

Early Cretaceous nonmarine ostracod biostratigraphy of western Liaoning area, NE China

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ABSTRACT: The Early Cretaceous ostracod fauna in western Liaoning is divided into eight successive ostracod assemblages. These assemblages have provided information about age constraint of relevant nonmarine Early Cretaceous strata: Yixian Formation – Hauterivian to Barremian, probably up to Aptian; Jiufotang Formation – Barremian to Aptian; Fuxin Formation – Aptian; Sunjiawan Formation – Albian. According to the revised age for the upper part of the Yixian Formation in the Kazuo – Chaoyang Basin, which is Hauterivian – Barremian, *Ziziphocypris linchengensis* is the earliest record of the genus *Ziziphocypris*. This work demonstrates that the supra-regionally distributed ostracod species, including species of *Cypridea*, are useful for biostratigraphic correlation and age determination of lacustrine deposits. In contrast, the endemic *Cypridea* species are helpful for regional biostratigraphic correlation of scattered basins within western Liaoning.

Key words: Ostracod assemblage zones, biostratigraphy, nonmarine Lower Cretaceous, northeastern China

INTRODUCTION

Nonmarine Early Cretaceous sedimentary rocks are widely exposed in China, especially in western Liaoning. Lithostratigraphically, they are composed, from base to top, of the Yixian, Jiufotang, Fuxin, and Sunjiawan formations. Particularly the Yixian and Jiufotang formations are famous for its fossil content, the so-called “Jehol Biota”, which consists of abundant remains of well-preserved invertebrates (e.g., ostracods, bivalves, gastropods, and arthropods) and vertebrates (e.g., feathered dinosaurs and birds) (e.g., Chang, Wang and Wang 2003, Zhou, Barrett and Hilton 2003).

Nonmarine ostracods and palynomorphs have proven to be valuable tools for age determination of nonmarine, aquatic and terrestrial strata (e.g., Nichols, Matsukawa and Ito 2006, Hayashi 2006, Sames 2011, Sames and Horne 2012). The taxonomic study of nonmarine ostracods from the Cretaceous sedimentary successions in western Liaoning dates back to 1958 (Hou 1958). Since then, numerous comprehensive studies have been published (Chen 1965, Zhang and Zhang 1982, Zhang 1985, 2004, Zhang, Pu and Wu 1985, Li, Su and Zhang 1988, Zhang et al. 2012, Cao 1999, Wang, Sha and Pan 2013). Besides, different biostratigraphic correlations were proposed by Zhang, Pu and Wu (1985), Zhang (2004), and Cao (1999), respectively. For example, the Yixian Formation was dated as Tithonian (Zhang 1985, Zhang, Pu and Wu 1985) or Tithonian to Berriasian (Cao 1999, Zhang 2004), the Jiufotang Formation as Valanginian to Barremian (Zhang 1985, Zhang, Pu and Wu 1985), the Fuxin Formation as Barremian to Aptian (Zhang, Pu and Wu 1985), and the Sunjiawan Formation as Late Aptian (Zhang, Pu and Wu 1985). In contrast, palynological studies suggest a Valanginian to Hauterivian or Barremian age of the Yixian Formation (Li and Batten 2007). Based on correlation of

nonmarine bivalves and radiometric dating, the ages of the re-

spective formations are much younger and the time span they represent substantially shorter (Sha 2007a, Sha et al. 2007, 2012). The Yixian, Jiufotang, Fuxin, and Sunjiawan formations are given ages of Barremian, Aptian and Albian, respectively (Sha 2007a).

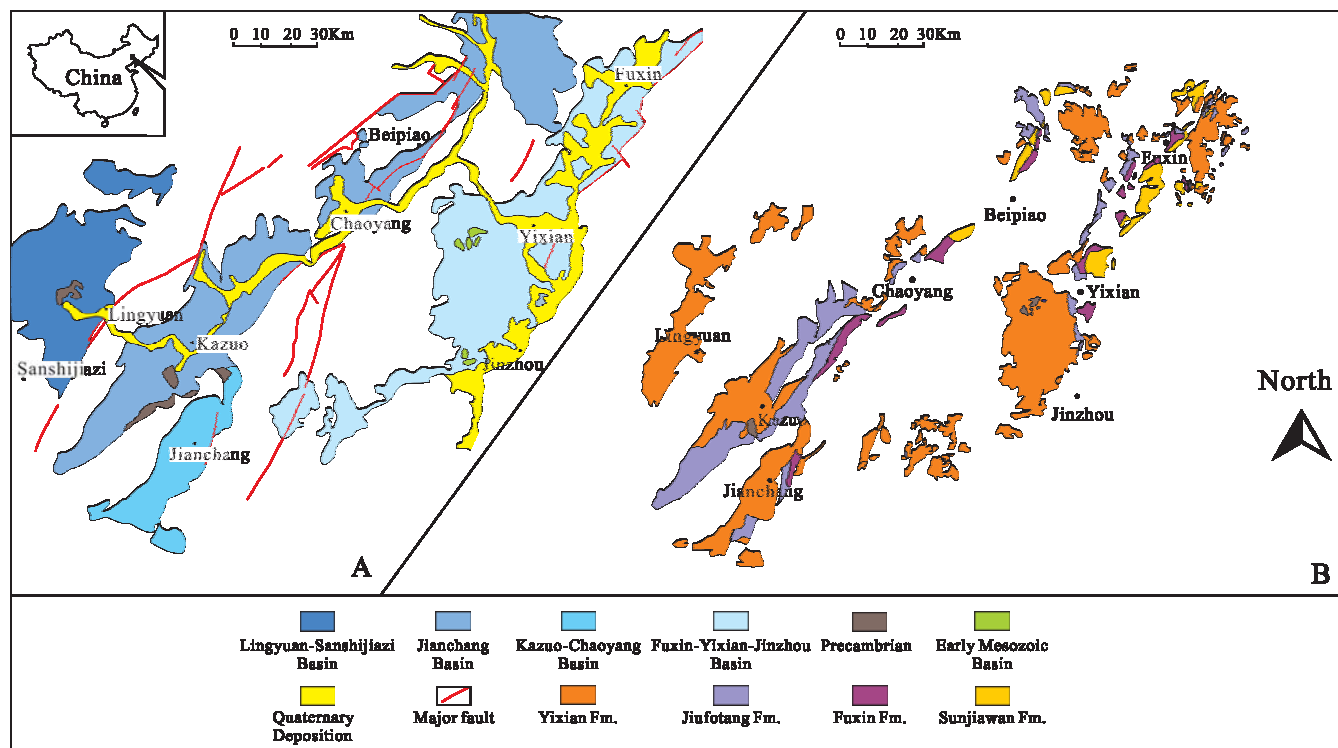
This work provides a synopsis of the state of knowledge on the biostratigraphy and age determination, based on the ostracod fauna from the nonmarine Early Cretaceous deposits in western Liaoning.

GEOLOGICAL SETTING

The investigated area comprises four basins along the Tan – Lu Fault System (Klimetz 1983, Jiang et al. 2010): the Lingyuan – Sanshijiazhi, Kazuo – Chaoyang, Jianchang, and Fuxin – Yixian – Jinzhou basins (Jiang et al. 2010) (text-fig. 1A). The Early Cretaceous rocks are, in ascending order, divided into the Yixian, Jiufotang, Fuxin, and Sunjiawan formations (text-fig. 1B) (Sha 2007a), of which the first three compose the Jehol Group.

Yixian Formation

The Yixian Formation, the lowest unit of the Jehol Group, is well exposed in the Lingyuan area (Lingyuan – Sanshijiazhi Basin), Kazuo area (Kazuo – Chaoyang Basin), Jianchang area (Jianchang Basin), and the southwestern and northeastern parts of the Fuxin – Yixian – Jinzhou Basin. It rests unconformably on the Tuchengzi Formation. The Yixian Formation, deriving its name from “Yixian volcanical rocks” (Gu 1962), consists of nonmarine fluvial/lacustrine deposits dominated by argillaceous lithologies (typically finely laminated silty mudstones), intercalated with numerous horizons of sandstone, limestone, con-



TEXT-FIGURE 1
Distribution of the Mesozoic sedimentary basins (A) and the various lithological units (B) in western Liaoning

glomerate and volcanic rocks such as tuffs (Sha 2007a). Traditionally, the Yixian Formation is informally divided into a lower part and upper part.

In the Fuxin – Yixian – Jinzhou Basin, the Yixian Formation has been divided into six beds (Wang et al. 2004), in ascending orders, the Zhuanchengzi, Laogonggou, Yenangou, Dakangpu, Zhujiagou, and Jingangshan beds (corresponding more or less to members). The commonly used term “Jianshangou Bed” was defined as the lowest bed of the Yixian Formation in Beipiao County yielding exceptionally preserved fossils (e.g., feathered dinosaurs and birds) (Chen et al. 2004). According to Wang et al. (2004), the “Jianshangou Bed” corresponds to the upper part of the Laogonggou Bed. The so-called Lujiatun Bed (Jiang and Sha 2007) is equal to the lower part of Laogonggou Bed in Beipiao County.

Jiufotang Formation

The Jiufotang Formation conformably overlies the Yixian Formation and consists mainly of medium grey to black, light grey, greyish-green, off-white, or yellowish-grey, finely laminated tuffaceous siltstones and shales, silty limestones, fine-grained sandstones, thin-bedded tuffs, medium-grained tuffaceous sandstones, tuffaceous grits and coarse-grained gravelly sandstones (Sha 2007a, Zhang et al. 2007). This formation is divided into a lower and upper member (Wang et al. 1989). It is mainly exposed in the middle and eastern parts of the Kazuo – Chaoyang Basin (text-fig. 1B).

Fuxin Formation

The Fuxin Formation lies conformably on the Jiufotang Formation and is characterized by coal-bearing siliciclastic rocks: sandstone, siltstone, and mudstone (Wang et al. 1989, Sha 2007a). It is divided into a lower and upper member (Zhang, Pu and Wu 1985). Its distribution was originally thought to be restricted to the Fuxin area (text-fig. 1B). However, the Shahai Formation of the southern Yixian area and Kazuo – Chaoyang Basin, and the Binggou Formation of the Jianchang Basin described by Wang et al. (1989) are, according to Jiang et al. (2010), synonyms of the Fuxin Formation. Therefore, the Fuxin Formation is exposed along narrow strips on the eastern edges of Jianchang and Kazuo – Chaoyang basins (text-fig. 1B).

Sunjiawan Formation

The Sunjiawan Formation is well exposed in the Fuxin – Yixian – Jinzhou Basin (text-fig. 1B). It rests unconformably on the Fuxin Formation and is composed of variegated conglomerates and rare intercalations of thin-bedded sandstones, siltstones and mudstones (Wang et al. 1989, Sha 2007a).

MATERIAL AND METHODS

More than 220 ostracod species have been described in western Liaoning by previous authors (e.g., Hou 1958, Chen 1965, Zhang and Zhang 1982, Zhang 1985, 2004, Zhang, Pu and Wu 1985, Cao 1999, Zhang et al. 2012). Admittedly, such a high ostracod species diversity is a considerable overestimation (Wang 2012). During the last ten years, the taxonomy of ostracods from the Yixian, Jiufotang, Fuxin, Sunjiawan formations has been revised by Hou, Gou and Chen (2002), Hou and Gou (2007), Wang (2009, 2012), and Wang, Sha and Pan

Yx		Jft		Fx		Sjw	Formation
L	U	L	U	L	U		
Hau.-Bar.	Bar.-Apt.	Apt.	Apt.-Alb.	Alb.			Stage Ostracod species
							<i>Cypridea muriculata</i> Zhang, 1985*
							<i>Cypridea venustata</i> Su et Li, 1985
							<i>Cypridea liaoningensis</i> (Zhang, 1985)
							<i>Cypridea koskulensis</i> Mandelstam, 1958*
							<i>Cypridea justa</i> Lübmova, 1956*
							<i>Cypridea uncostata</i> Lübmova, 1956
							<i>Cypridea jingangshanensis</i> (Zhang, 1985)
							<i>Cypridea deflecta</i> (Zhang, 1985)
							<i>Cypridea suborhocera</i> Zhang, 1985
							<i>Cypridea ganzhaoensis</i> Su et Li, 1985
							<i>Cypridea gujialingensis</i> Wang, 2012
							<i>Cypridea rostellata</i> Zhang, 1985
							<i>Cypridea decorosa</i> Zhang, 1985
							<i>Cypridea erisopsiformis</i> Zhang, 1985
							<i>Cypridea delnovi</i> (Galeeva, 1955)
							<i>Cypridea jiuftotangensis</i> Zhang, 1985
							<i>Cypridea tersa</i> Zhang, 1985
							<i>Cypridea vitimensis</i> Mandelstam, 1955
							<i>Cypridea robustirostris</i> Zhang, 1985
							<i>Cypridea ellipselloides</i> (Hou, 1958)
							<i>Cypridea jianchangensis</i> (Zhang, 1985)
							<i>Cypridea prognata</i> Lübmova, 1956
							<i>Cypridea echinulata</i> Zhang, 1985
							<i>Cypridea elegantula</i> Zhang, 1985
							<i>Cypridea subelongata</i> Zhang, 1985*
							<i>Cypridea subfracta</i> Zhang, 1985*
							<i>Cypridea regia</i> Lübmova, 1956*
							<i>Cypridea ihsienensis</i> Hou, 1958*
							<i>Cypridea obscurirostrata</i> Zhang, 1985*
							<i>Cypridea tumidiuscula</i> Zhang, 1985
							<i>Cypridea parvispina</i> Zhang, 1982
							<i>Cypridea subconcina</i> Zhang, 1982
							<i>Cypridea echinata</i> (Zhang, 1985)

TEXT-FIGURE 2

Stratigraphical ranges of the *Cypridea* species from western Liaoning (* indicates *Cypridea* species with RV>LV; species names printed in bold and black line indicate index taxa, grey line indicate co-occurred taxa; Yx = Yixian Formation, Jft = Jiufotang Formation, Fx = Fuxin Formation, Sjw = Sunjiawan Formation, L= Lower, U = Upper, Hau. = Hauterivian, Bar. = Barremian, Apt. = Aptian, Alb. = Albian) (after Wang 2013)

(2013). For instance, Wang, Sha and Pan (2013) merged 14 *Cypridea* species into three taxa, based on a large number of samples and detailed analysis of taxonomic features. This way, the number of species has been reduced to 115 (text-figs. 2, 3).

The illustrated ostracod fossils were collected from the Yixian and Jiufotang formations during 2007–2010 from sections near Sihetun (Libalanggou, Dabeigou), Beipiao County (co-ordinates: N41°34'43.5", E120°36'44.5"), Jingangshan (Zaocishan), Yixian County (N41°27'42.4", E121°09'12.8"), Pijiagou of Yixian County (GPS: N41°30'20.9", E121°10'10.4"), Sanguanmiao, Kazuo County (N41°18'44.4", E119°47'59.2"), Liujiawopo, Liyuan County (N41°07'21.9", E119°29'48.8"), and Weijialing, Jianchang County (N40°37'47.3?, E119°30'56.9").

At a small scale, the correlation of different basins of western Liaoning is based on *Cypridea* with short stratigraphic range (text-fig. 2). In fact, most *Cypridea* species display a limited geographic distribution within western Liaoning, which limits their biostratigraphic usefulness. Thus, some widely distributed

non-*Cypridea* species, such as species of *Limnocypridea* and *Ziziphocypris*, are used to determine and constrain the age of the respective strata (text-fig. 3).

BIOSTRATIGRAPHY

Lower part of the Yixian Formation

In the lower part of the Yixian Formation the *Cypridea liaoningensis* – *Damonella circulata* assemblage occurs (Wang 2012). Of the two diagnostic taxa *Damonella circulata* (Plate 1, L) is widely distributed in the Early Cretaceous sediments of China and Mongolia (Hou, Gou and Chen 2002). *Cypridea liaoningensis* (Plate 1, A) has been reported from the first member of the Saihantala Formation of Inner Mongolia. According to Cao (1999) and Wang, Sha and Pan (2013), *Cypridea miniflexicostata* Gou et al. (1986) shares the diagnostic features with *Cypridea liaoningensis* and therefore is a synonym of the latter. The Saihantala Formation shares 38% of the species of *Cypridea* with the lower part of the Zuunbayan Formation of the eastern Gobi area. Thus, both lithostratigraphic units can be well correlated (Gou et al. 1986). According to Vasilev et al.

(1959), the Shinekhudag Formation (Vasilev et al. 1959, Shuvalov 1975, 2000) of the eastern Gobi is equal to the lower part of the Zuunbayan Formation. Its age was suggested to be Hauterivian – Barremian (Khand et al. 2000). The Shinekhudag Formation originally has also been reported from southwestern Mongolia (Choyr Basin) (Matsukawa et al. 1997), but the rock succession has been renamed as Khuren Dukh Formation by Ito, Matsukawa and Nichols (2006), who assigned it a different age from that of the Shinekhudag Formation of the eastern Gobi, the presence of *Asteropollis asteroides* and co-occurring pollen of *Tricolpites* indicating an Albian age (Nichols, Matsukawa and Ito 2006, Sha et al. 2006). Since none of the ostracod species reported from the Khuren Dukh Formation of the Choyr Basin were found in the Saihantala Formation or Yixian Formation, the lower part of the Yixian Formation correlates with the Shinekhudag Formation of the eastern Gobi, rather than with the Khuren Dukh Formation of the Choyr Basin. Therefore, on the basis of ostracod fauna, an Hauterivian – Barremian age of the lower part of the Yixian Formation is suggested here.

Radiometric and palaeomagnetic dates of the lower part of the Yixian Formation give an age around the Hauterivian – Aptian time interval, mainly Barremian (Smith et al. 1995, Zhu et al. 2002, 2007, Zhou, Barrett and Hilton 2003, Yang, Li and Jiang 2007, Chang et al. 2009), which is consistent with the biostratigraphic data. It constrains the age of the lower part of the Yixian Formation to the Hauterivian – Barremian, mainly Barremian.

Upper part of the Yixian Formation and lower member of the Jiufotang Formation

In the Fuxin – Yixian – Jinzhou Basin, only three species were found in the upper part of the Yixian Formation, *Cypridea deflecta* (Plate 1, B), *C. jingangshanensis* (Plate 1, C), and *Lycopteroocypris infantilis* (Plate 1, J). The lower member of the Jiufotang Formation in the Fuxin – Yixian – Jinzhou Basin contains *Cypridea deflecta*, *Cypridea rostellata*, *Lycopteroocypris infantilis*, and *Alicenula contracta*. *Cypridea deflecta* and *Lycopteroocypris infantilis* are the most abundant taxa in both the upper part of the Yixian Formation and the lower member of the Jiufotang Formation. An assemblage of *Cypridea deflecta* – *Lycopteroocypris infantilis* is proposed herein. *Cypridea deflecta* is endemic to western Liaoning, and therefore cannot be used to constrain the age succession. *Lycopteroocypris infantilis* is widespread in Early Cretaceous strata of Mongolia, China, and Russia (Hou, Gou and Chen 2002), but have a long geologic range.

In the Kazuo – Chaoyang Basin, there is a stratigraphic unit which is regarded as the upper part of the Yixian Formation. It forms an unconformity with the underlying Cambrian rocks and is covered by volcanic rocks (Wang et al. 2004). *Cypridea liaoningensis*, *Cypridea ganzhaoensis* (Plate 1, E), *Cypridea gujialingensis* (Plate 1, F), *Cypridea semiovata*, *Ziziphocypris linchengensis* (Plate 1, M), *Djungarica camarata*, and *Rhinocypris tugurigenensis* have been described from this unit. Among them, *Cypridea liaoningensis* indicates an Hauterivian – Barremian age (see discussion in the section Lower part of the Yixian Formation); *Ziziphocypris linchengensis* first appeared (which is also the earliest record of the genus *Ziziphocypris*); *Cypridea gujialingensis* is the most abundant element. The *Cypridea liaoningensis* – *Ziziphocypris linchengensis* – *Cypridea gujialingensis* assemblage is established here, with an Hauterivian – Barremian age. Based on the lithostratigraphic

features this unit is the upper part of the Yixian Formation (Wang et al. 2004), but the ostracod evidence does not allow the biostratigraphic discrimination from the lower part of the Yixian Formation of western Liaoning.

In the Kazuo – Chaoyang Basin, only two species are recognized: *Cypridea deflecta* and *Lycopteroocypris liaoxiensis* from the lower member of the Jiufotang Formation. Accordingly, the *Cypridea deflecta* – *Lycopteroocypris liaoxiensis* assemblage is proposed here. Both species are endemic to western Liaoning, and therefore not suitable to constrain the age. However, this assemblage is similar to the *Cypridea deflecta* – *Lycopteroocypris infantilis* assemblage of the Fuxin – Yixian – Jinzhou Basin, as they share one index element, *Cypridea deflecta*.

So far, no radiometric or palaeomagnetic dates are available for the upper part of the Yixian Formation and the lower member of the Jiufotang Formation. Moreover the ostracod fauna from these two stratigraphic units are not helpful for age determination, except for the upper part of the Yixian Formation in the Kazuo – Chaoyang Basin (assigned an Hauterivian – Barremian age based on the *Cypridea liaoningensis* – *Ziziphocypris linchengensis* – *Cypridea gujialingensis* assemblage). Considering that the upper part of the Yixian Formation and the lower member of the Jiufotang Formation are sandwiched between the lower part of the Yixian Formation (Hauterivian – Barremian) and the upper member of the Jiufotang Formation (Aptian, see discussion in the section Upper member of the Jiufotang Formation), their age should be Barremian – Aptian.

Upper member of the Jiufotang Formation

The upper member of the Jiufotang Formation is characterized by the highest diversity of ostracod species (text-figs. 2, 3) in all of western Liaoning. Sixty-five species have been recorded so far, such as *Limnocypridea grammi* (Plate 1, I), *Scabriculocypris pingquanensis* (Plate 1, K), *Ziziphocypris costata* (Plate 1, N), *Z. simakovi* (Plate 1, O) and *Cypridea delnovi* (Plate 1, D), which all occur in high abundances. They represent the newly established *Limnocypridea grammi* – *Scabriculocypris pingquanensis* – *Cypridea delnovi* assemblage.

Limnocypridea grammi and *Cypridea delnovi* have been described by Lübmova (1956) and Galeeva (1955) from the Zuunbayan Formation of the eastern Gobi. The Zuunbayan Formation is considered as being Hauterivian – Albian in age (Khand 2000). *Scabriculocypris pingquanensis* has been reported from the Xiguayuan Formation of Hebei province (Hou, Gou and Chen 2002), which is Barremian – Aptian in age (Wang et al. 2012). Thus, the index elements suggest a Barremian – Aptian age for the *Limnocypridea grammi* – *Scabriculocypris pingquanensis* – *Cypridea delnovi* assemblage.

The age of the assemblage is supported by *Ziziphocypris simakovi* and *Ziziphocypris costata*, which co-occur with the index elements. The genus *Ziziphocypris* has been proposed by Chen (1965), on the basis of the specimens from the upper member of the Jiufotang Formation, and some species were originally assigned to the genus *Timiriasevia* by Galeeva (1955). According to Galeeva (1955), the species *Ziziphocypris costata* (= *Timiriasevia costata*) and *Z. simakovi* (= *Timiriasevia simakovi*) occur in the Upper Cretaceous of Mongolia. *Ziziphocypris costata* was found in the Nemegt Formation of Mongolia (Szczechura 1978), which is Maastrichtian in age (Khand 2000, Khand, Sames and Schudack 2007). In Korea,

Yx		Jft		Fx		Sjw	Formation
L	U	L	U	L	U		
Hau.-Bar.	Bar.-Apt.	Apt.		Apt.-Alb.		Alb.	Stage / Ostracod species
							<i>Candona praevara</i> (Zhang, 1982) <i>Candona subprona</i> Zhang, 1985 <i>Candona piflagouensis</i> Zhang, 1985 <i>Candona subprona</i> Zhang, 1985 <i>Candona yixianensis</i> Zhang, 1985 <i>Candona postirecta</i> Zhang, 1982 <i>Candona? dongliangensis</i> Zhang, 1982 <i>Candona rectangulata</i> Hao, 1974 <i>Candona curtalia</i> Zhang, 1982 <i>Candona</i> sp.
							<i>Limnocypridea jianchangensis</i> Su et Li, 1985 <i>Limnocypridea shundensis</i> Sinitaa <i>Limnocypridea bicornuta</i> Zhang, 1985 <i>Limnocypridea redunda</i> Zhang, 1985 <i>Limnocypridea propria</i> Zhang, 1985 <i>Limnocypridea tulongshanensis</i> Zhang, 1985 <i>Limnocypridea postcontracta</i> Zhang, 1985 <i>Limnocypridea grammis</i> Lübmova, 1956 <i>Limnocypridea levigata</i> Zhang, 1985 <i>Limnocypridea rara</i> Zhang, 1985 <i>Limnocypridea qinghemensis</i> Zhang, 1985 <i>Limnocypridea subreticulata</i> Zhang, 1985 <i>Limnocypridea elliptica</i> Zhang, 1982
							<i>Rhinocypris jurassica</i> (Martin, 1940) <i>Rhinocypris tugurigenis</i> (Lübmova, 1956) <i>Rhinocypris ulanbubensis</i> (Wang et Gou, 1986) <i>Rhinocypris echinata</i> (Mandelstam, 1963) <i>Rhinocypris pluscula</i> Li, 1974
							<i>Mongolianella zerussata</i> Zhang, 1985 <i>Mongolianella subtrapezoidea</i> Yang, 1981 <i>Mongolianella yixianensis</i> Zhang, 2004 <i>Mongolianella breviscula</i> Zhang, 2004 <i>Mongolianella sandaohaoensis</i> Zhang, 2004 <i>Mongolianella? laogongouensis</i> Zhang, 2004 <i>Mongolianella palmosa</i> Mandelstam, 1956
							<i>Mongolocypris yangtutunensis</i> (Zhang, 1985) <i>Mongolocypris kleinbergi</i> (Galeeva) <i>Mongolocypris globra</i> (Hou, 1958) <i>Mongolocypris? hatzhouensis</i> (Zhang, 1985) <i>Mongolocypris limpida</i> (Zhang, 1985)
							<i>Ziziphocypris hanchengensis</i> Su et Li, 1981 <i>Ziziphocypris simakovi</i> (Mandelstam, 1956) <i>Ziziphocypris costata</i> (Galeeva, 1955) <i>Ziziphocypris bicarinata</i> Zhang, 1985
							<i>Metacypris jianshangouensis</i> (Zhang, 1985) <i>Metacypris corcava</i> (Zhang, 1985) <i>Metacypris eminula</i> (Zhang, 1985) <i>Metacypris ventriflata</i> (Zhang, 1985) <i>Metacypris liaoxiensis</i> (Zhang, 1982)
							<i>Chellocypridea trapezoidea</i> Zhang, 1985 <i>Zonocypris expansa</i> (Tian, 1982)
							<i>Scabriculocypris pingquanensis</i> (Yang, 1985) <i>Scabriculocypris toutaiensis</i> (Zhang, 1985)
							<i>Yumenia acutiuscula</i> (Zhang, 1985) <i>Djungarica camarata</i> Zhang, 1985 <i>Djungarica procurva</i> Zhang, 1985 <i>Djungarica circulitriangula</i> Zhang, 1985
							<i>Lycoperocypris infantilis</i> (Lübmova, 1956) <i>Lycoperocypris debilis</i> (Lübmova, 1956) <i>Lycoperocypris liaxiensis</i> (Zhang, 1985) <i>Lycoperocypris sinuolata</i> (Zhang, 1985)
							<i>Damonella circulata</i> (Lübmova, 1956) <i>Damonella extensa</i> Wu et Yang, 1980 <i>Damonella subsymmetrica</i> Zhang, 1985 <i>Damonella semitrotunda</i> (Zhang, 1985)
							<i>Clinocypris</i> cf. <i>scolia</i> Mandelstam, 1956 <i>Clinocypris anterogrossa</i> Zhang, 1985 <i>Clinocypris oblique truncata</i> Zhang, 1985
							<i>Bisulcoocypridea edentula</i> (Ye, 1976) <i>Bisulcoocypridea</i> sp.
							<i>Yanshanina dabeigouensis</i> (Yang, 1981)
							<i>Mantelliana grandis</i> Zhang, 1985 <i>Mantelliana pustulosa</i> Zhang, 1985 <i>Mantelliana papulosa</i> (Zhang, 1985) <i>Mantelliana maxima</i> (Zhang, 1985)
							<i>Candoniella mordvilkoii</i> Mandelstam, 1963 <i>Candoniella bitruncata</i> Zhang et Zhang, 1982
							<i>Triangulocypris maxima</i> Zhang, 1985 <i>Triangulocypris longissima</i> Zhang, 1985
							<i>Alicenula leguminella</i> (Forbes, 1885) <i>Alicenula contracta</i> (Mandelstam, 1956) <i>Alicenula oblonga</i> (Roemer, 1839)

TEXT-FIGURE 3

Stratigraphical ranges of the non-Cypridea species from western Liaoning (species names printed in bold and black line indicate index taxa, grey line indicate co-occurred taxa; Yx = Yixian Formation, Jft = Jiufotang Formation, Fx = Fuxin Formation, Sjw = Sunjiawan Formation, L = Lower, U = Upper, Hau. = Hauterivian, Bar. = Barremian, Apt. = Aptian, Alb. = Albanian) (modified from Wang 2013).

Choi (1990) described a few new species of *Ziziphocypris* from the Aptian – Albian Daegu and Geoncheonri formations, and the Albian to the earliest Late Cretaceous Iljig Formation. In Japan, Cao (1996) reported *Z. simakovi* from the Yamaji Shale of the Early Cretaceous Inakura Formation and *Z. costata* from the Early Cretaceous Ohmi Formation. Based on the *Cypridea* species from the Yamaji Shale, Cao (1996) suggested that the shale is older than the Guantou Formation but younger than the Shouchang Formation of Zhejiang, China. In China, *Z. simakovi* has a wide distribution: it is known from the Shouchang and Guantou formations of Zhejiang province (Ye, Gou and Cao 1980); the Qingshankou, Yaojia, Mingshui and Sifangtai formations of the Songliao Basin (Ye et al. 2002); the Jiadian Formation of Hubei province (Hou, He and Ye 1978); the Puchanghe Formation of Yunnan province (Ye et al. 1977). Most of these formations have been referred to as being Late Cretaceous (Hou, He and Ye 1978, Ye et al. 2002, Hou, Gou and Chen 2002), except for the upper part of the Shouchang and Guantou formations (Jiang et al. 1993, Shou 1995, Hou, Gou and Chen 2002). The Shouchang Formation corresponds agewise to “Wealden” (Li 1989), which is Hauterivian – Aptian in age according to Horne (2009). Radiometric dates results of the Shouchang and Guantou formations give ages of 122 Ma (Aptian) (in Wan et al. 2007), and 113 to 103 Ma (mainly Albian) (Luo and Yu 2004), respectively. Sha (2007b) proposed an Aptian age for the Guantou Formation, based on trigonioidid (bivalve) assemblages. An Aptian age is accepted here for the Shouchang Formation and an Aptian – Albian age for the

Guantou Formations. *Z. costata* also has been mentioned from several Early Cretaceous formations such as the Guantou (Ye, Gou and Cao 1980, Jiang et al. 1993, Shou 1995), Hekou, and Xiguayuan formations (Hou, Gou and Chen 2002). The Hekou and Xiguayuan formation are considered to be Early Cretaceous in age (Hao et al. 1983, Yang 1979, Zheng et al. 2011). Reliable fossil records of both *Z. simakovi* and *Z. costata* are not earlier than Aptian. Therefore, the age of the *Limnocypridea grammis* – *Scabriculocypris pingquanensis* – *Cypridea delnovi* assemblage should be Aptian. Zircon from the tuffs within the upper member of the Jiufotang Formation produced an age of 120.3 ± 0.7 Ma (Aptian) (He et al. 2004). The combined biostratigraphic and radiometric data suggest that the upper member of the Jiufotang Formation is Aptian in age.

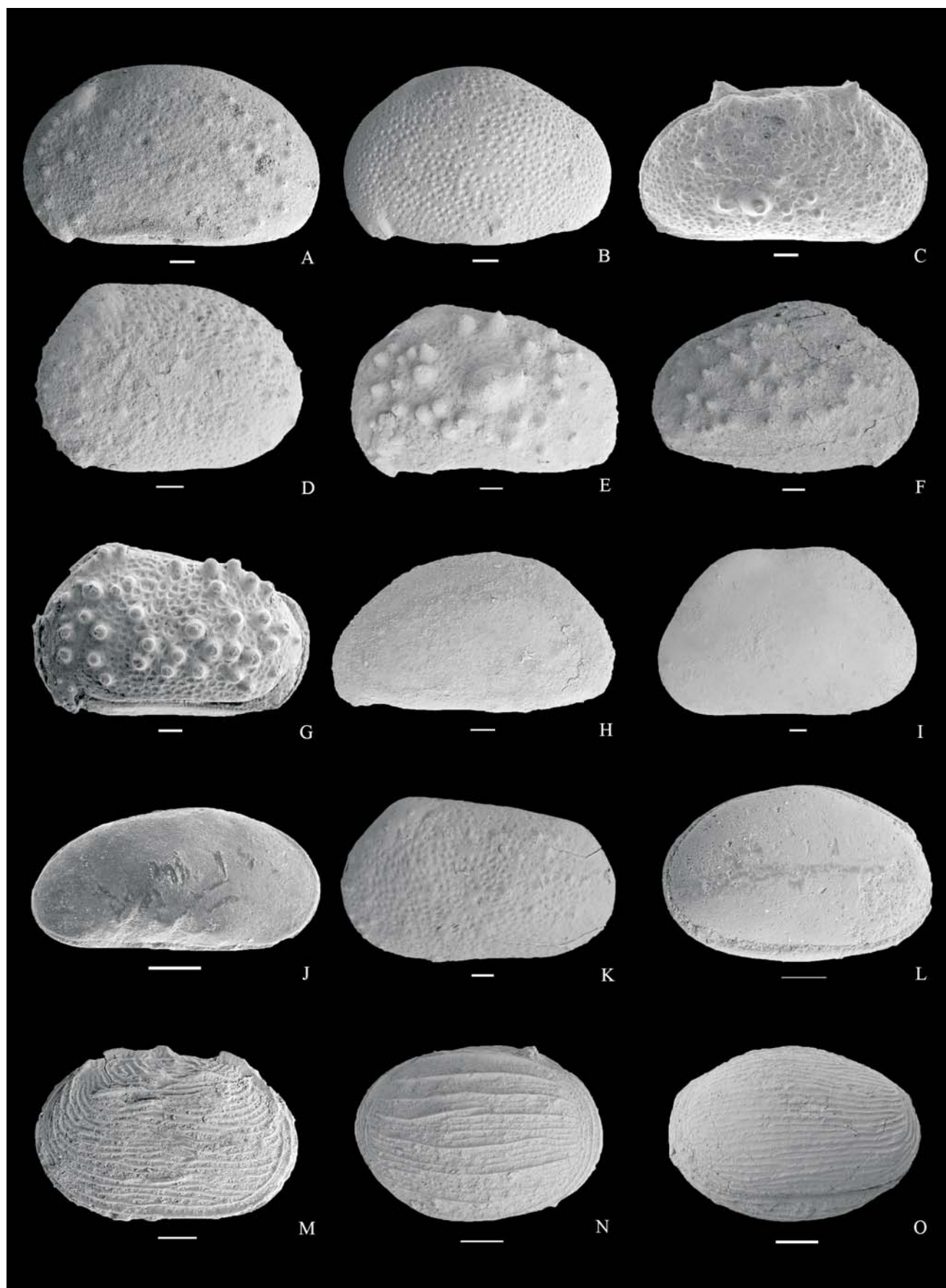
Fuxin Formation

Two assemblages are recognized in the Fuxin Formation, the *Pinnocypridea dictyodroma* – *Mantelliana palmosa* – *Cypridea tumidiusula* assemblage (corresponding to the lower member of the Fuxin Formation) and the *Mongolocypis globra* – *Candona? dongliangensis* assemblage (corresponding to the upper member of the Fuxin Formation) (Zhang, Pu and Wu 1985). According to Hou, Gou and Chen (2002), *Pinnocypridea dictyodroma* is a synonym of *Mongolocypis kleinbergi*. Accordingly, the assemblage has been changed into *Mongolocypis kleinbergi* – *Mantelliana palmosa* – *Cypridea tumidiusula*. Zhang, Pu and Wu (1985) pointed out that the Fuxin Formation is Barremian – Aptian in age, based on species

PLATE 1

Selected species from the Yixian and Jiufotang formations of western Liaoning. Scale bars represent 100µm

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| <p>A <i>Cypridea liaoningensis</i>, left view of carapace (Yixian Formation, Dabeigou of Beipiao County, sample DBG-1);</p> <p>B <i>C. deflecta</i>, left view of carapace (Yixian Formation, Jingangshan of Yixian County, sample JGS-3);</p> <p>C <i>C. jingangshanensis</i>, right view of carapace (Yixian Formation, Jingangshan of Yixian County, sample JGS-3);</p> <p>D <i>C. delnovi</i>, left view of carapace (Jiufotang Formation, Pijiagou of Yixian County, sample PJG-5);</p> <p>E <i>C. ganzhaoensis</i>, left view of valve (Yixian Formation, Sanguanmiao of Kazuo County, sample SGM-3);</p> <p>F <i>C. gujialingensis</i>, right view of carapace (Yixian Formation, Gujialing of Kazuo County, sample GJL-7);</p> <p>G <i>C. justa</i>, left view of carapace (Jiufotang Formation, Pijiagou of Yixian County, sample PJG-5);</p> <p>H <i>Cheilocypridea trapezoidea</i>, left view of carapace (Jiufotang Formation, Pijiagou of Yixian County, sample PJG-5);</p> | <p>I <i>Limnocypridea grammis</i>, left view of carapace (Jiufotang Formation, Tulunshan of Yixian County, sample TLS-2);</p> <p>J <i>Lycoperocypris infantilis</i>, right view of carapace (Yixian Formation, Jingangshan of Yixian County, sample JGS-3);</p> <p>K <i>Scabriculocypris pingquanensis</i>, left view of carapace (Jiufotang Formation, Tulunshan of Yixian County, sample TLS-4);</p> <p>L <i>Damonella circulata</i>, right view of carapace (Yixian Formation, Jianshangou of Beipiao County, sample JSG-3);</p> <p>M <i>Ziziphocypris linchengensis</i>, right view of valve (Yixian Formation, Sanguanmiao of Kazuo County, sample SGM-6);</p> <p>N <i>Z. costata</i>, left view of carapace (Jiufotang Formation, Pijiagou of Yixian County, sample PJG-5);</p> <p>O <i>Z. simakovi</i>, right view of carapace (Jiufotang Formation, Pijiagou of Yixian County, sample PJG-5)</p> |
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of *Candona* and *Candoniella*, which all occur in higher abundances than in the Barremian Jiufotang Formation. However, the underlying Jiufotang Formation is Aptian in age and the overlying Sunjiawan Formation is Early Albian, which has been supported by the biostratigraphy and radiometric dating. Thus, an Aptian – Albian age is suggested for the Fuxin Formation and for the *Mongolocypis kleinbergi* – *Mongolianella palmosa* – *Cypridea tumidiusula* and *Mongolocypis globra* – *Candona? Dongliangensis* assemblages.

Sunjiawan Formation

Zhang, Pu and Wu (1985) recognized the *Cypridea echinata* – *Cypridea (Bisulcocypridea) edentula* – *Triangulicypris* assemblage from the Sunjiawan Formation. *Bisulcocypridea* was first described from Late Aptian strata of North America as a subgenus of *Cypridea* (Sohn 1969), and has been raised to genus level (Hou, Gou and Chen 2002, Horne and Colin 2005, Sames 2011).

Bisulcocypridea is adopted as a genus here. Accordingly, the assemblage has been changed into *Cypridea echinata* – *Bisulcocypridea edentula* – *Triangulicypris*. *Bisulcocypridea* is quite common in the Upper Cretaceous sediments of China (Hou, Gou and Chen 2002), while in Lower Cretaceous strata it is rare. Jiang et al (1993) reported the occurrence of *Bisulcocypridea* from the Guantou Formation (Aptian – Albian) of Zhejiang province. Zhang, Pu and Wu (1985) compared the ostracod fauna from the Sunjiawan Formation to that from the Quantou Formation of the Songliao Basin and found out that all the genera of the Sunjiawan Formation occur also in the Quantou Formation. As a result, Zhang, Pu and Wu (1985) assigned the Sunjiawan Formation an Aptian age. However, the age of the Quantou Formation has been restudied (e.g. Sha 2007a, Huang et al. 2009, Wan et al. 2013), and an Albian – Turonian instead of an Aptian age has been suggested. Therefore, the ostracod fauna suggests that the Sunjiawan Formation is Albian – Cenomanian. As the overlying volcanic Daxingzhuan Formation had K/Ar ages of 93.32 ± 1.96 and 109.7 ± 1.0 Ma, this means that the Daxingzhuan Formation is Late Albian to Turonian in age (Zhu et al., 2002). Therefore, we assign the Sunjiawan Formation to the Lower Albian.

DISCUSSION

The re-evaluation of the ostracod biostratigraphy gives younger ages of the Yixian, Jiufotang, Fuxin, and Sunjiawan formations than the results of previous biostratigraphy studies on ostracods. There are several reasons for the conflicting ages.

Firstly, many ostracod taxa were incorrectly assigned. This directly influenced the results of biostratigraphic correlations and age determinations (for taxonomic revisions see Hou, Gou and Chen 2002, Wang 2009, 2012, Wang, Sha and Pan 2013). In this paper, we follow the revised taxonomy of these authors.

Secondly, the biostratigraphy framework of the formations under discussion and some of their Early Cretaceous correlates of western Liaoning has been revised, such as the Didao Formation and Zhidan Group (in Zhang, Pu and Wu 1985). An Early Cretaceous age instead of a Jurassic age is now accepted for the Didao Formation (Sha 2007a, Sha et al. 2007). A Barremian rather than Valanginian to Barremian age is suggested for the Zhidan Group according to new biostratigraphic correlations based on ostracods (Wang et al. 2012). All that updated information is considered in this work.

Thirdly, ostracod-based stratigraphic correlation should be applied using the same species. Some previous researchers used different species for correlations, which needs to be reevaluated. For example, Zhang, Pu and Wu (1985) and Cao (1999) correlated the Yixian Formation to the Purbeck beds (Purbeck Limestone Formation) of southern England, based on two different species *C. liaoningensis* (Yixian Formation) and *C. granulosa* (Purbeck Limestone Formation). The illustrations of *C. granulosa* (Anderson 1985, pl. 3, figs. 8, 12, Horne 2009, pl. 3, fig. 4) show an obvious rostrum and cyathus, a deep and elongate alveolar furrow, and a declining dorsal margin, which clearly differs from *C. liaoningensis* (Wang, Sha and Pan 2013). Thus, the correlation of the Yixian Formation with the Purbeck successions of Europe is not based on convincing evidence.

Fourthly, the biostratigraphic potential of non-*Cypridea* taxa has been neglected previously. For example, the species of the genus *Ziziphocypris* are biostratigraphically useful (see discussion in the section Upper member of the Jiufotang Formation).

The revised Early Cretaceous ostracod biostratigraphy of western Liaoning suggests that *Ziziphocypris* might have originated from western Liaoning. In Mongolia, the earliest record of *Ziziphocypris* species is Aptian – Albian (Khand 2000); in Korea and Japan, the earliest record of *Ziziphocypris* species is Aptian – Albian (Choi 1990, Cao 1996). In China, *Ziziphocypris linchengensis* from the upper part of the Yixian Formations of the Kazuo – Chaoyang Basin is the earliest record of the genus *Ziziphocypris*, and according to our study its age is Hauterivian – Barremian. Plate tectonics, paleogeography and paleoclimate should be considered for the reconstruction of origin, evolution and spreading directions of nonmarine ostracods, which needs further studies.

The genus *Mongolocypis* has been described from the Maastrichtian Nemegt Formation of Nemegt Basin, Mongolia, by Szczechura (1978). Khand (2000) regarded this genus as an index element of Upper Cretaceous rocks in Mongolia. In China, in contrast, *Mongolocypis* is widely distributed in the Lower Cretaceous strata (Hou, Gou and Chen 2002), but no precise age has yet been given. In western Liaoning, species of *Mongolocypis* already occur in the upper member of the Jiufotang Formation, whose revised age is Aptian. This is the first precise age date for the occurrence of *Mongolocypis* species in China.

CONCLUSIONS

Available ostracod-based biostratigraphic data provide much new information on the age of the Yixian, Jiufotang, Fuxin, and Sunjiawan formations: Yixian Formation – Hauterivian to Barremian, probably up to Aptian; Jiufotang Formation – Barremian to Aptian; Fuxin Formation – Aptian; Sunjiawan Formation – Albian. This study demonstrates the utility and potential of ostracods as a tool for nonmarine biostratigraphic correlation. Widespread species including species of *Cypridea* but also of other genera than *Cypridea* can be used for supraregional biostratigraphic correlations and age determinations of the Cretaceous lacustrine deposits. In addition, the endemic *Cypridea* species have proven to be useful for regional biostratigraphic correlation of the scattered nonmarine Cretaceous basins in NE China.

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