New Discovery of Oligocene Gastropod Opercula from the Yehucheng Formation in Northwestern China

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Abstract: Fourteen species of nonmarine gastropod opercula are found to be in high abundance in the Oligocene upper member of the Yehucheng Formation, Lanzhou Basin, northwest China. They are attributed to two families, namely Bithyniidae and Assimineidae, and four genera, namely Pseudemmericia, Bithynia, Mirolaminatus and Assiminea. Among them, three species are new, and they are Bithynia paramonolithic sp. nov., B. obliquus sp. nov., and B. disregularis sp. nov. Some of these species were first discovered in Paleogene strata of the vast Northwest China and can be compared with the opercula recovered from the Paleogene deposits in East and South China. It is inferred from the paleontology and sediment associations that the climate was slightly humid and the fauna probably inhabited the fresh or brackish water of a shallow lake in the Lanzhou Basin during the late early Oligocene period.

Key words: Lanzhou Basin, early Oligocene, Yehucheng Formation, gastropod opercula

1 Introduction

The gastropod operculum is a thin, light and flat structure attached to the dorsal surface of the foot, and associated with the shell aperture. It is variable in shape and chemical composition (Checa and Jimenez-Jimene, 1998). Most opercula are composed solely of calcium carbonate (calcite or aragonite) and are well preserved in sediments. Some are composed of proteins without mineral support and are rarely fossilized unless the opercula are mineralized by calcium (Penkman et al., 2013). In addition, the vast majority of recent marine and fresh water gastropods have only an organic operculum (Linsley et al., 1989). The corneous opercula are significantly less common than the calcium opercula and only exist in some mollusks, for example, Melanooides and Cleopatra. As a protection organ, the primary function of the operculum is its ability to close the aperture and provide shelter for the head-foot after withdrawing into its shell when confronting danger. The opercula of some prosobranchs, such as nassariids, can serve as offensive weapons, or as anchors for locomotion on the substrate.

Not all gastropods have opercula. Generally, most species of Prosobranchia develop opercula, whereas most Opisthobranchia and Pulmonata do not have them. Opercula are always densely deposited at the bottom of lakes or ponds, which is the only sign of the presence of snails (Henning and Matthais, 2013). Therefore, it is helpful to determine the features of gastropod fauna and estimate and compare the strata of different regions.

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Analyzing the fossil assemblage and comparing it with recent species may prove valuable for reconstructing the paleoenvironment (Pan et al., 2014). For example, Penkman et al. (2011, 2013) analyzed amino acids from the opercula of the freshwater gastropod Bithynia and established aminostratigraphy for the nonmarine Quaternary deposits of Britain correlated with the marine oxygen isotope record. This provided a framework for climatic and biostratigraphic tests.

Gastropod opercula have a worldwide distribution and have been found in, for example, Europe, America, Africa, and Asia since the Paleozoic. The earliest opercula fossils were recovered from the late Early Ordovician as well as the middle and late Ordovician (Yochelson and Barnett, 1972; Yochelson, 1975, 1986; Rohr and Potter, 1987, Rohr and Yochelson, 1999). In China, gastropod opercula fossils are abundant in Mesozoic and Cenozoic continental strata, and their ages mainly range from the Jurassic to the Quaternary. They are most abundant in the Paleogene, especially the Oligocene, and are distributed in Liaoning, Hebei, Shandong, Shanxi, Jiangsu, Anhui, Zhejiang, Hubei, Hunan, Yunnan, Guangxi, Guangdong, Hainan, Shaanxi, and a few records in Tibet (Wang, 1965, 1979, 1980, 1984; Yu and Wang, 1977, Yu et al., 1982; Zeng and Hu, 1982, 1985, 1991, 1996; Pan and Zhu, 2007; Pan et al., 2014; Li et al., 2015). However, there are few reports of gastropod opercula in the vast inland region of Northwest China. The gastropod opercula described here are found in the early Oligocene Yehucheng Formation in the Lanzhou Basin, and many fossils should be the first report in northwestern areas of China. Here, new fossil evidence is provided for understanding the distribution.
and evolution of gastropods in Paleogene China and the paleoclimate environment of the Lanzhou Basin.

2 Geological Setting

The Lanzhou Basin is a Cenozoic sedimentary basin on the northeastern edge of the Tibetan Plateau (Fig. 1). The geographical location is very unique because it is located in the transitional region between the Tibet Plateau and Loess Plateau, and also in the conjunction of the Tibetan Plateau cold region, the eastern monsoon region and the arid region of Northwest China (Zhang, 2015; Dmitrienko et al., 2018). The Cenozoic strata record key information of the Aeolian sediment accumulation, Asian interior aridification and uplift of the Tibetan Plateau.

The Tertiary strata of the Lanzhou Basin are well exposed in the northwest and southeast of Lanzhou City, and discordantly overlie the Cretaceous Hekou Group. In ascending order, the Tertiary strata consist of the Xiliugou, Yehucheng, Xianshuihe and Linxia formations. The Xiliugou Formation, is the late Paleocene to the early Eocene in age with a paleomagnetic dating of approximately (>58–51 Ma) (Yue et al., 2000), and should be aeolian desert deposition (dissertation in prepare) consisting of brick-red coarse-medium sandstone. The paleomagnetic age of the Yehucheng Formation is the late Early Eocene to Early Oligocene with an age of approximately 51–31.5 Ma (Yue et al., 2000). This formation is mainly composed of violet red sandstone, silty mudstone and mudstone interbedded with thin grayish green and grayish white fine sandstone. Tabular cross bedding, parallel bedding, and wavy bedding are well developed in the sandstone. A large amount of gypsum and mirabilite can be observed in the layers and cracks of the middle section but gradually decreases upward. There are more than a dozen layers of grayish green mudstone in the upper violet red mudstone of the Yehucheng Formation, in which abundant gastropod opercula, ostracoda, chara (Amblyochara subeiensis, Harnichara aff. lagenalis) and fish fossils were recovered (Fig. 2). Consequently, the main sedimentary environment of the Yehucheng Formation should be fluvial-lacustrine facies (Yue et al., 2001, 2003; Xie, 2004; Zhang et al., 2014). The paleomagnetic age of the bottom Xianshuihe Formation is of the late early Oligocene to the Miocene, approximately 31.5 Ma (Yue et al., 2000). It consists of yellow sandstone and brownish red mudstone in the lower part, white sandstone and red mudstone in the middle part, and light-yellow sandy conglomerate in the upper part, belonging to fluvial—delta-lacustrine deposits.

The Tertiary strata and sediments were roughly influenced by the paleoclimatic environment. The Paleocene and Eocene climate zones in China were mainly distributed in the east-west direction, dominated by the planetary wind system (Liu et al., 1998). The Lanzhou Basin was in the arid belt during the Paleocene-Eocene period, but the paleoclimate changed during the Oligocene. During the Paleogene, the average paleosalinity of water in the Lanzhou Basin was 12‰, indicating a brackish lake (Li et al., 2016a). Since the late early Eocene, the lake basin has experienced a relatively stable deposition process and has developed several hundred meters of red sediments of the Yehucheng Formation. The characteristic brownish red sediments are mainly contributed by hematite, which is a typical indicator of a hot and dry oxidation environment (Reineck and Singh, 1973). Influenced by the xerothermic climate, the lake’s evaporation exceeded recharge from rivers, rainfall and groundwater. Strong evaporation increased the concentration of dissolved ions, and large amounts of gypsum were precipitated. During the middle sedimentary period of the Yehucheng Formation, as the climate became slightly humid and the ancient lake water deepened, the salinity of the water declined (Deng et al., 2010; Li et al., 2016a). The grayish green siltstone and silty mudstone in the upper layer of the Yehucheng Formation reflected a weak oxidation-weak reducing environment (Reading, 1978).

In contrast to the high abundance of opercula, the gastropod shells were seldom found in grayish green lacustrine mudstone, that is, the opercula and shells rarely occurred in the same quantity. Postmortem transport patterns and different preservation of shells and opercula may explain this phenomenon. For some species such as...
bithyniid, shells are composed of aragonite but the opercula are calcitic (Penkman et al., 2011) and, therefore, more stable than aragonite. Consequently, shells are more likely to be disintegrated whereas opercula are robust, with integrity, and well preserved (Henning and Matthias, 2013).

3 Material, Method and Abbreviations

In this study, the gastropod opercula samples were elutriated and sieved with an 80 mesh sieve, and 156 undamaged fossils were obtained. All the samples were identified and attributed to two families, four genera and 14 species, including three new species. The genus *Pseudemmericia* was the most diverse with eight species, but in terms of the individual amount, *Assiminea retopercula* predominated and accounted for approximately 42% of the total specimens. To study the material composition of the opercula, samples were selected from each species and disposed of dilute hydrochloric acid. All the specimens bubbled violently and soon dissolved into the acid completely, suggesting that the opercula fossils had experienced strong calcification.

**Abbreviation:** NWUIV, invertebrate specimens of Northwest University.

**H** = height, namely the maximum height of the operculum, and **W** = width, that is, the maximum width of the operculum.

**Occurrence:** All specimens were from the late Early Oligocene Yehucheng Formation, Huangyangtou Village, northwest of Lanzhou City, Gansu Province.

4 Systematic Paleontology

**Class** Gastropoda, Cuvier, 1797

**Subclass** Prosobranchia Milne, Edwards, 1848

**Order** Mesogastropoda Thiele, 1925

**Superfamily** Pissoacea Gray, 1850

**Family** Bithyniidae Gray, 1857

**Genus** Pseudemmericia Schlickum, 1968

*Bithynia* (Pseudemmericia) *magnicirca* Wang, p. 317, pl. I, figs. 5–6; pl. II, fig. 2.

**Material:** NWUIV20L001, NWUIV20L002

**Diagnosis:** Operculum belonging to the spiro-
concentric type, translucent. Anterior end round and posterior end slightly pointed; outer lip edge more convex than inner edge; inner circle with clear spiral lines located in the middle of dorsal surface and protruding into a convex facet, parallel to the outer circle of operculum; opercular core located at the anterior end. Outer circle decorated with concentric lines. Ventral surface bearing a groove around it. According to Wang et al. (1980), this species develops 1–2 circles (rings) outside the inner circle and the distance between the two rings is almost equal (Figs. 4a–b).

**Dimensions** (mm) NWUIV20L001: H, 1.84; W, 1.35; W/H: 0.73; NWUIV20L002: H, 2.13; W, 1.63; W/H: 0.76.

**Remarks:** The species is similar to *Bithynia* (*Pseudemmericia*) *monocirca* Wang from the Eocene Hedi Formation, Yuanqu County, Shanxi Province, but differs in having spiro-concentric inner circle that is larger than the latter. Compared with *Bithynia* (*Pseudemmericia*) *magnicirca* Tolstikova, this species has a wider outer circle but a smaller inner circle.

**Bithynia (Pseudemmericia) monocirca**


2015 *Bithynia* (*Pseudemmericia*) *monocirca* Li, p. 647, pl. 4, figs. 13.

**Material:** NWUIV20L003

**Description:** Operculum semi-transparent, belonging to the spiro-concentric type. Wide outer circle decorated with concentric lines. In the middle of the operculum, the inner circle protrudes into a convex facet, having the same angle as the operculum. Convex facet-bearing sinistral spiral lines (Fig. 4c).

**Dimensions** (mm) NWUIV20L003: H, 2.7; W, 1.97; W/H: 0.73.

**Remarks:** The specimen is considered to be identical to *Bithynia* (*Pseudemmericia*) *magnicirca* Wang (1980) from the Oligocene Shahejie Formation, Kenli County, Shandong Province and *Bithynia* (*Pseudemmericia*) *monocirca* Li et al. (2015) from the Pliocene Youhe Formation in the Weihe Basin, Shaanxi Province. Compared with *Bithynia* (*Pseudemmericia*) *magnicirca*, this species has a wider outer circle but a smaller inner circle.

**Occurrence elsewhere:** In the Youhe Formation, Guanzhong area, Shaanxi, and Dingqing Formation, Dingqing area, Tibet.
**Bithynia (Pseudoemmericia) monolithic**

2015 *Bithynia (Pseudoemmericia) monolithic* Li, p. 646, pl. 4, fig. 12.

**Material:** NWUIV20L004

**Description:** The operculum of melon seed shape, opaque, belonging to spiro-concentric type. Outer lip edge more convex than inner edge, parietal edge slightly straight. The prominent feature lies in a large, flat and less...
decorative convex facet on the dorsal surface and a relatively narrow outer circle. Convex facet bearing a group of sinistral spiral lines, consistent with the angle of the operculum. The core was slightly concave and located in the middle of the anterior end. A shallow groove around the ventral surface (Fig. 4d).

**Dimensions** (mm) NWUIV20L004: H, 2.5; W, 1.81; W/H: 0.72.

**Remarks:** The specimen is smaller and thinner than *Bithynia* (*Pseudemmericia*) *monolithic* Li et al. (2015) from the Pliocene Youhe Formation in the Weihe Basin. Its morphology is also similar to that of *Bithynia* (*Pseudemmericia*) *magnicirca*, but differs from the latter in several ways, including having a large, flat convex surface and an extremely narrow outer circle.

*Bithynia* (*Pseudemmericia*) *hunanensis*

1985 *Bithynia* (*Pseudemmericia*) *hunanensis* Zeng, p. 392, pl. 1, figs. 4–5.

**Material:** NWUIV20L005

**Description:** Operculum in the shape of melon seed, large and thick, of spiro-concentric type; anterior end round and posterior end sharp; outer lip edge protruding obviously, parietal edge of inner lip concaving inwards; inner circle large; a wide and deep groove separating the operculum and inner circle bearing a bunch of sinistral spiral lines; core located in the middle of anterior part, slightly concave; narrow outer circle decorated with several concentric lines; ventral surface bearing an obvious groove (Figs. 4e–f).

**Dimensions** (mm) NWUIV20L005: H, 3.28; W, 2.29; W/H: 0.7.

**Remarks:** The specimen is considered to be identical to *Bithynia* (*Pseudemmericia*) *hunanensis* Zeng and Hu (1985) from the Tertiary Xinheku Formation, Yuankuang County, Hunan. Compared with *Parafossarulus kustoides* Tolstikova (1979) this species has a smooth ventral surface while the latter develops concentric circles on it. *B. hunanensis* resembles *B. magnicirca* Wang (1980) in its overall morphology, but *B. magnicirca* is smaller and wider, with a small convex surface and a wide outer circle (Fig. 3a).

*Bithynia* (*Pseudemmericia*) *paramonolithic* sp. nov.

2015 *Bithynia* (*Pseudemmericia*) *paramonolithic* Li, p. 646, pl. 4, figs. 12.

**Derivation of name:** Similar to *Bithynia* (*Pseudemmericia*) *monolithic* Li et al. (2015) in the overall morphology and surface decorative pattern, but it has one more circle than the latter.

**Material:** NWUIV20L006

**Diagnosis:** Large, with two convex surfaces, an extremely narrow outer circle, and a wide ring between the outer and inner circles.

**Description:** Operculum oval or subrounded, posterior end broadly round while anterior end blunt; two convex facets on the dorsal surface; inner circle located in the middle of the operculum, forming the upper convex surface; outer circle extremely narrow; a wide ring between outer circle and inner circle bearing dense concentric lines; opercular core located in the central part of anterior end; a bunch of sinistral spiral lines originating from the core (Figs. 4g–h).

**Dimensions** (mm) NWUIV20L006: H, 3.3; W, 2.37; W/H: 0.72; NWUIV20L007: H, 2.47; W, 1.87; W/H: 0.76.

**Remarks:** The new species resembles *B. magnicirca* Wang but differs in having a narrower outer circle and a spiral-type inner circle. Compared with *B. paramonolithic* Tolstikova, *B. paramonolithic* has a larger inner circle and a narrower outer circle.

*Bithynia* (*Pseudemmericia*) *inclinimarga*


**Material:** NWUIV20L008

**Description:** Operculum pyriform, anterior end broadly round and posterior blunt. Outer lip edge more convex than inner lip; parietal edge straight; dorsal surface slightly concave; outer circle extremely narrow; inner circle inclined to the peristome of the inner lip. There is a narrow concave between the outer and inner circles, decorated with clear concentric lines. The width of each circle on the inner lip side is narrower than that on the outer lip side. Opercular core situated in the central part of anterior end and slightly concave; ventral surface smooth, moderately convex, surrounded by an obvious groove (Fig. 4i).

**Dimensions** (mm) NWUIV20L008: H, 2.71; W, 2.03; W/H: 0.75.

**Remarks:** The most notable feature of this species is that all the circles (convex facets) are inclined to the inner lip edge and the space between the circles is unequal. This specimen is generally consistent with *B. inclinimarga* Wang (1980) from the Eocene deposits in Zhuoxian County, Hebei, but larger in size.

*Bithynia* (*Pseudemmericia*) *obliquus* sp. nov.

**Derivation of name:** Inner circle of the species is oblique.

**Material:** NWUIV20L009

**Diagnosis:** Outer circle of operculum rather narrow and inner circle oblique to the outer lip edge.

**Description:** Opercula oval, anterior end broadly round and posterior blunt. Two convex facets on the dorsal surface; the large lower convex facet bearing concentric lines, parallel to the operculum edge and the upper one inclined to the outer lip edge, forming an intersection angle of approximately ca. 20°. Exposed side of operculum wide; core slightly concave, located in the middle of the anterior part (Fig. 4j).

**Dimensions** (mm) NWUIV20L009: H, 2.52; W, 1.91; W/H: 0.76.

**Remarks:** This species resembles *B. monolithic* Li et al. (2015) from the Pliocene Youhe Formation in Weinan, Shaanxi in the narrow outer circle, but differs from it in the oblique upper convex facet. *B. parvobliqua* Wang (1980) which was discovered from the Eocene Hedi Formation in Yuanqu, Shanxi Province, also has an oblique upper convex surface (inner cycle), but *B. parvobliqua* has a melon seed shape and has a wider outer cycle.

*Bithynia* (*Pseudemmericia*) *disregularis* sp. nov.
Assiminea retopercula

**Derivation of name:** The width of the ring is irregular, and different from the known species.

**Material:** NWUIV20L010

**Diagnosis:** Oval, three rings outside the inner circle; the first two have equal widths, and the third one is rather fine.

**Description:** Operculum of ellipse shape, semitransparent; anterior and posterior ends equally round. The outer and inner lips display symmetrical arcs; the inner circle is located in the central part and inclined to the inner lip side, with sinistral spiral lines on it. The operculum core is located on the inner lip side of the anterior part. There are three rings between the inner circle and outer edge of the operculum. Except for the third ring, which is rather narrow, the width and angle of the other two rings are identical (Fig. 4k).

**Dimensions** (mm) NWUIV20L010: H, 2.7; W, 1.97; W/H: 0.73.

**Remarks:** The new species is similar to some specimens of *B. magnicirca* Wang (1980) but differs in having elliptical contour and extra fine ring outside the inner circle.

**Genus Bithynia Leach, 1818**

*Bithynia gigantea*


**Material:** NWUIV20L011

**Description:** Operculum large and thick, of melon weed shape; outer lip edge more convex than inner lip; parietal edge obviously concave. Two convex facets on dorsal surface and lower one large, bearing concentric lines while upper convex facet is small and oblique to the outer lip. Groove present between lower convex facet and operculum wide and deep, especially on inner lip side. Both convex facets are inclined to inner lip edge, making ring width of inner side narrower than outer side. Operculum core is located on the anterior part of upper convex facet (inner circle) and inclined to inner lip side, deeply concave (Figs. 4l-1).

**Dimensions** (mm) NWUIV20L011: H, 2.75; W, 1.99; W/H: 0.72.

**Remarks:** The specimen resembles *B. gigantea* Zeng and Hu (1991) from the late Cretaceous Huangkeng Formation in the Nanxiong Basin, Guangdong, with both having two prominent convex facets and deep grooves. However, the specimen from the Nanxiong Basin is obviously larger, approximately twice as large as our specimen from the Oligocene Yehucheng Formation in the Lanzhou Basin (Fig. 3b). The difference in individual size may be related to the allometric growth of organisms, or the size of some species probably changed to smaller from the Cretaceous to Oligocene.

**Genus Mirolaminatus Zeng et Hu, 1982**

**Type species:** *Mirolaminatus lamellatus* (Wang et al., 1979).

**Remarks:** *Mirolaminatus* was established by Wang based on specimens from the Eocene Dainan Formation in Changzhou, Jiangsu. This genus belongs to the spiral type and has one–four convex facets on the dorsal surface. The convex facets are inclined toward the outer lip edge, forming an intersection angle with the long axis of the operculum (Wang et al., 1979). It is common in non-marine deposits of the Late Cretaceous and Tertiary in Central and Eastern China, and is also found in the Paleogene strata of Mongolia, Russia, England, and North America (Wang et al., 1977, 1979, 1980; Zeng and Hu et al., 1982, 1985).

*Mirolaminatus validus*


**Material:** NWUIV20L012

**Description:** Operculum in the shape of melon seed, anterior round and posterior blunt; dorsal surface covered by coarse and dense spiral lines; an obvious convex facet inclined to the outer lip but not reaching the edge; core located in the central part of anterior end (Fig. 4m).

**Dimensions** (mm) NWUIV20L012: H, 2.55; W, 1.79; W/H: 0.7.

**Remarks:** The specimen resembles *Mirolaminatus validus* Wang (1979) from the Paleogene Zoumaling Formation in Jingmen City, Hubei Province, but the convex facet is slightly smaller than the latter.

**Occurrence elsewhere:** Widely distributed in the early Paleocene Xinhekou Formation, Yuanjiang County, Hunan Province, the early Tertiary Shuangta Group from Nanling County, Anhui Province, and in the Pliocene Youhe Formation, Weihe Basin, Shaanxi Province.

*Mirolaminatus validoides*


**Material:** NWUIV20L013

**Description:** Operculum large, melon seed shaped; anterior end round and posterior end blunt. Outer lip edge prominently convex and parietal edge rather straight; a small convex facet on the dorsal surface. Operculum posterior part exposed widely and decorated with two groups of spiral lines, interwoven into a mesh pattern. Compared with coarse and dense dextral spiral lines, fewer sinistral lines present. Core located on anterior end and inclined to inner lip side (Fig. 4n).

**Dimensions** (mm) NWUIV20L013: H, 3.03; W, 2.15; W/H: 0.71.

**Remarks:** The new specimen most resembled *M. validoides* (Wang, 1979) from the Eocene Yangxi Formation in Yidu County, Hubei. However, the new fossil is larger in size and the convex facet of the latter is closer to the outer lip edge. Compared with *M. validus* (Fig. 3c), this species has a smaller convex facet. *Mirolaminatus ovatus* (Wang, 1979) from the early Eocene Wutu Formation in Linqu County, Shandong Province also has an oblique convex facet, but it is larger than *M. validoides* and its anterior end is broadly round.

**Genus Assiminea Fleming, 1828**

*Assiminea retopercula*


**Material:** NWUIV20L014
Description: Operculum oval, belonging to sinistral spiral type; anterior end round and posterior end pointed; outer lip edge more convex than inner lip; two groups of spiral lines interwoven into a mesh pattern on the back of dorsal surface; core slightly concave, located at the central part of anterior end; ventral surface bearing a groove around (Fig. 4o).

Dimensions (mm) NWUIV20L014: H, 2.67; W, 1.93; W/H: 0.72.

Remarks: A. retopercula constitutes an important component of the aquatic mollusk assemblage from the Oligocene Yehucheng Formation in the Lanzhou Basin, accounting for more than one-third of the total identified specimens.

Occurrence elsewhere: Paleocene Funing Group in Changzhou City, Jiangsu; Yangxi and Cheyanghe Formation in Dangyang County, Hubei; Jundian Formation in Fangxian County, Hubei; Eocene Yuanjiang and Deshan Formation in Lixian County, Dongting Basin, Hunan; the Paleocene Sanliushi Formation in Hengyang Basin, Hunan; Early Eocene Huayong Formation in Nanhai County, Guangdong (Liu and Hu, 1985).

Assiminea pressoopercula

1980 Assiminea pressoopercula Wang, p. 316, pl. II, figs. 8, 10.

Material: NWUIV20L015

Description: Operculum small, melon seed shape, sinistral spiral type. Anterior end round and posterior end sharp; outer lip edge protruding; dorsal surface obviously depressing; coarse and dense spiral lines on the back of operculum. Core concave, inclined to the inner lip side (Fig. 4p).

Dimensions (mm) NWUIV20L015: H, 2.55; W, 1.78; W/H: 0.7.

Remarks: The species is characterized by an obviously concave dorsal surface, coarse spiral lines on the posterior part, with no reticular decoration, which differs from A. retopercula.

Occurrence elsewhere: Yangxi Formation from Dangyang and Zoumaling formations from Jingmen City, Hubei; the Paleocene Sanliushi Formation in Hengyang Basin, Hunan.

Assiminea mirabilis


Material: NWUIV20L016

Description: Operculum small, thin, semitransparent; anterior end broadly round, posterior end sharp; outer lip edge more convex than inner lip, parietal edge straight; sinistral spiral lines and several concentric circles can be observed on the dorsal and ventral surfaces respectively; core located at the anterior part and inclined to the columellae edge (Figs. 4q–q').

Dimensions (mm) NWUIV20L016: H, 1.78; W, 1.36; W/H: 0.76.

Remarks: Compared with the holotype of A. mirabilis described by Zeng and Hu (1985) from the Paleocene Xinhekou Formation in Yuanjiang County, Hunan, the new specimen has less concentric circles on the ventral surface. This species is characterized by the small size and transparent structure, which is different from other opercula of Genus Assiminea (Fig. 3d).

Occurrence elsewhere: Yuanjiang Formation, Changde City, Hunan, Youhe Formation, Weinan, Shaanxi.

5 Paleoenvironment

The gastropod opercula described above are dominated by the families Bithyniidae and Assimineidae, and terrestrial gastropods have not been found in the lacustrine deposits of the Yehucheng Formation. Extant gastropods belonging to members of the family Bithyniidae mainly inhabit ponds, rivers or lakes with abundant aquatic vegetation (Yen, 1950, 1951a, b, 1952; Pan and Zhu, 2007; Pan et al., 2014; Li et al., 2015). Species of Bithynia always thrive during warm stages but are generally absent in sediments deposited during cold periods (Penkman et al., 2013). Recent Assiminea sp. are widely distributed in the coastal areas of eastern China, Japan, Korea and Russia (Chen and Gao, 1988). According to the life habits of living gastropods, most species of Assiminea are euryhaline creatures that can adapt to fresh and brackish water and inhabit estuaries, lakes, intertidal zones and mangrove wetlands. They are also found to creep on aquatic plants or crawl at the bottom of water, and feed on detritus, algae and aquatic vegetation (Li, 2014, Li et al., 2014). Consequently, it can be speculated that the gastropods discovered from grayish green mudstone of the upper Yehucheng Formation probably inhabited the mud bottom of the shallow lake with organic materials and aquatic plants. Except for gastropod opercula, charophytes also occur in the same grayish green mudstone of the Yehucheng Formation. It is a large submerged plant that grows in fresh and brackish water of ponds, lakes and swamps. These are consistent with the sedimentary characteristics of fossil-bearing strata, and reflect a shallow freshwater lake or brackish lake environment under a subtropical or temperate climate, which is completely different from the dry hot climate marked by the thick brownish red deposits.

In conclusion, the xerothermal climate began to transform into a slightly humid environment and the shallow lake became slightly deeper with declining paleosalinity, and gypsum and other evaporative rocks reducing significantly during the late stage of the Yehucheng Formation deposition. All these changes provide suitable habitats for aquatic plants and animals such as gastropods, ostracods, and fishes within a certain period. In the late early Oligocene (~31Ma), the southern boundary of the arid zone in mainland China passed through the Lanzhou Basin and its surrounding areas which became a transitional environmental zone of dry and humid regions, and the climate of the Lanzhou Basin changed to semi-arid-semi humid (Sun et al., 2004; Deng et al., 2010; Yao et al., 2010; Li et al., 2016b). During the late Oligocene, with the disappearance of the east-west arid belt across the ancient mainland China (Liu et al., 1998), the arid zone in Northwest China appeared and evolved to date.
6 Conclusions

(1) Numerous gastropod opercula fossils were discovered in the early Oligocene Yehucheng Formation in the Lanzhou area with 156 opercula specimens analyzed and studied. All belong to the subclass Preselanbranchia and can be attributed to two families, four genera and 14 species, including three new species. Some species were the first to be discovered in Northwest China, which provides an important supplement for the study of the distribution and evolution of Cenozoic gastropods.

(2) A comparison with survival conditions of the living species, in addition to the sedimentary characteristics and paleosalinity of lake water, suggests that the gastropod and associated charophyta, ostracods and fishes once inhabited a fresh-brackish lake. Since the late early Oligocene, the Lanzhou Basin environment changed from strong oxidative arid to semiarid.

(3) The Paleogene gastropod opercula from Lanzhou Basin, Northwest China were also widely distributed in the vast central and eastern China regions, indicating that the gastropod evolution in Paleogene China is consistent, and can serve as a significant indicator for stratigraphic correlation.

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