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Transitional Ediacaran–Cambrian small skeletal fossil assemblages from South China and Kazakhstan: Implications for chronostratigraphy and metazoan evolution

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ABSTRACT

The Ediacaran–Cambrian transition records distinct evolutionary changes of metazoans. The Ediacaran fossils (*i.e.*, Ediacara-type biota and tubular fossils) are contrasting with the diverse small skeletal fossils (SSFs) from the early Cambrian. The apparent dissimilarities hindered studies deciphering their evolutionary relationships. This also led to a popular assumption that there exists a mass extinction of the Ediacara biota and cloudinids at the Precambrian–Cambrian (Pc–C) boundary. Here we report for the first time a transitional fauna which consists of typical elements of Ediacaran, *i.e.* cloudinids and related tubicolous organisms, together with Cambrian SSFs including protoconodonts, anabaritids and siphogonuchitids from South China and Maly Karatau (Kazakhstan). The sediments yielding the transitional fauna are characterized by siliceous rocks in both regions and were previously considered to be unfossiliferous. Their chronostratigraphic assignment in South China has been debated for years. Based on the new fossil assemblage, the siliceous strata of the Daibu Member (Northeast Yunnan, South China) and the basal Kuanchuanpu Formation (South Shaanxi, South China) can be assigned to the earliest Cambrian SSF biozone (*Anabarites trisulcatus–Protohertzina anabarica* Assemblage Zone) and thus can be considered of early Cambrian in age. A new subzone of the earliest SSF zone in eastern Yunnan (South China) is proposed herein defined as *Ganloudina symmetrica–Rugatotheca typica* Interval Subzone. The new fauna demonstrates that the cloudinids, originally confined to the late Ediacaran, persisted into the Cambrian Fortunian, and no major extinction event occurred at the Pc–C transition.

1. Introduction

The Cambrian bioradiation of metazoans ("Cambrian explosion") represents a major bio-revolution in Earth history during which most metazoan clades appeared within a short duration. Recent investigations showed that the radiation of metazoans was not an instantaneous event as previously postulated. New age datings on the terminal Ediacaran and basal Cambrian strata (e.g. Maloof et al. (2005, 2010)) also contributed to the new understanding of Cambrian bioradiation as a more gradual evolutionary process.

Fossil information on the early evolution of metazoans during the Ediacaran and Terreneuvian is mostly derived from imprints of soft-bodied organisms (Ediacara-type fossils), trace fossils, small skeletal fossils, and diagenetically replaced soft-tissued organisms. Trace fossils successively appeared during the Ediacaran Period and were interpreted as proof for metazoan mobility, organ differentiation, development of neural systems, and related diversified bauplans (Droser et al., 2005; Weber et al., 2007). However, interpretation of this indirect evidence for metazoan evolution is complicated by the arguments on possible protistan mobility during the Proterozoic (Matz et al., 2008).

The most distinct fossil information on the Ediacaran–Cambrian transition is derived from the skeletal fossil record (Bengtson, 2005; Li et al., 2007) and soft-tissue fossil lagerstätten. While soft-tissue preservation is exceptional, and may be exclusive for specific organisms, bulk data for the majority of metazoans are derived from organic and primarily biomineralized skeletons. Small skeletal fossils (SSFs) represent a specific taphonomical mode in preservation that is typical but not exclusive for the terminal Ediacaran to Cambrian Series 2. A wealth of data on SSFs have

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been compiled from major Cambrian carbonate platforms, such as Siberia (e.g. Shabanov et al. (2008), Varlamov et al. (2008)), South China (e.g. Li et al. (2007)), and Australia (e.g. Gravestock et al. (2001)). Based on these data, a general picture on the appearing sequence of biomineralized metazoans is being recently developed (Kouchinsky et al., 2012). It appears that an expansion of skeletal record occurred in three stages since the Ediacaran to the Cambrian Stage 3. The earliest skeletal fossils of Ediacaran can be probably assigned to poriferan and cnidarian grades of organization. Typical SSFs of the Ediacaran are poorly skeletonized cloudinids and other related organic tubular remains. Bilaterian metazoans radiated from the Terreneuvian to Cambrian Series 2. During the Fortunian and Cambrian Stage 2 the second radiation of skeletonized faunas embraced siphogonuchitids, molluscs, hyolithids, stem–group brachiopods, as well as protoconodonts, anabaritids, and tubular problematics. The major third increase in metazoan diversity was recognized during Cambrian Stage 3 and 4 (Atdabanian to Botoman in terms of Siberian regional stages and Qiongzhusian in terms of Chinese regional stages; Zhuravlev and Riding, 2001; Li et al., 2007). This is mostly due to the rapid diversification in Archaeocyatha and Arthropoda—, as well as the rapid speciation in other ecdysozoan clades, *i.e.* priapulids, and deuterostomes (e.g., echinoderms), all forms developed biomineralized or tanned organic skeletons. However, the recognized appearing sequence of biomineralized organisms requires further confirmation from more cratons to evaluate a global picture of metazoan evolution. There also exist indications that the early skeletal fossil record does not fully reflect the appearing sequence of metazoan phyla, as especially substantiated by the reports that less cuticularized ecdysozoan stem-group representatives already co-occurred with lophotrochozoans in the basal Cambrian (Steiner et al., 2004b; Steiner, 2010).

Despite the uncertainties with the existence of non-mineralized and non-cuticularized metazoan stem-group in the Ediacaran–Cambrian transition, SSFs have been applied for the chronostratigraphical subdivision of the early Cambrian strata (Qian et al., 1999; Steiner et al., 2007), besides acritarchs (Yao et al., 2005) and carbon isotope trends (Zhu et al., 2006). On the Yangtze Platform SSF biostratigraphy has been applied for decades with biozonations established from the Cambrian Fortunian to Stage 3 (Steiner et al., 2007; Yang et al., 2015). The terminal Ediacaran strata are well known for the occurrence of diverse tubular remains, such as *Cloudina*, *Corumbella*, *Conotubus*, *Gaojiashania*, *Sinotubulites etc*. The geographically broad distribution and formerly known temporal restriction to late Ediacaran led authors to propose *Cloudina* as a potential index fossil for the late Ediacaran biozone (Grant, 1990; Hua et al., 2005; Cortijo et al., 2015b). Gaucher et al. (2009) and Warren et al. (2011) formally described an Ediacaran *Cloudina* taxon range zone. However, early on doubts were expressed that *Cloudina* may partially be co-occurring with typical Cambrian SSFs such as *Anabarites* in Siberia (Vidal et al., 1994; Zhuravlev et al., 2009, 2012), although not adequately documented. On the other hand, for most carbonate platforms where both cloudinids and typical Cambrian SSFs are occurring, such as in Laurentia (Canada) or South China, there exists no fossil record between the cloudinid assemblage and the earliest Cambrian *Anabarites trisulcatus–Protohertzina anabarica* Assemblage Zone. In South China, the transitional Ediacaran–Cambrian strata represented by the Daibu Member of the Zhujiaqing Formation and the lower Kuanchuanpu Formation were previously thought to be barren of SSFs. Besides, the FAD of trace fossil *Treptichnus pedum* for defining the Fortunian Stage and Cambrian System (Brasier et al., 1994) is merely applicable to Avalonia and Baltica. Thus the exact placement of the Precambrian–Cambrian boundary remains under debate (Steiner et al., 2007; Babcock et al., 2014). The recent report of *Asteridium–Heliosphaeridium–Comasphaeridium* (AHC) acritarch assemblage (Ahn and Zhu, 2014) from the Daibu Member makes a likely Cambrian age for these strata. However, this leaves the question open, why up to now no skeletal fossils have been found in the thick deposits of the Daibu Member and lower Kuanchuanpu Formation.

The present study aims at the documentation of SSFs from the basal Cambrian cherty sequences of the Daibu Member and equivalent strata, such as the lower Kuanchuanpu Formation of South China and the Aksai Member of the Karatau–Naryn Terrain (Kazakhstan). More basically the study targets at drawing new evolutionary and chronostratigraphic clues by documenting the new transitional Ediacaran–Cambrian faunas from South China and Kazakhstan.

2. Geological setting and materials

Siliceous dolostone or limestone samples (ca. 2 kg/per sample) were taken from the Daibu Member at the Xiaotan section, the lower Kuanchuanpu Formation at the Shizhonggou section, the basal Hexi section, the lower Maidiping Formation at the Maidiping section (all South China), and the siliceous Aksai Member of the Ushbas section (Maly Karatau, Kazakhstan). Samples were immersed in 10% buffered acetic acid or formic acid (for dolomitic samples). Fossils were picked out from the residue and prepared for SEM scanning and energy-dispersive X-ray spectroscopy (EDS). Figured specimens are stored in the Institute of Geology, Chinese Academy of Geological Sciences (CAGS) and the Department of Earth Sciences, Freie Universität Berlin.

The *Anabarites trisulcatus–Protohertzina anabarica* Zone is found in early Cambrian carbonates of most Cambrian carbonate platforms, such as the Zhongyicun Member of the Zhujiaqing Formation, the Maidiping Formation (formerly considered a member of the Hongchunping Formation) in central Sichuan, and the upper Kuanchuanpu Formation in south Shaanxi, all of the South Chinese Yangtze Platform, as well as the uppermost Berkuty Member of Kyrshabakty Formation, Aksai Member and lower Karatau Member of Chulaktau Formation of Maly Karatau (Kazakhstan).

The Xiaotan Section (Fig. 1, GPS: N28°07′33.8″ E103°27′56.1″) located in the Yongshan County, eastern Yunnan Province, China, however, was recently flooded by the construction of a dam and the subsequent raising of water level. In this section the Ediacaran dolostones of the Dengying Formation underlies the Zhujiaqing Formation. Both the Dengying and Zhujiaqing formations are widely distributed in eastern Yunnan. In ascending order, the Zhujiaqing Formation consists of the Daibu, Zhongyicun, Dahai members. The Daibu Member is composed of bedded chert, chertified dolostones with minor phosphorite clasts, and siliciclastic limestone lenses. Fossils were recovered from the limestone lenses in the lower Daibu Member. Due to facies variation and disconformities (Yang et al., 2014), the thickness of the Daibu Member varies greatly from 8 m to 73 m (He, 1989) in different regions of East Yunnan or completely lacking in some other area. At the Xiaotan section, the member was reported with different thickness according to various authors, such as, 43.93 m (Luo et al., 1982, as Xiaowaitoushan Member), 44 m (Zhou et al., 1997), 46 m (Li et al., 2001), or 57.2 m (Li et al., 2013). The latter measurement (Li et al., 2013) is adopted in this study. Previously SSFs were only reported in the overlying Zhongyicun Member and higher intervals (Li and Xiao, 2004).

In the Shizhonggou section (Fig. 8, GPS: N32°58′16.1″ E106°15′45.0″) of southern Shaanxi, the Meishucunian strata are comprised of the ca. 55 m thick Kuanchuanpu Formation and lower part of the siliciclastic Guojiaba Formation (Steiner et al., 2004a). The Kuanchuanpu Formation is mainly composed of limestone and phosphatic limestone, with thick interlayers of chert in the low and