Cambrian small shelly fossils of South China and their application in biostratigraphy and palaeobiogeography

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Work Contributions

The thesis titled as "Cambrian small shelly fossils of South China and their application in biostratigraphy and palaeobiogeography", was written in a cumulative style, composed with three scientific Papers:

The first paper (Chapter 3.1 in the thesis) is published as: "Yang, B., Steiner, M., Li, G., Keupp, H., 2014b. Terreneuvian small shelly faunas of East Yunnan (South China) and their biostratigraphic implications. Palaeogeography, Palaeoclimatology, Palaeoecology 398, 28-58.".

Ben Yang and Michael Steiner the authors contributed to fieldwork. Ben Yang carried out the analyses, wrote the manuscript, and produced all the figures. Michael Steiner contributed to the discussion and improvements of the paper. Guoxiang Li and Helmut Keupp contributed to the improvements of the paper. The personal work input of Ben Yang for this publication exceeds 90%.

The second (Chapter 3.2 in the thesis) is published as: "Yang, B., Zhang, L., Danelian, T., Feng, Q., Steiner, M., 2014c. Chert-hosted small shelly fossils: expanded tool of biostratigraphy in the early Cambrian. GFF 136, 303-308.".

Ben Yang, Lei Zhang and Michael Steiner contributed to fieldwork. Lei Zhang made the SEM work of Fig. 2 A-L. Michael Steiner performed the SEM work of Fig. 2 M, N. Ben Yang performed the SEM work and EDS work of Fig. 2 O, P, Fig. 3, and Fig. 4. Michael Steiner contributed to the concept, discussion and improvements of the manuscript. Taniel Danelian and Qinglai Feng contributed to the improvements of the manscript. Ben Yang carried out the analyses, wrote the paper and made all the figures, with personal work input for this publication making up more than 85% concerning concept, content, writing and editing.

The third (Chapter 3.3 in the thesis) is submitted to Gondwana Research as: "Yang, B., Steiner, M., Keupp, H., 2014a. Early Cambrian palaeobiogeography of the Zhenba-Fangxian Block (South China): Independent terrane or part of the Yangtze Platform? Gondwana Research, *Submitted*.".

Ben Yang and Michael Steiner contributed to fieldwork. Ben Yang prepared all the material for the analyses, wrote the paper and made the figures, yielding a personal input for this publication of 90% concerning concept, content, writing and editing. Michael Steiner performed the SEM work of Fig. 12B, C-H, contributed to the concept and discussion. Helmut Keupp contributed to the improvements of the manuscript.

Declaration of Authenticity

I hereby certify sole authorship of the thesis “Cambrian small shelly fossils of South China and their application in biostratigraphy and palaeobiogeography” as submitted to the Department of Earth Sciences of the “Freie Universität Berlin” for the conferral of a doctorate, and that no sources other than those indicated have been used in its preparation. Parts of this thesis that have been drawn on the work of others with regard to contents or by literal quotation have been appropriately marked through indication of source. Where any collaboration has taken place with other researchers, I have clearly stated my own personal share in the investigation.

This work in the same or a similar form has not been submitted to any other examining body.

Erklärung zur Originalität (Ehrenwörtliche Erklärung)

Hiermit versichere ich an Eides statt, dass ich die der Fachrichtung Geowissenschaften der Freien Universität Berlin zur Promotion eingereichte Arbeit “Cambrian small shelly fossils of South China and their application in biostratigraphy and palaeobiogeography” selbstständig verfasst und keine anderen als die angegebenen Hilfsmittel verwendet habe. Teile der vorliegenden Arbeit, die anderen Werken wörtlich oder inhaltlich entnommen sind, wurden durch Angaben der Quellen gekennzeichnet. In allen Fällen einer Zusammenarbeit mit anderen Forschenden habe ich meinen persönlichen Arbeitsanteil klar dargestellt.

Diese Arbeit wurde in gleicher oder ähnlicher Form noch keiner Prüfungsbehörde vorgelegt.

Ben Yang

Extended Abstract

Undisputed mineralization of the metazoans happened around the Precambrian-Cambrian Boundary, although there are several Latest Precambrian forerunners such as *Sinotubulites, Cloudina, Corumbella,* etc.. The process started early during the Terminal Neoproterozoic, shown by some Ediacaran fossils e.g. *Cloudina hartmannae* and the Doushantuo phosphate fossils *Ramitubus increscens*. The small shelly fossils (SSFs) are of the earliest biomineralized animals distributed globally with high diversity. Appeared earlier than the trilobites and archaeocyathids, the SSFs are thus important for the biostratigraphy of early Cambrian. On the Yangtze Platform early Cambrian strata are widely developed with a great diversity and abundance of small shelly fossils.

The first study focuses on the Terreneuvian SSFs and the multiple hiati in eastern Yunnan of the western Yangtze Platform. Carbonates and phosphatic carbonates containing well preserved SSFs broadly developed in this area. Biostratigraphy of SFFs has been applied for decades with three SSF zones having been established for the Terreneuvian strata. But certain problems still exist. For instance, the stratigraphic distribution of some previously applied index fossils, the definition of some SSF zones, and their correlation remained unclear.This study selected four sections from eastern Yunnan, namely the Meishucun section in the Kunming region, the Laolin and Lishuping sections in Huize and the Xianfeng section in Xundian. Three regional SSF biozones are recognized and modified: Zone I, *Anabarites trisulcatus-Protohertzina anabarica* Assemblage Zone; Zone II, *Paragloborilus subglobosus-Purella squamulosa* Assemblage Zone; Zone III, *Watsonella crosbyi* Assemblage Zone. Zones II and III are modified as based in this study. Zone II is further divided into two subzones: the *Annelitellus yangtzensis-Obtusoconus honorabilis* Subzone and the superjacent *Maikhanella cambriana-Oelandiella korobkovi* Subzone. New fossils, e.g. *Claviconchella qianyii* gen. et sp. nov. and *Bubiites simplex* gen. et sp. nov. are reported from the Huize and Xianfeng regions. Extensive multiple hardgrounds and three major disconformities are developed in the Terreneuvian strata of the Yangtze Platform. The first disconformity occurred at the Precambrian-Cambrian Boundary. The second one is observed within the Dahai Member of the Zhujiaqing Formation, at the boundary of Zone II and Zone III. This disconformity led to a general missing of the Zone II strata in most of the other areas of the Yangtze Platform except for eastern Yunnan. The third disconformity happened on top of the Zhujiaqing Formation, namely the top of the SSF Zone III. The hiati related to the hardgrounds and the disconformities prompt reconsideration of the previous isotope stratigraphy. Most important, the disconformities at the very beginning of Phanerozoic are synchronous with the appearance of the SSFs and the global phosphogenetic event, shortly before the Cambrian Explosion. It is left to speculation that they are relevant inherently, while the details remain ambiguous.

It has been argued that SSFs are facies dependent, being restricted to the carbonate facies. The second main study of this work is dedicated to this problem. SSFs were successfully extracted from siliceous rocks applying a relatively new and rarely applied method revealing that some SSFs occur across different facies belts. A quick-etching method with weak hydrofluoric acid (HF) is being utilized. Cherts or siliceous samples, collected from the

Zhejiang and Hunan provinces, were immersed in 2-5% HF solution and sieved every 12 hours. SSFs such as *Seletellus seletinicus*, *Amphigeisina* cf. *danica* and sponge spicules etc. were recovered. The study confirms the possibility that the SSFs can be extracted from cherts. Energy dispersive X-ray spectroscopy (EDS) results reveal that SSFs extracted with HF are mainly composed of carbon and high amounts of sulfur, accompanied by phosphorus and fluorine. These SSFs extracted from cherts are comparable in morphological quality with those from carbonates. The study indicates the hydrofluoric acid-processing can provide valuable biostratigraphic data of SSFs that are complementary to standard methods. *Seletellus seletinicus* Gridina, 1991 is found for the first time on the Yangtze Block. It indicates the upper black shale unit of the Hetang Formation can be assigned to the *Rhombocorniculum cancellatum* Zone indicating the upper Qiongzhusian (middle-upper Cambrian Stage 3) in Zhejiang. Some of the protoconodonts may have had an original carbonaceous composition.

Quantitative analyses have been rarely attempted for the SSF study. Our third study focuses on the quantitative analysis of the SSFs and the palaeobiogeographic research. Published data on SSFs and lithology oft the Zhenba Region (Shaanxi) and the Fangxian Region (Hubei) hint at major differences from the Yangtze Block during the early Cambrian that require further investigation. To further understand the differences, samples were collected from the Xiaoyangba and Zengjiapo sections in Zhenba County, southeastern Shaanxi of China. The two sections contain well preserved Cambrian Stage 2 SSFs. Detailed biostratigraphic correlation were accomplished for this study. A new SSF zone is proposed, namely the *Cambroclavus fangxianensis-Rhombocorniculum cancellatum* Assemblage Zone. Moreover, *Gapparodus gapparites* sp. nov. is reported from the two sections. Combining with all published SSF data, 295 species from 32 areas of the world are recorded. A quantitative palaeobiogeographic analysis is carried out using hierarchical clustering calculation of the database. The SSFs of the study region, which is named as the Zhenba-Fangxian Block, have a low similarity index with other parts of the Yangtze Block. They are more associated with those of the Armorica, Tarim, as well as Maly Karatau & Talas Alatau (South Kazakhstan and North Kyrgyzstan, respectively) terranes. The Yangtze Block has a unique SSF pattern compared with other regions. Other factors corroborate the SSF differences. The Ediacaran manganese deposits as well as the Early Cambrian barite and witherite distribution patterns are different in the Zhenba-Fangxian Block from those of the Yangtze Block. Isopach maps of Neoproterozoic deposits of the Zhenba-Fangxian Block also differ from those of the Yangtze Block. Considering all these evidences, we regard the Zhenba-Fangxian Block as an independent terrane or part of the South Qinling Terrane during the Terminal Neoproterozoic-Early Paleozoic time interval.

Zusammenfassung

Erste eindeutige Biomineralisationen von Metazoen treten seit dem Übergang vom Präkambrium zum Kambrium auf, obwohl bereits einige Spät-Neoproterozoische mineralisierende Vorläufer, wie *Sinotubulites, Cloudina, Corumbella,* etc. existieren. Der Prozess der Biomineralisation begann während des ausgehenden Neoproterozoikums, wie durch einige Ediacara-Fossilien, wie z.B. *Cloudina hartmannae* und das phosphatische Doushantuo-Fossil *Ramitubus increscens* belegt wird. Die „Small Shelly Fossilien" (SSFs) der frühen biomineralisierten Tiere treten weltweit auf und zeigen bereits eine hohe Biodiversität. Die frühesten SSFs traten noch vor dem Erscheinen der Trilobiten und Archäocyathiden auf und sind insbesondere bedeutsam für die Biostratigraphie des frühen Kambriums. Frühkambrische Ablagerungen mit einer häufigen und artreichen Fauna von Small Shelly Fossilien sind auf der südchinesischen Yangtze Plattform weit verbreitet.

Der erste Abschnitt der vorgelegten Arbeit beschäftigt sich mit den SSFs des Terreneuviums und der Verbreitung vielfältiger Hiati im östlichenYunnan der West- Yangtze Plattform. Karbonate und phosphatische Karbonate dieser Region sind reich an gut erhaltenen SSFs. Biostratigraphie, basierend auf den SSFs, wurde seit Jahrzehnten für das Terreneuvium dieses Gebietes angewendet. Trotzdem existierten damit bis in die Gegenwart eine Vielzahl von Problemen. So z.B. blieb die stratigraphische Verbreitung einiger ursprünglich verwendeter SSFs, die Definition einiger SSF Zonen sowie deren Korrelation unklar. In der vorliegenden Arbeit wurden vier Profile in Ost-Yunnan, nämlich der Aufschluß Meishucun in der Kunming Region, die Profile Laolin und Lishuping im Kreis Huize und das Profil Xianfeng im Kreis Xundian im Datail untersucht. Drei regionale SSF Biozonen wurden festgestellt und teilweise in der Definition modifiziert: Zone I, *Anabarites trisulcatus-Protohertzina anabarica* Assemblage Zone; Zone II, *Paragloborilus subglobosus-Purella squamulosa* Assemblage Zone; Zone III, *Watsonella crosbyi* Assemblage Zone. Die Zonen Zones II und III wurden anhand der Ergebnisse dieser Arbeit modifiziert. Zone II wird weiter untergliedert in zwei Subzonen: die jüngere *Annelitellus yangtzensis-Obtusoconus honorabilis* Subzone und ältere *Maikhanella cambriana-Oelandiella korobkovi* Subzone. Einige neue Taxa, z. B. *Claviconchella qianyii* gen. et sp. nov und *Bubiites simplex* gen. et sp. nov. werden aus den Huize und Xianfeng Regionen beschrieben. Ausgedehnte und mehrfach auftretende Hartgründe, sowie drei größere Diskonformitäten sind in den terreneuvischen Ablagerungen der Yangtze Plattform vorhanden. Die erste wichtige Diskonformität tritt an der Präkambrium-Kambrium Grenze auf. Die zweite wird innerhalb des Dahai Members der Zhujiaqing Formation an der Grenze der SSF Zone II und SSF Zone III beobachtet. Diese Diskonformität ist dafür verantwortlich, dass Strata der Zone II in den meisten anderen Gebieten der Yangtze Plattform außerhalb von Ost- Yunnan fehlen. Die dritte größere Diskonformität tritt am Top der Zhujiaqing Formation in der obersten SSF Zone III auf. Die Ergebnisse zur Verbreitung kleinerer (Hartgründe) und größerer Hiati (Diskonformitäten) erfordern die Neubewertung der bisher angewendeten C-Isotopen-Stratigraphie. Es ist wichtig festzustellen, dass die Diskonformitäten am Beginn des Phanerozoikums synchron mit dem Erscheinen der Vielfalt der SSFs und dem globalen Phosphatisations-Ereignis, unmittelbar zu Beginn der Kambrischen

„Explosion“, sind. Es bleibt aber weitgehend spekulativ, inwieweit diese Ereignisse genetisch in Zusammenhang stehen.

Es ist in der Vergangenheit wiederholt diskutiert worden, dass SSFs faziesabhängig und auf die Karbonatfazies beschränkt sind. Diesem Problem widmet sich die Arbeit im zweiten Hauptabschnitt der Arbeit. Zu diesem Zwecke wurden erfolgreich SSFs mittels einer neuen und wenig angewendeten Methode aus silikatischen Gesteinen extrahiert und untersucht. Die Untersuchung zeigt, dass einige SSFs unabhängig von den Fazieszonen in verschiedenen Gesteinen auftreten. Der zweite Haupabschnitt der vorliegenden Arbeit beschreibt SSFs einer Tiefwasserfazies der östlichen Yangtze Plattform. Die angewendete Aufbereitungsmethode arbeitet mit verdünnter Flusssäure (HF) mit nur extrem kurzen Einwirkungszeiten. Die untersuchten Cherts bzw. silikatischen Gesteine aus den Provinzen Zhejiang und Hunan wurden in 2-5% iger HF angesetzt und alle 12 h abgesiebt. SSFs wie *Seletellus seletinicus*, *Amphigeisina* cf. *danica* und Schwamm- Nadeln konnten dabei gewonnen werden. Die Studie bestätigt, dass SSFs aus Cherts zu biostratigraphischen Zwecken gewonnen werden können. Energiedispersive Röntgen-Spektroskopie (EDS) an SSFs, die mittels HF gewonnen wurden, zeigt, dass die SSFs hauptsächlich aus Kohlenstoff (mit vergleichsweise hohem Anteil an Schwefel) sowie teilweise aus Phosphor und Fluor bestehen. Die aus den Cherts gewonnenen SSFs sind morphologisch vollständig vergleichbar mit Exemplaren die mittels Essigsäure aus Karbonat gewonnen wurden. Dies zeigt, dass vorsichtige HF- Aufbereitung wertvolle Informationen zur Biostratigraphie der SSFs beitragen kann. 1991 wurde *Seletellus seletinicus* Gridina zum ersten Mal aus dem Yangtze Block nachgewiesen. Dieses Vorkommen weist darauf hin, dass die höheren "Black Shales" der Hetang Formation der *Rhombocorniculum cancellatum* Zone des jüngeren Qiongzhusiums (mittlere-höheres Kambrium Stufe 3) in Zhejiang zugeordnet werden können. Einige der erhaltenen Protoconodonten zeigen eine vermutlich primäre organische Erhaltung.

Der dritte Hauptabschnitt der vorgelegten Arbeit widmet sich der quantitativen Analyse der SSFs und deren paläobiogeographischer Anwendung. Eine quantitative Analyse von SSF für paläobiogeographische Zwecke wurde bisher kaum durchgeführt. Publizierte Daten über SSFs und Lithologie der Zhenba Region (Shaanxi) und der Fangxiang Region (Hubei) weisen auf wesentliche Unterschiede zwischen der Untersuchungsregion und der Yangtze Platform hin, die hier weiter untersucht werden. Dazu wurden Proben aus den Profilen Xiaoyangba und Zengjiapo des Kreises Zhenba, SE Shaanxi im Detail untersucht. Die beiden Profile führten eine große Zahl gut erhaltener SSFs der Cambrium Serie 2, die eine biostratigraphische Korrelation ermöglichten. Die neue *Cambroclavus fangxianensis-Rhombocorniculum cancellatum* Assemblage Zone wird hier definiert. Außerdem wird die neue Art *Gapparodus gapparites* sp. nov. aus den beiden Profilen neu beschrieben. In der Auswertung der publizierten SSF-Daten für die Kambrium Stufe 3 werden weltweit 295 Arten aus 32 Gebieten festgestellt. Eine quantitative paläobiogeographische Analyse der Daten wurde mittels computergestützter hierarchischer Clusteranalyse durchgeführt. Die SSFs des Untersuchungsgebietes, des Zhenba-Fangxian Blocks, zeigen erstaunlicherweise nur eine geringe Ähnlichkeit mit den Assoziationen des Yangtze Blocks. Im Gegensatz dazu sind diese den Faunen der Armorica Terranes, von Tarim, und dem Maly Karatau & Talas Alatau (Süd-Kasachstan und N- Kirgisien) sehr ähnlich. Der Yangtze Block hingegen hat eine spezielle Assoziation von SSF in der Kambrium Stufe 3, die weltweit unterschiedlich verglichen mit den anderen Regionen ist. Andere geologische Faktoren ergänzen die Hinweise auf die Unterschiedlichkeit des Zhenba-Fangxiang Blocks. Die ediakarischen, sedimentär-stratiformen Mn-Lagerstätten und die frühkambrischen Baryt- und Witherit-Lagerstätten zeigen eine zonenförmige Verbreitung, die darauf hindeutet, dass der Zhenba- Fangxian Block im Kambrium unabhängig vom Yangtze Block war. Die Mächtigkeiten der neoproterozoischen Ablagerungen des Zhenba-Fangxian Blocks weichen ebenfalls stark vom Yangtze Block ab. Zusammenfassend betrachten wir den Zhenba-Fangxian Block als ein unabhängiges Terrane oder als Teil des Süd- Qinling Terranes während des späten Neoproterozoikums bis frühen Paläozoikums.

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Preamble

The thesis focuses on the "Cambrian small shelly fossils of South China and their application in biostratigraphy and palaeobiogeography". It was written in a cumulative style, comprising five chapters with three scientific papers included:

- Chapter 1: Introduction
- Chapter 2: Material and methods
- Chapter 3: Scientific Papers
- Chapter 4: References
- Chapter 5: Appendices
- Curriculum vitae

Chapter 1 is subdivided into four subchapters. The first subchapters gives an introduction to the scientific background of the topic, the general progresses made in the SSFs study and the problems existed for the early Cambrian biostratigraphy and palaeobiogeography. The other three subchapters correspond to the three publications on the thesis topic and provide detailed introduction on the Terreneuvian-Cambrian Stage 3 SSFs, hiati, methods of SSFs extraction, and plaeobiogeography background of the research regions (Zhenba-Fangxian Block and Yangtze Platform). Chapter 2 described the materials sampling and laboratory methods applied in the study. Chapter 3 is composed with three scientific Papers.

Chapter 3.1 is published as: "Yang, B., Steiner, M., Li, G., Keupp, H., 2014b. Terreneuvian small shelly faunas of East Yunnan (South China) and their biostratigraphic implications. Palaeogeography, Palaeoclimatology, Palaeoecology 398, 28-58. http://dx.doi.org/10.1016/j.palaeo.2013.07.003 ".

Chapter 3.2 is published as: "Yang, B., Zhang, L., Danelian, T., Feng, Q., Steiner, M., 2014c. Chert-hosted small shelly fossils: expanded tool of biostratigraphy in the early Cambrian. GFF 136, 303-308. http://dx.doi.org/10.1080/11035897.2014.882977 ".

Chapter 3.3 is submitted to Gondwana Research as: "Yang, B., Steiner, M., Keupp, H., 2014a. Early Cambrian palaeobiogeography of the Zhenba-Fangxian Block (South China): Independent terrane or part of the Yangtze Platform? Gondwana Research, *Submitted*.".

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Contents

1. Introduction

1.1. State of the art

Metazoan evolution has been better understood more recently. Attention is paid to every stage of the geohistoric timescale. Scientists believe that life existed as early as 3.5~ 3.8 billion years ago (Barghoorn and Tyler, 1965; Schopf, 1993; Mojzsis et al., 1996). While most of the reports were disputed (Brasier et al., 2002; Fedo and Whitehouse, 2002; Fralick et al., 2002; Lepland et al., 2005; Moorbath, 2005), relatively credible opinion currently is established that the multicellular eukaryotes appeared in Late Paleoproterozoic-Early Mesoproterozoic times (Knoll et al., 2006). Animals evolved continuously since then to the end of the Neoproterozoic but remained unmineralized in most cases. Major biomineralization events happened in the Late Neoproterozoic-early Cambrian as a critical point in evolution, thus providing a high chance for fossilization. The most significant mineralization was marked by the sudden appearance of the small shelly fossils (SSFs). The SSFs, main target of our study, emerged at the base of the Cambrian before the so-called “Cambrian Explosion”. They played an irreplaceable role in deciphering the evolution as well as the abiotic aspects of the geohistory at the Precambrian-Cambrian (Pc-C) boundary.

As a fulcrum point (Conway Morris, 2006) in the evolution of life and the geohistory, the abrupt diversity of the Cambrian animals has puzzled scientists ever since Darwin’s (1859) time and will continue in future. Both biotic and abiotic influences on the “Cambrian Explosion” have been discussed (Marshall, 2006), e.g., atmospheric oxygen levels (Canfield, 1998; Knoll, 2009; Sperling et al., 2013), “Snowball Earth” hypothesis (Hoffman and Schrag, 2002; Peterson et al., 2005), phosphogenesis (Cook and Shergold, 1984), chemical weathering (Vermeij, 1995), true polar wander and methane fuse (Kirschvink and Raub, 2003), supercontinental amalgamation (Brasier and Lindsay, 2001), star burst (Maruyama and Santosh, 2008), the advent of heterotrophy (Stanley, 1973), predator-prey “Arm’s Race” (Marshall, 2006), evolution of macrophagy (Peterson et al., 2005), phytoplankton diversification (Butterfield, 1997) and the rise of fossilizable skeletons (Hutchinson, 1961; Vermeij, 1990). In any case, the skeletonized SSFs together with few of mineralized Ediacaran animals such as *Cloudina*, marked the prelude of the “Cambrian Explosion”.

Diverse abiotic processes were the main external causes stimulating the “Cambrian Explosion”. Study of the depositional record around the Pc-C boundary would be necessary for understanding the existence of SSF and the later bioradiation. One of the key sedimentary events is the unusual enrichment of phosphorus at the Pc-C boundary. Global phosphogenetic events happened in several periods in Earth history, such as Miocene-Pliocene, late Cretaceous-Eocene, Jurassic, Permian, middle Ordovician and in late Proterozoic-Cambrian times (Cook and Shergold, 1984). The Proterozoic-Cambrian period is the first major episode (Cook and Shergold, 1984) for the phosphate enrichment. Studies estimated $1.4 * 10^{10}$ tonnes of phosphate rock or about 10% of total world resources are of Proterozoic-Cambrian origin (Notholt and Sheldon, 1986); and most of the resources are of early Cambrian age. Hundreds of phosphate deposits of Proterozoic and Cambrian age have been documented (Cook and Shergold, 1986; Cook, 1992). These phosphorites were discovered in all continents but

Antarctica. In China, sedimentary phosphate was deposited mainly on the Yangtze Block, taking up 85% of the total phosphate reserves. Of the deposited phosphate, the Sinian (Late Neoproterozoic) reserves accounted for 51%; and the early Cambrian reserves (Fig. 1) accounted for 44%. Only 4.9% of the total deposits found in Devonian strata; and 0.1% in other Periods of China (Ye et al., 1989). Cook & Shergold (1984) suggested that the phosphogenesis around the Pc-C boundary was related to the overturn of the ocean water that circulated the deep ocean phosphate to shallow-water photic zone. Nutrients in the photic zone accordingly increased, nourishing the phytoplankton and other metazoans. Meanwhile, the phosphogenesis indirectly increased the free oxygen content of the atmosphere as the photosynthesis level of the phytoplanktons raised up (Cook and Shergold, 1984). Phosphorous is not only an essential nutrient and energy carrier for life (Föllmi, 1996), but also provides chances for the animal skeletonization in the form of calcium phosphate. In another aspect, SSFs were originally or secondarily phosphatized because of the worldwide phosphogenesis (Brasier, 1990). And early Cambrian carbonate sediments are often interlayered with phosphorites, leaving chances for the SSFs to be extracted with weak acid. Probably the phosphogenetic event was induced by a phase of continental movements that induced the oceanic overturn (Cook and Shergold, 1984). Such opinions on the tectonic activities were supported by the disconformities and hardgrounds which are widely distributed in the early Cambrian strata (Yang et al., 2014b).

Fig. 1 Phosphate mine in the Zhujiaqing Formation of the Dahai section in Huize County, Yunnan.

Matthews and Missarzhevsky (1975) applied the term “small shelly fossils” to the early Cambrian problematics, poriferans, molluscs, and hyoliths. Subsequently, the term was expanded covering all the phosphatized problematics of the traditional Lower Cambrian

(Steiner et al., 2007). Some other terms were occasionally used with similar meaning, e.g., "small skeletal fossils", "Small Shelly Fauna", and "Tommotian Fauna". As a group of small and mineralized metazoans, SSFs are usually phosphatized and preserved in the early Cambrian strata. SSF was not meant to be a valid taxonomic unit, but a loosely defined preservation mode of the animals or their individual body parts (Steiner et al., 2007). The SSFs consist the earliest protoconodonts, molluscs, brachiopods, bradoriids, cap-like fossils, sponge spicules and fragments of arthropods such as trilobites. Origins of most of the SSFs are problematic. And many different species were finally shown to be components of complete organisms. For instance, the *Halkieria* (Conway Morris and Peel, 1990), *Wiwaxia* (Conway Morris, 1985) and chancelloriids (Walcott, 1920a; Janussen et al., 2002) were all reported with complete bodies.

SSF research started early in the 19th century (e.g., Billings, 1871, on hyolith and brachiopod). Since the 20th century, studies received more attention (Walcott, 1912; Cobbold, 1935) on the SSFs, and mainly on the molluscs and brachiopods, such as rostroconchs and acrotretids. Until the 1960s, the SSFs were obtained with help of physical methods in the field. In the 1960s, the Soviet Union palaeontologists obtained abundant SSFs from the Siberian Platform (Rozanov and Missarzhevsky, 1966; Missarzhevsky, 1967; Rozanov et al., 1969; Voronova and Missarzhevsky, 1969) using acid etching methods. In the meantime, they tried to use SSFs for biostratigraphic correlation. In the next decade, scientists carried out vast efforts on the SSFs of many other areas (Bengtson, 1970; Mambetov, 1972; Matthews, 1973; Missarzhevsky, 1974; Yu, 1974; Müller, 1975; Qian, 1977). From the end of 1970s to the 1990s, SSF biozones were widely accepted to be a candidate for the early Cambrian biostratigraphy. As studies marched forward, taxonomic and stratigraphic problems emerged consequently. In this case, the global boundary stratotype section and point (GSSP) of Pc-C boundary was set with trace fossils instead of the SSFs. The Pc-C boundary GSSP was set to the first appearance datum (FAD) of *Trichophycus* (*Phycodes*) *pedum* with controversies accompanying this decision (Jensen et al., 2000; Gehling et al., 2001; Steiner et al., 2007; Weber et al., 2007). Recently, the GSSP was modified to the base of the *T. pedum* Assemblage Zone (Landing et al., 2013a) while controversies still existed (see discussion below). In contrast, SSF taxa, zonations, and correlations were significantly improved in the last two decades (Qian and Bengtson, 1989; Elicki, 1994; Qian et al., 1999; Steiner et al., 2003; Steiner et al., 2004; Steiner et al., 2007; Parkhaev, 2008; Elicki and Gürsu, 2009; Vendrasco et al., 2009; Parkhaev and Demidenko, 2010; Elicki, 2011; Li et al., 2012; Li et al., 2014; Yang et al., 2014b). Comprehensive correlations with lithostratigraphies, chemostratigraphies, and biostratigraphies of other fossils (e.g., trilobite and archaeocyathids) were applied (Qian et al., 1999; Elicki, 2005; Steiner et al., 2007; Shabanov et al., 2008; Varlamov et al., 2008; Maloof et al., 2010; Kouchinsky et al., 2011; Kouchinsky et al., 2014). Generally, SSFs studies have been carried out on most of the continents especially where the carbonates and phosphate carbonates (see below) were well developed.

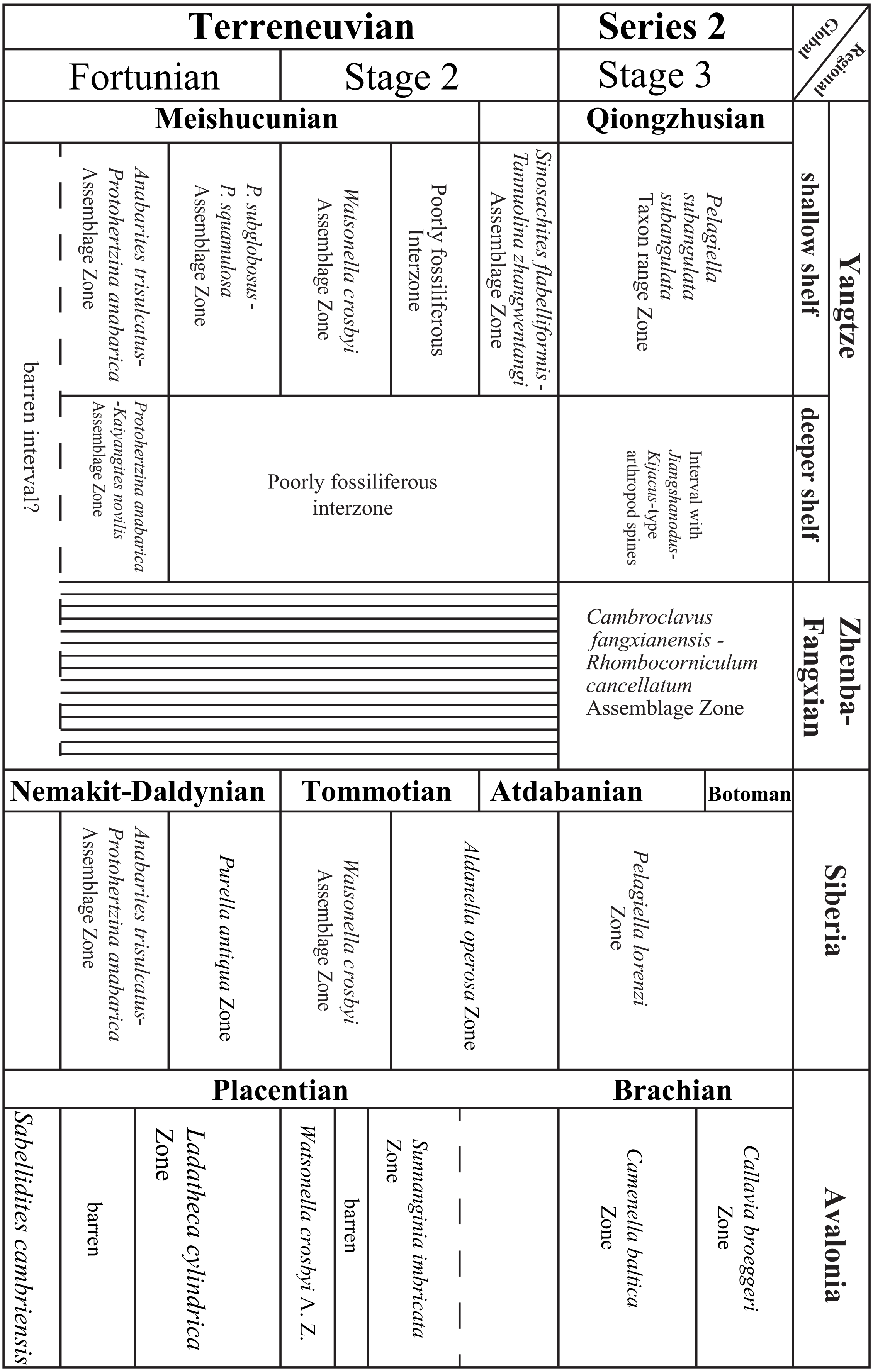

Fig. 2 Early Cambrian SSF biostratigraphic correlation of Yangtze Block, Zhenba–Fangxian Block, Siberia Block, and Avalonia Block.

Siberia has always been a focus for the SSFs studies ever since the 1960s (Rozanov and Missarzhevsky, 1966; Missarzhevsky, 1967; Rozanov et al., 1969). Rozanov and Missarzhevsky (1966) gave a comprehensive description on the SSFs in Siberia. Improvements on the taxonomy and correlation proceeded in the 1970s and 1980s (Missarzhevsky, 1973, 1974; Mambetov and Repina, 1979; Voronin et al., 1982; Voronova et al., 1983). Khomentovsky and Karlova (1993) made correlation of the biostratigraphy work of the Siberia. Rowland et al. (1998) studied the Vendian-Cambrian biostratigraphy of the Sukharikha River section, in northwestern Siberia. Including the SSF biostratigraphy, Knoll et al. (1995) focussed their study on the integrative stratigraphy of the Olenek Uplift, North Siberia. They also paid special attention to the sub-Tommotian unconformity. In recent years, SSF studies for different areas of the Platform were continually carried out. Comprehensive summarizations were made on the stratigraphy work of northeastern Siberia (Varlamov et al., 2008) and the Aldan-Lena River Area of southern Siberia (Shabanov et al., 2008), covering lithostratigraphy, chemostratigraphy as well as biostratigraphy of SSFs, trilobites, and archaeocyathids etc. Parkhaev et al.(2004) reported the early Cambrian molluscs in the East Transbaikalia Area. Demidenko (2006) reported some new lobopods and chaetognaths from the Aldan-Lena River area. Taxonomic studies of the brachiopods (Ushatinskaya, 2003) and the bradoriids (Andrey Yu Ivantsov et al., 2005) were also taken. In northern Siberia, Gubanov and Peel (1999) made taxonomic study on the Oelandiella while Kouchinsky et al. (2014) described diverse Cambrian Stage 3 (Atdabanian-Botoman) SSFs from the area along the Malaya Kuonamka and Bol’shaya Kuonamka Rivers in the eastern flanks of the Anabar Uplift.

The Yangtze Block is another well studied region for the SSFs. In the 1970s, Qian (1977) produced a preliminary study on the hyoliths of the Yangtze Block. Qian et al. (1979) reported the hyoliths and other coexisting SSFs, e.g., Paracarinachitids, Tommotiids, molluscs, Chanceloriids, from the Yangtze Gorge area on the northern margin of the Yangtze Block. Mounting studies were carried out in the 1980’s on the Block. Luo et al. (1980; 1982; 1984) made a comprehensive study on the stratigraphy of eastern Yunnan. Xing et al. (1984) summarized the studies covering the whole Yangtze Block and regions of in the southern margin of the North China. Studies were also carried out on the Qiongzhusian (Cambrian Stage 3) SSFs in the Zhenba Region of southern Shaanxi as well as the Fangxian Region of Northwest Hubei (Duan, 1983; Qian and Zhang, 1983; Xie, 1988, 1990). The SSFs of these two regions were later interpreted to be different from other parts of the Yangtze Block (Yang et al., 2014a). Qian et al. (1989) generalized the early Cambrian biostratigraphy of the Yangtze Block. Qian and Bengtson (1989) reported the Terreneuvian SSFs of the Meishucun Region in eastern Yunnan, providing widely accepted taxa and regional biozones. Studies were also made on the SSFs of the deeper water facies of the Yangtze Block. Qian and Yin (1984) reported diverse SSFs from Zhijin, Taijiang, Xishui, and Dayan. The fossils included *Anabarites trisulcatus*, *Protohertzina unguliformis*, *Zhijinites longistriatus*, *Kaiyangites novilis*, *Aurisella minutus* (*=A. tarimensis)*, sponge spicules, siphogonuchitiids, and other problematics. The fossils from Guizhou exhibited a transitional aspect between deeper and shallow water facies. Besides, the missing of the *Paragloborilus subglobosus*-*Purella squamulosa* Assemblage Zone was indicated (Yang et al., 2014b). Ding and Qian (1988) reported *P. anabarica*, *P. unguliformis*, *K. novilis*, and diverse sponge spicules etc., from the Yangjiaping area in North Hunan. Yue and Zhao and He and Yu (1992) studied the SSFs from the Jiangshan Region of Zhejiang. Steiner et al. (2003) improved the biostratigraphy and taxonomy of this region. Qian et al. (1999) reviewed the SSF study in China referring to the taxonomy, biostratigraphy, fossil composition, palaeogeography etc. The SSF research on the Yangtze Block was further advanced around the last decade. Li et al. (2001; 2004; 2004a; 2007; 2011; 2012) focus their taxonomic studies on the Northeast Yunnan and South Shaanxi regions. Steiner et al. (2003; 2004; 2007) gave biostratigraphic studies referring the regional zonations and their global correlation. Yang et al. (Fig. 2, 2014b) proposed improved Terreneuvian SSF biostratigraphies of eastern Yunnan. They also discussed the relationships of the Pc-C boundary hiati and the SSF biostratigraphy in the region, proposing minor influence of the hiati on the biostratigraphy.

In the southern region of Australia, well preserved SSFs have been reported for decades. The biozones of these SSFs were correlated globally (Bengtson et al., 1990; Gravestock et al., 2001; Skovsted et al., 2006; Paterson et al., 2007; Topper et al., 2009; Skovsted et al., 2012; Betts et al., 2014). Bengtson et al. (1990) gave detailed reports on the SSFs from this region. Gravestock et al. (2001) made detailed taxonomy and stratigraphy research on the Cambrian of the Stansbury Basin. Jago et al. (2006) gave a review on the Cambrian biostratigraphy of South Australia. Topper et al. (2009) reported the SSFs from the Lower Cambrian ‘Pararaia bunyerooensis’ Zone of Flinders Ranges, South Australia. Taxonomy work on special species, such as Tommotiids (*Eccentrotheca*, *Camenella*, *Paterimitra* etc.), bradoriids, and palaeoscolecids, have also been done (Skovsted et al., 2008; Skovsted et al., 2009a; Skovsted et al., 2009b; Topper et al., 2010). Betts et al. (2014) reported a new bradoriid assemblage from the North Flinders Range. Generally, the Terreneuvian SSFs correlated to the *Protohertzina anabarica-Anabarites trisulcatus* Assemblage Zone and *Paragloborilus subglobosus-Purella squamulosa* Assemblage Zone, were absent in southern Australia. The *Watsonella crosbyi*, index fossil of the *W. crosbyi* Assemblage Zone, was scantily reported in Australia (Daily, 1976; P. Yu Parkhaev, 2001) with controversial biostratigraphic indications. *Watsonella crosbyi* was globally reported from the upper Terreneuvian strata. Hence, it was considered as one of the best potential GSSP index fossil for the base of the Cambrian Stage 2 (Li et al., 2011). As the only exception, the latter fossil was reported in a Atdabanian-Botoman interval (P. Yu Parkhaev, 2001). While the other discovery was in a lower interval (Daily, 1976; Li et al., 2011). Considering this case, the taxa and the occurrence interval of *W. crosbyi* in Australia needs a careful reexamination. In general, a Terreneuvian gap in Australia existed between the early Cambrian and the Ediacaran strata. The SSFs are mainly restricted to the *Cambroclavus fangxianensis-Rhombocorniculum cancellatum* Assemblage Zone and younger intervals.

As another eastern Gondwana continent, Antarctica was reported with well preserved SSFs. Atdabanian and Botoman problematics, molluscs, brachiopods, bradoriids, and tommotiids were discovered from Antarctica. Major results were gained from the carbonate rocks of glacial erratics in King George Island of West Antarctica (Wrona, 1989; Evans and Rowell, 1990; Holmer et al., 1996; Wrona, 2003, 2004, 2009). Bradoriids (Rode et al., 2003) and probably *Dailyatia* (Rowell et al., 1992) were rarely reported in the Pensacola Mountains in East Antarctica. Because of the special preservation mode (the glacial erratics), the fossils are less abundant compared to Australia, hindering a refined biostratigraphic correlation in between. Notwithstanding, the relatively limited assemblages in Antarctica showed high similarity with the Australian fossils.

In North Avalonia, studies were also carried out. Hinz (1987) and Brasier et al. (1984; 1986) made detailed study on SSFs in the Home Farm Member of Nuneaton and the Comley Limestone of Comley and Rushton in England. As Terreneuvian records were completely missing, the Atdabanian-Botoman (Cambrian Stage 3) SSFs there were the oldest Phanerozoic fossils comparable to the Newfoundland fossils. Landing et al. (1988, 1991, 1995) described SSFs of Massachusetts and southeastern Newfoundland. The SSFs were composed of mollucs, tommotiids, brachiopods, bradoriids, trilobite fragments, and many other problematic fossils ranging from late Terreneuvian (*Watsonella crosbyi* Assemblage Zone) to Series 2. The early Terreneuvian SSFs failed to be recovered for the reason of the siliciclastic rocks at the base. Fossils from different areas of Avalonia can be correlated with each other, confirming high affinity and closed palaeogeographic relationships. On the Laurentia Craton, the East Pennsylvania (Skovsted and Peel, 2010), West Newfoundland (Skovsted et al., 2004; Skovsted and Peel, 2007), and Northeast Greenland (Skovsted, 2004) areas preserved a unique SSF composition distinct from other continents. Because of a siliciclastic interval at the base, the Terreneuvian SSFs were missing. Assigned to an Atdabanian-Botoman age, the overlying fossils were composed of Chancelloriids, helcionellids, hyoliths, and brachiopods, echinoderm ossicles, sponge spicules, and problematics such as *Triplicatella*.

In Mongolia, the SSFs have a wide range from the Terreneuvian to at least Cambrian Stage 3. The fossils have been intensively studied in the 1980s (Missarzhevsky, 1981; Voronin et al., 1982) and the 1990s (Pospelov et al., 1995; Brasier et al., 1996; Esakova and Zhegallo, 1996; Banerjee et al., 1997). In Kazakhstan and Kyrghyzstan, studies reported SSFs from the *Protohertzina anabarica* Assemblage Zone to the *Microcornus parvulus-Adyshevitheca* Zone (Missarzhevsky and Mambetov, 1981) in Maliy Karatau and Talas Alatau (Missarzhevsky and Mambetov, 1981; Holmer et al., 1997; Holmer et al., 2001; Dzik, 2003). The affinity of the SSFs in this region was ambiguous, though they have been correlated to Siberia (Missarzhevsky and Mambetov, 1981) and other areas. Together with the Yangtze Platform and Avalonia, the Tarim Block was located in the western Gondwana during Ediacaran-early Cambrian (Li et al., 2013; Torsvik and Cocks, 2013b). The block mainly preserved Cambrian Stage 3 SSFs in the Xiaoerbulake Formation and the Yuertusi Formation (Qian and Xiao, 1984; Yue and Gao, 1992; Qian et al., 1999; Qian et al., 2009). Fortunian (*Protohertzina anabarica-Anabarites trisulcatus* Assemblage Zone) fossils have also been reported (Xiao and Duan, 1992). SSFs between the Fortunian and Cambrian Stage 3 were, however, missing because of gaps. The fossils in Tarim share certain similarity to both Yangtze Platform and Kazakhstan.

Armorica is another western Gondwana block defined as a group of microplates. The microplates were distributed around the modern Mediterranean and Europe. Early Cambrian SSFs from Armorica microplates were studied for decades with various species reported from Görlitz (Elicki and Schneider, 1992; Elicki, 1994, 1996, 1998, 1999), Iberia (Vidal et al., 1999; Gubanov et al., 2004; Clausen and Álvaro, 2006; Hinz-Schallreuter et al., 2007), Sardinia (Elicki and Wotte, 2003; Elicki and Pillola, 2004), and Taurus Mountain of Turkey (Sarmiento et al., 2001; Elicki and Gürsu, 2009). The Terreneuvian SSFs were also missing in the Armorican microplates. Recorded SSFs were mainly from the Cambrian Stage 3 interval that overlay the Precambrian strata.

On the North China Block, SSFs have been reported from its southern margin, that is, from the central Shaanxi, South Henan, and North Anhui regions. The best preserved fossils are found in the Xinji Formation in South Henan (He et al., 1984; He and Pei, 1985; Pei, 1985; Zhang, 1987; Feng et al., 1994; Zhang, 2007). Atdabanian-Botoman (Cambrian Stage 3) hyoliths, molluscs, and cap-like fossils etc., resembling the faunas of Australia and Laurentia were recovered from central Shaanxi (Wang et al., 1989; Fang et al., 1992), South Henan (Feng et al., 1994), and North Anhui regions (Xiao and Zhou, 1984; Zhou and Xiao, 1984; Zhang and Sun, 1991). Poorly preserved Cambrian Stage 3 SSFs from the Taowan Group of the Luonan Region were reported (Wang et al., 1989). Cosmopolitan species *Pojetaia runnegari* having been found in many other places except for Yangtze Platform, were reported from the Henan, Central Shaanxi, and North Anhui regions of North China (He and Pei, 1985; Li and Zhou, 1986; Wang et al., 1989). *Apistoconcha* cf. *apheles* was recently found (Li et al., 2014) in the Luonan Region of North China. While the species (*Apistoconcha* sp.) in Mongolia (Esakova and Zhegallo, 1996) was questionable (Li et al., 2014), affirmative *Apistoconcha* were reported only from Australia (Bengtson et al., 1990) (Parkhaev, 1998; P.Yu. Parkhaev, 2001) and Northeast Greenland (Skovsted, 2006). Hence the discovery of *Apistoconcha* cf. *apheles* in Luonan further suggests an affinity of the Central Shaanxi to the Australia and Laurentia faunas. In general, the North China SSFs document a far palaeogeographic distance to the Yangtze Platform, and more similarity to the Australian and Laurentian faunas.

Many other areas were reported with SSFs including India, Iran, Jordan, and Morocco. SSFs from Maldeota of the Lesser Himalayas (Brasier and Singh, 1987) show high similarity to the *Protohertzina anabarica-Anabarites trisulcatus* Assemblage Zone of Xiaotan and Laolin regions, South China. The fossils reported in Iran (Hamdi et al., 1989) could be a mixture of the *P. anabarica-A. trisulcatus* Assemblage Zone and the *Paragloborilus subglobosus-Purella squamulosa* Assemblage Zone. SSFs of Indian and Iran need further investigation to update the data. Fossils from Jordan (Elicki, 2011) and Morocco (Skovsted et al., 2014) belong to late early-Middle Cambrian and were poorly preserved.

According to the international stratigraphic guide: “stratigraphy is the description of all rock bodies forming the Earth's crust and their organization into distinctive, useful, mappable units based on their inherent properties or attributes in order to establish their distribution and relationship in space and their succession in time, and to interpret geological history” (Salvador, 1994). Time is central for researches into the diverse geological sciences. Chronostratigraphy is “the element of stratigraphy that deals with the relative time relations and ages of rock bodies” (Salvador, 1994). Chronostratigraphic units are mainly set up according to the biostratigraphy and complemented with lithostratigraphy, isotope datings, etc. Following the establishment of the lithostratigraphy from Steno in the seventeenth century to Werner in the eighteenth century, biostratigraphy was developed ever since the nineteenth century by William Smith. It started from the recognition of the succession of fossil floras and faunas in sedimentary strata sequences (McGowran, 2008). Biostratigraphy is defined as “the element of stratigraphy that deals with the distribution of fossils in the stratigraphic record and the organization of strata into units on the basis of their contained fossils” (Salvador, 1994). According to McGowran (2008), biostratigraphy was developed on a three-part foundation: “(i) the recognition of successional assemblages of fossils in successional strata;

(ii) the successful testing and confirmation of that succession in other localities and other regions; and (iii) the perception that similarity among assemblages of fossils indicates similarity in geological age. Biostratigraphy and its correlation are based on the assemblage as well as the distributions of fossils." A regionally or globally accepted correlation is constructed of the biostratigraphic zones. Biozones are composed of five entities as well as the barren intervals which have no fossils. These five entities are range zones, interval zones, assemblage zones, abundance zones, and lineage zones.

Global chronostratigraphic work on the Pc-C boundary and the Cambrian System has been modified with significant progress (Brasier et al., 1994; Babcock et al., 2005). Ratified by the International Union of Geological Sciences (IUGS), the Pc-C boundary was defined by the first appearance datum (FAD) of *Trichophycus* (*Phycodes*) *pedum* (Brasier et al., 1994; Landing, 1994). The International Subcommission on Cambrian Stratigraphy (ISCS) voted to subdivide the Cambrian system into four series representing subequal spans of time (Babcock et al., 2005). The lower two series correspond approximately to the traditional Lower Cambrian, the third series corresponds approximately to the traditional Middle Cambrian, and the fourth series (Furongian Series) corresponds approximately to the traditional Upper Cambrian. The fourth series, called the Furongian Series, has been ratified by the International Union of Geological Sciences (IUGS).

As the earliest Phanerozoic period, the early Cambrian has been debated for its biostratigraphic conundrum. In the case that trilobites did not appear until the end of Stage 2, the Fortunian and early-middle Stage 2 needs some other fossils to establish the biostratigraphy and accordingly to give a detailed chronostratigraphic frame. Efforts have been made on various fossil candidates, such as trace fossils (Crimes, 1987; Narbonne et al., 1987; Jensen, 2003; Weber et al., 2007), SSFs (Qian and Bengtson, 1989; Bengtson et al., 1990; Elicki, 1994; Steiner et al., 2007; Kouchinsky et al., 2011), acritarchs (Moczydlowska, 1991) (Moczydlowska and Zang, 2006), and archaeocyathids (Debrenne and Debrenne, 1995; Shabanov et al., 2008; Varlamov et al., 2008; Álvaro and Debrenne, 2010). All of these candidates were disputable in varying degrees, whereas the SSF were considered to be the best choice with less controversies. SSF zones have been recognized and correlated between different continents (Steiner et al., 2007). Yet it has been argued that the SSFs' ranges were facies-controlled (Landing, 1992; Lindsay et al., 1996a). It was further argued (Landing and Geyer, 2012; Landing et al., 2013a) the FAD, the fundament of biostratigraphy, was a misleading concept for which biostratigraphy should be abandoned and hence be replaced by chemostratigraphic indicies for the chronostratigraphic conceptual frame. Landing et al. (2013a) claimed "the use of FAD of a fossil to define a global chronostratigraphic unit's base can lead to intractable correlation and stability problems". They suggested to apply the correlation of δ^{13}C peaks to define the GSSP of Series 2 and Cambrian Stage 3 of Cambrian. In general they suggested to replace biostratigraphy with chemostratigraphy. Self-contradictorily, Landing et al. (2013a), however, insisted and updated the *Trichophycus pedum* Assemblage Zone to define the GSSP of the Pc-C boundary. According to their opinion, this trace fossil biozone was treated as an exception, whereas other fossils were discarded.

The Cambrian GSSP was then redefined as follows (Landing et al., 2013a, p. 145): "The position of the conterminous bases of the Cambrian System, Terreneuvian Series, and Fortunian Stage at the Fortune Head section coincides with the base of the *Trichophycus* *pedum* Ichnozone Assemblage, that has its base defined immediately above the highest occurrences of *Harlaniella podolica* and *Palaeopascichnus delicatus*. This horizon lies slightly above the base of the *Asteridium tornatum*-*Comasphaeridium velvetum* Zone. The *T. pedum* FAD lies below the base of the *T. pedum* Ichnozone Assemblage, that features the appearance of such characteristic Phanerozoic ichno genera as *Arenicolites*, as well as taxa known elsewhere to appear in the terminal Ediacaran (e.g., *Cochlichnus*, *Didymaulichnus*, *Monomorphichnus*)."

According to their opinion, the FAD of *T. pedum* was abandoned, whereas the basal *T. pedum* Ichnozone Assemblage was designated to define the GSSP. They claimed the base of the assemblage zone was defined by: (i) the highest occurrences, namely the last appearance data (LAD), of *Harlaniella podolica* and *Palaeopascichnus delicatus*; (ii) the base *Asteridium tornatum*-*Comasphaeridium velvetum* Zone, namely the FAD of *A. tornatum* (Moczydlowska, 1991; Vidal and Moczyd, 1992). In this case, the GSSP lies on the trace fossil assemblage as well as the FAD and LAD of acritarchs. This restatement was inherently self-contradictory to their major opinion on the FAD. Though the trace fossils were more considered to be facies-dependent, Landing et al. (2013a) claimed *Trichophycus pedum* was eurytopic. Besides, evidences showed *T. pedum* was diachronous (Crimes, 1994; Jensen et al., 2000; Gehling et al., 2001; Weber et al., 2007; Aceñolaza et al., 2009). In comparison, the SSFs are more diverse than the coeval trace fossils with many elements (e.g., *Protohertzina anabarica*) also eurytopic. The early Cambrian trace fossils were not less, if not more, problematic than the SSFs concerning the taxonomic problems of *Trichophycus*, *Phycodes* and *Treptichnus* (Aceñolaza et al., 2009). Problems of *T. pedum* in the stratotype section (the Fortune Head section) have been reported as the fossil was found 3.11 m and 4.11 m below the GSSP point (Gehling et al., 2001). Re-evaluation of the trace fossil's stratigraphic ranges and taxonomic assignments have been recommended (Gehling et al., 2001). Restudying on the definition of the GSSP at the basal Cambrian System were also suggested (Peng and Babcock, 2011). Landing et al. (2013a) were partially correct as the FAD can not always mirror biological phenomena ranging from evolutionary origination, to dispersal, successful local colonization, and appearance of facies that allow a species' fossilization (Landing et al., 2013a). While none of the known knowledge can solve the problem of FAD, uncertainties will always existed and come out. Similar essential deficiencies existed, too, in the chemostratigraphy when referring to the basics (see discussion below). As they claimed the FAD was diachronous and failed to reflect the true time scale, their logics was biased to sophism. We cannot, in any case, refuse the validity of the FAD, the isotope dating, and the chemostratigraphic correlation, though general inaccuracy always exist.

Landing et al. (2013a) argued that the GSSP for the base of Cambrian Stage 2 should not use *Aldanella attleborensis* or *Watsonella crosbyi*. One of the claimed reasons was the thicknesses discrepancy of the early Cambrian succession in different regions which, as they claimed, indicated different depositional time ranges. *Watsonella crosbyi* was reported in: Avalonia with an extensional range of 650 m in a 3 Km thick succession; ca. 20 m range on the Yangtze Block (Qian et al., 1999; Yang et al., 2014b) and in Siberia (Rozanov et al., 1969); and a ca. 150 m thick range in western Mongolia (Parkhaev and Karlova, 2011). They suspected the smaller thickness of sections in the Yangtze and Siberia platforms had resulted from the hiati (unconformities/ disconformities, and hardgrounds). Our studies showed the disconformities/ disconformities and hardgrounds in South China were widely distributed, but with minor influence on the SSF biostratigraphy (Yang et al., 2014b). Besides, the hiatus were not limited to the South China or Siberia, but globally distributed in various areas, e.g., Montagne Noire in France (Kerber, 1988), Laurentia (Peters and Gaines, 2012), Iberia and Morocco (Álvaro et al.), South Australia , Görlitz in Germany (Germany, Elicki and Schneider, 1992; Buschmann et al., 2006), Middle East (Elicki and Geyer, 2013), Tarim (Qian and Xiao, 1984; Qian et al., 1999), North China (Li et al., 2014), and Kazakhstan (Missarzhevsky and Mambetov, 1981; Holmer et al., 1997; Meert et al., 2011). In another aspect, they probably ignored the variations of sediment patterns and accumulation rates which can remarkably affect the strata thicknesses. As Brasier and Lindsay (2001) proposed, the rates of subsidence and sediment accumulation increased through the Late Neoproterozoic-early Cambrian (ca. 550 and 530 Ma). This resulted from the contemporary amalgamation of continents (Brasier and Lindsay, 2001) when rapid subsidence took place along cratonic margins and interior basins. Besides, the coeval disconformities and hardgrounds indicated frequent erosion and high influx of clastics into the basins (Peters and Gaines, 2012; Smith and Harper, 2013) during the early Cambrian. Still, the accumulation and subsidence rates were not homogeneous, and there existed possibilities of sedimentation breaks in some basins (Grotzinger et al., 1995; Brasier and Lindsay, 2001). In general, carbonates and siliclastic facies have different depositional rates, compaction rates, and subsidence rates. Implied by hardgrounds and disconformities, tectonic movements such as continent amalgamation brought rapid subsidence of the basins, higher erosion of the land and more influx of clastics into the ocean (Smith and Harper, 2013). In this case, siliciclastic deposits accumulated faster than the carbonate. Consequently, the sections (as those in Avalonia and Namibia) containing siliclastic rocks owned a larger thickness than those contemporaneous carbonate strata (as those in the Yangtze and Siberia blocks). sections of carbonate ramp (as those in Mongolia) with sediment gravity flow deposits, such as slumps, debris flow deposits or turbidites, could equally have huge thickness. In contrast, pelagic carbonates which often have chert nodules and layers occurring usually belong to the condensed facies and commonly developed hardgrounds, Fe-Mn oxyhydroxide pavements, crusts and nodules, lithoclasts and borings (Tucker and Wright, 1990). Notwithstanding, the depositional rates are not consistent in all areas. Strata with parallel lithology could have different initial facies, hence, different depositional rates. Above all, thickness comparison of different sections with varied lithologies was not adequate. And the succession thickness can not be simply applied to judge the depositional time range, which has been well known in the sequence stratigraphy.

In this aspect, Landing et al. (2013a) give overwhelming support for the chemo-stratigraphic and the isotope dating. But the basics of it is as problematic as the FAD following their conjecture. Because of the allegedly physically unaffected periodic decaying, radioactive elements have been chosen for the timing of geohistory. As is known, the decay rates of the isotopes is a statistic result with a probabilistic nature. Though disputes existed (Ding et al., 2009; He et al., 2009; Bellotti et al., 2013), the invariability of the half-lives have been doubted (Daudel, 1947; Segre, 1947; Emery, 1972) and even disproved (Huh, 1999; Limata et al., 2006; He et al., 2007; Ohtsuki et al., 2007; Raiola et al., 2007; Jenkins et al., 2009; Ohtsuki et al., 2011). For many elements, e.g., ^{7}Be (Liu and Huh, 2000; Souza et al., 2002; Ohtsuki et al., 2004), ^{22}Na (Limata et al., 2006), ^{32}Si (Jenkins et al., 2009), and ^{26}Ra (Jenkins et al., 2009), either α or β decay rates with 0.1-1.0% variations were reported in different environmental samples, such as in fullerene and various metal environments. The decay rate dependences were rarely reported from heavy elements possibly because of the higher capture capacity of their nucleus with much more protons. However, variations were still detected in some studies (Raiola et al., 2007; Mikheev et al., 2008; Jenkins et al., 2009; Ray et al., 2009; Lindstrom et al., 2010). The variations of the decay rate might be too minor to be easily identified in most of heavy elements. Variation of the decay rate in natural and geological environments would be weaker, if it could be eventually detected. Comparable to the objection on the FAD (Landing et al., 2013a), the weak variations can be accumulated, devaluating isotope dating and chemostratigraphic correlations concerning the long lasting earth history. And under the case of the quite complex geohistory, the isotopes in rocks mostly were not in a closed system, inhibiting the raw precision of the values. Taking zircons for example, they can be formed in magma crystallization or metamorphic process. Zircons possessing various oscillatory zones are dependent on the crystallization temperature in various magmas, while metamorphically born zircons own various inner structures caused by the metamorphism. In another aspect, the theory and calculation method of the isotope datings have been controversial (Begemann et al., 2001; Renne et al., 2010; Renne et al., 2011; Schwarz et al., 2011). Isotope data of chemostratigraphy such as δ^{13}C are sensitive to kinds of factors, e.g., sedimentary differences, diagenetic impacts, tectonic movements, meteoric water eluviation, and metamorphic events. Correlation of isotope curves needs the control of biostratigraphy. More endurable against geological processes, the fossils can be recovered from kinds of sedimentary rocks as well as low-grade metamorphic rocks, producing no or minor bias for correlation in many cases.

Landing et al. (2013a) applied carbon isotope-based correlations of lowest Cambrian successions of Avalonia, South China, and the Siberian Platform. Grant (1992) concluded the lithology and diagenesis are important components in δ^{13}C stratigraphic variation in the lower Cambrian Forteau Formation Limestones and the contemporary SSFs (skeletal organisms) exerted “vital effect” on the carbon isotope. As mentioned above, hiatuses (hardgrounds and disconformities) developed globally in the early Cambrian that biased the chemostratigraphy and the subsequent correlation.

Brasier et al. (1990) correlated the carbon and oxygen isotope curves from the Meishucun and Maidiping sections of China and the Valiabad section of Iran. The Valiabad section has an ambiguous SSF distribution. The Maidiping section was demonstrated with a gap between Bed 35 and Bed 36 as the second SSF zone, *Paragloborilus subglobosus-Purella squamulosa* Assemblage Zone was missing in the section (See Chapter 1, Yang et al., 2014b). As this zone was preserved in the Meishucun section, the isotope curve correlation was under a incorrect biostratigraphic backgrounds. Maloof et al. (2010) reported studies on the chemostratigraphy of Cambrian strata in Anti-Atlas Mountains of Morocco with an international correlation between Morocco, Siberia, South China and Mongolia. Meanwhile, a comparison between the chemostratigraphy and SSF biostratigraphy were made based on the isotope data from Morocco (2010). The chemostratigraphic correlation by them suggested that the FADs of SSFs scattered over a changeable range of ca. 10 my. Based on this argument, they concluded that the SSF biostratigraphy was problematic and unreliable for the early

Cambrian chronostratigraphy. As discussed above, the chemostratigraphy itself is the problematic issue in this case. For the carbon isotope curves, the values are easily affected by the hiati, regional facies, potential surface to deep ocean gradient of the $\delta^{13}C$, and diagenetic alterations (Grant, 1992; Fike et al., 2006; Jiang et al., 2007). For some important SSFs and trilobites, they apparently produced incorrect scatter of the FADs. For instance, *Watsonella crosbyi* was claimed by them to be Nemakit-Daldynian in China. And the FAD of trilobites was Tommotian in China. However, none of the opinions were proven. And the data they collected were not fully examined as many were problematic (Brasier et al., 1997). Also they modified some published chemostratigraphic data (e.g., Zhou et al., 1997), stretching and compressing the isotope curves to construct their chemocorrelation. However, as the lithography and biostratigraphy were obscure for the referred sections (Zhou et al., 1997; Ishikawa et al., 2008), their conclusion based on the isotope curves was subjective and hence devaluated their correlation.

In general, the biostratigraphy is still basic for the early Cambrian chronostratigraphy. Whereas applying multiple supportive information, e.g., isotopic signatures, sea-level fluctuations, magnetostratigraphy, and geochronology, all these methods combined would better serve to define the chronostratigraphy (Babcock et al., 2005; Landing et al., 2013a).

1.2. Terreneuvian SSFs from East Yunnan and the related hiatuses

East Yunnan is the major part of the Yangtze Platform. During the early Cambrian, in this region carbonates with phosphorites were deposited, preserving prolific SSFs.

The SSFs on the Yangtze Platform were studied since the 1970s. Qian (1978) proposed a *Turcutheca -Sachites-Zhijinites* Assemblage and a *Circotheca- Tiksitheca- Anabarites-Protohertzina* Assemblage for the early Cambrian strata of eastern Yunnan. In the 1980s and 1990s, much work was done on the SSF biozonation of the Yangtze Platform. Luo et al. (1982; 1984) reported their systematic studies on the Meishucun section, Yulu section and other Eastern Yunnan sections. They established the *Anabarites- Circotheca- Protohertzina* Assemblage, the *Paragloborilus- Siphogonuchites* Assemblage, and the *Sinosachites-Eonovitalus* Assemblage for the Meishucunian strata.

Qian and Bengtson (1989) restudied the Meishucun Region (Fig. 3) giving an updated three zones for the succession: *Anabarites- Protohertzina- Arthrochites* Assemblage; *Siphogonuchites- Paragloborilus* Assemblage; *Lapworthella- Tannuolina- Sinosachites* Assemblage. He (in, Qian et al., 1999) proposed six SSF zones for the Yangtze Platform covering the Meishucunian and early Qiongzhusian strata. Steiner et al. (2007) comprehensively displayed the SSF biostratigraphy and global correlation of the Yangtze Platform. They systematically proposed the following zones in the Fortunian- Cambrian Stage 3 of shallow water facies in the Yangtze Platform: (I) *Anabarites trisulcatus- Protohertzina anabarica* Assemblage Zone; (II) *Paragloborilus subglobosus- Purella squamulosa* Assemblage Zone; (III) *Watsonella crosbyi* Assemblage Zone; (IV) poorly fossiliferous interzone; (V) *Sinosachites flabelliformis- Tannuolina zhangwentangi* Assemblage Zone; (VI) *Pelagiella subangulata* Taxon-range Zone. From South Shaanxi and North Hubei, along the northern margin of the Platform, two biozones were proposed: the *Ninella* (=*Aurisella*) *tarimensis- Cambroclavus fangxianensis* Assemblage Zone and the *Rhombocorniculum cancellatum* Taxon-range Zone. These two zones can be approximately correlated to the *P.*

subangulata Taxon-range Zone. Later on, the (I)-(III) biozones were modified by Yang et al (Chapter 1, 2014b). Index fossils of zone (II) and (III) were re-designated. Zone (II) were defined by the following index fossils: *Purella subglobosus (-a?), Paragloborilus squamulosa, Oelandiella korobkovi*; and the *W. crosbyi* Assemblage Zone, which was defined by *Watsonella Crosbyi, Aldanella yanjiahensis* and *Zhijinites longistriatus*. Two subzones were proposed for the zone (II): *Annelitellus yangtzensis-Obtusoconus honorabilis* Subzone and *Maikhanella cambriana-Oelandiella korobkovi* Subzone. The *N.* (*A.*) *tarimensis-C. fangxianensis* Assemblage Zone and *R. cancellatum* Taxon-range Zone of the northern Yangtze Platform were combined to a new zone, the *Cambroclavus fangxianensis-Rhombocorniculum cancellatum* Assemblage Zone (Yang et al., 2014a). Two biozones were recognized (Steiner et al., 2003; Steiner et al., 2007) in the deeper water facies of eastern Yangtze Platform: the *Protohertzina anabarica-Kaiyangites novilis* Assemblage Zone and a informal zone, the Interval with *Jiangshanodus-Kijacu* type arthropod spines. Global correlation with Siberia and west Avalonia were also proposed (Steiner et al., 2007), promoting the applicability of the SSF biostratigraphy for the early Cambrian. Several reports claimed a mixture of index fossils from different zones. In the Xianfeng section Huang et al. (1986) reported the Zone I index fossil *Protohertzina anabarica* mixed with the Zone III index fossil *Watsonella crosbyi* (third zone index fossil) and many second zone fossils. Parkhaev and Demidenko (2010) reported Zone II fossils together with Zone I fossils. Considering the small size of the SSFs, they can be reworked and buried with younger fossils if any reworking event happened. The reworking beds probably resulted from meteoric exposure, weathering, and tectonic events.

Fig. 3 Meishucun section in Kunming City of Yunnan Province, China. The obelisk marks the sections being suggested as candidate of the Pc-C boundary.

Generally, three SSF zones (Yang et al., 2014b) developed in the Terreneuvian strata of East Yunnan: The *Anabarites trisulcatus-Protohertzina anabarica* Assemblage Zone, the *Paragloborilus subglobosus-Purella squamulosa* Assemblage Zone and the *Watsonella crosbyi* Assemblage Zone. These zones can be either completely or partly recognized in other areas e.g. in the northern Sichuan region of the Yangtze Platform , in the lowermost part of Tarim (Xiao, 1989), in western Mongolia (Esakova and Zhegallo, 1996), as well as on the Siberian Platform, at Maldeota of the Lesser Himalayas (Brasier and Singh, 1987), in Maly Karatau and the Talass Alatau (Missarzhevsky and Mambetov, 1981). Except for the SSFs of the three zones, sedimentological phenomena would deserve studies such as hardgrounds, disconformities and other structures (Yang et al., 2014b), just as these were found in the Terreneuvian successions of eastern Yunnan.

Preliminary discussions were given on the hiatus around Pc-C boundary of Yangtze Platform (He et al., 1988; Qian et al., 1996). Siegmund et al. (1994; 1995) reported paleokarst, hardground, and stylolites in the Upper Neoproterozoic Dengying Dolomite. But in general, detailed study on the hiatus has rarely been carried out (Yang et al., 2014b).

The most abundant hiatus feature is the hardgrounds in the early Cambrian strata. According to the definition, hardground is a discontinuous surface of synsedimentary lithification, having existed as hard sea floor prior to the deposition of the overlying sediments (Wilson and Palmer, 1992; Flügel, 2010). In younger strata, hardgrounds are featured by the marine organisms colonizing the hard substrates and various bioturbations created by burrowing, boring, and encrusting biota (Goldring and Kazmierczak, 1974; Bromley, 2004). Various taxa were found on the hardgrounds such as brachiopods, bivalves, bryozoa, conulariids, corals, and foraminiferans. A hardground indicates an erosion or interruption in deposition before the substrate is lithified and covered by younger permanent deposits. Hardgrounds have been found in various strata of all geological periods since Cambrian (Palmer, 1982; Brett et al., 1983; Chow and James, 1992) to Holocene sediments (Last, 1992; Noé et al., 2006). Surfaces of hardgrounds are condensed cementation formed with glauconite on the shelf; calcium phosphate, iron hydroxides, manganese oxides in pelagic environments; and rarely baryte which replaced formal calcite (Lindström, 1979; Marshall and Ashton, 1980; Flügel, 2010).

Hardgrounds are common, both in deeper-marine facies, shallow subtidal environments, off-platform pelagic settings, as well as along shallow slopes (Flügel, 2010). Most of the ancient hardgrounds occurred in the winnowed carbonate sediments of shallow water and on the carbonate platforms (Palmer, 1982). Usually hardgrounds represent minor gaps with various duration. Described hardgrounds found in the upper Cretaceous chalk of England were thought to represent gaps ranging from hundreds to thousands of years (Bromley, 1965) .Whereas those reported from some Ordovician strata have a range of even about 200,000 years (Flügel, 2010).

Similar structures have been described with slight differences to hardgrounds. Condensation is a sedimentation suspension characterized by stagnant to low sedimentation rates during a long period of time from thousands to millions of years (Flügel, 2010). The initial stage of hardground formation is named as firmground, which is a stiff, unconsolidated sedimentary substrate (Goldring, 1995) with various bioturbations depending on its maturity (Ruffell and Wach, 1998). Rockground is a sea-ground with well-lithified sediments exposed

(Flügel, 2010). In younger strata rockground is enriched with encrusting and boring biota, e.g., oysters, serpulids, sponges, corals, crinoids, and bivalves (Goldring, 1995). Similarly, a discontinuity surface is a zone of a few cm thick at the sea bottom, the sediment of which is lithified to form a hardened surface, often encrusted, discolored, case-hardened, bored and solution ridden (Flügel, 2010). It implies a gap in sedimentation and may be preserved stratigraphically as an unconformity. Today the term is not restricted to submarine settings, but also includes subaerial unconformities (Flügel, 2010). Another type of hiatus is the paleokarst. According to Esteban and Klappa (1983, p. 11): “Karst is a diagenetic facies, an overprint in subaerially exposed carbonate bodies, produced and controlled by dissolution and migration of calcium carbonate in meteoric waters, occurring in a wide variety of climatic and tectonic settings, and generating a recognizable landscape.” While paleokarst (James and Choquette, 1988, p. 2; Flügel, 2010, p. 730) was defined as an ancient karst commonly buried by younger sediments or sedimentary rocks. It includes (James and Choquette, 1988) both relict paleokarst (present landscapes formed in the past) and buried paleokarst (karst landscapes buried by sediments). Because of the absence of terrestrial vegetation in the Early Paleozoic, the amount of paleokarst in this Era is relatively low (Flügel, 2010). Still a number of paleokarsts were recognized in the Cambrian as well as late Precambrian strata, e.g., the Cambrian Port au Port Group of western Newfoundland (Chow and James, 1992), the Late Neoproterozoic Dengying Formation in Dayong Area of Yangtze Platform (Siegmund and Erdtmann, 1994), Beidoushan, Weng'an County, Guizhou (Zhu et al., 2007), at the Precambrian-Cambrian boundary in the Olenek Region of Siberia (Pelechaty, 1996). As this mainly happened in carbonate deposits (Ford and Williams, 2007) the paleokarst usually indicated subaerial exposure and meteoric water invasion loading significant influences on the chemostratigraphic correlation. Additionally, paleokarsts can lead to fossil mixture by the reworking of sediments especially for the microfossils such as SSFs and conodonts.

An unconformity is a surface of erosion or non-deposition that separates younger strata from older rocks and represents a significant hiatus (Flügel, 2010). In sequence stratigraphy, the unconformity is a “key concept” defined as a surface that separates younger strata from the older strata with the subaerial truncation or exposure (Van Wagoner, 1988). There are four kinds of unconformities (Boggs, 2006): the angular unconformity, disconformity, paraconformity, and nonconformity. In an angular unconformity, younger sediments rest upon the eroded surface of tilted or folded older rocks. Paraconformity is an obscure unconformity in which no erosional surface or other physical evidence of unconformity is discernible (Boggs, 2006). The nonconformity developed between sedimentary rock and older igneous or massive metamorphic rock that has been exposed to erosion prior to being covered by sediments (Boggs, 2006). The most easily recognized unconformity is the disconformity. A disconformity is a visible, irregular or uneven erosional stratigraphic bounding surface above and below which the beds are parallel. A disconformity essentially possesses a gap in time documentation. Except for amounts of hardgrounds, unconformities especially the disconformities, were globally formed in the early Cambrian strata as mentioned above. A disconformity can result from erosion, abrasion, denudation, deflation, dissolution, corrosion, or non-deposition (Flügel, 2010). The hiati and global phosphogenetic events around the Precambrian-Cambrian boundary should reflect some global tectonic, palaeoclimatic or eustatic events. The indicated continental movements, palaeoclimatic variations, or eustacies have brought prolific nutrients to the marine animals by weathering and increase of continental sources (Peters and Gaines, 2012; Smith and Harper, 2013). Consequently, the evolution process, especially the biomineralization was stimulated by all these events. In another aspect, early Cambrian hardgrounds, disconformities, and unconformities induced diverse reworking beds, giving rise to mixtures of SSFs. The mixtures were, however, minor and controllable according to the SSF correlation (Yang et al., 2014b). For chemostratigraphic correlation, however, this presented a much greater problem-as discussed above.

Our first study (Yang et al., 2014b) dealt with the Terreneuvian biostratigraphy of the SSFs in eastern Yunnan and the hiati caused by the hardgrounds and several disconformities.

1.3. New methods for extracting the SSFs in deeper water facies

Until now, most of the SSFs were recovered from carbonate rocks. For this reason, scientists focused on the carbonate deposits of early Cambrian age to promote the SSF biostratigraphy. Although SSF specimens were occasionally reported in the siliciclastic rock, systematical extraction remained difficult. Partially for this reason, the SSFs were argued to have been facies-controlled (Landing, 1992; Mount and Signor, 1992; Landing et al., 2013a), hindering its applicability to biostratigraphy and correlation. The arguments were, however, essentially misplaced. All SSFs are not facies-controlled as biozonations have been established in both shallow water and deeper water facies (Missarzhevsky and Mambetov, 1981; Qian and Bengtson, 1989; Esakova and Zhegallo, 1996; Steiner et al., 2003; Steiner et al., 2007). The extraction method, that is, the weak acid etching, is traditionally "facies-controlled" rather than the fossils.

Using weak acid to extract SSFs has became a standard method for decades. The method was acquired from the conodont extraction procedures as large quantities of SSFs were phosphatic in the limestone or dolostone. They can be obtained by immersing bulks into 5-10% acetic or formic acid. The carbonatic components can be dissolved by the weak acid, whereas the phosphatized SSFs were left in the residue. The method is not absolutely secure, and may damage the SSFs to various extent depending on the operation. Jeppsson (1985) gave this warning on the conodont extraction which shared the same acid etching method as the SSFs. Jeppsson et al. (1999) made detailed laboratory studies to optimize the extraction technique and to minimize the damage to conodonts, just as this is equally suitable for the SSFs. Green (2001) gave a comprehensive description of various methods extracting microfossils which is also applicable to the SSFs. Jeppsson and Anehus (1995) proposed the buffered formic acid technique for conodont extraction. Other methods have been occasionally applied (Vendrasco et al., 2009) on the SSFs: heating and quenching (Pojeta and Balanc, 1989b); freeze/thawing with sodium acetate (Pojeta and Balanc, 1989a); 10% sodium hypochlorite (Green, 2001); hot 10% sodium carbonate (Allman and Lawrence, 1972).

Previously the SSFs could only be extracted from carbonate rocks, which are dissolvable with weak acids. The lithology of the siliceous rocks impedes this traditional method. For fossils in chert or other siliciclastic rocks, the original composition of the SSFs was phosphate, calcium carbonate or silicate. Using hydrofluoric acid (Yang et al., 2014c) one can extract the phosphate and carbonaceous SSFs from siliciclastic rocks. Carbonaceous SSFs are resisting to the acid etching, whereas calcium phosphate can be replaced and transformed to calcium fluoride by applying an appropriate process (Chapter 2, Yang et al., 2014c, personal observation). The new method could break through the lithologic limitations and extend the SSF biostratigraphy to the siliceous facies.

Deeper water facies developed in the eastern and southeastern area of the Yangtze Platform. The region is restricted to the northern Hunan Province, western Zhejiang Province, and eastern Guizhou Province. Research on the SSFs were carried out in this region since the 1980s (Zhao and Yue, 1987; Ding and Qian, 1988; Yue and He, 1989; He and Yu, 1992; Steiner et al., 2003). Steiner et al. (2007) erected two SSF zones for the deeper water facies of the Yangtze Platform: the *Protohertzina anabarica-Kaiyangites novilis* Assemblage Zone and the Interval with *Jiangshanodus-Kijacus*-type arthropod spines. As the strata are mainly composed of shales and cherts, the SSFs were extracted from the phosphatic carbonate nodules at the base of the shales from the Niutitang and Hetang formations. *Tarimspira plana* (*Fengzuella zhejiangensis*), *Protohertzina anabarica*, and *Protohertzina unguliformis* (Ding and Qian, 1988; He and Yu, 1992; Steiner et al., 2003) was shown to be pelagic as found in these regions. *Tarimspira plana* were reported in North Siberia (Müller et al., 1995; Kouchinsky et al., 2014), Aksu-Wushi Region of Tarim (Yue and Gao, 1992), Yichang Region of central Hubei Province (Ding et al., 1992), and Zhenba Region of southeastern Shaanxi Province (Yang et al., 2014a). Besides, *Seletellus seletinicus* were found in the Hetang Formation in the Jiangshan Region of Zhejiang Province which was previously reported in the Ermentau-Nijaski Anticline of central Kazakhstan (Gridina, 1991). The two problematic species together with other SSFs indicated a different SSF assemblage from that in the shallow shelf region of the Yangtze Block (Yang et al., 2014c). It could be a facies discrepancy to have caused the fossil assemblage difference. A palaeogeographic distinction cannot either be excluded, as the study (Yang et al., 2014a) revealed that the shallow water regions of the Yangtze Platform were geographically separated from other blocks.

The deeper water black shales were deposited in anoxic environments. Early Cambrian submarine-hydrothermal exhalative events were reported in the deposits (Li, 1997; Steiner et al., 2001) of western Zhejiang, northern Hunan and eastern Guizhou provinces. The region deposited sedimentary Fe-Ni-Mo-ore layers by the hydrothermal venting events (Fan et al., 1987; Ye and Fan, 2000; Steiner et al., 2001). In the strata, abundant SSFs which were bituminized to various extent were found in the black shales and the basal phosphatic carbonate nodules. There are plenty reports on the ore layers (Fan et al., 1973; Chen et al., 1982; Fan et al., 1987; Chen et al., 1990; Li, 1995, 1997; Ye and Fan, 2000; Steiner et al., 2001), whereas studies on the SSFs in the black shales and their composition have been rare or missing. A second study here (Chapter 2, Yang et al., 2014c) tried to make a composition analysis of the extracted SSFs of the deeper water facies from Yangtze Block using energy dispersive X-ray spectroscopy examination.

1.4. Quantitative analysis and palaeobiogeograhy of the SSFs

Tectonic movements were a critical factor affecting the Cambrian bioradiation, as this may have driven other abiotic as well as biotic events. On the other hand, palaeontologic and sedimentological studies for this special interval may, in turn, verify and interpret the tectonic details.

The Yangtze Platform is well known for its prolific animal fossil record during the Cambrian. SSFs provide chances to detect the initial point of the Phanerozoic, when life forms first got “armoured”. Based on the two studies (Chapter 1, Yang et al., 2014b; Chapter 2, Yang et al., 2014c), we are able to improve the biostratigraphy of the SSFs on the carbonate platform in eastern Yunnan as well as the deeper water region in western Zhejiang. More possibilities exist along the northern margin of the Yangtze Platform, in the southeastern Shaanxi-northwestern Hubei Region. For understanding the relationships of the hiati, the SSFs, and the Cambrian explosion, studies referring to the palaeobiogeographic aspects were carried out using SSF and sedimentary data.

Physical palaeogeography and palaeobiogeography during the early Paleozoic (mainly early-middle Cambrian) have been studied for decades (Bengtson et al., 1990; Pillola, 1990; Elicki, 2005; Williams et al., 2007; Álvaro et al., 2013). Using brachiopod and trilobite species such as lingulate brachiopods and olenellids, reconstruction of early Cambrian palaeobiogeography has been attempted (Lieberman, 1997; Brock et al., 2000; Álvaro et al., 2003). Most of the studies focus on the non-SSF fossils and remained qualitative or semiqualitive. Recent research tried SSFs as a new proxy for the ecology and palaeobiogeography of the early Cambrian (Elicki and Pillola, 2004; Elicki, 2005). Steiner et al. (2007) quantitatively analyzed the affinities of different SSF groups. However, palaeobiogeograhic study of the SSFs is missing for the pre-trilobite and early trilobite time of the early Cambrian. In our third study (Chapter 3, Yang et al., 2014a), SSFs were used with clustering analysis to assess the palaeobiogeography and the geometry of the palaeocontinents during the early Cambrian period.

Most of the geometric reconstruction of the early Cambrian lacked palaeontologic data for the pre-trilobitic to early trilobitic time. Álvaro et al. (2003) provided palaeogeographical maps of western Gondwana using trilobite genera for clustering analysis. Torsvik et al. (2013b) presented revised global maps at 10 myr intervals covering the whole of the Lower Palaeozoic from 540 Ma and two additional maps of the Early Devonian. However, the oldest three maps, 540, 530 and 520 Ma, are poorly constrained. As Torsvik (2013b) mentioned, although broad consensus were achieved on the Lower Palaeozoic positions of several major palaeocontinents such as Gondwana, Laurentia, Baltica and Siberia, opinions on the continental size and relative position of some blocks, such as the South China (Yangtze Block) remained controversial. People considered the Yangtze Block to have belonged to the eastern Gondwana Plate (Li et al., 2008; Zhao et al., 2014), whereas some studies located it at the western margin of the Gondwana Plate (Steiner et al., 2007; Li et al., 2013; Santosh et al., 2013; Torsvik and Cocks, 2013a; Safonova and Santosh, 2014). In general, the position of the Yangtze Block during the later Neoproterozoic-early Cambrian interval has not been well constrained.

During the Neoproterozoic to early Paleozoic, the Yangtze Block has been restricted with accepted boundaries (Huang et al., 1977; Ren and Huang, 1980; Pan et al., 2009). The block experienced the breakup of Rodinia and the assembly of Gondwana continents since Neoproterozoic to Cambrian. The South Qinling Terranes are a number of microplates having disputable relations with the North China Block and the South China Block during the end Neoproterozoic-early Cambrian time (Meng and Zhang, 2000; Sanzhong Li et al., 2007; Dong et al., 2011b). The microplates constituted the Qinling Orogenic Belt in modern time lying between the North and South China blocks. Studies of the contemporaneous evolution of the Yangtze Block and the South Qinling Terranes exerted extensive efforts on the sedimentology records, tectonics, palaeomagnetisms, and (radiometric?) isotope dating data. Sporadic reports and discussions associated to tectonic backgrounds were given on early Late Paleozoic radiolarians (Feng et al., 1996; Wang et al., 1999). However, attention paid to the palaeontologic data was minor in most cases. We focus our study on the SSFs of the traditional ‘North Yangtze Block, namely, the southeastern Shaanxi (Zhenba County and northeastern Xixiang County) and northwestern Hubei (Xihaoping region of Fangxian County) regions. The Zhenba-Fangxian Block deposited Cambrian Stage 2 strata with abundant SSFs and the earliest trilobites. Palaeontological studies started since the 1980s. Prosperous results on the taxonomy aspect were achieved (Xie, 1990; Zhang and Pratt, 1994; Guoxiang Li et al., 2003; Li and Holmer, 2004; Li et al., 2004a; Zhang, 2007). A detailed biostratigraphic study was missing, although Li et al. (2004a) gave a preliminary description on the Xiaoyang section in the Zhenba Region.

Steiner et al. (2004) erected the *Ninella* (=*Aurisella*) *tarimensis*-*Cambroclavus fangxianensis* Assemblage Zone and the *Rhombocorniculum cancellatum* Taxon-range Zone, which were later combined to a new zone, the *C. fangxianensis*-*R. cancellatum* Assemblage Zone (Yang et al., 2014a). The region has been suspected with a unique lithologic and tectonic history as well as a unique faunal composition during the early Cambrian (Steiner et al., 2007). Main fossils such as *C. fangxianensis*, *R. cancellatum* have been reported in no other places of the Yangtze Block. In the adjacent area, the Xiaowan area of northeastern Xixiang County, South Shaanxi (Ding et al., 1990; Ding et al., 1992; Steiner et al., 2004; Moore et al., 2014), the Cambrian Stage 3 strata contained “bizarre” SSFs, e.g., *Acidocharacus longiconus*, *Aurisella tarimensis*, and *Cambrothyra ampulliformis*, distinct from the fauna of the other regions of the Yangtze Platform. All the SSFs composition in the Zhenba-Fangxian Block and the adjacent Xixiang Areas indicated different palaeobiogeographic characteristics from those of the rest of the Yangtze Block (Fig. 2, Yang et al., 2014a, Chapter 3).

To further resolve this doubtful point, clustering analysis was tentatively applied to the Cambrian Stage 3 SSFs. Sedimentary records such as baryte and witherite deposits, isopach maps of late Neoproterozoic and early Cambrian strata were analysed for a supplementary use.

2. Material and Methods

For the study on the Terreneuvian small shelly fossils (SSF) in eastern Yunnan, samples were collected from the Meishucun, Laolin, Lishuping, and Xiaotan sections during two field trips respectively in December of 2010 and May of 2011. Samples from the Xianfeng section were collected in 2009 by M. Steiner. Carbonate and phosphate carbonate rocks were especially favored during sampling since these are more easily to be dissolved and render better preserved SSFs. The second study dealt with the samples from Zhejiang Province and Hunan Province. These samples were collected by Michael Steiner and Lei Zhang. Carbonate, phosphate and chert nodules were all sampled. Chert nodules were especially selected for applying the new method of extracting SSFs.

All the samples were cut into two slices. For sedimentological study, one of the slices of each sample was ground up (crushed) and some of them were transformed to thin sections. Limestone or phosphatic limestone samples were immersed with 10% acetic acid. Dolostone and phosphatic dolostone samples were immersed with 10% formic acid. When the acid solution was poured into the container at the beginning, it was buffered with calcium phosphate. The containers (beakers or buckets) were placed in the fume hoods. The acid solution was refreshed every 3-5 days. Residues were sieved every 5-15 days depending on the reaction progress. They were separated into three classes of sizes (>2 mm, >125 µm, >63 µm) and dried at 60 °C. Most of the fossils were in the >125 µm residues. Thes residues were systematically checked under a stereobinocular microscope (LEICA). Well preserved fossils were picked out and glued on aluminum stubs using adhesive carbon foil. Afterwards, the fossils on the stubs were coated with gold for scanning electron microscopy (SEM, ZEISS Supra 40 VP). Some fossils were utilized without coating for energy dispersive X-ray spectroscopy (EDS). The SEM and EDS studies were carried out at Freie Universität Berlin (FUB) and China University of Geoscience (CUG) at Wuhan, China.

Thin sections were made in both FUB and CUG. They were studied under polarizing microscopes. For SEM study, thin section were carbon coated. Whereas for EDS analyses, the thin sections were uncoated. All figured specimens were housed either at the Department of Earth Sciences, Freie Universität Berlin or the Faculty of Earth Sciences of CUG. A SSF database was restored with Microsoft Excel 2003. The clustering calculation was operated in the IBM SPSS 20.0 software. Data were transposed in the SPPS before calculation. Pearson correlation was chosen for the hierarchical clustering analysis. The cluster method was set as between-group linkage.

The geological map in the third study was extracted from a 1: 500000 geological map database from the China Geological Survey. Archean to Early Ordovician data was extracted to Mapgis files (Mapgis 6.7 version). A final picture of the map was exported from the Mapgis.

3. Scientific Papers

Terreneuvian small shelly faunas of East Yunnan (South China) and their biostratigraphic implications

Abstract

The study discusses the detailed composition of Terreneuvian small shelly fossil (SSF) assemblages of eastern Yunnan Province (Meishucun, Xianfeng and Huize regions). The described sections represent shallow water deposits of the Yangtze Platform that include a number of stratigraphical hiati. The reported SSF assemblages can be assigned to the regional SSF biozones I-III (*Anabarites trisulcatus*-*Protohertzina anabarica* Assemblage Zone; *Paragloborilus subglobosus*-*Purella squamulosa* Assemblage Zone; *Watsonella crosbyi* Assemblage Zone). Zones II and III are slightly redefined based on new data. Two subzones of Zone II are proposed here, namely, *Annelitellus yangtzensis-Obtusoconus honorabilis* subzone and *Maikhanella cambriana-Oelandiella korobkovi* subzone. *Claviconchella qianyii* gen. et sp. nov. and *Bubiites simplex* gen. et sp. nov. are reported. Here we also provide a critical revision of the SSF distribution for the well-known Meishucun section. The correlation scheme for East Yunnan documents the extent and duration of stratigraphical hiati. The distribution of SSFs and the lithological characterization indicate three major events of exposure of the carbonate platform resulting in sedimentary breaks and possible karstification. This prompts new consideration of the previously described stable isotope stratigraphy of shallow platform strata. Considering the complexity of the Terreneuvian Earth history as well as the uniqueness of SSF, an integration of sedimentology, geochemistry and palaeontology is needed for future SSF study.

Keywords: Terreneuvian; Small shelly fossils; Biostratigraphy; Yangtze Platform; East Yunnan; Cambrian

1. Introduction

A time scale for the traditional “Lower Cambrian” is pivotal for understanding the Cambrian bioradiation. Although the Global Stratotype section and Point (GSSP) of the Pc-C boundary was defined at Fortune Head, Southeast Newfoundland, Canada, based on the first appearance datum (FAD) of the trace fossil *Trichophycus pedum* (Brasier et al., 1994, Fig. 61A4; Landing, 1994), this index fossil could only be used in Avalonia, Baltica, and parts of Laurentia. The FAD of *T. pedum* in carbonate platform settings, such as the Yangtze Platform, lies in slightly younger strata due to facies restriction and thus is not applicable to define the Pc-C boundary. Meanwhile, small shelly fossils (SSFs) have been proved widely useful for Cambrian biostratigraphy (Qian et al., 1999; Steiner et al., 2007).

In recent years more efforts have been undertaken to improve the part-based taxonomy of SSFs and their biostratigraphy (Qian et al., 1999; Steiner et al., 2007; Parkhaev and Demidenko, 2010; Kouchinsky et al., 2011; Li et al., 2011; Parkhaev and Karlova, 2011). However, for a long time it has been questioned whether SSFs have a diachronous appearance in the rock record and thus their biostratigraphic application was doubted (Conway Morris, 1988; Qian and Bengtson, 1989; Landing, 1994; Maloof et al., 2010; Landing and Geyer, 2012). The fossil aspect of the dispute has been solved to some extent (Guoxiang Li et al., 2007; Steiner et al., 2007), and here we further improve our knowledge about the stratigraphic distribution of SSFs and their potential as a biostratigraphic tool for the early Cambrian of the Yangtze Platform. As a consequence of earlier uncertainties about the biostratigraphic applicability of SSFs and the lack of other biostratigraphically applicable faunas in the early Cambrian, chemostratigraphy has found a wider application for regional and intercontinental correlation purposes (Kouchinsky et al., 2007; Li et al., 2009; Maloof et al., 2010; Landing and Geyer, 2012). In some major chemostratigraphic and chronometric studies of Cambrian strata of Morocco (Maloof et al., 2005; Maloof et al., 2010) that also aimed at an international correlation between Morocco, Siberia, South China and Mongolia, the authors concluded that the FADs of all SSFs scattered over a considerable time interval of approximately 10 my. Maloof et al. (2010) and Landing & Geyer (2012) considered all early Cambrian metazoan fossils to be unreliable for chronostratigraphy. However, it is obvious that a correlation solely based on carbon isotopic curves may likewise create considerable miscorrelations if sections include stratigraphic breaks and reworking horizons. Another challenge to the chemostratigraphy of carbon isotopes is the local impact of regional facies that may mask global seawater signals, a potential surface-to-deep ocean $\delta^{13}C$ gradient and the diagenetic alteration of stable isotopic signatures (Fike et al., 2006; Jiang et al., 2007). Maloof et al. (2010) may have come to an incorrect wide scatter of the FAD of some important SSFs and even trilobites because of miscorrelations, especially between strata of South China, Mongolia and Siberia. They claimed that *Watsonella* appeared in the Nemakit-Daldynian in China (Maloof et al., 2010, Fig A3) and trilobites occurred already in the Tommotian in China (Maloof et al., 2010, Fig A4, 5). None of this can be proven. This interpretation was partially based on an uncritical incorporation of data from the literature that included problematical chemostratigraphic correlation attempts (Brasier et al., 1997) or insufficient sedimentological and biostratigraphical data (Zhou et al., 1997; Ishikawa et al., 2008).

The aims of the present study are to re-investigate the biostratigraphic applicability of SSF and to present an updated SSF biozonation for the shallow water region of the Yangtze Platform.

We study the distribution of SSFs in context with the sedimentary features to allow a recognition of major and minor disconformities, reworked horizons and major geological events, such as tectonic uplift, seismic brecciation and karstification of the shallo-water carbonate sequences. This integrative palaeontological- sedimentological study aims to identify breaks in sedimentation that may have diminished the utility of SSFs in biostratigraphy and to evaluate the approximate duration of hiati recognizable by sedimentary features.

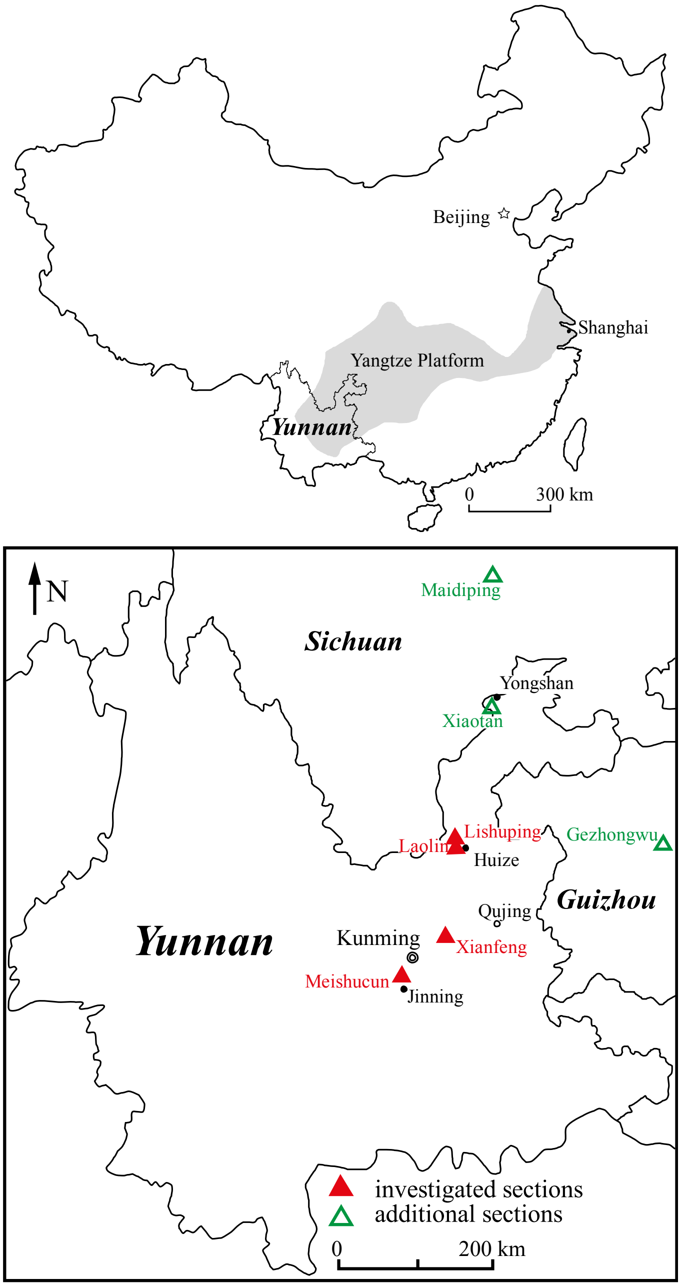

Fig. 1 Map of studied and complementary sections in East Yunnan.

2. Materials and Methods

Samples were taken from four sections (Meishucun, Xianfeng, Laolin, Lishuping, all East Yunnan; Fig. 1) applying a fine sampling grid for carbonates or carbonatic phosphorites. One part of every sample was polished and stored for sedimentological documentation. The rest was dissolved in 10% buffered acetic acid under a fume hood. Some dolostones were dissolved in 10% buffered formic acid. The acid was changed every 3 to 4 days depending on the utilization of acid and remaining pH. The residues were sieved into three size classes (>2 mm, >125 µm, >63 µm) and dried at 60°C. The yield of the residue (>125 µm<2 mm) containing most of the SSFs is 1-10% of the sample. Residues were picked systematically from microfossil trays under a stereobinocular microscope (LEICA) and the fossils stored in microcells. For detailed investigation, selected SSFs were glued on aluminum stubs by double-sided adhesive carbon foil, coated with gold, and scanned under an environmental SEM (ZEISS Supra 40VP) at Freie Universität Berlin. All figured specimens are housed at the Department of Earth Sciences, Freie Universität Berlin.

3. Lithology of studied sections

3.1. Xianfeng

Two sections of early Cambrian strata are exposed in the Xianfeng Region, only about 1.2 km apart. The original section (Huang, 1986; Qian, 1989) is nowadays covered and unavailable for study. Later Qian & Bengtson (1989) presented part of the fauna from Xianfeng, but did not provide the detailed stratigraphical fossil occurrences. Recently, Vendrasco et al. (2009) discussed the *Ocruranus*-*Eohalobia* group from the new Xianfeng section and provided basic stratigraphical data. The section is restudied in detail herein for biostratigraphical purposes. The herein studied section is located in the southwest of Xianfeng County (N 25°31′24.0″, E 103°4′11.1″; Fig. 1), about 25 km away from Xianfeng. The exposed early Cambrian phosphorite has been mined in a quarry and underground tunnels. The section comprises the 6.3 m thick Zhongyicun Member and more than 10 m of the Dahai Member of the Zhujiaqing Formation disconformably overlying the dolostones of the Neoproterozoic Dengying Formation (Fig. 2a).

The Zhongyicun Member is mainly composed of thick phosphorites interlayered with thin dolostone layers. The basal Zhongyicun Member comprises 1 m of conglomeratic dolostone and limy dolostone interlayered with phosphorite. This interval is overlain by a 4.2 m thick phosphorite interlayered with minor dolostone lenticles. The overlying dolostone and dolomitic phosphorite is 1 m thick bearing abundant ooids, oncoids and chert or phosphate nodules (Fig. 3D).

The Dahai Member is characterized by whitish dolostone, silty dolostone and few layers of chertified phosphorite. SSFs are common in the silty dolostone that overlies a chertified phosphorite (Fig. 6, sample No. xif1/22).

3.2. Meishucun

Having been investigated for more than 35 years (Qian, 1977; Qian, 1978; Luo et al., 1980; Luo et al., 1982; Luo et al., 1984; Xing et al., 1984; Qian, 1989; Qian and Bengtson, 1989; Parkhaev and Demidenko, 2010), the Meishucun section (Fig. 1, 2b) in Jinning County represents one of the best studied Cambrian outcrops in China. This section was one candidate section for the GSSP of the basal Cambrian System (Luo et al., 1980; Luo et al., 1982), and has attracted considerable international attention. The Meishucun Phosphate Mine of Jinning contains numerous partial sections in addition to the protected classical outcrop that was proposed as stratotype. The herein studied sequence of basal Cambrian strata in the Meishucun phosphate mine is composed of four partial sections (GPS: N 24°43′27.3″, E 102°33′44.5″) which are correlated by main lithological characters (lower and upper phosphorite bed separated by the clastic middle member; massive Dahai dolostone). From the Dengying dolostone to the Dahai dolostone, Luo et al (1982) defined 8 beds as Beds 1--8 accordingly (Fig. 2).

The Pc-C boundary is represented by a major erosional surface with high relief differences between Bed 2 and Bed3. We were not able to detect SSFs in the massive gray dolostone below the disconformity, confirming that these dolostones of the Dengying Formation are of Precambrian age. An approximately 0.7 m conglomeratic, phosphatic dolostone, which is partially silicified, overlies the disconformity. This bed is equal to Bed 3 (Fig. 2) of Luo et al. (1982), but a differentiation in the field between Beds 3 and 4 (Luo et al., 1982; Qian and Bengtson, 1989) is currently impossible because of their homogeneous lithology. Phosphatized stromatolites (Fig. 3B) are locally developed at topographic highs within this lower phosphorite bed. The thickness of the lower phosphorite varies considerably owing to the topographic relief of the Pc-C disconformity and mostly reaches less than 1.5 m thickness in the currently exposed sites of the mine.

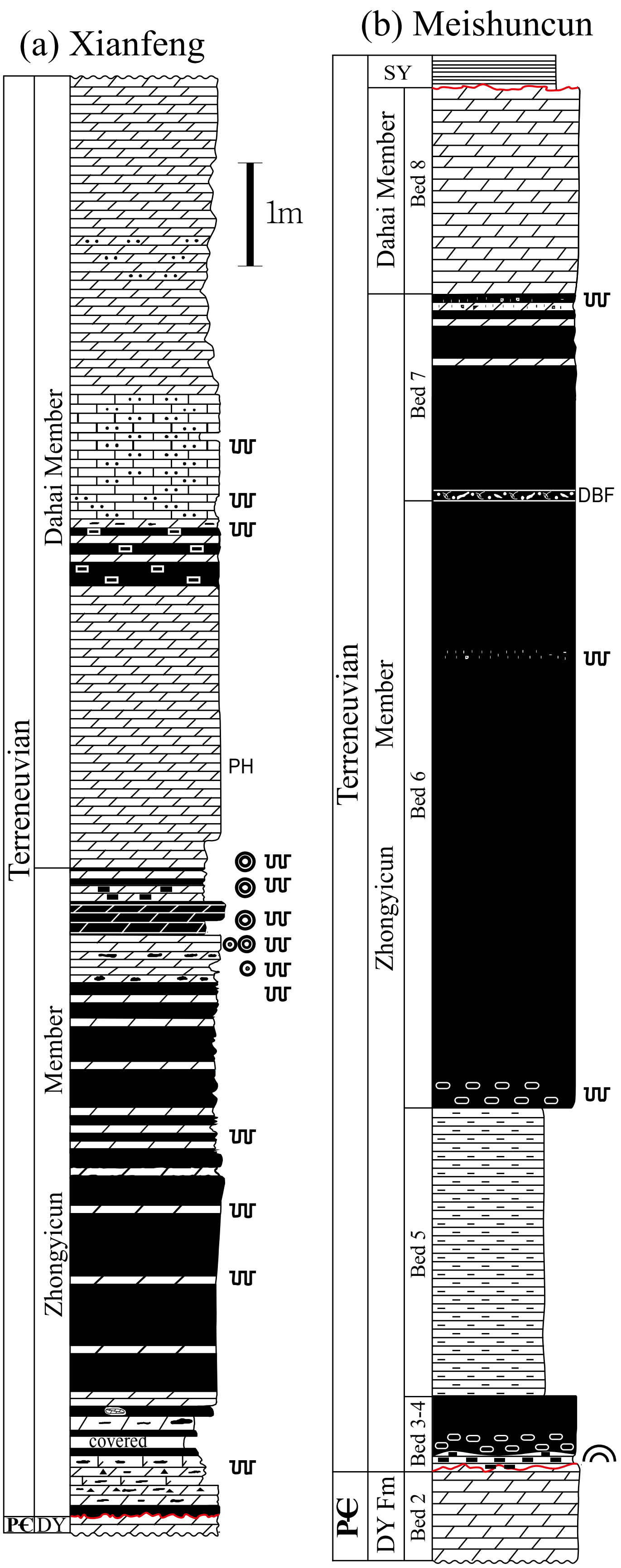

Fig. 2 Stratigraphic columns of (a) Meishucun and (b) Xianfeng sections in East Yunnan, SW China. See legends in Fig. 4.

The lower phosphorite (Beds 3-4, see Fig. 2) is separated from the thicker upper phosphorite bed (Bed 6) by a gray clay bed (Bed 5) with a thickness of ca. 2.7 m. This clastic bed was described as tuff and dated to 539.4±2.9 Ma (Compston et al., 2008). Because of the clay lithology, we did not obtain SSFs from the acid treatment, although abundant Zone I fossils can be observed in crack out specimens. A 30 cm thick intraclastic phosphate forms the base of the Bed 6. Bed 6 is nearly 6 m thick and strongly phosphatized. A 15 cm debris flow bed (Fig. 3C) was observed at the boundary between Beds 6 and 7. The overlying 2 m thick phosphorite (Bed 7) is interlayered with dolostone, containing reworked phosphate grains in the upper part and typical Zone II fossils. This interval is characterized by numerous hardgrounds and smaller erosional surfaces and channels. The Dahai Member precedes the Zhongyicun Member and consists of ca. 2 m pure unfossiliferous dolostone.

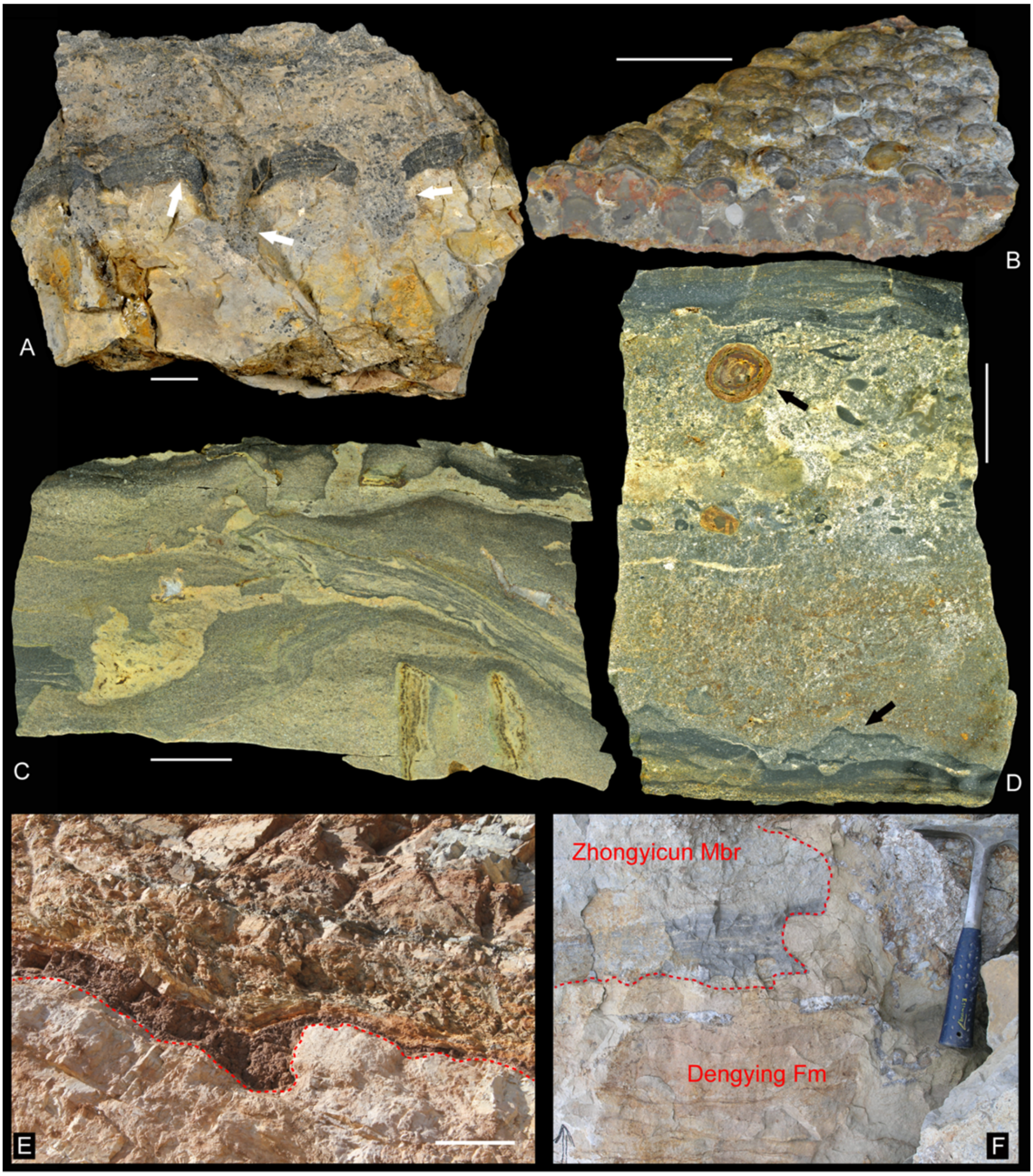

Fig. 3 A. Erosional structures of phosphatic dolostone from the upper economic horizon of the middle Zhongyicun Member of Lishuping section, No. LspLes. The phosphorite layers (black layers, left arrow) are truncated by deep erosional channels that are infilled with phosphorite litho-and bioclasts (middle and right arrows). B. Stromatolites from the Pc-C boundary of Meishucun section, No. Msc00. C. Debris flow bed of upper phosphorite of the Zhongyicun Member, Meishucun section, No. Msc13. D. Oncoids (upper arrow) and hardground (bottom arrow) in the Zhongyicun Member of Xianfeng section, No. Xif1-12. E. Field photograph of a major disconformity (dotted line) at the top of the Zhongyicun Member of Lishuping section. F. Field photography of the major disconformity (dotted line) at the Pc-C boundary at Meishucun section. Scale bars: A-D, 2 cm, E, 0.5 m.

3.3. Laolin

The Laolin section (GPS: N 26°16′44.1″; E 103°13′25.1″; Fig. 1) is located in Huize County, about 8 km from Dahai Town and 200 km from the Meishucun section. Luo et al. (1991) described this section with only a preliminary report on SSFs. Other reports of SSFs are from nearby sections (Zhujiaqing, Xiaomaidi and Nizheqing sections) within the 10Km range of Laolin (Luo et al., 1982; Qian et al., 1996; Qian et al., 2002). Li et al. (2009) carried out a detailed study of carbon isotope geochemistry of the Laolin section and developed a regional correlation for East Yunnan (including Meishucun and Xiaotan) based on these data. This correlation is mainly based on the carbon isotope curve and lacks a robust biostratigraphic control. Previous stratigraphical work (Luo et al., 1982; Xing et al., 1984; Qian et al., 1999; Qian et al., 2002 etc.) indicates that the Laolin section is of great importance for a regional and international correlation of the Cambrian Stages 1-3, and especially for the further biostratigraphical subdivision of the Cambrian System. Landing and Geyer (2012) proposed to erect Cambrian Stage 2in the Laolin section.

Luo et al. (1991) described a thickness of 134.4 m for the Zhujiaqing Formation in Laolin, and Li et al. (2009) reported it as 163.6 m. Our measurements show the Zhujiaqing Formation in Laolin about 109 m thick (Fig. 4a). The total thickness is difficult to measure since large intervals of the Daibu Member are covered and especially the lower part of Zhongyicun Member is disturbed by faults and folding. The phosphorite interval of the upper Zhongyicun Member also revealed an overthrust horizon (Fig. 4a). A similar tectonic complication for the lower part of the Zhujiaqing Formation is found in the nearby Lishuping section (see below).

The Zhongyicun Member is underlain by 7.5 m of silicified dolostone of the Daibu Member, which has been heavily deformed by tectonics. The basal Zhongyicun Member is composed of 13 m of horizontally bedded dark limestone and dolomitic limestone containing various SSFs of Zone I such as *Anabarites trisulcatus*, *Cambrotubulus decurvatus*, *Mongolodus longispina* and *Hexaconularia sichuanensis*. The superimposed 28 m of limy dolostone and dolomitic siltstone containing phosphatic conglomerates is interlayered with thin muddy siltstone. The limy dolostone (Fig. 8, sample No. lal38) contains rare SSFs of Zone I. The succeeding 7.6 m dark phosphorite is interlayered with small phospholithoclastic limestone lenses containing numerous SSFs of Zone II. A tectonic overthrust horizon is evident at the top of this phosphorite bed. The top Zhongyicun Member is composed of 4.7 m massive phosphatic dolostone.

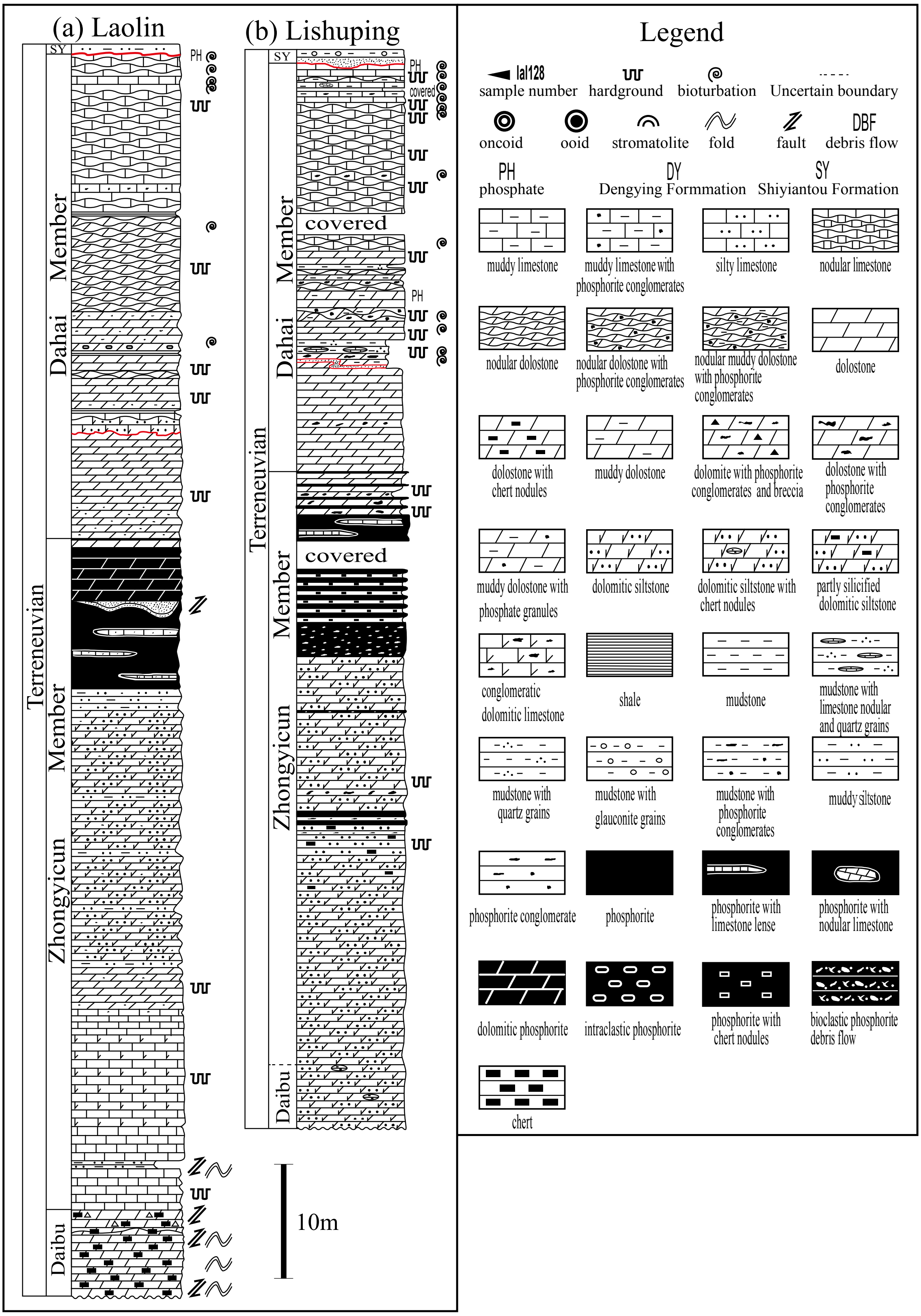

Fig. 4 Stratigraphic columns of (a) Laolin and (b) Xianfeng sections in East Yunnan, SW China. Red lines mark the disconformity.

About 9.5 m of phospholithoclastic dolostone and pure whitish dolostone belonging to the Dahai Member overlies the Zhongyicun Member. This lower Dahai Member is truncated by an irregular disconformity surface. Above this major disconformity lie ca. 10 m gray silty dolomitic limestone, dolostone and nodular dolostone which are interlayered with shales and are rich in hardgrounds.

The upper part of the Dahai Member consists of 22 m nodular limestone interbeded with limestone and shales.This unit is disconformably overlain by the Shiyantou Formation. The base of the Shiyantou Formation is marked by a 0.25 m thick conglomeratic phosphorite.

3.4. Lishuping

The Lishuping section (GPS: N26°22′38.1″, E 103°12′51.7″; Fig. 1) lies ca. 11 km northwest of the Laolin section. It was studied here for the first time and complements the lithological, biostratigraphical, and geochemical observations from the Laolin section. As in Laolin, the lower Zhujiaqing Formation appears to be more tectonically disturbed than the upper part. Thus the total thickness of about 93 m for the recorded section of the Zhujiaqing Formation is incomplete (Fig. 4b). However, at one place in the mining district the boundary between the Daibu Member and the Dengying Formation was exposed as a fault contact.

The lowest part of the recorded section consists of ca. 5.6 m of dolomitic siltstone containing few chert nodules, tentatively assigned here to the upper part of Daibu Member. The boundary between the Daibu and Zhongyicun Members is gradual and difficult to draw exactly because of silicification in the basal Zhongyicun Member. The lower part of the Zhongyicun Member consists of 35.5 m silty and occasionally silicified phospholithoclastic dolomitic siltstone containing thin phosphorite beds. The silicification and the high siliciclastic content of the lower Zhongyicun Member make it impossible to extract fossils. The overlying 16 m phosphorite, chertified phosphorite and phosphatic dolostone represent the topmost Zhongyicun Member and are the main economic interval mined in the quarry and in underground tunnels.

This interval is succeeded by the base of the Dahai Member of 9 m white massive, whitish dolostone. An obvious disconformity (Fig. 3E) surface with high relief, truncates the pure dolostone. About 3.9 m of sandy mudstone and silty dolostone with limestone nodules overlies the major disconformity surface and marks the onset of the sedimentary sequence of the Dahai Member. The higher Dahai Member comprises ca. 20 m of nodular dolostone or limestone interlayered with dolostone and silty limestone, containing phosphorite litho-and bioclasts. The top of the Dahai Member is disconformably overlain by a phosphatic basal conglomerate of the lower Shiyantou Formation.

4. Stratigraphic gaps

For a convincing biostratigraphic subdivision of Cambrian strata and regional and intercontinental correlations, it is essential to complement the biostratigraphic data with sedimentological data, and here especially to examine indications of hiati that represent breaks or interruptions in the continuity of the stratigraphic record.

The investigated sections represent a shallow depositional environment at the Pc-C boundary, in the upper Zhongyicun and the middle-upper Dahai members respectively. This is indicated by the stromatolites (Fig. 3B) in the Meishucun section, the ooids and the oncoids (Fig. 3D) in the Xianfeng section, as well as the bioturbation (Fig. 4) in the middle-upper Dahai Member at Lishuping and Laolin. The comparably low thicknesses may also indicate depositional interruptions. The thickest and most complete sequence of the Zhujiaqing

Formation is recorded with 189 m in the Xiaotan section (Li et al., 2001), followed by the Laolin-Lishuping section, showing approximately 165 m of the same interval contrasting with a strongly reduced thickness of ca. 34 m for the Zhujiaqing Formation in Xianfeng (Qian, 1989, Bed3-Bed13 in the old Xianfeng section), respectively ca. 10-15 m of the Zhujiaqing Formation in Meishucun. The general comparison of thicknesses and completeness of lithological units in East Yunnan reveals that the sections are more complete and thicker and complete in the north (Fig. 10, 11).

4.1. Hardgrounds

A common sedimentological feature indicating stratigraphical breaks in all investigated sections is hardgrounds (Figs. 2, 3A, 3D, 4), representing surfaces of synsedimentary lithification, having existed as hardened seafloor prior to the deposition of the overlying sediment. The hardgrounds here are often accompanied by conglomeratic beds indicating erosional structures (Fig. 3A). Though hardgrounds can be formed in a semi-emergent to emergent environment as well, we interpret the observed hardgrounds in East Yunnan as formed by retardation of sedimentation in a submergent marine environment. In any case, the hardgrounds represent at least minor stratigraphical gaps of unknown duration, as previously described hardgrounds were found to represent gaps ranging from several hundreds to thousands of years in the upper Cretaceous chalk of England (Bromley, 1965) to about 200 000 years for some Ordovician hardgrounds (Flügel, 2010).

In the four studied sections, hardgrounds are widespread from the base of the Zhongyicun Member to the upper part of the Dahai Member. They are thought to include only shorter time gaps (of at most some thousand to ten thousand years) since they are not associated with major changes in the fossil assemblages.

Hardgrounds can be observed in the lowest part of the Zhongyicun and are associated with ooids and oncoids in the upper Zhongyicun Member (Fig. 3D) in the Xianfeng Region. In Laolin and Lishuping the frequency of hardgrounds increases toward the upper Zhongyicun Member and the Dahai Member.

4.2. Erosional disconformities

An erosional surface (He et al., 1988; Qian et al., 1996) developed on top of the Dengying Formation (Baiyanshao Member) in the Meishucun section. We also observed deep erosional reliefs in Meishucun (Fig. 3F) and deep karst crack infills in Bajie (pers. observation Steiner, 1991). One of the consequences is that most of the Daibu Member and larger fractions of the lower Zhongyicun Member are lacking in the Jinning and Chengjiang regions (Steiner et al., 2007). This major disconformity at the Pc-C boundary is also shown in the Xianfeng Region and in Northeast Yunnan (e.g. Xiaotan, but with fewer stratigraphic hiati in the Zhujiaqing Formation). The disconformity can be assumed to exist in the Huize Region. However, the studied sections all show a covered or tectonically disturbed boundary interval.

The disconformity may be interpreted in context with a subaerial exposition of the carbonate platform and partial erosion. An extremely shallow water environment is evident from the phosphatic sediments of the Zhongyicun Member that immediately overlie the major Pc-C disconformity, as indicated by tabular stromatolites with bulbous to nodular columns in the lowest exposed Zhongyicun strata of Meishucun (Fig. 3B). In the Xianfeng Region most of the strata with SSFs of zone I are missing. The higher layers with oncoidic and ooidic carbonates (Fig. 2, 3D) in the topmost Zhongyicun Member (Zone II) further indicate an intertidal-subtidal facies.

Another major disconformity occurred in the dolostones of the lower Dahai Member at Lishuping and Laolin. The disconformity surface was not observed in Xianfeng or Meishucun, but a thickness comparison between the regions and distribution of the SSF assemblages indicates a considerable gap (Fig. 10; He et al., 1988). The upper Zone II (*Annelitellus yangtzensis-Obtusoconus honorabilis* Subzone, see below) is extremely reduced in thickness in Xianfeng and completely lacking in Meishucun (Fig. 10). Also the immediately overlying interval of the Dahai Member shows a continuous decrease in thickness from Xiaotan (ca. 67m, Li et al., 2001), through Laolin (32 m; compare with Fig. 4), Xianfeng (13.6m, Qian, 1989) and Meishucun (1.1 m-2 m; Fig. 2). All these data show a trend of increasing stratigraphical gaps from the northern sections, such as Laolin, toward the Meishucun Region. This also explains the complete absence of Zone III fossils in the Meishucun section (Qian and Bengtson, 1989).

The whole East Yunnan Region (from Meishucun to Xiaotan) shows a third major disconformity at the boundary of the Dahai Member and the overlying Shiyantou Formation. In Xianfeng this needs further investigation as the relevant interval has not been studied due to more limited exposure. In Meishucun most of the Dahai Member is missing due to non-deposition or later erosion.

The faunal mixing phenomena in intervals of conglomerate and debris flow beds in Southeast Yunnan indicate periods of reworking and therefore hiati that are typical of the shallow water environment with increased numbers of sedimentary breaks (as evident for Meishucun and Xianfeng). In general, the hiati do not affect the main biostratigraphic zonation but require increased care with the interpretation of the SSF associations for biostratigraphic purposes.

Generally speaking, the disconformities represent three major time gaps (Fig. 10, 11; Steiner et al., 2007): the major gap at the Pc-C boundary, the gap in the Dahai Member (upper part of Zone II), and the major gap at the top of the Dahai Member. The three major disconformities recognized in East Yunnan have the greatest impact on the missing rock and time data, and are likely distributed throughout most of the shallow carbonate platform.

Sea level changes or tectonic events have led to subaerial exposition, erosion and possible karstification of carbonate strata. It has been observed that the completeness of early Cambrian strata gradually increases from the Kunming Region, through the Xianfeng Region toward Huize County (Lishuping and Laolin) and further to Xiaotan (Fig. 11) of Yongshan County, and conversely the extent of gaps decreases toward northern East Yunnan (Fig. 11).

<table>
<tr><th rowspan="2">Qian 1978</th><th rowspan="2">Zhou and Yuan 1980</th><th rowspan="2" colspan="2">Luo et al. 1982, 1984</th><th rowspan="2">Qian and Bengtson 1989</th><th rowspan="2">Luo et al. 1994</th><th rowspan="2">Qian et al. 1996</th><th rowspan="2" colspan="2">He in Qian et al. 1999</th><th rowspan="2" colspan="2">Zhu et al. 2001</th><th colspan="4">Steiner et al. 2007 and This paper</th><th rowspan="2" colspan="2">Chrono-stratigraphy</th></tr>
<tr><th>Deeper shelf</th><th colspan="3">Shallow shelf</th></tr>
<tr><td rowspan="3"></td><td rowspan="3">*Yunnanocephalus -Malungia* Zone
Eoredlichia-Wutingaspis Zone
Parabadiella-Mianxiandiscus Zone</td><td rowspan="2" colspan="2">*Eoredlichia* Zone</td><td rowspan="3"></td><td rowspan="2">*Eoredlichia* Zone</td><td rowspan="3"></td><td rowspan="2">*Eoredlichia* Zone</td><td rowspan="2">*Rhombo-corniculum cancellatum* Zone</td><td rowspan="2">*Eoredlichia-Wutingaspis* Z.</td><td>*Yunnano-cephalus* Zone</td><td>*Rhombocorniculum cancellatum* Taxon Range Zone ?</td><td rowspan="3">*Pelagiella subangulata* Taxon Range Zone</td><td rowspan="2">*Wutingaspis-Eoredlichia* Interval Zone</td><td>*Yunnano-cephalus* Subzone</td><td rowspan="3">Stage 3</td><td rowspan="3">Series 2</td></tr>
<tr><td>*Tsunyidiscus* Zone</td><td rowspan="2">? *Ninella tarimensis-Cambroclavus fangxiangensis* Assemblage Zone</td><td>*Tsunyidiscus* Subzone</td></tr>
<tr><td colspan="2">*Parabadiella* Zone</td><td>*Parabadiella* Zone</td><td>*Parab-adiella* Zone</td><td>*R. insolutum* Zone</td><td colspan="2">*Parabadiella* Zone</td><td colspan="2">*Parabadiella* Zone</td></tr>
<tr><td rowspan="9">*Turcutheca-Sachites-Zhijinites* Assemblage
Circotheca-Tiksitheca-Anabarites-Protohertzina Assemblage</td><td rowspan="9">*Siphogonuchites-Zhijinites-Sachites* Assemblage
Anabarites-Circotheca-Protohertzina Assemblage</td><td rowspan="3">*Sinosachites-Eonovitalus* Ass.</td><td>*S. flabelliformis* Subassemblage</td><td rowspan="6">*Lapworthella-Tannuolina-Sinosachites* Assemblage
Siphogonuchites-Paragloborilus Assemblage</td><td rowspan="6">*Sinosachites-Lapworthella* Zone
Siphogonuchites-Paragloborilus Zone</td><td rowspan="3">*Sinosachites-Lapworthella* Assemblage Zone</td><td rowspan="3" colspan="2">*Lapworthella-Tannuolina-Sinosachites* Assemblage Zone</td><td rowspan="2" colspan="2">*Sinosachites flabelliformis Tannuolina zhangwentangi* Assemblage Zone</td><td rowspan="6">Poorly fossiliferous Interzone</td><td rowspan="2" colspan="3">*Sinosachites flabelliformis Tannuolina zhangwentangi* Assemblage Zone</td><td rowspan="4">Stage 2</td><td rowspan="10">Terreneuvian</td></tr>
<tr><td rowspan="2">*E. longevaginatus* Subassemblage</td></tr>
<tr><td colspan="2">*Barren interval*</td><td colspan="3">Poorly fossiliferous Interzone</td></tr>
<tr><td rowspan="3">*Paragloborilus-Siphogonuchites* Ass.</td><td>*Paragloborilus subglobosus* Suba.</td><td>*Heraultipegma yunnanensis* Zone</td><td colspan="2">*Heraultipegma yunnanensis* Zone</td><td colspan="2">*Heraultipegma yunnanensis* Assemblage Zone</td><td colspan="3">*Watsonella crosbyi* Assemblage Zone</td></tr>
<tr><td rowspan="2">*Siphogonuchites triangularis* Subassemblage</td><td rowspan="2">*Paragloborilus subglobosus-Siphogonuchites triangularis* Assemblage Zone</td><td rowspan="2" colspan="2">*Siphogonuchites-Paragloborilus* Assemblage Zone</td><td rowspan="2" colspan="2">*Siphogonuchites triangularis-Paragloborilus subglobosus* Assemblage Zone</td><td rowspan="2">*P. subglobosus-Purella squamulosa* Assemblage Zone</td><td colspan="2">*A. yangtzensis-O. honorabilis* Subzone</td><td rowspan="6">Fortunian</td></tr>
<tr><td colspan="2">*M. cambriana-O. korobkovi* Subzone</td></tr>
<tr><td rowspan="5">*Anabarites-Circotheca-Protohertzina* Ass.</td><td>*A.trisulcatus* Suba.</td><td rowspan="3">*Anabarites-Protohertzina-Arthrochites* Assemblage</td><td rowspan="5">*Anabarites-Protohertzina* Zone</td><td rowspan="3">*A. trisulcatus-P. anabarica* Assemblage Zone</td><td rowspan="3" colspan="2">*Anabarites-Protohertzina-Arthrochites* Assemblage Zone</td><td rowspan="3" colspan="2">*Anabarites trisulcatus-Protohertzina anabarica* Assemblage Zone</td><td rowspan="3">*Protohertzina anabarica-Kaiyangites novilis* Assemblage Zone</td><td rowspan="3" colspan="3">*Anabarites trisulcatus-Protohertzina anabarica* Assemblage Zone</td></tr>
<tr><td>*Barbitositheca ansatus* Suba.</td></tr>
<tr><td>*C. longiconica* Subassemblage</td></tr>
<tr><td rowspan="2"></td><td rowspan="2"></td><td rowspan="2">*A. primitivus* Subassemblage</td><td rowspan="2"></td><td rowspan="2"></td><td rowspan="2" colspan="2"></td><td rowspan="2" colspan="2"></td><td>?</td><td colspan="3">? barren interval</td></tr>
<tr><td></td><td colspan="3"></td><td colspan="2">Ediacaran</td></tr>
</table>

Fig. 5 Zonation chart of SSFs and trilobites in the early Cambrian of East Yunnan.

5. Biostratigraphy

SSF biozonation in East Yunnan has been carried out for more than three decades (Fig. 5). In the 1970s, Qian proposed two assemblages for central and southwest China. Later Luo et al. (1982; 1984) proposed three assemblages with eight subassemblages for the Terreneuvian of East Yunnan. Qian et al. (1996), established a three-zone subdivision for the SSFs in the Zhujiaqing Formation of East Yunnan. Although the definition of these three zones was modified later, the three-zone scheme has been followed (Zhu et al., 2001; Steiner et al., 2007; this paper). He in Qian et al. (1999) introduced the *Rhombocorniculum cancellatum* and *Rhombocorniculum insolutum* zones as correlated with the earliest trilobite zones in the Yuanshan Formation. This expanded the biostratigraphic application of SSFs into Series 2 of the Cambrian. Steiner et al. (2007) improved the SSF zones of the shallow water facies and established SSF zones for deeper water regions of the Yangtze Platform. Here we modify the definition of the three zones (Fig. 11) of the Zhujiaqing Formation of East Yunnan and introduce two subzones of the *Paragloborilus subglobosus*-*Purella squamulosa* Assemblage Zone.

5.1. Zone I: Anabarites trisulcatus-Protohertzina anabarica Assemblage Zone

Zone I was first used by Qian et al. (1996) and defined by Steiner et al. (2007). In Yunnan, it occurs from the base to the middle of the Zhongyicun Member and represents the first appearance of diverse SSFs (Fig. 10, 12). It is characterized by the protoconodonts *Protohertzina anabarica* (Fig. 12A, B), *Protohertzina unguliformis* (Fig. 12C) and the triradially symmetrical tubes *Anabarites trisulcatus* (Fig. 12D, E). The zone is well recognizable throughout most of East Yunnan and South China.

In Xianfeng, this zone is limited to the lowest 1 meter of carbonates of the Zhongyicun Member, while in Meishucun it is further distributed from the base of the Zhongyicun Member to about 9.5 m above the base (Figs. 6, 7).

In Laolin, it occurs in an even thicker interval, about 40 m (Fig. 8). In upper zone boundary there is deduced from the lithology as fossils could not be extracted from the dolomitic siltstones of the upper Zhongyicun Member.

In Lishuping the assemblage was not detected as the lower Zhongyicun Member is composed of siltstones, dolomitic siltstones, cherts and silicified phosphorite, which were not dissolvable by acid treatment.

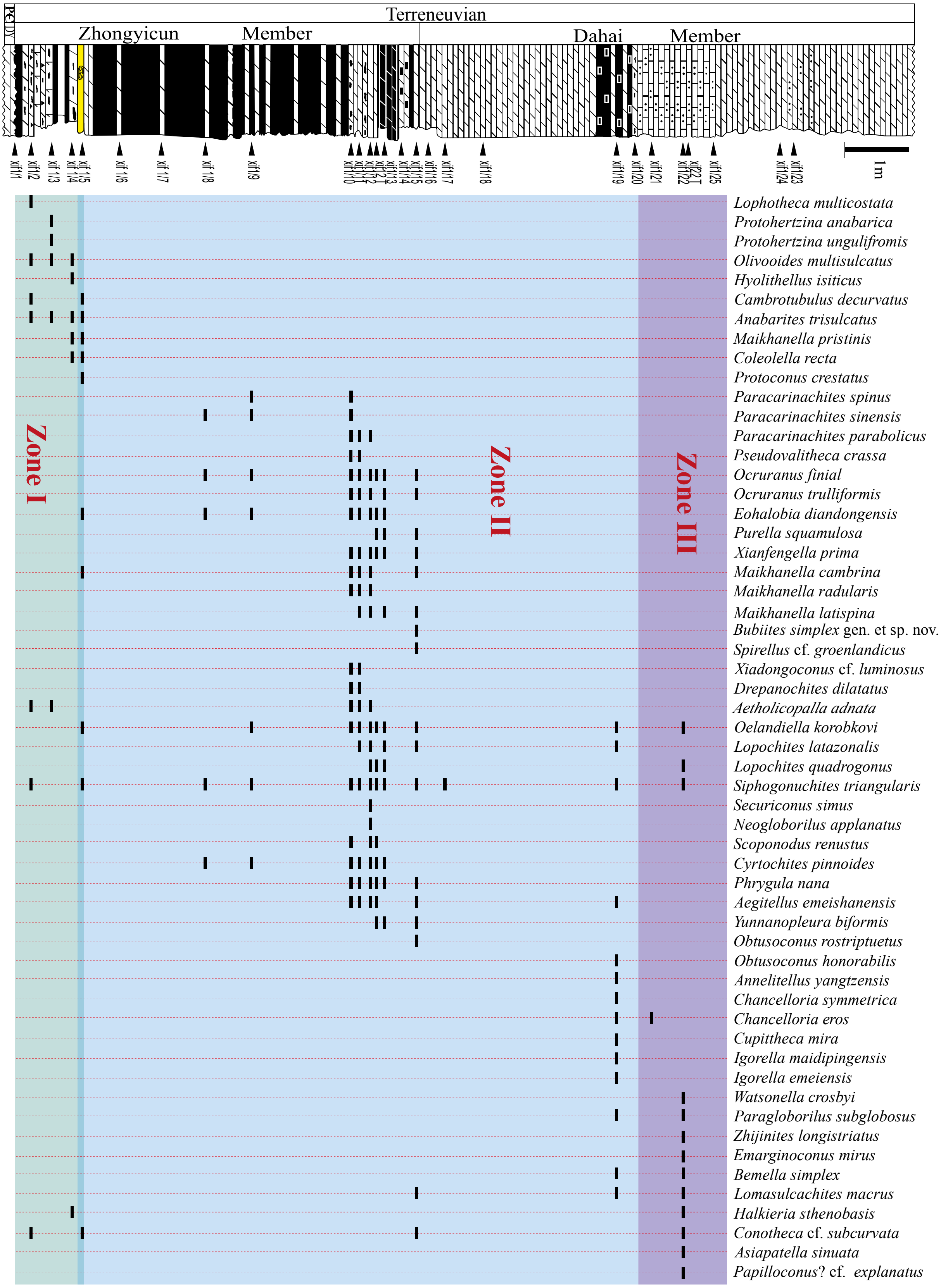

Fig. 6 Biostratigraphic distribution of SSFs in Xianfeng section in East Yunnan, SW China.

As mentioned before, in Xianfeng Zone I fossils such as *Cambrotubulus decurvatus* and *Anabarites trisulcatus* are occasionally found together with Zone II fossils in one 8cm thick phosphatic conglomerate bed. Considering the conglomeratic lithology of this bed and the rareness of Zone I fossils, we consider these Zone I fossils as reworked.

A similar situation can be observed in the Meishucun section. At the boundary between Bed 6 and Bed 7, a 15 cm thick debris flow bed (Fig. 3C, Fig. 7) exists in which a few specimens of *Mongolodus rostriformis* and *Anabarites trisulcatus* were found together with Zone II fossils, such as *Oelandiella korobkovi*. This is herein interpreted to be due to slumping and reworking.

5.2 Zone II: Paragloborilus subglobosus-Purella squamulosa Assemblage Zone

Here we re-define the *Paragloborilus subglobosus-Purella squamulosa* Assemblage Zone based on the appearance of *Oelandiella korobkovi* (Fig. 18 C, D), besides the previously chosen *P. subglobosus* and *P. squamulosa*.

This zone was first established by Steiner et al. (2007) because the authors realized that all index fossils of the former *Paragloborilus-Siphogonuchites* Zone of Luo et al. (1980) ranged into the overlying Zone III. At the same time the authors noted that Zone II is the most problematic zone in South China because, except for *Purella squamulosa*, most other species occurring in this zone also range into the lower Zone III. Yet *P. squamulosa* is relatively rare in South China and we report this species from Xianfeng only (Fig. 17A-C, E). In the Huize Region, only *Purella elegans* was detected (Fig. 17D). Parkhaev & Demidenko (2010) have arbitrarily listed *P.squamulosa* as a synonym of *Purella arcana* and combined *P.elegans* with *Protoconus*-an opinion that we would not follow without a detailed revision of the material of *Purella* and related forms from Siberia. The variability and different preservation in steinkerns and shell preservation need to be considered (e.g. for *Purella antiqua, P. cristata, P. arcana*).

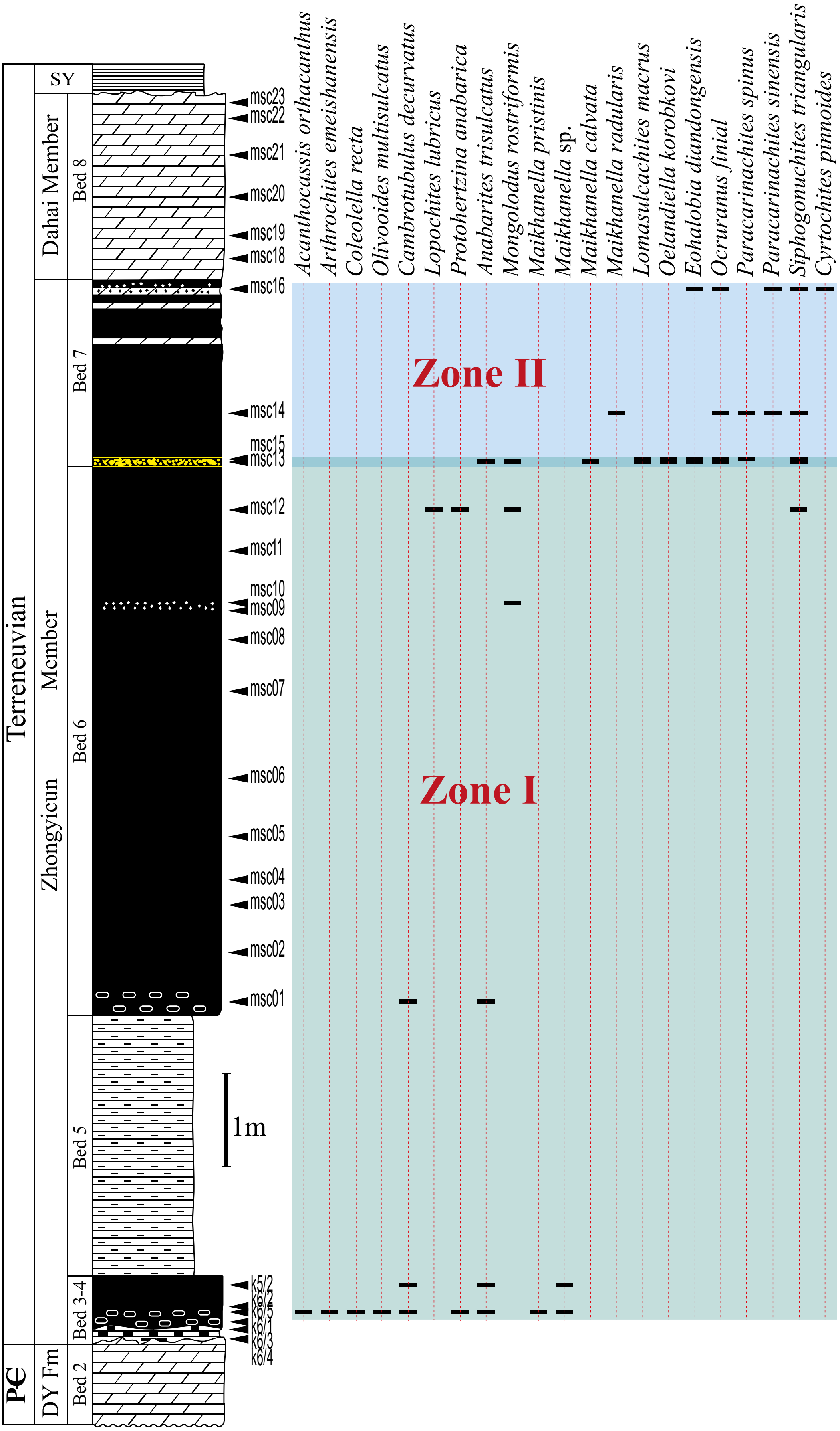

Fig. 7 Biostratigraphic distribution of SSFs in Meishucun section in East Yunnan, SW China.

Paragloborilus subglobosus (Fig. 14B, C) occurs in both zones II and III and its type specimens (Qian, 1977) were probably recovered from the base of zone III (Bed 36 of Gaoqiao section), where the lowest appearance of *Watsonella crosbyi* in the Mt. Emei Region is reported (Steiner et al., 2007). This is also true for the studied sections in East Yunnan (Fig. 6, 8, 9).

Parkhaev & Demidenko (2010) claimed that *Paragloborilus* sp. occurred in the *Anabarites trisulcatus-Protohertzina anabarica* Zone (Bed 4) jointly with *Annelithellus yangtzensis, Xianfengella primus, Igorella emeiensis, Ocruranus finial, Bemella simplex, and 'Latouchella' korobkovi* (= *Oelandiella korobkovi*) in the Meishucun section, a statement that is not confirmed by our investigations herein, nor by any other previous reports (Jiang, 1980b; Luo et al., 1980; Luo et al., 1982; Qian and Bengtson, 1989). It is possible that Parkhaev & Demidenko (2010) have mistakenly considered samples from the Zone II interval as samples of Bed 4 because they do not figure and describe any individuals of *A. trisulcatus* (Fig. 12D, E), true *P. anabarica* (Fig. 12A, B) or *Protohertzina unguliformis* (Fig. 12C) that are very common in Beds 3 and 4. As in Xianfeng, Laolin, and Lishuping, *Paragloborilus subglobosus* is usually found in the upper part of Zone II and always in Zone III. Another complication may arise from the fact that most individuals of *Paragloborilus subglobosus* are steinkerns (Fig. 14B, C) which makes a species assignment different.

Besides *Paragloborilus subglobosus* and *Purella squamulosa*, Steiner et al. (2007) based the *P. subglobosus-P. squamulosa* Assemblage Zone on the presence of *Zhijinites longistriatus*, though it was mentioned that this species had not been found in the Kunming Region. After our detailed re-study of the sections we can confirm that *Zhijinites* does not occur in Zone II in East Yunnan. It was mainly described from Gezhongwu (Guizhou Province; Qian and Yin, 1984; Wang et al., 1984; Qian et al., 1999). In East Yunnan we recognized *Z. longistriatus* (Fig. 21F) in Zone III in Xianfeng, Lishuping and Laolin (Fig. 6, 8, 9). Li & Xiao (2004) only reported *Z. longistriatus* from the Zone III interval (Dahai Member) from Xiaotan, and Qian et al. (1999) indicated a distribution in Zone III (Beds 36-39) of the Maidiping section (Sichuan Province). This distribution pattern requires a redefinition of Zone II.

Oelandiella korobkovi is most common in Zone II in East Yunnan and thus utilizable as an index fossil. Because this species was formerly an index fossil for Zone III (Steiner et al., 2007), Zone III has to be re-defined accordingly. Still the species extends to Zone III in some regions (Fig. 6, 8) of East Yunnan.

Additional SSFs that occur commonly in Zone II are *Ocruranus finial* (Fig. 16E, F), *Ocruranus trulliformis, Eohalobia diadongensis* (Fig. 16A-C), *Paracarinachites sinensis* (Fig. 13A), *Paracarinachites spinus* (Fig. 13B), *Paracarinachites parabolicus* (Fig. 13C), *Scoponodus renustus* (Fig. 13F), *Maikhanella cambrina* (Fig. 15A, B), *Maikhanella radularis* (Fig. 15C, D), *Maikhanella latispina* (Fig. 15E, F), *Yunnanopleura biformis* (Fig. 18E), *Securiconus simus* (Fig. 18F), *Xianfengella prima* (Fig. 19A), *Phrygula nana* (Fig. 20A, B, G) and fossils that commonly appear in the Upper Subzone of Zone II (see below). However, there exist indications that some species such as *Paracarinachites sinensis* may range into the lower Zone III.

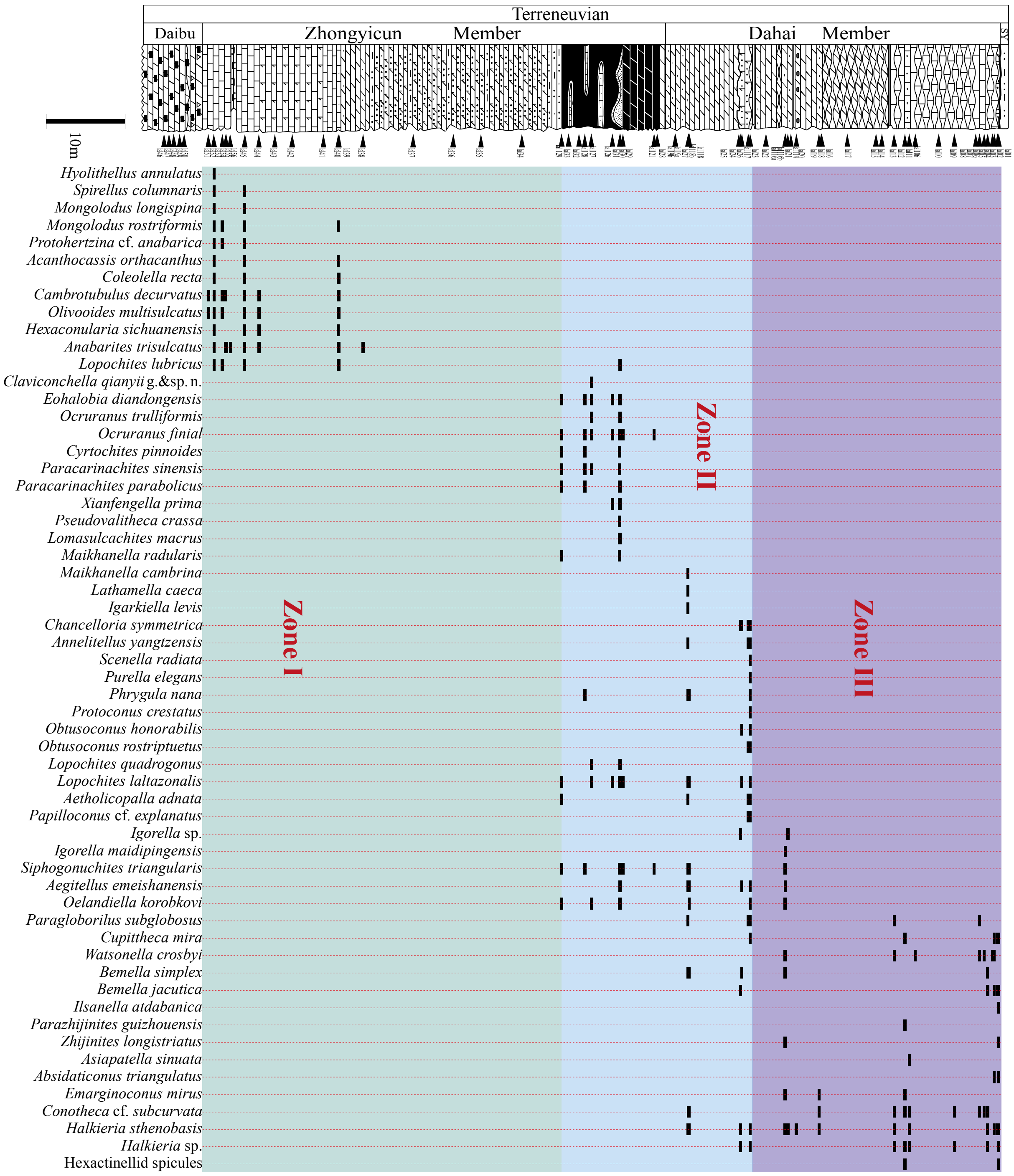

Fig. 8 Biostratigraphic distribution of SSFs in Laolin section in East Yunnan, SW China.

Zone II in the Xianfeng section embraces sediments of about 8.6m of thickness, from the mixed bed of the lower Zhongyicun Member to the lower Dahai Member. The assemblage is rich in species and individuals. In Meishucun, Zone II is limited to Bed 7 (Fig. 7), namely the upper part of the upper phosphorite bed. In Lishuping, Zone II is distinguishable by the occurrence of *Paragloborilus subglobosus* and *Oelandiella korobkovi* only. In the upper part, the occurrence of *Obtusoconus* and *Annelitellus* defines the upper limit of *Annelitellus yangtzensis-Obtusoconus honorabilis* Subzone (see below). The lower limit of Zone II cannot be exactly determined because of partial cover of the outcrop and poor solubility of the rocks from the lower Zhongyicun Member. Zone II fossils in Laolin appeared first and mostly in the thin limestone lenses found in the dark phosphate of upper Zhongyicun Member. SSFs of the *A. yangtzensis-O. honorabilis* Subzone were detected in the dolostone of the basal Dahai Member (Fig. 8).

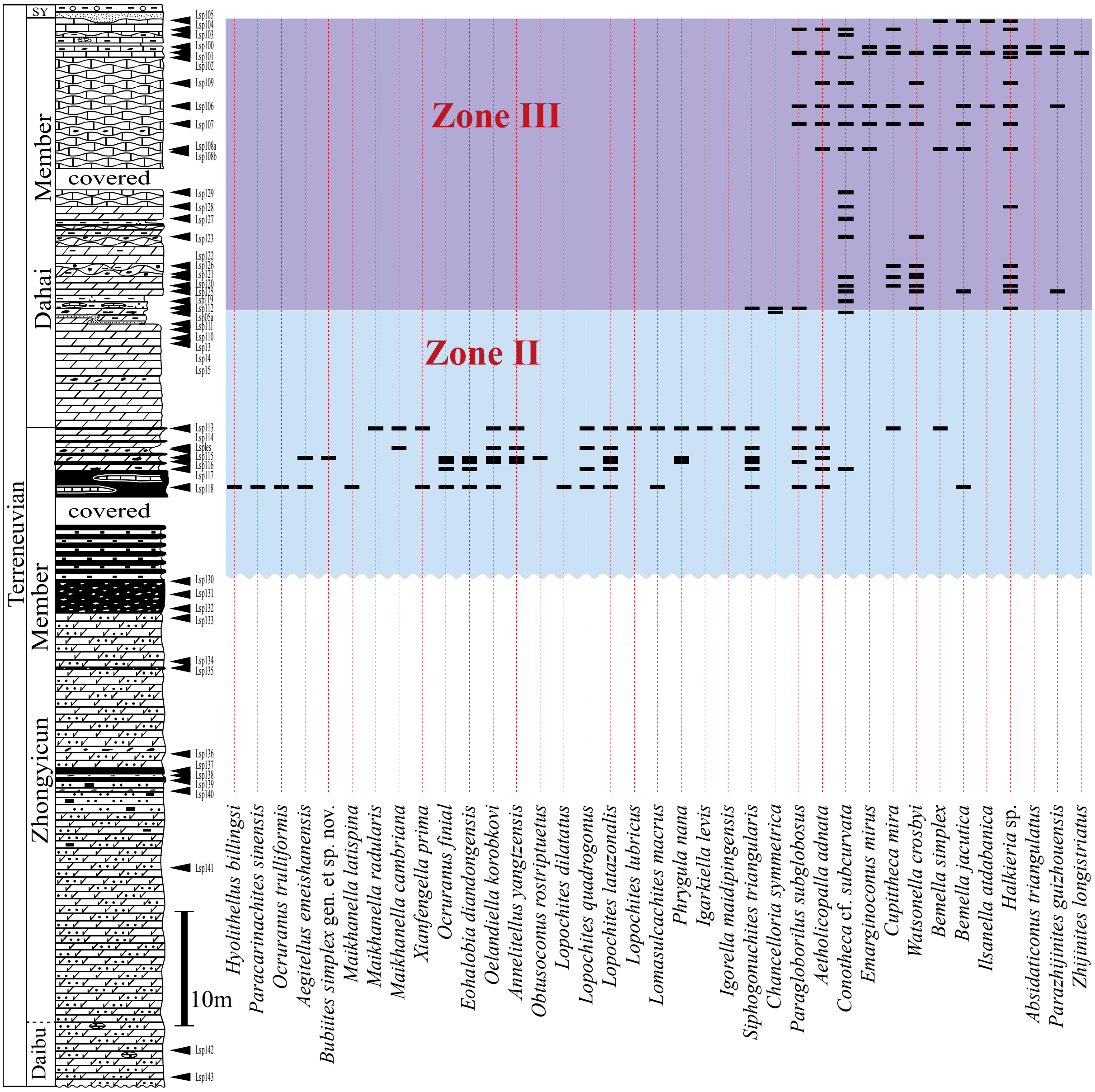

Fig. 9 Biostratigraphic distribution of SSFs in Lishuping section in East Yunnan, SW China.

5.3. Subzones of Zone II

Considering all the studied sections in East Yunnan, we recognize a new subzone,-the *Annelitellus yangtzensis-Obtusoconus honorabilis* Subzone-defined by the appearance of *O. honorabilis* (Fig. 14J, K), *Chancelloria symmetrica* (Fig. 19E) and *A. yangtzensis* (Fig. 14D, E). It may also contain *Obtusoconus rostriptuetus* (Fig. 14G), *Cupittheca mira* (Fig. 14F), *Lomasulcachites macrus* (Fig. 14H, I), *Igorella emeiensis* (Fig. 18A), *Igorella maidipingensis* (Fig. 18B), and *Bemella simplex* (Fig. 19B, C).

This subzone is emphasized here for its special composition compared with the lower part of Zone II. Though *Chancelloria*, *Bemella* as well as *Halkieria* show an affiliation also to Zone III, neither *Watsonella crosbyi* nor *Zhijinites longistriatus* is found in this subzone. It is possible that this subzone represents a transition interval between zones II and III.

Correspondingly, the lower part of Zone II is identified as the *Maikhanella cambriana-Oelandiella korobkovi* Subzone. It is defined by the appearance of *M. cambriana*, *O. korobkovi* and *Ocruranus finial*. Fossils such as *Eohalobia diadongensis*, *Maikhanella radularis*, *Maikhanella latispina*, *Paracarinachites sinensis*, *Paracarinachites parabolicus*, *Scoponodus renustus*, *Xianfengella prima* and *Phrygula nana* are common in this subzone of East Yunnan. However, *Paracarinachites sinensis* was also found together with *Watsonella crosbyi* in the Montagne Noire of France (Kerber, 1988).

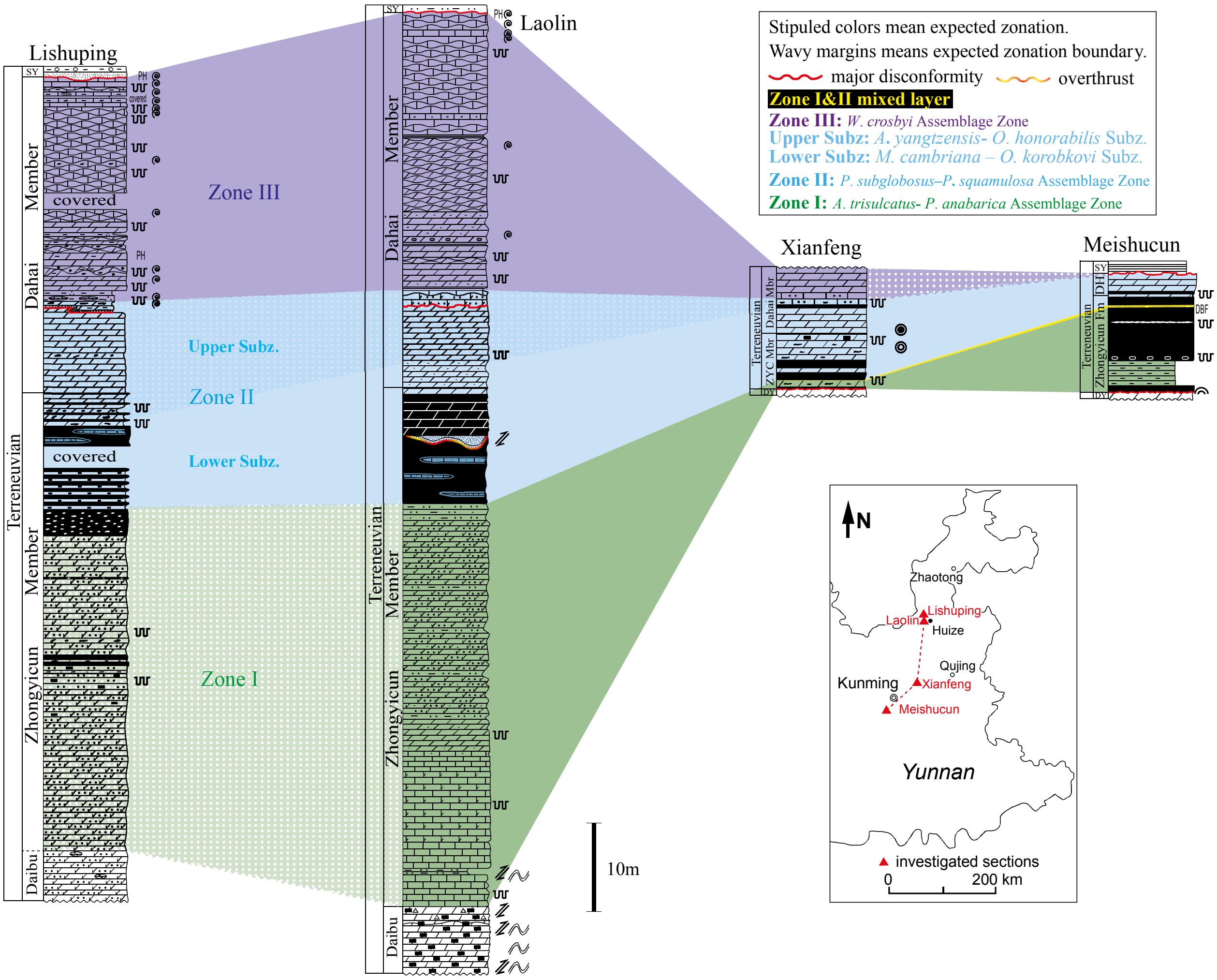

Fig. 10 Biostratigraphic correlation between Meishucun, Xianfeng, Laolin, Lishuping sections in East Yunnan, SW China.

5.4. Zone III: Watsonella crosbyi Assemblage Zone

We redefine the *Watsonella crosbyi* Assemblage Zone based on the formerly utilized index fossils *W. crosbyi* (Fig. 21A-C), *Aldanella yanjiahensis*, and the herein applied *Zhijinites longistriatus* (Fig. 21F).

The zone was first introduced as the *Heraultipegma yunnanensis* Zone by Qian et al.

(1996), then defined as the *Watsonella crosbyi* Assemblage Zone by Steiner et al. (2007). It has a good coverage in East Yunnan and South Siuchuan, where *W. crosbyi* is widely distributed (Figs. 6-9; Qian et al., 1999; Li and Xiao, 2004). The earlier utilized index fossil *Oelandiella korobkovi* is more common in Zone II and is herein considered as an index fossil for Zone II. As discussed before, *Zhijinites longistriatus* first appeared with or later than *W. crosbyi* in East Yunnan. However, the youngest occurrence of *Z. longistriatus* requires further study. Reports of *Z. longistriatus* in strata younger than Zone III remain to some extent ambiguous (Yue and Gao, 1992, text-fig. 2, Plate 3, fig. 8). This report may in fact represent fragments of cambroclaviids as no common basal part of *Zhijinites* was shown in the figure, nor did the spine own any characteristic ornamentation. *Aldanella yanjiahensis* could not be detected in the studied sections and was only reported from the Dahai Member in Xiaotan (Li and Xiao, 2004).

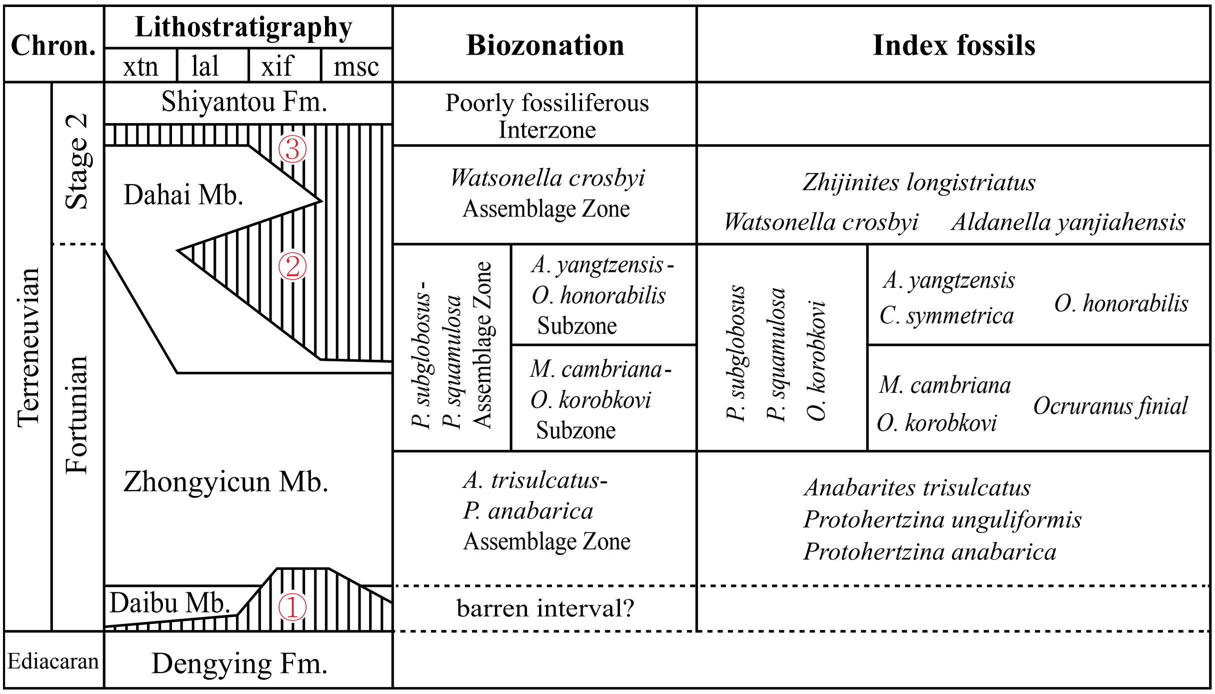

Fig. 11 Correlation chart of Terreneuvian strata in East Yunnan with biozonation and index fossils. xtn-Xiaotan Region; hz-Huize Region, including Laolin and Lishuping regions; xif-Xianfeng Region; msc-Meishucun region. Vertical hatching represents depositional break. Red numbers mark three major disconformities.

In Xianfeng, Zone III fossils such as *Watsonella crosbyi*, *Zhijinites longistriatus* and *Emarginoconus mirus* were detected in the silty limestones of the Dahai Member. As no sampling was possible for the overlying carbonates of the Dahai Member, the upper boundary of Zone III could not be reached in Xianfeng. No Zone III fossils have been found in the Meishucun section as the Dahai Member there is reduced to about 2m thickness and represents nearly pure dolostone with no phosphatic litho-and bioclasts. In Laolin, *W. crosbyi* first appears in the lower middle of the Dahai Member jointly with *Z. longistriatus*. It is has been recovered from most layers of the Dahai Member and occurs up to the top of the Dahai Member. In the Lishuping section, *W. crosbyi* first appears shortly above the second major disconformity at the base of the Dahai Member and is commonly distributed in the nodular limestone/dolostone up to the top of the Dahai Member.

Other fossils commonly found in this zone are *Emarginoconus mirus* (Fig. 20F, J, K), *Papilloconus* cf. *explanatus* (Fig. 21D, E), *Asiapatella sinuata* (Fig. 22C), *Bemella jacutica*, *Ilsanella atdabanica* (Fig. 22D), *Absidaticonus triangulatus* (Fig. 22E), *Lathamella caeca* (Fig. 22 A), etc. The exact appearance of these fossils is not clear yet although they are mostly found in Zone III, the possibility of discovery in younger strata is not excluded.

It is noteworthy that *Watsonella crosbyi* was not obtained at the topmost ca. 0.5 m of the Dahai Member though another index fossil *Zhijinites longistriatus* (Fig. 8) was recovered in this interval at Laolin.

5.5. Correlation of early Cambrian strata in East Yunnan

The present study further supports the applicability of SSFs for biostratigraphic purposes in pre-trilobitic Cambrian strata. It confirms earlier results of regional correlation in Yunnan, the correlation with other regions in South China such as Guizhou, Sichuan, and Shaanxi provinces, and intercontinental correlations with Siberia and Western Avalonia (Qian et al., 1996; Qian et al., 1999; Steiner et al., 2007). Here we update the data with additional material from the northern East Yunnan Region (Xianfeng and Huize counties).

Zone I can be correlated within the Laolin, Xianfeng, and Meishucun sections in the Zhongyicun Member (Fig. 10), though the sediment thickness decreases sharply from ca. 40m (Laolin) to 1m (Xianfeng) and 9.5 m in Meishucun. In both, Xianfeng and Meishcun, there is one layer with mixed SSFs of Zones I and II that occurred at the boundary between two zones. As we failed to recover Zone I from Lishuping, its range is inferred and its correlation with other sections remains uncertain (Fig. 10). Zone II is well distributed and detected in all the studied regions except for the Dahai Member of Meishucun section. Generally this zone overlies Zone I and shows up within the major phosphate beds of Lishuping, Laolin, and Xianfeng sections, as well as the upper phosphorite bed of Meishucun section. It extends to the typical dolostone of the lower Dahai Member that usually contains many phosphate clasts. The sediment thickness decreases from north to south. The upper Subzone of Zone II decreases in toward and disappears in the Meishucun section. Zone III exists in the carbonates of the upper Dahai Member in East Yunnan except for the Meishucun Region. This zone also decreases from north to south. As mentioned above, in Laolin and Lishuping the upper limit of Zone III might be lower than the top boundary of the Dahai Member as *Watsonella crosbyi* does not reach the topmost bed (ca. 0.5 m) of the Dahai Member.

Fig. 12 SEM micrographs of SSFs of Zone I from East Yunnan. A, B. *Protohertzina anabarica* Missarzhevsky. 1973. A. No. Kunb6-5-016. A1. Proximal view. A2. Lateral view; B. No. Xif1-03-008. B1. Detail of proximal view. B2. Anterior view. C. *Protohertzina unguliformis* Missarzhevsky, 1973, No. Xif1-03-023. D, E. *Anabarites trisulcatus* Voronova & Missarzhevsky, 1969. D. No. Xif1-02-001. E. No. Lal52-003. E1. Lateral view, E2. Detail of cross-section. F. *Cambrotubulus decurvatus* Rozanov et al, 1969, No. Lal44-001. F1. Lateral view. F2. Detail of cross-section. G. *Hyolithellus isiticus* Hinz, 1987, No. Xif1-04-024. H. *Mongolodus longispina* (Yang & He, 1984), No. Lal52-002. I, J. *Acanthocassis orthacanthus* Yang & He, 1984. I. No. Kunb6-5-004: I1. View of tentacles; I2. Lateral view. J. No. Kunb6-5-003. K. *Lophotheca multicostata* Qian, 1977, No. Xif1-02-006. K1. Longitudinal view. K2. Detail of cross-section. L. *Coleolella recta* (Mambetov in Missarzhevsky & Mambetov, 1981), No. Xif1-04-018. L1. Longitudinal view; L2. Detail of cross-section. M. *Spirellus columnaris* Jiang in Luo et al., 1982, No. Lal52-007. M1. Lateral view. M2. Detail of terminal view. N.

Hexaconularia sichuanensis He & Yang, 1986, Lal39-001. N1,2. Lateral views. O. *Arthrochites emeishanensis* Chen, 1982, No. Kunb6-5-002. P. *Olivooides multisulcatus* Qian, 1977, No. Xif1-02-002. Scale bars: A1-3, D, F1, 2, 200 μm; others, 100 μm.

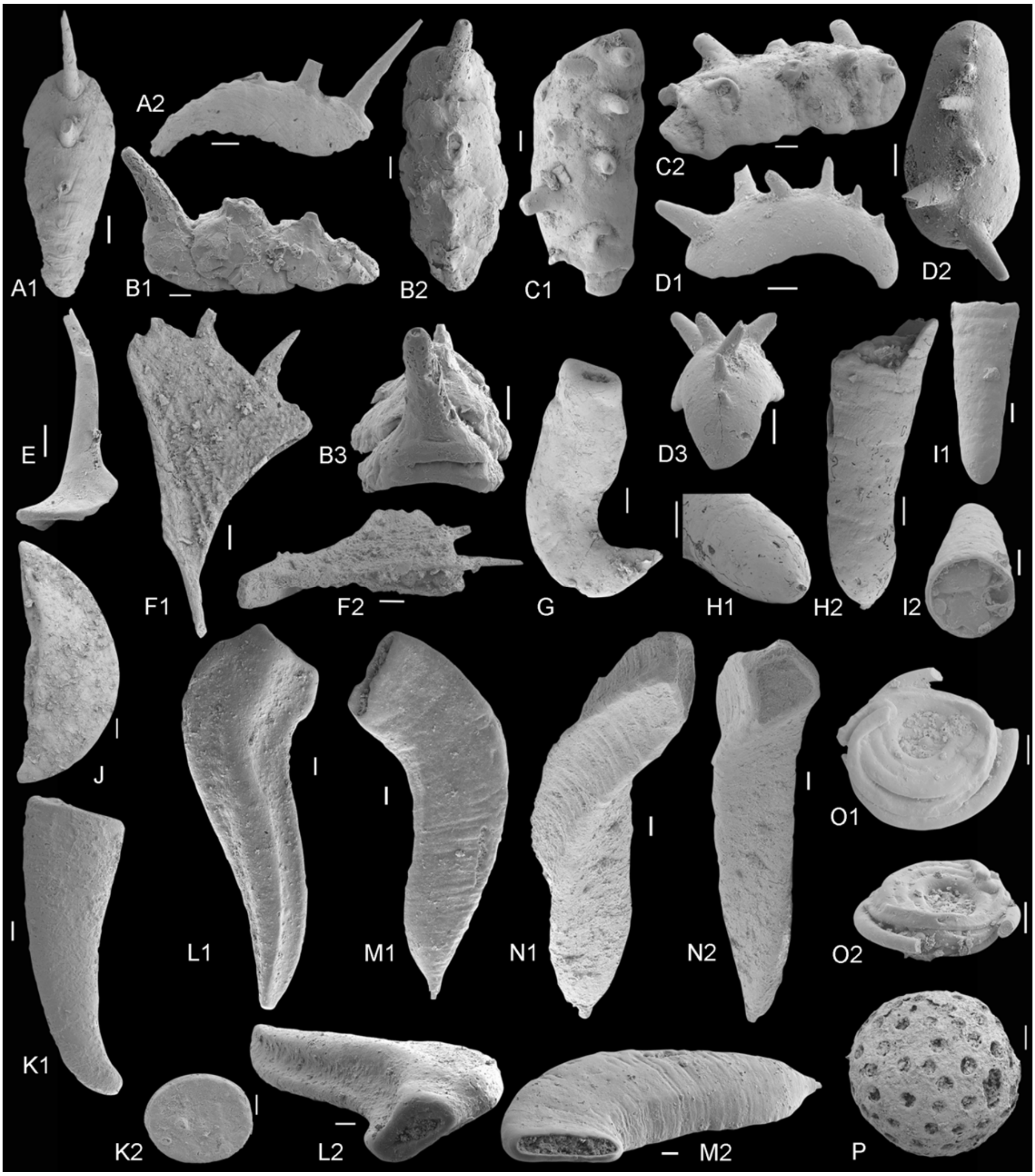

Fig. 13 SEM micrographs of SSFs of Zone II from East Yunnan. A. *Paracarinachites sinensis* Qian & Jiang in Luo et al., 1982, No. Xif1-08-021. A1. Distal view. A2. Lateral view. B. *Paracarinachites spinus* (Yu, 1984), No. Kun4-5-006. B1. Lateral view. B2. Distal view. B3. Proximal view. C, D. *Paracarinachites parabolicus* Qian & Bengtson, 1989. 3. No. Xif1-12-002. C1. Distal view. C2. Lateral view. D. No. Lsples2-011. D1. Lateral view. D2. Distal view. E. *Paracarinachites* sp, No. Kun4-5-010d. F. *Scoponodus renustus* Jiang in Luo et al., 1982, No. Xif1-10-012. F1. Distal view. F2. Lateral view. G. *Drepanochites dilatatus* Qian & Jiang in Luo et al., 1982, No. Xif1-11-005. H. *Neogloborilus applanatus* Qian & Zhang, 1983, No. Xif1-12-009. H1. Distal view. H2. Lateral

view. I, K. *Conotheca* cf. *subcurvata* (Yu, 1974). I. No. Xif1-15-008. I1. Lateral view. I2. Detail of cross-section. K. No. Xif1-22-023. K1. Lateral view. K2. Detail of cross-section. J. *Cyrtochites pinnoides* Qian, 1984, No. Xif1-10-014. L. *Lopochites quadrogonus* Qian, 1984, No. Xif1-12-022. L1, Lateral view. L2. Proximal view. M. *Lopochites latazonalis* Qian, 1977, No. Xif1-12-020. M1. Lateral view. M2. Proximal view. N. *Siphogonuchites triangularis* Qian, 1977, No. Xif1-19-011. N1, N2. Lateral view. O. *Spirellus* cf. *groenlandicus* (Peel, 1988) , No. Xif1-15-007. O1. Detail of terminal view. O2. Lateral view. P. *Aetholicopalla adnata* Bengtson et al., 1990, no. Xif1-12-003. Scale bars equal 100 µm.

The mixing of zone fossils is mostly confined to conglomeratic or debris flow beds at zone boundaries (see Fig. 10). The mixture beds of Zone I and Zone II occur in Xianfeng sections in a similar stratigraphic position, representing a minor hiatus. The increasing number of hardgrounds in the upper Zhongyicun Member and the Dahai Member may be related to a general uplift of the carbonate platform, but the single hiatus is of shorter duration, likely thousands to tens of thousands of years, in analogy to other Phanerozoic hardgrounds (Bromley, 1965; Flügel, 2010) and therefore does not have a major impact on the fossil distributions (likely hundreds of thousands to one to two million years), but may explain lower recorded sediment thicknesses.

The sequence and general composition of the main SSF zones in East Yunnan are similar from the Kunming Region toward Yongshan County. However, the thicknesses of these zones decrease toward the south as the extent of hiati increases. As stated earlier (Landing, 1994; Steiner et al., 2007), hiati of different extent have a major impact on the sedimentary sequences of the shallo-water carbonate platforms, such as exemplified by the East Yunnan Region. Despite the existence of three major hiati and numerous short sedimentary breaks (e.g. obvious hardground formation), the biozonation of subtrilobitic carbonate sequences is well established in East Yunnan (Fig. 11) and supports a platform-wide correlation and partially intercontinental correlation (mostly for Zones I and III).

6. Discussion

The recorded SSF associations support the zonation in the Terreneuvian of East Yunnan and South Sichuan and allow a better correlation and consideration of depositional breaks. Previous uncertainty with reports of co-occurrence of index fossils and auxiliary fossils from Zones I to III (Huang, 1986; Qian, 1989; Steiner et al., 2004) can now be eliminated or explained by geological processes. The hardgrounds and debris flow beds indicate sea level change or slumping (Meishucun section, Fig. 3C) that leads to a zone mixture in limited intervals.

Zone I (*Anabarites trisulcatus-Protohertzina anabarica*) has the widest distribution of investigated SSF zones on the Yangtze Platform. Zone I can be recognized not only in shallow water carbonate sequences, but also in deeper water sections and other palaeoenvironments (Steiner et al., 2007). It covers wide regions of Yunnan, Sichuan, South Shaanxi, Guizhou, Hunan, Hubei, Jiangxi, and Zhejiang provinces.

Huang (1986) reported *Prothohertzina anabarica* from Bed 10 of the old Xianfeng section together with typical Zone II and III faunal elements such as *Ocruranus trulliformis*, *Xiafengella prima*, *Lomasulcachites macrus*, *Paracarinachites sinensis, Paragloborilus subglobosus* and *Watsonella crosbyi* (*Herautipegma yunnanensis*). In the same paper, the author claims that *P. anabarica* was found again 13m below Bed 10. According to our work, *Protohertzina anabarica* and other *Protohertzina* species in Xianfeng are found only at the base of the Zhongyicun Member below strata with Zone II fossils. *Watsonella crosbyi* is present just above Zone II. As the zones are very thin (e.g. Zone I and Zone II, Fig.6), large sample intervals (Bed 10 with a thickness of 4.05 m, Huang, 1986) in the field may explain the virtual coexistence of *Watsonella crosbyi* and Zone II fossils in one bed. It cannot be fully ruled out that some Zone I elements were introduced by the reworking of the older beds.

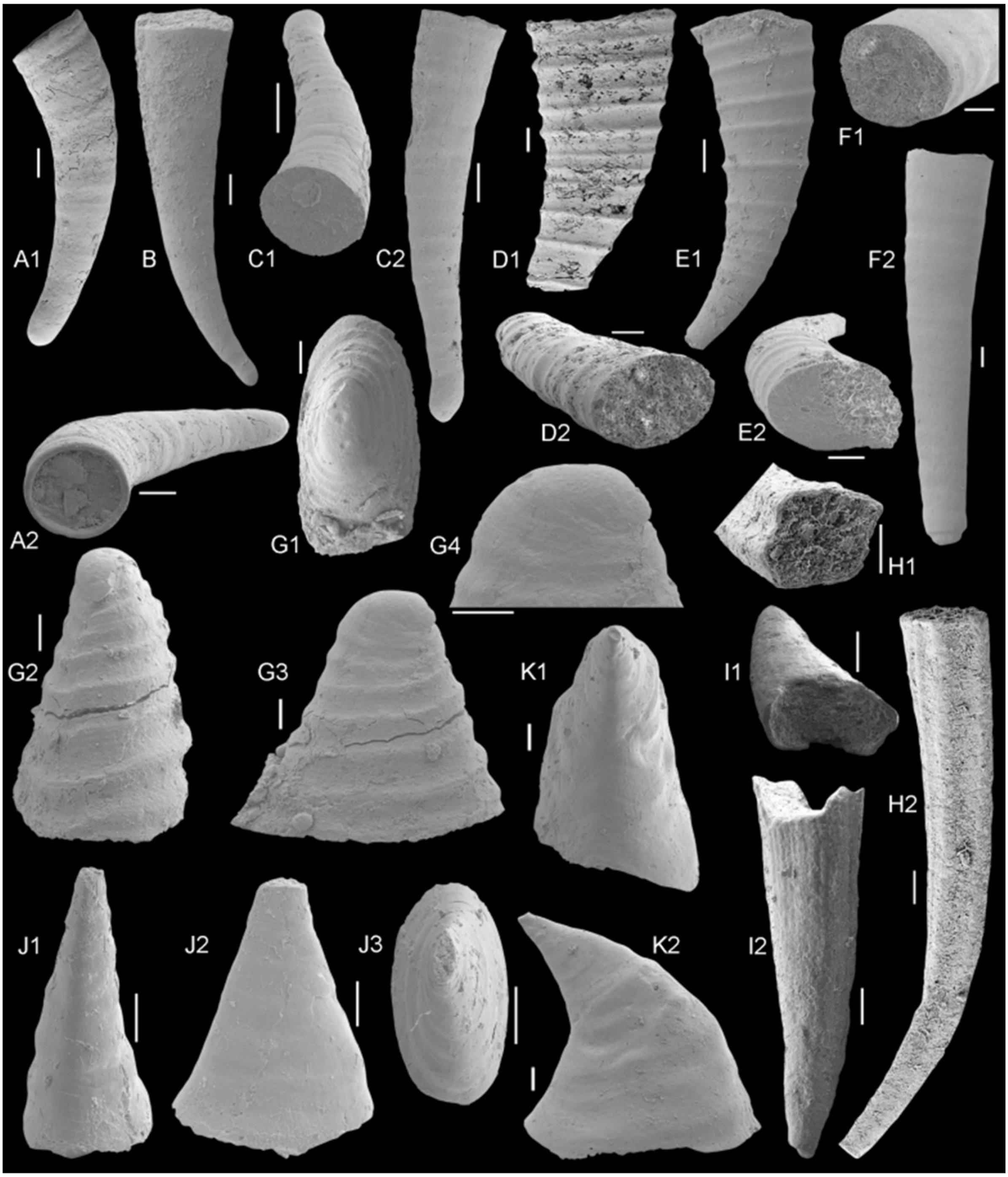

Fig. 14 SEM micrographs of SSFs of Zone II from East Yunnan. A. *Pseudovalitheca crassa* Yu, 1974, No. Lsples1-005. A1. Lateral view. A2. Detail of cross-section. B, C. *Paragloborilus subglobosus* He in Qian, 1977. B. No. Xif1-22-029. C. No. Lsp113-008. C1. Detail of cross-section. C2. Lateral view. D, E. *Annelitellus*

yangtzensis Qian, 1989. D. No. Xif1-19-041b. D1. Lateral view. D2. Detail of cross-section. E. No. Xif1-19-012. E1. Lateral view. E2. Detail of cross-section. F. *Cupittheca mira* (He in Qian, 1977), No. xif1-19-013. F1. Detail of cross-section. F2. Lateral view. G. *Obtusoconus rostriptuetus* (Qian, 1978), No. Xif1-15-010. G1. Distal view. G2. Lateral view. G3. Lateral view. G4. Detail of the top of G3. H, I. *Lomasulcachites macrus* Qian & Jiang in Luo et al., 1982. H. Form1 (Qian, 1989, p. 210), No. Xif1-19-002. H1. Detail of the cross-section. H2. Lateral view. I. Form2 (Qian, 1989, p. 210), No. xif1-15-020. I1. Detail of the cross-section. I2. Lateral view. J, K. *Obtusoconus honorabilis* (Qian et al., 1979). J. No. Xif1-19-018. J1. Lateral view. J2. Lateral view. J3. Distal view. K. No. Xif1-19-008d. K1, K2. Lateral views. Scale bars equal 200 μm.

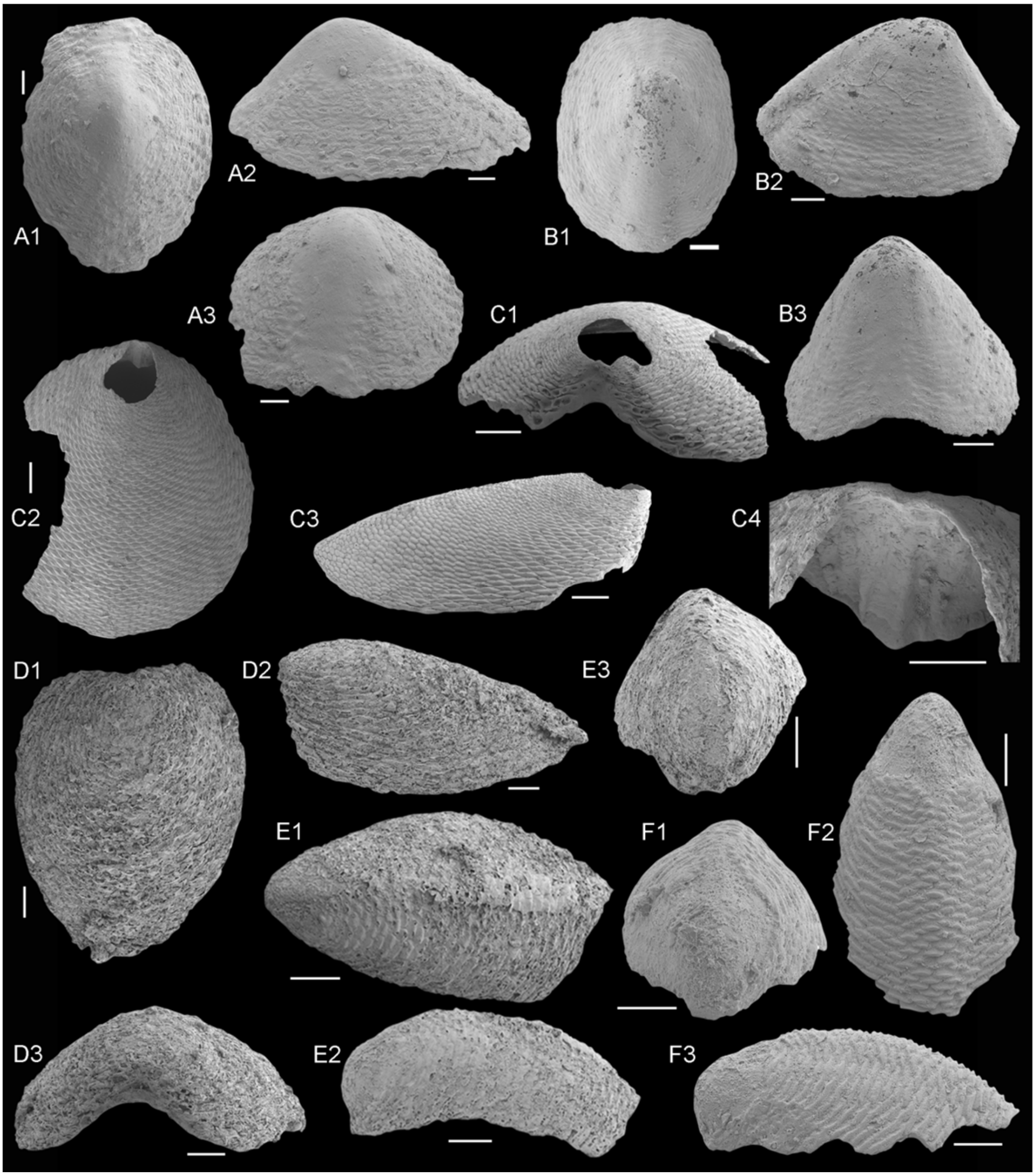

Fig. 15 SEM micrographs of SSFs of Zone II from East Yunnan. A, B. *Maikhanella cambrina* (Jiang in Luo et al., 1982). A. No. Xif1-15-002. A1. Distal view. A2. Lateral view. B. No. Lsp113-011. B2. Distal view. B2.

Lateral view. C, D. *Maikhanella radularis* (Qian & Bengtson, 1989). C. No. Xif1-12-007. C1. Proximal view. C2. Distal view. C3. Lateral view. C4. Detail of the interior. D. No. Xif1-10-021. D1. Distal view. D2. Lateral view. E, F. *Maikhanella latispina* (Feng et al, 2001). E. No. Xif1-11-017. E1. Distal view. E2. Lateral view. F. No. Xif1-15-003. F1. Proximal view. F2. Distal view. F3. Lateral view. Scale bars: C1-3, 500 μm; others, 200 μm.

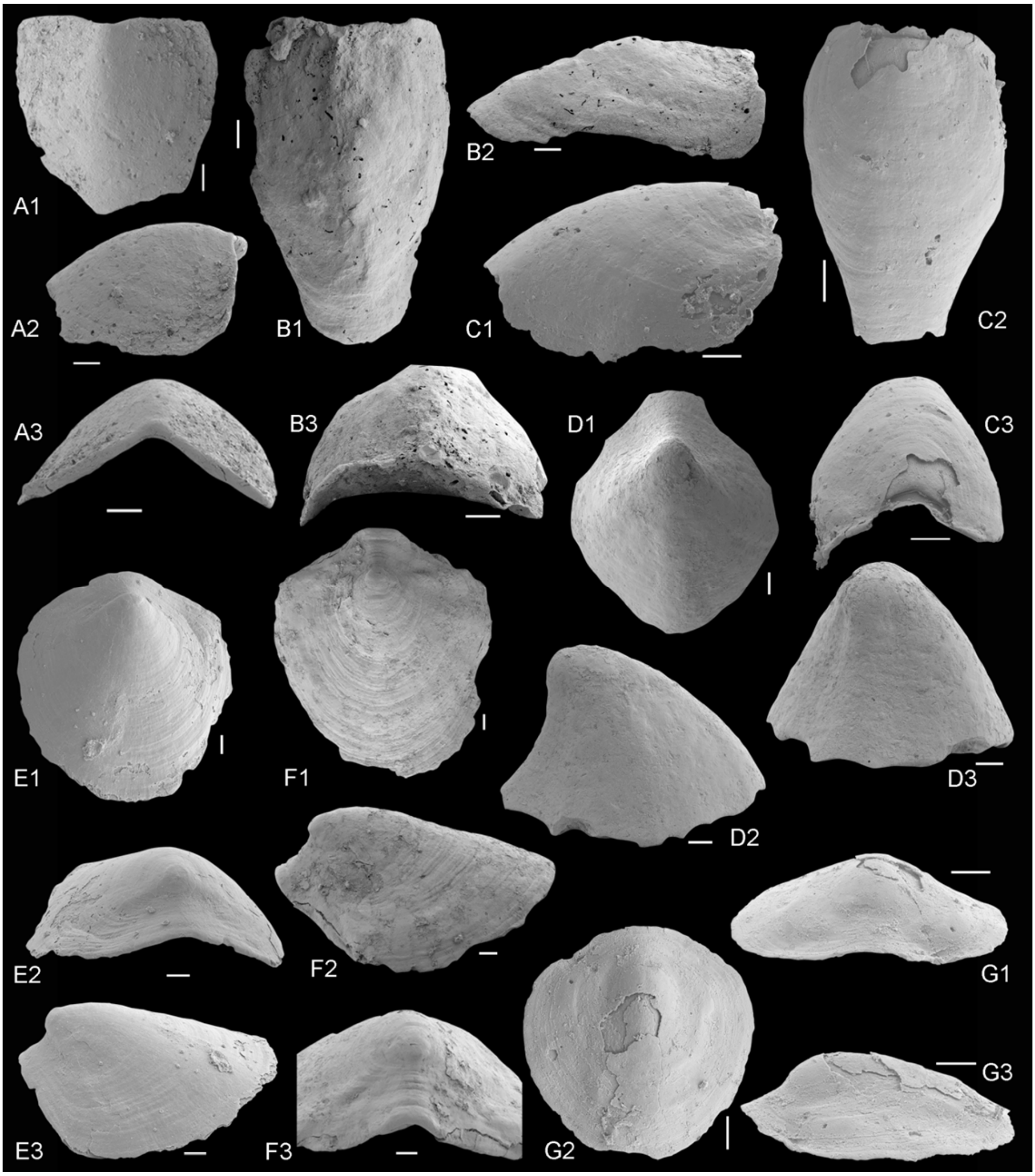

Fig. 17 SEM micrographs of SSFs of Zone II from East Yunnan. A-C. *Eohalobia diandongensis* Jiang in Luo et al., 1982. 1. No. Xif1-09-045. A1. Distal view. A2. Lateral view. A3. Proximal view. B. No. Xif1-05-016. B1. Distal view. B2. Lateral view. B3. Lateral view. C. No. Lsples1-012. C1. Lateral view. C2. Distal view. C3. Proximal view. D. *Ocruranus trulliformis* (Jiang, 1980) , No. Xif1-11-001. D1. Distal view. D2. Lateral view. D3. Proximal view. E, F. *Ocruranus finial* Liu, 1979. E. No. Xif1-15-011. E1. Distal view. E2. Proximal view. E3. Lateral view. F. No. Xif1-09-018. F1. Distal view. F2. Lateral view. F3. Proximal view. G. Unknown cap-like fossil,

No. Lal23-012. G1. Proximal view. G2. Distal view. G3. Lateral view. Scale bars: B1-3, C1-3, 200 μm; others, 100 μm.

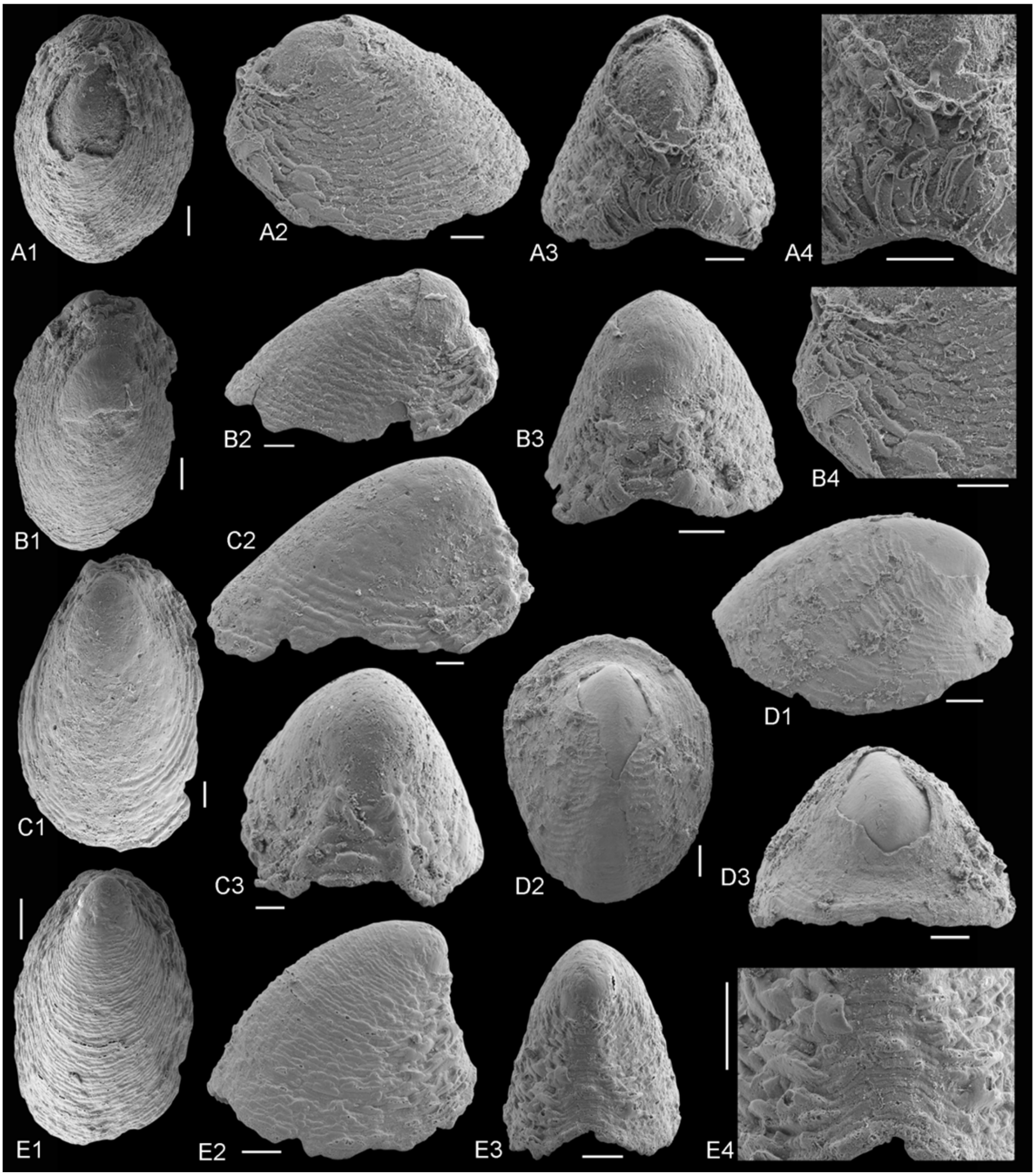

Fig. 17 SEM micrographs of SSFs of Zone II from East Yunnan. A-C, E. *Purella squamulosa* Qian & Bengtson, 1989. A. No. Xif1-12top-02. A1. Distal view. A2. Lateral view. A3. Proximal view. A4. Detail of A3. B. No. Xif1-12top-03. B1. Distal view. B2. Lateral view. B3. Proximal view. B4. Detail of the scaly ornaments. C. No. Xif1-13-004. C1. Distal view. C2. Lateral view. C3. Proximal view. E. No. Xif1-13-005. E1. Distal view. E2. Lateral view. E3. Proximal view. E4. Detail of E3. D. *Purella elegans* Yu, 1979, No. Lal23-001. D1. Lateral view. D2. Distal view. D3. Proximal view. Scale bars: D1-3, E1-3, 200 μm; others, 100 μm.

From the Shatan section, Steiner et al. (2004) listed the co-occurrence of *Protohertzina* *unguliformis*, *Zhijinites longistriatus, Maikhanella multa, Bemella costa, Chancelloria* cf.*eros* and *Purella* cf. *squamulosa* in the top of the Kuanchuanpu Formation, which is interpreted as a reworking of Zone I fossils into younger Zone II (or even Zone III) sediments in a typical breccia bed (Steiner et al., 2004). While it has been claimed that *Zhijinites* sp. is present in a Zone I assemblage from the limestone underlying the reworked breccia bed, our sedimentological restudy of the bed revealed previously unrecognized crack infills penetrating ca. 0.7 m from the phosphatic breccia bed into the underlying carbonates. These may have resulted from karstification or seismic activity, during which smaller individuals of younger SSF assemblages were introduced into the underlying strata.

Another complication for the biostratigraphic application of SSF assemblages in South China arose from the report by Parkhaev and Demidenko (2010) who claimed that SSFs of Zone II were found in Bed 4 of the Meishucun section assigned to the *Anabarites trisulcatus-Protohertzina anabarica* Zone. We re-sampled the basal Cambrian strata (Beds 3-4) from Meishucun and were not able to recover any Zone II SSFs from either Bed 4 or Bed 3. Instead a typical Zone I assemblage (Fig. 7, Fig. 12A, I, J, O) was found. In the upper phosphorite, both Zone I and Zone II fossils from a thin debris flow bed were obtained at the boundary between Bed 6 and Bed 7. Also the report of *Protohertzina unguliformis* in Bed 7 of Meishucun section by Parkhaev and Demidenko (2010: Pl. 29, figs. 2, 3.) appears unjustified because the figured remains do not show the typical characters, such as the keels of the genus *Protohertzina*. Thus the stratigraphical conclusions by Parkhaev and Demidenko (2010) are rejected herein.

Vendrasco et al. (2009) stated that specimens of the *Eohalobia-Ocruranus* group in Xianfeng are from the “lower phosphorite”, which is stratigraphically comparable with the lower phosphorite of Meishucun Region. They imply that *Eohalobia-Ocruranus* has a FAD in Zone I. This mostly results from a misinterpretation of the white dolostone overlying the main phosphorite bed in Xianfeng as correlative with the white-gray muddy Bed 5 of Meishucun. In fact the *Eohalobia-Ocruranus* group of fossils occurs at Xianfeng in a Zone II association. The white massive dolostone correlates with the whitish dolostone of Huize County that immediately underlies the prominent disconformity at the top of Zhongyicun Formation.

Purella squamulosa in North Sichuan (Steiner et al., 2004) comes from a reworked horizon containing Zone I and II fossils. *P. squamulosa* from Hubei (Xing et al., 1984) originated from a reworked bed with Zone I to III fossils. In South Sichuan (Mt. Emei Region) the Zone II interval is completely missing and *Paragloborilus subglobosus* and *Olelandiella korobkovi* make their first appearance jointly with *Watsonella crosbyi* in Bed 36. This indicates that the major disconformity in Zone II it is even more extended. The assignment of strata in West Guizhou (Zhijin Region) to Zone II is ambiguous because although the strata contain *Zhijinites longistriatus*, neither the typical Zone III index fossil *W. crosbyi* nor the Zone II index fossil *O. korobkovi* is reported there. The only indication that this thick sequence of granular phosphorites could belong to Zone II is from the co-occurrence of *P. subglobosus* with *Z. longistriatus* and questionable *Eohalobia diandongensis* and lithological similarities with the Xianfeng Region. However, a Zone III assignment cannot be fully ruled out.

It is considered here that *Obtusoconus* and *Annelitellus* were often wrongly assigned to *Lapworthella* or *Tannuella* in Guizhou and Hubei (Chen and Zhang, 1980; Chen et al., 1981; Qian and Yin, 1984). Following this opinion, the fossils of upper Subzone of Zone II such as

Obtusoconus, *Annelitellus*, *Cupittheca* and *Chancelloria* (Qian and Yin, 1984) were reported in the Gezhongwu Formation of Zhijin County (Guizhou) and the reworked Huangshandong Formation of Hubei Province. Besides, *Paragloborilus subglobosus-Purella squamulosa* Zone (Zone II) is mostly restricted to East Yunnan. It is thought that Zone II, especially the lower Subzone, is missing in other carbonate deposit regions (Sichuan, South Shaanxi, Guizhou and Hubei, etc.) than East Yunnan, possibly because the fossils are facies limited but may also because of erosion and deposition interuption (Cheng et al., 1992).

The *Watsonella crosbyi* Zone (Zone III) can be widely found and well correlated in East Yunnan and toward South Sichuan. Reports of *W. crosbyi* and *Aldanella yanjiahensis* from South Shaanxi (Xing et al., 1984) and the South Huangling anticline of Southwest Hubei (Chen, 1984) are all confined to reworked conglomerate beds with a mixing of SSFs from zones I to III. These prominent reworked horizons are also recorded in western and southwestern Hubei (Qian et al., 1979; Chen et al., 1981; Qian et al., 1999), as well as northern Sichuan (Steiner et al., 2004). The fossil assemblage in the Shatan section of Nanjiang County (North Sichuan) is similar to that of the Huangshandong Formation, as *Zhijinites*, *Bemella*, *Helcionella* and *Igorella* were found in the breccia beds overlying strata containing Zone I fossils (Steiner et al., 2004).

The early SSF assemblages from the northern margin of the Yangtze Platform (North Sichuan, North Hubei, and South Shaanxi regions) do not allow far-reaching biostratigraphic conclusions. In this region, hiati in strata younger than Zone I indicate a more typical seal level change or higher tectonic activity. In addition, the basement of the South Shaanxi and North Hubei Regions possess a complicated tectonic history different from the major part of the Yangtze Block (Dong et al., 2011a; Peng et al., 2012).

Landing (1994) suggested that no stratigraphic continuity exists for the early Cambrian strata of Yunnan and that the abrupt faunal changes between the three pre-trilobitic SSF faunas (Zone I to III) of East Yunnan reveal extremely long-lasting hiati. Our data do not fully support this suggestion and the durations of the stratigraphical breaks were over-estimated.Toward the northern region of East Yunnan the sediment sequences are more continuous and faunas have gradual transitions. The seemingly abrupt faunal change between Zones I and II (e.g. in Laolin, Fig. 8) is indicated by the long interval of clastic rocks where no fauna could be recovered. In the even more complete section of Xiaotan the distinction between zones I and II was ambiguous (Li and Xiao, 2004), which may be due to a gradual transition between the faunas.

Landing and Geyer (2012) further suggested to abandon any biostratigraphical subdivision for the early Cambrian and base the subdivision of the Cambrian Stages entirely on carbon isotopic markers. They proposed a “Laolinian Stage” based on the positive carbon isotope excursion (ZHUCE) that starts in the lower Dahai Member in Xiaotan and the middle Dahai Member of the Laolin section. It is slightly preceded by the FAD of *Watsonella crosbyi*. This proposal has to be rejected for formal and scientific reasons. It lacks significant scientific data as correlation tools. Potential stratotype sections require discussion in the relevant international working groups. Besides, a solely chemostratigraphical subdivision of subtrilobitic Cambrian strata would lack any stratigraphical control. In addition, the hiati and fault/overthrust horizons need to be taken into consideration if the Laolin section is further considered for the placement of a potential stratotype section.

Although hiati exist in various regions, most of the Precambrian-Cambrian deposits of shallow carbonate platform of the Yangtze Platform are continuous (Fig. 11; Qian et al., 1996). Still, we call for attention that detailed sedimentological work is required to complement the biostratigraphical and chemostratigraphical studies. Our recent investigation reveals that hiati are widespread on the shallow carbonate platform but are mostly of short duration. We conclude that a firm biostratigraphic subdivision of the early Cambrian strata is possible when the fossil distribution is critically evaluated and complemented with sedimentological data. For a regional biostratigraphic framework and geochemical study of shallo-water carbonate sequences it is thus suggested to choose sections in the northern region of East Yunnan rather than those in the classical Meishucun Region.

7. Systematic Palaeontology

MOLLUSCS and PROBLEMATIC SHELLS

Genus *Absidaticonus* Yue in Xing et al., 1984

Absidaticonus triangulatus Yue in Xing et al., 1984

Fig. 22E

Absidaticonus triangulatus Yue, 1984: Yue in Xing et al., 1984, p. 160, pl. 26, 5-7.

Material: More than ten specimens from the Dahai Member at the Laolin section.

Description: The fossil is small and curved downward. Aperture is oval; the apex protrudes out of the aperture range and downwards. The steinkern surface is smooth with some polygnal cell imprints.

Remarks: Compared with *Xianfengella prima*, no specimen of *Absidaticonus triangulatus* has expanded lateral shoulders. The apex of the latter is smoother, rounder and extends outside the aperture margin (Fig. 22E), whereas *X. prima* expands at the shoulder and then contracts sharply (Fig. 19A1). Recently, Parkhaev & Demidenko (2010, p. 1035) ascribed *Xianfengella ovata* (=*X. prima*) to *Absidaticonus,* although, as mentioned above, the apex and aperture of these two species are different. No specimens of *X. prima* were found together with *A. triangulatus* at the same level (top of the Dahai Member). However, considering the oval aperture and short pointed apex, *Bemella* ? *mirabilis* (Yu, 1979, p. 251, pl. III, 8-11.) looks more like *X. prima* (Qian and Bengtson, 1989, Fig. 78F; Qian, 2001, text-fig. 2, figs. 3, 6).

Occurrence: Zone III, Dahai Member, Zhujiaqing Formation, Laolin section, Yunnan Province, China.

Genus *Aegitellus* Feng, Sun et Qian, 2000

Aegitellus emeishanensis (He in Yin et al., 1980)

Figs. 18G, 20C, D, E, H, I

Scenella emeishanensis He in Yin et al., 1980, p. 152, pl. 14, figs. 8, 9

Scenella undulata Yu; Yu, 1981, p. 553, pl. 1, figs. 1-4

Aegides placus Jiang: Luo et al., 1982, p. 192, text-fig. 1, pl. 20, fig. 13 (places) [non figs. 12, 14, 15]; Qian and Bengtson, 1989, p. 122, text-fig. 81 (“Aegides”).

Tannuella retusa Jiang in Luo et al.: Luo et al., 1982, p. 191, pl. 20, figs. 8, 9 [sic! retuses on p. 191].

(?) *Scenella hujingtanensis* Yu: Xing et al., 1984, pl. 4, fig. 9.

(?) *Aegides* cf. *places* Jiang: Jiang and Huang, 1986, pl. 2, fig. 9.

Aegitellus placus (Jiang): Feng et al., 2000, pp. 364, 371; Parkhaev, 2005, pl. 1, Fig. 4;

2006, text-figs. 3a, 3b; 2008, text-figs. 3.11A, 3.11B; Demidenko and Parkhaev, 2006, text-figs. 4m, 4n.

"*Aegites*" sp.: Zhu et al., 2001, text-fig. 5.15 [sic!].

Aegitellus placus, Parkhaev, 2010, p. 1017, pl. 55, figs. 1-7

Description: Shell cap-shaped, low conical, very rapidly expanding from apex toward aperture. Apex is straight, located centrally (Fig.20C, E) or subcentrally (Fig. 20D, H). Aperture is round, long oval, or widely egg-shaped, and sometimes with a minor depression (Fig. 20C1, C2). A few specimens have flattened margins of the aperture (Fig. 20H), but this feature differs from that of hyolith opercula such as *Emarginoconus mirus*, as the margin protrudes downward for the purpose of covering the hyolith tube (Fig. 20J, K). Shell ornamentation represented by distinct concentric growth lines. There are four kinds of this species (Fig. 20C, D, E, H) and the steinkern form specimens (Fig. 18G) should belong to at least one of the different forms. Further division is difficult with regard to simple morphology and minor differences.

Occurrence Zone II and especially the *Maikhanella cambriana-Oelandiella korobkovi* subzone, Zhujiaqing Formation, Xianfeng, Laolin, Lishuping sections, Yunnan Province, China.

Genus *Emarginoconus* Yu, 1979

Emarginoconus Yu: Yu, 1979, pl. II, figs. 1-4

Diandongoconus He: He, 1982, p.87, pl.II, fig.7-10, 13, pl. III, figs.1-5

Type species: *Emarginoconus mirus* Yu, 1979

Composition: Only type species.

Diagnosis: Small, round or oval operculum of unknown organism (Possibly the operculum of *Hyolithellus*). The base is concave with a ridge along the margin. The ridge protrudes downward along the margin and is sometime slightly sinuous (Fig. 20J, K). The dorsal surface is decorated with comarginal growth lines.

Remarks: It was very often confused with *Aegitellus placus* or *Phrygula nana* in the past. He and Yang (1982) interpreted this fossil as a hyolith operculum on the basis of the special convex margin on the aperture. Though Xing et al. (1984, p. 156) suggested that these flat opercula are related to *Allatheca*, no clear evidence could support this opinion. It is abundantly found in coexistence with *Conotheca* cf. *subcurvata*. Because it is found only in Zone III, it maybe regarded later as a candidate index fossil of Zone III.

Emarginoconus mirus Yu, 1979

Fig. 20F, J, K

Diandongoconus mirus He, 1982, p.88, pl.II, fig.9, 13; pl.III, fig.1-5

Diandongoconus varians He, 1982, p.88, pl.II, fig.7, 8, 10

Allatheca sp. operculum, Xing et al., 1984, pl.14, fig.19, 20

Material: Hundreds of specimens from Dahai Member of Xianfeng, Laolin, and Lishuping sections.

Description: The simple operculum has a diameter of ca. 750 μm and a height of about 500 μm. It is round, low and cone-like, with growth lines and shallow grooves on the surface. Its aperture margin has a co-marginal ridge which is symmetrical and sinuous. The shell is probably calcareous as the inner side of the shell is often found dissolved.

Occurrence: Zone III, Dahai Member, Zhujiaqing Formation, Xianfeng, Laolin, and Lishuping sections, Yunnan Province, China.

Genus *Maikhanella* Zhegallo, 1982

Ramentoides Feng, Sun et Qian: Feng et al., 2001, pp. 199, 207.

Mediata Feng, Sun et Qian: Feng et al., 2001, pp. 200, 207.

"for further synonymy see under" *Maikhanella*, in Bengtson, 1992, p. 403

Diagnosis (Emended from Bengtson, 1992) : Fossils having patelliform shells with smooth, rounded apical regions and a peripheral regions bearing a distinct scaly or undulating surface pattern, consisting of spicules embedded in an intermediate matrix.

Remarks: Because of their identical surface decoration, all the genera in the synonym list are junior synonyms of *Maikhanella*. Feng et al.(2001) kept *Ramenta* and erected *Ramentoides*, *Mediata* as genera of Maikhanellids mainly on the basis of the shell morph, apex position as well as the pattern of surface ornamentation. It is considered here that these characters mostly represent species differences and no significant genus level variation could be achieved.

Maikhanella latispina (Feng et al., 2001)

Fig. 15E, F

Mediata kunyangensis Feng et al., 2001, pp. 200, 207, pl. 3, figs. 6, 7.

Ramentoides latispinus Feng, Sun et Qian: Feng et al., 2001, pp. 200, 207, pl. 3, figs. 2-5.

Canopoconus superatus (Feng et al., 2001): Parkhaev and Demidenko, 2010, P1001, pl.49, fig. 2, pl. 50, figs. 1, 2.

Material: About 5 specimens from the Xianfeng and Laolin sections.

Description: Small, low conical shell with elongated oval aperture which is usually cracked. The apex protrudes out of the margin. While the other part of the fossil is decorated with rhombic scaly ornaments, the apex is bare with no ornaments. Along the mid-dorsal axis a ridge extends from the apex to the margin.

Remarks: It was first named *Mediata kunyangensis* and *Ramentoides latispinus* by Feng et al who described both as having a ridge on the back, similar outline and scale-like ornamentation. The scale-like ornamentation is common among all the Maikhanellids, (for *Yunnanoplurella* it is varied), whereas the ridge on the surface was also characteristic of other species of *Maikhanella* (Fig. 15B), *Purella* (Fig. 17D), also see (Qian and Bengtson, 1989, Fig. 61A4) and even non-Maikhanellids such as *Protoconus* (Fig. 19H, I), especially the steinkern of *Protoconus* and *Purella*. Thus these two genera in addition to *Ramenta* could be ascribed to *Maikhanella.* Considering the *Maikhanellids*' unclear phylogeny, its intra-specie/genus relationship or that with other groups such as *Protoconus* is worth further study. The morph transition is indicated by present data; for instance species described here-*Maikhanella cambriana* (Fig. 15A, B), *Maikhanella latispina* (Fig. 15E, F), *Purella elegans* (Fig. 17D) and *Protoconus crestatus* (Fig. 19H, I)-either have similar ridges on the back or similar outlines.

Occurrence: Zone II, Zhujiaqing Formation, Xianfeng and Lishuping sections, Yunnan Province, China.

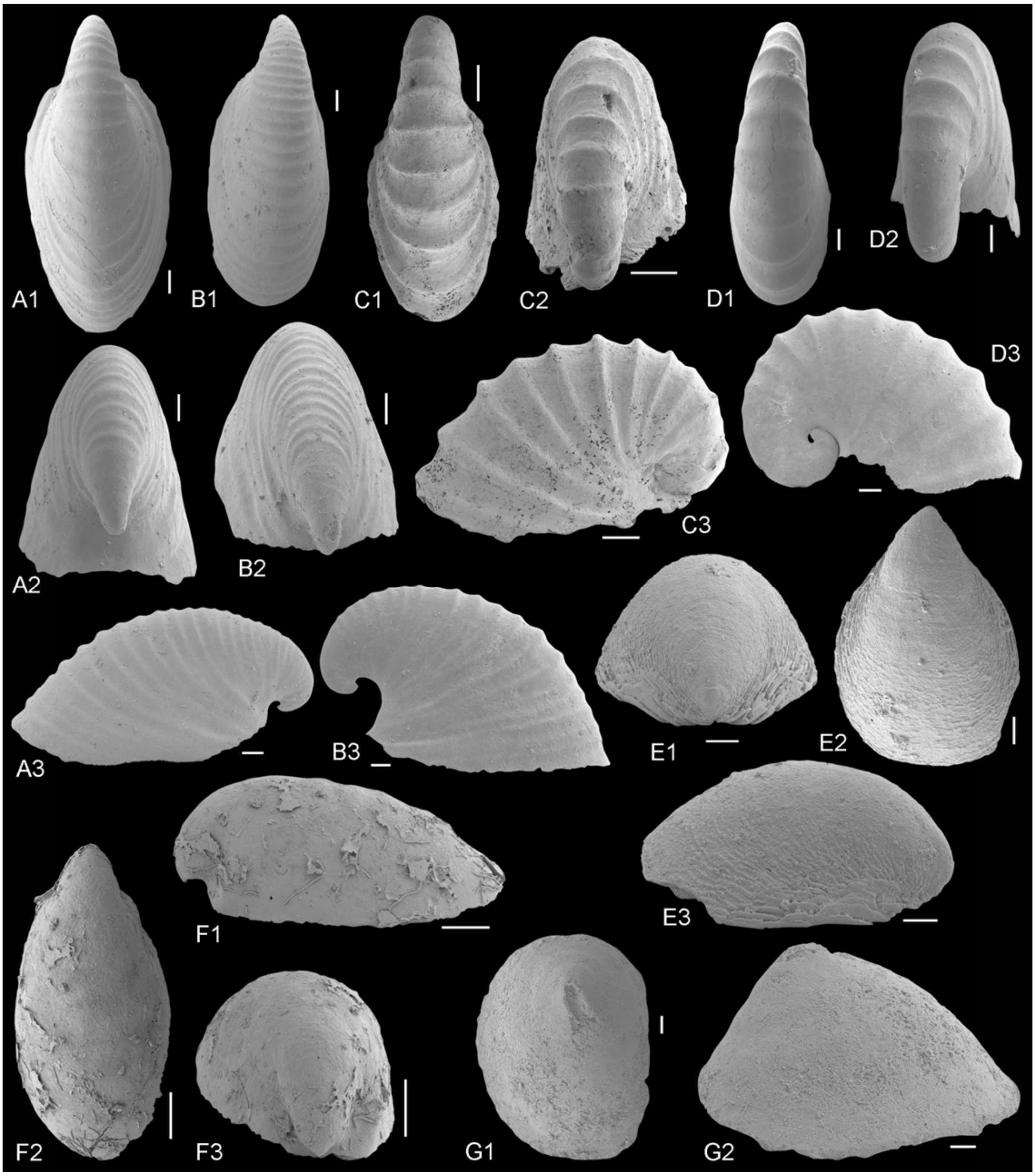

Fig. 18 SEM micrographs of SSFs of Zone II from East Yunnan. A. *Igorella emeiensis* (Yu, 1987), No. xif1-19-022. A1. Distal view. A2. Proximal view. A3. Lateral view. B. *Igorella maidipingensis* (Yu, 1974), No. Xif1-19-015. B1. Distal view. B2. Proximal view. B3. Lateral view. C, D. *Oelandiella korobkovi* Vostokova, 1962. C. No. Xif1-11-012. C1. Distal view. C2. Proximal view. C3. Lateral view. D. No. Xif1-19-020. D1. Distal view. D2. Proximal view. D3. Lateral view. E. *Yunnanopleura biformis* Yu, 1987, No. Xif1-15-009. E1. Proximal view. E2. Distal view. E3. Lateral view. F. *Securiconus simus* Jiang, 1980, No. xif1-12-010. F1. Lateral view. F2. Distal view. F3. Proximal view. G. *Aegitellus emeishanensis* He in Yin et al, 1980, Steinkern, No. Xif1-19-009. G1. Distal view. G2. Lateral view. Scale bars equal 200 μm.

Genus *Phrygula* gen. nov.

Helcionella Grabau et Shimer; Chen and Zhang, 1980, p. 26

Emarginoconus Yu; Parkhaev and Demidenko, 2010, p.1019

Etymology: The name was derived from the Latin words '*phrx*', '*-ygis*', meaning the inhabitants of the country of Phrygia. The fossil looks like the Phrygian cap, a conical cap with the top pulled forward.

Type species: *Phrygula nana* (Chen & Zhang, 1980)

Diagnosis: A low, small cap with a round, pointed apex. The apex curved forward and displaced the aperture margin. The aperture is nearly round and dented below the apex. The dorsal side is smooth and slightly curved. The external surface is ornamented with fine comarginal growth lines.

Composition: Type species only.

Phrygula nana (Chen & Zhang, 1980)

Fig. 20A, B, G

Helcionella nana Chen & Zhang: Chen & Zhang, 1980, p. 26, pl. 2, fig. 27.

Emarginoconus cf. *mirus* Qian & Bengtson, 1989, p. 121, text-fig. 80 (cf. *mirus)*;

Parkhaev, 2005, pl. 1, fig. 1; 2006, text-figs. 3n, 3o; 2008, text-figs. 3.11K, 3.11L;

Demidenko and Parkhaev, 2006, text-figs. 4o, 4p; Parkhaev and Demidenko, 2010, p.1019, plate 56, figs. 1-6, plate 57, figs. 1-6.

Description (Emended from Qian and Bengtson, 1989 on 'Emarginoconus cf. mirus', p. 121) : The fossil is ca. 1 mm wide and ca. 0.4 mm high. The apex is close to the proximal margin; in the sagittal plane the distal profile is convex (Fig. 20B3) and the proximal one concave (Fig. 20A3), so that there may be a slight apical overhang. The surface is decorated with growth lines (Fig. 20B1). The aperture is simply concave and filled with detritus (Fig. 20G1).

Remarks: Compared with *Aegitellus emeishanensis* which is high-coned and has a straight apex, round or oval margin, *Phrygula nana* is usually low cap-like with a forward-curved apex.

Occurrence: Zone II and mostly in the Lower Subzone, Zhujiaqing Formation, Xianfeng, Laolin, and Lishuping sections, Yunnan Province, China.

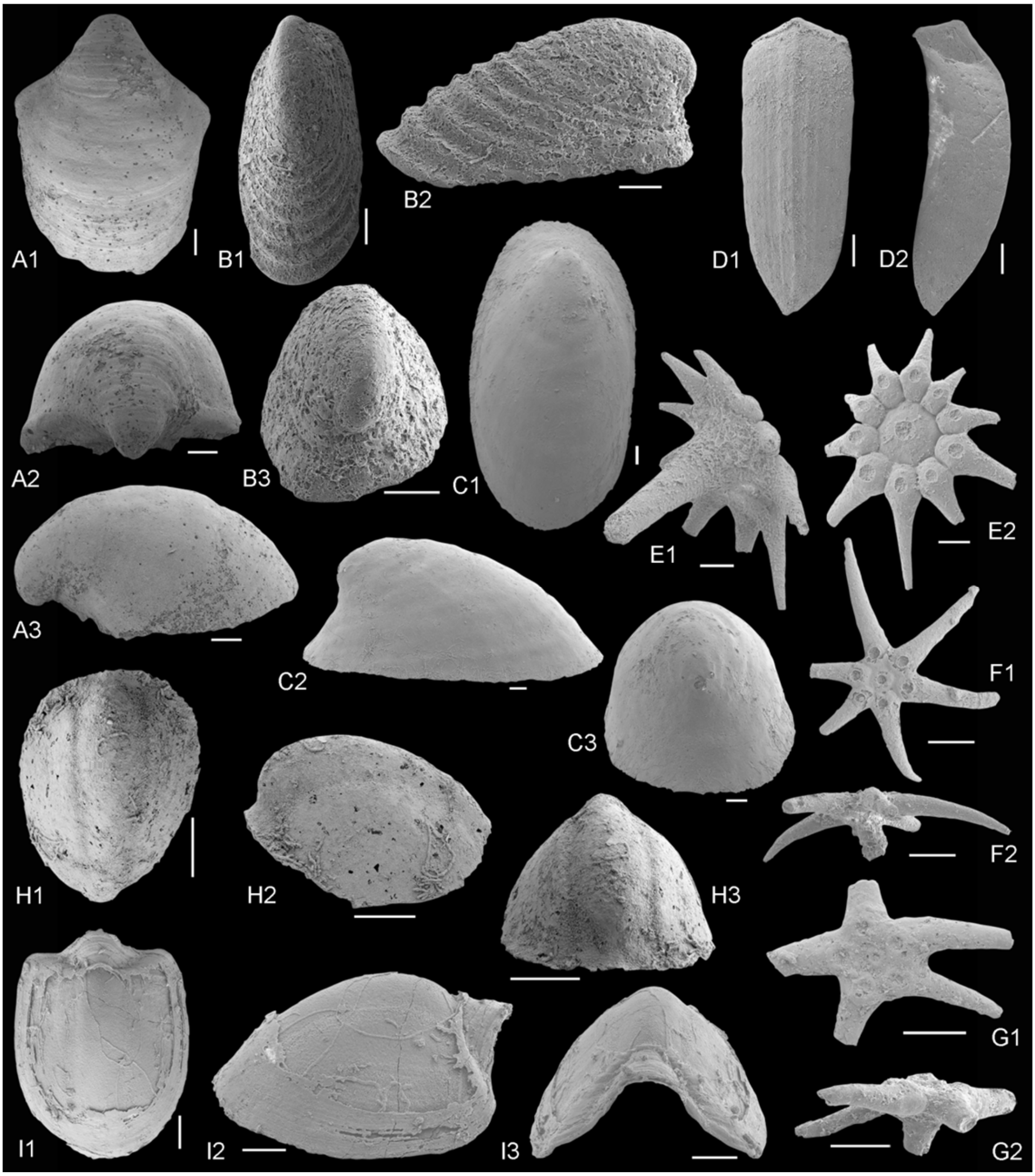

Fig. 19 SEM micrographs of SSFs of Zone II from East Yunnan. A. *Xianfengella prima* He & Yang, 1982, No. Xif1-11-015. A1. Distal view. A2. Proximal view. A3. Lateral view. B, C. *Bemella simplex* Yu, 1979. B. No. Xif1-19-028. B1. Distal view. B2. Lateral view. C3. Proximal view. C. No. Xif1-19-005. C1. Distal view. C2. Lateral view. C3. Proximal view. D. *Halkieria sthenobasis* Jiang in Luo et al, 1982, No. Xif1-22-027. D1. Distal view. D2. Lateral view. E. *Chancelloria symmetrica* Vassiljeva, 1985, No. Xif1-19-017. E1. Distal view. E2. Lateral view. F, G. *Chancelloria eros* Walcott, 1920. F. No.Xif1-19-006. F1. Distal view. F2. Lateral view. G. No. Xif1-19-004. G1. Distal view. G2. Lateral view. H, I. *Protoconus crestatus* Yu, 1979. H. No.Xif1-05-029. H1. Distal view. H2. Lateral view. H3. Proximal view. I. No. Lal23-005. 9a. Distal view. I2. Lateral view. I3. Proximal view. Scale bars equal 200 μm.

Genus *Protoconus* Yu, 1979

Protoconus crestatus Yu, 1979

Fig. 19H, I

Description: Low long oval semiellipsoid shell with prominent ridge on the back. It is ca. 0.5-0.8 mm high, 0.6-1 mm wide and 0.8-1.3 mm in length. The front part is curved up (Fig. 19H2, I2, I3). The proximal region protrudes forward with a dent between this and the central ridge (Fig. 19H2, I2). The shell is decorated with fine growth lines.

Remarks: Fig. 19I shows the shell of this species with clear fine growth lines. Most specimens of this species are steinkerns and the genus is also possibly erected on the base of steinkern specimens. Here the specimen (Fig. 19I) with shell preserved shows the growth lines distinguishing the genus from *Purella*.

Genus *Purella* Missarzhevsky,1974

Purella squamulosa Qian & Bengtson, 1989

Fig. 17A, B, C, E

Purella squamulosa Qian & Bengtson; Qian and Bengtson, 1989, p. 97, text-fig. 61; Yu, 2001, text-figs. 10E-10H; Feng et al., 2001, pl. 3, figs. 8, 9.

Purella cf. *squamulosa* Qian & Bengtson; Steiner et al., 2004, text-figs. 6.3, 6.4.

Description: See description by Qian & Bengtson (1989, p. 97).

Remarks: Fig. 17A4 shows the detail of the ornaments in the front part of the specimen. It indicates a certain similarity between these ornaments and *Lopochites latazonalis* (Fig. 13M1, M2). Their coexistence in several layers could also add weight to a very preliminary conjecture of potential synonymy.

Occurrence: Zone II, Zhongyicun Member, Zhujiaqing Formation, Xianfeng section, Yunnan Province, China.

Purella elegans Yu, 1979

Fig. 17D

Purella elegans Yu; Yu, 1979, p. 253, pl. 2, figs. 13, 14; Zhao et al., 1980, p. 50; Qian, 1983a, p. 6; Yu, 1987b, p. 188, text-fig. 55, pl. 37, figs. 1-5.

Igarkiella elegans (Yu); Parkhaev, 2005, pl. 3, fig. 2.

Protoconus elegans (Yu); Demidenko and Parkhaev, 2006, text-figs. 4sh, 4sch; Parkhaev, 2008, text-figs. 3.13F-3.13H; Parkhaev, 2010, p.1049, pl. 71, figs. 1-4

Material: Three specimens from Dahai Member, Laolin section.

Description: The small low cap-like fossil is ca. 1.75 mm long, 1.32 mm wide and 0.95 mm high. It has an oval aperture and a short apex curved slightly downward. The surface is decorated with wavy striates and seems to be interrupted by the central ridge on the back. The ridge broadens from the apex to the margin.

Remarks: The type specimen described by Yu (1979) is a steinkern. The outer morphology of the type specimen is closer to *Purella* than *Protoconus*, with its high, pointed (Fig. 17B2, C2, D2, E2) and forward-curved apex and the oval aperture. By contrast, the aperture of *Protoconus* is elongate-oval (Fig. 19I1) or subelliptical. The subapical margin of *Protoconus* slightly curves upwards and the surface of *Protoconus crestatus* is decorated with the traces of comarginal growth lines. The *P. elegans* presented here (Fig.17D) shows a undulated surface sculpture that is typical for the Maikhanellidae (Bengtson, 1992).

Occurrence: Zone II, Dahai Member, Zhujiaqing Formation, Laolin section, Yunnan Province.

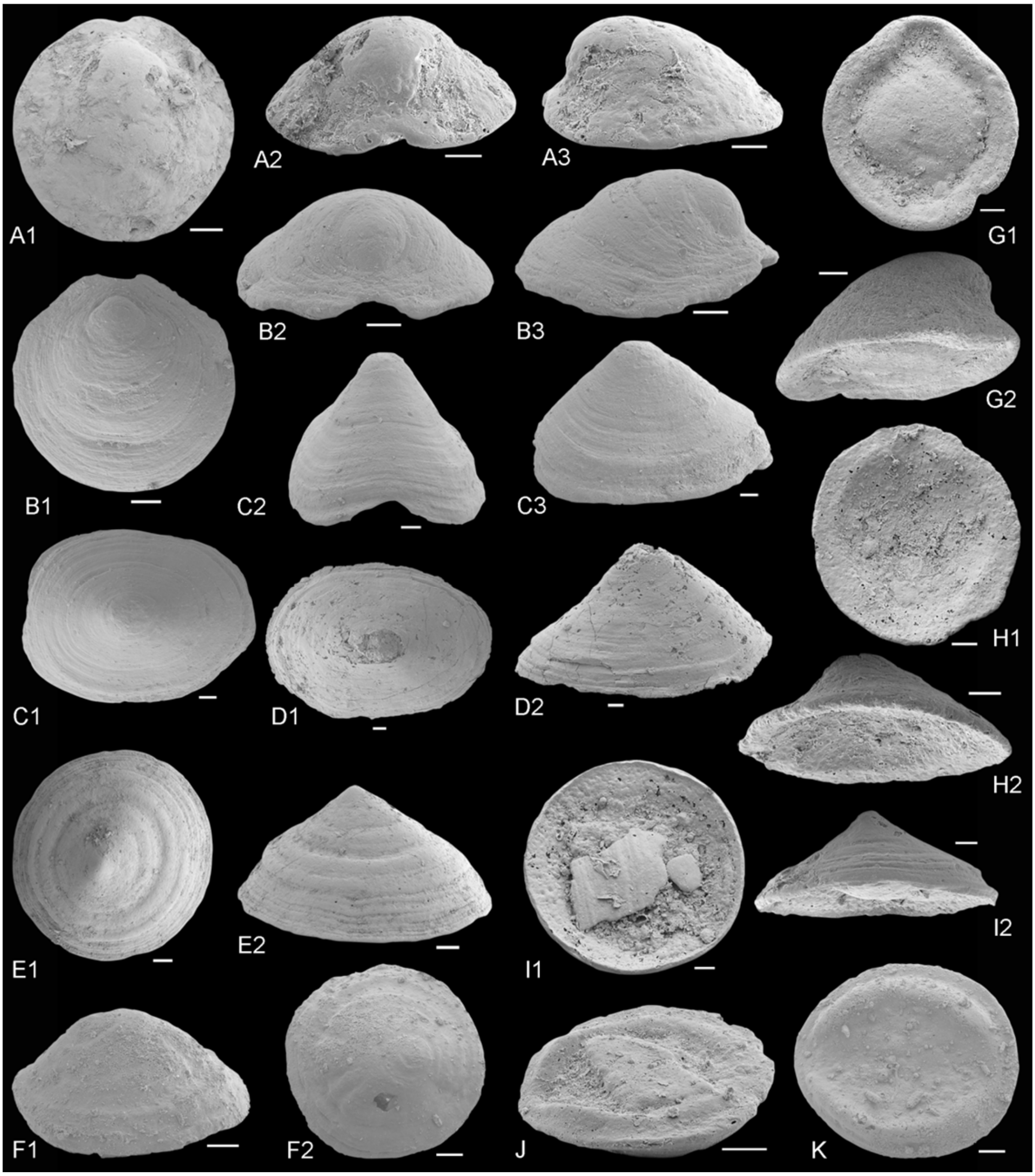

Fig. 20 Cap-like fossils of zones II & III from East Yunnan. A, B, G. *Phrygula nana* (Chen & Zhang, 1980). A. No. Xif1-11-009. A1. Distal view. A2. Proximal view. A3. Lateral view. B. No. Xif1-15-005. B1. Distal view. B2. Proximal view. B3. Lateral view. G. No. Xif1-12-030. G1. Bottom view. G2. Lateral view of the bottom. C-E, H, I. *Aegitellus emeishanensis* (He in Yin et al 1980). C. No. Xif1-15-013. C1. Distal view. C2. Proximal view. C3. Lateral view. D. No. Lsp115. D1. Distal view. D2. Lateral view. E. No. Xif1-12-012. E1. Distal view. E2. Lateral view. H. No. Xif1-12-024. H1. Bottom view. H2. Lateral view of the bottom. I. No. Xif1-12-029. I1. Bottom view. I2. Lateral view of the bottom. F, J, K. *Emarginoconus mirus* Yu, 1979. F. No. Lsp108a-002. F1. Lateral view. F2. Distal view. J. No. Xif1-22-040, Lateral view of the bottom. K. No. Lsp108a-003, bottom view. Scale bars equal 100 μm.

Genus *Watsonella* Grabau, 1900

Watsonella crosbyi Grabau, 1900

See synonym list by Li et al. (2011, p.311).

Material: Hundreds of specimens from the Dahai Member of Laolin section, tens of specimens from Xianfeng, and Lishuping sections.

Description: See Li et al.(2011, p. 314).

Remarks: Although *Herautipegma varensalensis* has been synoymized (P.Yu. Parkhaev, 2001; Li et al., 2011) with *Watsonella crosbyi*, there exist two different morphotypes of the species. Many of the specimens from Montagne Noire of France (Cobbold, 1935; Kerber, 1988) and some from Xiaotan of Yunnan Province, China (Li et al., 2011) have straight dorsal margins (Cobbold, 1935, pl. II, fig3; Kerber, 1988, pl. 4(1a, 2a, 4a, 5a, 7a, 9, 10, 11a); Li et al., 2011, Fig. 1(l, o)), whereas the other morphotype is round, i.e. it has a more or less convex dorsal margin (Fig. 22A-C). The two morphotypes of *W. crosbyi* probably represent end-members of a variation series of the same species. Until now, specimens with straight dorsal margins have only been in the Yongshan Region (Xiaotan section) of Northeast Yunnan in China, the Montagne Noire Region in France and possibly in southeastern Newfoundland (Landing et al., 1989, Fig. 8-8), though *Watsonella* has been widely recovered from South China, Mongolia, France, South Australia, Siberia and North America.

Occurrence: Zone III, Dahai Member, Zhujiaqing Formation, Xianfeng, Lishuping, and Laolin, Yunnan Province, China.

PARACARINACHITIDS

Genus Paracarinachites Qian and Jiang in Luo et al., 1982

Paracarinachites parabolicus Qian & Bengtson, 1989

Fig. 13C, D

Material: Tens of specimens from the Zhongyicun Member of Xianfeng, Laolin, Lishuping sections.

Description: See Qian & Bengtson(1989, p. 54).

Remarks: Some forms show a transitional morphology between *Paracarinachites sinensis and Paracarinachites parabolicus* (Fig. 13D, compared with Fig. 13A-C). Fig. 13D2 shows the feature of *Paracarinachites sinensis* with one row spines at the slender end and two alternating rows of spines toward the broader end. The figured species by Qian & Bengtson (1989, Fig. 30 B) possibly also show this similar character. It could be possible that *P. sinensis* and *P. parabolicus* are sclerites only representing slightly differing form-taxa of the same bio-species.

Occurrence: Zone II, Zhongyicun Member, Zhujiaqing Formation, Xianfeng, Laolin, and Lishuping sections, Yunnan Province, China.

Paracarinachites sp.

Fig. 13E

Zhijinites longistriatus Qian; Parkhaev and Demidenko, 2010, pl. 20, figs. 1-8, pl. 21, figs. 1-9, pl. 22, figs. 1-11

Material: Tens of specimens from Zhongyicun Member of Meishucun, Xianfeng, Laolin, and Lishuping sections.

Remarks: These fragmental fossils could be misidentified as *Zhijinites*. The

Paracarinachites spine has no ornamentation on the surface, and its base is irregularly broken and curved (Fig. 13E). Whereas *Zhijinites longistriatus* is decorated with longitudinal lines and obscure transverse annuli, its uncurved basal disk is ornamented with radial lines and annular striae (Fig. 21F).

Occurrence: Zone II, Zhongyicun Member, Zhujiaqing Formation, Meishucun, Xianfeng, Laolin, and Lishuping sections, Yunnan Province, China.

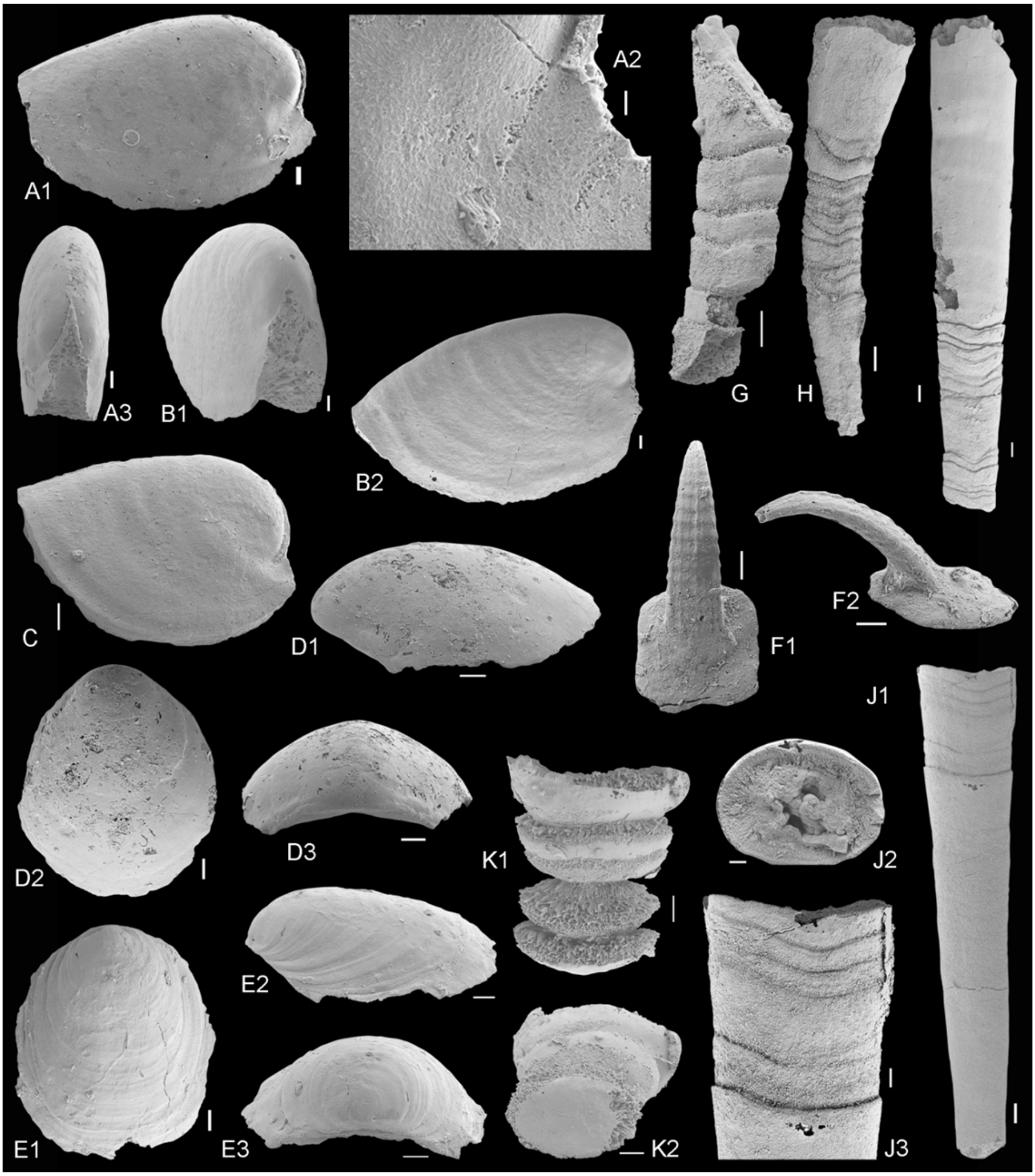

Fig. 21 SEM micrographs of SSFs of Zone III from East Yunnan. A-C. *Watsonella crosbyi* Grabau, 1900. A. No. Lal116a-002. A1. Lateral view. A2. Detail of polygonal imprints. A3. Anterior view. B. No. Lal116a-003. B1. Anterior view. B2. Lateral view. C. No. Xif1-22-030. D, E. *Papilloconus* cf. *explanatus* (Feng et al, 2000) . D. No. Lsples1-002. D1. Lateral view. D2. Distal view. D3. Proximal view. E. No. Lal23-007. E1. Distal view. E222. Lateral view. E3. Proximal view. F. *Zhijinites longistriatus* Qian, 1978, No. xif1-22-017. F1. Distal view. F2.

Lateral view. G-K. Unknown tube with chambers. G. No. Lal116a-012, lateral view. H. No. Lal116a-009, lateral view. I. No. Lal121-010, lateral view. J. No. Lal121-008. J1. Lateral view. J2. Detail of the cross-section. K. No. Lal116. K1. Lateral view of the chambers. K2. Detail of the chamber bottom. Scale bars: A2, 20 μm; G-J, 200 μm; others, 100 μm.

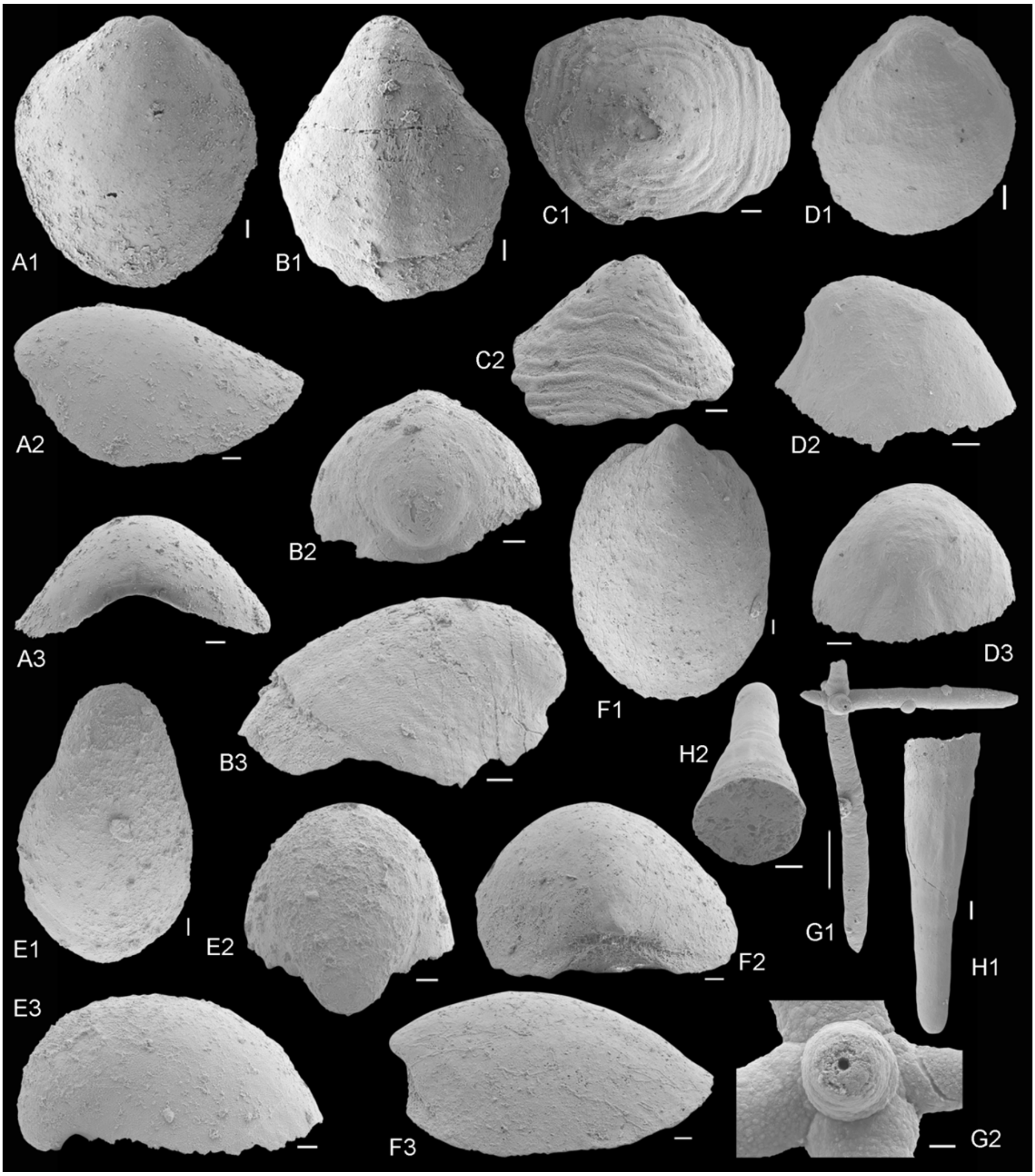

Fig. 22 SEM micrographs of SSFs of Zone II & III from East Yunnan. A. *Lathamella caeca* Liu, 1979, No. Lal27-001. A1. Distal view. A2. Lateral view. A3. Proximal view. B. *Igarkiella levis* Vassiljeva, 1998, No. Lal23-004. B1. Distal view. B2. Proximal view. B3. Lateral view. C. *Asiapatella sinuata* Parkhaev, 2010, No. Xif1-22-014. C1. Distal view. C2. Lateral view. D. *Ilsanella atdabanica* (Missarzhevsky in Rozanov & Missarzhevsky, 1966), No. Lal01-009. D1. Distal view. D2. Lateral view. D3. Proximal view. E. *Absidaticonus triangulatus* Yue in Xing et al, 1984, No. lal03-001. E1. Distal view. E2. Proximal view. E3. Lateral view. F.

Papilloconus? cf. *explanatus* (Feng et al, 2000), No. xif1-22-020. F1. Distal view. F2. Proximal view. F3. Lateral view. G. Hexactinellid spicule, No. Lal01-004. G1. Distal view. G2. Detail of the ray apex. H. Unknown tube, No. Lal116b-002. H1. Distal view. H2. Detail of the cross-section. Scale bars: G2, 10 μm; others, 100 μm.

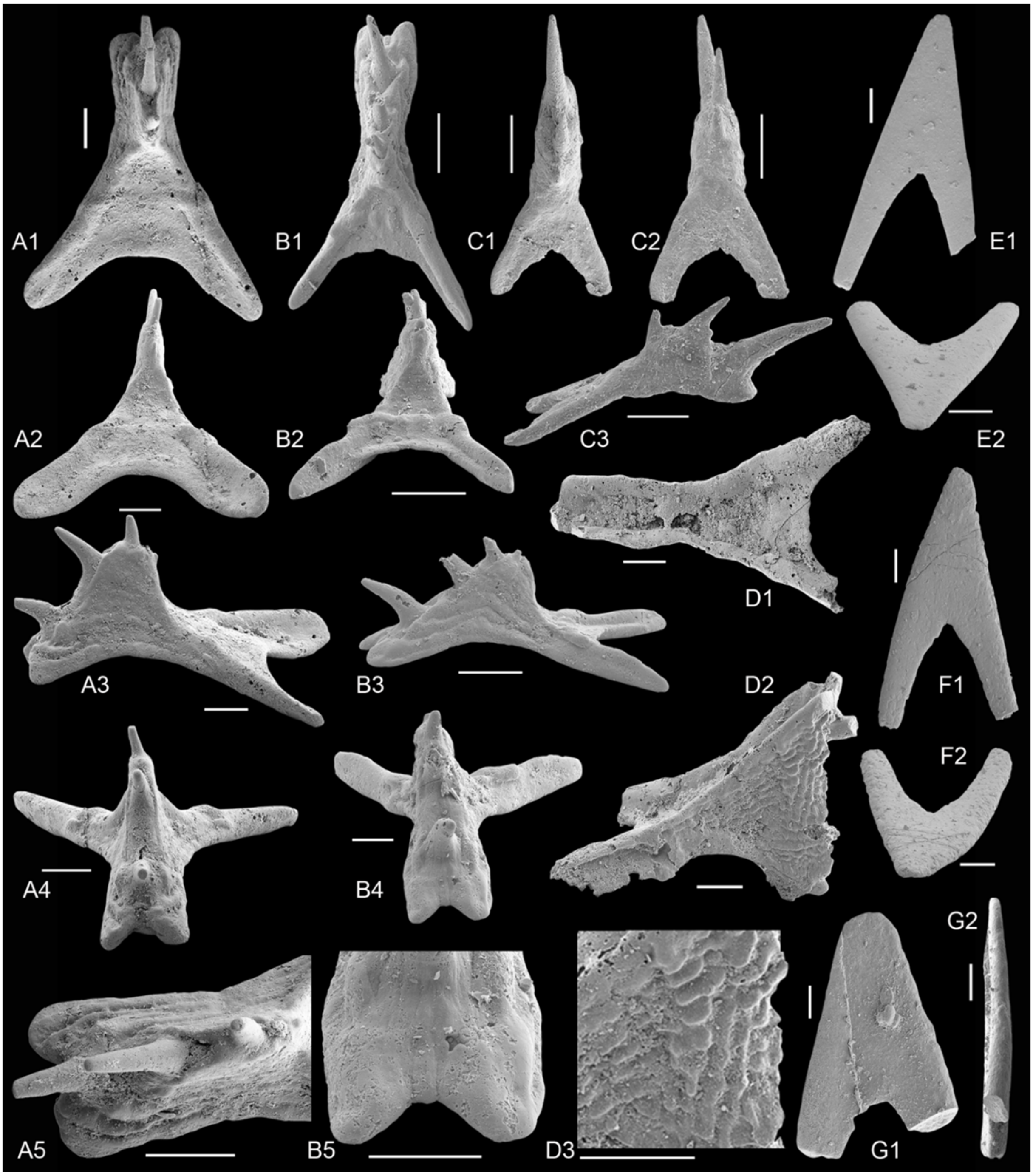

Fig. 23 SEM micrographs of SSFs of Zone II & III from East Yunnan. A-D. *Claviconchella qianyii* gen. et sp. nov. A. No. Lsples2-014. A1. Distal view. A2. Lateral view. A3. Lateral view. A4. Proximal view. A5. Detail of the spines. B. No. Lsples2-013. B1. Distal view. B2. Lateral view. B3. Lateral view. B4. Proximal view. B5. Detail of B4. C. No. Lal127-07. C1. Distal view. C2. Lateral view. C3. Lateral view. D. No. Lsples2-005. D1. Bottom view. D2. Lateral view of the bottom. D3. Detail of the ornament on the lateral surface. E-G. *Bubiites simplex* gen. et sp. nov. E. No. Lsp115-003. E1. Distal view. E2. Proximal view. F. No. Lsples1-006. F1. Distal view. F2. Proximal view. G. No. Xif1-15-021. G1. Distal view. G2. Lateral view. Scale bars: B5, C1-3, 100 μm; others, 200 μm.

PROBLEMATIC SCLERITES

Genus *Bubiites* gen. nov.

Etymology: The name was derived from a kind of ancient Chinese coin called ‘Bubi’ (spade coin), as the fossil looks like the round foot spade coin.

Type species: *Bubiites simplex* gen. et sp. nov.

Composition: The type species only.

Diagnosis: Flat bifurcate simple fossil without any decoration on the surface.

Remarks: The bifurcated fossil figured by Xing et al. (1984, pl.28, fig. 8) may be similar to *Bubiites simplex*, but this is difficult to confirm as only one view is presented.

Occurrence: Zone II, Zhujiaqing Formation, Zhongyicun Member, Xianfeng, and Lishuping sections, Yunnan Province, China.

Bubiites simplex gen. et sp. nov.

Fig. 23E-G

Etymology: The species name refers to the simplicity of the sclerite's morphology.

Holotype: Lsp115-003, Fig. 23E, Zhongyicun Member of Lishuping section in Dahai Town of Huize County, Yunnan Province, China; reposited at the Department of Earth Sciences, Freie Universität Berlin.

Material: 2 specimens from Xianfeng section, and about 10 specimens from Lishuping section.

Description: Flat bifurcate fossils with no decoration on the surface. The outer divergence angle (Outer Div.) is about 30°and the inner divergence angle (Inner Div.) is ca. 35°. The thickness is about 90 µm, while the species is 1500 µm long on average and 800µm wide. The ends of the two branches are usually broken, and the top of the join part is smooth.

Measurement:

Table 1 Measurements of *Bubiites simplex* gen. et sp. nov. specimens.

Sample	length (µm)	width (µm)	Outer Div. (°)	Inner Div. (°)
lsp115-003	1636.1	842.6	30.3	39.2
lsples1-006	1570	840	32.5	37.2
xif1-15-021	1470.3	966.7	32.5	50

Occurrence: Zone II, Zhujiaqing Formation, Zhongyicun Member, sample Lsp115, Lishuping section, Dahai Town, Huize County, Yunnan Province, China.

Genus *Claviconchella* gen. nov.

Etymology: The name is derived from the Latin words ‘clavi’(key) and ‘conchella’(small shell). It indicates that the fossil looks like a key.

Type species: *Claviconchella qianyii* gen. et sp. nov.

Composition: The type species only.

Diagnosis: Sclerites with a basement and three or four upward-projecting spines. The basement bifurcates with an acute angle. It is decorated with longitudinal grooves on the surface.

Claviconchella qianyii gen. et sp. nov.

Fig. 23A-D

Etymology: The species name is in honor of Professor Yi Qian, Nanjing.

Material: One complete specimen from the Zhongyicun Member of Laolin section; three complete specimens from the Zhongyicun Member of Lishuping section.

Holotype: LspLes2-014 (Fig. 23A), Zhongyicun Member of Lishuping section in Dahai Town of Huize County, Yunnan Province, China; reposited at the Department of Earth Sciences, Freie Universität Berlin.

Description: The fossil has a unique three-dimensional outline. It is composed of two parts, the basis and projecting spines. The basis is triangular as a whole and concave downward, being further divided into one joint part and two branches. The two branches are connected with a plane in between (Fig. 23A2, C2). The basis is thickened upwards with grooves on the surface (Fig. 23A3, B3, D2, D3). The grooves also show some similarity with that of *Scoponodus renustus* (Fig. 23D3, Fig. 13F1). Three or four straight-slightly bent spines are on the top of the basis.

Measurement:

Table 2 Measurements of Claviconchella qianyii gen. et sp. nov. specimens.

Sample	lengths (μm)	width (μm)	height (μm)
lsples2-014	1527.8	1202.8	789.6
lsples2-013	1071.7	624.5	408.7
lal127-07	485.6	211.5	175.2

Occurrence: Zone II, Zhujiaqing Formation, Zhongyicun Member: sample lsples2 and lal127, Lishuping section and Laolin sections, Dahai Town, Huize County, Yunnan Province, China.

PROBLEMATIC TUBES

Unknown tube

Fig. 21G-K

Material: Tens of specimens from the Dahai Member of Laolin section.

Description: Some problematic tubes (Fig. 21G-K) with bowl-like septa were found together with the FAD of *Watsonella crosbyi* in the Dahai Member of Laolin section. The tube is oblong (Fig. 21G, J2), straight (Fig. 21I, J1) or slightly curved (Fig. 21H), having an oval aperture (Fig. 21G, J2, K2). The septa are concave toward the aperture (Fig. 21G-I, J3) and exposed near the apex region or near the aperture (Fig. 21H, I, J1). The inner side of the tube is thus considered to have been fully equipped with septa. The septa can be independently preserved as steinkerns (Fig. 21K).

Remarks: The affinity of this septate tube is uncertain. It could be related to some allathecid such as *Tchuranitheca* sp. (A. V. Kouchinsky, 2000, Fig. 6C) that has a similar septa structure but a round aperture and a different shell structure from the former one. The shell structure with radial phosphatic rods (Fig. 21J2, K1) shows its similarity to that of an orthothecid (A. V. Kouchinsky, 2000, Fig. 7K) As *Cupittheca* might be septate due to its special apex shape, it could be related to the herein discussed tube too. It is considered that certain hyolithids and problematic tubes of the early Cambrian are septate but are likely of polyphylogenetic origin.

Description: Zone III, Dahai Member, Zhujiaqing Formation, Laolin, Lishuping, Laolin, Yunnan Province, China.

Unknown tube

Fig. 22H

Material: Tens of specimens from Dahai Member of Laolin section.

Description: Steinkerns of unknown tubes with longitudinal thin ridges and faint transversal annulation on the surface. The apex shows a similar protococh (but less bulbous) to that of *Paragloborilus subglobosus*.

Occurrence: Zone III, Dahai Member, Zhujiaqing Formation, Laolin, Lishuping, Laolin, Yunnan Province, China.

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Chert-hosted small shelly fossils: expanded tool of biostratigraphy in the Early Cambrian

Abstract

SSFs are widely utilized for Cambrian biostratigraphy of shallo-water carbonates. The apparent linkage of SSFs to carbonate facies reflects an observational bias. Our study on the deeper siliceous facies of the Yangtze Craton in Zhejiang and Hunan provinces (China) reveals that SSFs also can be extracted from cherts. For this purpose a quick-etching method with weak hydrofluoric acid is applied. SSFs extracted from cherts are comparable with those from carbonates. EDS analyses indicate a primary composition of SSFs of organic carbon and apatite. HF-processing can provide valuable biostratigraphic data of SSFs that are complementary to standard methods.

Keywords: Small shelly fossils, chert, deeper shelf, Cambrian, Yangtze Platform, China

1. Introduction

Small shelly fossils (SSFs), which are usually extracted with weak organic acids (mainly acetic or formic acid), are widely found in early Cambrian carbonate sequences and are broadly utilized for biostratigraphic correlation within and between carbonate platform sequences. A SSF-based biozonation of Cambrian shallo-water carbonate platforms has been in use for decades (e. g. Rozanov and Missarzhevsky, 1966; Missarzhevsky, 1974; Missarzhevsky and Mambetov, 1981; Luo et al., 1982; Qian and Bengtson, 1989; Bengtson et al., 1990; Steiner et al., 2007; Yang et al., 2014b). Many species were thought to be restricted to these shallo-water carbonate facies, limiting the applicability of SSFs for a chronostratigraphic subdivision of Cambrian strata (Lindsay et al., 1996a). However, data from Avalonia indicate that SSFs are also present in largely siliciclastic shelf-ramp deposits (Landing, 1989; Landing et al., 1989). These studies based the biostratigraphic record of SSFs on crack-out specimens from a mudstone-dominated facies, complemented with specimens yielded from acid etching. The application of crack-out samples in biostratigraphy, however, may also include stronger statistical sample-size effects than etch-out samples, where fossils are extracted from the whole rock volume. This needs to be taken into account in biostratigraphic studies interpreting distribution patterns of SSF assemblages by semiquantitative or quantitative approaches. Previous investigations of the distribution of SSFs on the Yangtze Platform also indicated that SSFs are equally found in deeper depositional settings (Qian and Yin, 1984; Steiner et al., 2003; 2007). However, the SSFs there were only extracted from thin carbonate interbeds or nodules. Thin-section investigations of early Cambrian cherts from Tarim revealed the presence of the SSF *Kaiyangites* in a deeper facies rich in cherts (Xiao et al., 2004).

The present study highlights the notion that the alleged connection of SSFs to carbonate facies is biased by the method of investigation. Here we document SSFs recovered with hydrofluoric acid from cherts that occur in the deeper-water facies of the Yangtze Platform.

2. Method

For HF processing, cherts or siliceous samples (≥ 2.5kg weight) were crushed into pieces of 1-2 cm size and immersed in 2-5% HF solution at room temperature. Residues were sieved every 12 hours with a 54μm mesh and dried at 60℃. Every sample was processed for about 2 months. Fossils from the residue were picked under a binocular microscope. In addition to the HF acid etching, carbonate samples were processed with acetic acid. Carbonate nodules were immersed in buffered 10% acetic acid under a fume hood. The acid was exchanged every 3~5 days. The residue was sieved into the size-classes >2mm, >125μm, >63μm and dried at 60°C. Selected fossils were glued on stubs and coated with gold for SEM, while some fossils were used without coating for energy-dispersive X-ray spectroscopy (EDS). SEM and EDS analyses were carried out at China University of Geoscience in Wuhan, China, and Department of Earth Sciences, Freie Universität Berlin, Germany. Figured specimens are stored either in the Faculty of Earth Sciences of CUG or the Department of Earth Sciences, FU-Berlin.

Thin sections were studied under a polarizing microscope to locate SSFs; they were carbon coated afterwards for SEM observations. For EDS analyses thin sections were scanned uncoated.

3. Geological background

The two studied sections are situated in a deeper protected shelf basin of the Yangtze Platform (Steiner et al., 2001), in which sediments accumulated in a dysoxic to anoxic environment. Previous studies suggested hydrothermal exhalations in the early Cambrian of northwest Hunan (Li, 1997; Steiner et al., 2001).

The Xintangwu section (28°49.38′ N, 118°37.32′ E) is situated at the southeastern margin of the Yangtze Platform (Jiangshan City, Zhejiang Province, Fig. 1). There Cambrian strata consist of 25.5 m of the Hetang Formation (Fig. 1) overlying Neoproterozoic dolostones of the Dengying Formation. The lower part of the Hetang Formation is composed of a 0.5 m thick ‘chert unit’ and an overlying 4 m thick ‘stone coal unit’. The succeeding 11 m of the ‘black shale unit’ also contains a few large limestone nodules at the base. Black shale and chert samples were collected from the upper part of the black shale unit (Fig. 1).

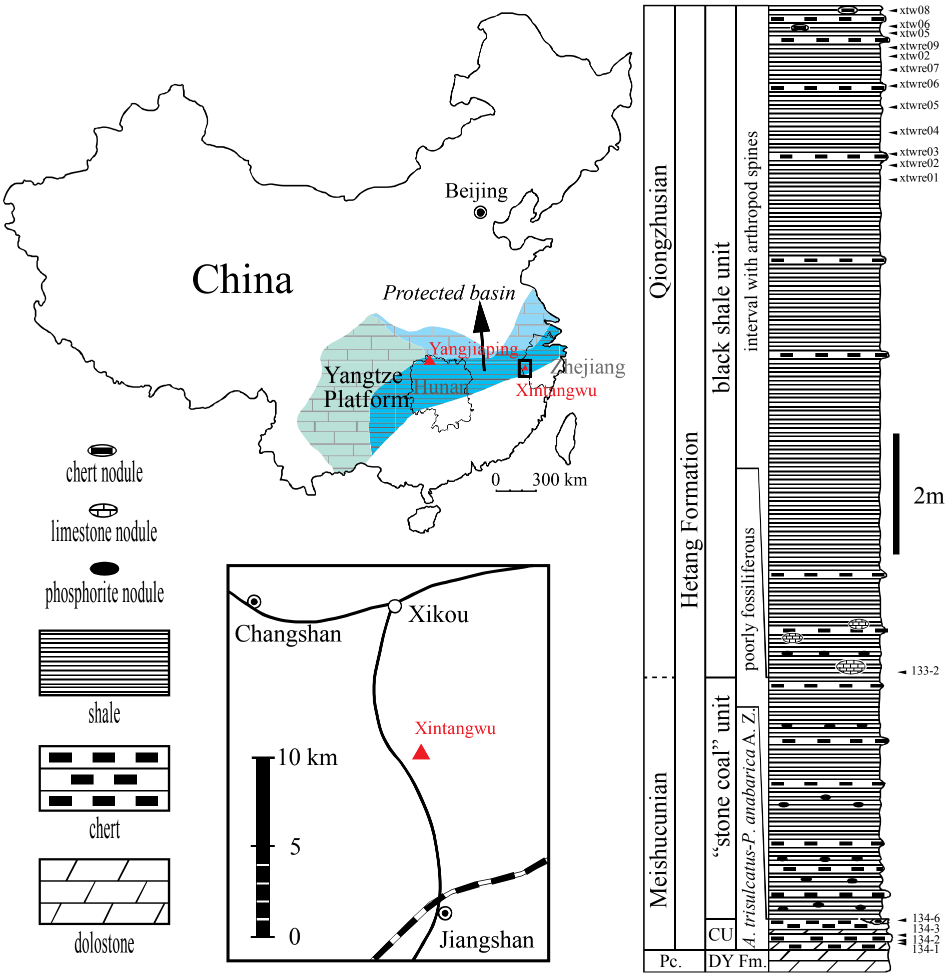

Fig. 1 Location of Xintangwu and Yangjiaping sections and stratigraphic column of Xintangwu section. The two sections belong to Zhejiang Province and Hunan Province respectively. They lie in the protected basin of Yangtze Platform. DY means Dengying; CU means chert unit; Pc., abbreviation of Precambrian; Fm., abbreviation of Formation; A. Z., abbreviation of Assemblage Zone.

The Yangjiaping section (29°58.758′ N, 110°43.383′ E) of northwestern Hunan Province is situated in the same facies belt as the Xintangwu section. The Niutitang Formation (lower part of the Cambrian) consists of dark cherts and black shales similar in composition and sequence to the Hetang Formation of Xintangwu. The chert unit and the stone coal unit of the Hetang Formation in Xingtanwu and the lower basal unit of the Niutitang Formation in Yangjiaping have been assigned to the *Protohertzina anabarica-Kaiyangites novilis* Assemblage Zone (Steiner et al., 2007).

4. Composition of small shelly fossils in siliceous rocks

In western Zhejiang, SSFs were described from the base of the Hetang Formation (Zhao and Yue, 1987; Yue and He, 1989; He and Yu, 1992; Steiner et al., 2003). SSFs reported before were recovered mostly from the phosphatic carbonate nodules that are present in the chert unit or the base of the black shale unit.

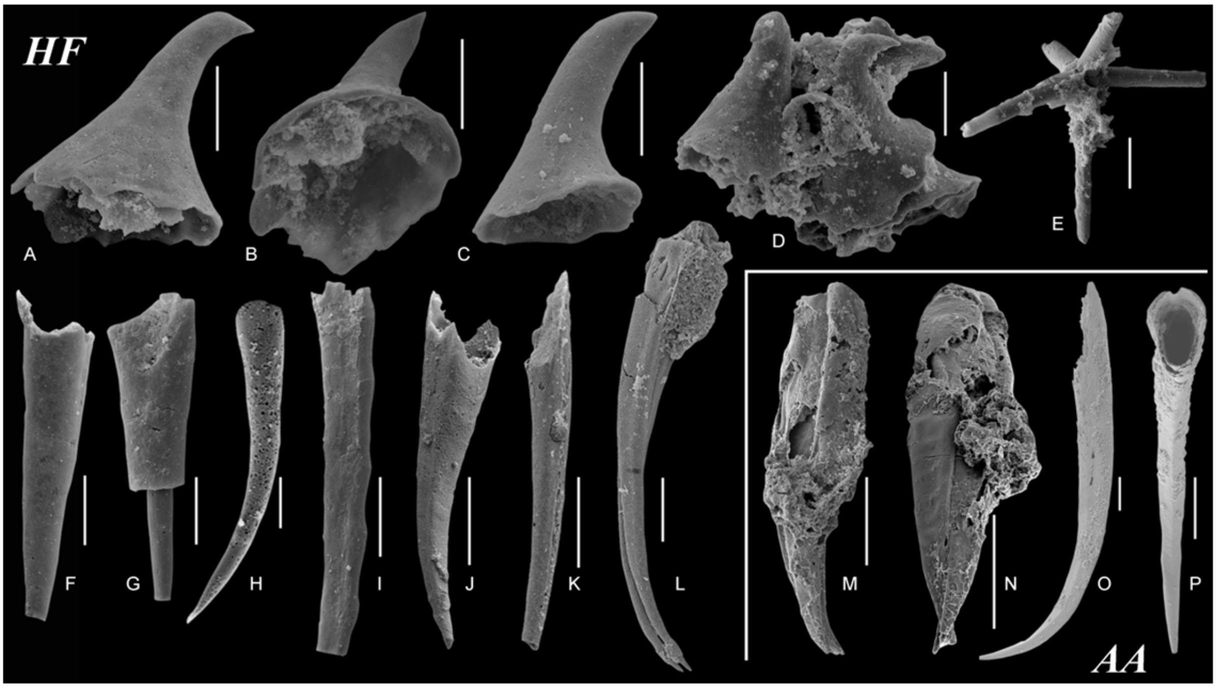

Fig. 2 SEM micrographs of SSFs from Xintangwu and Yangjiaping. A-N. SSFs from the Qiongzhusian interval with *Kijacus*-type arthropod spines in Xintwangwu. A-D. *Seletellus seletinicus*. A. Lateral view, No. xtwre06019. B. Apertural view of A. C. Lateral view, No. xtwre09008. D. Cluster of *Seletellus seletinicus*, No. xtwre06034. E. Hexactinellid sponge spicule, No. xtw05005. F, H. *Kijacus*-type arthropod spines, lateral views; F. No. xtwre05001; H. No. xtw02014. G. Trilobite spine, lateral view, No. xtwre2-01016. I. Problematic protoconodonts, lateral views; I. xtmet5011. J. *Amphigeisina* cf. *danica*, lateral view, No. xtw A1-5004. K, L. *Gapparodus* cf. *bisulcatus*; K. Lateral view, No. xtwre1-06020; L. Clusters, No. XTWre4-9028. M, N. Clusters of problematic protoconodonts recovered with acetic acid, lateral view, No. 133-2-14. O, P. *Protohertzina unguliformis* from the *Protohertzina anabarica-Kaiyangites novilis* Assemblage Zone, in the basal unit of Niutitang Formation at Yangjiaping with acetic acid, No. yap532002. O. Apertural view; P. Lateral view. *HF* marks SSFs recovered with hydrofluoric acid; *AA* marks SSFs recovered with acetic acid at the lower right corner delimited by the white line. Scale bars: A-G, 50 µm; H-J, 100 µm; K-P, 200 µm.

A more detailed biostratigraphy of the deeper shelf region of the Yangtze Craton was hitherto hindered by the very limited distribution of carbonate beds. Therefore, only a preliminary zonation was proposed (Steiner et al., 2007; Fig. 1), i.e. the *Protohertzina anabarica*-*Kaiyangites novilis* Assemblage Zone in the basal chert unit and the "interval with arthropod spines" at the base of the black shale unit (Steiner et al., 2003; Steiner et al., 2007). The black shale overlying the *P. anabarica*-*K. novilis* Assemblage Zone was assigned to the interval with *Jiangshanodus*-*Kijacus*-type arthropod spines (Steiner et al., 2003; Steiner et al., 2007). Records of arthropod spines and bradoriids (Yue and He, 1989; Steiner et al., 2003) indicate that this interval can be correlated with the *Parabadiella* Zone or *Wutingaspis*-*Eoredlichia* Zone (Steiner et al., 2007), or even slightly younger zones. Samples from this black shale unit were etched with diluted HF. More than ten tiny hook-like spines of *Seletellus seletinicus* Gridina, 1991 (Fig. 2A-C) were recovered, either disaggregated or within a cluster (Fig. 2D). Other common elements from the chert are sponge spicules (Fig. 2E), trilobite spines (Fig. 2G), *Jiangshanodus*-type and *Kijacus*-type arthropod spines (Fig. 2F-H), problematic protoconodonts (Fig. 2I, 3H), *Amphigeisina* cf. *danica* (Fig. 2J) and *Gapparodus* cf. *bisulcatus* (Fig. 2K, L). Some specimens of *Gapparodus* cf. *bisulcatus* occur in clusters (Fig. 2K, L). Clustered protoconodonts also were recovered from the carbonate samples by acetic acid digestion (Fig. 2M, N).

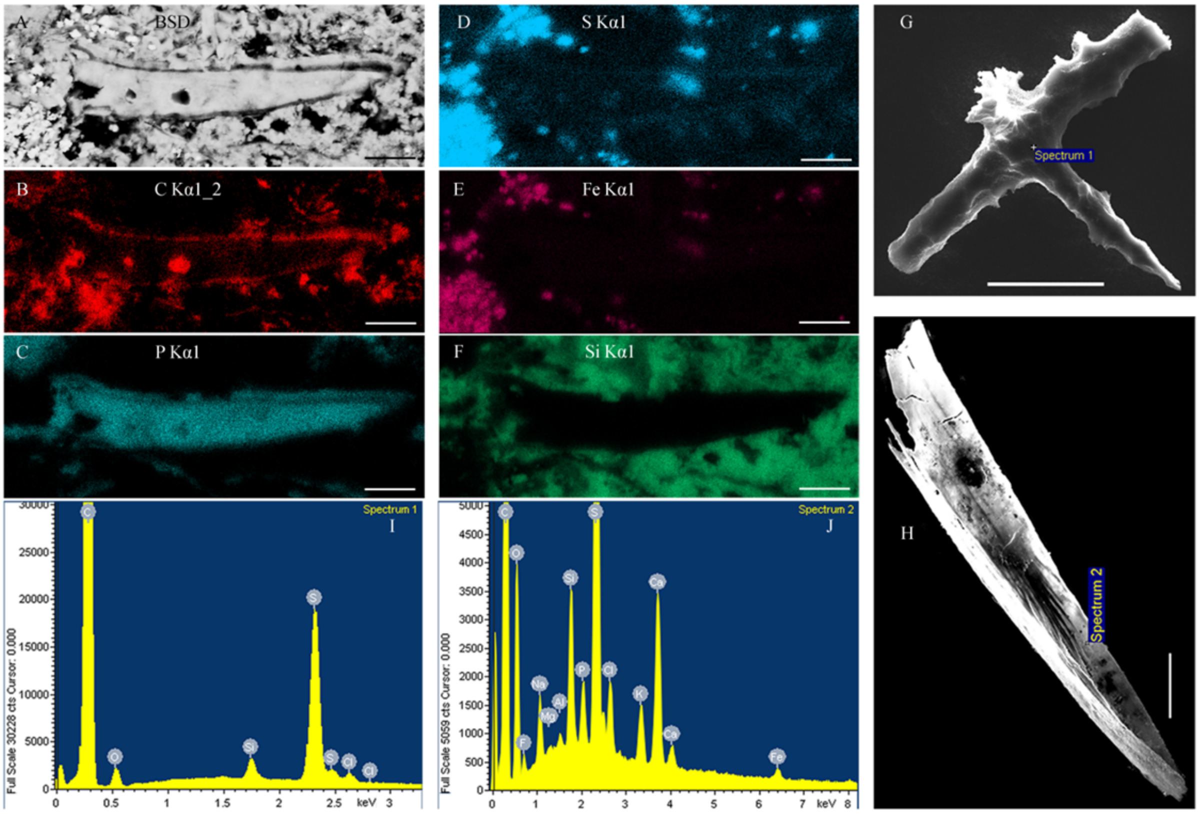

Fig. 3 SEM and EDS data of SSFs from the Qiongzhusian interval with *Kijacus*-type arthropod spines in Xintangwu. A. Electron backscatter diffraction (EBSD) image of chert thin section with problematic protoconodont spine, No. xtwre1-9-001. B-F. EDS elemental maps of A. B. Carbon Kα1_2 map. C. Phosphorus Kα1 map. D. Sulfur Kα1 map. E. Iron Kα1 map. F. Silicon Kα1 map. G. Hexactinellide sponge spicule recovered with HF, No. xtw1001. I. EDS point analysis of G. H. SEM picture of problematic protoconodont recovered with HF, No. xtw6002. J. EDS point analysis of H. Scale bars: A-F, 100 μm; G, H, 50 μm.

EDS results reveal that SSFs extracted with HF are mainly composed of carbon together with remarkably high amounts of sulfur (Fig. 3G-J; 4-5wt.%), accompanied by phosphorus and fluorine (Fig. 3J). It is interpreted that HF dissolved some of the phosphorite (occasionally replacing it with calcium fluoride) leaving only minor amounts of detectable phosphorus. Element mapping of untreated thin-sections show a more significant phosphorus signal in the fossils than in HF-etchings (Fig. 3A, C). The sulfur-rich carbonaceous matter replacing sponge spicules (Fig. 3G, I) is here interpreted as a product of low-temperature hydrothermal replacement. Similar replacements of sponge spicules by pyrobitumen have been reported earlier from northern Hunan (Steiner et al., 2001, Fig. 13). Problematic protoconodonts (Fig. 3A) display a composition of thin carbonaceous interlayers within phosphorite (Fig. 3B, C). The carbon of the thin layer is also associated with minor amounts of sulfur (Fig. 3D), which is in contrast to sulphidic phases, such as in pyrite, neither associated with an iron signal (Fig. 3E). The carbonaceous lamellae may represent remains of a primarily tanned organic skeletal element or later replacements by migrated bitumen. Carbon enrichments found on both, the inside phosphate infilling and the surrounding matrix (Fig. 3B) probably also represent infill of migrated bitumen.

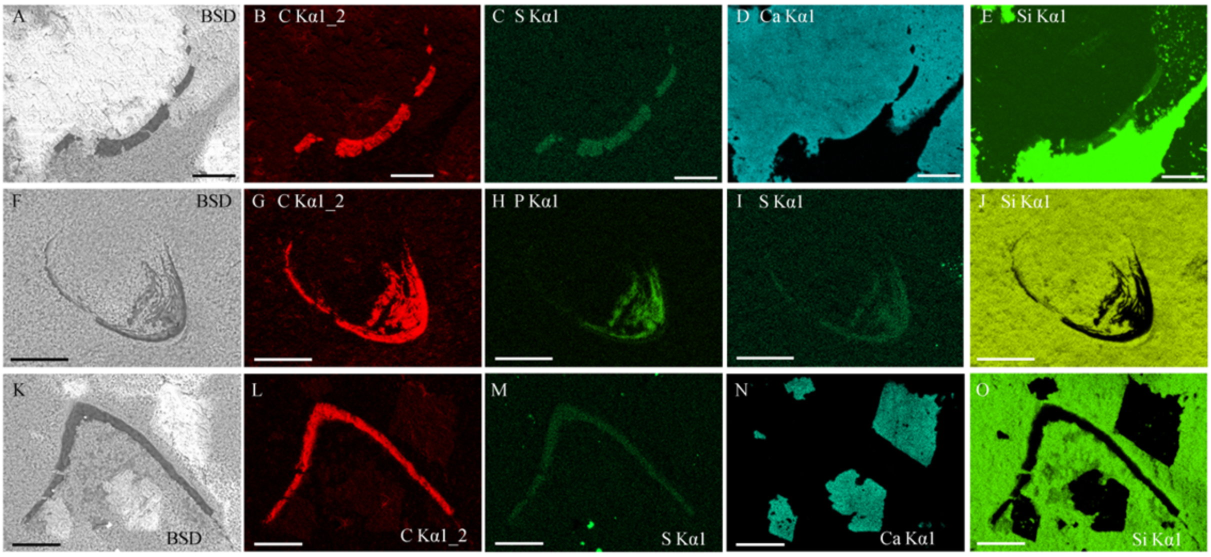

Fig. 4 EBSD and EDS data of thin sections with SSFs from the *Protohertzina anabarica-Kaiyangites novilis* Assemblage Zone in Yangjiaping. A. EBSD image of thin-section containing *Protohertzina* cf. *unguliformis*, No. yap55002. B-E. EDS elemental maps of A. B. Carbon Kα1_2 map. C. Sulfur Kα1 map. D. Calcium Kα1 map. E. Silicon Kα1 map. F. EBSD image of thin-section with problematic SSF, No. yap55003. G-J. EDS elemental maps of F. G. Carbon Kα1_2 map. H. Phosphorus Kα1 map. I. Sulfur Kα1 map. J. Silicon Kα1 map. K. EBSD image of thin-section with *Kaiyangites novilis*, No. yap55009. L-O. EDS elemental maps of K. L. Carbon Kα1_2 map. M. Sulfur Kα1 map. N. Calcium Kα1 map. O. Silicon Kα1 map. Scale bars are 50 μm.

SSFs reported from Yangjiaping (Ding and Qian, 1988) include *Protohertzina unguliformis* (Fig. 2O, P), *P. anabarica*, *Kaiyangites novilis* (Fig. 4K) and *Siphogonuchites* appearing at the base of the Niutitang Formation. The fossils recovered through acetic acid treatment from carbonate nodules have a composition of calcium phosphate. Fossils in the thin sections show significant but lower contents of sulfur (<1wt.%) which is associated with carbon

(Fig. 4). Samples with *Protohertzina* cf. *unguliformis* (Fig. 4A) and *Kaiyangites novilis* (Fig. 4K) also contain some carbonate (Fig. 4B, D, L, N) and the abundant silicon (Fig. 4E, O).

A lamellate SSF of uncertain assignment (Fig. 4F) is composed of carbon enriched with smaller amounts of sulfur and phosphate. The calcium phosphate shows a stronger enrichment on the inner side of the organic main lamella and a weaker appearance on the outer side (Fig. 4H), which is likely due to inner and outer coatings on the originally organic fossil. This investigation indicates that SSFs with apatitic and organic composition are common in siliceous rocks of deeper shelf facies and bear potential for extended biostratigraphic application if the fossils can be extracted from the rocks in large quantities.

5. Discussion and conclusion

Our study shows that siliceous rocks of deeper shelf settings contain phosphatic and carbonaceous SSFs that can be extracted through weak HF etching. Highly concentrated HF (~40%) etching has been utilized as a routine method in various micropalaeontology fields, e.g. in radiolarian and pollen analyses. The diluted HF (2-5%) etching method is rarely applied and has not yet been used for SSF research. Our study proves the applicability of this method for the SSF study from cherts and deeper water sedimentary sequences. SSFs can rarely be obtained from crack-out hand specimens because of uneven splitting and strong dispersal of fossils in siliciclastic or cherty sediments. Thus, the mechanical separation approach has considerable practical limits for the biostratigraphic application. The diluted HF method, as all chemical extraction procedures, provides a more quantitative record of SSFs compared with any physical method, highlighting a better biostratigraphical applicability, even though some mineralized skeletal remains such as siliceous spicules may be dissolved partially.

Due to the low concentration of the acid and the short duration, the applied method rarely transforms original phosphate to fluorite. Thus, the structure of fossils is not coarsened by the formation of secondary fluorite crystals. The extracted SSFs from cherts display a quality comparable with those from standard dissolution of carbonate by weak organic acids (Fig. 2). This allows the application of the new method for SSF-based stratigraphy and correlation in siliciclastic and siliceous environments.

The discovery of SSFs through HF digestion confirms previous biostratigraphic assignments of the Hetang Formation in Zhejiang and the Niutitang Formation in Hunan (Steiner et al., 2007). *Jiangshanodus*-type and *Kijacus*-type arthropod spines have been reported with *Liangshanella* etc. from the base of the black shale unit, which was correlated with the Qiongzhusian and *Pelagiella subangulata* Zone of eastern Yunnan (Steiner et al., 2003). *Seletellus seletinicus* is here found for the first time on the Yangtze Craton. The taxon was previously only reported from the Kikbaj Series in the Ermentau-Nijaski Anticline of central Kazakstan, associated with *Rhombocorniculum* aff. *insolutum* (=*R. cancellatum*), *Amphigeisina danica* and *Dabashanella*? (Gridina, 1991). *Rhombocorniculum insolutum* was considered to be synonymous with *R. cancellatum* (Hinz, 1987). As the *R. cancellatum* Zone (Steiner et al., 2007) of southeastern Shaanxi and northwestern Hubei covers the late Qiongzhusian and possibly the earliest Canglangpuian, these finds may further indicate that the higher black shale unit of the Hetang Formation can be assigned to the *R. cancellatum* Zone and thus represents the upper Qiongzhusian in Zhejiang.

The occurrence of *Protohertzina anabarica*, *P. unguliformis* and *Kaiyangites novilis* in the highly condensed, carbonaceous shales and cherts of basal units of the Niutitang and Hetang formations in Zhejiang and Hunan also confirms the presence of Meishucunian strata in the deeper shelf region of the Yangtze Craton. It is remarkable that protoconodonts are common in the carbonaceous cherts, shales and carbonate nodules of deeper shelf deposits and may represent a valuable tool for intercontinental biostratigraphic correlation. Clusters of protoconodonts found both in cherts of the higher black shale unit (Fig. 2L) and limestone nodules (Fig. 2M, N) may represent remains of grasping apparatuses of chaetognaths (Vannier et al., 2007), similar to *Protohertzina* from the basal unit of Niutitang and Hetang formations.

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Early Cambrian palaeobiogeography of the Zhenba-Fangxian Block (South China): Independent terrane or part of the Yangtze Platform?

Abstract

Early Cambrian small skeletal fossils (SSFs) are studied and revised from the Zhenba-Fangxian Block of the transitional zone between the Yangtze Block and the South Qinling Terrane. The study reveals a diverse fauna with 47 species of various biological affinities, including the new species *Gapparodus gapparites* sp. nov. The SSFs are assigned to the newly defined *Cambroclavus fangxianensis -Rhombocorniculum cancellatum* Assemblage Zone. Based on the investigated SSF fauna from Zhenba County, Southeast Shaanxi of China and published data, a palaeobiogeographic study is carried out for the Cambrian Stage 3 (equivalent to the Atdabanian-Botoman of Siberia). A hierarchical Pearson similarity cluster analysis of 295 species from 32 regions of the world indicates distinct palaeobiogeographic pattern with seven faunal provinces. The result is mostly consistent with existing palaeogeographic reconstructions for the early Cambrian. However, it is also shown that the SSF assemblages of the Zhenba-Fangxian Block have low similarity with those of the Yangtze Block. Instead, they share high similarity with those from Armorica, Tarim and Karatau-Naryn terranes (South Kazakhstan/ North Kyrgyzstan). The Yangtze Block has an unique SSF assemblage dissimilar to most of other regions. The Terreneuvian-Cambrian Stage 3 sedimentary sequence of the Zhenba-Fangxian Block is more consistent with that of the South Qinling Terrane. Besides, sedimentary Ediacaran manganese ore deposits and Cambrian barite/ witherite deposits have unique distribution pattern on the Zhenba-Fangxian Block. Derived from the profound dissimilarities in faunal composition, sedimentary sequence and distribution of sedimentary ore deposits, we hypothesize that during the Neoproterozoic-Cambrian transition, the Zhenba-Fangxian Block might have been an independent terrane and more distant from the Yangtze Block. The palaeobiogeographic analysis of SSFs also indicates a closer alliance between Avalonia and Siberia. And it corroborates the palaeogeographic reconstruction of North China at the margin of Gondwana, in the vicinity of Australia, Antarctica, and Armorica.

Keywords: Palaeobiogeography; Small shelly fossils; Zhenba-Fangxian Block; South Qinling Terrane; Yangtze Block; early Cambrian; Gondwana

1. Introduction

The Cambrian bioradiation of metazoans (Cambrian "explosion") represents a major biotic revolution in Earth history (Conway Morris, 2006; Marshall, 2006), which has puzzled scientists ever since Darwin's (1859) time. As most of the clades appeared in the fossil records within a short duration (Marshall, 2006; Shu et al., 2014), necessary information on the evolution of metazoans is mostly derived from two lines: The incomplete fossil record (Shu et al., 1999), and the biology of modern metazoans with theoretical considerations on diversification of detailed bauplans (Vannier et al., 2007; Vannier et al., 2010) as well as the estimates of divergences of major clades based on molecular data (Budd and Jensen, 2000; Peterson et al., 2005). Fossil information on the early evolution of metazoans during the Ediacaran and Terraneuvian Series is mostly derived from imprints of soft-bodied organisms (Ediacara-type fossils), trace fossils, mineralized small skeletal fossils (SSFs), and diagenetically replaced soft-tissued organisms. Trace fossils appeared successively during the Ediacaran Period and were interpreted as evidence of metazoan mobility, organ differentiation, development of neural systems, and related diversified bauplans (Seilacher et al., 2005). Most distinct fossil information is derived from the skeletal fossil record (Steiner et al., 2007) and soft-tissued fossil *Lagerstätten* (Conway Morris, 1989; Conway Morris, 1998; Shu et al., 2001; Shu et al., 2003). While soft-tissue preservation is exceptional and may be exclusive for specific organisms, bulk data for the majority of metazoans is derived from organic and primarily biomineralized skeletons. Small shelly fossils (SSFs) represent a specific taphonomical mode in preservation typical but not exclusive for the terminal Ediacaran to Cambrian Series 2 (Steiner et al., 2007). In most cases SSFs are of millimetric size but ranging from tens of micrometers to centimeters. The SSFs are usually carbonatic or phosphatized and sometimes organic, silicified, pyritic/ limonitic. This allows to extract the microfossils in great quantities by dissolving rocks with weak acids, mostly acetic and formic acid, or diluted hydrofluoric acid (Yang et al., 2014c) and to apply the fossils for a reconstruction of the early evolution of metazoans, biostratigraphy and palaeobiogeography.

SSFs have been widely applied as a biostratigraphic tool in the early Cambrian (Rozanov and Missarzhevsky, 1966; Qian, 1978; Missarzhevsky and Mambetov, 1981; Qian, 1989; Qian and Bengtson, 1989; Bengtson et al., 1990; Elicki and Schneider, 1992; Esakova and Zhegallo, 1996; Gravestock et al., 2001; Steiner et al., 2003; Steiner et al., 2004; Skovsted, 2006; Steiner et al., 2007; Shabanov et al., 2008; Varlamov et al., 2008; Kouchinsky et al., 2014; Yang et al., 2014b). It has been argued that many elements of SSFs were endemic and facies-dependent (Landing, 1992; Mount and Signor, 1992; Landing et al., 2013a). However, this also allows to apply SSFs for reconstructions of the ecology and palaeobiogeography (Qian et al., 1999; Elicki and Pillola, 2004; Elicki, 2005; Steiner et al., 2007; Yang et al., 2014b).

Palaeobiogeographic reconstructions of fossil assemblages are one of the main palaeobiological applications for palaeogeography and thus a broader Earth history research. Palaeobiogeographical work on the critical Ediacaran to Cambrian time interval is of special significance for understanding the evolution of life and other major geological events, e.g., innovations in the atmo-, hydro-and geosphere of this time. Quantitative and semiquantitative studies of Cambrian faunas, mostly trilobites and brachiopods, have been carried out for decades for palaeobiogeographic applications (Pillola, 1990; Lieberman, 1997; Brock et al., 2000; Álvaro et al., 2003; Elicki, 2005; Williams et al., 2007; Álvaro et al., 2013). Some ecological and regional environmental studies have also been made based on some Burgess Shale-type *lagerstätten* (e.g., Caron and Jackson, 2006; Zhao et al., 2009). However, pre-trilobitic SSFs have only been rarely used for quantitative palaeobiogeographic reconstructions (Steiner et al., 2007).

Current palaeogeographic reconstructions for the Ediacaran to Cambrian time remain a matter of controversy on the geometry of the supercontinents and the arrangement of crustal blocks. Recent palaeogeographic reconstructions (Li et al., 2013; Torsvik and Cocks, 2013b) revealed considerable uncertainties still exist on the positions of several continental blocks (e.g., North China and South China) or terranes (Kazakh terranes). Only larger continents, such as Baltica or Laurentia, show robust consistency in different reconstruction attempts. There are two major opinions considering the relative position of Yangtze Block during the Ediacaran-Cambrian time. Some studies consider both the Yangtze and North China blocks as part of the eastern Gondwana nearby Australia and Antarctica (Li et al., 2008; Zhao et al., 2014). Whereas the other opinions regard it as part of the western Gondwana (Steiner et al., 2007; Li et al., 2013; Torsvik and Cocks, 2013a; Safonova and Santosh, 2014; Santosh et al., 2014). Most of the palaeogeographic reconstructions are fully based on the tectonic, sedimentary as well as palaeomagnetic evidences. However, palaeobiogeographic analyses could provide considerable data that may resolve discrepancies in the different palaeogeographic models. Palaeobiogeographical reconstructions are rarely applied for the Cambrian Period (Brock et al., 2000; Steiner et al., 2007) and if so are mostly based on studies of trilobites (Álvaro et al., 2003). It would be important to further expand the knowledge on the provincialism of Cambrian faunas. And for palaeogeographic reconstructions, the distribution patterns of benthic communities, such as archaeocyatha, brachiopods or other SSFs, worth further attempt.

Considering the position of the Yangtze Block and the marginal terranes (Zhenba-Fangxian Block, partially termed as SE Shaanxi-NW Hubei Region; South Qinling terrane), it has been questioned how their positions were to each other and in regard to Gondwana during the Ediacaran-Cambrian transition (Steiner et al., 2007). To date there is only sparse information on the distribution of Cambrian fossils of the South Qinling Terrane and Zhenba-Fangxian Block (Li et al., 1975; Duan, 1983; Li and Holmer, 2004; Li et al., 2004a; Li et al., 2012), while most reports and discussions are on later Paleozoic radiolarians (Feng et al., 1996; Wang et al., 1999). And no quantitative study of Cambrian SSFs has been carried out for this region so far.

Therefore, the present study aims at re-study and revise the early Cambrian SSFs of the Zhenba-Fangxian Block for a detailed biostratigraphical and palaeobiogeographic application. Further more, it aims to illuminate the palaeogeographic position of Yangtze and Zhenba-Fangxian blocks during the early Cambrian.

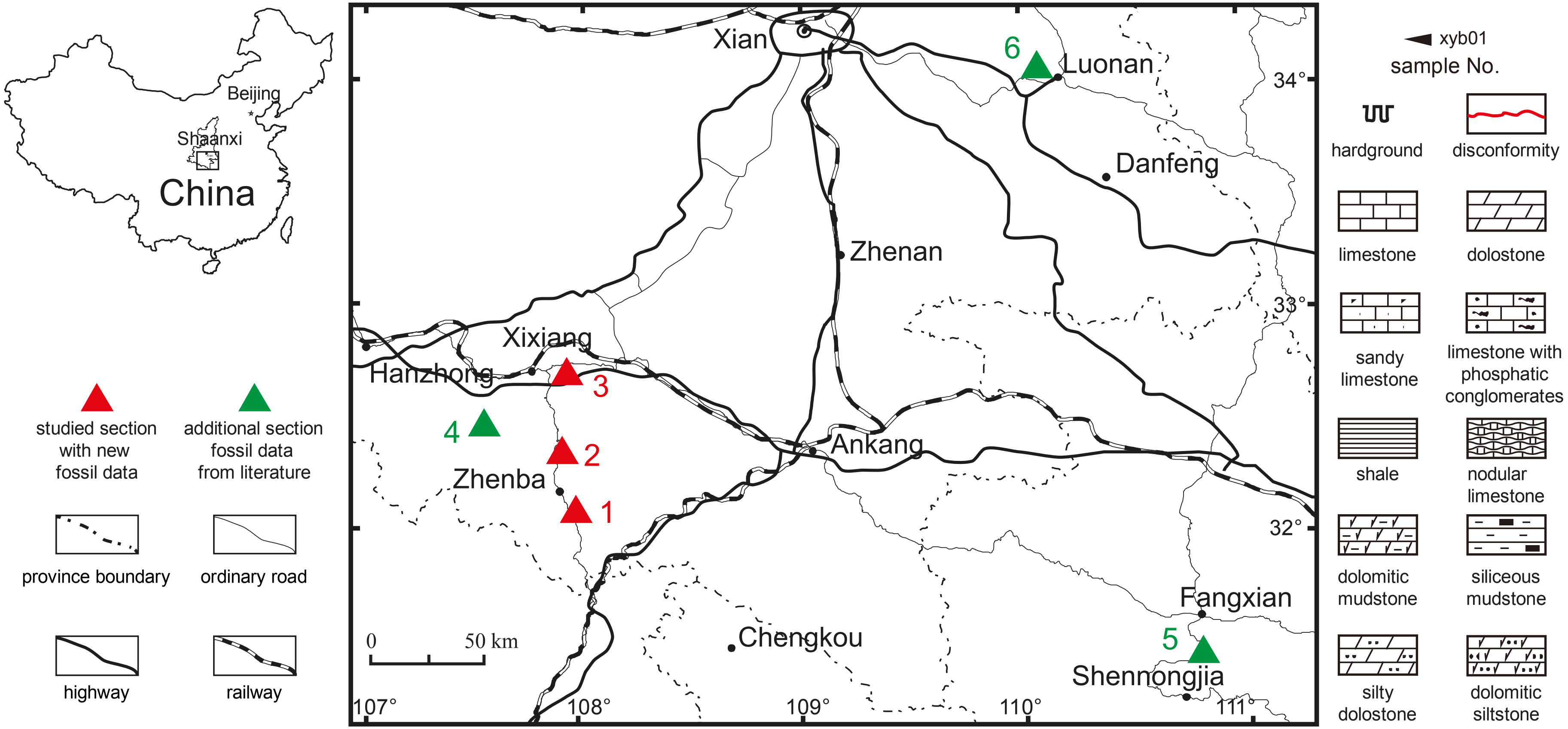

Fig. 1. Location of the studied sections in South Shaanxi, China: (1) Xiaoyangba Section, (2) Zengjiapo Section, (3) Sanlangpu & Xiaowan sections, NW Xixiang County, (4) Hexi Section, SW Xixiang County, (5) Xihaoping Section, S Fangxian County, (6) Luonan Section.

2. Material and Methods

Samples were collected from the sections with a stratigraphic sampling resolution of about two samples per one meter. Every single sample is 1~2 kg in average except for the Dengying Formation. All samples were cut with a diamond saw in the lab to obtain thin slices for the purpose of sedimentological study. The rest was immersed in 10% buffered acetic acid or 10% buffered formic acid (mostly for dolostone). The acids were replaced every 3 days and the residue was retrieved every 1~2 weeks depending on the reaction speed. The residue was sieved into >2mm, >125 µm, >64 µm grain classes simultaneously and then dried at 60℃ in the oven. Acid resistant residues of < 64 µm were discarded. Subsequently, fossils were hand-picked under a binocular microscope. Selected specimens were glued on sample stubs by double-sided adhesive carbon tabs, coated with gold and inspected by Scanning electron microscopy (SEM) at Freie Universität Berlin using a ZEISS Supra 40VP Scanning electron microscope. All the figured samples are stored at the Department of Earth Sciences of Freie Universität Berlin.

The geological map of Qinling Belt and North Yangtze Block was extracted from the 1: 500 000 geological map database developed by the China Geological Survey. The Precambrian to Cambrian geological data were extracted to Mapgis format files (Mapgis 6.7 version) and exported to a TIFF file finally. Hierarchical cluster analysis was carried out using the computer program SPSS 20.0. The data matrix (Appendix 1) were calculated using SPSS 20. The data matrix was transpose before cluster analysis. We chose hierarchical cluster analysis with the Pearson Correlation interval. The cluster method is Between-groups linkage. The 295 species were set as variables and the 32 places were set as cases.

3. Geological data

3.1. Precambrian-Cambrian geology of Zhenba-Fangxian Block

The terms "Yangtze Block", "Yangtze Platform" and "Yangtze Craton" have been variously used referring to the Neoproterozoic-early Paleozoic strata and tectonic crustal units (Huang et al., 1977; Ren and Huang, 1980; Huang, 1984; Wang and Mo, 1995; Bai and Zhu, 1996; Pan et al., 2009). The Yangtze Craton is composed of Archean-Paleoproterozoic crystalline basement that is overlain by an unmetamorphosed Cryogenian and Ediacaran sedimentary cover (Dong et al., 2011b). It experienced the formation and the breakup of the Rodinia from the end of the Mesoproterozoic to Neoproteorozic and assembly to the Gondwana continent in latest Neoproterozoic-early Paleozoic.

Most of the studies considered the Yangtze Block's boundaries as follows: (1) In the north, the Yangtze Block is separated from the South Qinling Terrane by the Mianlue Suture Zone (Zhang et al., 2001; Dong et al., 2011a) and the Chengkou-Fangxian-Xiangfan-Guangji Fault (Bai and Zhu, 1996); (2) In the Northwest the Yangtze Block is bordered toward the Bikou Terrane, Songpan-Ganze Orogeny by the Longmenshan Fault; (3) In the Southwest toward the Sanjiang Region it is defined by the Jinshajiang-Honghe Fault; (4) In the East the Yangtze Block is defined by the Tancheng-Lujiang and Jiashan-Xiangshui faults; And (5) In the Southeast, the Yangtze Block is bordered toward the Cathaysia Block by the Jiangnan Orogeny (Guo et al., 1989; Guo et al., 1996).

Traditionally, there are four blocks (terranes) in Central-West China divided by three boundaries (Fig. 2). The Luonan-Luanchuan Fault (LLF) borders the southern North China Block that experienced a Mesozoic-Cenozoic intra-continental orogenic deformation (Dong et al., 2011b). It is composed of Mesoproterozoic-Neoproterozoic volcanic and clastic rocks, Mesoproterozoic granites and Mesoproterozoic-Cambrian intermediate rocks. Cambrian-Ordovician sediments overlay this basement in the Luonan Region. And early Cambrian and Ordovician fossils have been reported from Luonan (Wang et al., 1989; Wang et al., 2007). To the south the Luonan-Luanchuan Fault separates the North Qinling Terrane from the North China Block. It is composed by Mesoproterozoic-Neoproterozoic volcanic and clastic rocks (Kuanping Group) in the north, Paleoproterozoic-Mesoproterozoic metamorphic rocks (Qinling Group) in the south and Archean-Paleoproterozoic gneiss and complexes in-between. Recent studies revealed an ophiolitic belt along the Shangzhou-Danfeng Fault with early Cambrian-early Devonian magmatic activity (Dong et al., 2011b) and Ordovician radiolarians from the chert of the ophiolitic belt were reported (Cui et al., 1995).

The South Qinling Terrane is separated from the North Qinling Terrane by the Shangzhou-Danfeng Fault (SDF) and the Mianxian-Lueyang Fault (MLF). It borders on the Yangtze Block in the south and the Bikou Block in the southwest. Traditionally, the northern margin of Yangtze Block is marked by the Mianlue Suture Belt and the Chengkou-Fangxian Fault. The South Qinling Terrane includes the Foping Block, Wudang Block and the Dabashan Region, that is situated between the Hannan and the Wudang blocks. The basement of the South Qinling Terrane is mainly exposed in the Foping Block, Wudang Block and the Dabashan Region and consists of Mesoproterozoic basic and ultramafic rocks as well as Mesoproterozoic-Neoproterozoic volcanic and clastic rock. Cambrian-early Ordovician sediments are common in the South Qinling Terrane and here especially crop out in the Dabashan area and the margins of the Wudang and the Foping blocks. Intercalated to the carbonatic, argillaceous and siliceous sediment sequences, sedimentary barite and witherite deposited in the early Cambrian (Gao, 1998; Tu, 1999; Lü et al., 2004a) in two major belts, the Zhenba-Chengkou-Zhenping Region and the Hanyin-Ankang-Zhuxi Region (Fig. 2).

Previous studies suggested that the northern Yangtze Block includes the Hannan Block, Guangwushan Block, Shennongjia Region and the Huangling Anticline. On the Guangwushan Block Paleoproterozoic-Mesoproterozoic basic and ultramafic rocks are exposed and associated with Neoproterozoic granites and Cambrian sediments. In contrast, the Hannan Block mainly constitutes of Neoproterozoic granites with certain basic and ultramafic rocks, Archean-Paleoproterozoic gneiss complexes, and sporadically distributed Neoproterozoic-Cambrian sediments at the southwestern, southeastern and eastern margin.

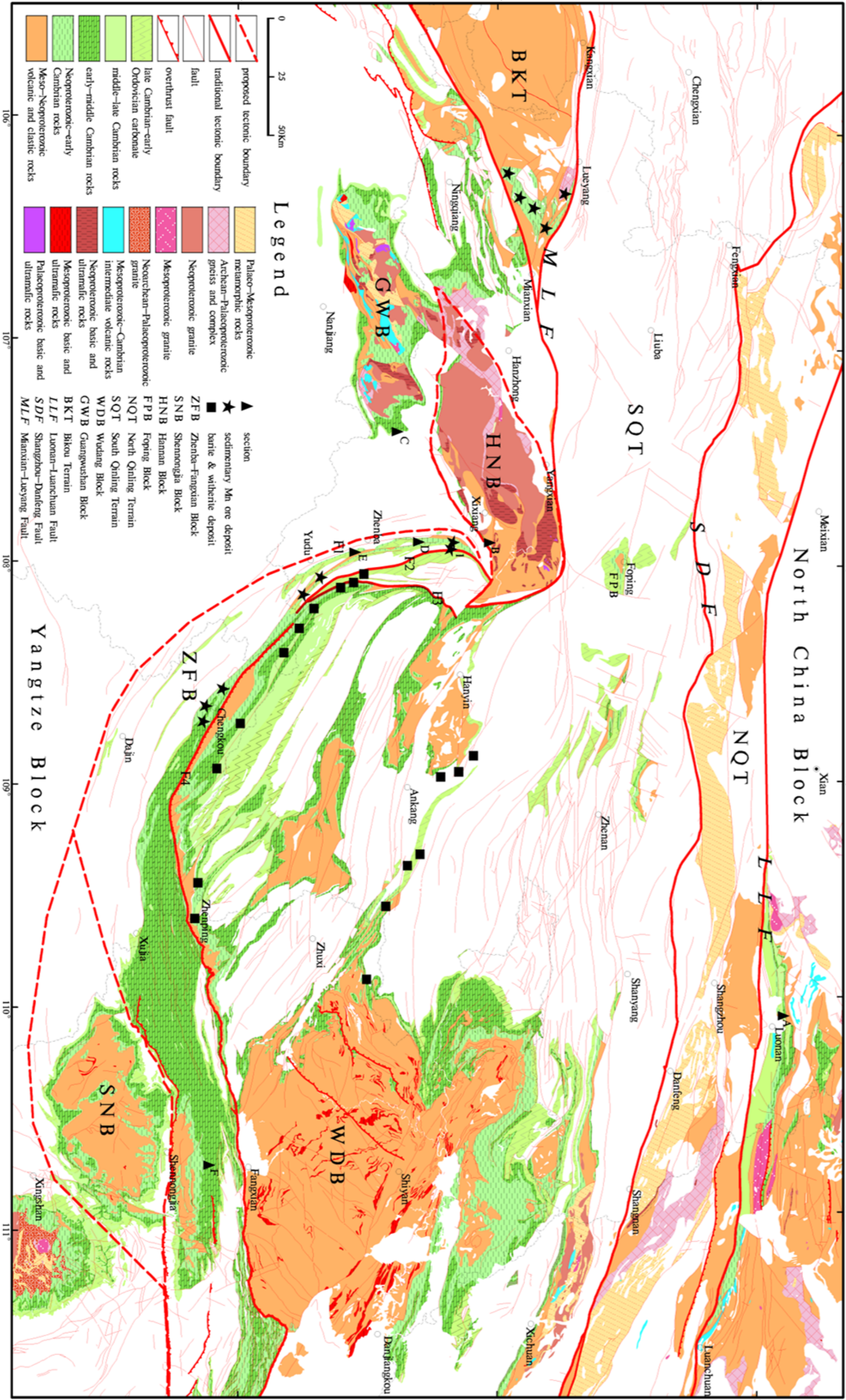
North China Block
Yangtze Block
NQT
SQT
BKT
GWB
HNB
FPB
ZFB
WDB
SNB
SDF
LLF
MLF
F1
F2
F3
F4
A
B
C
D
E
F
I
Xian
Meixian
Chengxian
Fengxian
Liuba
Kangxian
Lueyang
Mianxian
Ningqiang
Nanjiang
Hanzhong
Yangxian
Xixiang
Foping
Zhenan
Shanyang
Shangzhou
Luonan
Danfeng
Shangnan
Xichuan
Luanchuan
Danjiangkou
Shiyan
Fangxian
Shennongjia
Xingshan
Xujia
Zhenping
Zhuxi
Ankang
Hanyin
Chengkou
Dajin
Ziyang
Zhenba
Yudu
32°
33°
34°
106°
107°
108°
109°
110°
111°
0
25
50Km
Legend
proposed tectonic boundary
traditional tectonic boundary
fault
overthrust fault
late Cambrian–early Ordovician carbonate
middle–late Cambrian rocks
early–middle Cambrian rocks
Neoproterozoic–early Cambrian rocks
Meso–Neoproterozoic volcanic and clastic rocks
Palaeo–Mesoproterozoic metamorphic rocks
Archean–Palaeoproterozoic gneiss and complex
Neoproterozoic granite
Mesoproterozoic granite
Neoarchean–Palaeoproterozoic granite
Mesoproterozoic–Cambrian intermediate volcanic rocks
Neoproterozoic basic and ultramafic rocks
Mesoproterozoic basic and ultramafic rocks
Palaeoproterozoic basic and ultramafic rocks
▲ section
★ sedimentary Mn ore deposit
■ barite & witherite deposit
ZFB Zhenba–Fangxian Block
SNB Shennongjia Block
HNB Hannan Block
FPB Foping Block
NQT North Qinling Terrain
SQT South Qinling Terrain
WDB Wudang Block
GWB Guangwushan Block
BKT Bikou Terrain
LLF Luonan–Luanchuan Fault
SDF Shangzhou–Danfeng Fault
MLF Mianxian–Lueyang Fault

Fig. 2. Simplified geological map of study area. Distribution of sedimentary barite deposits is based on Wu et al., (2010) and Luo et al. (2012), distribution of sedimentary Manganese ores is according to Zhao and Wang (2009), Wan et al. (2012), Wang et al. (2008) and own observation. ▲A, Luonan Section; ▲B, Sanlangpu & Xiaowan sections, NW Xixiang County; ▲C, Hexi Section, SW Xixiang County; ▲D, Zengjiapo Section, Zhenba County; ▲ E, Xiaoyangba Section, Zhenba County; ▲F, Xihaoping Section, southern Fangxian County.

In the study region, the Zhenba-Fangxian Block (Fig. 2), Qiongzhusian (Cambrian Stage 3) sediments of the Xihaoping Member and Shuijingtuo Formation overlie Neoproterozoic carbonates unconformably (Figs. 1, 4, 5). The Terreneuvian strata are missing on the Zhenba-Fangxian Block and in the Northwest Xixiang Region (Fig. 2, Section B; Fig. 3D). It was earlier noted that lithological and biostratigraphical correlation of the early Cambrian strata of the Zhenba-Fangxian Block with other regions of the Yangtze Block are problematic (Steiner et al., 2007). This is mostly due to the fact that the Cambrian Stage 3 fossil assemblages are different; lithology is partially dissimilar or ubiquitous on many palaeocontinents; and the huge Terreneuvian hiatus is structurally linked to the Zhenba-Fangxian Block. The isopach map of the Ediacaran carbonate platform sediments (Dengying Formation) was also not suggestive for a continuous and undisturbed facies between the Zhenba-Fangxian Block and the other regions of the Yangtze Block (Steiner et al., 2007). It is important to note that early Cambrian sedimentary barite and witherite deposits are distributed along the Chengkou-Fangxian Fault (Fig. 2, F4), just separating the Zhenba-Fangxian Block from the South Qinling Terrane. In another belt, the Hanyin-Ankang-Zhuxi Region, the barite and witherite deposits extend toward the Wudang Block within the South Qinling Terrane (Fig. 2). Ediacaran sedimentary manganese ores developed in Sishang (Fig. 3C), Zhenba, and Chengkou regions in a belt within the Zhenba-Fangxian Block resembling phosphatic manganese ores in the western Mianxian Region of the Bikou Block (Fig. 2). The sedimentary ores are distributed in belts that are apparently linked to the faults defining the blocks. They are commonly thought to have been developed during the collision of Yangtze Craton with the North China Craton during the later Paleozoic. However, the sedimentary ores indicate typical primary sedimentary structures (Fig. 3C) and were likely deposited during the Ediacaran respectively early Cambrian. It is therefore worth to analyze the faunal affinities and palaeobiogeographic links of the early Cambrian fossil assemblages in detail.

3.2. Lithology of studied sections

The Zengjiapo section (Fig. 1; 5 km from Yangjiahe Town, Zhenba County, South Shaanxi , 32°43.75’ N, 107°53.847’E) was first described by Li et al. (1991). SSFs are preserved in the Xihaoping Member and lower Shuijingtuo Formation which disconformably overlay the Neoproterozoic Dengying Formation (Fig. 4). The 0.5m thick Xihaoping Member is composed of pyritic, gray blocky dolostone unconformably overlying the Dengying dolostone. The upper Dengying Formation is partially strongly brecciated and impregnated by black pyrobitumen along fine cracks. The top Dengying Formation shows some fine cracks that are filled with granular, phosphatic dolostone of the overlying Xihaoping Member. The Xihaoping Member is composed of limestone containing mounts of pyrite grains.The upper Xihaoping Member is also brecciated. The Xihaoping Member is superimposed by the Shuijingtuo Formation over a disconformable contact. The lower part of lower Shuijingtuo

Member is composed of dark, slightly pyritic limestone, nodular limestone interbedded with black shales, and the upper part by middle thick-bedded limestone interlayered with thin shales or few siltstones. It showed numerous phosphatic hardgrounds (7 in ca. 12 m; Fig. 3A). The lowermost 3 m of Shuijingtuo Formation contain some limestone beds with vertical disturbances markings that are interpreted as gas escape structures.

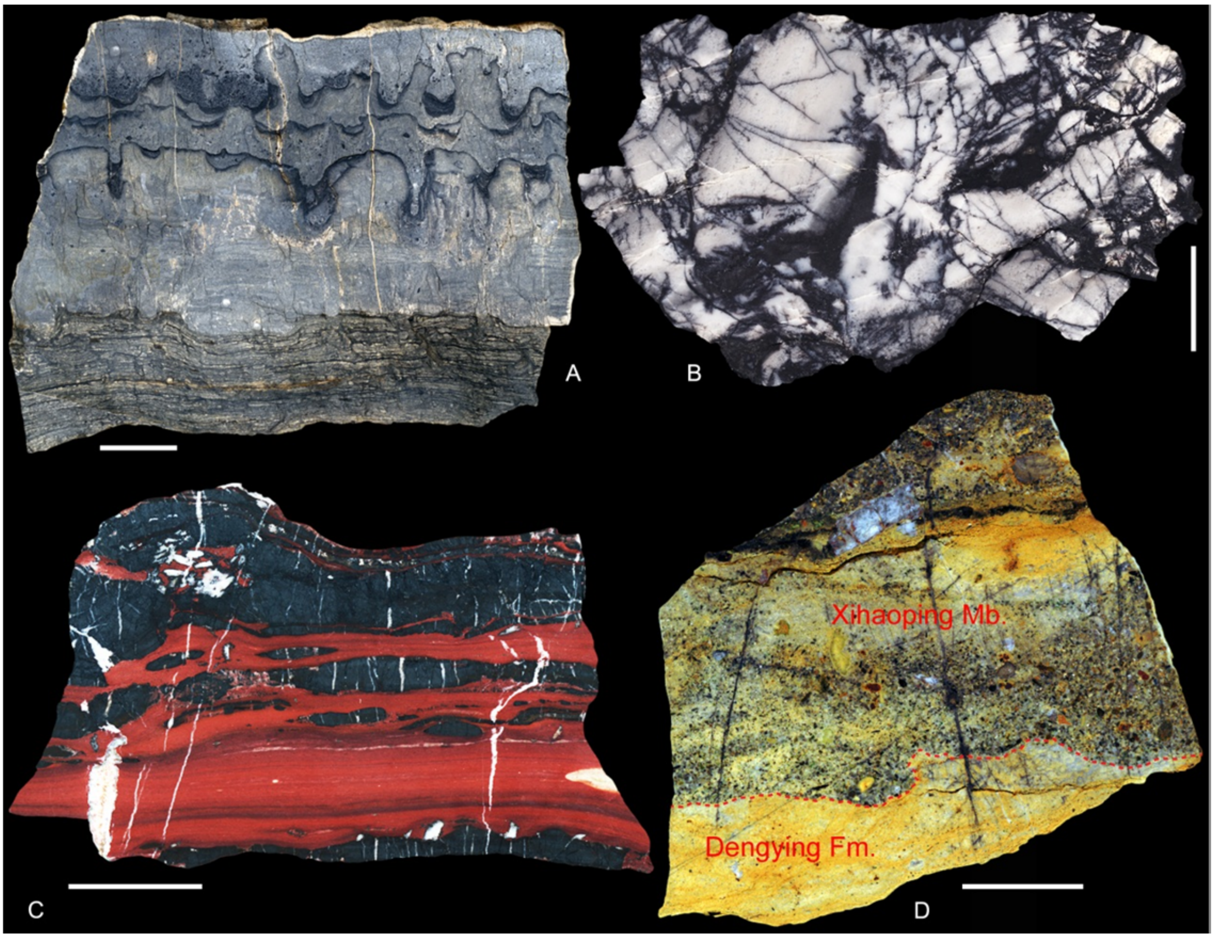

Fig. 3. Photographs of grinded handspecimens showing; A. Hardground features from the Shuijingtuo Formation, sample no. Zjp15; B. Strongly brecciated dolostone of the top Dengying Formation with migrated pyrobitumen along cracks, sample no. XybLes; C. Early Neoproterozoic sedimentary Manganese ore from Sishang, ★1 in Fig. 2, from strata equal to the Doushantuo Formation of the Yangtze Platform. Energydispersive X-ray spectroscopy reveals the red layers are rich in iron oxide and the black lenticles consists of Mn oxide; D, Unconformable contact of the Dengying Formation and the Xihaoping Member at Sanlangpu, see Fig. 2 section B, NE Xixiang County, Sample no. San 1. Scale bars equal 2cm.

Xiaoyangba section (Fig. 1) has been studied intensively in the past decades (Li et al., 1975; Xie, 1988; Tong, 1989; Li et al., 2004a). The section (32°29.488’ N, 107°57.040’E) lies in the northeastern Zhenba County, ca. 10 km SE Zhenba town. In a river-cut section an Edicacaran-Cambrian sequence embracing the Nantuo, Mingyue, Doushantuo, and Dengying formations, the Xihaoping Member and the Shuijingtuo Formation is exposed. The Nantuo Formation is about 200m thick and consists of diamictites of probably glaciomarine origin and of conglomerates. Developed only on the Zhenba-Fangxian Block, the ca. 40 m thick Mingyue Formation is represented by purple sandstones with conglomeratic lenses and beds as well as greenish siltstone at the top. The overlying 45 m of black shales are assigned to the Doushantuo Formation. The terminal Ediacaran Dengying Formation is composed of about 100 m of grey or whitish blocky, partially stromatolitic dolostone. The topmost ca. 16 m are partially strongly brecciated and impregnated by migrated pyrobitumen along fine cracks (Fig. 3B). The Xihaoping Member overlies the gray Dengying dolostones, however, the direct contact being not exposed. At the boundary occur ca. 45 cm of limy siltstone. The Xihaoping Member consists of 7m dolomitized grayish, pyritic, blocky limestone interbedded with silty dolostone. It shows numerous phosphatic hardgrounds (11 in 7m). A 5-10 cm conglomeratic limestone bed marks the disconformity between Xihaoping Member and overlying Shuijingtuo Formation. The lower Shuijingtuo Formation (ca. 23m) constitutes thin limestone beds and shales interbedded with limestone lenses or nodules (Fig. 5). The number of phosphatic hardgrounds is conspicuously lower (5 in 23 m) than that of the underlying Xihaoping Member, whereas the organic content is higher. This indicates a deepening trend from the Ediacaran Dengying Formation toward the Shuijingtuo Formation.

All investigated sections contained well-preserved SSFs in the Xihaoping Member and the Shuijingtuo Formation, whereas most of the SSFs and the best preserved SSFs were recovered from the Shuijingtuo Formation. Disconformities and hardgrounds (Fig. 3, 4, 5) are common in all investigated sections, however, it is obvious that the number of hardgrounds and the duration of hiati is increasing within the Zhenba-Fangxian Block from the South toward the North. This is also reflected by the thickness of the Xihaoping Member that decreases from the South (Xiaoyang section, 7.0 m) toward the North (Sanlangpu; ca. 5-10 cm; Fig. 3D). A major hiatus occurs in all sections of the Zhenba-Fangxian Block at the Precambrian-Cambrian transition that comprise of the whole Terreneuvian and thus has a duration of at least 18 million years, but possibly 24 million years. This may have resulted from major tectonic events like tectonic uplifting, collision or volcanic activities during that time.

4. Small Shelly Fossils of Zhenba-Fangxian Block

4.1 SSF assemblages of Xihaoping Member and Shuijingtuo Formation

The studied sections in Zhenba and Xixiang counties preserved diverse SSFs, including protoconodonts, chancelloriids, molluscs, brachiopod, trilobites, bradoriids, arthropod fragments, and other problematic fossils. Previous studies mostly focused on the description of specific faunal components of the SSF assemblages of Zhenba County, such as the conodont-like fossils (Xie, 1988), bradoriids (Zhang, 2007), brachiopods (Li and Holmer, 2004), phosphatic tubular fossils (Li et al., 2004b), eodiscid trilobites and disarticulated trilobite spines (Li et al., 2012). Li et al. (1991) reported echinoderm skeletal plates with a brief introduction of the fossils from Zengjiapo. Li et al. (2004a) studied the general biodiversity of Xiaoyangba section and presented a brief biostratigraphic frame for the section, although they only reported an incomplete fauna with 10 taxa for the Xihaoping Member and 12 taxa for the Shuijingtuo Formation. The latter study formed the basis for the detailed biostratigraphic correlation of the region with other regions of the Yangtze Platform in Steiner et al. (2007). Here we describe the SSF assemblages of Xihaoping Member and Shuijingtuo Formation from two sections (Zengjiapo, Xiaoyangba) of Zhenba County in greater detail (Figs. 4, 5) and report 50 taxa in total with13 taxa known from the Xihaoping Member and 46 taxa from the Shuijingtuo Formation. The SSF assemblages of Fangxian County (Hubei Province) have been described by Duan (1983), Qian & Zhang (1983), Qian et al. (1999), and Na and Li (2011) and show strong similarity with the assemblages of Zhenba and Xixiang counties (Appendix 1, NW Hubei). The SSF assemblage of Xihaoping Member of Xixiang County is as in Zhenba of moderate diversity and was described in detail by Ding et al. (1990; 1992), Qian et al. (1999) and Steiner et al. (2004).

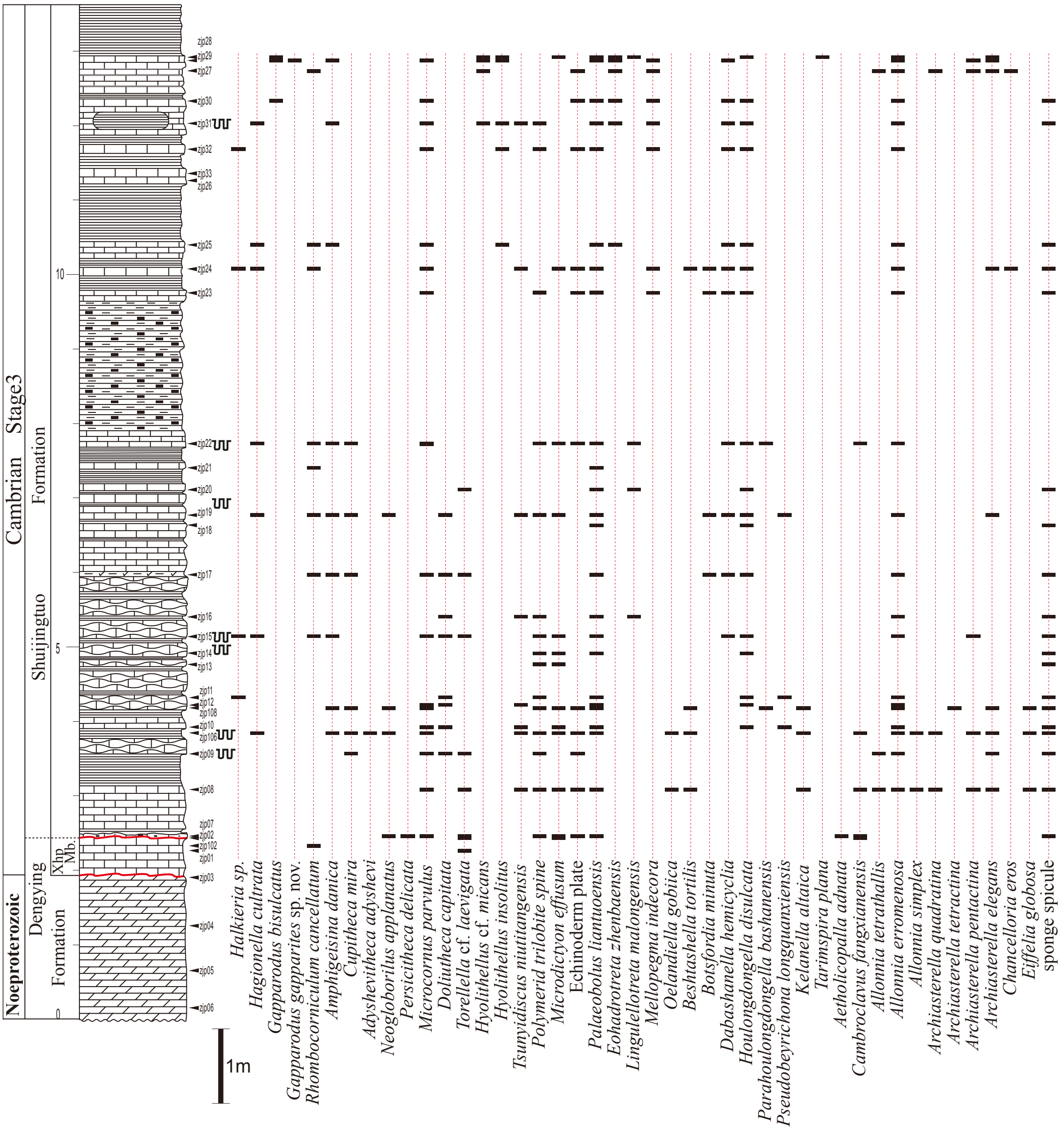

Fig. 4. Stratigraphic column with the distribution of SSFs in Zengjiapo Section, Zhenba County, South Shaanxi, China. For legends see Fig. 1.

In Zengjiapo (Fig. 4) the Xihaoping Member is strongly reduced in thickness and only contains few fossils such as *Torellella* cf. *laevigata* (Fig. 8C) and fragments of *Rhombocorniculum cancellatum*. About 40 km south of Zengjiapo, in Xiaoyangba, the Xihaoping Member is more complete and SSFs are abundant (Fig. 8A, B). Most of the fossils in the Xihaoping Member are fractured indicating transportation and strong reworking. *Torellella*, *Eoobolus* aff. *viridis*, polymerid trilobite fragments, *Cupitheca mira*, *Cambroclavus fangxianensis* (Fig. 7C), *Allonnia*, *Archiasterella*, *Chancelloria eros*, and hexactine sponge spicules represent the major elements of the SSF assemblage of the Xihaoping Member (Fig. 4). *Aetholicopalla adnata* (Fig. 7U) is rare in this interval. The only bradoriid in this member, *Haoia shaanxiensis* (Fig. 10A), only occurs in the upper Xihaoping Member (Fig. 4) and does not range into the overlying Shuijingtuo Formation, which is otherwise rich in bradoriid species. Some polymerid trilobite spines (Fig. 11N) show strong morphological similarity with *Zhijinites,* which, however, only occurs in the SSF Zone III of Yunnan (Yang et al., 2014b). This could explain why *Zhijinites* sp. was reported for the Xiaoyangba Section (Li et al., 2004a: Fig. 1) although we were unable to confirm the occurrence of *Zhijinites*. The trilobite spines resembling *Zhijinites* are distinguished from the latter genus by the larger size, different surface ornament and the curved irregular basal plate. *Cupitheca mira* is common in the Xihaoping Member and some specimens from the basal Shuijingtuo Formation with in-situ operculi of hyolith-type (Fig. 8O2) and a typical decollate hemispherical initial part (Fig. 8O1). Previously, it was considered to have a simple disc-like operculum (Bengtson et al., 1990), as *Actinotheca* p.203, 209, Fig. 138) rather typical for circothecids. Although it is obvious that the specimens of *Cupitheca* from Zengjiapo are related to hyolithids which abort the embryonic and initial part of conch, it is very likely that the genus is of polyphyletic origin. It can be assumed that the decollation of the embryonic and initial part may be a more common ontogenetic phenomenon among different groups of hyolithids and hyolithid-like animals. Before more data are available on operculum structure and surface texture to allow a taxonomic revision of *Cupitheca mira*, we still consider the taxon as valid in this study.

Persicitheca delicata (Fig. 8I, J) is reported here from the conglomeratic bed on the top of the Xihaoping Member at Zengjiapo. It was originally reported by Duan (1983) from the Xihaoping Region of Northwest Hubei Province (Fig. 2, section F). Later Qian (1989) synonymized it with *Neogloborilus applanatus*. We consider it considerably differing from *Neogloborilus applanatus* (Fig. 8H), for instance, by the straight, unique bolded growth lines, and the slender embryonic part, and thus retain the species. *Eoobolus* aff. *viridis* (Fig. 9A) is the only brachiopod in the Xihaoping Member. It is characterized by pustulose ornamentation on the outer surface (Fig. 9A3) and common in the succession. Echinoderm plates with epispires appear in the Xihaoping Member too. They are simple and considered to be centralias of the theca plates. Hexactinid sponge spicules preserved as phosphatic replacements also occur in the Xihaoping Member, but no demosponge spicules were yielded from this member, whereas they are common in the overlaying Shuijingtuo Formation.

A conglomeratic bed at the base of the Shuijingtuo Formation is widespread in the region and probably represents a reworking horizon of the topmost Xihaoping Member. This thin bed contains a mixed fossil assemblage with SSFs such as *Torellella* cf. *laevigata*, *Eoobolus* aff. *viridis* typical for the Xihaoping Member co-occurring with fossils typical for the Shuijingtuo Formation, such as *Palaeobolus liantuoensis*, *Eohadrotreta zhenbaensis*, *Microdictyon effusum* and *Microcornus parvulus* from the Shuijingtuo Formation. The overlying Shuijingtuo Formation contains diverse and well preserved SSF assemblage, including polymerid trilobites, eodiscoids *Tsunyidiscus niutitangensis*, the bradoriids *Dabashanella hemicyclia* (Fig. 10G, H), *Houlongdongella disulcata* (Fig. 10N), *Houlongdongella elevata*, *Kunmingella bimarginata*, *Kunmingella douvillei* (Fig. 10B), *Kunmingella xiaoyangensis*, *Parahoulongdongella bashanensis* (Fig. 10E, F), *Pseudobeyrichona longquanxiensis*, *Duibianella cf. elongata*, *Neoduibianella bella*, *Beyrichona chinensis*, the molluscs *Beshtashella tortilis*, *Mellopegma indecora* and *Oelandiella gobiica* (Fig. 9K-M), the brachiopods *Botsfordia minuta* (Fig. 9D), *Eohadrotreta zhenbaensis* (Fig. 9E, F), *Palaeobolus liantuoensis*, *Lingulellotreta malongensis*, the tommotiids *Lugoviella ojmuranica*, *Kelanella altaica*, the hyolithids, *Microcornus parvulus*, and a number of problematic fossils, such as *Rhombocorniculum cancellatum*, *Hagionella cultrata* (Fig. 6E), *Gapparodus bisulcatus*, *Amphigeisina danica*, *Microdictyon effusum*, *Tarimspira plana*, *Doliutheca* capitata (Fig. 8P, Q), *Neogloborilus applanatus*, *Torellella* cf. *laevigata*, *Hyolithellus* cf. micans, *Hyolithellus insolitus*.

Cambroclavus fangxianensis (Fig. 7C, D) which previously has been thought to only occur in the Xihaoping Member can also be rarely found in the lower Shuijingtuo Formation of Zhenba Region (Figs. 4,5). Eodiscoid trilobites are represented by *Tsunyidiscus niutitangensis* Chang, 1964 in the Zhenba regions. Formerly, this individuals were assigned to *Hupeidiscus orientalis* (Li et al., 2004a; Li et al., 2012), however, are different from the type-material of *Hupeidiscus* (Zhang, 1953). The former has typical axial rings and no pleural ribs on the pygidium. By considering the two genera as highly variable some studies (Lin et al., 2004) have synonymized them. However, it can be observed that typical *Hupeidiscus*-morphs occur in somewhat younger strata than *Tsunyidiscus*-morphs. Thus we consider both genera as valid until the ontogeny of them is fully resolved. Some polymerid genal and occipital spines and one redlichiid pygidium (Fig. 11I) were also recovered, which may belong to *Zhenbaspis* or *Wutingaspis*.

Echinoderm ossicles, sclerites of chancelloriids and *Eiffelia* are common in the Shuijingtuo Formation. The sponge spicules become more diverse and include hexactines (Fig. 7O), acanthohexactines (Fig. 7P) and demosponge spicules such as pentactinal plesiasters (Fig. 7Q), dichostauracts (Fig. 7R) and oxasters (Fig. 7S). Some star-shaped spicules (Fig. 7V) remotely resemble spicules of *Microcoryne cephalata* Bengtson et al., 1990 (Bengtson et al., 1990: P. 38, Fig.19P, T), but are more similar to sponge polyactins (Mehl, 1998: Plate 5, figs. 2-8) due to the presence of central canals. The majority of recovered echinoderm ossicles (Fig. 11Q, S) may have originated from eocrinoids similar to *Gogia* (Zamora et al., 2009; Zamora et al., 2013), *Sinoeocrinus* or *Globoeocrinus* (Zhao et al., 2011). They are especially common in the late early Cambrian- Guanshan Fauna (Hu et al., 2007) and early middle Cambrian Kaili Biota (Zhao et al., 2011). Some ossicles also resemble pinnulars (with saw-thoothed-like edges) of the camerates (Pisera, 1994: Pl. 59: 9), the marginalia of some echinoderms (Zamora et al., 2012: Fig. 3D), or thecal plates (Fig. 11T) of early ontogenic stages of *Gogia* (Zamora et al., 2013) or other pelmatozoans such as *Balangicystis* (Zhao et al., 2011: P176, Fig. 217) which are common in the Kaili Biota. Some stellate ossicles (Fig. 11W) resemble the centralia of solutes (Ubaghs, 1963: Plate 151, Figs. 1, 3, 4) or rhombiferans (Zamora and Smith, 2012). The pore-bearing ossicles (Fig.11X, Y) are similar to the diploporite thecal plates as shown by Pisera (1994). However, since none of the homalozoans or the blastozoans have been found in strata older than the early Middle Cambrian, the assignment of the herein figured ossicles remain questionable except for the the eocrinoids.

Fig. 5. Stratigraphic column with the distribution of SSFs in Xiaoyangba Section, Zhenba County, South Shaanxi, China. For legends see Fig. 1.

Phosphatic tubular organisms are common in the Shuijingtuo Formation. *Sphenothallus* and *Torellella* are typical representatives of the phosphatic tubular organisms in the Cambrian Stage 3, but have very few diagnostic characters and are partially difficult to distinguish. Both the genera are theca with fine transverse growthlines. Both of them may own apical holdfast or attachments disk (see *Torellella* in Fig. 8B, C). Differences of them existed in minor details according to the fossil records. As *Torellella* exhibits phosphatic tubes with less defined longitudinal thickenings and shallow and coarse transversal annulations, the longitudinal thickenings are prominent in *Sphenothallus* and the transversal ornamentation is finer and mostly restricted to the thinner wall between the longitudinally thickened regions. Kouchinsky et al. (2014) described tubular remains as *Torellella* although they are close to the characteristics of *Sphenothallus*. Although it is very possible that the genera were inherently different, the fossil records and reports show indistinct results. The tubular phosphatic remains of Zhenba County are here assigned to *Torellella* (Fig. 8A-C) although there exist minor differences between specimens from the Xihaoping Member and the Shuijingtuo Formation. These differences are here explained by variations in taphonomy.

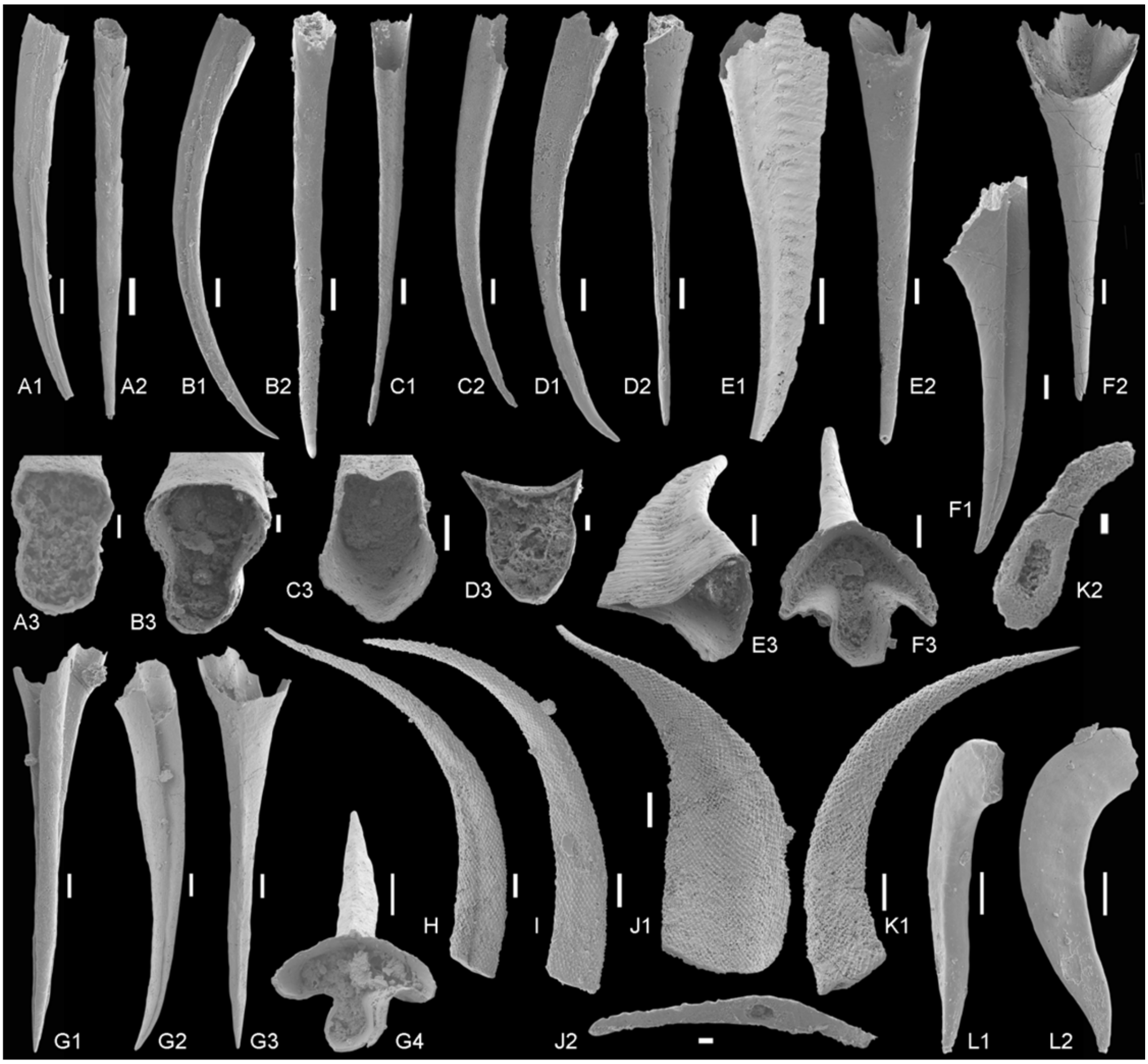

Fig. 6. SEM micrographs of SSFs from Zengjiapo (abbreviation Zjp) and Xiaoyangba (abbreviation Xyb), Zhenba County, Shaanxi. A, B. *Gapparodus bisulcatus* (Müller, 1959). A. No. Zjp28005. B. No. Xyb48041. A1, B1, lateral view; A2, B2, proximal view; A3, B3, detail of proximal view. C. Undetermined conodont-like fossil, no. Xyb34003. C1, proximal view; C2, lateral view; C3, Detail of proximal view. D. *Amphigeisina danica* (Poulsen, 1966), no. Xyb4808. D1, Lateral view; D2, proximal view; D3, detail of proximal view. E. *Hagionella cultrata* (Missarzhevsky, 1977), no. Xyb48040. E1, lateral view; E2, proximal view; E3, detail of proximal view. F, G. *Gapparodus gapparites* sp. nov. F. No. Xyb48045. G. Holotype No. Zjp30001. F1, G2, lateral view; F2, G1, G3, proximal view; F3, G4, detailed proximal view. H-K. *Rhombocorniculum cancellatum* (Cobbold, 1920). H. No. Xyb48044. I. No. Zjp25001. J. No. Xyb48020. K. No. Xyb48049. H, I, J1, K1, lateral view; J2, K2 detailed

proximal view. L. *Halkieria* sp., no. Zjp32001. L1, proximal view; L2, lateral view. All samples are from from Shuijingtuo Formation. Scale bars: A3, B3, D3, J2, K2 equal 20μm; C1, C2, E1 equal 200μm; others, 100μm.

The tommotiids are considered as stem-group representatives of the brachiopods, but remain very problematic because only few remains are reported with partially articulated sclerites. In the lower Shuijingtuo Formation we recorded different sclerite types that are assigned to *Lugoviella ojmuranica* (Fig. 12F).and *Kelanella altaica. Lugoviella ojmuranica* can be differentiated from other tommotiids by its unique longitudinal surface structure. However most of the tommotiids have more than two morphotypes of sclerites. For instance, Hinz (1987) suggested that *Lapworthella* have four morphotypes in the Comley Region. The most common tommotiids in the lower Shuijingtuo Formation have three different types of sclerites with numerous internal septae. They resemble materials previously described as *Sonella jinshaensis* (Yuan and Zhang, 1983) which is synonymous to *Kelanella altaica* from the Gorny Altai of Russia. The variability within the multimembranate scleritomes of most genera is not well documented. Some high sclerites of *Kelanella altaica* with rounded cross section (Fig. 12G) also resemble the sclerites of *Lugoviella ojmuranica* but are herein distinguished by the existence of strong longitudinal ridges.

4.2. Biostratigraphy

Species and thus biologically well-defined taxa of SSFs are the primary fundamental unit that forms the basis of palaeobiogeography, biostratigraphy and correlation of strata and links them. Application of SSF assemblages for a biozonation of the early Cambrian and correlation has been discussed by many studies (Brasier, 1989; Esakova and Zhegallo, 1996; Gubanov, 1998; Qian et al., 1999; Steiner et al., 2007). Originally, doubts have been casted on the utility of SSFs for biostratigraphy and international correlation (Qian and Bengtson, 1989; Landing, 1994; Maloof et al., 2010; Landing et al., 2013a), because of multiple problems with the taxonomy of SSFs (part-based taxonomy, different taxonomic approaches of national working groups), endemism in the Cambrian, prevalence of benthic species, and supposed facies-dependence of the early Cambrian faunas. However, more recent work revealed that specific taxa of SSFs are suitable for biostratigraphy and correlation of faunal zones on regional and intercontinental scale (Gubanov, 1998; Steiner et al., 2007; Yang et al., 2014b). It was also shown that specific taxa of SSFs, most likely with pelagic lifestyle or ontogenetic stages with planktonic distribution, such as species of *Protohertzina*, are not facies-dependant and have a wide cosmopolitan occurrence, allowing utility for biostratigraphic purposes (Steiner et al., 2007; Yang et al., 2014c).

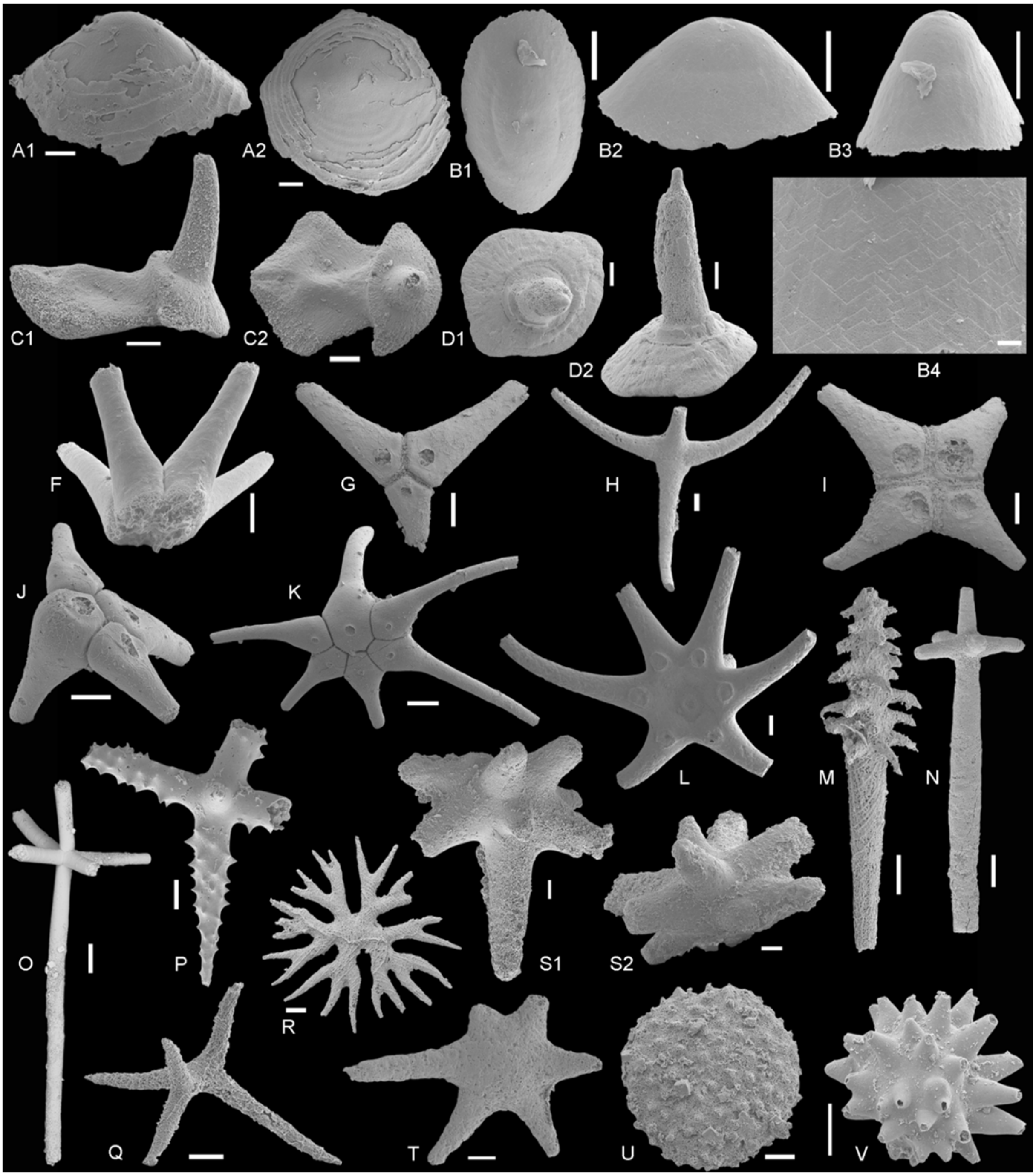

Fig. 7. SEM micrographs of SSFs from Zengjiapo (abbreviation Zjp) and Xiaoyangba (abbreviation Xyb), Zhenba County, Shaanxi. A, B. “smooth cones”. A. No. Xyb34001. B. No. Xyb47005. A1, B2, B3, lateral view; A2, B1, top view; B4 detail of B3 showing imprints of shell crystallites (calcite?). C, D, *Cambroclavus fangxianensis* Qian et Zhang, 1983. C. No. Zjp08002. D. No. Xyb47040. C1, D2, lateral view; C2, D1, distal view. F, I. *Allonnia tetrathallis* (Jiang in Luo et al., 1982). F. Zjp27001. I. No. Xyb20003. G. *Allonnia erromenosa* Jiang in Luo et al., 1982, no. Xyb08004. H. *Archiasterella quadratina* Lee, 1987, no. Xyb34031. J. *Archiasterella tetractina* Duan, 1984 no. Xyb09002. K. *Archiasterella elegans* Vassiljeva and Sayutina, 1993, no. Xyb28022. L. *Chancelloria eros* Walcott, 1920, no. Xyb33026. M. pinular diactine, no. Xyb48009. N. subtylostyle hexactine, no. Xyb34013. O. Hexactine. O. No. Xyb33001. P. Acanthohexactine, no. Zjp29004. Q. Pentactinal plesiaster, no. Xyb48052. R. Dichostauract, no. Xyb48017. S. Oxaster, no. Zjp08006. S1, distal view; S2, proximal view. T. *Eiffelia globosa* Walcott, 1920, no. Zjp106019. U. *Aetholicopalla adnata* Bengston et al. 1990, no. Xyb08002. V.

polyactin , no. Zjp106014. Samples G, J, and U are from Xihaoping Member, otherwise Shuijingtuo Formation. Scale bars: B4, 10 µm; G, I, J-L, T, 200 µm; others, 100 µm.

Maloof et al. (2010) correlated early Cambrian strata between Morocco, Siberia, South China and Mongolia by independent chemostratigraphical means and concluded that the first appearance dates (FADs) of all SSFs scattered over a considerable time interval of approximately 10 my. Based on this, Maloof et al. (2010) and Landing et al. (2013a) considered all early Cambrian metazoan fossils to be unreliable for chronostratigraphy and proposed to solely apply chemostratigraphical tools, like carbon isotopes, to achieve a chronostratigraphical correlation for the pre-trilobitic Cambrian strata. However, it is obvious that a correlation solely based on carbon isotopic curves may likewise create considerable miscorrelations if sections include stratigraphic breaks and reworking horizons (Steiner et al., 2013). Another challenge to the chemostratigraphy of carbon isotopes is the local impact of the regional facies that may not represent global seawater signals, a potential surface-to-deep ocean $\delta^{13}C$ gradient, a postgenetic impact by migrated hydrocarbons and the diagenetic alteration of stable isotope signatures (Fike et al., 2006; Jiang et al., 2007). Maloof et al. (2010) may have come to an incorrect wide scatter of the FAD of some important SSFs and even trilobites because of miscorrelations of isotopic peaks, especially between strata of South China, Mongolia and Siberia.

Qian et al. (1999) first established the *Rhombocorniculum cancellatum* Acme Zone and *Rhombocorniculum insolutum* Acme Zone for the Qiongzhusian of the Zhenba Region and the *Rhombocorniculum cancellatum-Microcornus parvulus* Assemblage Zone and *Lapworthella hubeiensis-Cambroclavus fangxianensis* Assemblage Zone for the Fangxian Region. Li et al. (2004a) could not confirm the occurrence of *Rhombocorniculum* in the Xihaoping Member. Thus, the zones were replaced by the *Ninella* (=*Aurisella*) *tarimensis-Cambroclavus fangxianensis* Assemblage Zone and *Rhombocorniculum cancellatum* Taxon-range Zone (Steiner et al., 2004; Steiner et al., 2007). However, in this study we can show, that *Rhombocorniculum cancellatum* occurred in both the Xihaoping Member and the Shuijingtuo Formation and *Cambroclavus fangxianensis* extends from the Xihaoping Member into the lower Shuijingtuo Formation (Figs. 4, 5). This confirms the earlier report of *Rhombocorniculum* from the Xihaoping Member (Xie, 1990). The new observations make a revision of biozones of the Zhenba-Fangxian Block necessary. Herein a new SSF zone, the *Cambroclavus fangxianensis-Rhombocorniculum cancellatum* Assemblage Zone is proposed. This new zone combines the former *N.* (=*Aurisella*) *tarimensis-C. fangxianensis* Assemblage Zone and *R. cancellatum* Taxon-range Zone but also replaces the former *Rhombocorniculum cancellatum-Microcornus parvulus* Assemblage Zone and *Lapworthella hubeiensis-Cambroclavus fangxianensis* Assemblage Zone. The new zone is defined by *Cambroclavus fangxianensis* (Fig. 7C, D), *Rhombocorniculum cancellatum* (Fig. 6H-K) and *Beshtashella tortilis* (Fig. 10I, J). The lower boundary is marked by the first appearance (FAD) of *Cambroclavus fangxianensis* and the upper boundary is defined at the latest occurrence (LAD) of *Rhombocorniculum cancellatum* and *Beshtashella tortilis*. This zone occurred from the base of the Xihaoping Member to the Shuijingtuo Formation in southeastern Shaanxi and northwestern Hubei.

The fauna in the Zhenba Region can be correlated with the early-middle Cambrian Stage 3. Intercontinental correlation is especially well established with regions where two or three of the index fossils of the *Cambroclavus fangxianensis*-*Rhombocorniculum cancellatum* Assemblage Zone are reported, such as Maly Karatau, Saxo-Thuringia of Armorica (all with three species) and Tarim, Spain, South Australia (two species).The SSFs from the Zhenba Region are assigned to the Qiongzhusian and may extend to the lower Canglanpuan regional stages of South China. These are correlated with the middle-upper Atdabanian to-lower Botoman regional stages of Siberia. *Beshtashella* has been also reported from Maly Karatau & Talas Alatau, Saxo-Thuringia of Armorica (the Görliz Region of Germany), Spain, Antarctica and South Australia. Except for the Zhenba-Fangxian Block, *Cambroclavus* is also occurring in Tarim, Maly Karatau & Talas Alatau, Armorica (Saxo-Thuringia, Sardinia, Spain) and South Australia (Appendix 1). *Rhombocorniculum cancellatum* is a cosmopolitan species reported from 13 occurrences that can be assigned to four bioprovinces (out of seven) recognized herein (Fig. 13, Appendix 1). They are (i) Tarim, Maly Karatau & Armorica including the Zhenba-Fangxian Block, (ii) western "Kipchak" Island Arc including Mongolia and Kusnetzk Alatau, (iii) Siberia & Avalonia (Nova Scotia, Massachusetts, England), and possibly (iv) Australia. Only one specimen of *R*. cf. *cancellatum* (Gravestock et al., 2001: Plate XI, Fig. 4) has been reported from South Australia, but it remains questionable. No specimens have been reported from Laurentia although this continent is grouped with the Siberia and North Avalonia. These two genera co-occurred in Northwest Hubei, Tarim, Maly Karatau and Talas Alatau, Saxo-Thuringia (Görliz) of Germany and Sardinia.

In addition to the co-occurrence of *Rhombocorniculum cancellatum* and *Cambroclavus fangxianensis* many other species are also co-occurring in the Xihaoping Member and Shuijingtuo Formation. Only few species, like *Haoia shaanxiensis*, are discriminative for the Xihaoping Member, whereas a number of species only occurred in the Shuijingtuo Formation. It is herein hypothesized that the slight difference in the faunal composition is likely due to a facies-dependance of part of the fauna in the sedimentary regime of a deepening depositional setting. In the Fangxian Region of North Hubei in general a very similar SSF assemblage (Qian and Zhang, 1983; Wang et al., 2010) as in the Zhenba Region has been reported. Bradoriids such as *Liangshanella*, *Beyrichona* have a geological range from lower part of Cambrian to middle or upper Cambrian (Zhang, 2007). Some brachiopods such as *Eoobolus* (Holmer et al., 1996; Skovsted and Peel, 2007), *Botsfordia* (Holmer et al., 1996), acrotretids (Hinz, 1987; Li and Holmer, 2004; Landing et al., 2008), *Palaeobolus* and *Lingulellotreta* (Holmer et al., 2001) have a long range from late early Cambrian to early middle Cambrian. *Lingulellotreta malongensis* occurs in the Qiongzhusian in South China generally correlated with the Atdabanian of Siberia. Before it was also reported in the Botoman and younger strata of Maly Karatau, Kazakhstan (Holmer et al., 1997). Our own observation revealed that *Neogloborilus applanatus*, *Lingulellotreta malongensis* and *Eohadrotreta zhenbaensis* occurred in the early Cambrian strata -of Maly Karatau that are equivalent to the Atdabanian-Botman strata of Siberia (Appendix 1).

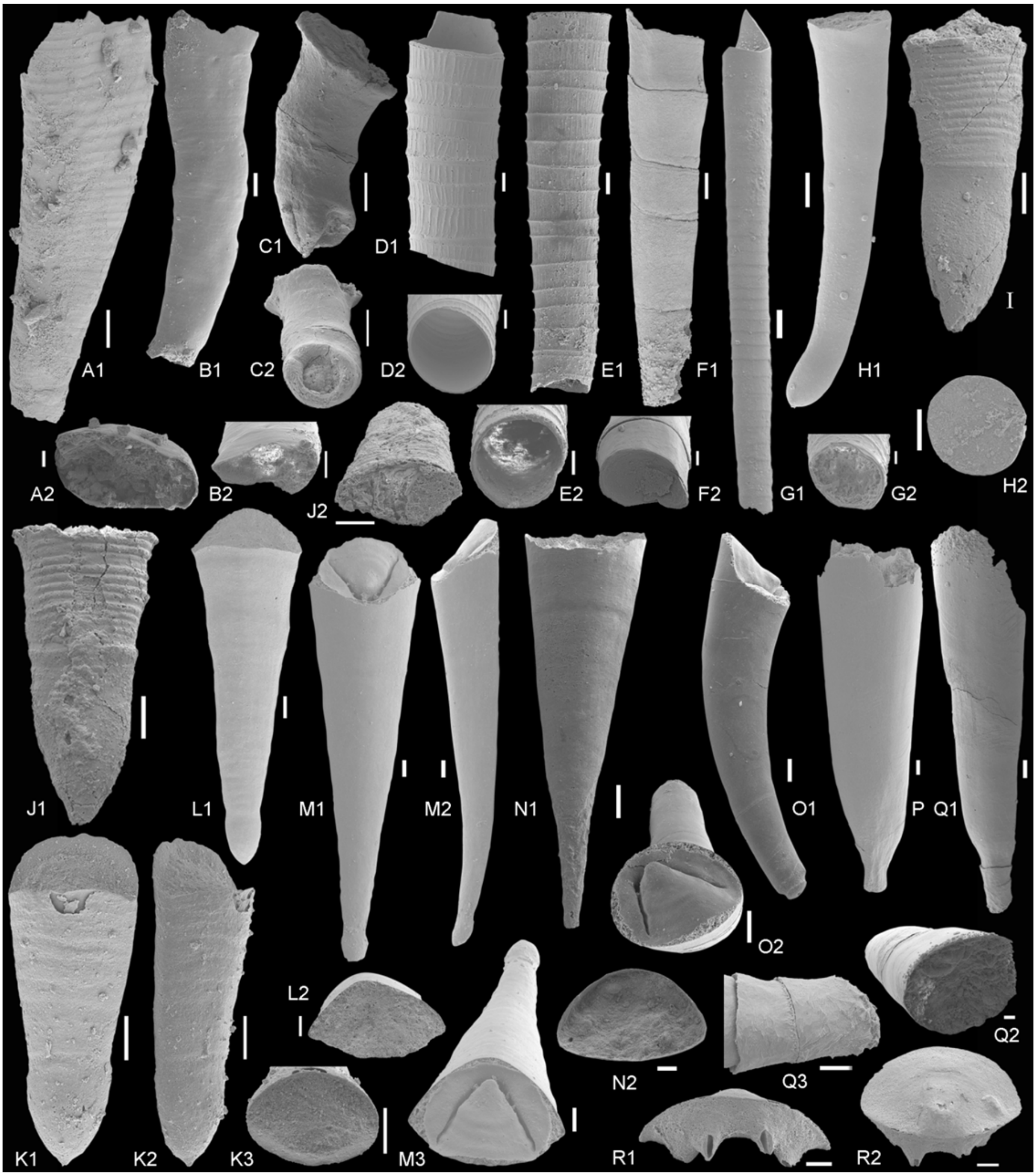

Fig. 8. SEM micrographs of SSFs from Zengjiapo (abbreviation Zjp) and Xiaoyangba (abbreviation Xyb), Zhenba County, Shaanxi. A-C. *Torellella* cf. *laevigata* (Linnarson, 1871). A. No. Xyb151001. B. No. Xyb07003. C. No. Zjp02001. A1, B1, C1, lateral view. A2, B2, C2, detail of cross-section. D, E. *Hyolithellus insolitus* Grigor'eva in (Voronin et al., 1982). D. No. Zjp28010. E. No. Zjp29011. D1, E1, lateral view. D2, E2, detail of cross-section. F. Undetermined hyolith, no. Xyb47019. F1, longitudinal view; F2, detail of cross-section. G. *Hyolithellus* cf. *micans* Billings, 1871, no. Zjp28012. G1, longitudinal view; G2, detail of cross-section. H. *Neogloborilus applanatus* Qian and Zhang, 1983, No. Zjp106007. H1, longitudinal view; H2, detail of cross-section. I, J. *Persicitheca delicata* Duan, 1983. I. No. Zjp07010. J. No. Zjp07006. I, J1, longitudinal view; J2, detail of cross-section. K-M. *Microcornus parvulus* Mambetov, 1972. K. No. Zjp106010. L. No. Zjp108003. M. No. Zjp106001. K1, L1, M1, dorsal view. K2, M2, lateral view. K3, L2, M3, apertural view. N. *Dipterygovitus lentiformis* (Qian, 1978), No. Xyb128-41. N1, lateral view; N2, apertural view. O. *Cupitheca mira* (He in Qian,

1977), no. Zjp106-42. O1. longitudinal view; O2, detail of cross-section. P, Q. *Doliutheca capitata* (Jiang in Luo et al., 1982) P. No. Zjp108004. Q. No. Xyb48051. P, Q1, longitudinal view; Q2, detail of cross-section; Q3, detail of the apex. R. Disarticulated hyolithid operculum, no. Xyb34026. R1, proximal view; R2, top view. Samples A-C are from Xihaoping Member, otherwise Shuijingtuo Formation. Scale bars: G2, 20 µm; A1, F1, N1, Q1, 200 µm; others, 100 µm.

The *Cambroclavus fangxianensis*-*Rhombocorniculum cancellatum* Assemblage Zone of Zhenba-Fangxian Block can be correlated with the *Pelagiella subangulata* Taxon-range Zone and the *Wutingaspis*-*Eoredlichia* Zone of the Yangtze Block, the *Abadiella huoi* Zone of Australia, the *Callavia broeggeri* Zone in West Avalonia. It is important to note that the index fossils of the *Cambroclavus fangxianensis*-*Rhombocorniculum cancellatum* Assemblage Zone do not occur on the Yangtze Platform and the index fossil of the *Pelagiella subangulata* Taxon-range Zone is not known from the Zhenba-Fangxian Block. Correlation between these regions is only supported by the occurrences of *Tsunyidiscus niutitangensis, Microdictyon effusum* and *Kunmingella douvillei*.

5. Palaeobiogeography of Cambrian Stage 3 SSFs

The evolution of metazoan species has a distinct geographic component besides the temporal aspect. Geographic speciation is one of the major types in speciation (Rosenzweig, 1995). Geographic isolation is a common, but not the only, factor that leads to a separation of the gene pool of an ancestor species and may form at a slow rate deviating gene pools representing than new species. Species and communities that are separated by physical barriers, such as on different continents separated by deep oceanic basins or high mountains, develop independently and form specific biogeographic regions and provinces. In palaeobiogeography, the reconstruction of faunal provinces may help to understand the palaeogeography, especially if palaeomagnetic data are not available or are unreliable. For the Ediacaran and early Cambrian times only few attempts of reconstructing the palaeobiogeography are available (Pillola, 1990; Lieberman, 1997; Álvaro et al., 2003; Meert and Lieberman, 2004, 2008). These studies were mostly based on the distribution of trilobites or other arthropods. Early on it was recognized that three distinct trilobite provinces existed during later early Cambrian (Pillola, 1990), reflecting the major palaeogeographic constellation of this time with four larger continents (Baltica, Siberia, Laurentia and Gondwana) separated by deep oceans. This indicates that part of the fauna developed a high degree of endemism during Cambrian Series 2 and 3. Here we attempt to test the application of Cambrian Stage 3 SSFs for reconstructing the palaeobiogeographic pattern and develop a hypothesis for the palaeogeographic relationship of the Zhenba-Fangxian Block.

Systematic global presence/ absence data of SSF species of the Cambrian Stage 3 (equivalent Atdabanian-Botoman of Siberia and Qiongzhusian of South China) were assembled in an Excel-based data matrix for the various palaeocontinents or terranes (Appendix 1, 2). The taxonomic assignments of the SSFs of the inserted species of this time interval were critically evaluated to minimize artificial oversplitting or incomparability by different taxonomic concepts by the various national working groups. Thus some species were combined in the database under one species according to our taxonomic judgment even if an official revision is not yet published. Taxa in open nomenclature (e. g. *Alisina* sp.) were recorded in the database, but not accounted for the final statistical test (Appendix 1). Due to the fact that several form-taxa of SSFs are based on few and simple characters of partial shell material, that likely do not represent single bio-species, simple tube-like fossils, such as *Hyolithellus* species, are excluded from the database. Problematic hyolithids that are often only known from compressed imprints in shales were also not included in the database considering their problematic taxonomy. Only species of several genera were listed that are known with preserved embryonic shell and operculi, such as *Microcornus*, *Neogloborilus*, *Triplicatella* (Skovsted et al., 2004). Species of *Mongolitubulus* were excluded from the database as they were shown with an polyphyletic origin (Skovsted, 2005; Li et al., 2012; Caron et al., 2013). Species were also combined if previous studies have made synonymy likely, such as for numerous species of the micro-mollusc *Aldanella* (Landing, 1988). Tommotiids, such as *Kulparina*, *Eccentrotheca*, *Camenella*, *Sunnaginia*, and *Lapworthella* sclerites are of multielement and have various morphotypes. Their taxonomy has been improved toward a more biologically defined species concept in recent years (Skovsted et al., 2009a; Skovsted et al., 2011; Skovsted et al., 2014). We are aware that there still remains uncertainties with the taxonomy of some SSFs. However, we are confident that our revised database reflects the regional biodiversity based on biologically defined species in principle. To avoid strong sample size effects we deleted all regional faunas with less than 5 recorded species and split extremely large faunas into smaller geographic sub-units. Finally, 295 species from 32 regions were included in the database.

We took specific care of selecting the faunas with a firm biostratigraphic assignment and assigning them to internationally recognizable time bins. In the Cambrian Stage 3, many species of the bradoriids, molluscs and brachiopods extend into younger strata. Thus, the time boundaries and especially the upper boundary are of key importance for the analysis. We preferentially assigned the published SSF data according to the appearance of potential guide SSFs (distribution of *Rhombocorniculum cancellatum*, *Cambroclavus fangxianensis* Group, *Lapworthella cornu* Group, FADs of *Pelagiella subangulata, Amphigeisina danica/ renae, Microdictyon effusum* Group) and of trilobites. If no internationally correletable species of SSFs and trilobites are present in specific regions, the basal threshold for the assignment of data is the appearance of earliest trilobites.

Species-based similarity studies were carried out using the data matrix (Appendix 1) by Hierarchical Cluster Analysis with Pearson Correlation interval in SPSS 20 (Fig. 13). Phylogenetic parsimony analysis could not be applied in the present study, because no firm phylogenetic cladistic analyses are available for the most SSFs. The cluster dendrogram reveals faunal relationships that are generally consistent with the latest palaeogeographic models for the early Cambrian (Torsvik and Cocks, 2013b). The cluster analysis reveals seven major clades (Fig. 13) interpreted here as palaeobiogeographic provinces with high faunal similarity.

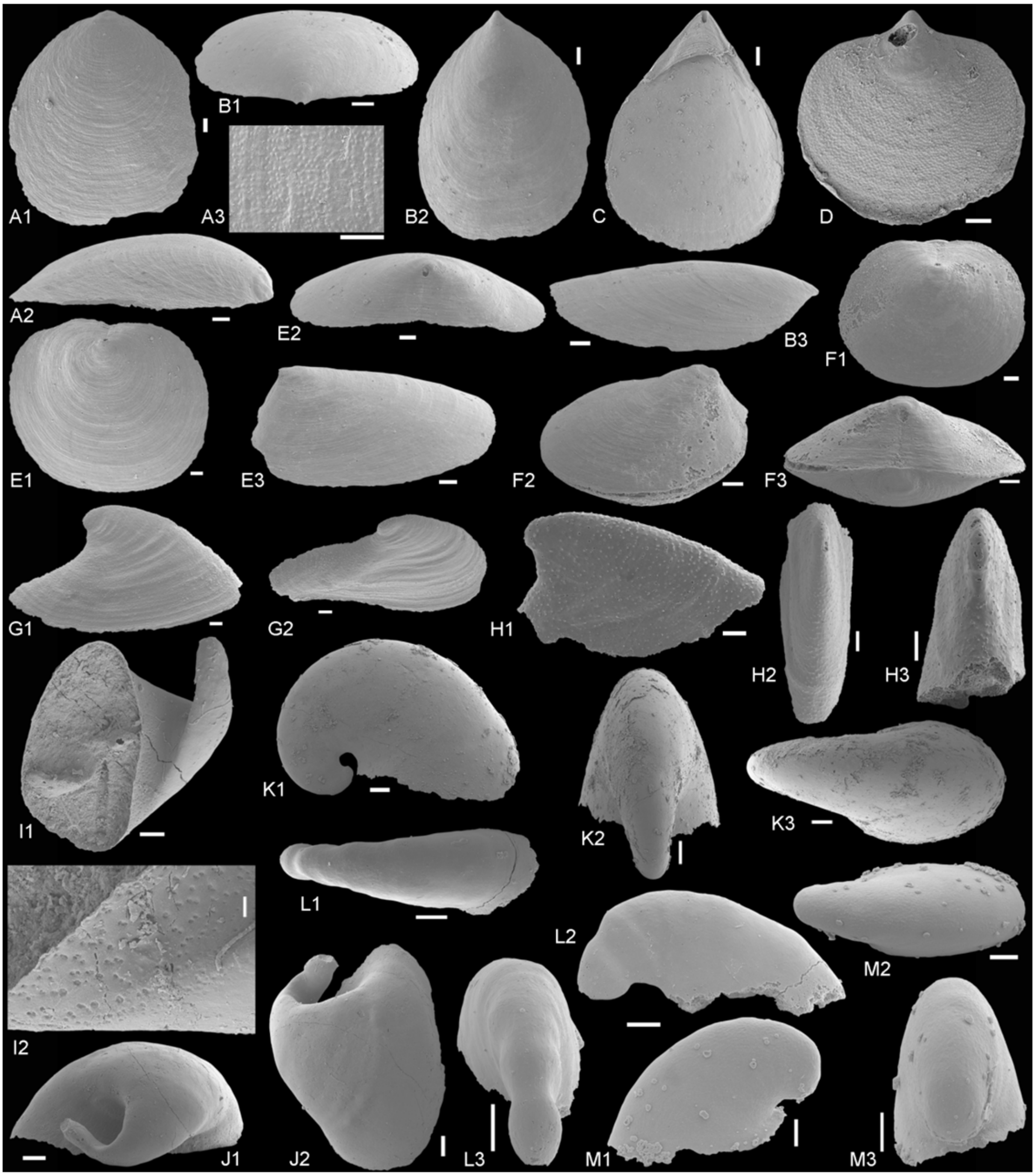

Fig. 9. SEM micrographs of SSFs from Zengjiapo (abbreviation Zjp) and Xiaoyangba (abbreviation Xyb), Zhenba County, Shaanxi. A. *Eoobolus* aff. *viridis* (Cobbold, 1920), no. Xyb07004, dorsal valve. A1, dorsal view; A2, lateral view; A3, detail of pustulose ornamentation. B. *Palaeobolus liantuoensis* Zeng, 1987, no. Zjp29009, ventral valve. B1, anterior view; B2, ventral view; B3, lateral view. C. *Lingulellotreta malongensis* (Rong, 1974), no. Xyb3600, ventral valve, exterior. D. *Botsfordia minuta* Li and Holmer, 2004, no. Xyb28001, ventral valve. E, F. *Eohadrotreta zhenbaensis* Li and Holmer, 2004. E. No. Zjp29006, dorsal valve. F. No. Zjp29015, articulated shells. E1, F1, dorsal exterior; E2, F3, anterior view; E3, F2, lateral view. G, H. *Mellopegma indecora* (Rozanov et al., 1969). G. No. Zjp24009. H. No. Zjp24004. G1, H1, lateral view; G2, H2, top view; H3, proximal view. I, J. *Beshtashella tortilis* Missarzhevsky and Mambetov, 1981. I. No. Zjp08010. J. No. Xyb34037. I1, apertural view; I2, detail of the pitted shell microstructure; J1, proximal view; J2, top view. K-M. *Oelandiella gobiica* (Zhegallo in Voronin et al., 1982). K. No. Xyb47014. L. No. Xyb39004. M. Xyb47001. K1, L2, M1, lateral view; K2, L3, M3,

proximal view; K3, L1, M2, top view. Sample A is from Xihaoping Member, otherwise Shuijingtuo Formation. Scale bars: I2, 20 µm; B1-3, C, K1-3 200 µm; others, 100 µm.

(I) The first faunal province includes the terranes of Mongolia and the adjacent terranes of western Siberia such as the Mongolian Transitional Zone, Tuva-Mongolia, Dzhabkan Terrane, and the Kuznetsk Alatau that may be considered as western part of an “Kipchak” island arc (Sengor et al., 1993). This province is stronger related to the second province (II) that includes Siberia and Avalonia, comprising Nova Scotia, East Massachusetts, England (including the Comley, Nuneaton and Rushton regions) and the northern and southern Siberia Platform. This province further supports a unified terrane with parts of eastern and western Avalonia and its independence from Western Gondwana (Landing et al., 2013b). However, it also suggests closer links between Avalonia with Siberia during Cambrian Stage 3. (III) The third faunal province represents Laurentia including western Newfoundland and Greenland.

The faunal provinces (IV) to (VI) are more closely related to each other, indicating links to Gondwana (Fig. 13). (IV) The fourth faunal province encloses parts of East Gondwana such as Antarctica and Australia. This confirms previous recognition of strong similarities of the SSF assemblages from Antarctica with those of South Australia (Wrona, 2003, 2004). However, the statistical distance in the Pearson Correlation-analysis also shows some dissimilarity in the faunas from Antarctica and South Australia. This may be because of the asymmetry in the data of the two regions. As 99 species of SSFs were recorded from South Australia, only 35 were reported from Antarctica, possibly reflecting an observational bias for Antactica (Appendix 1).

(V) The fifth faunal province is confined to the North China Block including regions in southern Henan, central Shaanxi (e.g. Luonan region) and northern Anhui. The statistical distance in the Pearson Correlation-analysis reveals a stable cluster with especially high faunal similarity in the neighboring Henan and Shaanxi regions. The North China Province indicates slightly higher affinities toward the (VI) of Zhenba-Fangxian/ Armorica/ Tarim/ Karatau-Naryn assemblages than to East Gondwana.

(VI) The sixth faunal province covers numerous smaller terranes or micro-continentsof the Armorica Terrane Assemblage (including Sardinia, Saxo-Thuringia of Germany, Taurus Mountains of Turkey, Spain), Karatau-Naryn Terrane (South Kazakhstan-North Kyrgyzstan) and Tarim, but also includes the main region of this study, the Zhenba-Fangxian Block (Southeast Shaanxi and North Hubei). This faunal province is related to the western Gondwanan Realm. Faunas from the Xihaoping Member of the Zhenba-Fangxian Block form a stable cluster with a low statistical distance (Fig. 13) that are next grouped with faunas from Tarim, and a cluster of the slightly younger SSF assemblage (of the Shuijingtuo Formation) from Zhenba-Fangxian Block and that from the Maly Karatau-Talass Alatau. Compared with Gondwanan faunas of North China, Australia, and Armorica, the fauna of Zhenba-Fangxian Block lacks many important molluscs such as *Pojetaia*, *Stenotheca*, *Mackinnonia* and *Protowenella*, etc., indicating its distinction of the SSF composition and therefore the palaeonbiogeography.

(VII) The seventh faunal province is the Yangtze Province, which is most separated from any other provinces included in this study. The reasons for this dissimilarity remain uncertain. Notwithstanding, it may be hypothesized that the Yangtze Platform was more detached from Western Gondwana during Cambrian Stage 3 than in earlier ages of the Cambrian.

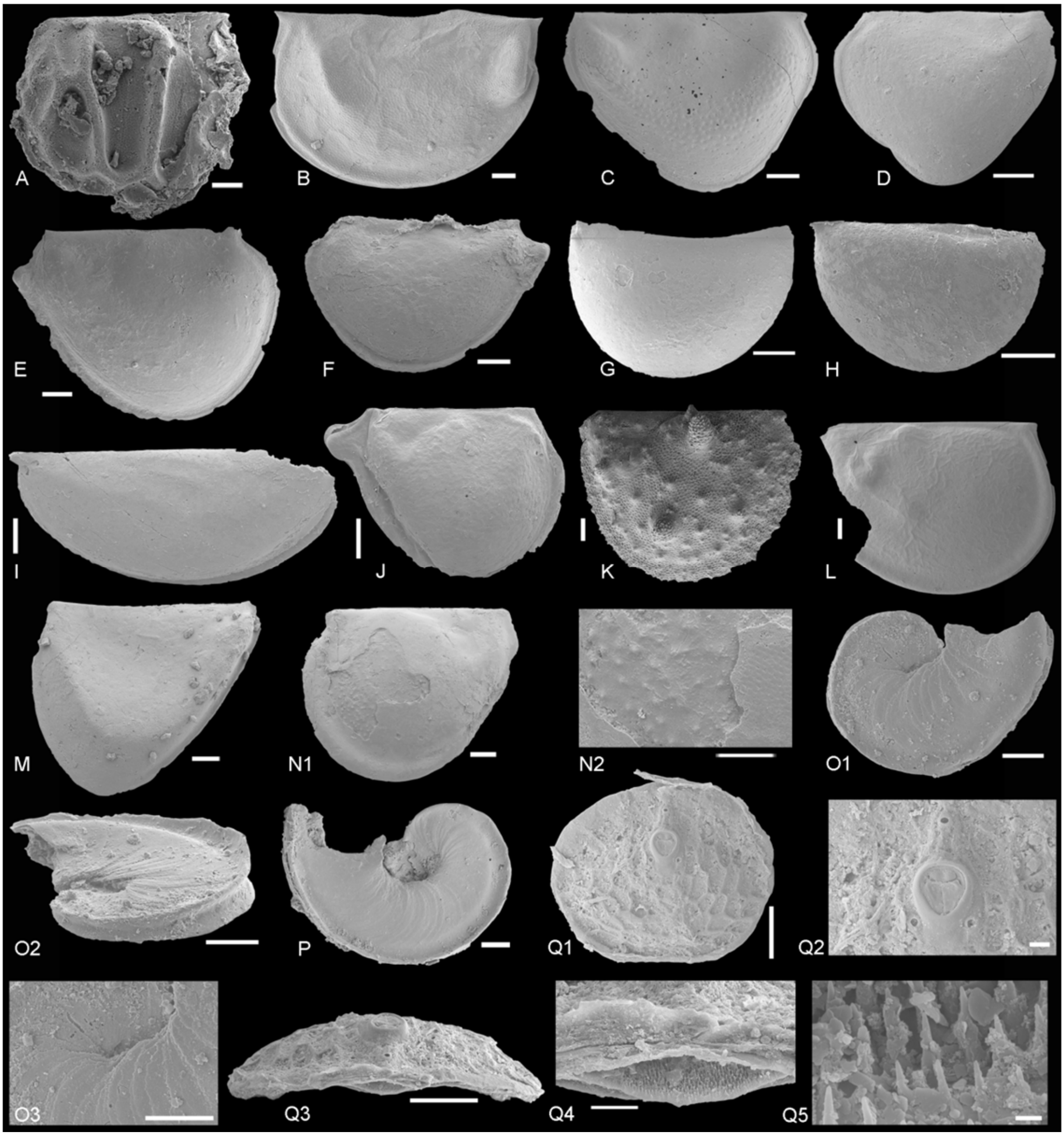

Fig. 10. SEM micrographs of SSFs from Zengjiapo (abbreviation Zjp) and Xiaoyangba (abbreviation Xyb), Zhenba County, Shaanxi. A. *Haoia shaanxiensis* Shu, 1990, no. Xyb22001. B. *Kunmingella douvillei* (Mansuy, 1912), no. Xyb28018. C. *Beyrichona chinensis* Shu, 1990, no. Xyb42002. D, E, F. *Parahoulongdongella bashanensis* Shu, 1990. D. No. Xyb34025. E. No. Xyb28006. F. No. Xyb28025. G, H. *Dabashanella hemicyclia* Huo et al., 1983. G. No. Zjp19002. H. No. Zjp29005. I. *Isoxys* sp., no. Xyb39010. J. Undetermined bradoriid, no. Xyb42001. K. *Neoduibianella bella* Shu, 1990, no. Xyb33005. L. Undetermined bradoriid, no. Xyb33030. M. *Pseudobeyrichona longquanxiensis* (Cui and Huo, 1987), no. Xyb48012. N. *Houlongdongella disulcata* Li, 1975, no. Xyb48010. N2, detail of N1. O, P. *Tarimspira plana* Yue and Gao, 1992. O. No. Zjp28003. P. No. Xyb48032. O1, P, top view; O2, proximal view; O3, detail of the whorl centre. Q. Bradoriid?, no. Xyb46002. Q1, top view; Q2, detail of the central part of Q1; Q3, proximal view; Q4, detail of Q3; Q5, detail of Q4. Samples A, is from Xihaoping Member, otherwise Shuijingtuo Formation. Scale bars: C-F, J, L-N, 200 μm; Q2, Q4, 20 μm; Q5, 1 μm; others 100 μm.

The East Transbaikalia and the Yichang Region (Central Hubei Province) remain weakly constrained in our statistical analysis. This is probably caused by the incompleteness of the fossil data from these two regions. For East Transbaikalia there is only data on the molluscs available (Parkhaev, 2004) and the fauna from the Yichang Region is poor too (Wang et al., 2010). It will be a target of future investigation to gather more reliable data on SSFs for these two regions.

In general, the palaeobiogeography of the SSF faunas shows that the Zhenba-Fangxian Block has a quite different SSF assemblage from the Yangtze Block that is rather similar to that of the Tarim/ Karatau-Naryn and Armorica Province. This further supports doubts if the Zhenba-Fangxian Block was part of the Yangtze Platform during the Ediacaran-early Cambrian.

6. Discussion of the affinity of Zhenba-Fangxian Block and conclusion

Together with the North Qinling Terrane, the South Qinling Terrane composes the Qinling Orogeny. The South Qinling Terrane is adjacent to the northern margin of the Yangtze Block, bounded by the Mianlue Suture Zone in the southwest and the Shangzhou-Danfeng Suture Zone in the North (Fig. 2). The origin of South Qinling Terrane, and its relationship with the North Qinling Terrane and the Yangtze Block, have been discussed in detail by numerous authors (Zhang et al., 1996; Zhang et al., 2001; Lai et al., 2002; Ling et al., 2007). For long time the South Qinling Terrane has been regarded as part of the active continental margin of the Yangtze Block (Zhang et al., 1996; Zhou et al., 2002; Zhengxiang Li et al., 2003; Zhao and Cawood, 2012; Cawood et al., 2013) in the late Meso-Neoproterozoic. According to this opinion, the northern Yangtze Craton also included the Bikou Terrane, Hannan Block, Zhenba-Fangxian Block and the Wudang Block (Zhengxiang Li et al., 2003; Zhao and Cawood, 2012; Cawood et al., 2013). Following this, the Qinling Terranes developed as an extended region between the North China Block and the Yangtze Block, being influenced by rifting and collision processes (Zhang et al., 1996; Meng and Zhang, 2000; Zhang et al., 2004; Xiao et al., 2011; Shi et al., 2013). The theory implied that only a limited ocean basin developed in the position of the nowadays Mianlue Suture Zone during the late Neoproterozoic and early Paleozoic (Yan et al., 2007; Wang et al., 2009). The South Qinling Belt includes accretionary complexes, arc and back-arc complexes, forearc basins, continental slope of back arc basins and foreland thrust fold belts (Pan et al., 2009; Wang et al., 2009). However, there has also been expressed doubt that the South Qinling Terrane may not be divided from the Yangtze Block (Ling et al., 2010).

It has been regarded that many of the blocks on the northern margin of the Yangtze Block, such as the Bikou Terrane, Hannan Block, Wudang Block and South Qinling Terrane were derived from the Yangtze Block during the Neoproterozoic (Zhang et al., 1996; Zhengxiang Li et al., 2003; Ling et al., 2007; Dong et al., 2011b; Zhao and Cawood, 2012). Bikou Terrane, Hannan Block and Wudang Block are located in a similar tectonic position at the northern margin of Yangtze Craton or within the South Qinling Terrane and indicate similar ages (846-776 Ma–Bikou Terrain, Yan et al., 2003; 860-745 Ma–Hannan Block, Zhao and Zhou, 2008; 830-780 Ma–Wudang Block, Ling et al., 2010). Zircon U-Pb age spectra of the South Qinling Terrane and the Yangtze Craton were interpreted to show a great similarity (Shi et al., 2013). But the conclusion is mostly based on some age spectra that are globally distributed (Shi et al., 2013). And some age spectra included to the northern Yangtze Craton may possibly not be assigned to the Yangtze Block sensu stricto, but rather to the South Qinling Terrane. As Ling et al. (2010) pointed out, the ~750 Ma (Ling et al., 2008) magmatic suites are restricted to the northern and western margin of the Yangtze Block. In general, magmatic events centered at ~750 Ma, 1850 Ma and 2480 Ma are globally distributed (e.g., Wang et al., 2014). For instance, volcanic suites of the Dzhabkhan-Mongolia micro-continent also showed ages of 805-770 Ma and older gneiss and granites have ages of ~1850 Ma, 2365 Ma and 2650 Ma (Levashova et al., 2010). Tuffs of the Kurgan Formation from the Maly Karatau of South Kazakhstan also revealed zircon U-Pb ages of 803-750 Ma and yielded some older populations with ages of 860-835 Ma, 2049-2015 Ma or single older grains (Levashova et al., 2011).Therefore the events of these ages are not a robust evidence for the connection of all the small blocks at the northern margin of Yangtze Craton and the South Qinling Terrane with the Yangtze Block sensu stricto.

The meta-volcanic, meta-sedimentary and mafic rocks of the Wudang Block within the South Qinling Terrane (see Zhang et al., 2013) also show multistage zircon ages centered at 680 Ma, 780-730 Ma, 1975-1925 Ma. The ~680 Ma magmatic events of the Wudang Block are not known from the Yangtze Block (Ling et al., 2010). Mafic-ultramafic intrusions of the Hannan Block show typical arc-specific geochemical characteristics and some intrusions indicated εNd values similar to that of 750-Ma MORB (Zhao and Zhou, 2009). Similarly it was shown that the Bikou Terrane includes tholeiitic rocks similar to basalts in arc settings and the geochemical signatures are mostly of initial and oceanic arcs (Yan et al., 2003). Also Wang et al. (2008) showed that the upper basaltic rocks of Bikou Terrane have ocean-island basalt signatures, however, concluding that they were continental flood basalts. An mélange zone with ophiolites is also interpreted to separate the South Qinling Terrane from the Yangtze Craton, Bikou Terrane, Hannan Block and Zhenba-Fangxian Block (Dong et al., 2011b). Geochemical signatures, petrology and tectonic settings of the Bikou Terrane, Hannan Block and Wudang Block that surround the Zhenba-Fangxian Block indicate an arc-derived nature of this tectono-magmatic units during the Neoproterozoic. The common view is that the South Qinling Terrane was a continuous facies belt of the northern Yangtze Craton and a continental island arc developed during the Neoproterozoic (Meng and Zhang, 2000; Dong et al., 2011b). However, doubt was expressed early on whether the convergences and divergences affecting the formation of South and North Qinling terranes always happened between the Yangtze and North China cratons (Mattauer et al., 1985; Ling et al., 2010). Jiang et al. (2000, P. 90-91) considered that North China and South China Blocks did not converge until the late Caledonian, because early Phanerozoic lithofacies, biofacies, and palaeomagnetics of both blocks were quite dissimilar. Recent palaeogeographic reconstructions do not suggest a close proximity between the Yangtze Craton and the North China Craton during Neoproterozoic-Cambrian transition (Torsvik and Cocks, 2013b). In general it appears unlikely that the position of the North China and South China cratons has been in a relatively stable position during multiple divergences and convergences over a period of about 300 million years as suggested by numerous authors (e.g., Dong et al., 2011b).

Our palaeobiogeographic analysis also shows that the Zhenba-Fangxian Block bears an early Cambrian SSF fauna that is quite different from that of the Yangtze Craton. Nor does it have any high similarity with the North China Province (Fig. 13). Considering the discussion above, it is possible that some small blocks, such as the Bikou Terrane, Wudang Block and the

Zhenba-Fangxian Block may have been more distant from the Yangtze Craton and originated from another craton or smaller terrane chains (such as Maly Karatau-Naryn, Armorica).

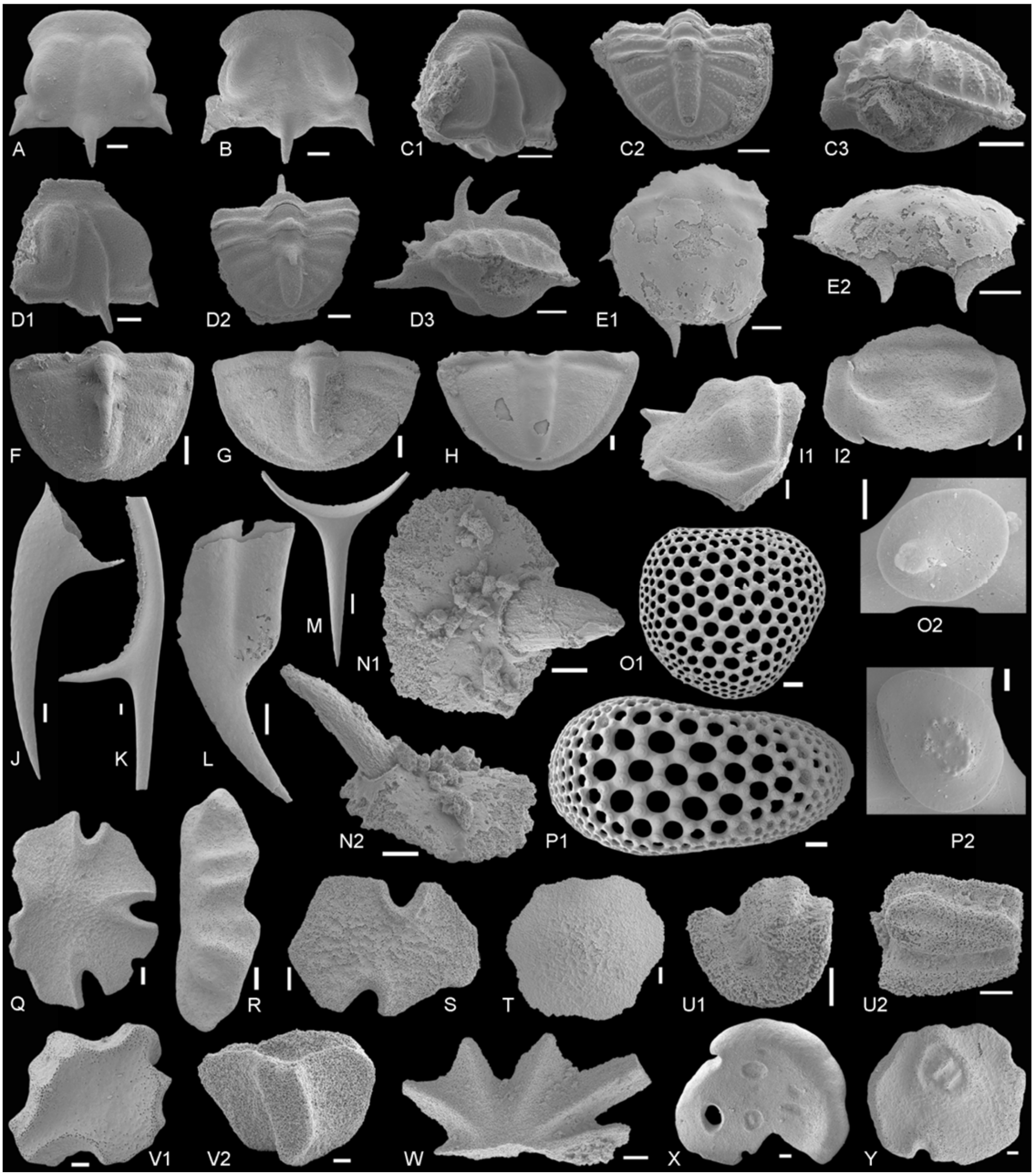

Fig. 11. SEM micrographs of SSFs from Zengjiapo (abbreviation Zjp) and Xiaoyangba (abbreviation Xyb), Zhenba County, Shaanxi. A-D, F, G, H. *Tsunyidiscus niutitangensis* (Chang, 1964). A. No. Xyb28026, cranidium. B. No. Xyb28014, cranidium. C. No. Zjp24015, enrolled whole holaspid. D. No. Zjp24014, enrolled whole meraspid (M2). C1, D1, lateral dorsal view of the cranidia; C2, D2, dorsal view of the pygidia; C3, D3, lateral view. F. No. Xyb28008, meraspid (M1) pygidium. G. No. Xyb28024, meraspid (M2) pygidium. H. No. Xyb47031, holaspid (H1?) pygidium. E. Redlichiid metaprotaspid (P1), no. Xyb34015. I. pygidium of undetermined redlichiid (? *Zhenbaspis*), no. Zjp106021. I1, lateral view; I2, dorsal view. J, K. Librigenal spines of polymerids. J. No. Xyb33028. K. No. Xyb33029. L. Pleural spine of polymerid, no. Xyb33027. M, N. Occipital spines of polymerid. M. No. Xyb33032. N. No. Xyb13003. N1, dorsal view; N2, lateral view. O, P. *Microdictyon effusum*

Bengtson et al. in Missarzhevsky and Mambetov, 1981. O. No. Xyb44005. P. No. Xyb48033. O1, P1, top view; O2, detail of O1; P2, detail of P1. Q-Y. Echinoderm ossicles. Q, S. Plates with epispires. Q. No. Xyb39002. S. No. Xyb47017. R. Pinnular with saw-like edges, no. Xyb47025. T. Thecal plate without epispires hinting at an early ontogenetic stage, no. Xyb34022. U. Biserial brachioles, No. Zjp23004. U1, proximal view; U2, distal view. V. Thecal plate, no. Xyb47018. V1, distal view; V2, proximal view. W. Stellate plate, no. Zjp24001. X, Y. Pore-bearing echinoderm plates. X. No. Xyb47044. Y. No. Xyb47026. Sample N is from Xihaoping Member, otherwise Shuijingtuo Formation. Scale bars: Q2, P2, 20μm; C1-3, J-M, P1, Q-T, W, X, 200 μm; others 100 μm.

At this point it is worth to illuminate if the Neoproterozoic-Cambrian lithofacies of the northern Yangtze Craton, South Qinling Terrane, and Zhenba-Fangxian Terrane represents a continuous depositional setting as the common geotectonic interpretation would imply. Steiner et al. (2007) emphasized that the distribution of major hiatuses, lithofacies, thickness of the terminal Neoproterozoic Dengying Formation and fauna changes abruptly between the Yangtze Craton and the Zhenba-Fangxian Block (= southeast Shaanxi-western Hubei Region). An overview on the facies distribution of the Yangtze Block and Zhenba-Fangxian Block is given by Feng et al., (2001). Relatively unmetamorphosed Cryogenian, Ediacaran and Cambrian sedimentary strata occur on both the Yangtze and Zhenba-Fangxian Blocks, while equivalent strata of the South Qinling Terrane indicate a stronger tectonic overprint. Traditionally the same lithostratigraphic units, such as the Nantuo, Doushantuo and Dengying formations have been applied on the Yangtze and Zhenba-Fangxian blocks, although obvious differences exist. The Cryogenian Nantuo Formation of the Yangtze Platform is represented by typical glaciogenic tillites of low to moderate thickness. In contrast to this there exist extremely thick strata of diamictites (Zhou et al., 2010) on the Zhenba-Fangxian Block. However, a recent study questioned the glaciomarine origin of this diamictites and considered them as conglomerates and sandstones deposited by subaqueous debris flows and high-density turbidity currents, and derived from the Hannan Complex in a forearc facies (Yan et al., 2010). In Xiaoyangba, Zhenba County, the diamictites are overlain by ca. 40 m of purple sandstones with thinner conglomeratic beds of the Mingyue Formation which is not developed on the Yangtze Block. About 50 m of black pyritic shales are superimposed to the Mingyue Formation that are considered to represent the organic rich Ediacaran Doushantuo Formation (with interlayered black shales, black carbonates and black cherts) of the Yangtze Platform.

Besides, red Fe-rich shales and bedded sedimentary Manganese ores (Fig. 3C) exist in this interval and have been economically exploited. These rich Ediacaran Manganese deposits are distributed in a belt-like arrangement on the Zhenba-Fangxian Block (Personal observation, Fig.1, 3C; Li and Li, 2005) and at the northern margin of Bikou Terrane (Qiao et al., 2009). Mn ore deposits have also been reported from the Jiangnan Orogeny and the Yichang Region (Yao et al., 1995) of Yangtze Platform. The Ediacaran black shales are overlain by whitish blocky dolostones commonly assigned to the Dengying Formation. The Dengying Formation formed a typical carbonate platform on the Yangtze Craton with locally over 1000 m thickness (Steiner et al., 2007: Fig. 5B). It has a quite reduced thickness (ca. 100 m) E and NE of the fault zone separating the Zhenba-Fangxian Block from the Yangtze Block. It is obvious, that, although the same lithological terms are applied on both blocks, the different appearance and succession of strata sheds considerable doubts whether the Zhenba-Fangxian Block represents a continuation of the depositional environment in the northern Yangtze Platform. Moreover, the mentioned

Ediacaran lithologies, such as the whitish Ediacaran carbonates, black shales or the diamictites are widely distributed on many other palaeocontinents, e. g., North Namibia (Hoffman et al., 1998), South Kazakhstan (Meert et al., 2011) and West Mongolia (Lindsay et al., 1996b; Serezhnikova et al., 2014).

It is important to note that no Terreneuvian sediments are preserved on the Zhenba-Fangxian Block. Here dark carbonates and shales of the Xihaoping Member and Shuijingtuo Formation overlay the terminal Neoproterozoic dolostones of Dengying Formation with an erosional unconformity (Fig. 3D, 4, 5). The topmost interval of the Neoproterozoic carbonates shows tectonic disturbance, brecciation and mobilization of migrating hydrocarbons (Fig. 3B). In contrast to this, in all regions of Yangtze Platform, such as East Yunnan (Yang et al., 2014b), West Guizhou (Qian and Yin, 1984), North Hunan (Ding and Qian, 1988), West Zhejiang (Steiner et al., 2003), Southwest Xixiang and Nanjiang Region of North Sichuan Province (Steiner et al., 2004), Terreneuvian strata containing earliest SSFs (Zone I~ IV) are widely distributed in both the shallow water facies and the deeper water facies. Thick Fortunian sediments with SSFs of the *Anabarites trisulcatus-Protohertzina anabarica* Assemblage Zone are just exposed ca. 40 km W of the Zhenba-Fangxian Block in the Hexi area of southwestern Xixiang County on the marginal northern Yangtze Block (Fig. 2: section C; Li, 1984). A similar sequence is recorded in the Sanlangpu area (Northeast Xixiang County) which is exposed at the eastern rim of the Hannan Block. The Cambrian sequence of the North China Block does not preserve Terreneuvian sediments either. And the reported SSFs (Wang et al., 1989) from the Luonan Region can be assigned to the *Pelagiella subangulata* Zone (Zone V) that also occurs on the Yangtze Craton.

To the East and Northeast of the Zhenba-Fangxian Block, in the Hanyin-Ankang-Zhuxi area of South Qinling Terrane, the early Cambrian sedimentary sequence comprises black siliciclastic rocks, cherts and dark carbontes of the Lujiaping Formation that also contains sedimentary barite and witherite deposits (Fig. 2; Tu, 1999; Lü et al., 2004a). The deposits occur in a belt-like arrangement that is fault bounded. A similar situation exists in the belt immediately east of the Zhenba-Fangxian Block along the Chengkou-Zhenping Fault (Fig. 2, F3+F4). There Cambrian stratiform barite and witherite deposits occur over a distance of more than 150 km. It should be noted that early Cambrian strata of the Jiangnan Orogenic Belt of southern Yangtze Block also contain sedimentary barite and witherite deposits (Gao, 1998). Sedimentary-stratiform barite and witherite deposits are generally deposited in extreme oceanic environments, e.g., the rift basin with volcanic and hydrothermal activities (Tu, 1999; Lü et al., 2004b; Liu et al., 2010), though a biogenic depositional model for the barite and witherite deposits has also been proposed (e.g., Lü et al., 2004a). Based on geochemical characteristics of the barite and witherite deposits of the South Qinling Terrane, Pi et al. (2014) also concluded that the source of the barium for these deposits were submarine hydrothermal fluids. Although the detailed palaeogeographic relationship with the South Qinling Terrane remains questionable, the Zhenba-Fangxian Block, as discussed above, revealed a tectonic disturbance of the terminal Neoproterozoic strata and a syngenetic mobilization of hydrocarbons, both providing the possiblity of the influence by submarine hydrothermal activity.

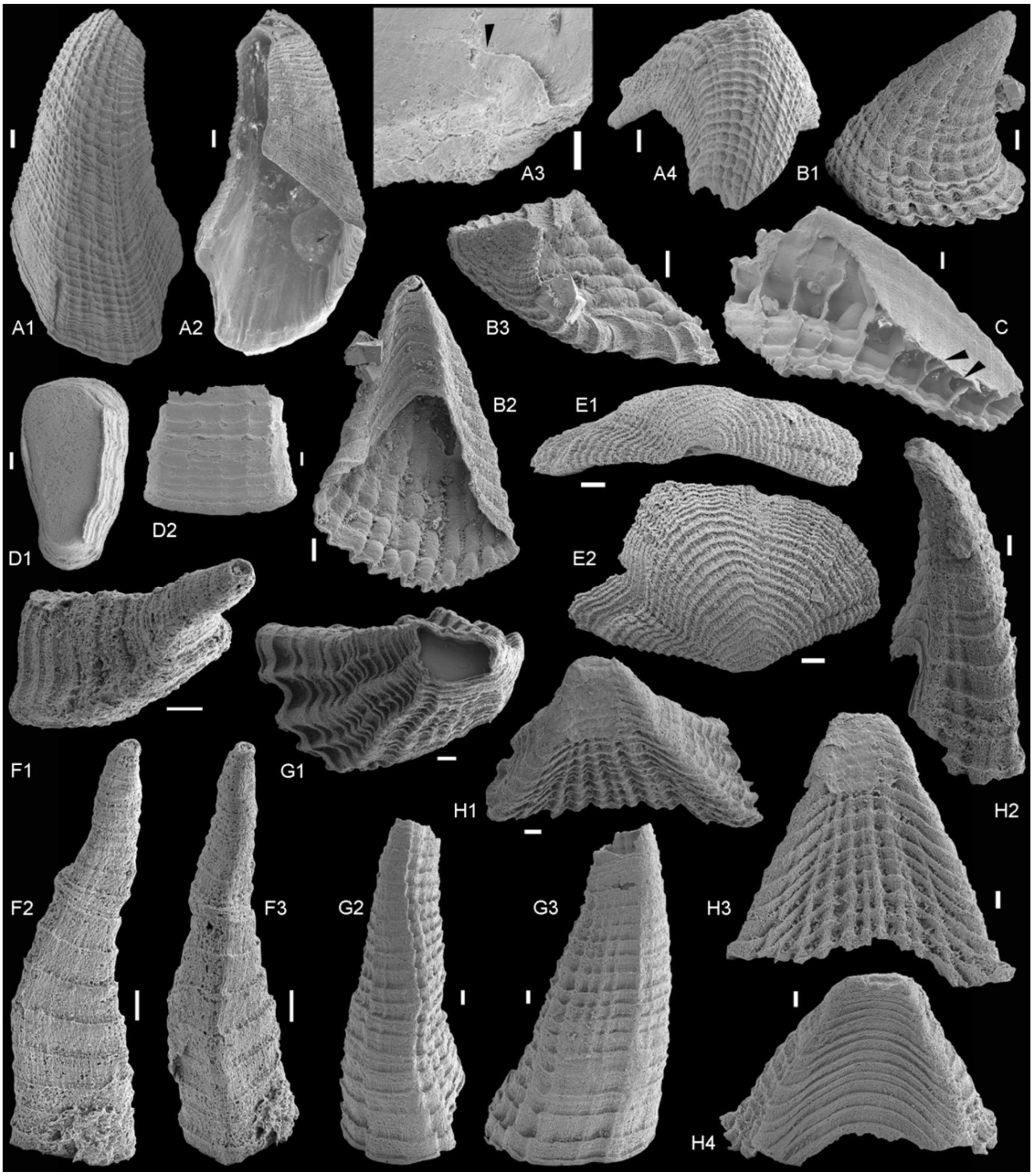

Fig. 12. SEM micrographs of SSFs from Zengjiapo (abbreviation Zjp) and Xiaoyangba (abbreviation Xyb), Zhenba County, Shaanxi. A-C, E, G, H. *Kelanella altaica* Missarzhevsky in Rozanov and Missarzhevsky, 1966. A. No. Xyb48026. A3, detail of A2 showing a thin thin-wall (arrow) extending from outside to the inner wall of shell. B. No. Zjp108-15. C. fragment showing the internal tabulae which partially branch near to the outer shell (arrows). No. Zjp108009. E. No. Zjp108-02. G. Individual of *Kelanella altaica* with some similarity in the sclerite morphotype to *Lugoviella ojmuranica* (Fig. 10F) and G1 internal tabula, No. Zjp108-12. H. No. Zjp108-13, H3 and H4 showing the different surface ornament on the opposite facets of the specimen. A1, B1, E2, apical view; A2, B2, G2, G3, H2-4, lateral view; A4, E1, proximal view; B3, G1, H1, apical view. D, F. *Lugoviella ojmuranica* Gregoryeva, 1983. D. No. Xyb34007. F. No. Zjp108-05. D1, F1, top view, D1 shows the internal tabulae; D2, F2, F3, lateral view. All samples are from Shuijingtuo Formation. Scale bars: A1, A2, A4, C, 200 μm; others 100μm.

In general, the existence of sedimentary Ediacaran Mn deposits and Cambrian barite and witherite deposits that are strictly confined to belt-like arrangements on the Zhenba-Fangxian Block, the Bikou Terrane, and the South Qinling Terrane. The hydrocarbon and unconformity in or on top of, the terminal Ediacaran strata indicated that the whole Zhenba-Fangxian Region was suspected to large-scale tectonic processes. Major faults may have been developed in this process, which were originally thought to have formed during a later Paleozoic collision (between the Yangtze and North China Cratons) and the formation of arc complexes in the South Qinling Terrane (Wang et al., 2009).

Above all, arguments were listed as follows: a) Our new palaeobiogeographic study indicated certain distance between the Cambrian Stage 3 faunas of Zhenba-Fangxian and the Yangtze blocks; b) There were greater differences in lithofacies than previousely noted; c) From metavolcanites and metasediments of the South Qinling Terrane, there are U-Pb age spectra of zircons (ca. 680 Ma volcanic activity of Wudang Terrane) which are unknown from the Yangtze Craton; d) Syngenetic tectonizations happened in the terminal Ediacaran to early Cambrian strata; e) There are submarine-hydrothermal activities on the Zhenba-Fangxian Block and South Qinling Terrane. All taken together allow us to hypothesize that the Yangtze Craton experienced a compressional history in the Ediacaran- Cambrian with another palaeocontinent or terrane than the North China Craton. Part of the blocks at the northern perisphere of Yangtze Craton, such as the Wudang Block and the Zhenba-Fangxian Block may have originated from this collision. Our palaeobiogeographic results make it likely that the early Plaeozoic collision of the Yangtze Craton occurred with parts of a terrane chain, *e.g.*, the Armorica/ Tarim/ Karatau-Naryn Terrane Assemblage. This would revive previous hypotheses that the Wudang Block might not be derived from the Yangtze Block (Ling et al., 2010), and the earlier Paleozoic convergence of the Yangtze Craton did not occur with the North China Craton (Mattauer et al., 1985).

Though no significant proof of an orogeny or ultramafic rocks were reported between the Zhenba-Fangxian and the Yangtze blocks, or the Zhenba-Fangxian Block and the South Qinling Terrane, the Zhenba-Fangxian and adjacent regions may have expericened “soft collisions” (Ren, 1996; Ren et al., 1999; Kröner et al., 2014). The“soft collisions” man led to the assembly of the various terranes at the northern margin of Yangtze Craton, and resemble those collisions in Cambrian/ Ordovician in the Central Asian Orogeny Belt (Kröner et al., 2014) where some terrane fragments (e.g. the Kusnetzk Alatau) survived relatively unmetamorphosed. Our palaeobiogeographic analysis challenges the older interpretation that the Zhenba-Fangxian Block, Bikou Terrane and South Qinling Terrane were part of the Yangtze Craton in the Neoproterozoic to early Cambrian time (Fig. 14). Future studies are needed to further investigate SSF distribution of Cambrian terranes in the Qinling region and Armorica/ Tarim/ Karatau-Naryn bioprovinces as well as provenances of clastic sediments by combined U-Pb age dating and Lu-Hf isotope analyses on detrital zircon grains.

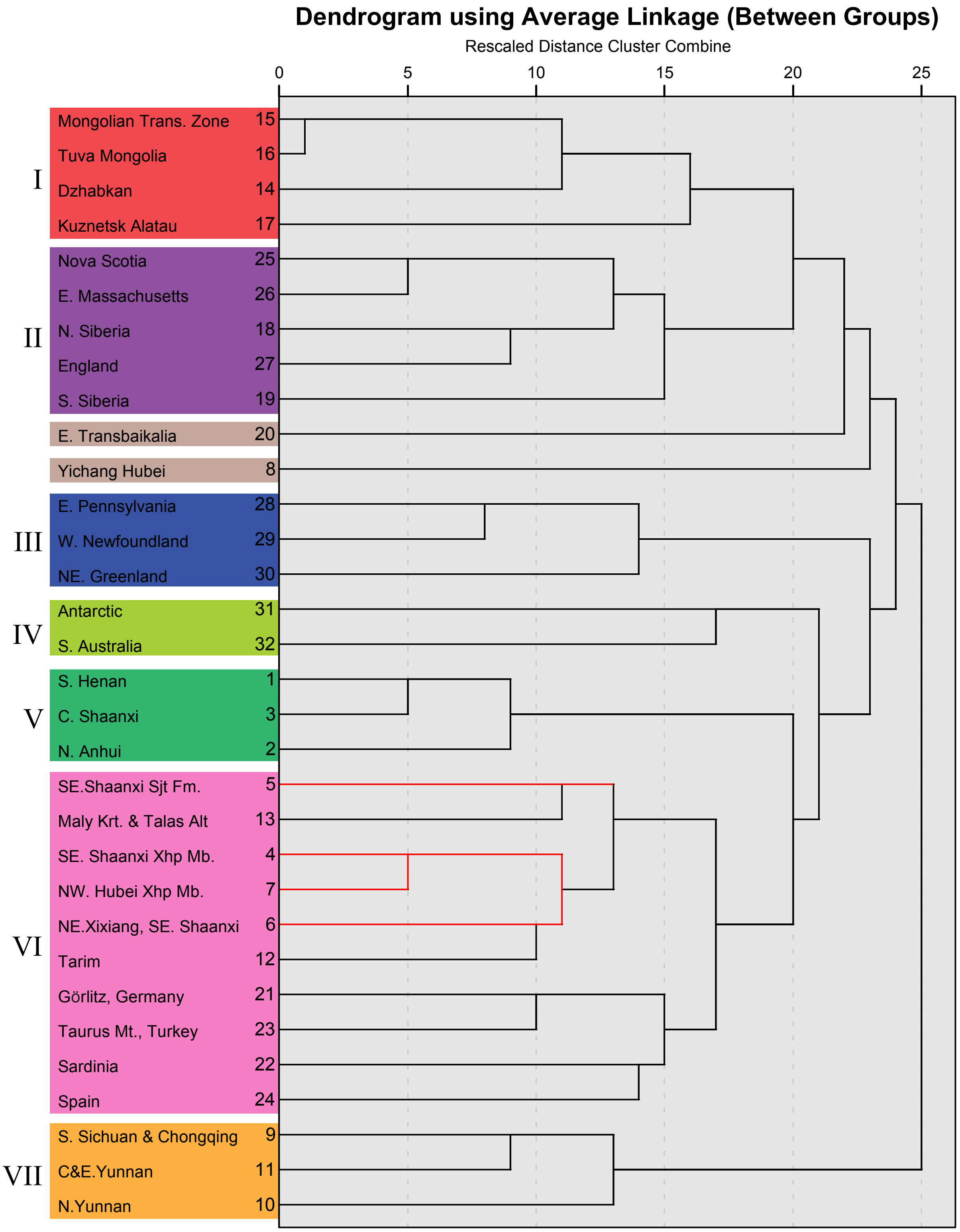

Fig. 13. Dendrogram of hierarchical cluster analysis using Pearson similarity of a data matrix of 295 Cambrian Stage 3 SSF species from 32 regions (Appendix 1). Red lines mark data from the herein studied Zhenba-Fangxian Block. Faunal provinces in different colors are: I. Western “Kipchak” Island Arc (including Mongolian terranes); II, Siberia & Avalonia; III, Laurentia; IV, East Gondwana; V, North China; VI, Armorica Terrane Assemblage/ Karatau-Naryn Terrane/ Tarim/ Zhenba-Fangxian Block; VII, Yangtze.

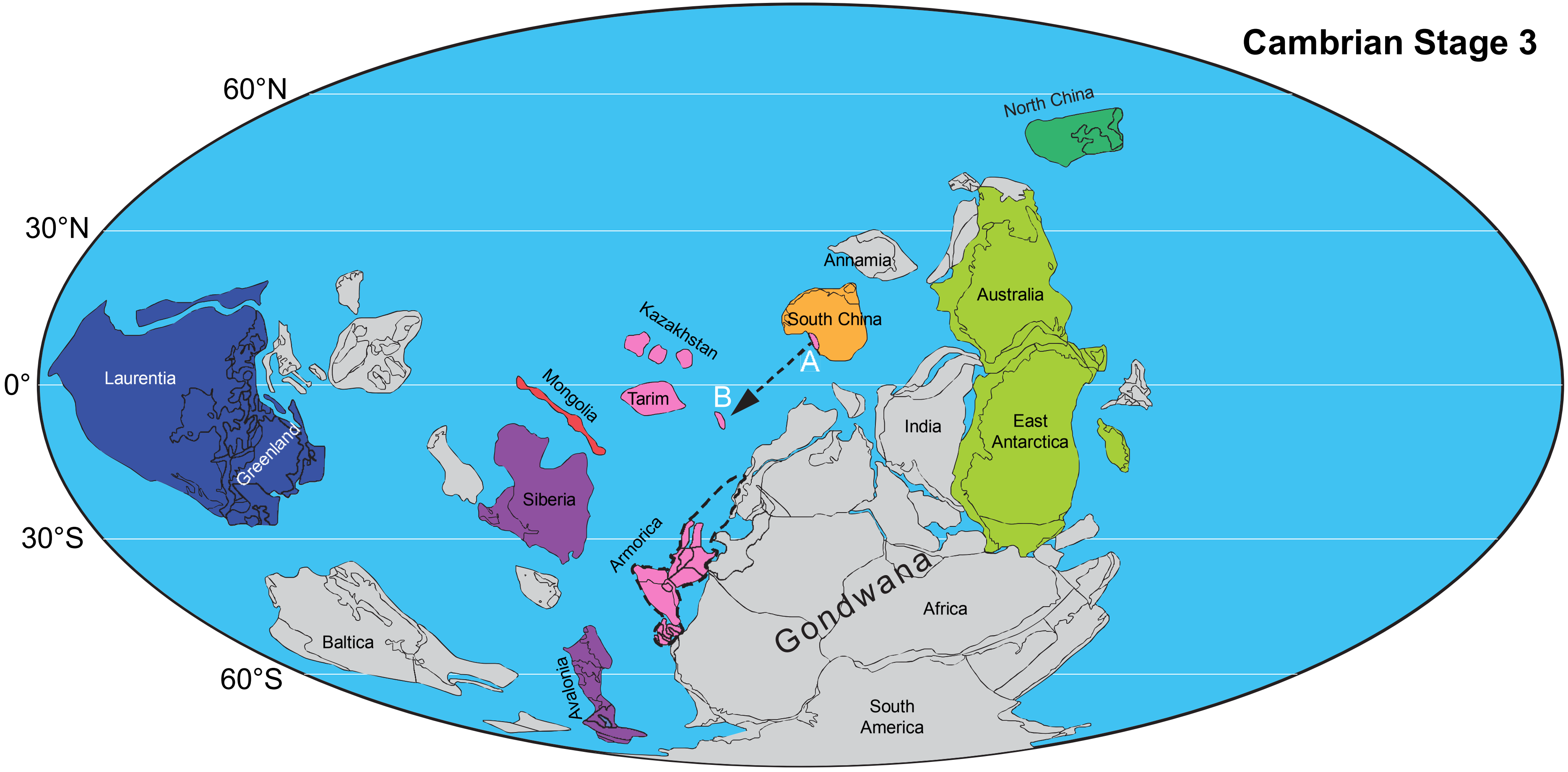

Fig. 14. Palaeogeographic reconstruction for the Cambrian Stage 3 with the different faunal provinces (colors as in Fig. 13) and the position of the Zhenba-Fangxian Block (base map modified from Torsvik and Cocks, 2013b; position of Avalonia derived from Landing et al, 2013b). Position A marks the traditional reconstruction of the Zhenba-Fangxian Block as distal depositional center of the Yangtze Platform; Position B marks the hypothetic position of the Zhenba-Fangxian Block according to this palaeobiogeographic analysis.

7. Systematic Paleontology

PROBLEMATIC SCLERITES

Family Furnishinidae Müller & Nogami, 1971

Genus ***Gapparodus*** Abaimova 1978

Description. Slender, hollow and slightly curved apatitic sclerites with a cross-section like an "8". There is one shallow to deep longitudinal groove on each lateral flanks. The surface is smooth or with weak growth-lines.

Type species. *Gapparodus bisulcatus* (Müller, 1959)

Composition. *G. bisulcatus*, *Gapparodus gapparites* sp. nov.

Gapparodus gapparites sp. nov.

Fig. 6F, G

Holotype. No. Zjp30001 (Fig. 6G) from the lower Shuijingtuo Formation, Zengjiapo, Zhenba County, Shaanxi Province; Repository at the Freie Universität Berlin, Department of Earth Sciences.

Etymology. Named in honor of Gappar Kh. Ergaliev, Almaty, Kazakhstan, who contributed much to the knowledge of Cambrian biostratigraphy and evolution.

Diagnosis. Hollow sclerites with partially a cross section like an "8". The spine has a great divergent angle nearby the aperture that leads to a sharply broadened base (Fig. 6F3, G4) It has two deep grooves on the two lateral flanks. The apertural cross section has two unequal parts, the one on the concave side is much larger than that of the convex side. The groove extends to the apex of the spine. The inner part is significantly expanded. A keel could be observed on the concave facet (Fig. 6G3) while the convex side is somehow flat and smooth (Fig. 6G1).

Description. The outer surface of the hollow sclerites is smooth. The preserved sclerites are about 1.5mm in length. The aperture broadened sharply with a divergent angle of ca. 40°. The aperture is separated into two parts by the two grooves on the lateral sides. The bigger part of the aperture is about 0.45mm in width and the smaller part is about 0.15mm with a ratio of the two parts of about 2.5.

Remarks. The sclerites have a typically shaped cross section of an "8" as the other *Gapparodus* species. But in *G. bisulcatus* the aperture shows a cross section divided in two equal parts separated by the grooves or indicates slightly smaller part on the concave side. Besides, the *G. bisulcatus* is smooth on the concave face while the new species here has a keel or smooth ridge. On the convex side the new species is flat and smooth. *G. communis*, Xie 1990 differs from *G. bisulcatus* by a narrower and more slender aperture. *Hertzina bokononi* (Landing, 1974) was a drawing without any specimen photograph. Although it was tentatively synonymized to the *Hertzina*? *bisulcata* (=*Gapparodus bisulcata*) by Bengtson (1976), the species does resemble *Amphigeisina* rather than *Gapparodus* as judged from the cross-section. The *Gapparodus trisulcatus* Dong, 1990 (Fig. I-7, 9) is partially similar to *Gapparodus gapparites*. But its concave facet is flat or with a furrow in. Besides, the *G. trisulcatus* seems to have smaller divergent angle than our new species although no description for the was given to *G. trisulcatus* in the original publication (Dong, 1990).

Occurrence. Cambrian Stage 3 (equivalent to the Atdabanian of Siberian regional subdivision), lower Shuijingtuo Formation in Zengjiapo and Xiaoyangba section, Zhenba

County, Shaanxi Province, China.

Family Unknown
Genus ***Tarimspira*** Yue & Gao, 1992
Fengzuella He & Yu 1992, p. 5
Tarimspira Yue & Gao 1992, p. 153
Otoformilites Qin and Li; Ding et al., 1992, p. 89

Diagnosis See Steiner et al. 2004, p. 37

Tarimspira plana
Fig. 10O, P
? *Lopochites* ? sp.; Ding & Qian, 1988, pl. II, Figs. 6, 7
? *Protohertzina cultrata*; Yue & He, 1989 pl. I, Fig. 2
Fengzuella zhejiangensis; He & Yu 1992, p. 5, pl. II, Fig. 17; Steiner et al. 2004, p. 38, Figs. 3a~ s;
Kouchinsky et al., 2014, Fig. 54
Tarimspira plana; Yue & Gao 1992, p. 153, 154, pl. 7~ 9,
Otoformilites wangjiapingensis Qin and Li; Ding et al., 1992, p. 90, pl. II, Figs. 12, 13
Discoidal problematicum, Müller et al., 1995, p. 113, Figs. 5E, F

Description and *Occurrence.* see Steiner 2004, p. 38

Remarks. Discoidal sclerites of *Tarimspira plana* are discovered on the Zhenba-Fangxian Block. Morphologically similar sclerites have been reported from Hubei, Zhejiang (He and Yu, 1992; Steiner et al., 2003), Tarim (Yue and Gao, 1992), Anabar and Olenek uplifts of Siberia (Müller et al., 1995; Kouchinsky et al., 2014). Due to the fact that *Fengzuella zhejiangensis* He and Yu, 1992 is a homonym of the Ordovician brachiopod *Fengzuella zhejiangensis* Li and Han, 1980 (Li and Han, 1980) this name is invalid. Hence, the taxonomic priority has the name *Tarimspira plana* Yue and Gao, 1992, published in June 1992.

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4. References

Abaimova, G.P., 1978. Late Cambrian conodonts of central Kazakhstan. Paleontologicheskii Zhurnal 4, 77-87.

Aceñolaza, G.F., Germs, G.J.B., Aceñolaza, F.G., 2009. Trace Fossils and the Agronomic Revolution at the Neoproterozoic-Cambrian Transition in Southwest Gondwana, in: Gaucher, C., Sial, A.N., Frimmel, H.E., Halverson, G.P. (Eds.), Developments in Precambrian Geology. Elsevier, Amsterdam, pp. 339-347.

Allman, M., Lawrence, D.F., 1972. Geological laboratory techniques. Blandford Press London, London, 335 pp.

Álvaro, J., Elicki, O., Geyer, G., Rushton, A.W., Shergold, J.H., 2003. Palaeogeographical controls on the Cambrian trilobite immigration and evolutionary patterns reported in the western Gondwana margin. Palaeogeography, Palaeoclimatology, Palaeoecology 195, 5-35.

Álvaro, J.J., Debrenne, F., 2010. The Great Atlasian Reef Complex: An early Cambrian subtropical fringing belt that bordered West Gondwana. Palaeogeography, Palaeoclimatology, Palaeoecology 294, 120-132.

Álvaro, J.J., Zamora, S., Clausen, S., Vizcaïno, D., Smith, A.B., 2013. The role of abiotic factors in the Cambrian Substrate Revolution: A review from the benthic community replacements of West Gondwana. Earth-Science Reviews 118, 69-82.

Álvaro, J.J., Bellido, F., Gasquet, D., Pereira, M.F., Quesada, C., Sánchez-García, T., 2014. Diachronism in the late Neoproterozoic-Cambrian arc-rift transition of North Gondwana: A comparison of Morocco and the Iberian Ossa-Morena Zone. Journal of African Earth Sciences, *In press*.

Atkins, C.J., Peel, J.S., 2008. *Yochelcionella* (Mollusca, Helcionelloida) from the lower Cambrian of North America. Bulletin of Geosciences 83, 23-38.

Babcock, L.E., Peng, S., Geyef, G., Shergold, J.H., 2005. Changing perspectives on Cambrian chronostratigraphy and progress toward subdivision of the Cambrian System. Geosciences Journal 9, 101-106.

Bai, L., Zhu, R., 1996. A review of the tectonic evolution and paleomagnetic research for the Yangtze Block during Paleozoic. Progress in Geophysics 11, 109-114.

Banerjee, D., Schidlowski, M., Siebert, F., Brasier, M., 1997. Geochemical changes across the Proterozoic–Cambrian transition in the Durmala phosphorite mine section, Mussoorie Hills, Garhwal Himalaya, India. Palaeogeography, Palaeoclimatology, Palaeoecology 132, 183-194.

Barghoorn, E.S., Tyler, S.A., 1965. Microorganisms from the Gunflint Chert These structurally preserved Precambrian fossils from Ontario are the most ancient organisms known. Science 147, 563-575.

Begemann, F., Ludwig, K., Lugmair, G., Min, K., Nyquist, L., Patchett, P., Renne, P., Shih, C.-Y., Villa, I., Walker, R., 2001. Call for an improved set of decay constants for geochronological use. Geochimica Et Cosmochimica Acta 65, 111-121.

Bellotti, E., Broggini, C., Di Carlo, G., Laubenstein, M., Menegazzo, R., Pietroni, M., 2013. Search for time modulations in the decay rate of ^{40}K and ^{232}Th and influence of a scalar field from the Sun. arXiv: 1311.7043.

Bengtson, S., 1970. Lower Cambrian Fossil Tommotia. Lethaia 3, 363-392.

Bengtson, S., 1976. The structure of some Middle Cambrian conodonts, and the early evolution of conodont structure and function. Lethaia 9, 185-206.

Bengtson, S., 1977. Early Cambrian button-shaped phosphatic microfossils from the Siberian Platform. Palaeontology 20, 751-762.

Bengtson, S., Fedorov, A.B., Missarzhevsky, V.V., Rozanov, A.Y., Zhegallo, E.A., Zhuravlev, A.Y., 1987. *Tumulduria incomperta* and the case for Tommotian trilobites. Lethaia 20, 361-370.

Bengtson, S., Conway Morris, S., Cooper, B.J., Jell, P.A., Runnegar, B.N., 1990. Early Cambrian fossils from south Australia. Association of Australasian Palaeontologists, Brisbane, 364 pp.

Bengtson, S., 1991. Paleontology-Oddballs from the Cambrian Start to Get Even. Nature 351, 184-185.

Bengtson, S., 1992. The cap-shaped Cambrian fossil *Maikhanella* and the relationship between coeloscleritophorans and molluscs. Lethaia 25, 401-420.

Betts, M.J., Topper, T.P., Valentine, J.L., Skovsted, C.B., Paterson, J.R., Brock, G.A., 2014. A new early Cambrian bradoriid (Arthropoda) assemblage from the northern Flinders Ranges, South Australia. Gondwana Research 25, 420-437.

Billings, E., 1871. On some new species of Paleozoic fossils. American Journal of Science 3, 352-360.

Billings, E., 1872. On some fossils from the Primordial rocks of Newfoundland. The Canadian Naturalist VI, 465-479.

Boggs, S., 2006. Principles of sedimentology and stratigraphy. Pearson Prentice Hall New Jersey, 662 pp.

Brasier, M., Hewitt, R., Brasier, C., 1978. On the late precambrian–early cambrian Hartshill Formation of Warwickshire. Geological Magazine 115, 21-36.

Brasier, M., 1984. Microfossils and small shelly fossils from the Lower Cambrian Hyolithes Limestone at Nuneaton, English Midlands. Geological Magazine 121, 229-253.

Brasier, M., Singh, P., 1987. Microfossils and Precambrian-Cambrian boundary stratigraphy at Maldeota, Lesser Himalaya. Geol. Mag 124, 323-345.

Brasier, M., 1990. Phosphogenic events and skeletal preservation across the Precambrian-Cambrian boundary interval. Geological Society, London, Special Publications 52, 289.

Brasier, M., Cowie, J., Taylor, M., 1994. Decision on the Precambrian–Cambrian boundary stratotype. Episodes 17, 3-8.

Brasier, M., Dorjnamjaa, D., Lindsay, J., 1996. The Neoproterozoic to early Cambrian in southwest Mongolia: an introduction. Geological Magazine 133, 365-369.

Brasier, M., Green, O., Shields, G., 1997. Ediacarian sponge spicule clusters from southwestern Mongolia and the origins of the Cambrian fauna. Geology 25, 303-306.

Brasier, M.D., 1986. The succession of small shelly fossils (especially conoidal microfossils) from English Precambrian–Cambrian boundary beds. Geological Magazine 123, 237-256.

Brasier, M.D., 1989. Towards a biostratigraphy of the earliest skeletal biotas, in: Cowie, J.W., Brasier, M.D. (Eds.), The Precambrian-Cambrian Boundary. Clarendon Press, Oxford, pp.

117-165.

Brasier, M.D., Magaritz, M., Corfield, R., Huilin, L., Xiche, W., Lin, O., Zhiwen, J., Hamdi, B., Tinggui, H., Fraser, A., 1990. The carbon-and oxygen-isotope record of the Precambrian–Cambrian boundary interval in China and Iran and their correlation. Geological Magazine 127, 319-332.

Brasier, M.D., Lindsay, J.F., 2001. Did supercontinental amalgamation trigger the “Cambrian Explosion”, in: Zhuralev, A.Y., Riding, R. (Eds.), The ecology of the Cambrian radiation. New York, Columbia University Press, pp. 69-89.

Brasier, M.D., Green, O.R., Jephcoat, A.P., Kleppe, A.K., Van Kranendonk, M.J., Lindsay, J.F., Steele, A., Grassineau, N.V., 2002. Questioning the evidence for Earth's oldest fossils. Nature 416, 76-81.

Brett, C.E., Liddell, W.D., Derstler, K.L., 1983. Late Cambrian hard substrate communities from Montana/Wyoming: the oldest known hardground encrusters. Lethaia 16, 281-289.

Brock, G., Engelbretsen, M., Jago, J., Kruse, P., Laurie, J., Shergold, J., Shi, G., Sorauf, J., 2000. Palaeobiogeographic affinities of Australian Cambrian faunas. Memoir of the Association of Australasian Palaeontologists 23, 1-61.

Bromley, R.G., 1965. Studies in the lithology and conditions of sedimentation of the chalk rock and comparable horizons. Queen Mary, University of London, Thesis.

Bromley, R.G., 2004. A stratigraphy of marine bioerosion. Geological Society, London, Special Publications 228, 455-479.

Budd, G.E., Jensen, S., 2000. A critical reappraisal of the fossil record of the bilaterian phyla. Biological Reviews 75, 253-295.

Buschmann, B., Elicki, O., Jonas, P., 2006. The Cadomian unconformity in the Saxo-Thuringian Zone, Germany: Palaeogeographic affinities of Ediacaran (terminal Neoproterozoic) and Cambrian strata. Precambrian Research 147, 387-403.

Butterfield, N.J., 1997. Plankton ecology and the Proterozoic-Phanerozoic transition. Paleobiology 23, 247-262.

Canfield, D., 1998. A new model for Proterozoic ocean chemistry. Nature 396, 450-453.

Caron, J.-B., Jackson, D.A., 2006. Taphonomy of the greater phyllopod bed community, Burgess Shale. Palaios 21, 451-465.

Caron, J.-B., Smith, M.R., Harvey, T.H., 2013. Beyond the Burgess Shale: Cambrian microfossils track the rise and fall of hallucigeniid lobopodians. Proceedings of the Royal Society B: Biological Sciences 280, 1-6.

Cawood, P.A., Wang, Y., Xu, Y., Zhao, G., 2013. Locating South China in Rodinia and Gondwana: A fragment of greater India lithosphere? Geology 41, 903-906.

Chen, M., Chen, Y., Zhang, S., 1981. The small shell fossil assemblage in the limestone of the uppermost part of Dengying Formation at Songlinpo,Yichang. Earth Science (Journal of China University of Geosciences) 1981, 32-41.

Chen, M., 1982. The new knowledge of the fossil assemblages from Maidiping section, Emei County, Sichuan with reference to the Sinian–Cambrian boundary. Scientia Geologica Sinica 7, 253–263.

Chen, N., Yang, X., Li, D., Xiao, X., Fan, D., Wang, L., 1982. Lower Cambrian black argillaceous and arenaceous rock series in South China and its associated stratiform deposits. Mineral Deposits 1982, 39-51.

Chen, N., Yang, X., Liu, D., Xiao, X., Fan, D., Wang, L., 1990. Lower Cambrian black rock series and associated stratiform deposits in southern China. Chinese Journal of Geochemistry 9, 244-255.

Chen, P., 1984. Discovery of Lower Cambrian small shelly fossils from Jijiapo, Yichang, West Hubei and its significance. Professional Papers of Stratigraphy and Palaeontology 13, 49-66.

Chen, Y., Zhang, S., 1980. Small shelly fossils from early Lower Cambrian of Songlinpo of the eastern Yangtse Gorge. Geological Review 26, 190-197.

Cheng, H., Wang, M., Chen, X., Xu, A., Chen, S., 1992. The Zhenba Rise of the Dabashan Uplift. Journal of Stratigraphy 16, 196-199.

Chow, N., James, N.P., 1992. Synsedimentary diagenesis of Cambrian peritidal carbonates: evidence from hardgrounds and surface paleokarst in the Port au Port Group, western Newfoundland. Bulletin of Canadian Petroleum Geology 40, 115-127.

Clausen, S., Álvaro, J.J., 2006. Skeletonized microfossils from the Lower-Middle Cambrian transition of the Cantabrian Mountains, northern Spain. Acta Palaeontologica Polonica 51, 223.

Cobbold, E., 1935. Lower Cambrian faunas from Hérault, France. Annals and Magazine of Natural History (series 10) 16, 25-48.

Cobbold, E.S., 1920. The Cambrian Horizons of Comley (Shropshire), and their Brachiopoda, Pteropoda, Gasteropoda, etc. Quarterly Journal of the Geological Society 76, 325-386.

Compston, W., Zhang, Z., Cooper, J.A., Ma, G., Jenkins, R.J.F., 2008. Further SHRIMP geochronology on the early Cambrian of South China. American Journal of Science 308, 399-420.

Conway Morris, S., 1985. The Middle Cambrian metazoan Wiwaxia-Corrugata (Matthew) from the Burgess Shale and Ogygopsis Shale, British-Columbia, Canada. Philosophical Transactions of the Royal Society of London Series B-Biological Sciences 307, 507-582.

Conway Morris, S., 1988. Metazoan evolution near the Precambrian–Cambrian boundary: use and misuse of small shelly fossils. New York State Museum Bulletin 463, 9-10.

Conway Morris, S., 1989. Burgess Shale Faunas and the Cambrian Explosion. Science 246, 339-346.

Conway Morris, S., Peel, J.S., 1990. Articulated halkieriids from the Lower Cambrian of North Greenland. Nature 345, 802-805.

Conway Morris, S., 1998. The crucible of creation: the Burgess Shale and the rise of animals. Oxford University Press, Oxford, 310 pp.

Conway Morris, S., 2006. Darwin's dilemma: the realities of the Cambrian 'explosion'. Philosophical Transactions of the Royal Society B-Biological Sciences 361, 1069-1083.

Cook, P.J., Shergold, J.H., 1984. Phosphorus, phosphorites and skeletal evolution at the Precambrian[mdash]Cambrian boundary. Nature 308, 231-236.

Cook, P.J., Shergold, J.H., 1986. Phosphate Deposits of the World: Volume 1: Proterozoic and Cambrian Phosphorites. Cambridge University Press, 391 pp.

Cook, P.J., 1992. Phosphogenesis around the Proterozoic-Phanerozoic transition. Journal of the Geological Society 149, 615-620.

Crimes, T.P., 1987. Trace fossils and correlation of late Precambrian and early Cambrian strata. Geological Magazine 124, 97-119.

Crimes, T.P., 1994. The period of early evolutionary failure and the dawn of evolutionary success: The record of biotic changes across the Precambrian-Cambrian boundary, in: Donovan, S. (Ed.), The paleobiology of trace fossils. Wiley and Sons, London, pp. 105-133.

Cui, Z., Zhang, X., Tong, H., Huo, S., 1987. Ontogeny of some Cambrian bradoriids from China. Journal of Northwest University 17, 68-77.

Cui, Z., Sun, Y., Wang, X., 1995. Discovery of radiolarias from the Danfeng ophiolite zone, North Qinling, and their geologic significance. Chinese Science Bulletin 40, 1686-1688.

Daily, B., 1976. New data on the base of the Cambrian in South Australia. Izv. Akad. Nauk. SSSR, Ser. Geol 3, 45-52.

Darwin, C., 1859. On the Origin of Species by Means of Natural Selection, or the Preservation of Favoured Races in the Struggle for Life. John Murray, London, 479 pp.

Daudel, R., 1947. Alteration of radioactive periods of the elements with the aid of chemical methods. Rev. Sci 85, 162.

Debrenne, F., Debrenne, M., 1995. Archaeocyaths of the Lower Cambrian of Morocco, in: Geyer, G., Landing, E. (Eds.), Morocco '95: The Lower-Middle Cambrian Standard of Western Gondwana. Beringeria (Special Issue), Würzburg, pp. 121-145.

Demidenko, Y.E., 2006. New Cambrian lobopods and chaetognaths of the Siberian Platform. Paleontological Journal 40, 234-243.

Demidenko, Y.E., Parkhaev, P.Y., 2006. Taxonomic diversity of the Early Cambrian small shelly fauna of China, in, Evolution of the Biosphere and Biodiversity: Contributions to A.Yu. Rozanov’s 70th Birthday. KMK Scientific Press Ltd., Moscow, pp. 492-505.

Ding, L., Qin, H., Li, Y., 1990. Study on the boundary between Sinian and Cambrian in the South of Shaanxi Province, China. Professional Papers in Stratigraphy and Palaeontology, 96-130.

Ding, L., Zhang, L., Li, Y., Dong, J., 1992. The Study of the Late Sinian–Early Cambrian Biota from the Northern Margin of Yangtze Platform. Scientific and Technical Documents Publishing House, Beijing, 156 pp.

Ding, W., Qian, Y., 1988. Late Sinian to Early Cambrian small shelly fossils from Yangjiaping, Shimen, China. Acta Micropalaeontologica Sinica 5, 39-55.

Ding, Y., Sun, H., Yang, Z., Liang, X., Wang, X., Zhang, S., Cui, A., 2009. Can the decay rate of ^{32}P be changed by mechanic motion? Science in China Series B: Chemistry 52, 690-692.

Dong, X., 1990. A Potential Candidate For the Middle - Upper Cambrian Boundary Stratotype—An Introduction to the Paibi Section in Huayuan, Hunan. Acta Geologica Sinica - English Edition 3, 309-327.

Dong, Y., Liu, X., Santosh, M., Zhang, X., Chen, Q., Yang, C., Yang, Z., 2011a. Neoproterozoic subduction tectonics of the northwestern Yangtze Block in South China: Constrains from zircon U–Pb geochronology and geochemistry of mafic intrusions in the Hannan Massif. Precambrian Research 189, 66-90.

Dong, Y., Zhang, G., Neubauer, F., Liu, X., Genser, J., Hauzenberger, C., 2011b. Tectonic evolution of the Qinling orogen, China: Review and synthesis. Journal of Asian Earth Sciences 41, 213-237.

Duan, C., 1983. Small shelly fossils from the Lower Cambrian Xihaoping Formation in the Shennongjia District, Hubei Province-hyoliths and fossil skeletons of unknown affinities.

Bulletin of the Tianjin Institute of Geology and Mineral Resources 7, 143-188.

Dzik, J., 2003. Early Cambrian lobopodian sclerites and associated fossils from Kazakhstan. Palaeontology 46, 93-112.

Elicki, O., Schneider, J., 1992. Lower Cambrian (Atdabanian/Botomian) Shallow-Marine carbonates of the Görlitz Synclinorium (Saxony/Germany). Facies 26, 55-66.

Elicki, O., 1994. Lower Cambrian carbonates from eastern Germany: palaeontology, stratigraphy and palaeogeography. Neues Jahrbuch für Geologie und Paläontologie, Abhandlungen 191, 69-93.

Elicki, O., 1996. Die Gastropoden und Monoplacophoren der underkambrischen Görlitz-Fauna. Freiberg Forschunghefte C464, 145-173.

Elicki, O., 1998. First report of *Halkieria* and enigmatic globular fossils from the Central European Marianian (Lower Cambrian, Görlitz Syncline, Germany), in, Revista Española de Paleontología. Homenaje al Prof. Gonzalo Vidal, Madrid, pp. 51–64.

Elicki, O., 1999. Palaeoecological significance of calcimicrobial communities during ramp evolution: an example from the Lower Cambrian of Germany. Facies 41, 27-39.

Elicki, O., Wotte, T., 2003. Cambroclaves from the Cambrian of Sardinia (Italy) and Germany: constraints for the architecture of western Gondwana and the palaeogeographical and palaeoecological potential of cambroclaves. Palaeogeography, Palaeoclimatology, Palaeoecology 195, 55-71.

Elicki, O., Pillola, G.L., 2004. Cambrian microfauna and palaeoecology of the Campo Pisano Formation at Gutturu Pala (Iglesiente, SW Sardinia, Italy). Bollettino della Societa Paleontologica Italiana 43, 383-401.

Elicki, O., 2005. The utility of late Early to Middle Cambrian small shelly fossils from the western Mediterranean. Geosciences Journal 9, 161-171.

Elicki, O., Gürsu, S., 2009. First record of *Pojetaia runnegari* Jell, 1980 and *Fordilla* Barrande, 1881 from the Middle East (Taurus Mountains, Turkey) and critical review of Cambrian bivalves. Paläontologische Zeitschrift 83, 267-291.

Elicki, O., 2011. First skeletal microfauna from the Cambrian Series 3 of the Jordan Rift Valley (Middle East). Memoirs of the Association of Australasian Palaeontologists 42, 153-173.

Elicki, O., Geyer, G., 2013. The Cambrian trilobites of Jordan–taxonomy, systematic and stratigraphic significance. Acta Geologica Polonica 63, 1-56.

Emery, G.T., 1972. Perturbation of nuclear decay rates. Annual Review of Nuclear Science 22, 165-202.

Esakova, N., Zhegallo, E., 1996. Biostratigraphy and fauna of Lower Cambrian of Mongolia. Nauka, Moscow, 214 pp.

Esteban, M., Klappa, C.F., 1983. Subaerial exposure environment, in: Scholle, P.A., Bebout, D.G., Moore, C.H. (Eds.), Carbonate Depositional Environments: American Association of Petroleum Geologists, Memoir. The American Association of Petroleum Geologists, Tulsa, pp. 1-54.

Evans, K., Rowell, A., 1990. Small shelly fossils from Antarctica: an Early Cambrian faunal connection with Australia. Journal of Paleontology 64, 692-700.

Evans, K.R., 1992. Marocella: Antarctic Specimens of an Enigmatic Cambrian Animal. Journal of Paleontology 66, 558-562.

Föllmi, K., 1996. The phosphorus cycle, phosphogenesis and marine phosphate-rich deposits. Earth-Science Reviews 40, 55-124.

Fan, D., Yang, X., Wang, L., Chen, N., 1973. Petrological and geochemical characteristics of a nickel-molybdenum-multi-element-bearing Lower Cambrian black shale from a certain district in South China. Geochimica 1973, 143-164.

Fan, D., Ye, J., Yang, R., Huang, Z., 1987. The geological events and ore mineralization nearby the Precambrian-Cambrian boundary in Yangtze Platform. Acta Sedimentologica Sinica 5, 81-95.

Fang, Y., He, T., Yin, K., Liu, X., Gao, Y., Ju, R., Chen, M., Liu, K., Zhang, Y., Qiao, X., Xu, D., Chen, T., Tao, X., Li, Z., Wang, Z., Tang, R., Du, D., Lin, Q., Jiao, P., Xiao, S., 1992. The research on small shelly fossils and the use for geology of exploration. Bureau of geology and mineral exploration and developemtn of Shaanxi Province, Xian, 90 pp.

Fedo, C.M., Whitehouse, M.J., 2002. Metasomatic origin of quartz-pyroxene rock, Akilia, Greenland, and implications for Earth's earliest life. Science 296, 1448-1452.

Feng, Q., Du, Y., Yin, H., Sheng, J., Xu, J., 1996. Carboniferous radiolaria fauna firstly discovered in Mian-Lue ophiolitic Melange Belt of South Qinling Mountains. Science in China (Series D) 26, 78-82.

Feng, W., Qian, Y., Rong, Z., 1994. Study of Monoplacophora and Gastropoda from the Lower Cambrian Xinji Formation in Ye Xian, Henan. Acta Micropalaeontologica Sinica 11, 1-19.

Feng, W., Sun, W., Qian, Y., 2000. Earliest Cambrian Monoplacophora in northeastern Yunnan with some new genera and species. Acta Micropalaeontologica Sinica 17, 362–377.

Feng, W., Sun, W., Qian, Y., 2001. Skeletalization characters, classification and evolutionary significance of Early Cambrian monoplacophoran Maikhanellids. Acta Palaeontologica Sinica 40, 195-213.

Feng, Z., Peng, Y., Jin, Z., Jiang, P., Bao, Z., Luo, Z., Ju, T., Tian, H., Wang, H., 2001. Lithofacies Paleogeography of the Cambrian and Ordovician in South China. Geological Publishing House, Beijing, 221 pp.

Fike, D., Grotzinger, J., Pratt, L., Summons, R., 2006. Oxidation of the Ediacaran ocean. Nature 444, 744-747.

Flügel, E., 2010. Microfacies of carbonate rocks. Springer, New York, 984 pp.

Ford, D.C., Williams, P.W., 2007. Karst hydrogeology and geomorphology. John Wiley & Sons, London, 562 pp.

Fralick, P., Davis, D.W., Kissin, S.A., 2002. The age of the Gunflint Formation, Ontario, Canada: single zircon U-Pb age determinations from reworked volcanic ash. Canadian Journal of Earth Sciences 39, 1085-1091.

Gao, H., 1998. The biochemical sedimentary metallogenic model of baritic and witheritic deposits in Lower Cambrian in China. Journal of Mineralogy and Petrology 18, 70-77.

Gehling, J.G., Jensen, S.R., Droser, M.L., Myrow, P.M., Narbonne, G.M., 2001. Burrowing below the basal Cambrian GSSP, Fortune Head, Newfoundland. Geological Magazine 138, 213-218.

Goldring, R., Kazmierczak, J., 1974. Ecological succession in intraformational hardground formation. Palaeontology 17, 949-962.

Goldring, R., 1995. Organisms and the substrate: response and effect. Geological Society, London, Special Publications 83, 151-180.

Grabau, A.W., 1900. Palaeontology of the Cambrian terranes of the Boston Basin. Occasional Papers of the Boston Society of Natural History 4, 601-694.

Grant, S.W.F., 1992. Carbon isotopic vital effect and organic diagenesis, Lower Cambrian Forteau Formation, northwest Newfoundland: Implications for $\delta^{13}C$ chemostratigraphy. Geology 20, 243-246.

Gravestock, D.I., Alexander, E.M., Demidenko, Y.E., Esakova, N.V., Holmer, L.E., Jago, J.B., T.Lin, Melnikova, L.M., Parkhaev, P.Y., Rozanov, A.Y., Ushatinskaya, G.T., Zang, W., Zhegallo, E.A., Zhuravlev, A.Y., 2001. The Cambrian biostratigraphy of the Stansbury Basin, South Australia. Nauka / Interperiodica, Moscow, 343 pp.

Green, O.R., 2001. A manual of practical laboratory and field techniques in palaeobiology. Springer, 538 pp.

Gregoryeva, N.V., Melnikova, L.M., Pelman, L.Y., 1983. Brachiopods, ostracodes (bradoriids) and problematical fossils from the stratotype region of the Lower Cambrian stages. Paleontologicheskii Zhurnal 17, 51-56.

Gridina, N.M., 1991. Remains of conodonts and phosphatic problematica in the Lower Cambrian of central Kazakstan. Paleontologitscheskii Zhurnal 1991, 102-108.

Grotzinger, J.P., Bowring, S.A., Saylor, B.Z., Kaufman, A.J., 1995. Biostratigraphic and geochronologic constraints on early animal evolution. Science 270, 598-598.

Gubanov, A., 1998. The Early Cambrian molluscan evolution and its palaeogeographic implications. Acta Universitatis Carolinae - Geologica 42, 419-422.

Gubanov, A.P., Kouchinsky, A.V., Peel, J.S., 1999. The first evolutionary-adaptive lineage within fossil molluscs. Lethaia 32, 155-157.

Gubanov, A.P., Peel, J.S., 1999. Oelandiella, the earliest Cambrian helcionelloid mollusc from Siberia. Palaeontology 42, 211-222.

Gubanov, A.P., Remolar, D.C.F., Peel, J.S., 2004. Early Cambrian molluscs from Sierra de Cordoba (Spain). Geobios 37, 199-215.

Guo, L., Shi, Y., Lu, H., Ma, R., Dong, H., Yang, S., 1989. The pre-Devonian tectonic patterns and evolution of South China. Journal of Southeast Asian Earth Sciences 3, 87-93.

Guo, L., Lu, H., Shi, Y., Ma, R., Sun, Y., Shu, L., Jia, D., Zhang, Q., Charvet, J., Faure, M., 1996. On the Meso-Neoproterozoic Jiangnan Island Arc: Its kinematics and dynamics. Geological Journal of Universities 2, 1-13.

Hamdi, B., Brasier, M., Zhiwen, J., 1989. Earliest skeletal fossils from Precambrian–Cambrian boundary strata, Elburz Mountains, Iran. Geological Magazine 126, 283-289.

He, S., Yu, G., 1992. The Small Shelly Fossils from the Palaeocambrian Meishucunian Stage in Western Zhejiang. Geology in Zhejiang 8, 1-7.

He, T., Yang, X., 1982. Lower Cambrian Meishucun stage of western Yangtze stratigraphic region and its small shelly fossils. Bulletin of the Chengdu Institute of Geology and Mineral Resources. Chinese Academy of Geological Sciences 3, 69-95.

He, T., Pei, F., Fu, G., 1984. Some small shelly fossils from the Lower Cambrian Xinji Formation in Fangcheng County, Henan Province. Acta Palaeontologica Sinica 23, 350-357.

He, T., Pei, F., 1985. The discovery of bivalves from the Lower Cambrian Xinji Formation in Fangcheng County, Henan Province. Journal of Chengdu College of Geology 1985, 61-66.

He, T., Shen, L., Yin, J., 1988. A new understanding on Meishucun Sinian-Cambriax Boundary Section in Jinning, Yunnan. Journal of Chengdu University of Technology (Science & Technology Edition) 15, 41-47.

He, Y., Yang, X., 1986. Early Cambrian coelenterates from Nanjiang, Sichuan. Bulletin of the Chengdu Institute of Geology and Mineral Resources 7, 31-43.

He, Y., Qi, F., Qi, S., 2007. Changes of decay rates of radioactive ^{111}In and ^{32}P induced by mechanic motion. Science in China Series B: Chemistry 50, 170-174.

He, Y., Zeng, L., Qi, S., 2009. Discussions about whether radioactive half life can be changed by mechanic motion. Science in China Series B: Chemistry 52, 693-698.

Hinz-Schallreuter, I., Gozalo, R., Linan, E., 2007. New bradorid arthropods from the Lower Cambrian of Spain. Micropaleontology 53, 497-510.

Hinz, I., 1987. The Lower Cambrian microfauna of Comley and Rushton, Shropshire/England. Palaeontographica Abteilung A 198, 41-100.

Hoffman, P.F., Kaufman, A.J., Halverson, G.P., Schrag, D.P., 1998. A Neoproterozoic snowball earth. Science 281, 1342-1346.

Hoffman, P.F., Schrag, D.P., 2002. The snowball Earth hypothesis: testing the limits of global change. Terra Nova 14, 129-155.

Holmer, L., Koneva, S., Bassett, M., Popov, L., 2001. Cambrian-early Ordovician brachipods from Malyi Karatau, the western Balkash region, and Tien Shan, Central Asia. Special Papers in Palaentology 65, 1-180.

Holmer, L.E., Popov, L.E., Wrona, R., 1996. Early Cambrian lingulate brachiopods from glacial erratics of King George Island (South Shetland Islands), Antarctica. Palaeontologia Polonica 55, 37-50.

Holmer, L.E., Popov, L.E., Koneva, S.P., Jia-Yu, R., 1997. Early Cambrian *Lingulellotreta* (Lingulata, Brachiopoda) from South Kazakhstan (Malyi Karatau Range) and South China (Eastern Yunnan). Journal of Paleontology 71, 577-584.

Hou, X., Siveter, D.J., Williams, M., Xiang-hong, F., 2001. A monograph of the Bradoriid arthropods from the Lower Cambrian of SW China. Earth and Environmental Science Transactions of the Royal Society of Edinburgh 92, 347-409.

Hou, X., Aldridge, R., Bergstrom, J., Siveter, D.J., Siveter, D., Feng, X., 2004. The Cambrian fossils of Chengjiang, China: the flowering of early animal life. Blackwell, Oxford, 248 pp.

Hu, S., Luo, H., Hou, S., Erdtmann, B.-D., 2007. Eocrinoid echinoderms from the Lower Cambrian Guanshan Fauna in Wuding, Yunnan, China. Chinese Science Bulletin 52, 717-719.

Huang, J., Ren, J., Jiang, C., Zhang, Z., Xu, Z., 1977. An outline of the tectonic charateristics of China. Acta Geologica Sinica, 117-135.

Huang, J., 1984. New researches on the tectonic characteristics of China. Bulletin of the Chinese Academy of Geological Scineces 9, 5-18.

Huang, Z., 1986. Biostratigraphic features of the Lower Cambrian Phosphorus-bearing Rock Formation in Xianfeng of Xundian County and its correlation in eastern Yunnan. Yunnan Geology 5, 146-156.

Huh, C.-A., 1999. Dependence of the decay rate o ^{7}Be on chemical forms. Earth and Planetary Science Letters 171, 325-328.

Huo, S., Shu, d., Zhang, X., Cui, Z., Tong, H., 1983. Notes on Cambrian bradoriids from

Shaanxi, Yunnan, Sichuan, Guizhou, Hubei and Guangdong. Journal of Northwest University 39, 56-75.

Huo, S., Cui, Z., 1989. On the ages of the Tsunyiellid-bearing strata in China. Geological Review 35, 72-83.

Hutchinson, G., 1961. The biologist poses some problems, in: Sears, M. (Ed.), Oceanography. American Association for the Advancement of Science Publication, Washington, DC, pp. 85-94.

Ishikawa, T., Ueno, Y., Komiya, T., Sawaki, Y., Han, J., Shu, D., Li, Y., Maruyama, S., Yoshida, N., 2008. Carbon isotope chemostratigraphy of a Precambrian/Cambrian boundary section in the Three Gorge area, South China: Prominent global-scale isotope excursions just before the Cambrian Explosion. Gondwana Research 14, 193-208.

Ivantsov, A.Y., Zhuravlev, A.Y., Krassilov, V., Leguta, A., Mel’nikova, L., Urbanek, A., Ushatinskaya, G., Malakhovskaya, Y.E., 2005. Unique Sinsk localities of Early Cambrian organisms (Siberian Platform). Trudy paleontologicheskogo instituta 284, 143.

Ivantsov, A.Y., Zhuravlev, A.Y., Leguta, A.V., Krassilov, V.A., Melnikova, L.M., Ushatinskaya, G.T., 2005. Palaeoecology of the Early Cambrian Sinsk biota from the Siberian platform. Palaeogeography, Palaeoclimatology, Palaeoecology 220, 69-88.

Jago, J., Zang, W.-l., Sun, X., Brock, G., Paterson, J., Skovsted, C., 2006. A review of the Cambrian biostratigraphy of South Australia. Palaeoworld 15, 406-423.

James, N.P., Choquette, P.W., 1988. Paleokarst. Springer, New York, 416 pp.

Janussen, D., Steiner, M., Maoyan, Z., 2002. New well-preserved scleritomes of Chancelloridae from the early Cambrian Yuanshan Formation (Chengjiang, China) and the middle Cambrian Wheeler Shale (Utah, USA) and paleobiological implications. Journal of Paleontology 76, 596-606.

Jenkins, J.H., Fischbach, E., Buncher, J.B., Gruenwald, J.T., Krause, D.E., Mattes, J.J., 2009. Evidence of correlations between nuclear decay rates and Earth–Sun distance. Astroparticle Physics 32, 42-46.

Jensen, S., Saylor, B.Z., Gehling, J.G., Germs, G.J., 2000. Complex trace fossils from the terminal Proterozoic of Namibia. Geology 28, 143-146.

Jensen, S., 2003. The Proterozoic and Earliest Cambrian Trace Fossil Record; Patterns, Problems and Perspectives. Integrative and Comparative Biology 43, 219-228.

Jeppsson, L., Fredholm, D., Mattiasson, B., 1985. Acetic acid and phosphatic fossils: a warning. Journal of Paleontology 59, 952-956.

Jeppsson, L., Anehus, R., 1995. A buffered formic acid technique for conodont extraction. Journal of Paleontology 69, 790-794.

Jeppsson, L., Anehus, R., Fredholm, D., 1999. The optimal acetate buffered acetic acid technique for extracting phosphatic fossils. Journal of Paleontology 73, 964-972.

Jiang, C., Wang, Z., Li, J., 2000. Tectonics of Opening and Closing of the Central Orogenic Belt in China. Geological Publishing House, Bejing, 154 pp.

Jiang, G., Kaufman, A.J., Christie-Blick, N., Zhang, S., Wu, H., 2007. Carbon isotope variability across the Ediacaran Yangtze platform in South China: Implications for a large surface-to-deep ocean δ13C gradient. Earth and Planetary Science Letters 261, 303-320.

Jiang, Z., 1980a. Monoplacophorans and gastropods fauna of the Meishucun stage from the Meishucun Section, Yunnan. Acta Geologica Sinica 54, 112–123.

Jiang, Z., 1980b. The Meishucun Stage and fauna of the Jinning County, Yunnan. Acta Geoscientica Sinica 2, 112-123.

Kerber, M., 1988. Microfossils from Lower Cambrian rocks of the Montagne Noire, France. Palaeontographica Abteilung A 202, 127-203.

Kirschvink, J.L., Raub, T.D., 2003. A methane fuse for the Cambrian explosion: carbon cycles and true polar wander. Comptes Rendus Geoscience 335, 65-78.

Knoll, A.H., Grotzinger, J.P., Kaufman, A.J., Kolosov, P., 1995. Integrated approaches to terminal Proterozoic stratigraphy: an example from the Olenek Uplift, northeastern Siberia. Precambrian Research 73, 251-270.

Knoll, A.H., Javaux, E.J., Hewitt, D., Cohen, P., 2006. Eukaryotic organisms in Proterozoic oceans. Philosophical Transactions of the Royal Society B: Biological Sciences 361, 1023-1038.

Knoll, A.H., 2009. The coevolution of life and environments. Rendiconti Lincei 20, 301-306.

Kouchinsky, A., 2000. Shell microstructures in Early Cambrian molluscs. Acta Palaeontologica Polonica 45, 119-150.

Kouchinsky, A., Bengtson, S., Pavlov, V., Runnegar, B., Torssander, P., Young, E., Ziegler, K., 2007. Carbon isotope stratigraphy of the Precambrian-Cambrian Sukharikha River section, northwestern Siberian platform. Geological Magazine 144, 609-618.

Kouchinsky, A., Bengtson, S., Runnegar, B., Skovsted, C., Steiner, M., Vendrasco, M., 2011. Chronology of early Cambrian biomineralization. Geological Magazine 149, 221-251.

Kouchinsky, A., Bengtson, S., Clausen, S., Vendrasco, M.J., 2014. A lower Cambrian fauna of skeletal fossils from the Emyaksin Formation, northern Siberia. Acta Palaeontologica Polonica, http://dx.doi.org/10.4202/app.2012.0004.

Kouchinsky, A.V., 2000. Skeletal microstructures of hyoliths from the Early Cambrian of Siberia. Alcheringa 24, 65-81.

Kröner, A., Kovach, V., Belousova, E., Hegner, E., Armstrong, R., Dolgopolova, A., Seltmann, R., Alexeiev, D.V., Hoffmann, J.E., Wong, J., Sun, M., Cai, K., Wang, T., Tong, Y., Wilde, S.A., Degtyarev, K.E., Rytsk, E., 2014. Reassessment of continental growth during the accretionary history of the Central Asian Orogenic Belt. Gondwana Research 25, 103-125.

Lü, Z., Liu, C., Liu, J., Wu, F., 2004a. The bio-barite in witherite deposits from Southern Qinling and its significance. Progress in Natural Science 14, 889-895.

Lü, Z., Liu, C., Liu, J., Wu, F., 2004b. Geochemical Studies on the Lower Cambrian Witherite-bearing Cherts in the Northern Daba Mountains. Acta Geologica Sinica 78, 390-406.

Lai, S., Zhang, G., Pei, X., 2002. Geochemistry of the Pipasi ophiolite in the Mianlue suture Zone, South Qinling, and its tectonic significance. Geological Bulletin of China 21, 465-470.

Landing, E., 1974. Early and Middle Cambrian conodonts from the Taconic allochthon, eastern New York. Journal of Paleontology, 1241-1248.

Landing, E., Nowlan, G.S., Fletcher, T.P., 1980. A microfauna associated with Early Cambrian trilobites of the Callavia Zone, norther Antigonish Highlands, Nova Scotia. Canadian Journal of Earth Sciences 17, 400-418.

Landing, E., 1988. Lower Cambrian of eastern Massachusetts: stratigraphy and small shelly fossils. Journal of Paleontology 62, 661-695.

Landing, E., 1989. Paleoecology and distribution of the Early Cambrian rostroconch *Watsonella crosbyi* Grabau. Journal of Paleontology 63, 566-573.

Landing, E., Myrow, P., Benus, A.P., Narbonne, G.M., 1989. The Placentian Series: appearance of the oldest skeletalized faunas in southeastern Newfoundland. Journal of Paleontology 63, 739-769.

Landing, E., 1991. Upper Precambrian through Lower Cambrian of Cape Breton Island: faunas, paleoenvironments, and stratigraphic revision. Journal of Paleontology 65, 570-595.

Landing, E., 1992. Lower Cambrian of southeastern Newfoundland: epeirogeny and Lazarus faunas, lithofacies–biofacies linkages, and the myth of a global chronostratigraphy, in: Lipps, J.H., Signor, P.W. (Eds.), Origins and Early Evolution of Metazoa. Plenum Press, New York, pp. 283–309.

Landing, E., 1994. Precambrian-Cambrian boundary global stratotype ratified and a new perspective of Cambrian time. Geology 22, 179-182.

Landing, E., 1995. Upper Placentian-Branchian Series of mainland Nova Scotia (middle-upper Lower Cambrian): faunas, paleoenvironments, and stratigraphic revision. Journal of Paleontology 69, 475-495.

Landing, E., Johnson, S.C., Geyer, G., 2008. Faunas and Cambrian volcanism on the Avalonian marginal platform, southern New Brunswick. Journal of Paleontology 82, 884.

Landing, E., Geyer, G., 2012. Misplaced faith —(FAD) in chronostratigraphy & proposal of more robust Lower Cambrian correlation standards. Journal of Guizhou University 29, 170-171.

Landing, E., Geyer, G., Brasier, M.D., Bowring, S.A., 2013a. Cambrian Evolutionary Radiation: Context, correlation, and chronostratigraphy—Overcoming deficiencies of the first appearance datum (FAD) concept. Earth-Science Reviews 123, 133-172.

Landing, E., Westrop, S.R., Bowring, S.A., 2013b. Reconstructing the Avalonia palaeocontinent in the Cambrian: A 519 Ma caliche in South Wales and transcontinental middle Terreneuvian sandstones. Geological Magazine, 1-25.

Last, W.M., 1992. Petrology of modern carbonate hardgrounds from East Basin Lake, a saline maar lake, southern Australia. Sedimentary Geology 81, 215-229.

Lee, H.-Y., 1987. Discovery of the early Cambrian small shelly fossils from the Choseon Supergroup at the Kurangni area. Mungyong-Kun, South Korea. Journal of the Paleontological Society of Korea 3, 93-107.

Lepland, A., van Zuilen, M.A., Arrhenius, G., Whitehouse, M.J., Fedo, C.M., 2005. Questioning the evidence for Earth's earliest life—Akilia revisited. Geology 33, 77-79.

Levashova, N.M., Kalugin, V.M., Gibsher, A.S., Yff, J., Ryabinin, A.B., Meert, J.G., Malone, S.J., 2010. The origin of the Baydaric microcontinent, Mongolia: Constraints from paleomagnetism and geochronology. Tectonophysics 485, 306-320.

Levashova, N.M., Meert, J.G., Gibsher, A.S., Grice, W.C., Bazhenov, M.L., 2011. The origin of microcontinents in the Central Asian Orogenic Belt: Constraints from paleomagnetism and geochronology. Precambrian Research 185, 37-54.

Li, D., Ling, H., Jiang, S., Pan, J., Chen, Y., Cai, Y., Feng, H., 2009. New carbon isotope stratigraphy of the Ediacaran–Cambrian boundary interval from SW China: implications for global correlation. Geological Magazine 146, 465-484.

Li, G., Zhang, J., Zhu, M., 2001. Litho-and biostratigraphy of the Lower Cambrian Meishucunian Stage in the Xiaotan section, eastern Yunnan. Acta Palaeontologica Sinica 40, 40-53.

Li, G., Zhu, M., Steiner, M., 2003. Microstructure and functional morphology of the Early Cambrian problematical fossil *Rhombocorniculum*. Progress in Natural Science 13, 831-835.

Li, G., Holmer, L.E., 2004. Early Cambrian lingulate brachiopods from the Shaanxi Province, China. GFF 126, 193-211.

Li, G., Xiao, S., 2004. *Tannuolina* and *Micrina* (Tannuolinidae) from the Lower Cambrian of eastern Yunnan, South China, and their scleritome reconstruction. Journal of Paleontology 78, 900-913.

Li, G., Zhu, M., Steiner, M., Qian, Y., 2004a. Skeletal faunas from the Qiongzhusian of southern Shaanxi: Biodiversity and lithofacies-biofacies links in the Lower Cambrian carbonate settings. Progress in Natural Science 14, 91-96.

Li, G., Zhu, M., Van Iten, H., Li, C., 2004b. Occurrence of the earliest known *Sphenothallus* Hall in the Lower Cambrian of Southern Shaanxi Province, China. Geobios 37, 229-237.

Li, G., Steiner, M., Zhu, X., Yang, A., Wang, H., Erdtmann, B.D., 2007. Early Cambrian metazoan fossil record of South China: Generic diversity and radiation patterns. Palaeogeography, Palaeoclimatology, Palaeoecology 254, 229-249.

Li, G., Zhao, X., Gubanov, A., Zhu, M.Y., Na, L., 2011. Early Cambrian Mollusc *Watsonella crosbyi*: A Potential GSSP Index Fossil for the Base of the Cambrian Stage 2. Acta Geologica Sinica 85, 309-319.

Li, G., Steiner, M., Zhu, M., Zhao, X., 2012. Early Cambrian eodiscoid trilobite *Hupeidiscus orientalis* from South China: ontogeny and implications for affinities of *Mongolitubulus*-like sclerites. Bulletin of Geosciences 87, 159-169.

Li, G., Zhang, Z., Hua, H., Yang, H., 2014. Occurrence of the Enigmatic Bivalved Fossil Apistoconcha in the Lower Cambrian of Southeast Shaanxi, North China Platform. Journal of Paleontology 88, 359-366.

Li, H., Li, Z., 2005. Research on metallogenic geology characteristics and exploration indications of manganese, North edge of Yangzi Platform. Geology and Prospecting 41, 18-21.

Li, L., Han, N., 1980. Discovery of Ordovician Trimerellidae (Brachiopoda) from western Zhejiang and its significance. Acta Palaeontologica Sinica 19, 8-21.

Li, S., Kusky, T.M., Wang, L., Zhang, G., Lai, S., Liu, X., Dong, S., Zhao, G., 2007. Collision leading to multiple-stage large-scale extrusion in the Qinling orogen: insights from the Mianlue suture. Gondwana Research 12, 121-143.

Li, Y., 1975. On the Cambrian Ostracoda with new material from Sichuan, Yunnan and southern Shaanxi, China, Professional papers on Stratigraphy and Palaeontology. Geological Publishing House, Beijing, pp. 37-72.

Li, Y., Song, L., Zhou, Z., Yang, J., 1975. Early Palaeozoic stratigraphy of western part of Dabashan. Geological Publishing House, Beijing, 372 pp.

Li, Y., Zhou, B., 1986. Discovery of old microfossil bivalvias in China and its significance. Scientia Geologica Sinica 1986, 38-45.

Li, Y., Qin, H., Ding, L., 1991. A kind of strange bone lamella fossils from the Early

Cambrian in Zhenba County South Shaanxi. Journal of Xi'an College of Geology 13, 8-14.

Li, Y., 1995. New advances in the study of associated elements in Lower Cambrian black shale of northwestern Hunan. Mineral Deposits 14, 346-354.

Li, Y., 1997. The geological characteristics of sea-floor exhalation-sedimentary chert in Lower Cambrian black shales in Dayong-Cili Area, Hunan Province. Acta Petrologica Sinica 13, 121-126.

Li, Z., 1984. The discovery and its significance of Small Shelly Fossils in Hexi area, Xixiang, Shaanxi. Geology of Shaanxi 2, 73-78.

Li, Z., Li, X., Kinny, P., Wang, J., Zhang, S., Zhou, H., 2003. Geochronology of Neoproterozoic syn-rift magmatism in the Yangtze Craton, South China and correlations with other continents: evidence for a mantle superplume that broke up Rodinia. Precambrian Research 122, 85-109.

Li, Z., Bogdanova, S., Collins, A.S., Davidson, A., De Waele, B., Ernst, R., Fitzsimons, I., Fuck, R., Gladkochub, D., Jacobs, J., 2008. Assembly, configuration, and break-up history of Rodinia: a synthesis. Precambrian Research 160, 179-210.

Li, Z., Evans, D.A., Halverson, G., 2013. Neoproterozoic glaciations in a revised global palaeogeography from the breakup of Rodinia to the assembly of Gondwanaland. Sedimentary Geology 294, 219-232.

Lieberman, B.S., 1997. Early Cambrian paleogeography and tectonic history: a biogeographic approach. Geology 25, 1039-1042.

Limata, B., Raiola, F., Wang, B., Yan, S., Becker, H., D'Onofrio, A., Gialanella, L., Roca, V., Rolfs, C., Romano, M., 2006. First hints on a change of the ^{22}Na β^+-decay half-life in the metal Pd. The European Physical Journal A-Hadrons and Nuclei 28, 251-252.

Lin, T., Peng, S., Zhu, X., 2004. Restudy on the eodiscoids fromthe Shuijingtuo Formation (Early Cambrian) in eastern Yangtze Gorge Area, western Hubei. Acta Palaeontologica Sinica 43, 502-514.

Lindsay, J., Brasier, M., Dorjnamjaa, D., Goldring, R., Kruse, P., Wood, R., 1996a. Facies and sequence controls on the appearance of the Cambrian biota in southwestern Mongolia: Implications for the Precambrian-Cambrian boundary. Geological Magazine 133, 417-428.

Lindsay, J., Brasier, M., Shields, G., Khomentovsky, V., Bat-Ireedui, Y., 1996b. Glacial facies associations in a Neoproterozoic back-arc setting, Zavkhan Basin, western Mongolia. Geological Magazine 133, 391-402.

Lindström, M., 1979. Diagenesis of Lower Ordovician hardgrounds in Sweden, 22 pp.

Lindstrom, R., Fischbach, E., Buncher, J., Greene, G., Jenkins, J., Krause, D., Mattes, J., Yue, A., 2010. Study of the dependence of ^{198}Au half-life on source geometry. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 622, 93-96.

Ling, W., Ren, B., Duan, R., Liu, X., Mao, X., Peng, L., Liu, Z., Cheng, J., Yang, H., 2007. Timing of the Wudangshan, Yaolinghe volcanic sequences and mafic sills in South Qinling: U-Pb zircon geochronology and tectonic implication. Chinese Science Bulletin 52, 1445-1456.

Ling, W., Ren, B., Duan, R., Liu, X., Mao, X., Peng, L., Liu, Z., Cheng, J., Yang, H., 2008. Timing of the Wudangshan, Yaolinghe volcanic sequences and mafic sills in South Qinling: U-Pb zircon geochronology and tectonic implication. Chinese Science Bulletin 53, 2192-2199.

Ling, W., Duan, R., Liu, X., Cheng, J., Mao, X., Peng, L., Liu, Z., Yang, H., Ren, B., 2010. U-Pb dating of detrital zircons from the Wudangshan Group in the South Qinling and its geological significance. Chinese Science Bulletin 55, 2440-2448.

Liu, D., 1979. Earliest Cambrian Brachiopods from Southwest China. Acta Palaeontologica Sinica 18, 93–100.

Liu, J., Wu, S., Liu, Z., Su, W., Wang, J., 2010. A discussion on the origin of witherite deposits in large-scale barium metallogenic belt, southern Qinling Mountains, China. Earth Science Frontiers 17, 222-238.

Liu, L., Huh, C., 2000. Effect of pressure on the decay rate of ^{7}Be. Earth and Planetary Science Letters 180, 163-167.

Luo, H., Jiang, Z., Xu, C., Song, X., Xue, X., 1980. On the Sinian–Cambrian boundary of Meishucun and Wangjiawan, Jinning county, Yunnan. Acta Geologica Sinica 54, 95–111.

Luo, H., Jiang, Z., Wu, X., Song, X., Ou, Y., 1982. The Sinian–Cambrian boundary in eastern Yunnan. Yunnan People's Publishing House, Kunming, 265 pp.

Luo, H., Jiang, Z., Wu, X., Song, X., Ou, Y., Xing, Y., Liu, G., Zhang, S., Tao, Y., 1984. Sinian–Cambrian Boundary Stratotype Section at Meishucun, Jinning, Yunnan, China. Peoples Pub. House, Yunnan, Kunming, 154 pp.

Luo, H., Wu, X., Ouyang, L., 1991. Facies changes and transverse correlation of the Sinian–Cambrian boundary strata in eastern Yunnan. Sedimentary Geology and Tethyan Geology 65, 27–35.

Luo, L., Pi, D., Yang, J., Wu, H., 2012. Ore-genesis of the witherite deposit in Ziyang, Shaanxi Province: Evidence from ore texture, redox-sensitive trace elements and C-O isotopes. Acta Petrologica Sinica 28, 4021-4030.

Müller, K., Walossek, D., Zakharov, A., 1995. 'Orsten' type phosphatized soft-integument preservation and a new record from the Middle Cambrian Kuonamka Formation in Siberia. Neues Jahrbuch fur Geologie und Palaontologie-Abhandlungen 197, 101-118.

Müller, K.J., 1959. Kambrische Conodonten. Zeitschrift der Deutschen Geologischen Gesellschaft 111, 434-485.

Müller, K.J., 1975. *Heraultia varensalensis* Cobbold (crustacea) aus dem unteren kambrium, der älteste fall voti geschlechtsdimorphismus. Paläontologische Zeitschrift 49, 168-180.

Maloof, A.C., Schrag, D.P., Crowley, J.L., Bowring, S.A., 2005. An expanded record of Early Cambrian carbon cycling from the Anti-Atlas Margin, Morocco. Canadian Journal of Earth Sciences 42, 2195-2216.

Maloof, A.C., Porter, S.M., Moore, J.L., Dudas, F.O., Bowring, S.A., Higgins, J.A., Fike, D.A., Eddy, M.P., 2010. The earliest Cambrian record of animals and ocean geochemical change. Bulletin of the Geological Society of America 122, 1731-1774.

Mambetov, A.M., 1972. A new Lower Cambrian hyolithid genus from Maly Karatau (Northwestern Tien Shan). Paleontologicheskii Zhurnal 6, 268-269.

Mambetov, A.M., Repina, L.N., 1979. The Lower Cambrian of the Talassk Ala-Too and its correlation with the sections of Karatau Minor and the Siberian Platform. Rossiiskaya Akademiya Nauk Sibirskoe Otdelenie Trudy Instituta Geologii i Geofiziki 406, 98-138.

Mansuy, H., 1912. Geological Survey of East Yunnan. Memoire service geologie 1'Indochine 1, 1-23.

Marshall, C.R., 2006. Explaining the Cambrian “explosion” of animals. Annual Review Earth Planetary Science 34, 355-384.

Marshall, J.D., Ashton, M., 1980. Isotopic and trace element evidence for submarine lithification of hardgrounds in the Jurassic of eastern England. Sedimentology 27, 271-289.

Maruyama, S., Santosh, M., 2008. Models on Snowball Earth and Cambrian explosion: A synopsis. Gondwana Research 14, 22-32.

Mattauer, M., Matte, P., Malavieille, J., Tapponnier, P., Maluski, H., Qin, X.Z., Lun, L.Y., Qin, T.Y., 1985. Tectonics of the Qinling belt: Build-up and evolution of eastern Asia. Nature 317, 496-500.

Matthews, S., 1973. Lapworthellids from the Lower Cambrian Strenuella Limestone at Comley, Shropshire. Palaeontology 16, 139-148.

Matthews, S.C., Missarzhevsky, V.V., 1975. Small shelly fossils of late Precambrian and early Cambrian age: a review of recent work. Journal of the Geological Society 131, 289.

McGowran, B., 2008. Biostratigraphy: microfossils and geological time. Cambridge University Press, 459 pp.

Meert, J.G., Lieberman, B.S., 2004. A palaeomagnetic and palaeobiogeographical perspective on latest Neoproterozoic and early Cambrian tectonic events. Journal of the Geological Society 161, 477-487.

Meert, J.G., Lieberman, B.S., 2008. The Neoproterozoic assembly of Gondwana and its relationship to the Ediacaran–Cambrian radiation. Gondwana Research 14, 5-21.

Meert, J.G., Gibsher, A.S., Levashova, N.M., Grice, W.C., Kamenov, G.D., Ryabinin, A.B., 2011. Glaciation and ~770 Ma Ediacara (?) Fossils from the Lesser Karatau Microcontinent, Kazakhstan. Gondwana Research 19, 867-880.

Mehl, D., 1998. Porifera and Chancelloriidae from the Middle Cambrian of the Georgina Basin, Australia. Palaeontology 41, 1153-1182.

Meng, Q., Zhang, G., 2000. Geologic framework and tectonic evolution of the Qinling orogen, central China. Tectonophysics 323, 183-196.

Mikheev, V., Morozov, V., Morozova, N., 2008. A possibility of controlled variation of radioactive decay rate of atomic nuclei. Physics of Particles and Nuclei Letters 5, 371-373.

Missarzhevsky, V., 1967. First occurrences of Lapworthella in Lower Cambrian of the Siberian Platform. International Geology Review 9, 353-358.

Missarzhevsky, V.V., 1973. Conodont-shaped organisms from Precambrian–Cambrian boundary strata of the Siberian Platform and Kazakhstan, in: Zhuravleva, I.T. (Ed.), Palaeontological and biostratigraphic problems in the Lower Cambrian of Siberia and the Far East. Nauka, Novosibirsk, pp. 53–57.

Missarzhevsky, V.V., 1974. New data on the oldest Early Cambrian fossils of the Siberian Platform, in, Biostratigraphy and paleontology of the Lower Cambrian of Europe and northern. AsiaAkedemiya Nauk SSSR, Moscow, pp. 179-189.

Missarzhevsky, V.V., 1977. Conodonts (?) and phosphatic problematica from the Cambrian of Mongolia and Siberia. Trudy Sovmestanya Sovetsko-Mongolskaya Paleontologicheskaya Ekspeditsiya 5, 10–19.

Missarzhevsky, V.V., 1981. Early Cambrian hyoliths and gastropods of Mongolia. Paleontologicheskii Zhurnal 1981, 21–28.

Missarzhevsky, V.V., Mambetov, A.M., 1981. Stratigraphy and fauna of Cambrian and

Precambrian boundary beds of Maly Karatau. Trudy Akademii Nauka SSSR, Moscow, 326 pp.

Moczydlowska, M., 1991. Acritarch biostratigtaphy of the Lower Cambrian and the Precambrian-Cambrian boundary in southeastern Poland. Fossils Strata 29, 1-127.

Moczydlowska, M., Zang, W.-L., 2006. The Early Cambrian acritarch *Skiagia* and its significance for global correlation. Palaeoworld 15, 328-347.

Mojzsis, S.J., Arrhenius, G., McKeegan, K., Harrison, T., Nutman, A., Friend, C., 1996. Evidence for life on Earth before 3,800 million years ago. Nature 384, 55-59.

Moorbath, S., 2005. Palaeobiology: Dating earliest life. Nature 434, 155-155.

Moore, J.L., Porter, S.M., Li, G., 2014. Two Unusual Small Shelly Fossils from the Lower Cambrian of Southeastern Shaanxi Province, China. Journal of Paleontology 88, 348-358.

Mount, J.F., Signor, P.W., 1992. Faunas and facies—fact and artifact. Paleoenvironmental controls on the distribution of Early Cambrian faunas, in: Lipps, J.H., Signor, P.W. (Eds.), Origins and Early Evolution of Metazoa. Plenum Press, New York, pp. 27–51.

Na, L., Li, G., 2011. Nail-shaped sclerite fossils from the Lower Cambrian Xihaoping Member of Fangxian, Hubei Province. Acta Micropalaeontologica Sinica 28, 35-51.

Narbonne, G.M., Myrow, P.M., Landing, E., Anderson, M.M., 1987. A candidate stratotype for the Precambrian-Cambrian boundary, Fortune Head, Burin Peninsula, southeastern Newfoundland. Canadian Journal of Earth Sciences 24, 1277-1293.

Noé, S., Titschack, J., Freiwald, A., Dullo, W.-C., 2006. From sediment to rock: diagenetic processes of hardground formation in deep-water carbonate mounds of the NE Atlantic. Facies 52, 183-208.

Notholt, A., Sheldon, R., 1986. Proterozoic and Cambrian phosphorites—regional review: World resources, in: Cook, P., Shergold, J. (Eds.), Proterozoic and Cambrian Phosphorites, Phosphate Deposits of the World, Proterozoic and Cambrian Phosphorites. Cambridge University Press, Cambridge, pp. 9-19.

Ohtsuki, T., Yuki, H., Muto, M., Kasagi, J., Ohno, K., 2004. Enhanced Electron-Capture Decay Rate of B 7 e Encapsulated in C 60 Cages. Physical Review Letters 93, 112501.

Ohtsuki, T., Ohno, K., Morisato, T., Mitsugashira, T., Hirose, K., Yuki, H., Kasagi, J., 2007. Radioactive Decay Speedup at $T = 5$ K: Electron-Capture Decay Rate of ^{7}Be Encapsulated in C_{60}. Physical Review Letters 98, 252501.

Ohtsuki, T., Hirose, K., Ohno, K., Morisato, T., 2011. Half-life measurement of ^{7}Be in host beryllium metal. Proceedings in Radiochemistry A Supplement to Radiochimica Acta 1, 101-104.

Palmer, T., 1982. Cambrian to Cretaceous changes in hardground communities. Lethaia 15, 309-323.

Pan, G., Xiao, Q., Lu, S., Deng, J., Feng, Y., Zhang, K., Zhang, Z., Wang, F., Xing, G., Hao, G., Feng, Y., 2009. Subdivision of tectonic units in China. Geology in China 36, 1-28.

Parkhaev, P.Y., 1998. Siphonoconcha-A New Class of Early Cambrian Bivalved Organisms. Paleontologicheskii Zhurnal 32, 1-15.

Parkhaev, P.Y., 2001. Molluscs and siphonoconchs, in: Alexander, E.M., Jago, J.B., Rozanov, A.Y., Zhuravlev, A.Y. (Eds.), The Cambrian Biostratigraphy of the Stansbury Basin, South Australia. Nauka, Moscow, pp. 133-210.

Parkhaev, P.Y., 2001. Molluscs and siphonoconchs., in: Alexander, E.M., Jago, J.B., Rozanov, A.Yu., and Zhuravlev, A.Yu. (Ed.), The Cambrian biostratigraphy of the Stansbury Basin, South Australia. Nauka, Moscow, pp. 133-210.

Parkhaev, P.Y., 2004. Malacofauna of the Lower Cambrian Bystraya Formation of eastern Transbaikalia. Paleontologicheskii Zhurnal 38, 590-608.

Parkhaev, P.Y., 2005. Cambrian Helcionelloid mollusks as the evolutionary foundation of Gastropoda, in, Modern Russian Paleontology: Classical and New Methods. Paleontological Institute of Russian Academy of Sciences, Moscow, pp. 63-84.

Parkhaev, P.Y., 2005. Two new species of the Cambrian helcionelloid mollusks from the northern part of the Siberian Platform. Paleontologicheskii Zhurnal 39, 615-619.

Parkhaev, P.Y., 2008. The Early Cambrian radiation of Mollusca, in: Ponder, W.F., Lindberg, D.R. (Eds.), Phylogeny and Evolution of Molluscs. University of California Press, Berkeley, pp. 33-69.

Parkhaev, P.Y., Demidenko, Y.E., 2010. Zooproblematica and Mollusca from the Lower Cambrian Meishucun Section (Yunnan, China) and Taxonomy and Systematics of the Cambrian Small Shelly Fossils of China. Paleontologicheskii Zhurnal 44, 883-1161.

Parkhaev, P.Y., Karlova, G., 2011. Taxonomic revision and evolution of Cambrian mollusks of the genus *Aldanella* Vostokova, 1962 (Gastropoda: Archaeobranchia). Paleontologicheskii Zhurnal 45, 1145-1205.

Paterson, J.R., Skovsted, C.B., Brock, G.A., Jago, J.B., 2007. An early Cambrian faunule from the Koolywurtie Limestone Member (Parara Limestone), Yorke Peninsula, South Australia and its biostratigraphic significance. Memoirs of the Association of Australasian Palaeontologists 34, 131-146.

Peel, J.S., 1988. *Spirellus* and related helically coiled microfossils (cyanobacteria) from the Lower Cambrian of North Greenland. Grønlands Geologiske Undersøgelse, Rapport 137, 5-32.

Peel, J.S., Skovsted, C.B., 2005. Problematic cap-shaped fossils from the Lower Cambrian of North-East Greenland. Paläontologische Zeitschrift 79, 461-470.

Pei, F., 1985. First discovery of *Yochelcionella* from the Lower Cambrian in China and its significance. Acta Micropalaeontologica Sinica 2, 395-400.

Pei, F., 1988. Restudy of conodontomorpha *Henaniodus* from the Lower Cambrian Xinji Formation, Henan. Acta Micropalaeontologica Sinica 5, 179-182.

Pelechaty, S.M., 1996. Stratigraphic evidence for the Siberia-Laurentia connection and Early Cambrian rifting. Geology 24, 719-722.

Peng, S., Babcock, L.E., 2011. Continuing progress on chronostratigraphic subdivision of the Cambrian System. Bulletin of Geosciences 86, 391-396.

Peng, S., Kusky, T.M., Zhou, H., Wang, L., Xiang, W., 2012. New research progress on the pre-Sinian tectonic evolution and neotectonics of the Huangling anticline region, South China. Journal of Earth Science 23, 639-647.

Peters, S.E., Gaines, R.R., 2012. Formation of the/Great Unconformity/'as a trigger for the Cambrian explosion. Nature 484, 363-366.

Peterson, K.J., McPeek, M.A., Evans, D.A., 2005. Tempo and mode of early animal evolution: inferences from rocks, Hox, and molecular clocks. Paleobiology 31, 36-55.

Pi, D., Jiang, S., Luo, L., Yang, J., Ling, H., 2014. Depositional environments for stratiform witherite deposits in the Lower Cambrian black shale sequence of the Yangtze Platform, southern Qinling region, SW China: Evidence from redox-sensitive trace element geochemistry. Palaeogeography, Palaeoclimatology, Palaeoecology 398, 125-131.

Pillola, G., 1990. Lithologie et Trilobites du Cambrien inférieur du SW de la Sardaigne (Italie): implications paléobiogéographiques. Comptes rendus de l'Académie des sciences. Série 2, Mécanique, Physique, Chimie, Sciences de l'univers, Sciences de la Terre 310, 321-328.

Pisera, A., 1994. Echinoderms of the Mojcza Limestone. Palaeontologia Polonica 53, 283-307.

Pojeta, J.J., Balanc, M., 1989a. Freezing and thawing of fossils, in: Feldman, R.M., Chapman, R.E., Hannibal, J.T. (Eds.), Paleotechniques. The Paleontological Society Special Publication, Knoxville, pp. 223-226.

Pojeta, J.J., Balanc, M., 1989b. Heating and quenching of fossils, in: Feldman, R.M., Chapman, R.E., Hannibal, J.T. (Eds.), Paleotechniques. The Paleontological Society Special Publication, Knoxville, pp. 218-222.

Pospelov, A., Pelman, Y.L., Zhuravleva, I., Luchinina, V., Kuznetsova, V., Esakova, N., Ermak, V., Aksarina, N., 1995. Biostratigraphy of the Kiya River section. Annales de Paléontologie 81, 169-246.

Poulsen, V., 1966. Early Cambrian distacodontid conodonts from Bornholm. Munksgaard, Copenhagen, 9 pp.

Qian, J., Xiao, B., 1984. An Early Cambrian small shelly fauna from Aksu-Wushi region, Xinjiang. Professional Papers of Stratigraphy and Palaeontology 13, 65-90.

Qian, Y., 1977. Hyolitha and some problematica from the Lower Cambrian Meishucun Stage in central and S. W. China. Acta Palaeontologica Sinica 16, 107-130.

Qian, Y., 1978. The Early Cambrian hyolithids in central and southwest China and their stratigraphical significance. Memoirs of Nanjing Institute of Geology and Palaeontology. Academia Sinica 11, 1–50.

Qian, Y., Chen, M., Chen, Y., 1979. Hyolithids and other small shelly fossils from the Lower Cambrian Huangshandong Formation in the eastern part of the Yangtze Gorge. Acta Palaeontologica Sinica 18, 207–229.

Qian, Y., 1983. The Sinian–Cambrian Boundary in China, in, Studies on Stratigraphic Boundaries in China. Science Press, Beijing, pp. 1-11.

Qian, Y., Zhang, S., 1983. Small shelly fossils from the Xihaoping Member of the Tongying Formation in Fangxian County of Hubei Province and their stratigraphical significance. Acta Palaeontologica Sinica 22, 82-94.

Qian, Y., 1984. Several Groups of Bizarre Sclerite Fossils from the Earliest Cambrian in Eastern Yunnan. Bulletin of the Nanjing Institute of Geology and Palaeontology, Academia Sinica 6, 87–99.

Qian, Y., Yin, G., 1984. Small shelly fossils from the lowerest Cambrian in Guizhou. Professional Papers of Stratigraphy and Palaeontology 13, 91-123.

Qian, Y., 1989. Early Cambrian small shelly fossils of China with special reference to the Precambrian–Cambrian boundary. Nanjing University Publishing House, Nanjing, 341 pp.

Qian, Y., Bengtson, S., 1989. Palaeontology and biostratigraphy of the Early Cambrian Meishucunian Stage in Yunnan Province, South China. Fossils and Strata 24, 1-156.

Qian, Y., Zhu, M., He, T., Jiang, Z., 1996. New investigation of Precambrian–Cambrian

Boundary sections in eastern Yunnan. Acta Micropalaeontologica Sinica 13, 225–240.

Qian, Y., Chen, M., He, T., Zhu, M., Yin, G., Feng, W., Xu, J., Jiang, Z., Liu, D., Li, G., Di, L., Mao, Y., Xiao, B., 1999. Taxonomy and biostratigraphy of small shelly fossils in China. Science Press, Beijing, 247 pp.

Qian, Y., 2001. *Yangtzedonta* and the early evolution of shelled molluscs. Chinese Science Bulletin 46, 1730-1734.

Qian, Y., Zhu, M., Li, G., Jiang, Z., 2002. A supplemental Precambrian–Cambrian boundary global stratotype section in SW China. Acta Palaeontologica Sinica 41, 19–26.

Qian, Y., Feng, W., Li, G., Yang, A., Feng, M., Zhao, X., Xiao, B., 2009. Taxonomy and biostratigraphy of the early Cambrian univalved mollusc fossils from Xinjiang. Acta Micropalaeontologica Sinica, 193-210.

Qiao, G., Yang, Z., Li, Z., Yang, X., 2009. Geological and Geochemical Characteristics of P and Mn Layering Mineralization of Hougou-Dapingshan Area in Mianxian, Shaanxi Province. Northwestern Geology 42, 37-45.

Raiola, F., Spillane, T., Limata, B., Wang, B., Yan, S., Aliotta, M., Becker, H., Cruz, J., Fonseca, M., Gialanella, L., 2007. First hint on a change of the ^{210}Po alpha-decay half-life in the metal Cu. The European Physical Journal A 32, 51-53.

Ray, A., Das, P., Saha, S., Goswami, A., De, A., 2009. Observation of enhanced orbital electron-capture nuclear decay rate in a compact medium. Physics Letters B 679, 106-110.

Ren, J., Huang, J., 1980. The geotectonic evolution of China. Science Press, Beijing, 124 pp.

Ren, J., 1996. The continental tectonics of China. Journal of Southeast Asian Earth Sciences 13, 197-204.

Ren, J., Niu, B., Liu, Z., 1999. Soft collision, superposition orogeny and polycyclic suturing. Earth Science Frontiers 6, 85-93.

Renne, P.R., Mundil, R., Balco, G., Min, K., Ludwig, K.R., 2010. Joint determination of ^{40}K decay constants and ^{40}Ar∗/^{40}K for the Fish Canyon sanidine standard, and improved accuracy for ^{40}Ar/^{39}Ar geochronology. Geochimica Et Cosmochimica Acta 74, 5349.

Renne, P.R., Balco, G., Ludwig, K.R., Mundil, R., Min, K., 2011. Response to the comment by WH Schwarz et al. on "Joint determination of ^{40}K decay constants and ^{40}Ar∗/^{40}K for the Fish Canyon sanidine standard, and improved accuracy for ^{40}Ar/^{39}Ar geochronology" by PR Renne et al.(2010). Geochimica Et Cosmochimica Acta 75, 5097.

Rode, A.L., Lieberman, B.S., Rowell, A., 2003. A new early Cambrian bradoriid (Arthropoda) from East Antarctica. Journal of Paleontology 77, 691-697.

Rong, J., 1974. Cambrian brachiopods, in: Nanjing Institute of Geology and Paleontology, A.S. (Ed.), Handbook of the stratigraphy and palaeontology of southwest China. Science Press, Beijing, pp. 113-114.

Rosenzweig, M.L., 1995. Species diversity in space and time. Cambridge University Press, Cambridge, 460 pp.

Rowell, A.J., Rees, M.N., Evans, K.R., 1992. Depositional setting of the Lower and Middle Cambrian in the Pensacola Mountains. Antarctic Journal of the United States 25, 40-42.

Rowland, S.M., Luchinina, V.A., Korovnikov, I.V., Sipin, D.P., Tarletskov, A.I., Fedoseev, A.V., 1998. Biostratigraphy of the Vendian-Cambrian Sukharikha River section, northwestern Siberian Platform. Canadian Journal of Earth Sciences 35, 339-352.

Rozanov, A.Y., Missarzhevsky, V., 1966. Biostratigraphy and fauna of Lower Cambrian horizons. Trudy Geologicheskiy Institut Moscow 148, 1–126.

Rozanov, A.Y., Missarzhevsky, V.V., Volkova, N., Voronova, L., Krylov, I., Keller, B., Korolyuk, I., Lendzion, K., Michniak, R., Pychova, N., 1969. The Tommotian Stage and the Cambrian lower boundary problem. Trudy Geoligske Institut Leningrad 206, 1-379.

Ruffell, A., Wach, G., 1998. Firmgrounds -key surfaces in the recognition of parasequences in the Aptian Lower Greensand Group, Isle of Wight (southern England). Sedimentology 45, 91-107.

Safonova, I.Y., Santosh, M., 2014. Accretionary complexes in the Asia-Pacific region: Tracing archives of ocean plate stratigraphy and tracking mantle plumes. Gondwana Research 25, 126-158.

Salvador, A., 1994. International stratigraphic guide: a guide to stratigraphic classification, terminology, and procedure. Geological Society of America, 214 pp.

Santosh, M., Maruyama, S., Sawaki, Y., Meert, J.G., 2014. The Cambrian Explosion: Plume-driven birth of the second ecosystem on Earth. Gondwana Research 25, 945–965.

Sarmiento, G.N., Fernández Remolar, D., Cemal Goncüoglu, M., 2001. Cambrian small shelly fossils from the Çal Tepe Formation, Taurus Mountains, Turkey. Coloquios de Paleontología 52, 117-134.

Schopf, J.W., 1993. Microfossils of the Early Archean Apex chert: new evidence of the antiquity of life. Science 260, 640-646.

Schwarz, W.H., Kossert, K., Trieloff, M., Hopp, J., 2011. Comment on the “Joint determination of ^{40}K decay constants and ^{40}Ar∗/^{40}K for the Fish Canyon sanidine standard, and improved accuracy for ^{40}Ar/^{39}Ar geochronology” by Paul R. Renne et al.(2010). Geochimica Et Cosmochimica Acta 75, 5094.

Segre, E., 1947. Possibility of altering the decay rate of a radioactive substance. Physical Review 71, 274-275.

Seilacher, A., Buatois, L.A., Gabriela Mangano, M., 2005. Trace fossils in the Ediacaran–Cambrian transition: behavioral diversification, ecological turnover and environmental shift. Palaeogeography, Palaeoclimatology, Palaeoecology 227, 323-356.

Sengor, A.M.C., Natal'in, B.A., Burtman, V.S., 1993. Evolution of the Altaid tectonic collage and Palaeozoic crustal growth in Eurasia. Nature 364, 299-307.

Serezhnikova, E.A., Ragozina, A.L., Dorjnamjaa, D., Zaitseva, L.V., 2014. Fossil microbial colonies in Neoproterozoic interglacial rocks of Western Mongolia. Precambrian Research 245, 66-79.

Shabanov, Y.Y., Korovnikov, I.V., Pereladov, V.S., Fefelov, A.F., Lazarenko, N.P., Gogin, I.Y., Pegel, T.V., Sukhov, S.S., G.P. Abaimova, Egorova, L.I., Fedorov, A.B., Raevskaya, E.G., Ushatinskaya, G.T., 2008. The Cambrian System of the Siberian Platform. Part 2: North-east of the Siberian Platform. PIN RAS, Moscow-Novosibirsk, 139 pp.

Shaler, N., Foerste, A., 1888. Preliminary description of North Attleborough fossils. Harvard Museum of Comparative Zoology Bulletin 16, 27-41.

Shi, Y., Yu, J.-H., Santosh, M., 2013. Tectonic evolution of the Qinling orogenic belt, Central China: New evidence from geochemical, zircon U–Pb geochronology and Hf isotopes. Precambrian Research 231, 19-60.

Shu, D., 1990. Cambrian and Lower Ordovician Bradoriida from Zhejiang, Hunan and Shaanxi Provinces. Northwest University Press, Xi'an, 95 pp.

Shu, D., Isozaki, Y., Zhang, X., Han, J., Maruyama, S., 2014. Birth and early evolution of metazoans. Gondwana Research 25, 884-895.

Shu, D.G., Luo, H.L., Conway Morris, S., Zhang, X.L., Hu, S.X., Chen, L., Han, J., Zhu, M., Li, Y., Chen, L.Z., 1999. Lower Cambrian vertebrates from South China. Nature 402, 42-46.

Shu, D.G., Conway Morris, S., Han, J., Chen, L., Zhang, X.L., Zhang, Z.F., Liu, H.Q., Li, Y., Liu, J.N., 2001. Primitive deuterostomes from the Chengjiang Lagerstatte (Lower Cambrian, China). Nature 414, 419-424.

Shu, D.G., Morris, S.C., Han, J., Zhang, Z.F., Yasui, K., Janvier, P., Chen, L., Zhang, X.L., Liu, J.N., Li, Y., Liu, H.Q., 2003. Head and backbone of the Early Cambrian vertebrate Haikouichthys. Nature 421, 526-529.

Siegmund, H., Erdtmann, B.D., 1994. Facies and diagenesis of some upper proterozoic dolomites of South China. Facies 31, 255-263.

Siegmund, H., Erdtmann, B., 1995. Lower Cambrian phosphorites of south China: Microfacies and genetic interpretation. Zentralblatt für Geologie und Paläontologie 1994, 257-270.

Skovsted, C.B., 2004. Mollusc fauna of the Early Cambrian Bastion Formation of North-East Greenland. Bulletin of the Geological society of Denmark 51, 11-37.

Skovsted, C.B., Peel, J.S., Atkins, C.J., 2004. The problematic fossil *Triplicatella* from the Early Cambrian of Greenland, Canada, and Siberia. Canadian Journal of Earth Sciences 41, 1273-1283.

Skovsted, C.B., 2005. A carapace of the bradoriid arthropod *Mongolitubulus* from the Early Cambrian of Greenland. GFF 127, 217-220.

Skovsted, C.B., 2006. Small shelly fauna from the upper lower Cambrian Bastion and Ella Island formations, North-east Greenland. Journal of Paleontology 80, 1087-1112.

Skovsted, C.B., Brock, G.A., Paterson, J.R., 2006. Bivalved arthropods from the Lower Cambrian Mernmerna Formation, Arrowie Basin, South Australia and their implications for identification of Cambrian 'small shelly fossils'. Memoirs of the Association of Australasian Palaeontologists 32, 7-41.

Skovsted, C.B., Peel, J.S., 2007. Small shelly fossils from the argillaceous facies of the Lower Cambrian Forteau Formation of western Newfoundland. Acta Palaeontologica Polonica 52, 729-748.

Skovsted, C.B., Brock, G.A., Paterson, J.R., Holmer, L.E., Budd, G.E., 2008. The scleritome of *Eccentrotheca* from the Lower Cambrian of South Australia: lophophorate affinities and implications for tommotiid phylogeny. Geology 36, 171.

Skovsted, C.B., Balthasar, U., Brock, G.A., Paterson, J.R., 2009a. The tommotiid *Camenella reticulosa* from the early Cambrian of South Australia: Morphology, scleritome reconstruction, and phylogeny. Acta Palaeontologica Polonica 54, 525-540.

Skovsted, C.B., Holmer, L.E., Larsson, C.M., Högström, A.E.S., Brock, G.A., Topper, T.P., Balthasar, U., Stolk, S.P., Paterson, J.R., 2009b. The scleritome of *Paterimitra*: an Early Cambrian stem group brachiopod from South Australia. Proceedings of the Royal Society B: Biological Sciences 276, 1651.

Skovsted, C.B., Peel, J.S., 2010. Early Cambrian brachiopods and other shelly fossils from the basal Kinzers Formation of Pennsylvania. Journal Information 84, 754-762.

Skovsted, C.B., Brock, G.A., Topper, T.P., Paterson, J.R., Holmer, L.E., 2011. Scleritome construction, biofacies, biostratigraphy and systematics of the tommotiid *Eccentrotheca helenia* sp. nov. from the Early Cambrian of South Australia. Palaeontology 54, 253-286.

Skovsted, C.B., Brock, G.A., Topper, T.P., 2012. First occurrence of a new *Ocruranus*-like helcionelloid mollusc from the lower Cambrian of East Gondwana. Gondwana Research 22, 256-261.

Skovsted, C.B., Clausen, S., Álvaro, J.J., Ponlevé, D., 2014. Tommotiids from the early Cambrian (Series 2, Stage 3) of Morocco and the evolution of the tannuolinid scleritome and setigerous shell structures in stem group brachiopods. Palaeontology 57, 171-192.

Smith, M.P., Harper, D.A.T., 2013. Causes of the Cambrian Explosion. Science 341, 1355-1356.

Souza, D.J., Kegel, G.H., Egan, J.J., Desimone, D.J., Seo, P.-N., 2002. Measurement of difference in decay rate for ^{7}Be in Li and ^{7}Be in Ta. Journal of NUCLEAR SCIENCE and TECHNOLOGY 2, 470-473.

Sperling, E.A., Frieder, C.A., Raman, A.V., Girguis, P.R., Levin, L.A., Knoll, A.H., 2013. Oxygen, ecology, and the Cambrian radiation of animals. Proceedings of the National academy of Sciences.

Stanley, S.M., 1973. An ecological theory for the sudden origin of multicellular life in the late Precambrian. Proceedings of the National academy of Sciences 70, 1486.

Steiner, M., Wallis, E., Erdtmann, B.D., Zhao, Y., Yang, R., 2001. Submarine-hydrothermal exhalative ore layers in black shales from South China and associated fossils -insights into a Lower Cambrian facies and bio-evolution. Palaeogeography, Palaeoclimatology, Palaeoecology 169, 165-191.

Steiner, M., Li, G., Qian, Y., Zhu, M., Erdtmann, B.D., 2003. Lower Cambrian small shelly faunas from Zhejiang (China) and their biostratigraphical implications. Progress in Natural Science 13, 852-860.

Steiner, M., Li, G., Qian, Y., Zhu, M., 2004. Lower Cambrian small shelly fossils of northern Sichuan and southern Shaanxi (China), and their biostratigraphic importance. Geobios 37, 259-275.

Steiner, M., Li, G., Qian, Y., Zhu, M., Erdtmann, B.D., 2007. Neoproterozoic to early Cambrian small shelly fossil assemblages and a revised biostratigraphic correlation of the Yangtze Platform (China). Palaeogeography, Palaeoclimatology, Palaeoecology 254, 67-99.

Steiner, M., Li, G., Yang, B., Ergaliev, G., 2013. Chemostratigraphy versus biostratigraphy for a chronostratigraphic subdivision of the traditional "Lower Cambrian", in: Lindskog, A., Mehlqvist, K. (Eds.), 3rd IGCP 591 Annual Meeting. Department of Geology, Lund University, Lund, pp. 303-304.

Tong, H., 1989. A preliminary study on the *Microdictyon* from the Lower Cambrian of Zhenba, South Shaanxi. Acta Micropalaeontologica Sinica 6, 97-99.

Topper, T.P., Brock, G.A., Skovsted, C.B., Paterson, J.R., 2009. Shelly Fossils from the Lower Cambrian 'Pararaia bunyerooensis' Zone, Flinders Ranges, South Australia. Memoirs of the Association of Australasian Palaeontologists 37, 199-246.

Topper, T.P., Brock, G.A., Skovsted, C.B., Paterson, J.R., 2010. Palaeoscolecid scleritome fragments with *Hadimopanella* plates from the early Cambrian of South Australia.

Geological Magazine 147, 86-97.

Topper, T.P., Skovsted, C.B., Brock, G.A., Paterson, J.R., 2011. The oldest bivalved arthropods from the early Cambrian of East Gondwana: Systematics, biostratigraphy and biogeography. Gondwana Research 19, 310-326.

Torsvik, T.H., Cocks, L.R.M., 2013a. Gondwana from top to base in space and time. Gondwana Research 24, 999-1030.

Torsvik, T.H., Cocks, L.R.M., 2013b. New global palaeogeographical reconstructions for the Early Palaeozoic and their generation. Geological Society, London, Memoirs 38, 5-24.

Tu, H., 1999. Metallogenic Feature of barite and witherite deposits in Qinling-Dabashan region. Geology of Chemical Minerals 21, 157-162.

Tucker, M.E., Wright, V.P., 1990. Carbonate sedimentology. John Wiley & Sons, Oxford, 482 pp.

Ubaghs, G., 1963. Cothurnocystis Bather, Phyllocystis Thoral and an undetermined member of the order Soluta (Echinodermata, Carpoidea) in the uppermost Cambrian of Nevada. Journal of Paleontology 37, 1133-1142.

Ushatinskaya, G., 1987. Unusual inarticulate brachiopods from the Lower Cambrian sequence of Mongolia. Paleontologicheskii Zhurnal 21, 59-66.

Ushatinskaya, G., 2004. An Ancient Brachiopod with an Organic Integument from the Lower Cambrian of Mongolia. Paleontologicheskii Zhurnal 38, 358-365.

Ushatinskaya, G., 2008. Origin and dispersal of the earliest brachiopods. Paleontologicheskii Zhurnal 42, 776-791.

Ushatinskaya, G.T., 2003. The larval shell of Cambrian phosphatic brachiopods: Morphological and ecological aspects. Paleontologicheskii Zhurnal 37, 49-56.

V. V. Missarzhevsky, A.M.M., 1981. Stratigraphy and fauna of the Precambrian-Cambrian boundary beds of the Malyy Karatau. Trudy Ordena Trudovogo Krasnogo Znameni Geologicheskiy Institut Akademiya NAUK SSSR, 1-90.

Van Wagoner, J., 1988. An overview of the fundamentals of sequence stratigraphy and key definitions. SEPM Special Publication 42, 39-45.

Vannier, J., Steiner, M., Renvoisé, E., Hu, S.X., Casanova, J.P., 2007. Early Cambrian origin of modern food webs: evidence from predator arrow worms. Proceedings of the Royal Society B: Biological Sciences 274, 627-633.

Vannier, J., Calandra, I., Gaillard, C., Żylińska, A., 2010. Priapulid worms: Pioneer horizontal burrowers at the Precambrian-Cambrian boundary. Geology 38, 711-714.

Varlamov, A.I., Rozanov, A.Y., Khomentovsky, V.V., Shabanov, Y.Y., Abaimova, G.P., Demidenko, Y.E., Karlova, G.A., Korovnikov, I.V., Luchinina, V.A., Malakhovskaya, Y.E., Parkhaev, P.Y., T.V. Pege, Skorlotova, N.A., Sundukov, V.M., S.S. Sukhov, A.B.F., Kipriyanova, L.D., 2008. The Cambrian System of the Siberian Platform. Part 1: The Aldan-Lena Region. PIN RAS, Moscow-Novosibirsk, 299 pp.

Vassiljeva, N.I., 1985. A Contribution to the Systematics of the Order Chancelloriida Walcott, 1920 (incertaesedis) from Lower Cambrian Deposits of the East Siberian Platform, in: Sokolov, B.S., Zhurauleva, I.T. (Eds.), Problematical Fossils of the Late Precambrian and Paleozoic: Proceedings of the Institute of the Geology and Geophysics of the Siberian Division of the Academy of Sciences of the USSR. Nauka, Novosibirsk, pp. 115-126.

Vassiljeva, N.I., 1998. Small Shelly Fauna and Biostratigraphy of the Lower Cambrian of the

Siberian Platform Vseross.Nauchno-Issled. Geologorazv. Neft. Inst. (VNIGRI), Saint-Petersburg, 139 pp.

Vendrasco, M.J., Li, G., Porter, S.M., Fernandez, C.Z., 2009. New data on the enigmatic *Ocruranus–Eohalobia* group of Early Cambrian small skeletal fossils. Palaeontology 52, 1373-1396.

Vermeij, G.J., 1990. The origin of skeletons. SEPM Society for Sedimentary Geology 4, 585-589.

Vermeij, G.J., 1995. Economics, volcanoes, and Phanerozoic revolutions. Paleobiology 21, 125-152.

Vidal, G., Moczyd, M., 1992. Patterns of phytoplankton radiation across the Precambrian-Cambrian boundary. Journal of the Geological Society 149, 647-654.

Vidal, G., Palacios, T., Moczyd owska, M., Gubanov, A.P., 1999. Age constraints from small shelly fossils on the early Cambrian terminal Cadomian Phase in Iberia. GFF 121, 137-143.

Voronin, Y.I., Voronova, L., Grigorieva, N., Drosdova, N., Shegallo, E., Zhuravlev, A.Y., Ragozina, A., Rozanov, A.Y., Sayutina, T., Syssoiev, V., 1982. The Precambrian-Cambrian boundary in the Geosynclinal areas (The reference section of Salany-Gol, MPR). Transactions of the Joint Soviet-Mongolian palaeontological expedition 18.

Voronova, K.G., Grigorev, N.V., Zhegallo, E.A., Missarzhevskii, V.V., Sysoev, V.A., 1983. The age of layers including *Oelandiella korobkovi-Anabarella plana* in Siberian Platform. Izvestiya Akademii Nauk Sssr Seriya Geologicheskaya, 80-84.

Voronova, L.G., Missarzhevsky, V.V., 1969. Finds of algae and worm tubes in the Precambrian–Cambrian boundary beds of the northern part of the Siberian Platform. Doklady Akademii Nauk SSSR 184, 207-210.

Vostokova, V.A., 1962. Cambrian gastropods from Siberian Platform and Taimyr. Sbornik statey po paleontologii i biostratigrafii 28, 51-74.

Walcott, C.D., 1912. Cambrian brachiopoda. Monographys of the United State Geological Survey LI, 1-872.

Walcott, C.D., 1920a. Middle Cambrian Spongia. Misc. Coll. 67, 261-364.

Walcott, C.D., 1920b. Cambrian Geology and Paleontology, IV, no. 6. Smithsonian Miscellaneous Collections 67, 261-364.

Wan, P., Hou, L., Zheng, H., 2012. Geological characteristics and evaluating method of manganese ore in Chengkou Region of Chongqing. Acta Geologica Sichuan 32, 146-151.

Wang, H., Mo, X., 1995. An outline of the tectonic evolution of China. Episodes 18, 6-16.

Wang, Q., Deng, J., Li, C., Li, G., Yu, L., Qiao, L., 2014. The boundary between the Simao and Yangtze blocks and their locations in Gondwana and Rodinia: Constraints from detrital and inherited zircons. Gondwana Research, *In press*.

Wang, S., Yan, W., 2008. High quality manganese ore distibution rules and resource potential prediction of the manganese ore belt in the Bashan Region, Shaanxi Province. West-China Exploration Engineering 2008, 142-144.

Wang, X., Li, X., Li, W., Li, Z., Liu, Y., Yang, Y., Liang, X., Tu, X., 2008. The Bikou basalts in the northwestern Yangtze block, South China: Remnants of 820–810 Ma continental flood basalts? Geological Society of America Bulletin 120, 1478-1492.

Wang, Y., Yin, G., Zheng, H., Qian, Y., 1984. Stratigraphy of the boundary Sinian–Cambrian in the Yangtze area of Guizhou, in: Wang, Y. (Ed.), The upper Precambrian and Sinian–Cambrian boundary in Guizhou. Guizhou People's Publishing House, Guiyang, pp. 1-36.

Wang, Y., Li, Y., Zhang, Z., 2010. Note on small skeletal fossils from the uppermost Shuijingtuo Formation (Early Cambrian) in the Yangtze Gorge Area. Acta Palaeontologica Sinica 49, 511-523.

Wang, Z., Tang, R., Yin, K., Wang, F., 1989. The discovery of Early Cambrian fossils in the "Taowan Group" in Shaanxi and their geological significance. Regional Geology of China 1989, 17-26.

Wang, Z., Chen, H., Li, J., Hao, J., Zhao, Y., Han, F., Hao, J., 1999. Discovery of radiolarian fossils in the Xixiang Group, the Southern Qinling, central China, and its implications. Science in China (Series D) 29, 38-44.

Wang, Z., Gao, L., Wang, T., Jiang, C., 2007. New microfossils from the Taowan Group of North Qinling and the stratigraphic restriction. Science in China (Series D) 37, 1467-1473.

Wang, Z., Yan, Q., Yan, Z., Wang, T., JIang, C., Gao, L., Li, Q., Chen, J., Zhang, Y., Liu, P., Xie, C., Xiang, Z., 2009. New division of the main tectonic units of the Qinling Orogenic Belt, central China. Acta Geologica Sinica 83, 1527-1546.

Weber, B., Steiner, M., Zhu, M.Y., 2007. Precambrian-Cambrian trace fossils from the Yangtze Platform (South China) and the early evolution of bilaterian lifestyles. Palaeogeography, Palaeoclimatology, Palaeoecology 254, 328-349.

Williams, M., Siveter, D.J., 1998. British Cambrian and Tremadoc bradoriid and phosphatocopid arthropods. Palaeontographical Society, London, 49 pp.

Williams, M., Siveter, D.J., Popov, L.E., Vannier, J., 2007. Biogeography and affinities of the bradoriid arthropods: cosmopolitan microbenthos of the Cambrian seas. Palaeogeography, Palaeoclimatology, Palaeoecology 248, 202-232.

Wilson, M.A., Palmer, T.J., 1992. Hardgrounds and Hardground Faunas. University of Wales,, Aberystwyth, 131 pp.

Wrona, R., 1989. Cambrian limestone erratics in the Tertiary glacio− marine sediments of King George Island, West Antarctica. Polish Polar Research 10, 533-553.

Wrona, R., 2003. Early Cambrian molluscs from glacial erratics of King George Island, West Antarctica. Polish Polar Research 24, 181-216.

Wrona, R., 2004. Cambrian microfossils from glacial erratics of King George Island, Antarctica. Acta Palaeontologica Polonica 49, 13-56.

Wrona, R., 2009. Early Cambrian bradoriide and phosphatocopide arthropods from King George Island, West Antarctica: biogeographic implications. Polish Polar Research 30, 347-377.

Xiao, A., Wei, G., Shen, Z., Wang, L., Yang, W., Qian, J., 2011. Basin-mountain system and tectonic coupling between Yangtze Block and South Qinling Orogen. Acta Petrologica Sinica 27, 601-611.

Xiao, B., Zhao, J., 1986. Lower Cambrian bradoriids from Aksu-Wushi Region of Xinjiang. Journal of Northwest University 1986, 73-90.

Xiao, B., 1989. Review of the age of Uyirtus Formation in the light of the discovery of *Anabarites*. Xinjiang Geology 16, 35-39.

Xiao, B., Duan, C., 1992. Review of small shelly fauna of Yultus, early Cambrian of Xinjiang. Xinjiang Geology, 212-232.

Xiao, L., Zhou, B., 1984. Early Cambrian hyolitha from Huainan and Huoqiu County in Anhui Province. Professional Papers of Stratigraphy and Palaeontology 13, 141-153.

Xiao, S., Bao, H., Wang, H., Kaufman, A.J., Zhou, C., Li, G., Yuan, X., Ling, H., 2004. The Neoproterozoic Quruqtagh Group in eastern Chinese Tianshan: evidence for a post-Marinoan glaciation. Precambrian Research 130, 1-26.

Xie, Y., 1988. Small shelly fossils in Qiongzhusi Stage of Lower Cambrian in Zhenba County Shaanxi Province. Journal of Chengdu College of Geology 15, 24-32.

Xie, Y., 1990. The conodont-like fossils of Early Cambrian in Zhenba, Shaanxi. Journal of Chengdu College of Geology 17, 16-22.

Xing, Y., Ding, Q., Luo, H., He, T., Wang, Y., 1984. The Sinian–Cambrian boundary of China, 10. Bulletin of the Institute of Geology. Chinese Academy of Geological Sciences (Special Issue), 260 pp.

Yan, Q., Wang, Z., Hanson, A., Druschke, P., Yan, Z., Liu, D., Jian, P., Song, B., Wang, T., Jiang, C., 2003. SHRIMP age and geochemistry of the Bikou volcanic terrane: Implications for Neoproterozoic tectonics on the northern margin of the Yangtze Craton. Acta Geologica Sinica - English Edition 77, 479-490.

Yan, Q., Wang, Z., Yan, Z., Xiang, Z., Chen, J., Wang, T., 2007. Shrimp analyses for Ophiolitic-Mafic Blocks in the Kangxian-Mianxian Section of the Mianxian-Lueyang Melange: Their geological implications. Geological Review 53, 755-764.

Yan, Z., Wang, Z., Chen, J., Yan, Q., Wang, T., 2010. Detrital record of Neoproterozoic arc-magmatism along the NW margin of the Yangtze Block, China: U–Pb geochronology and petrography of sandstones. Journal of Asian Earth Sciences 37, 322-334.

Yang, B., Steiner, M., Keupp, H., 2014a. Early Cambrian palaeobiogeography of the Zhenba-Fangxian Block (South China): Independent terrane or part of the Yangtze Platform? Gondwana Research, *Submitted*.

Yang, B., Steiner, M., Li, G., Keupp, H., 2014b. Terreneuvian small shelly faunas of East Yunnan (South China) and their biostratigraphic implications. Palaeogeography, Palaeoclimatology, Palaeoecology 398, 28-58.

Yang, B., Zhang, L., Danelian, T., Feng, Q., Steiner, M., 2014c. Chert-hosted small shelly fossils: expanded tool of biostratigraphy in the early Cambrian. GFF 136, 303-308.

Yang, X., He, T., 1984. New Small Shelly Fossils from Lower Cambrian Meishucun Stage of Nanjiang area, northern Sichuan. Professional Papers in Stratigraphy and Palaeontology 13, 35-47.

Yao, J., Wang, L., Su, C., Zhang, Q., 1995. Study on the manganese ores of the South marginal zone of the Yangze Platform and adjacent region. Metallurgical Industry Press, Beijing, 247 pp.

Ye, J., Fan, D., 2000. Characteristics and mineralization of ore deposits related to black shale series. Bullet in of Mineralogy, Petrology and Geochemisty 19, 95-102.

Ye, L., Chen, Q., Zhao, D., Chen, Z., Chen, Y., Liu, K., 1989. The phosphorites of China. Science Press, Beijing, 339 pp.

Yin, J., Ding, L., He, T., Li, S., Shen, L., 1980. Palaeontology and sedimentary environment of the sinian system in Emei–Ganluo area, Sichuan. Sichuan People's Publishing House, Chengdu, 231 pp.

Yu, W., 1974. Cambrian hyoliths, in: Nanjing Institute of Geology and Paleontology, A.S.

(Ed.), Handbook of the stratigraphy and palaeontology of southwest China. Science Press, Beijing, pp. 111-113.

Yu, W., 1979. Earliest Cambrian monoplacophorans and gastropods from western Hubei with their biostratigraphical significance. Acta Palaeontologica Sinica 18, 233-270.

Yu, W., 1984. On Merismoconchids. Acta Palaeontologica Sinica 23, 432–446.

Yu, W., 1987. Yangtze Micromolluscan Fauna in Yangtze Region of China with Notes on the Precambrian–Cambrian Boundary, in, Stratigraphy and Palaeontology of Systemic Boundaries in China: Precambrian–Cambrian Boundary. Nanjing University Publishing House, Nanjing, pp. 19-344.

Yu, W., 2001. The earliest Cambrian polyplacophorans from China. RECORDS-WESTERN AUSTRALIAN MUSEUM 20, 167-186.

Yuan, K., Zhang, S., 1983. Discovery of the *Tommotia* Fauna in SW China. Acta Palaeontologica Sinica, 31-41.

Yue, Z., He, S., 1989. Early Cambrian Conodonts and Bradoriids from Zhejiang. Acta Micropalaeontologica Sinica 6, 289-300.

Yue, Z., 1990. Discovery of trilobites from the Xihaoping Member (Lower Cambrian) of the Dengying Formation in Fangxian County Hubei Province. Regional Geology of China 1990, 277-282.

Yue, Z., Gao, L., 1992. Paleontology, biostratigraphy and geological significance of the Early Cambrian protoconodonts and other skeletal microfossils from Aksu-Wushi Region, Xinjiang, China. Bulletin of the Institute of Geology, Chinese Academy of Geological Sciences 23, 133-160.

Zamora, S., Gozalo, R., Linñán, E., 2009. Middle Cambrian gogiid echinoderms from Northeast Spain: Taxonomy, palaeoecology, and palaeogeographic implications. Acta Palaeontologica Polonica 54, 253-265.

Zamora, S., Rahman, I.A., Smith, A.B., 2012. Plated Cambrian bilaterians reveal the earliest stages of echinoderm evolution. Plos One 7, e38296.

Zamora, S., Smith, A., 2012. Cambrian stalked echinoderms show unexpected plasticity of arm construction. Proceedings of the Royal Society B: Biological Sciences 279, 293-298.

Zamora, S., Darroch, S., Rahman, I.A., 2013. Taphonomy and ontogeny of early pelmatozoan echinoderms: A case study of a mass-mortality assemblage of Gogia from the Cambrian of North America. Palaeogeography, Palaeoclimatology, Palaeoecology 377, 62-72.

Zeng, Q., 1987. Brachiopoda, in: Wang, X. (Ed.), Biostratigraphy of the Yangtze Gorge Area, Part 2. Early Palaeozoic Era. Geological Publishing House, Beijing, pp. 209-245.

Zhang, G., Meng, Q., Yu, Z., Sun, Y., Zhou, D., Guo, A., 1996. Orogenesis and dynamics of the Qinling Orogen. Sicence in China 39, 225-234.

Zhang, G., Zhang, B., Yuan, X., Xiao, Q., 2001. Qinling Orogen Belt and continental dynamics. Science Press, Beijing, 855 pp.

Zhang, G., Cheng, S., Guo, A., Dong, Y., Lai, S., Yao, A., 2004. Mianlue paleo-suture on the southern margin of the Central Orogenic System in Qinling-Dabie-with a discussion of the assembly of the main part of the continent of China. Geological Bulletin of China 23, 846-853.

Zhang, S., Sun, C., 1991. Early Cambrian small shelly fossils from Chaohu area, Anhui. Acta Micropalaeontologica Sinica 8, 19-40.

Zhang, W., 1953. Some lower Cambrian trilobites from western Hubei. Acta Palaeontological Society of China 24, 121-136.

Zhang, X., 1987. Moult stages and dimorphism of Early Cambrian bradoriids from Xichuan, Henan, China. Alcheringa 11, 1-19.

Zhang, X., Pratt, B.R., 1994. New and extraordinary Early Cambrian sponge spicule assemblage from China. Geology 22, 43-46.

Zhang, X., Hua, H., 2005. Soft-bodied fossils from the Shipai Formation, Lower Cambrian of the Three Gorge area, South China. Geological Magazine London 142, 699-709.

Zhang, X., 2007. Phosphatized bradoriids (Arthropoda) from the Cambrian of China. Palaeontographica Abteilung A 281, 93-173.

Zhang, Y., Zhang, J., Li, H., Lu, S., 2013. Zircon U-Pb geochronology of the meta-acidic volcanic rocks from the Wudangshan Group, Southern Qinling Mountains, Central China. Acta Geologica Sinica 87, 922-930.

Zhang, Z., Robson, S.P., Emig, C., Shu, D., 2008. Early Cambrian radiation of brachiopods: A perspective from South China. Gondwana Research 14, 241-254.

Zhao, F., Caron, J.-B., Hu, S., Zhu, M., 2009. Quantitative analysis of taphofacies and paleocommunities in the early Cambrian Chengjiang Lagerstätte. Palaios 24, 826-839.

Zhao, G., Cawood, P.A., 2012. Precambrian geology of China. Precambrian Research 222-223, 13-54.

Zhao, J.-H., Zhou, M.-F., 2009. Secular evolution of the Neoproterozoic lithospheric mantle underneath the northern margin of the Yangtze Block, South China. Lithos 107, 152-168.

Zhao, J., Yue, Z., 1987. Discovery of Meishucunian small shelly fossils and the Precambrian-Cambrian boundary in western part of Zhejiang Province. Chinese Science Bulletin 1987, 1168-1170.

Zhao, J., Zhou, M., 2008. Neoproterozoic adakitic plutons in the northern margin of the Yangtze Block, China: Partial melting of a thickened lower crust and implications for secular crustal evolution. Lithos 104, 231-248.

Zhao, P., Chen, Y., Zhan, S., Xu, B., Faure, M., 2014. The Apparent Polar Wander Path of the Tarim block (NW China) since the Neoproterozoic and its implications for a long-term Tarim-Australia connection. Precambrian Research 242, 39-57.

Zhao, S., Wang, M., 2009. Search direction for manganese ore in the surroundings of Presinian Bikou Ancient Land. Northwestern Geology 42, 46-52.

Zhao, Y., Zhu, M., Peng, J., 2011. The Kaili Biota. Guizhou Sciencev& Techonology Publishing House, Guiyang, 251 pp.

Zhao, Z., Xing, Y., Ma, G., Yu, W., Wang, Z., 1980. The Sinian System of Eastern Yangtze Gorges, Hubei, in, Research on Precambrian Geology: Sinian Suberathem in China. Tianjin Science and Technology Press, Tianjin, pp. 31-35.

Zhou, B., Xiao, L., 1984. Early Cambrian monoplacophorans and gastropods from Huainan and Huoqiu counties, Anhui Province. Professional Papers of Stratigraphy and Palaeontology 13, 125-179.

Zhou, C., Zhang, J., Li, G., Yu, Z., 1997. Carbon and oxygen isotopic record of the Early cambrian from the Xiaotan section, Yunnan, South China. Chinese Journal of Geology (Scientia Geologica Sinica) 32, 201-211.

Zhou, C., Bao, H., Peng, Y., Yuan, X., 2010. Timing the deposition of ^{17}O-depleted barite at the aftermath of Nantuo glacial meltdown in South China. Geology 38, 903-906.

Zhou, M., Kennedy, A.K., Sun, M., Malpas, J., Lesher, C.M., 2002. Neoproterozoic arc-related mafic intrusions along the northern margin of South China: implications for the accretion of rodinia. The Journal of Geology 110, 611-618.

Zhu, M., Li, G., Zhang, J., Steiner, M., Qian, Y., Jiang, Z., 2001. Early Cambrian Stratigraphy of East Yunnan, Southwestern China. Acta Palaeontologica Sinica 40, 4-39.

Zhu, M., Zhang, J., Yang, A., 2007. Integrated Ediacaran (Sinian) chronostratigraphy of South China. Palaeogeography, Palaeoclimatology, Palaeoecology 254, 7-61.

5. Appendices

5.1. Appendex 1: Data base of the fossils for clustering analysis

species/stratum	S.Henan	N.Anhui	C. Shaanxi, Luonan	SE. Shaanxi, Xihaoping Mb.	SE. Shaanxi, Shuijingtuo Fm.	NE. Xixiang, SE. Shaanxi	NW. Hubei, Xihaoping Mb.	Yichang, Hubei, Shuijingtuo Fm.	S. Sichuan & Chongqing	N. Yunnan	C&E. Yunnan Yuanshan Fm.	Tarim	Maly Karatau & Talas Alatau	Dzhabkan	Mongolian Transitional Zone	Tuva Mongolia	Kuznetsk Alatau	N. Siberia, Olenek, Emyaksin Fm.	S. Siberia	E. Transbaikalia	Gorlitz, Germany	Sardinia	Taurus Mt. Turkey, Cal Tepe Fm.	Spain	Nova Scotia, Little Hollow Fm.	E. Massachusetts, Weymouth Fm.	England	E. Pennsylvania	W. Newfoundland	NE. Greenland	Antarctic	S. Australia
Acrothele orbicularis	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Acrothyra comleyensis / sera / cf. / (signata sera)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
Adyshevitheca adyshevi / utchbasica / cf. / sinica	0	0	0	0	1	0	1	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
Aetholicopalla adnata / Blastulospongia monothalamos / Gaparella porosa	1	0	0	1	0	0	1	0	0	0	0	1	1	0	0	0	0	1	0	0	1	1	0	0	0	0	0	0	0	0	1	1
Albrunnicola bengtsoni	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1
Aldanella / attleborensis / yanjiaheensis / utchurica / rozanovi / operosa / crassa / iberica	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	1	1	1	0	0	0	0	0	0
Aldanolina magna	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Allonnia erromenosa	1	0	1	1	1	1	0	0	0	1	1	1	1	0	0	0	1	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0
Allonnia tetrathallis	1	0	1	1	1	1	1	0	0	1	1	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0
Allonnia tripodophora / cf.	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1
Amphigeisina danica / renae (Protohertzina yudomica) / sp.	0	0	0	0	1	0	0	1	0	1	1	1	1	0	0	0	0	1	1	0	0	0	0	0	0	0	1	0	0	0	0	0
Anabarella australis / argus / tshitaensis	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	1	1	1
Anabarites cf. A. kelleri / Anabarites cf. Kotuithes biplicatus	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Anabarites compositus	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0
Anabarites sexalox	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Anabarites trymatus	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Anhuiconus microtuberus	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Anuliconus magnificus	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Anuliconus tannuelliformis	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Apistoconcha adnata	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Apistoconcha apheles / presiphonalis / cf.	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Apistoconcha celsa	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Apistoconcha siphonalis	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1
Archaeopetasus excavatus	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Archiasterella elegans	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0
Archiasterella hirundo	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	1
Archiasterella pentactina	0	0	1	1	1	1	1	0	0	1	1	1	1	0	0	0	0	0	1	0	1	0	0	1	0	0	0	0	0	0	0	1
Archiasterella quadratina	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1
Archiasterella tetractina	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0
Archicladium tridactyles	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Archicladium yurtusensis (Polycladium yurtusensis)	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ardrossania paveyi	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Aroonia seposita	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Askepasma saproconcha	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Askepasma toddense	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Asperconella troyensis	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0

Appendix 1. 1

species/stratum	S.Henan	N.Anhui	C. Shaanxi, Luonan	SE. Shaanxi, Xihaoping Mb.	SE. Shaanxi, Shuijingtuo Fm.	NE. Xixiang, SE. Shaanxi	NW. Hubei, Xihaoping Mb.	Yichang, Hubei, Shuijingtuo Fm.	S. Sichuan & Chongqing	N. Yunnan	C&E. Yunnan Yuanshan Fm.	Tarim	Maly Karatau & Talas Alatau	Dzhabkan	Mongolian Transitional Zone	Tuva Mongolia	Kuznetsk Alatau	N. Siberia, Olenek, Emyaksin Fm.	S. Siberia	E. Transbaikalia	Gorlitz, Germany	Sardinia	Taurus Mt. Turkey, Cal Tepe Fm.	Spain	Nova Scotia, Little Hollow Fm.	E. Massachusetts, Weymouth Fm.	England	E. Pennsylvania	W. Newfoundland	NE. Greenland	Antarctic	S. Australia
Auriculatella typica	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Bagenoviella pectinata	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Barskovia simplex	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Bemella communis / incomparabilis	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Bemella kijanica	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Beshtashella tortilis	0	0	0	0	1	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	1	1
Beyrichona chinensis	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Bicarinella evansi	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
Bioistodina planuta	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Botsfordia caelata	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	1	0
Botsfordia minuta	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Botsfordia pulchra	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
Cambridium nikiforovae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Cambrocassis verrucata	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cambroclavus fanxianensis / antis / absonus / ludwigsdorfensis	0	0	0	1	1	1	1	0	0	0	0	1	1	0	0	0	0	0	0	0	1	1	0	1	0	0	0	0	0	0	0	1
Cambroskiadeion xiaowanense	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cambrothyra ampulliformis (C. truncata)	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Camenella garbowskae / monoglica / baltica / parilobata / plana / reticulosa / korolevi / kozlowskii	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	1	1	0	0	0	0	0	1	1	1	0	0	0	0	0
Capitoconus artus	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0
Capitoconus inclinatus	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
Cassitella baculata	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0
Caveacus rectus	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
Chancelloria arida / eros / Chancelloriella irregularis / Chancelloriella bella / symmetrica / sardinica / altaica / sp. / spp.	1	0	1	1	1	0	1	0	0	0	0	0	1	1	1	0	1	1	1	0	0	1	1	1	1	0	1	1	1	1	1	1
Clavitella curvata	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
Comptaluta leshanensis	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cordubiella pedrochensis	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
Cowiella reticulata / granulata / undulata / verrucata	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
Cryptotreta neguertchenensis	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Cupitheca clathrata	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Cupitheca hemicyclata	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1
Cupitheca holocyclata / mira	0	1	1	1	1	1	1	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1
Curdus pararaensis	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Curticia minula	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
Dabashanella hemicyclia	0	0	0	0	1	0	0	0	0	1	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	1
Daedalia dadalia	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Dailyatia ajax / braddocki / macroptera / odyssei	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1

Appendix 1. 2 (continued)

species/stratum	S.Henan	N.Anhui	C. Shaanxi, Luonan	SE. Shaanxi, Xihaoping Mb.	SE. Shaanxi, Shuijingtuo Fm.	NE. Xixiang, SE. Shaanxi	NW. Hubei, Xihaoping Mb.	Yichang, Hubei, Shuijingtuo Fm.	S. Sichuan & Chongqing	N. Yunnan	C&E. Yunnan Yuanshan Fm.	Tarim	Maly Karatau & Talas Alatau	Dzhabkan	Mongolian Transitional Zone	Tuva Mongolia	Kuznetsk Alatau	N. Siberia, Olenek, Emyaksin Fm.	S. Siberia	E. Transbaikalia	Gorlitz, Germany	Sardinia	Taurus Mt. Turkey, Cal Tepe Fm.	Spain	Nova Scotia, Little Hollow Fm.	E. Massachusetts, Weymouth Fm.	England	E. Pennsylvania	W. Newfoundland	NE. Greenland	Antarctic	S. Australia
Diandongia pista	0	0	0	0	0	0	0	1	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Dipterygovitus lentiformis	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Discinella micans	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
Duibianella cf. elongata	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Duibianella tuberosa	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Eccentrotheca helenia	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Eccentrotheca kanesia	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0
Echinoderm plate	0	0	0	1	1	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	1	0	1	1	0	0	1	1	1	1	0	1
Eiffelia globosa / araniformis / sp. / Chancelloria cf. asteroidea	0	0	1	0	1	0	1	0	0	0	0	0	1	0	0	0	1	0	0	0	1	1	1	1	0	0	1	0	0	1	1	1
Emargimantus angulatus	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Emargimantus septentrionalis (Ocruranus septentrionalis)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
Emargimantus tunuensis (Ocruranus tunuensis)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
Emeiella venusta	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Enigmaconus ? pyramidalis	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Eodicellomus elkaniiformis	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Eohadrotreta zhenbaensis / zhujiahensis	0	0	0	0	1	1	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Eoobolus aff. elatus	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1
Eoobolus priscus	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	1
Eoobolus rotundus	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Eoobolus triparilis	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
Eoobolus viridis / aff.	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1
Eoobolus? Shaanxiensis	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Eothele tubulus	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Eotlzele spurri	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
Eremactis conara	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1
Eremactis mawsoni	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Fenqiaronia proboscis	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Figurina figurina / nana / cf.	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Figurina groeniadica	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
Fomitchella infundibuliformis	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0
Fordilla troyensis / germanica	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	1	0	1	0	1	0	0	1	0	0
Gapparodus bisulcatus / sp.	0	0	0	0	1	0	0	0	0	0	0	1	1	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0
Gapparodus gapparites	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Glauderia multifidus	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Guadalquivirospira carinata	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
Hadimopanella knappologica / antarctica / apicata / oezgueli / cf. / staurata	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	1	0	0	0	1	0	0	1	1	1
Hadrotreta djagoran (Vandalotreta djagoran)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1
Hagionella cultrata	0	0	0	0	1	0	0	0	0	1	0	1	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Appendix 1. 3 (continued)

species/stratum	S.Henan	N.Anhui	C. Shaanxi, Luonan	SE. Shaanxi, Xihaoping Mb.	SE. Shaanxi, Shuijingtuo Fm.	NE. Xixiang, SE. Shaanxi	NW. Hubei, Xihaoping Mb.	Yichang, Hubei, Shuijingtuo Fm.	S. Sichuan & Chongqing	N. Yunnan	C&E. Yunnan Yuanshan Fm.	Tarim	Maly Karatau & Talas Alatau	Dzhabkan	Mongolian Transitional Zone	Tuva Mongolia	Kuznetsk Alatau	N. Siberia, Olenek, Emyaksin Fm.	S. Siberia	E. Transbaikalia	Gorlitz, Germany	Sardinia	Taurus Mt. Turkey, Cal Tepe Fm.	Spain	Nova Scotia, Little Hollow Fm.	E. Massachusetts, Weymouth Fm.	England	E. Pennsylvania	W. Newfoundland	NE. Greenland	Antarctic	S. Australia
Halkieria fordi / curvativa / sacciformis / mira / sthenobasis / parva / sp.	0	0	1	1	1	1	0	0	0	1	1	1	1	0	0	0	0	1	0	0	1	0	1	0	1	0	0	0	0	0	1	1
Hanchiangella minor	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Haoia shaanxiensis	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Helcionella abrupta	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Helcionella tschernivschevae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Heliomedusa orienta	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Henaniodus magicus	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hertzina elongata	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0	1	0	0	0	0	0
Hipponicharion cuii / hispanicum / ichnusum / eos / cf.	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	1	0	1	0	0	0	0	0	0	0	0
Hippopharangites dailyi	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Hispanoconus cordobaensis	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
Homotreta changyangensis	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Houlongdongella elevata / disulcata / brevidorsa / Wushiella tuberculata (H. sp.)	0	1	1	0	1	0	0	0	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Humilispira adelcosma	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Hyptiotheca karraculum	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1
Igarkiella carinata	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Igorella arta / levis	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Igorella striata	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
Igorella talassica	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ilsanella aksarinae	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ilsanella applanata / yorkensis	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Ilsanella atdabanica (Helcionella atdabanica)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0
Indiana secunda	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
Iphidella liantuoensis	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Jayceia deltaformis	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
Jiangshanodus carinatus / triangulus	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Jiucunella paulula	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Jiucunella phaseloa	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Jixinlingella clithrocosta	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Jixinlingella daimonikoa	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Kaimenella reticulata	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Karathele napuru	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
karatheles yorkensis	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Kelanella altaica (Sonella jinshaensis / Lapworthella hubeiensis) / Sonella deplanata	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
Kennardia reticulata / sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1
khairkhania evoluta/ rotata	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
Kijacus kijanicus	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Appendix 1. 4 (continued)

species/stratum	S.Henan	N.Anhui	C. Shaanxi, Luonan	SE. Shaanxi, Xihaoping Mb.	SE. Shaanxi, Shuijingtuo Fm.	NE. Xixiang, SE. Shaanxi	NW. Hubei, Xihaoping Mb.	Yichang, Hubei, Shuijingtuo Fm.	S. Sichuan & Chongqing	N. Yunnan	C&E. Yunnan Yuanshan Fm.	Tarim	Maly Karatau & Talas Alatau	Dzhabkan	Mongolian Transitional Zone	Tuva Mongolia	Kuznetsk Alatau	N. Siberia, Olenek, Emyaksin Fm.	S. Siberia	E. Transbaikalia	Gorlitz, Germany	Sardinia	Taurus Mt. Turkey, Cal Tepe Fm.	Spain	Nova Scotia, Little Hollow Fm.	E. Massachusetts, Weymouth Fm.	England	E. Pennsylvania	W. Newfoundland	NE. Greenland	Antarctic	S. Australia
Kuangshanotreta malungensis	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Kulparina rostrata / Eccentrotheca guano	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Kundatoides perplexus	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
kunmingella bimarginata	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Kunmingella douvillei / xiaoyangensis / szechuanensis	0	0	0	0	1	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Kunmingella typica / zhuazhuayanensis	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Kunyangella cheni	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Kunyangella daedala	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Kutorgina cingulata	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
kyrshabaktella certa / cf.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Lapworthella cornu / dentata / cf. tortuosa / schodakensis / nigra / ludvigseni / cf. fasciculata / fasciculata / rete / sp. / spp.	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	1	1	0	0	0	0	0	1	1	1	0	1	1	0	1
Lapworthella puttapensis	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Latouchella arcuata	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
Oelandiella (Latouchella) gobiica	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Oelandiella (Latouchella) nazarovi	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Latouchella ostenfeldense	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
Leptostega hyperborea	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Liangshanella circumbolina	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Liangshanella liangshanensis / birkenmajeri / baensis / lubrica / rotundata / aff. / sp.	0	0	0	0	1	0	1	0	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
Liangshanella sayutinae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
Linguella viridens	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
Lingulella chengjiangensis	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Lingulellotreta malongensis	0	0	0	0	1	1	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Lingulepis malongensis	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Linnarssonia rowelli	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Longtancunella chengjiangensis	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Lugoviella ojmuranica/ chizhovi (Camenella admiranda of Kouchinsky, 2013)	0	0	0	0	1	0	0	0	0	1	0	0	0	0	1	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Mackinnonia anabarica	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Mackinnonia corrugata / plicata / Leptostega? Corrugata	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Mackinnonia rostrata / davidi / obliqua	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1
Mackinnonia taconica (Stenotheca taconica)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
Majatheca tumefacta	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Marocella mira / australica	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1

Appendix 1. 5 (continued)

species/stratum	S.Henan	N.Anhui	C. Shaanxi, Luonan	SE. Shaanxi, Xihaoping Mb.	SE. Shaanxi, Shuijingtuo Fm.	NE. Xixiang, SE. Shaanxi	NW. Hubei, Xihaoping Mb.	Yichang, Hubei, Shuijingtuo Fm.	S. Sichuan & Chongqing	N. Yunnan	C&E. Yunnan Yuanshan Fm.	Tarim	Maly Karatau & Talas Alatau	Dzhabkan	Mongolian Transitional Zone	Tuva Mongolia	Kuznetsk Alatau	N. Siberia, Olenek, Emyaksin Fm.	S. Siberia	E. Transbaikalia	Gorlitz, Germany	Sardinia	Taurus Mt. Turkey, Cal Tepe Fm.	Spain	Nova Scotia, Little Hollow Fm.	E. Massachusetts, Weymouth Fm.	England	E. Pennsylvania	W. Newfoundland	NE. Greenland	Antarctic	S. Australia
Mellopegma indecora / uslonica (Anabarella indecora) / Parailsanella sayutinae / sp. / Trenella bifrons	0	0	0	0	1	0	0	1	0	0	0	1	0	1	0	0	0	1	0	1	0	0	0	0	0	0	1	0	0	0	0	1
Melvillella corniculata	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
Michniakia minuta	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0
Mickwitzia occidens / cf. / sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0
Micrina etheridgei / pusilla / xiaotanensis	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Microcornus parvulus / talasicus / egregius / eximius	1	1	1	0	1	0	1	1	0	0	0	0	1	1	0	0	0	0	0	0	1	1	0	0	0	0	1	1	0	1	1	1
Microcornus petilus	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1
Microcornus simus	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Microdictyon sinicum/fuchengense/effusum/rhomboidale/rozanovi/sp.	0	0	0	0	1	0	0	1	0	0	1	0	1	0	1	0	0	1	1	0	0	0	1	0	1	1	1	0	0	1	0	1
Micromitra bella	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0
Micromitra labradorica	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
Micromitra phillipsi	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0
Minlatonia tuckeri	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Miroconulus sinitsae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Mobergella radiolata	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Mobergella scutata	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Mongolitesta nativa	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Mongolitubulus squamifer / dilatatus / anthelios / henrikseni / cf. henrikseni / spinosus	0	0	0	0	1	0	0	0	0	0	0	0	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	1	1	1
Mongolodus rostriformis	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Nanchengella acuta / jiningensis	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Neoduibianella bella	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Neoduibianella ramispina	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Neogloborilus applanatus / spinatus	0	0	1	0	1	0	1	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Neokunmingella moroensis	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Neokunmingella shuensis	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Aurisella tarimensis (Ninella tarimensis)/ serebrjanikovae	0	0	0	0	0	1	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Nisusia liantuoensis	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Nongoliella rotunda / sinistrivolubilis / australiensis	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Obolella chromatica	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Obolella crassa	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0
Obolus parvulus	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
Obtusoconus brevis / magnus / nurmogoicus	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Obtusoconus reduncus	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0

Appendix 1. 6 (continued)

species/stratum	S.Henan	N.Anhui	C. Shaanxi, Luonan	SE. Shaanxi, Xihaoping Mb.	SE. Shaanxi, Shuijingtuo Fm.	NE. Xixiang, SE. Shaanxi	NW. Hubei, Xihaoping Mb.	Yichang, Hubei, Shuijingtuo Fm.	S. Sichuan & Chongqing	N. Yunnan	C&E. Yunnan Yuanshan Fm.	Tarim	Maly Karatau & Talas Alatau	Dzhabkan	Mongolian Transitional Zone	Tuva Mongolia	Kuznetsk Alatau	N. Siberia, Olenek, Emyaksin Fm.	S. Siberia	E. Transbaikalia	Gorlitz, Germany	Sardinia	Taurus Mt. Turkey, Cal Tepe Fm.	Spain	Nova Scotia, Little Hollow Fm.	E. Massachusetts, Weymouth Fm.	England	E. Pennsylvania	W. Newfoundland	NE. Greenland	Antarctic	S. Australia
Onychodictyon ferox (Onychomicrodictyon spiniferum)	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0
Palaeobolus liantuoensis	0	0	0	0	1	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Paracornus poulseni	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
Parahoulongdongella bashanensis	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Parailsanella murenica / lata / khairkhanica / dzhargalantica / sp. / (Anabarella indecora fro Comley)	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	1	0	1	0	0	0	0	0	0	1	0	0	0	0	1
Pararaconus staitorum	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Parazhijnites guizhouensis	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Parkula bounites	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1
Parkula esmeraldina / cf.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Paterimitra pyramidalis	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Pedrocheotheca andalusica	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
Pelagiella lorenzi/ emeishanensis/ adunca / madianensis / primaeva	1	1	1	0	0	0	0	0	1	0	1	0	1	0	0	0	0	1	1	1	1	0	0	1	1	1	0	0	0	1	1	1
Persicitheca delicata	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Phasoia cf. spicata	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Planutenia flectata (P. inclinata)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	1	0	0	0
Platysolenites antiquissimus	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
Plinthokonion arthion	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Pojetaia runnegari	1	1	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	1	0	1	0	0	0	0	0	1	1	0	1
Protohertzina cf. siciformis	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Protowenella huainanensis / primaria / plena	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Pseudobeyrichona longquanxiensis	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Purella insueta	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Quadricona madonnae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Randomia aurorae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0
Resegia glandiformis	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Retaluta granulosa	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Rhombocorniculum cancellatum / insolutum / Strictocornicumum vanallerum	0	0	0	0	1	0	1	0	0	0	0	1	1	0	1	1	1	1	1	0	1	0	0	0	1	1	1	0	0	0	0	0
Rushtonites insolutum	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Rushtonites spinosus	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
Salanygolina obliqua	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Salterella macculochi /cf. / sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0
Samsonoffoclavus matthewi	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
Scenella reticulata	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0
Shetlandia multiplicata	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
Shingeinella indefinita	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sibiria magna	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0

Appendix 1. 7 (continued)

species/stratum	S.Henan	N.Anhui	C. Shaanxi, Luonan	SE. Shaanxi, Xihaoping Mb.	SE. Shaanxi, Shuijingtuo Fm.	NE. Xixiang, SE. Shaanxi	NW. Hubei, Xihaoping Mb.	Yichang, Hubei, Shuijingtuo Fm.	S. Sichuan & Chongqing	N. Yunnan	C&E. Yunnan Yuanshan Fm.	Tarim	Maly Karatau & Talas Alatau	Dzhabkan	Mongolian Transitional Zone	Tuva Mongolia	Kuznetsk Alatau	N. Siberia, Olenek, Emyaksin Fm.	S. Siberia	E. Transbaikalia	Gorlitz, Germany	Sardinia	Taurus Mt. Turkey, Cal Tepe Fm.	Spain	Nova Scotia, Little Hollow Fm.	E. Massachusetts, Weymouth Fm.	England	E. Pennsylvania	W. Newfoundland	NE. Greenland	Antarctic	S. Australia
Sinosachites falbelliformis	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sinskolutella cuspidata	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Sinskolutella ordinata	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Sphenopteron boomerang	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
Spinaluta qinensis	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Spinella amargina	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Spinella unilata	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Spinospitella coronata	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Stefania longula	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Stenotheca drepanoida / cf.	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Stenotheca rugosa abrupta (Leptostega abrupta)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0
Stenotheca transbaikalica	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Stenothecella sibirica	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Stenothecoides minutus	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Stoibostrombus crenulatus / mirus	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Sunnaginia imbricata / acuta	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	1	1	1	0	0	0	0	0
Tannuella ampla (="Tanuella" ampla)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
Tannuella cf. elata	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Tannuella elinorae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Tannuolina fonini / sp. / zhangwentangi / minuta	0	0	0	0	0	0	0	0	0	1	1	1	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Tarimspira plana	0	0	0	0	1	0	0	1	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Thambetolepis delicata	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Torellella sp. / biconvexa / curva / gracilenta / laevigata / lentiformis /Sphenothallus sp. / Byronia sp. / ? Bifida / Khagnura aspera / Koksuja costulifera / Koksuja acricostalis	0	0	0	0	1	1	1	1	0	0	0	0	1	1	1	1	1	1	1	0	1	0	1	1	1	1	1	0	0	1	1	1
Triplicatella disdoma	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Triplicatella peltata	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0
Triplicatella sinuosa	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
Tsunyiella diandongensis	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Tsunyiella luna	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Tsunyiella steatocula	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Tubuterium ivantsovi	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Tunudiscus duovittarius	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
Vandalotreta djagoran	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1
Wangyuia chengjiangensis	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Wutingella binodosa	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Xianfengella yatesi / cf.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1
Xianshanella haikouensis	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Yakutingella intricata	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Yaoyingella inflata	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Appendix 1. 8 (continued)

species/stratum	S.Henan	N.Anhui	C. Shaanxi, Luonan	SE. Shaanxi, Xihaoping Mb.	SE. Shaanxi, Shuijingtuo Fm.	NE. Xixiang, SE. Shaanxi	NW. Hubei, Xihaoping Mb.	Yichang, Hubei, Shuijingtuo Fm.	S. Sichuan & Chongqing	N. Yunnan	C&E. Yunnan Yuanshan Fm.	Tarim	Maly Karatau & Talas Alatau	Dzhabkan	Mongolian Transitional Zone	Tuva Mongolia	Kuznetsk Alatau	N. Siberia, Olenek, Emyaksin Fm.	S. Siberia	E. Transbaikalia	Gorlitz, Germany	Sardinia	Taurus Mt. Turkey, Cal Tepe Fm.	Spain	Nova Scotia, Little Hollow Fm.	E. Massachusetts, Weymouth Fm.	England	E. Pennsylvania	W. Newfoundland	NE. Greenland	Antarctic	S. Australia
Yochelcionella americana	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0
Yochelcionella chinensis / cf. chinensis / greenlandica / cf. greenlandica / sp. / erecta	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	1	1	0	1
Yochelcionella parva	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Yochelcionella recta / crassa / sp. / stylifera	0	0	0	0	0	1	0	0	0	0	0	0	1	1	1	1	0	1	1	1	0	0	0	0	0	0	1	0	0	0	0	0
Yucola bucerus	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Yuwenia bentleyi / juliana / Yuwenia sp. (Juwenia sp.)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1
Zepaera jagoi	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Zhegallina antiqua	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Appendix 1. 9 (continued)

5.2. Appendex 2: Species not adapted for clustering analysis

Species \ Locality	Alisina sp.	Albrunnicola spp.	Anabarites sp.	Apistoconcha sp.	Archiasterella sp.	Botsfordia ? sp.	Duibianella sp.	Egdetheca sp.	Eothele sp.	Pelagiella sp.	Hadrotreta sp.	Hesslandona? sp.	Hipponicharion sp.	Igorella sp. / Latouchella adunca	Kutorgina sp.	Kyrshabaktella sp.	Latouchella sp. / Oelandiella sp.	Mackinnonia sp.	Micromitra sp.	Nabaviella spp. / sp.	Oobolus? Meneghini	Pararaconus sp. (Purella sp. / ?Pararaconus cf. P. staitorum)	Parkula sp.	Phasoia sp.	Phosphatocopina gen. et. sp.	Randomia sp.	Scenella sp.	Stenotheca sp.	Vandalotreta sp.
S.Henan	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
N.Anhui	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C. Shaanxi, Luo Nan	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0
SE. Shaanxi, Xihaoping Mb.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SE. Shaanxi, Shuijingtuo Fm.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0
NE. Xixiang, Shaanxi Prov.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
NW. Hubei, Xihaoping Mb.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Yichang, Hubei, Shuijingtuo Fm.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S. Sichuan & Chongqing	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
N. Yunnan	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C&E. Yunnan Yuanshan Fm.	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	1	0	0	0	0	0
Tarim	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
Maly Karatau & Talas Alatau	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Dzhabkan	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Mongolia Transitional Zone	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Tuva Mongolia	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Kuznetsk Alatau	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
N. Siberia, Olenek, Emyaksin Fm.	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0
S. Siberia	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E. Transbaikalia	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Gorlitz, Germany	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sardinia	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Taurus Mt. Turkey, Cal Tepe Fm.	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
Spain	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Nova Scotia, Little Hollow Fm.	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
E. Massachusetts, Weymouth Fm.	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
England	0	0	0	0	0	0	0	1	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
E. Pennsylvania	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
W. Newfoundland	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
NE. Greenland	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	1
Antarctic	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
S. Australia	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0

5.3. Appendex 3: References for the data base

The ordering numbers are corresponding to the region numbers shown in P. 114, Fig. 13.

1. South Henan, North China

(He et al., 1984; He and Pei, 1985; Pei, 1985; Zhang, 1987; Pei, 1988; Feng et al., 1994; Zhang, 2007)

2. North Anhui (Huainan, Huoqiu and Chaohu regions), North China

(Xiao and Zhou, 1984; Zhou and Xiao, 1984; Li and Zhou, 1986; Zhang and Sun, 1991)

3. Central Shaanxi (Luonan County and Lianshang Town of Nanzheng County), North China

(Wang et al., 1989; Ding et al., 1992; Yin in Fang et al., 1992; Li et al., 2014; Moore et al., 2014)

4. Southeast Shaanxi, Xihaoping Member

(Li and Holmer, 2004; Li et al., 2004a); This study

5. Southeast Shaanxi, Shuijingtuo Formation

(Li and Holmer, 2004; Li et al., 2004a; Zhang, 2007) ; This study

6. Norhteast Xixiang, Southeast Shaanxi

(Ding et al., 1990; Ding et al., 1992; Steiner et al., 2004; Own observation)

7. North Hubei (Fangxian Region), Xihaoping Mb.

(Duan, 1983; Qian and Zhang, 1983; Yue, 1990; Na and Li, 2011)

8. Yichang Region in Hubei, Shuijingtuo Fm., South China

(Ding et al., 1992; Zhang and Hua, 2005; Zhang et al., 2008; Wang et al., 2010)

9. Southern and central Sichuan and Chongqing, South China

(Yin et al., 1980; Qian, 1989; Hou et al., 2001; Zhang, 2007)

10. North Yunnan (Xiaotan Section), South China

(Li and Xiao, 2004; Zhang, 2007)

11. Central and eastern Yunnan, South China

(Hou et al., 2001; Hou et al., 2004; Steiner et al., 2007; Zhang, 2007; Zhang et al., 2008; pearsonal observation)

12. Tarim

(Qian and Xiao, 1984; Xiao and Zhao, 1986; Huo and Cui, 1989; Yue and Gao, 1992)

13. Mali Karatau and Talas Alatau

(Missarzhevsky and Mambetov, 1981; Bengtson, 1991; Holmer et al., 1997; Holmer et al., 2001; Dzik, 2003)

14. Dzhabkan, Mongolia

(Ushatinskaya, 1987; Esakova and Zhegallo, 1996; Ushatinskaya, 2004, 2008)

15. Mongolian Transitional zone
(Esakova and Zhegallo, 1996)

16. Tuva Mongolia, Mongolia
(Esakova and Zhegallo, 1996)

17. Kuznetsk Alatau
(Missarzhevsky, 1977; Pospelov et al., 1995)

18. North Siberia, Emyaksin Fm.
(Müller et al., 1995; Gubanov et al., 1999; A. Kouchinsky, 2000; Skovsted et al., 2004; P. Y. Parkhaev, 2005; Kouchinsky et al., 2014)

19. South Siberia
(Rozanov et al., 1969; Bengtson, 1977; Bengtson et al., 1987; Ushatinskaya, 2003; A Yu Ivantsov et al., 2005; Demidenko, 2006; Varlamov et al., 2008)

20. East Transbaikalia, Siberia
(Parkhaev, 2004)

21. Görlitz, Germany
(Elicki, 1994, 1996, 1998)

22. Sardinia
(Elicki and Wotte, 2003; Elicki and Pillola, 2004)

23. Taurus Mt. Turkey, Cal Tepe Fm.
(Sarmiento et al., 2001; Elicki and Gürsu, 2009)

24. Spain
(Vidal et al., 1999; Gubanov et al., 2004; Clausen and Álvaro, 2006; Hinz-Schallreuter et al., 2007)

25. Nova Scotia
(Landing et al., 1980; Landing, 1991, 1995)

26. East Massachusetts
(Shaler and Foerste, 1888; Landing, 1988)

27. East Pennsylvania
(Skovsted and Peel, 2010)

28. West Newfoundland
(Billings, 1872; Skovsted et al., 2004; Skovsted and Peel, 2007)

29. Northeast Greenland

(Bengtson, 1991; Skovsted et al., 2004; Peel and Skovsted, 2005; Skovsted, 2005, 2006; Atkins and Peel, 2008)

30. England (Comley, Nuneaton and Rushton)

(Brasier et al., 1978; Brasier, 1984; Hinz, 1987; Williams and Siveter, 1998)

31. Antarctic

(Wrona, 1989; Evans and Rowell, 1990; Evans, 1992; Holmer et al., 1996; Rode et al., 2003; Wrona, 2003, 2004, 2009)

32. South Australia

(Bengtson et al., 1990; Gravestock et al., 2001; Skovsted et al., 2006; Paterson et al., 2007; Topper et al., 2009; Topper et al., 2011; Skovsted et al., 2012; Betts et al., 2014)

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