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Authors: Jing, Xiuchun, Zhou, Hongrui, and Wang, Xunlian

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Conodont biostratigraphy of the Gongwusu Formation (Upper Ordovician) in the Wuhai area of Inner Mongolia, North China

XIUCHUN JING[1,2], HONGRUI ZHOU[2] AND XUNLIAN WANG[1,2]

[1]*State Key Laboratory of Geobiology and Environmental Geology, China University of Geosciences, Beijing 100083, China (e-mail: jxch@cugb.edu.cn)*
[2]*School of Earth Sciences and Resources, China University of Geosciences, Beijing 100083, China*

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Abstract. **A well preserved Late Ordovician conodont fauna of 18 species has been recovered from seven limestone samples of the Gongwusu section in the Wuhai area of Inner Mongolia, North China. This conodont fauna is composed of *Ansella* sp., *Belodina monitorensis*, *Coelocerodontus trigonius*, *Complexodus* sp., *Dapsilodus viruensis*, *Drepanoistodus* sp., Gen. et sp. indet, *Oslodus semisymmetricus*, *Panderodus gracilis*, *Periodon* cf. *aculeatus*, *Protopanderodus* cf. *cooperi*, *P. varicostatus*, *Protopanderodus* sp., *Pseudooneotodus mitratus*, *Scabbardella altipes*, *Venoistodus* cf. *balticus*, *Yaoxianognathus* sp. A, and *Yaoxianognathus* sp., and shows a mixture of North Atlantic, North China and North American Midcontinent affinities. The presence of *Belodina monitorensis*, *Periodon* cf. *aculeatus*, *Protopanderodus varicostatus*, *Scabbardella altipes* and *Yaoxianognathus* sp. A in the fauna indicates an early Sandbian (late Sa1) age. The fauna is dominated by *Periodon* cf. *aculeatus*, *Scabbardella altipes* and *Panderodus gracilis* and these together with the occurrence of *Protopanderodus* species, *Drepanoistodus* sp. and *Ansella* sp. characterize the *Periodon* Biofacies, typical of a deeper water (upper slope) setting. Because of its slope habitat, the Gongwusu fauna differs from the contemporaneous faunas reported from the interior North China Platform, but shows a similarity to the coeval faunas in Baltoscandia, South China and Argentina.**

Key words: biostratigraphy, conodonts, Gongwusu Formation, North China, Upper Ordovician

Introduction

Late Ordovician conodont faunas are relatively rare in North China, where they are mainly confined to the platformal Fengfeng Formation composed of shallow-water carbonates (e.g. An *et al*., 1983) and to the Upper Ordovician formations the strata of which accumulated in the platform margin to slope settings (e.g. Lin *et al*., 1984; Wang and Luo, 1984; An and Zheng, 1990). The Fengfeng Formation is mainly distributed in the central North China carbonate platform, while the deep-water Upper Ordovician formations are extensively exposed along the southwestern and northern margins of the North China Craton (e.g. Feng *et al*., 2004, 2014; Zhen *et al*., 2016). The Wuhai area was located on the western slope of the North China Craton in the early Late Ordovician (Figure 1), and consists of fossiliferous carbonate and clastic sedimentary rocks with a total thickness of *ca.* 285 m (An and Zheng, 1990). These Upper Ordovician strata are assigned to the upper part of the Wulalike, Lashizhong, Gongwusu and Sheshan formations (An and Zheng, 1990; Wang *et al*., 2013a; Jing *et al*., 2015).

The present study centers on the Gongwusu Formation. So far, there have been several reports and descriptions of graptolites, conodonts and trilobites (Lin, 1980; Chen *et al*., 1984; Wang and Luo, 1984; An and Zheng, 1990) from the Gongwusu Formation in the Wuhai area. The present authors investigated the Gongwusu Formation of the Wuhai area in August of 2011. New conodont collections from this formation are from the type section for the Gongwusu Formation and provide significant new information on genera and species occurrences and ranges, and necessitate revisions of and additions to the biostratigraphic data provided previously.

Regional geological and stratigraphic setting

The North China Craton, the largest and oldest cratonic block in China, is bounded in the north by the Central Asian Orogenic Belt and in the south by the Qinling-

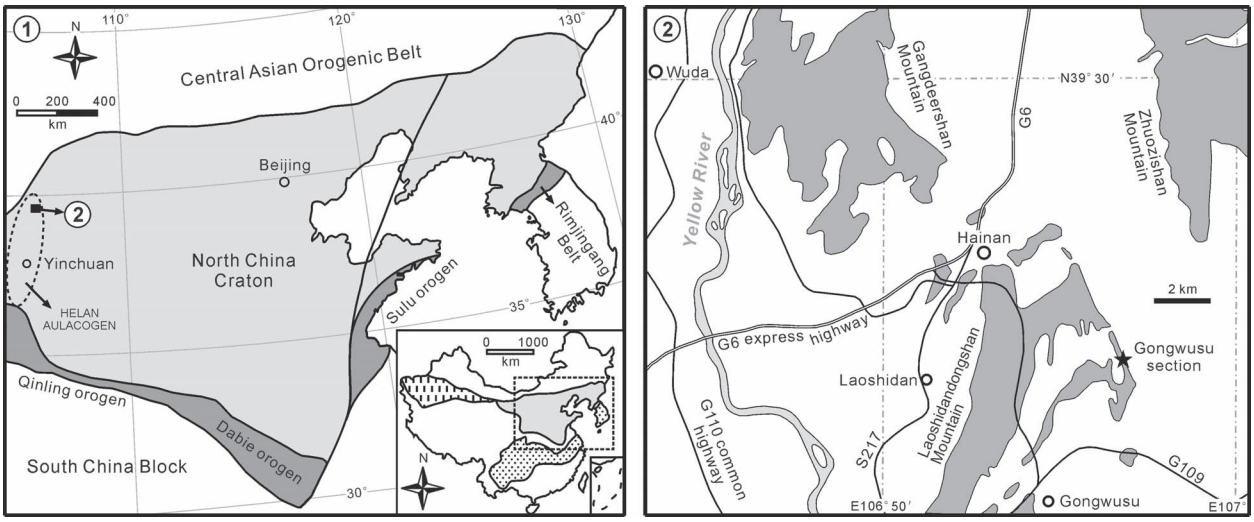

Figure 1. Simplified geology of North China and location maps. **1,** Major tectonic stratigraphic framework of the Ordovician (modified after Zhu *et al*., 2012), and the location of the field area in the western Inner Mongolia region. The dashed ellipse indicates the approximate area of the Helan Aulacogen. The inset map showing the location of the North China Craton within China. **2,** Close-up map showing the distribution of Ordovician rocks in the study area, the location of the Gongwusu section is marked by a black star.

Dabie-Sulu Orogenic Belt (Figure 1.1; also see Zhu *et al*., 2012). The North China Craton experienced a long and complicated geological history, stabilizing during the Paleoproterozoic and subsequently received a thick succession of Mesoproterozoic to Cenozoic sedimentary deposits (Zhao and Zhai, 2013; Zheng *et al*., 2013). The Precambrian sedimentary rocks are predominantly marine dolostone and siliciclastics, and mainly developed in continental rift basins (Zhao and Zhai, 2013). An unconformity, which separates the Precambrian and Paleozoic strata of the North China Craton, resulted from a regional uplift during the Neoproterozoic (Myrow *et al*., 2015). The Paleozoic strata are dominated by marine carbonates and characterized by a great sedimentary hiatus from the latest Ordovician through the latest Mississippian (Zhen *et al*., 2016), whereas its sediments were primarily of continental origin from the Permian onwards. The Ordovician rocks of the North China Craton can be subdivided into two major depositional settings, i.e., the broad North China Platform and the narrow western slope to northern and southern marginal platform (Yang *et al*., 2005; Cao *et al*., 2011; Feng *et al*., 2014; Zhen *et al*., 2016). Our study site is located in the western slope setting, which was represented in the eastern flank of a northeast-trending aulacogen–the Helan Aulacogen (Figure 1.1; also see Sun and Liu, 1983; Myrow *et al*., 2015).

The Gongwusu Formation, which comprises greenish-gray thin-bedded limestone, argillaceous siltstone and sandstone, is lithologically distinctive and has a zonal distribution on the northeast side of the town of Gongwusu (Figure 1.2). It is overlain conformably by the Sheshan Formation consisting of turbidite sandstone, bioclastic limestone and shale, and underlain conformably by the Lashizhong Formation dominated by turbidite sandstone and siltstone. At its type locality (namely the Gongwusu section; location coordinates: 39°23′12″N, 106°55′22″E; Figure 1.2) near a newly built industrial park about 5 km northeast of the town of Gongwusu, southern Inner Mongolia, the Gongwusu Formation is composed of a 115 m-thick succession of grayish-green to gray thin-bedded limestone and silty mudstone, with medium- to thin-bedded sandstone in the top part (Figure 2; also see Chen *et al*., 1984). Just as described by Chen *et al*. (1984, p. 9) and An and Zheng (1990, p. 38), the stratigraphic contact between the Gongwusu Formation and the underlying Lashizhong Formation is covered by Quaternary fluvial sediments. However, unfortunately, both the already rarely exposed Sheshan Formation and its stratigraphic contact with the Gongwusu Formation were also covered recently by the above-mentioned industrial park.

Previous work

Conodonts from the Gongwusu Formation were first reported by Chen *et al*. (1984, p. 8). The conodont fauna consists of two species (using their original assignments), *Periodon grandis* and *Protopanderodus insculptus*, which were recovered from the middle part of the Gongwusu Formation of the Gongwusu section. On this basis, Chen *et al*. (1984, table 3, p. 27) proposed the *Protopan-*

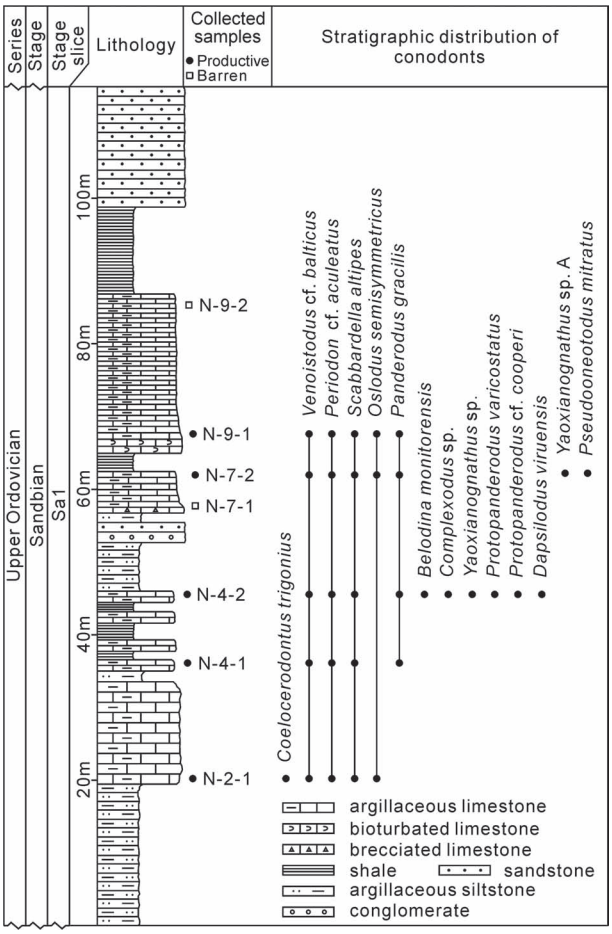

Figure 2. Ranges of selected species of the Gongwusu Formation at the Gongwusu section.

derodus insculptus Assemblage Zone for the fauna, and correlated it with the North American conodont fauna 9 to fauna 12, and the similar faunas from the Pagoda Formation of South China. Shortly afterward, Wang and Luo (1984, p. 242) documented in more detail the conodonts of this formation. A more diverse conodont fauna, including (Wang and Luo's original identifications) *Belodella devonica*, *Drepanodus*? *altipes*, gen. et sp. nov., *Panderodus compressus*, *Periodon grandis*, *Periodon* sp. A and *Protopanderodus liripipus*, was recorded from the Gongwusu Formation. Moreover, the same authors recognized the *Protopanderodus insculptus-Phragmodus undatus-Drepanodus*? *altipes-Periodon grandis* Assemblage Zone and referred it to both the Gongwusu Formation and the overlying Sheshan Formation (Wang and Luo, 1984, p. 239, table 3). An and Zheng (1990, p. 37) subsequently reported a rather low-diversity conodont fauna, which contains five species including (authors' original identifications) *Panderodus* sp., *Paroistodus* sp., *Periodon grandis*, *Periodon* sp. and *Protopanderodus* cf. *liripipus*, from the Gongwusu Formation. A correlation of the Gongwusu Formation with the top part of the endemic *Tasmanognathus sishuiensis-Erismodus typus* Zone established in the Fengfeng Formation was suggested (An and Zheng, 1990, table 3).

In these publications, however, conodont data were only provided in the stratigraphic logs of the Gongwusu section, with neither any illustrations nor any detailed systematic treatment for the conodont fauna given. Thus, it is almost impossible to reassess the previous identifications by using the latest taxonomic views. The present paper together with two other contributions (Jing *et al*., 2015, 2016) aims to provide a more precise conodont biostratigraphic correlation and age interpretation for the Ordovician successions deposited in the slope setting of the North China Craton.

Conodont fauna

Our current investigation of the Gongwusu Formation at the Gongwusu section has resulted in the recovery of a much more diverse conodont fauna consisting of 18 species (Table 1, Figures 3, 4), among others, includes *Ansella* sp., *Belodina monitorensis* Ethington and Schumacher, 1969, *Coelocerodontus trigonius* Ethington, 1959, *Complexodus* sp., *Dapsilodus viruensis* (Fåhræus, 1966), *Drepanoistodus* sp., Gen. et sp. indet, *Oslodus semisymmetricus* (Hamar, 1966), *Panderodus gracilis* (Ethington, 1959), *Periodon* cf. *aculeatus* Hadding, 1913, *Protopanderodus* cf. *cooperi* (Sweet and Bergström, 1962), *P. varicostatus* (Sweet and Bergström, 1962), *Protopanderodus* sp., *Pseudooneotodus mitratus* (Moskalenko, 1973), *Scabbardella altipes* (Henningsmoen, 1948), *Venoistodus* cf. *balticus* Löfgren, 2006, *Yaoxianognathus* sp. A and *Yaoxianognathus* sp. Overall, this represents a mixed assemblage of North Atlantic (with representation of species of *Complexodus*, *Dapsilodus*, *Oslodus*, *Periodon*, *Protopanderodus*, *Scabbardella* and *Venoistodus*), North American Midcontinent (*Belodina monitorensis* and *Panderodus gracilis*), and North China (*Yaoxianognathus* species) affinities.

In the present collection, however, several stratigraphically important species (e.g. *Protopanderodus insculptus*, *P. liripipus*, and *Periodon grandis*) reported previously from the Gongwusu Formation were not found. Instead, we obtained some stratigraphically older species of the corresponding genera, such as *Protopanderodus varicostatus* and *Periodon* cf. *aculeatus*. Moreover, biostratigraphically significant species in the present study also indicate a relatively older age (see below) for the fauna than that was previously regarded. Most conodonts in the present collection are relatively long-ranging, conse-

Table 1. Distribution of conodont species in the Gongwusu Formation at the Gongwusu section.

Species / Samples	*Ansella* sp	*Belodina monitorensis*	*Coelocerodontus trigonius*	*Complexodus* sp.	*Dapsilodus viruensis*	*Drepanoistodus* sp.	*Oslodus semisymmetricus*	*Panderodus gracilis*	*Periodon* cf. *aculeatus*	*Protopanderodus* cf. *cooperi*	*Protopanderodus* sp.	*Protopanderodus varicostatus*	*Pseudooneotodus mitratus*	*Scabbardella altipes*	*Venoistodus* cf. *balticus*	*Yaoxianognathus* sp. A	*Yaoxianognathus* sp.	Gen. et sp. indet	Total
N-2-1			1			1	3		9					2	1				17
N-4-1								1	3					2	1				7
N-4-2		1		1	2			2	23	1		1		4	2		5	1	43
N-7-2	1						1	2	2		1		1	2	1	1			12
N-9-1							1	6	1					3	1				12
Total no. of specimens	1	1	1	1	2	1	5	11	38	1	1	1	1	13	6	1	5	1	91

quently we selected five biostratigraphically significant species, comprising *Belodina monitorensis*, *Periodon* cf. *aculeatus*, *Protopanderodus varicostatus*, *Scabbardella altipes* and *Yaoxianognathus* sp. A in the following discussion for the age constraint of the present fauna.

Belodina monitorensis is a significant species for the age determination of the present fauna, although the stratigraphical range of this species is relatively worse known than those of the descendant *B. compressa* and *B. confluence* (Bauer, 1990, 1994; Zhen *et al*., 2004). Bauer (1990, 1994) reported that *B. monitorensis* occurs under the range of *Plectodina aculeata* in the Bromide Formation of Oklahoma. Pyle and Barnes (2003) made a similar discovery in the Skoki Formation of northeastern British Columbia, Canada. However, *B. monitorensis* was recorded as having a stratigraphic range up to the *B. compressa* Zone in the Wahringa Limestone Member of Central New South Wales, Australia (Zhen *et al*., 2004). Nevertheless, what is clear is that *B. monitorensis* ranges across the Middle to Late Ordovician boundary, occurring stratigraphically much earlier than the widely known zonal index species *B. compressa*. Based on the material from North America, *B. monitorensis* ranges in the Chazyan and Blackriveran regional stages (Sweet, 1981), which correlates to the late Darriwilian to late Sandbian interval (Bergström *et al*., 2009).

The species *Periodon aculeatus* had been treated as a long-ranging taxon bearing a broad species concept until a revision of the species definition of *Periodon* was recently made by Stouge (2012) for the Dapingian and early Darriwilian species. Similarly for the upper Darriwilian, numerous specimens identified as *Periodon aculeatus* by previous authors need to be reassessed. Stouge's (2012) concept, which shortens the stratigraphical range of *P. aculeatus*, is followed herein to define the taxon as a Pa element bearing five anterior denticles. According to this redefinition, *Periodon aculeatus* is considered as the descendant of *P. zgierzensis* and the ancestor of *P. grandis*, and stratigraphically ranges from the late Darriwilian *Pygodus serra* Zone (Stouge, 2012) to the middle Sandbian *Baltoniodus gerdae* Subzone (Lindström, 1977; Bergström, 2007).

The presence at the study section of *Protopanderodus varicostatus*, a species that does not range any higher than the *Baltoniodus variabilis* Subzone of the *Amorphognathus tvaerensis* Zone in Baltoscandia (Bergström, 1971, 2007), indicates that the studied fauna is not younger than this conodont subzone unit.

Scabbardella altipes has a cosmopolitan distribution and occurs in variable numbers in different facies deposits of the Upper Ordovician (Orchard, 1980; Tolmacheva *et al*., 2009). This taxon has its stratigraphically lowermost record in the *Pygodus anserinus* Zone (Dzik, 1994; Rasmussen, 2001), and went extinct in the second part of the Hirnantian (Tolmacheva *et al*., 2009).

Yaoxianognathus sp. A is reminiscent of *Yaoxianognathus wrighti* Savage, 1990, which was erected based on material from the Gleesons Limestone Member of the Upper Ordovician Cliefden Cave Limestone Group in central-western New South Wales, Australia (Savage, 1990). Although only one specimen (Figure 4.16) was found in the present study, this relatively well preserved

Figure 3. **1,** *Ansella* sp., geniculate element, inner view, from N-7-2, CUGB-jxch882. **2,** *Belodina monitorensis* Ethington and Schumacher, 1969, compressiform element, lateral view, from N-4-2, CUGB-jxch864. **3–6,** *Oslodus semisymmetricus* (Hamar, 1966); 3, Sa element, lateral view, from N-9-1, CUGB-jxch889; 4, 5, Sc element, lateral view; 4, from N-2-1, CUGB-jxch861; 5, from N-7-2, CUGB-jxch349; 6, M element, lateral view, from N-2-1, CUGB-jxch341. **7, 8,** *Dapsilodus viruensis* (Fåhræus, 1966), distacodiform element, lateral view, from N-4-2, CUGB-jxch878, CUGB-jxch342. **9,** *Drepanoistodus* sp., drepanodontiform element, lateral view, from N-2-1, CUGB-jxch340. **10,** *Complexodus* sp., Sd element, posterior view, from N-4-2, CUGB-jxch344. **11,** Gen. et sp. indet, lateral view, from N-4-2, CUGB-jxch343. **12–18,** *Panderodus gracilis* (Branson and Mehl, 1933); 12, 13, graciliform element, lateral view; 12, from N-4-1, CUGB-jxch863; 13, from, N-9-1, CUGB-jxch891; 14–16, aequaliform element, lateral view, 14, from N-4-2, CUGB-jxch879, 15, from N-9-1 CUGB-jxch892, 16, from N-7-2, CUGB-jxch884; 17, arcuatiform element, lateral view, from N-9-1, CUGB-jxch890; 18, falciform element, inner view, from N-4-2, CUGB-jxch351. **19–21,** *Scabbardella altipes* (Henningsmoen, 1948); 19, 20, drepanodiform element, lateral view; 19, from N-9-1, CUGB-jxch887; 19b, detail of the fine striae on the surface of the cusp; 20, from N-2-1, CUGB-jxch858; 21, distacodiform element, lateral view, from N-4-2, CUGB-jxch877. Scale bars are 50 μm.

specimen shows distinctive features of an Sd element of *Y. wrighti* (see further discussion under Systematic Paleontology section). Considering a formal apparatus reconstruction including the Sd element for *Y. wrighti* has not been formally proposed, the specimen at hand is tentatively referred to *Yaoxianognathus* sp. A, but is treated as representing the same evolutionary stage as *Y. wrighti*. Savage (1990) determined a middle Caradocian (late Sa1 to Sa2) age for the temporal distribution of *Y. wrighti* according to the co-occurring age-diagnostic conodonts. On the basis of a large collection from the Bowan Park succession, central New South Wales, Zhen *et al*. (1999) suggested an extended stratigraphical range for this species, up to the middle Eastonian (middle Katian). Thus the range of *Yaoxianognathus* sp. A, as age equivalent to *Y. wrighti*, can be considered to be from the early Sandbian to the middle Katian.

To sum up, this species association of the Gongwusu fauna enables us to constrain its biostratigraphical position in a range from the *Pygodus anserinus* Zone to the *Baltoniodus varabilis* Subzone of the *Amorphognathus tvaerensis* Zone. Furthermore, the conodonts of the underlying clastic-dominated Lashizhong Formation were also investigated by An and Zheng (1990, p. 36) and the present authors, but unfortunately, neither the former authors nor we obtained biostratigraphically useful taxa to effectively constrain the age of this formation. Jing *et al*. (2015) reported the conodont fauna of the Wulalike Formation which underlies the Lashizhong Formation, and ascribed the top part of the formation to the earliest Sandbian age. Therefore, we concluded that the Lashizhong Formation is restricted to the upper part of the *Pygodus anserinus* Zone, and the Gongwusu Formation is confined to an interval ranging from the uppermost part of the *Pygodus anserinus* Zone to the *Baltoniodus varabilis* Subzone of the *Amorphognathus tvaerensis* Zone.

Conodont paleoecology

The Gongwusu fauna is numerically dominated by specimens of *Periodon* cf. *aculeatus*, *Scabbardella altipes* and *Panderodus gracilis* (Table 1). Among them, *Periodon* cf. *aculeatus* is usually pandemic and likes the deeper water offshore to deep water upper slope environments (Rasmussen and Stouge, 1995; Rasmussen, 1998; Zhang, 1998), *Scabbardella altipes* is more or less pandemic like *Periodon* (Tolmacheva *et al*., 2009), while *Panderodus gracilis* is common in high-energy nearshore environments (Sweet, 1988; Zhang *et al*., 2006). Additionally, the presence of *Protopanderodus*, *Drepanoistodus* and *Ansella* also suggests an outer shelf - slope setting (Rasmussen and Stouge, 1995; Serra *et al*., 2015), whereas some minor components such as *Belodina monitorensis* and *Yaoxianognathus* sp. A are probably benthic and show an inner shelf or platform environment (Zhen *et al*., 1999, 2004).

The dominance of *Periodon* characterizes a *Periodon* Biofacies *sensu* Pohler (1994) and Zhang (1998). Combined with lithology, we consider the Gongwusu fauna lived in an upper-slope environment, whereas the shallow-water taxa represented in the fauna are referred to down-slope transportation.

Correlations

The Gongwusu conodont fauna differs in composition from the contemporaneous conodont faunas reported from the interior North China Platform, but shows a similarity to the coeval conodont faunas in Baltoscandia and South China. Additionally, the present fauna shares a few characteristic taxa with the coeval faunas of the North America Midcontinent. The correlations of the Gongwusu fauna are shown in Figure 5.

North China.—Conodonts of the platform margin–slope setting are significantly different from the counterparts of the North China Platform, although these regions are geographically close together. As a representative of the Sandbian successions in the slope setting, the fossiliferous Pingliang Formation in eastern Gansu Province has been intensively investigated for biostratigraphic purposes (e.g. An and Zheng, 1990; Finney *et al*., 1999; Wang, 2001; Wang *et al*., 2013a, b, 2016b). In a recent review of the conodont biostratigraphy of the Pingliang section, Wang *et al*. (2013a) recognized four conodont zones in the Pingliang Formation in ascending order: the *Pygodus anserinus*, the *Plectodina aculeata*, the *Erismodus quadridactylus* and the *Belodina compressa* zones. The Pingliang Formation and the Gongwusu Formation share several biostratigraphically useful species, such as *Belodina monitorensis*, *Periodon* cf. *aculeatus*, *Protopanderodus varicostatus* and *Scabbardella altipes*, which allow a correlation of the Gongwusu Formation with the lower part of the Pingliang Formation (i.e., the stratigraphic interval including the upper *Pygodus anserinus* Zone and the lower *Plectodina aculeata* Zone).

The Fengfeng Formation in central Shandong Province typifies the Sandbian successions of the shallow-water interior platform setting. A detailed documentation of the conodont zonation for the Fengfeng Formation was provided by An and Zheng (1990), who proposed the *Scandodus handanensis* Zone in the lower part of this formation (the Gezhuang Member) and the *Tasmanognathus sishuiensis* Zone in the upper part of the formation (the Badou Member), respectively. *Tasmanognathus sishuiensis* co-occurs with *Belodina compressa* in the Badou Member of the Fengfeng Formation (Badou sec-

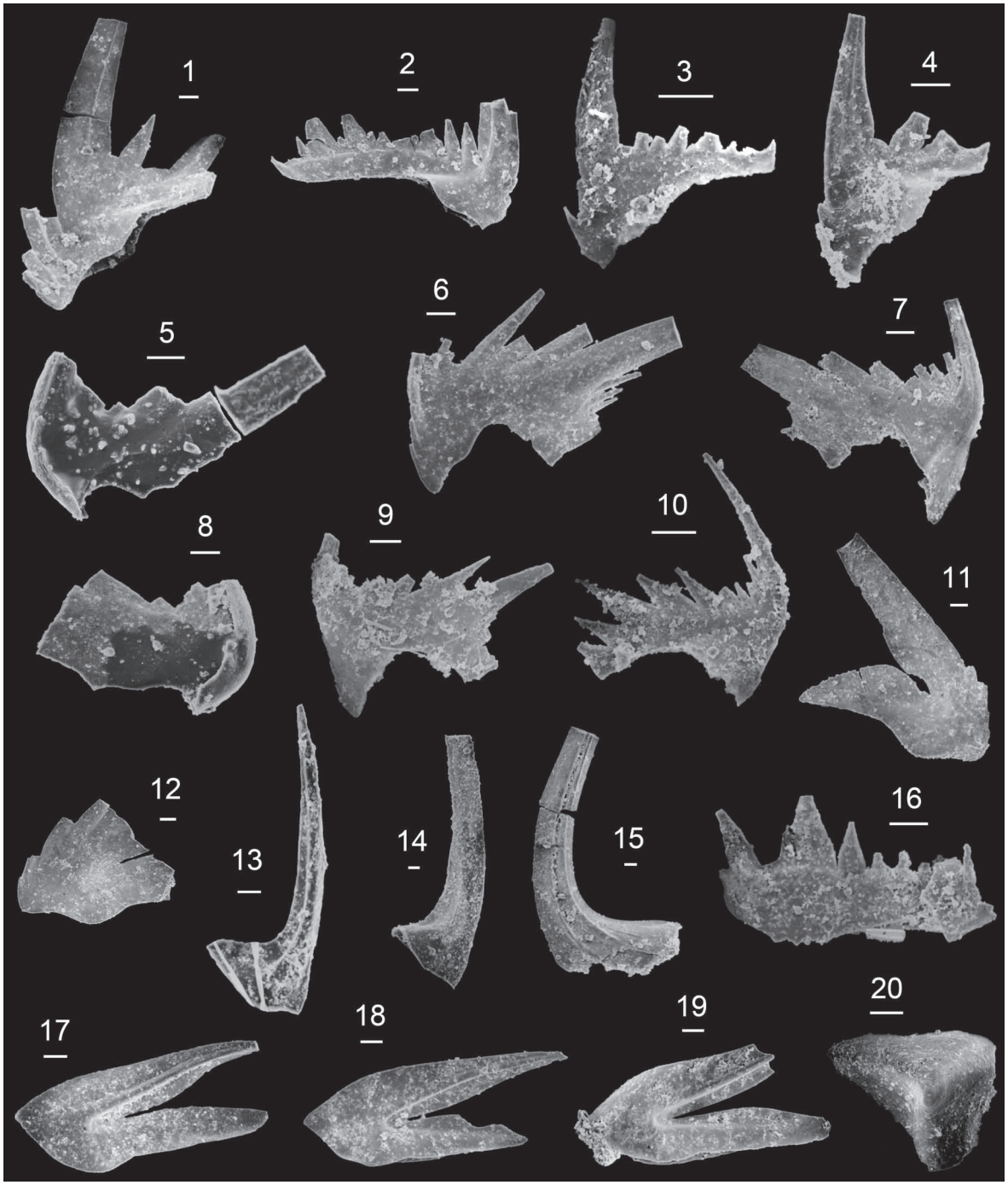

Figure 4. **1–12,** *Periodon* cf. *aculeatus* Hadding, 1913; 1, 2, Pa element, inner view, from N-4-2, CUGB-jxch876, CUGB-jxch874; 3, 4, Pb element, outer view; 3, from N-7-2, CUGB-jxch885; 4, from N-4-2, CUGB-jxch347; 5, 8, Sa element, lateral view, from N-4-2, CUGB-jxch353, CUGB-jxch348; 6, 7, Sb element; 6, inner view, from N-2-1, CUGB-jxch857; 7, outer view, from N-4-2, CUGB-jxch871; 9, 10, Sc element, outer view; 9, from N-9-1, CUGB-jxch888; 10, from N-7-2, CUGB-jxch881; 11, 12, M element, lateral view, from N-4-2, CUGB-jxch873, CUGB-jxch872. **13, 17–19,** *Venoistodus* cf. *balticus* Löfgren, 2006; 13, drepanodotiform element, lateral view, from N-9-1, CUGB-jxch350; 17–19, oistodontiform element, lateral view; 17, from L-2-1, CUGB-jxch860; 18,19, from N-4-2, CUGB-jxch886, CUGB-jxch862. **14,** *Protopanderodus* cf. *cooperi* (Sweet and Bergström, 1962), scandodiform element, inner view, from N-4-2, CUGB-jxch346. **15,** *Protopanderodus varicostatus* (Sweet and Bergström, 1962), symmetrical bicostate element, lateral view, from N-4-2, CUGB-jxch870. **16,** *Yaoxianognathus* sp. A, Sd element, posteriolateral view, from N-7-2, CUGB-jxch883. **20,** *Pseudooneotodus mitratus* (Moskalenko, 1973), Pa element, upper view, from N-7-2, CUGB-jxch880. Scale bars are 50 μm.

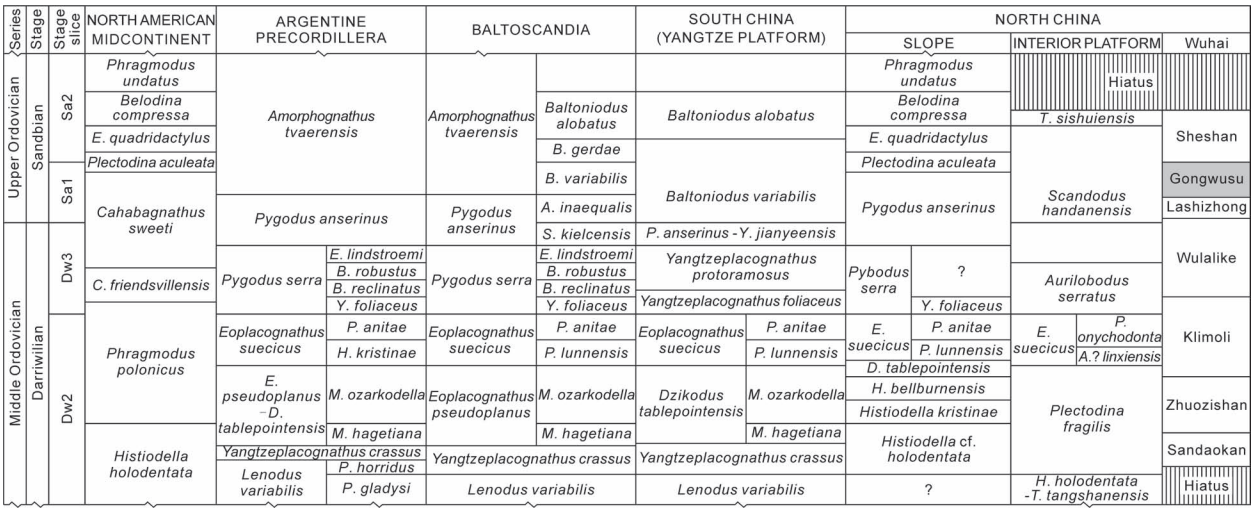

Figure 5. Conodont zones for the Darriwilian and Sandbian stages (from stage slice Dw2 to Sa2 of Bergström *et al*., 2009) in North China (slope setting after Jing *et al*., 2015, 2016; Wang *et al*., 2016b; platform setting after An and Zheng, 1990; Wang *et al*., 2016b), Yangtze Platform of South China (after Zhang, 1998; Wang *et al*., 2016a), and correlation with the standard Baltoscandian zonation (after Löfgren and Zhang, 2003; Bergström, 2007; Bergström and Leslie, 2010), Argentine Precordillera (after Albanesi and Ortega, 2002; Feltes *et al.*, 2016) and North America Midcontinent (after Webby *et al*., 2004) conodont successions. The stratigraphic position of the coeval units in the Wuhai area, the correlations of the Sandaokan and Zhuozishan formations are adopted from Jing *et al*. (2016), the Klimoli and Wulalike formations are from Jing *et al*. (2015), the correspondences of the Lashizhong and Sheshan formations are based on An and Zheng, 1990. Gray color marks a stratigraphic interval of the Gongwusu Formation based on the present study.

tion: the type section of the Badou Member, see An *et al*., 1983, text-figure 8), which indicates that the older *B. monitorensis*-yielding Gongwusu fauna is restricted to an interval corresponding to the *S. handanensis* Zone. Considering that the *S. handanensis* Zone spans the base of the Sandbian to the base of the *B. compressa* Zone (Wang *et al*., 2016b), the Gongwusu fauna is consistent herein with the middle part of the *S. handanensis* Zone.

Yangtze Platform.—Sandbian conodonts from the Yangtze Platform have been reported by several authors (see, for instance, An and Ding, 1982; An *et al*., 1985a; An, 1987; Ni and Li, 1987; Wang *et al*., 1996, 2016a; Chen *et al*., 2011; Bagnoli and Qi, 2014; Wu *et al*., 2016), but there have been some disagreements regarding the biostratigraphic interpretation. Wang *et al*. (2016a) recently summarized the Sandbian conodont zonation of the Yangtze Platform, referring the Sandbian conodont succession to the upper *Yangtzeplacognathus jianyeensis-Pygodus anserinus* (Assemblage) Zone, the *Baltoniodus variabilis* Zone and the *Baltoniodus alobatus* Zone, in ascending order. What should be noted is that the *B. variabilis* Zone of the Yangtze Platform is not age equivalent to the Swedish *B. variabilis* Subzone, because the Chinese *B. variabilis* Zone with its base marked by the first appearance of the zonal species (Wang *et al*., 1996, p. 36) has a stratigraphically lower base than the Swedish *B. variabilis* Subzone with its lower boundary defined by the appearance of *Amorphognathus tvaerensis* and *Baltoniodus variabilis*. The *B. variabilis* Subzone extends to the appearance of *Baltoniodus gergae*, which however is a species that has not been recorded from China. For practical purposes, Bagnoli and Qi (2014) and Wu *et al*. (2016) proposed to apply FAD of *B. variabilis* (namely the base of the *B. variabilis* Zone in Yangtze Platform) for the base of the Sandbian. Therefore, the Gongwusu Fauna corresponds to the middle part of the *Baltoniodus variabilis* Zone of the Yangtze Platform.

Baltoscandia.—The Sandbian conodont biostratigraphic framework proposed by Bergström (1971) and then slightly revised by Bergström (1983) has been used as a standard reference for Baltoscandia. Following this standard zonal succession, the base of the Sandbian Stage is very close to the lower boundary of the *Amorphognathus inaequalis* Subzone of the *Pygodus anserinus* Zone, while the top of the Sandbian was placed in the upper part of the *Amorphognathus tvaerensis* Zone and is stratigraphically higher than the top of the *Baltoniodus alobatus* Subzone. Most of the identified species in the Gongwusu fauna are common to the conodont species of the coeval faunas in Baltoscandia, and this allows an easily operated correlation between them. As constrained in the Conodont fauna section above, the Gongwusu fauna is comparable with the stratigraphic interval from the topmost part of the *Pygodus anserinus* Zone to the *Baltonio-*

dus varabilis Subzone of the *Amorphognathus tvaerensis* Zone in Baltoscandia.

Argentine Precordillera.—Upper Ordovician conodonts were documented from several stratigraphic sections in the Argentine Precordillera (e.g. Albanesi *et al*., 1998; Lehnert *et al*., 1999). Albanesi and Ortega (2002) reviewed the Ordovician conodont biostratigraphic units of the Argentine Precordillera, and proposed a similar Sandbian conodont biostratigraphic framework to that of Baltoscandia. The *Pygodus anserinus* Zone and the *Amorphognathus tvaerensis* Zone of the Argentine Precordillera were correlated with the homonymous zones of Baltoscandia, respectively. However, the subdivisions—on the subzonal level—of these two zones have not yet been made. Similarly to the correlation with the Baltoscandian succession, the Gongwusu fauna is consistent with the top part of the *Pygodus anserinus* Zone to the lower part of the *Amorphognathus tvaerensis* Zone in the Argentine Precordillera.

North America Midcontinent.—The Ordovician conodont-based biozones reported by Sweet (1984) were widely employed as a standard zonal succession for the North America Midcontinent. Following this conodont zonal succession, the upper *Cahabagnathus sweeti*, the *Plectodina aculeata*, the *Erismodus quadridactylus*, the *Belodina compressa* and the lower *Phragmodus undatus* zones are included in the Sandbian Stage (Webby *et al*., 2004; Goldman *et al*., 2007; Cooper and Sadler, 2012). Nevertheless, the Gongwusu conodont fauna are significantly different from the counterparts of the North America Midcontinent, only one stratigraphically useful species, *Belodina monitorensis*, can be used directly to correlate the present fauna with the North America Midcontinent zonation (see discussion under the Conodont fauna section). Combined with the matches of the North Atlantic and North America Midcontinent conodont zonal successions (Bergström, 1986; Webby *et al*., 2004; Goldman *et al*., 2007; Cooper and Sadler, 2012), the Gongwusu fauna is comparable to the interval including the uppermost part of the *Cahabagnathus sweeti* Zone and the lower part of the *Plectondina aculeata* Zone.

Systematic paleontology

All specimens illustrated and described in this study are housed in the School of Earth Sciences and Resources, China University of Geosciences (Beijing), with the prefix CUGB. Collection numbers of all illustrations shown in Figures 3 and 4 are prefixed CUGB-jxch. Most of the conodont collections so far obtained from the Gongwusu Formation are well known taxa that have been described adequately in previous publications. The material at hand is sparse, and therefore does not add anything substantially new to the current understanding of the species. Only two species of biostratigraphically significant taxa are described below. Taxa documented herein are alphabetically listed according to their generic assignment, with family level and higher classification omitted.

Genus ***Periodon*** Hadding, 1913

Type species.—*Periodon aculeatus* Hadding, 1913

Periodon cf. ***aculeatus*** Hadding, 1913

Figures 4.1–4.12

cf. *Periodon aculeatus* Hadding, 1913, p. 33, pl. 1, fig. 14; Lindström, 1955, p. 110, pl. 22, figs.10, 11, 14–16.

Material.—Thirty-eight specimens from five samples (see Table 1).

Remarks.—The Sb elements (Figures 4.6, 4.7) of our specimens are closely similar to the holotype described and illustrated by Hadding (1913, p. 33, pl. 1, fig. 14) and again by Lindström (1955, p. 110, pl. 22, fig. 14). However, the Gongwusu specimens are slightly more advanced than the holotype in several respects, such as having a distinguished large denticle on the posterior process. The present specimens most likely represent an intermediate species between *Periodon aculeatus* and *P. grandis* (Stouge, 2016, personal communication), but it seems impossible to erect a new species based on the insufficient material at hand. We prefer to use *Periodon* cf. *aculeatus* for these advanced conodonts until a detailed taxonomic revision can be undertaken.

Genus ***Yaoxianognathus*** An in An *et al*., 1985b

Type species.—*Yaoxianognathus yaoxianensis* An in An *et al*., 1985b.

Yaoxianognathus sp. **A**

Figure 4.16

Material.—One Sd element (CUGB-jxch870).

Description.—Digyrate Sd element has a recurved cusp and two lateral processes. The cusp, flanked by small denticles, has a diamond-shaped cross section and sharp anterior and posterior margins. The inner-lateral process is sharply curved posteriorly, with almost straight lower margin which is, however, poorly preserved distally. The denticles on the inner-lateral process vary in size and comprise four small denticles close to the cusp and a large flattened denticle between two small flanking denticles farther from the cusp. Unfortunately, the outer-lateral process is broken off.

Remarks.—Zhen *et al.* (1999, p. 97) suggested a septimembrate apparatus including a digyrate Sd element for *Yaoxianognathus ani*. The single specimen recovered from the Gongwusu Formation resembles the Sd element of *Y. ani* in outline, but the latter has a more complex denticle pattern (hindeodellid denticles) than that of the former. The Gongwusu specimen is morphologically more primitive than *Y. ani* and shows a quite similar denticle pattern to the S elements of *Y. wrighti*, which was erected and reconstructed by Savage (1990, p. 826). However, Savage (1990) did not recognize an Sd element for *Yaoxianognathus wrighti*. Since the material at hand is too sparse to reconstruct the species apparatus, whether this specimen, as an Sd element, can be grouped into the apparatus of *Y. wrighti* will remain uncertain until a septimembrate apparatus is formally proposed. To be practical, the single specimen was tentatively referred to as *Yaoxianognathus* sp. A.

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