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New Evidence for a Cretaceous Age for a Mesozoic Nonmarine Bivalve Assemblage from Paekto-dong, Sinuiju City, The Democratic People's Republic of Korea

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Abstract: The Sinuiju Formation in Paekto-dong, Sinuiju City in the Democratic People's Republic of Korea has yielded Mesozoic nonmarine bivalve fossils, which is the first occurrence of such in the DPRK. Based on these fossil specimens, a new Cretaceous bivalve assemblage, the *Arguniella yanshanensis-Sphaerium anderssoni* Assemblage is erected. This assemblage includes *Arguniella yanshanensis*, *A. lingyuanensis* and *Sphaerium anderssoni* and can be compared with the Jehol Biota. The age of the Sinuiju Formation is also clarified and on the basis of the bivalves and the presence of a *Eosestheria–Ephemeropsis–Lycoptera* (*E–E–L)* assemblage, the formation is not Upper Jurassic, but Lower Cretaceous in age.

Key words: biostratigraphy, nonmarine bivalves, Sinuiju Formation, Early Cretaceous, DPRK

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1 Introduction

In 1967, several taxa of bivalves, *Lymnocyrena ovalis, L. amgensis, L. wilujca, L. sibirica, L. elongate, L.* cf. *huphensis, L. abrokgangensis, L. baiktoensis, L. yendaeensis, L. sinizuensis, L. tani, L. shantungensis, L. obtusale, L.altiformis, L. rotunda, L. tignensis, Cyrena hupanensis* and *L.*(?) *anderssoni* were found in the Sinuiju Formation at Paekto-dong near Sinuiju City in the Democratic People's Republic of Korea (DPRK) (Choe, 1967). Since then, no new Mesozoic bivalve fossils have not been published from Paekto-dong.

In 2014–2016, we returned to Paekto-dong and found many nonmarine bivalve fossils in the Sinuiju Formation (Fig. 1). We have undertaken a systematic review of them and, therefore, we document here the first presence of a nonmarine bivalve assemblage from the Sinuiju Formation in Paekto-dong and consider the age of the Sinuiju Formation is also discussed.

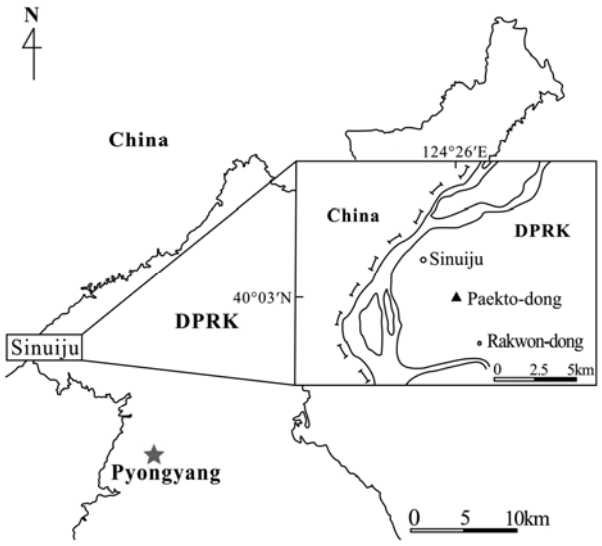

Fig. 1. Map showing the new fossil locality in Paekto-dong, Sinuiju City, DPRK.

2 General Geologic Setting and Material

The Sinuiju Formation in Sinuiju City is distributed mainly in the Sinuiju basin, which has a length of 50 km and a width of 15 km. The Sinuiju Formation comprises, in ascending order, eight members. The first member consists of purplish-yellow siltstones, fine-grained sandstones and mudstones containing invertebrate and plant fossils. This member is in unconformity with underlying Precambrian basement. The second member is composed of andesites, tuffaceous siltstone with sedimentary intercalations, conformably overlying the lower first unit. The third member consists of grayish-green sandstones, gray to black mudstones and siltstones and yields fossil vertebrate, insects, conchostracans, bivalves, gastropods, ostracodes, and terrestrial plant fossils (Pak and Kim, 1996). This member, which conformably overlies the second unit, is 200–300 m in thickness. The lower part of the fourth unit is made of volcanic sandstones, siltstones, claystones and shales. The

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fifth to the eighth units consist of andesites, tuffaceous siltstone and sandstone. They are not exposed in outcrop. Based on the fossils, Pak and Kim (1996) regarded the Sinuiju Formation as Upper Jurassic to Lower Cretaceous in age.

Most of the bivalve fossils collected by us derive mainly from Member 3 of the Sinuiju Formation, whereas Member 2 contains no bivalve fossils. All the specimens described in this paper are housed in the Paleontology Laboratory at the Geology faculty of Kim Il Sung University, Pyongyang. Images of the bivalves and others were taken using a Canon camera.

3 Bivalve Taxonomy

Order Unionida Stoliczka, 1871
Superfamily Anthracosioidea Amalitsky, 1892
Family Ferganoconchidae Martinson, 1956
Genus *Arguniella* Kolesnikov, 1980 [emended]

Synonymy
1967 *Limnocyrena*; Choe, p. 20
1976 *Ferganoconcha* Chernyshev; Gu et al., p. 292 (pars).
1976 *Ferganoconcha*; Zhu, p. 25 (pars).
1980 *Arguniella* Kolesnikov, p. 25.
1980 *Ferganoconcha*; Zhu, p. 11 (pars).
1980 *Ferganoconcha*; Ma, p. 109; 1986, p. 183.
1982 *Ferganoconcha*; Shi, p. 4 (pars).
1982 *Ferganoconcha*; J.S. Yu, p. 38.
1984 *Ferganoconcha*; Yu, Wang, Liu and Zhang, p. 33 (pars).
1984 *Xishanoconcha* Wang, in Yu, Wang, Liu and Zhang, p. 45.
1987 *Ferganoconcha*; Yu, Dong and Yao, p. 9.
1997 *Arguniella*; Gu, Li and Yu, p. 145.
1999 *Arguniella*; Chen, p. 102.
2007 *Arguniella*; Jiang, Sha and Cai, p. 206

Diagnosis: Hinge plate narrow and nearly straight. No cardinal and lateral teeth. A lamellar ridge arising directly from dorsal margin presents in left valve and a lamellar socket presents in right valve. Lamellar ridge extends across umbo from anterior to posterior; anterior part strong, becoming feeble towards posterior.

Occurrence: Upper Jurassic?–Lower Cretaceous; Central Asia, Mongolia, Siberia, northern and eastern China, DPRK

Discussion: Choe (1967) was the first to report freshwater bivalves from the Sinuiju Formation in Paekto-dong when he considered provisionally that the many bivalves belonged to "*Limnocyrena*". Few notable revisions were made during the next decades. Based on our re-examination, the bivalves more closely resemble *Arguniella* Kolesnikov, 1980 in shell outline and hinge structure because: (1) the shell is rather inflated, with a projecting umbo and posterior ridge, and a smooth surface with broad concentric wrinkles; and (2) the ligament is opisthodetic.

Arguniella yanshanensis (Gu, 1976)
Fig. 3c–d

1967 *Lymnocyrena ovalis*; Choe, p. 21, fig. 1.
1976 *Ferganoconcha yanshanensis* Gu, in Gu et al., p. 295, pl. 80, figs 17, 18 (non 16).
1976 *Ferganoconcha* cf. *subcentralis* Chernyshev; Gu et al., p. 293, pl. 80, figs. 11, 12 (non 10, 13)
1976 *Ferganoconcha quadrata* (Martinson), Gu et al., p. 295, pl. 80, figs. 30, 32—35 (non 31) (non *Leptesthes quadratus* Martinson, 1961, p. 271, pl. 2, fig. 14).
1980 *Ferganoconcha curta* Chernyshev; Zhu, p. 11, pl. 3, figs. 13—16.
1980 *Ferganoconcha* cf. *jeniseica* Martinson; Zhu, 1980, p. 14, pl. 3, figs. 17—19.
1980 *Ferganoconcha* cf. *yanshanensis* Gu; Zhu, p. 14, pl. 2, figs. 44—46.
1980 *Ferganoconcha* cf. *jorekonsis* Chenyshev; Zhu, pl. 14, figs. 38—41.
1987 *Ferganoconcha curta* Chernyshev; Yu, Dong and Yao, p. 10, pl. 1, fig. 19.
1987 *Ferganoconcha sibirica* Chenyshev; Yu, Dong and Yao, p. 10, pl. 1, fig. 17.
1987 *Ferganoconcha yanshanensis* Gu, in Gu et al.; Yu, Dong and Yao, p. 10, pl. 1, figs. 15, 16.
1999 *Arguniella yanshanensis* (Gu); Chen, p. 103, pl. 1, figs. 4, 15; pl. 2, figs. 3, 4; pl. 3, fig. 1.
2007 *Arguniella yanshanensis* (Gu); Jiang, Sha and Cai, p. 207, pl. 1, figs. 3A—K, 7C—D.

Description: The shell is small to moderate in size, up to 26 mm long and 17 mm high, and rather inflated. The shape is rounded trigonal to obliquely oval in outline, and nearly equilateral. Anterior and posterior dorsal margins are nearly straight to slightly convex towards the dorsal side with an umbonal angle between 85 and 105º; anterior and ventral margins are broadly rounded, and the posterior margin is narrowly rounded. The posterior ridge varies from distinct to broadly rounded. The umbo is situated at the anterior two-fifths to one-half of the shell length. The shell surface exhibits commarginal growth lines.

Material examined: 38 specimens (GPSP 20140621—2015047), mostly single-valved replicas and composite moulds. All are from the Sinuiju Formation in Paekto-dong.

Occurrence: Third member; Sinuiju Formation.

Discussion: Judging from the shell outline, ornament and occurrence of the projecting, inflated umbones, *Lymnocyrena ovalis* of Choe (1967) should be re-assigned to *Arguniella yanshanensis*. The variation of shell outline in the Paekto-dong specimens varies from rounded trigonal to obliquely oval but all are regarded as belonging to the same species. *A. quadrata* (Martinson, 1956; see Martinson, 1961, p. 230) differs from *A. yanshanensis* in being smaller (length 13–15 mm, height 9–10 mm) and in having a multi-angular outline.

Arguniella lingyuanensis (Gu, 1976)
Fig. 3a–b

1967 *Lymnocyrena baektoensis*; Choe, p. 23, fig. 7
1976 *Ferganoconcha lingyuanensis* Gu, in Gu et al., p.

296, pl. 81, figs. 11–17; Zhu, 1980, p. 14, pl. 3, figs. 42, 43.

1976 *Ferganoconcha* aff. *burejensis* Chernyshev; Gu et al., p. 294, pl. 80, figs. 24, 25 (non 26–29).

1980 *Ferganoconcha lingyuanensis* Gu, in Gu et al.; Zhu, 1980, p. 14, pl. 3, figs. 42, 43.

1987 *Ferganoconcha* cf. *burejensis* Chernyshev; Yu, Dong and Yao, 1987, p. 9, pl. 1, fig.6.

1987 *Ferganoconcha shouchangensis* Ma; Yu, Dong and Yao, 1987, p. 9, pl. 1, fig.7.

1987 *Ferganoconcha* cf. *distensa* Yu; Yu, Dong and Yao, 1987, p. 10, pl. 1, fig.10.

1987 *Ferganoconcha lingyuanensis* Gu; Yu, Dong and Yao, 1987, p. 10, pl. 1, figs. 12, 20.

1999 *Arguniella lingyuanensis* (Gu); Chen, 1999, p. 103, pl. 1, figs. 1–3, 5–14; pl. 2, figs. 2, 7, 12–14; pl. 3, figs. 2–4, 8–13.

2007 *Arguniella lingyuanensis* (Gu); Jiang, Sha and Cai, p. 208, figs. 3L–W, 7E–F.

Description: The shell is small to moderate in size, largest specimen 22 mm long and 15 mm high, moderately inflated, subquadrate in outline, slightly to moderately inequilateral. The anterodorsal margin is nearly straight, inclined towards the ventral side in plan view; the posterodorsal margin is straight and subparallel with the ventral margin; the anterior margin is broadly rounded, the posterior margin truncated, and the ventral margin nearly straight. The umbonal angle ranges between 105° and 135°. The posterior ridge is commonly strong, defining a slightly concave posterior dorsal slope. The umbo is situated at the anterior one-quarter to two-fifths of the shell length. The shell surface is marked with broad commarginal growth lines.

Material examined: 29 specimens (GPSP 2014058–2014612), mostly single-valved replicas and moulds. All are from the Sinuiju Formation in Paekto-dong.

Occurrence: Third member; Sinuiju Formation.

Discussion: This species is characterized by its subparallel posterodorsal and ventral margins, truncate posterior margin and strong posterior ridge. Therefore, we consider that *Lymnocyrena baektoensis* of Choe (1967) belongs to *Arguniella lingyuanensis*.

Based on the characters outlined in the original description and photograph (Choe 1967, fig. 11) of *Lymnocyrena*(?) *anderssoni*, some specimens are very similar to *Sphaerium anderssoni* in size and ornament. Judging from the photograph and the original description of the specimen, the characters including small shell, 17 mm long and 13 mm high, rounded to trigonally elliptical in outline, slightly prosocline; the anterodorsal margin gently concave towards the ventral side; the posterodorsal margin nearly straight to gently convex towards the dorsal side; the anterior margin narrowly rounded; the posterior margin broadly rounded and prolonged in a posteroventral direction; the posterior ridge rounded to indistinct; the umbo projected above the hinge line, moderately prosogyrate; the shell surface ornamented with densely spaced commarginal growth lines all most likely attribute this species to *Sphaerium anderssoni*.

4 Discussion

4.1 Bivalve assemblage and concentration

Based on the abovementioned, the fossil bivalves from the Sinuiju Formation are *Arguniella yanshanensis* (Gu, 1976), *A. lingyuanensis* (Gu, 1976) and *Sphaerium anderssoni* (Choe, 1967). These fossils are characterized by their wide distribution and great abundance. Hence, the specimens are referred to as the *Arguniella yanshanensis–Sphaerium anderssoni* Assemblage, which only consists of three species belonging to two genera. *Arguniella yanshanensis* (Gu, 1976) is most abundant, followed by *A. lingyuanensis* (Gu, 1976); *Sphaerium anderssoni* is comparatively rare. The fossils are not evenly distributed throughout the Sinuiju Formation. Even within the same package of finely laminated layers, the fossil density may vary from extremely high to moderate or low, and some bedding planes may be devoid of fossils.

Bivalve concentrations also exist in the third member and they are not thick (mostly around 20 mm). Most of the concentrations form beds, but some can be referred to as clumps and lenses (Fig. 2). In the bivalve concentrations, there are only two bivalve species, *Arguniella lingyuanensis* and *Arguniella yanshanensis*, and they occur in high abundance (Fig. 2). Usually these bivalves are preserved in the same bed. Besides bivalves, additional organisms preserved have been recorded in the bivalve concentrations, including gastropods and conchostracans (Fig. 2).

Within the finely laminated layers, most of the bivalves and conchostracans are strongly compacted. In the bivalves, mainly the umbonal areas with the greatest convexity were affected, whereas conchostracans are strongly compacted and flattened. Compaction was most likely also responsible for the commonly sheared arrangement of the two valves of *Eosestheria*. Kobayashi and Kusumi (1953) noted a similar arrangement of valves when analyzing conchostracans from eastern Asia. They explained the dislodgement of the two valves as caused by weak currents. A prerequisite is the partial or complete decay of the soft parts (in particular the ligament and muscles) that keeps the two valves connected during life

Fig. 2. Concentration of *Arguniella*. GPSP 20140506 (Scale bar 10 mm).

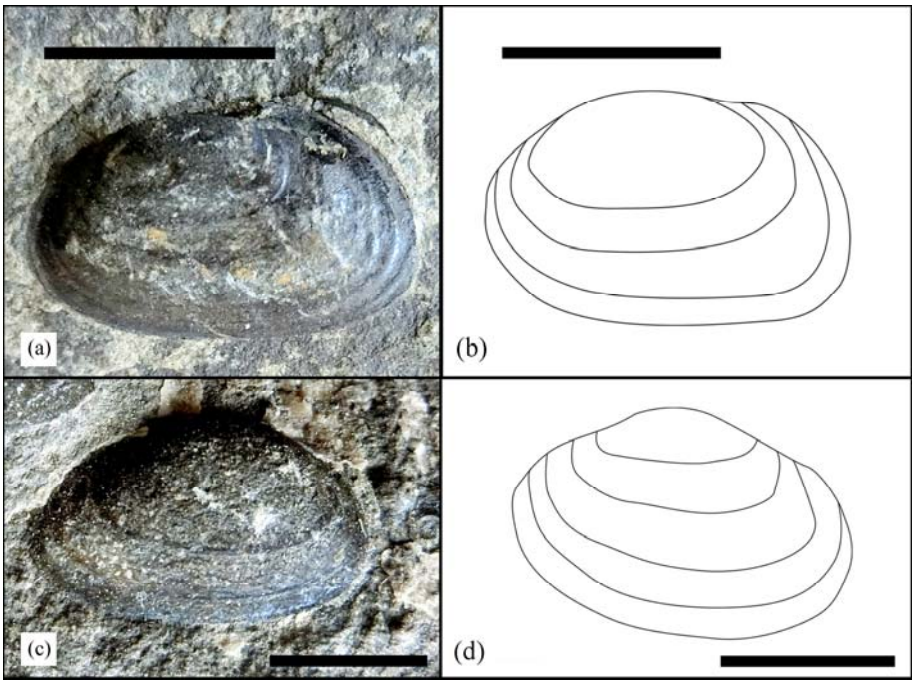

Fig. 3. (a) *Arguniella lingyuanensis* GPSP 20140508; (b) line drawing of GPSP 20140508; (c) *Arguniella yanshanensis* GPSP 20140621; (d) lLine drawing of GPSP 20140621 (Scale bars 10 mm).

(Fürsich et al., 2007; Pan et al., 2012a; Pan et al., 2012b). However, in our case, currents as a causative factor can be ruled out, because not only are the conchostracan valves randomly oriented but also the displacement occurred in all possible directions.

4.2 Correlation and age

4.2.1 *Arguniella–Sphaerium* Assemblage

The *Arguniella–Sphaerium* Fauna and its counterparts are widely distributed in northern and eastern China, Mongolia and the far east of Russia. In northern China, this fauna has been found in the Jehol Group in western Liaoning and northern Hebei (Chen, 1999), the Chengzihe Formation in eastern Heilongjiang (Gu et al. 1997), the Yingzhuilazi, Linzitou, Xiahuapidianzi and Hengtongshan formations in eastern Jilin (Zhu, 1989), the Zhalannuoer Group in the Hailar Basin (Zhao et al. 1980), and the Donglanggou and Dahuichang formations in Beijing city (Bureau of Geology and Mineral Resources of Beijing, 1991). Among the *Arguniella-Sphaerium* Fauna, only *Margaritifera* (Late Triassic?, Early Jurassic–Recent) and *Solenoides* (Early Jurassic–Late Cretaceous) are known from early Jurassic times (Ma, 1996). None of the other genera has been reported from known Jurassic strata to date. Beyond Asia, *Nippononaia* is present in the Barremian (and possibly late Hauterivian) of southern England (Barker et al. 1997) and *Sphaerium* first appears in the Upper Cretaceous in North American (Henderson, 1935; Gray, 1988). The Chengzihe Formation of the Jixi Group in eastern Heilongjiang, northeast China, yields not only the nonmarine *Arguniella—Sphaerium* fauna but also contains fossiliferous marine intercalations. Based on the study of ammonites and marine bivalves, its age and that of its counterparts in eastern Heilongjiang has been considered to range from late Barremian to early Albian, but mainly Aptian (Sha et al. 2002, 2003; Sha, 2007; Futakami et al. 1995; Gu et al. 1997; Jiang and Feng, 2001; Jiang and Cai, 2004; Jiang et al., 2004) (Fig. 5).

Consequently, the inferred age range of the *Arguniella–Sphaerium* Fauna should be considered as being mainly late Barremian–early Albian (Jiang et al., 2007). Many radiometric ages have been obtained from the volcanic rocks using Ar-Ar, K-Ar, U-Pb, and Rb-Sr dating methods in China (Sha, 2007). Most of the resulting dates range between 119 and 133 Ma, with a concentration around 125 Ma (late Barremian–middle Aptian) (Smith et al. 1995; Chen and Chen, 1997; Swisher et al. 1999, 2002). The Fuxin Formation contains the highest known horizon of the *Arguniella–Sphaerium* Fauna (Jiang and Sha, 2006). In Transbaikalia and adjacent areas of Russia, this fauna is distributed in the lower Zhaskoiskii Stage and the upper Osezhinskii Stage (Kolesnikov, 1980). In Mongolia, it is found in the Tormhonskar and Unduruhinskar formations in the central region and in the Shaganshabskii Formation in the southeast (Martinson, 1961; Zaitsev et al. 1975). As a result, the known ages of the *Arguniella–Sphaerium* Fauna range from late Barremian to early Albian. On the basis of species composition and stratigraphic distribution, it can be subdivided into, in ascending order: the *Arguniella yanshanensis–Sphaerium anderssoni*, *Margaritifera* (*Mengyinaia*) *mengyinensis–Nakamuranaia subrotunda* and *Arguniella liaoxiensis–Musculiopsis yixianensis* assemblages (Figs. 4, 5).

The *Arguniella yanshanensis–Sphaerium anderssoni* Assemblage is the lowest one in the *Arguniella–Sphaerium* Fauna and occurs within the Yixian Formation

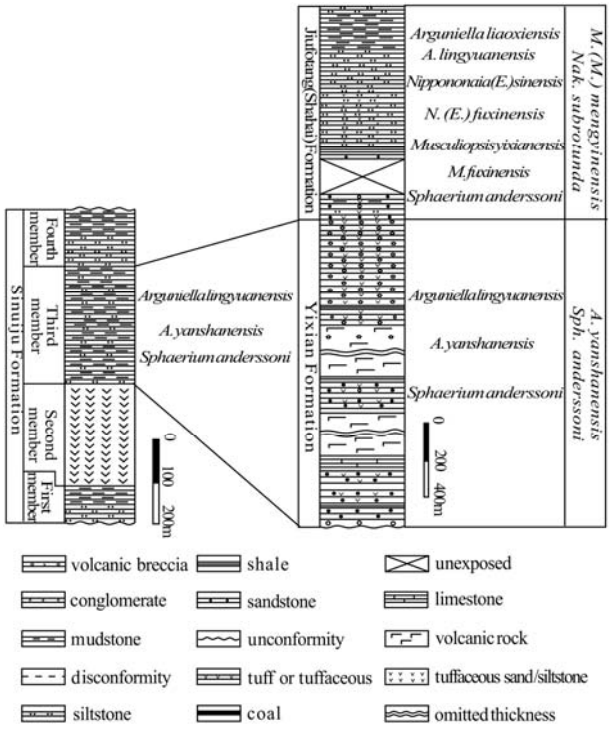

Fig. 4. Distribution of bivalves and their assemblage in the third member of the Sinuiju Formation and correlation with the eastern region of western Liaoning.

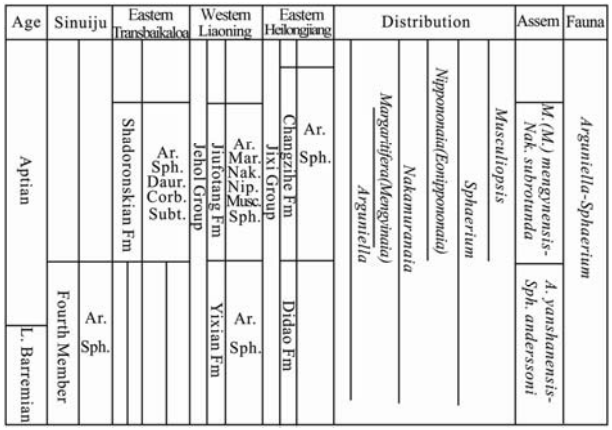

Fig. 5. Correlation of the Sinuiju Formation with its counterparts in adjacent areas based mainly on bivalve assemblages. References for Transbaikalia and eastern Heilongjiang are based on Kolesnikov (1980), Gu et al. (1997) and Jiang et al. (2007), respectively.

Abbreviations: Ar., *Arguniella*; Subt., *Subtilia*; Musc., *Musculiopsis*; Sph., *Sphaerium*; Daur., *Daurinia*; Corb., *Corbicula*; Nak., *Nakamuranaia*; Mar., *Margaritifera*; Nip., *Nippononaia*.

(Fig. 4). It consists of only three species belonging to two genera. Besides the two representative species, the other is *A. lingyuanensis*. *Arguniella yanshanensis* is most abundant, followed by *A. lingyuanensis*, and *Sphaerium anderssoni* is comparatively rare (Jiang et al., 2007). The *Arguniella yanshanensis–Sphaerium anderssoni* Assemblage is dated as late Barremian–early Aptian by radiometric dating, hence the age of the Sinuiju Formation bearing this assemblage is late Barremian to early Aptian (Sha, 2007).

In the study area, the *Arguniella yanshanensis–Sphaerium anderssoni* Assemblage occurs within the Sinuiju Formation and consists of only three species belonging to two genera, of which *A. yanshanensis* is the most abundant, followed by *A. lingyuanensis*; *Sphaerium anderssoni* is comparatively rare.

Although *Arguniella yanshanensis, A. lingyuanensis*, and *Sphaerium anderssoni* also occur in the Jiufotang Formation, the Sinuiju Formation, unlike in the former, does not contain the trigonioidid bivalve *Nippononaia*, and *Musculiopsis liaoningensis* is not preserved (Ma, 1986; Zhu, 1989; Jiang et al., 2007).

Hence the *Arguniella yanshanensis–Sphaerium anderssoni* Assemblage from Paekto-dong is comparable with that from the Yixian Formation.

4.2.2 *E–E–L Assemblage*

Besides the bivalve assemblage, we also have many fossils including the insect *Ephemeropsis*, conchostracans *Eosestheria* and the bony fish *Lycoptera* (Fig. 6). *Ephemeropsis trisetalis* is the most representative fossil insect in the Sinuiju Formation, and also one of the typical fossils of the Jehol Biota (Zhou et al., 2003; Pan et al., 2013). *Lycoptera* is also one of the typical representatives of the Sinuiju Formation. *Eosestheria* is also found in abundance in the Sinuiju Formation. Hence, there exists an assemblage of *Eosestheria–Ephemeropsis–Lycoptera* in the Sinuiju Formation (Fig. 6). These genera are very common in this formation and clearly dominate.

The Jehol Biota of northeastern China is defined as the organisms that lived in the Early Cretaceous volcanic-influenced environments, and were buried in lacustrine and, rarely, fluvial sediments, where most turned into exceptionally preserved fossils. Up to now, it has only been discovered in the Yixian and the Jiufotang formations of western Liaoning and adjacent Inner Mongolia and Hebei, and in the Huajiying Formation of northern Hebei. It is limited to a comparatively small area

Fig. 6. The typical fossils of the Sinuiju Formation in Paekto-dong, Sinuiju City.

(a) *Eosestheria*; (b, c) *Ephemeropsis trisetalis*; (d) pterosaur; (e) *Lycoptera davidii*; (f) *Czekanowskia*. Scale bars=20mm

throughout the Barremian and into the Aptian, i.e. for about 10 Ma.

Since 1976, the Jehol Biota as a lacustrine biota represented by the "*Eosestheria–Ephemeropsis–Lycoptera*" (*E–E–L*) assemblage has gradually been accepted and become well known in China (e.g., Chen, 1988). Zhang et al. (1994) restudied the anatomical characters and morphological variation of the "*Lycoptera longicephalus*" material from the Jiufotang Formation, and revised it as *Jinanichthys longicephalus*. Thus, the temporal range of *Lycoptera*, which has often been regarded as a representative fossil of the Jehol Biota, is now actually limited to the Yixian Formation. Although the aquatic *E–E–L* assemblage probably no longer well represents the composition of the Early Cretaceous terrestrial ecosystem in western Liaoning, a generally accepted and unambiguous definition of the biota is still lacking (Pan et al., 2013).

E–E–L from the Sinuiju Formation is well comparable with *E–E–L* from the Lower Cretaceous strata of western Liaoning. This implies that the Yixian and Jiufotang formations and the Sinuiju Formation are chronologically very close. However, the Sinuiju Formation does not contain the trigonioidid bivalve *Nippononaia*.

Consequently, the Sinuiju Formation is not Jurassic, but Lower Cretaceous, i.e. Barremian and into the Aptian (Jiang et al., 2007).

5 Conclusions

The new nonmarine bivalve assemblage from the Sinuiju Formation of Paekto-dong comprises the following: *Arguniella yanshanensis*, *A. lingyuanensis* and *Sphaerium anderssoni*.

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