (8) SI-slenderness index, the ratio of height of the tooth crown to its maximum width (Upchurch, 1998); (9) w-maximum mesiodistal width of crown; (10) w.f.-wear facet (Fig. 2).

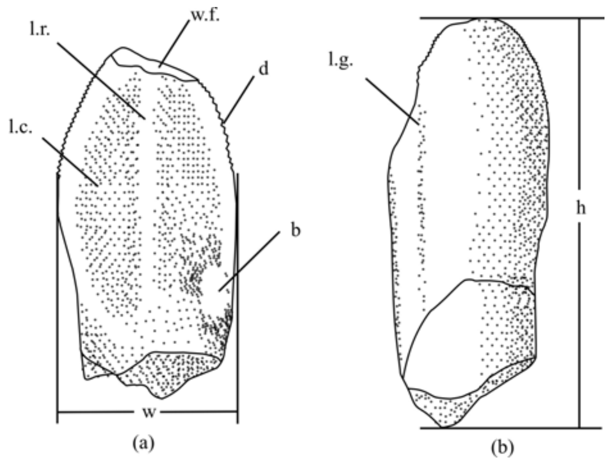

Fig. 2. Terminology used to describe morphology of the sauropod teeth. (a), lingual view; (b), labial view.
Abbreviations: b, buttress; d, denticles; h, height of the tooth crown; l.c., lingual concavity; l.g., labial groove; l.r., lingual ridge; w, maximum mesiodistal width of the tooth crown; w.f., wear facet.

3 Description

Sauropoda Marsh, 1878
Eusauropoda Upchurch, 1995
Neosauropoda Bonaparte, 1986
Titanosauriformes Salgado et al., 1997
Euhelopus Romer, 1956
Euhelopus sp.

The remains of a large number of sauropod teeth have been recovered from Luohandong Formation. These teeth were isolated and were not discovered in associated with relevant bones. However, some of them were broken; thus, we chose to describe four tooth specimens, i.e., NMG001, NMG002, NMG003, and NMG004 (Fig. 3). There is no reasonable to confirm these sauropod teeth are from either maxilla or dentary.

Specimen NMG001 (Fig. 3a–b) just has a little damage in the labial view. The crown is clearly demonstrated surface details. The tooth possesses an extensive basal portion but tapers toward narrower apices, the mesial and distal margins of the tooth are almost parallel to each other before converging apically. The lingual concavity is distinct. Moreover, the mesial and distal labial grooves are ambiguously developed. The crown shows a D-shaped transverse cross-section near apex owing to the presence

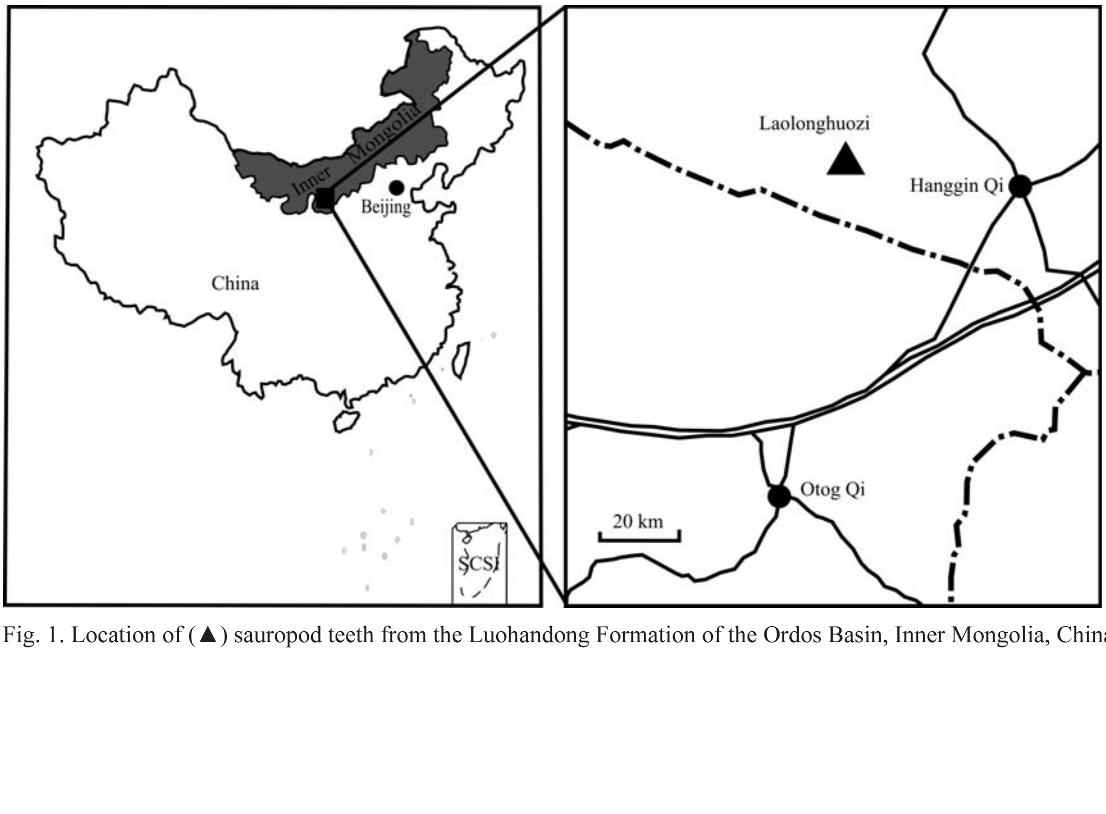

Fig. 1. Location of (▲) sauropod teeth from the Luohandong Formation of the Ordos Basin, Inner Mongolia, China.

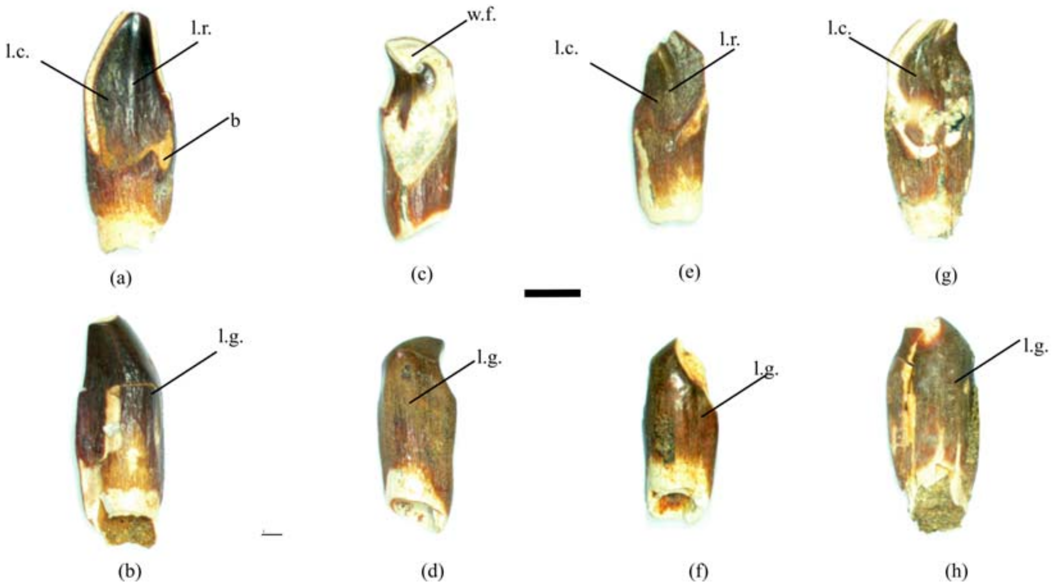

Fig. 3. Isolated sauropod teeth from the Luohandong Formation of the Ordos Basin in lingual views (a, c, e, g) and labial views (b, d, f, h).
(a), (b), NMG001; (c), (d), NMG002; (e), (f), NMG003; (g), (h), NMG004. Scale bar=10 mm. b, buttress; l.c., lingual concavity; l.g., labial groove; l.r., lingual ridge; w.f., wear facet.

of the mesiodistal concavity on the lingual surface of the crown. In addition, the cross-section is asymmetrical outline in apical view. As a result, the mesial part of the labial surface is angled away more steeply from the mesiodistally than the distal part from the mesiodistal axis of the tooth crown. The base of crown has an elliptical cross-section. The slenderness index value (SI: Upchurch, 1998) is at least 2.0 (Table 1). Wrinkled enamel covers most of labial and lingual surfaces of the tooth, resulting in a rugose crown but the enamel near the apex of tooth is smooth. High-angled mesial and distal wear facets are present on the lingual surface of the crown, converge apically, and are continuous around the tip of the tooth. However, this tooth lacks denticles, and the prominent lingual buttress is distinct on the distal margin near the base of the lingual concavity.

NMG002 (Fig. 3c–d) bears a strongly superficial resemblance to NMG001, but the crown apex is slightly curved toward the distal side; therefore, it has no flat, apical wear facet of the crown, producing an asymmetrical outline in labial view. The most extensive wear tends to be situated on the distal margin of the crown, widely expanded in lingual concavity. NMG003 (Fig. 3e–f) is congruent with NMG002 however, its wear facet merely develops in distal margin of the crown and has a broad wear surface. NMG004 (Fig. 3g–h) differs from the previous three specimens. The mesial and distal margins of the tooth don't extend parallel to each other before converging apically, and it seems that the apical part of the crown is mesiodistally expanded relative to the more basal section.

Table 1 The slenderness index (SI) of sauropod teeth from the Early Cretaceous Luohandong Formation of Ordos Basin, Inner Mongolia

Specimens	h (mm)	w (mm)	SI
NMG001	34	16	2.1
NMG002	32	14	2.3
NMG003	29	12	2.4
NMG004	32	16	2.0

Abbreviations: h-height of the tooth crown; w-maximum mesiodistal width of crown; SI-slenderness index (the ratio of tooth crown height to its maximum width).

4 Comparison and Disscusion

Sauropod teeth have several characteristic features: wrinkled tooth enamel, the presence of lingual concavity, D-shaped cross-section of mid-crown, possession of mesial and distal grooves on the labial crown surface (Upchurch, 1998; Wilson and Sereno, 1998; Barrett et al., 2002; Wilson, 2002; Upchurch et al., 2004; Barrett and Wang, 2007). Likewise, the teeth described here from Luohandong Formation show these remarkable characters. The lack of mesiodistally expansive crowns relative to the roots and from Early Cretaceous sedimentary unit indicates these teeth appeared in both eusauropod lineages: Titanosauriformes and Diplodocoidea. Diplodocoidea is basal Neosauropoda while Titanosauriformes is developed Neosauropoda, Titanosauria is placed within Titanosauriformes (Upchurch, 1998; Wilson and Sereno, 1998; Wilson, 2002; Upchurch et al., 2004; Barrett and Wang, 2007). Diplodocoids and derived titanosauriforms (titanosaurians) have very slender, parallel-sided teeth with SI values over 4.0 and reduced lingual concavities (Upchurch, 1998).

However, the SI values of those teeth from Luohandong Formations range from 2.0–2.4 (Table 1) and clearly exhibit lingual concavities. Similarly, the SI values of some basal titanosauriform teeth range from 2.0–4.0 (Barrett et al., 2002) (also see Table 2); thus, we infer that these teeth belong to basal titanosauriform rather than diplodocoid or titanosaurian.

The basal titanosauriforms have teeth in some respects intermediate between the broad spatulate (*Camarasaurus*) condition and that seen in peg-like (titanosaurians and diplodocoids) (Calvo, 1994; Upchurch et al., 2004). The teeth morphologies in *Camarasaurus*, *Euhelopus*, and *Brachiosaurus* are quite similar. The tooth crowns of *Euhelopus* expand slightly mesiodistally adjacent to the root, but not prominently to form the broad spatulate crowns found in *Camarasaurus* and several basal eusauropods, such as *Omeisaurus*. As a result, the tooth crowns in *Euhelopus* are more parallel sided in labial view (Willson and Upchurch, 2009). Furthermore, *Camarasaurus* appeared in Late Jurassic (Zheng, 1996; Upchurch et al., 2004). The tooth of *Euhelopus* is distinguishable from those of *Brachiosaurus* based on the well-developed longitudinal striations from the base to summit of the enamel surface. The former possesses the longitudinal striations that are absent in the latter (Russell and Zhang, 1993). Moreover, *Brachiosaurus* teeth often possess large, mesiodistally broad, apicobasally short, flat and high-angled apical wear facets (Upchurch and Barrett, 2000; Barrett et al., 2002; Wilson and Upchurch, 2009). In addition, the lingual ridge on teeth of *Brachiosaurus* is mesiodistally board as well as covers much of the lingual concavity; in contrast, the *Euhelopus* has a much narrower lingual ridge (Wiman, 1929; Janensch, 1935–1936; Barrett et al., 2002). Raised sub-circular bosses are present on the lingual surfaces of numerous teeth from *Euhelopus* (Wiman, 1929; Canudo et al., 2002; Barrett and Wang, 2007; Wilson and Upchurch, 2009; Salakka, 2014), so we infer the teeth depicted in this paper are *Euhelopus* teeth. *Euhelopus* was initially described by Wiman (1935), and subsequent studies were made by Mateer and McIntosh (1985), Wilson and Upchurch (2009), Poropat and Kear (2013), and Seela (2014). Upchurch (1998, 2004) put *Euhelopus* into non-neosauropod; however, Wilson (1998) demonstrated *Euhelopus* as being closely related to *Titanosaurus* and a sister group of *Titanosaurus*. Presently, there is a growing consensus that *Euhelopus* is a sister group of *Titanosaurus* (Barrett and Wang, 2007; Wilson, 2009; Poropat and Kear, 2013; Salakka, 2014).

Euhelopus has been previously reported from Shandong and Liaoning Provinces as well as from the Ordos Basin of Inner Mongolia in this paper. Furthermore, several same genera (different species) belonging to some different tetrapod clades have also been found in the above-mentioned three places during the Early Cretaceous deposits (Fig. 4). These tetrapod taxa include the following:

(1) Turtles *Ordosemys leios*, *Sinemys gamera* and *S. brevispinus* in the Luohandong Formation in Ordos Basin (Brinkman and Peng, 1993a, 1993b; Tong and Brinkman, 2013); *S. lens* from the Mengyin Formation in Shandong (Wiman, 1930); and *O. liaoxiensis* from the Yixian Formation in Liaoning (Tong et al., 2004);

(2) Choristoderes *Ikechosaurus sunailinae* from the Luohandong Formation in Ordos Basin (Brinkman and Dong, 1993), while *I. pijiagouensis* from the Jiufotang Formation in Liaoning (Liu Jun, 2003);

(3) Psittacosaurs *Psittacosaurus neimongoliensis* and *P. ordosensis* from the Luohandong Formation in Ordos Basin (Russell and Zhao, 1996); *P. lujiatunensis*, *P. major* and *P.* sp. from the Yixian Formation in Liaoning (Xu Xing and Wang Xiaolin, 1998; Zhou Changfu et al., 2006, Sereno et al., 2007), and *P. meileyingensis* from the Jiufotang Formation in Liaoning (Sereno et al., 1988), and *P. sinensis* from the Mengyin Formation in Shandong (Young, 1958);

(4) Birds *Cathayornis chabuensis* from the Jingchuan Formation in Ordos Basin (Li Jianjun et al., 2008), and *C. yandica* from the Jiufotang Formation in Liaoning (Zhou Zhonghe et al., 1992).

These fossils provide more evidences that there should be some connections about vertebrate faunas in Ordos Basin of Inner Mongolia, Liaoning Province, and Shandong Province during the Early Cretaceous.

5 Conclusions

(1) Well-preserved sauropod teeth from the Lower Cretaceous Luohandong Formation of the Ordos Basin possess large V-shaped wear facet, low slenderness index, labial grooves, lingual ridge and concavity, and prominent buttress in the distal margin of the crown. Such characters indicate these teeth should be identified as *Euhelopus* teeth, representing the first presence of *Euhelopus* in Ordos Basin, Inner Mongolia Autonomous Region.

(2) The occurrence of *Euhelopus* respectively came

Table 2 The slenderness index value (SI) of *Euhelopus* teeth from northern China.

Taxa	SI	Occurrence	References
Euhelopus zdanskyi	~2.0	Mengyin Formation, Shandong Province	Wilson and Upchurch, 2009
cf. *Euhelopus* sp.	1.9–3.11	Yixian Formation, Liaoning Province	Barrett and Wang, 2007
Euhelopus sp.	2.0–2.4	Luohandong Formation, Inner Mongolia Autonomous Region	This paper

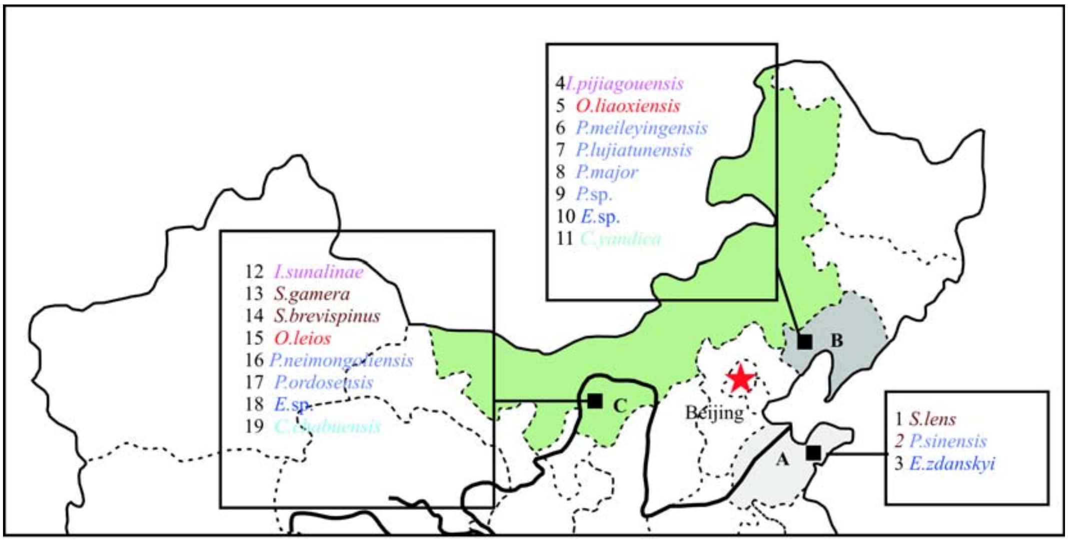

Fig. 4. Distribution of some vertebrate taxa in Ordos Basin of Inner Mongolia, Shandong, and western Liaoning during the Early Cretaceous. A, Shandong Province; B, western Liaoning Province; C, Ordos Basin of Inner Mongolia.

1 *Sinemys lens*; 2 *Psittacosaurus sinensis*; 3 *Euhelopus zdanskyi*; 4 *Ikechosaurus pijiagouensis*; 5 *Ordosemys liaoxiensis*; 6 *Psittacosaurus meileyingensis*; 7 *Psittacosaurus lujiatunensis*; 8 *Psittacosaurus major*; 9 *Psittacosaurus* sp.; 10 *Euhelopus* sp.; 11 *Cathayornis yandica*; 12 *Ikechosaurus sunailinae*; 13 *Sinemys gamera*; 14 *Sinemys brevispinus*; 15 *Ordosemys leios*; 16 *Psittacosaurus neimongoliensis*; 17 *Psittacosaurus ordosensis*; 18 *Euhelopus* sp.; 19 *Cathayornis chabuensis*.

from Ordos Basin of Inner Mongolia, Shandong Province, and Liaoning Province. Moreover, other vertebrate clades, such as turtles (*Sinemys*, *Ordosemys*), choristoderes (*Ikechosaurus*), psittacosaurs (*Psittacosaurus*) and birds (*Cathayornis*) have been also reported in Ordos Basin of Inner Mongolia, Liaoning Province and Shandong Province or two of these places. So there should be some connections about vertebrate fauna among Ordos Basin of Inner Mongolia, Liaoning Province and Shandong Province during the Early Cretaceous.

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