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Geobiology of a palaeoecosystem with Ediacara-type fossils: The Shibantan Member (Dengying Formation, South China)

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ABSTRACT

Despite the importance of palaeoecosystems with Ediacara-type fossils for the early evolution of metazoans, only little is known about the interplay of geological and biological processes in these environments. The reason is that sedimentary structures, biogenic structures and (bio-) geochemical signatures (e.g. hydrocarbon biomarkers) are commonly not well preserved due to the predominance of volcanic and siliciclastic lithologies. The Shibantan Member (Dengying Formation, South China) is one of only few carbonate settings with Ediacara-type organisms worldwide and its lithology promises an excellent preservation of sedimentary facies and (bio-) geochemical signatures. Here we provide the first comprehensive geobiological characterisation of the Shibantan Member in order to reconstruct the interplay between sedimentary and (bio-) geochemical processes and to assess the microbial activities in the palaeoecosystem with Ediacara-type fossils. Facies analyses revealed that carbonate and organic matter were autochthonously formed by (bio-) geochemical processes linked to microbial mats. However, the material was frequently reworked and re-deposited within the same setting (i.e. para-autochthonous) as evidenced by small-scale (hummocky-) cross stratification, erosional contacts, lenticular bedding and load casts. Negative Ce anomalies (Ce/Ce*) and low V/Cr ratios demonstrate that molecular O_2 was present in the water column, whereas characteristic Ni/Co-, V/(V + Ni), and V/Sc ratios suggest the contemporaneous presence of sub- to anoxic water. Taken together, these observations imply a temporarily stratified water body frequently mixed and ventilated by storms. ^{13}C-enrichments in the Shibantan carbonates ($\delta^{13}C$ = +3.29 to +3.98‰, VPDB) together with ^{13}C-depletions of syngenetic *n*-alkanes cleaved from the extraction residue using catalytic hydropyrolysis (HyPy; $\delta^{13}C = -31.7$ to -36.3‰, VPDB) could indicate a significant withdrawal of ^{12}C by primary producers that thrived within the mats. At the same time, sulphurised biomarkers in the bitumen and HyPy-pyrolysate hint at organic matter decomposition and concomitant sulphide production by sulphate reducing bacteria. When oxygen was available at the sediment–water interface due to mixing by storms, sulphide oxidising bacteria were possibly temporarily favoured. The results demonstrated that palaeoenvironmental conditions dynamically changed through a complex interplay of biogenic and abiogenic processes.

1. Introduction

The Ediacaran Period (635–541 million years ago; Ma) spanned the time between the last Neoproterozoic global glaciation (Marinoan) and the Cambrian Explosion (Knoll et al., 2004, 2006; Walker et al., 2013). This period is generally regarded as a critical interval because of the strong influence of the Gaskiers glaciation (∼580 Ma), the establishment of architecturally complex organisms of partly metazoan affinity (Ediacara-type fossils or Vendobionta; 575–541 Ma), the first potential trace fossils of bilaterian organisms, and the advent of biomineralisation and predation (*Cloudina* community) (e.g. Germs, 1972; Bengtson and Zhao, 1992; Grotzinger et al., 2000; Knoll et al., 2004, 2006; Narbonne, 2005; Jensen et al., 2006). Thus, the Ediacaran Period is characterised by one of the most dramatic revolutions of

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the Earth's biosphere with consequences for the entire Earth's system.

Despite the importance of palaeoecosystems with Ediacara-type fossils for the early evolution of metazoans in this time (e.g. Narbonne, 2005, and references therein), only little is known about the geobiology (i.e. the interplay of geological and biological processes) of these environments. The reason is that sedimentary structures, biogenic structures and/or various (bio-) geochemical signatures (e.g. organic biomarkers) are usually not preserved together. Particularly (bio-) geochemical proxies are critical in this regard, since palaeoecosystems with Ediacara-type fossils are usually restricted to volcanic and siliciclastic sediments with a low preservational potential (Narbonne, 2005; Callow and Brasier, 2009). For instance, organic biomarkers are, with one exception from the Ediacaran White Sea setting (Kelly, 2009), not preserved in these environments. Carbonate systems may be more promising to fill this major preservational gap since sedimentary structures, biogenic structures as well as various (bio-) geochemical signatures (e.g. organic biomarkers, trace elements) are preserved. However, only few carbonate settings with Ediacara-type organisms exist: the Khatyspyt Formation in Siberia and the Shibantan Member in South China (e.g. Sun, 1986, 1989; Fedonkin, 1990; Knoll et al., 1995; Xiao et al., 2005; Fedonkin and Vickers-Rich, 2007; Grazhdankin et al., 2008; Shen et al., 2009; Chen et al., 2013, 2014).

The Shibantan Member (Dengying Formation, ca. 551–541 Ma; Zhu et al., 2003, 2007; Condon et al., 2005) exhibits dark, organic-rich limestones deposited in a distal offshore basin situated within the Yangtze carbonate platform (e.g. Wang et al., 1998; Steiner, 2001; Zhu et al., 2003, 2007; Ling et al., 2013) (Fig. 1A). The Shibantan Member is stratigraphically sandwiched between peritidal dolomites of the Hamajing Member and the Baimatuo Member of the Dengying Formation (Fig. 1B). It contains an exceptional fossil association with putative algal or bacterial colonies (*Vendotaenia antiqua*; e.g. Sun, 1986; Zhao et al., 1988; Steiner, 1994; Weber et al., 2007; Zhu et al., 2007; Anderson et al., 2011), Ediacara-type fossils (*Paracharnia dengyingensis*; Ding and Chen, 1981; Sun, 1986; Dzik, 2002; *Yangtziramulus zhangi*; Xiao et al., 2005; Shen et al., 2009; *Hiemalora*, *Pteridinium*, *Rangea*, *Charniodiscus*; Chen et al., 2014) as well as the first trace fossils of mobile benthic animals on the Yangtze Platform (e.g. Zhao et al., 1988; Weber et al., 2007; Zhu et al., 2007; Chen et al., 2013; Meyer et al., 2014). Furthermore, a new annulated tubular fossil (*Wutubus annularis*; Chen et al., 2014) has been described. Further studies reported on occurrences of early sponge spicules (Steiner et al., 1993) and suggested specimens of the tubular fossil *Sinotubulites baimatuoensis* (Chen et al., 1981; Zhao et al., 1988). The Shibantan Member thus comprises a unique Ediacara fossil Lagerstätte, but almost nothing is known about the geobiology of this palaeoecosystem. Because of its carbonate lithology, however, the Shibantan Member allows for a comprehensive geobiological characterisation by means of sedimentological and various (bio-) geochemical approaches.

Here we provide the first comprehensive geobiological characterisation of the Shibantan Member as an Ediacara palaeoecosystem, addressing both sedimentary and (bio-) geochemical processes. Facies, stable isotopes, trace elements (including rare earth elements), and organic biomarkers were analysed for a sample from directly underneath an Ediacara-type organism, which facies is typical for the fossiliferous lower Shibantan Member. The combination of various approaches allows for a comprehensive characterisation of the Shibantan environment with respect to the local environmental conditions, the microbial community, and the interplay between sedimentary and (bio-) geochemical processes. The results of our study therefore potentially have implications for other palaeoecosystems with Ediacara-type organisms.

2. Material and methods

2.1. Samples

Petrographical analyses were performed on various samples from the Shibantan Member in the Yichang area (Fig. 1A). All samples were collected in the Zhoujia'ao Quarry (30° 46′ 51.30″ N; 111° 02′ 31.45″ E), stratigraphically positioned in the fossil-bearing lower part of the Shibantan Member (Fig. 1B). In order to understand the interplay between sedimentary and (bio-) geochemical processes in the palaeoenvironment better, a sample block characterised by an Ediacara-type fossil on top (Fig. 2) was additionally sampled for comprehensive petrographical and (bio-) geochemical analyses. The entire sample block has a consistent facies which is typical for the lower Shibantan Member and is therefore regarded as being representative for the palaeoenvironment in which the Ediacara-type organisms lived. The analysed sample was isolated from the central part of the sample block (Fig. 2B) in order to obtain a pristine and unaltered sample, which was particularly important for the biomarker analysis.

2.2. Bulk analyses

2.2.1. C/N/S

Bulk total inorganic carbon and N/S analysis was performed with a Hekatech Euro EA CNS instrument.

Total organic carbon (TOC) was determined by combustion-infrared detection using a Leco SC-632. First, diluted HCl was added to the crushed rock sample to remove carbonate. The sample was then introduced into the Leco combustion oven, and the amount of carbon in the sample was measured as carbon dioxide by infrared (IR) detection.

T_{max} data were obtained for selected samples with a standard Rock-Eval 6 instrument (APT Norway). For TOC analyses of these samples, the temperature programme started with 300 °C (3 min) before temperature was raised by 25 °C min^{-1} to 650 °C (0 min). A reference sample (NGS JR-1) was run as every tenth sample and checked against the acceptable range given in NIGOGA (Weiss et al., 2000).

2.2.2. Mineralogy

The mineralogical composition was determined by X-ray diffraction (XRD) analysis of whole-rock powder using a Philips X Pert MPD equipped with a PW3050 Goniometer (Cu as anode material). Data were collected from 4° to 69.5° 2θ with a step size of 0.02° 2θ and a scan step time of 2 s.

2.3. Element-geochemistry

Trace elements including rare earth elements and yttrium (REE + Y) were analysed with laser ablation inductively coupled plasma mass spectrometry (LA-ICPMS) using a Perkin-Elmer SCIEX Elan DRII coupled to a laser ablation system from Lamda Physik (operating conditions: 27 kV, 7 Hz; pit Ø 120 μm). In order to minimise analytical errors, 17 spots were measured on different layers. NBS610 was used as internal standard, and ablation yields were corrected by referencing to ^{43}Ca. Anomalies were calculated based on shale normalised values (PAAS; McLennan, 1989) using published formulae for Eu/Eu*, Ce/Ce*, Pr/Pr*, Gd/Gd* (e.g. Bau and Dulski, 1996), and La/La* (e.g. Alibo and Nozaki, 1999). Relative standard derivations were <30% for 0.01 ppm, <15% for 0.1 ppm, <10% for 1–10 ppm, and <5% for 100–1000 ppm.