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Research paper

Three-step modernization of the ocean: Modeling of carbon cycles and the revolution of ecological systems in the Ediacaran/Cambrian periods

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ABSTRACT

Important ecological changes of the Earth (oxidization of the atmosphere and the ocean) increase in nutrient supply due to the break-up of the super continent (Rodinia) and the appearance of multi-cellular organisms (macroscopic algae and metazoan) took place in the Ediacaran period, priming the Cambrian explosion. The strong perturbations in carbon cycles in the ocean are recorded as excursions in carbonate and organic carbon isotope ratio ($\delta^{13}C_{carb}$ and $\delta^{13}C_{org}$) from the Ediacaran through early Cambrian periods. The Ediacaran–early Cambrian sediment records of $\delta^{13}C_{carb}$ and $\delta^{13}C_{org}$, obtained from the drill-core samples in Three Gorges in South China, are compared with the results of numerical simulation of a simple one-zone model of the carbon cycle of the ocean, which has two reservoirs (i.e., dissolved organic carbon (DOC) and dissolved inorganic carbon (DIC). The fluxes from the reservoirs are assumed to be proportional to the mass of the carbon reservoirs. We constructed a model, referred to here as the Best Fit Model (BFM), which reproduce $\delta^{13}C_{carb}$ and $\delta^{13}C_{org}$ records in the Ediacaran–early Cambrian period noted above. BFM reveals that the Shuram excursion is related to three major changes in the carbon cycle or the global ecological system of the Earth: (1) an increase in the coefficient of remineralization by a factor of ca. 100, possibly corresponding to a change in the dominant metabolism from anaerobic respiration to aerobic respiration, (2) an increase of carbon fractionation index from 25‰ to 33‰, possibly corresponding to the change in the primary producer from rock-living cyanobacteria to free-living macro algae, and (3) an increase in the coefficient of the organic carbon burial by a factor of ca. 100, possibly corresponding to the onset of a biological pump driven by the flourishing metazoan and zooplankton. The former two changes took place at the start of the Shuram excursion, while the third occurred at the end of the Shuram excursion. The other two excursions are explained by the tentative decrease in primary production due to cold periods, which correspond to the Gaskiers (ca. 580 Ma) and Bikonor (ca. 542 Ma) glaciations.

1. Introduction

In the Ediacaran period, two biological and environmental changes took place before the Cambrian explosion of the metazoan. First, macroscopic fossils of multicellular organisms with sizes exceeding 1 m are identified in the sedimentological record (e.g. Narbonne, 2005). Their morphological diversity rapidly increased

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through Ediacaran to early Cambrian by two orders of magnitude (Fig. 1; Knoll and Carroll, 1999; Brasier and Antcliffe, 2004; Payne et al., 2009). Second, the oxygen level of the atmosphere and the ocean is increased by a five orders of magnitude in the late Ediacaran (Fig. 1). As suggested by the size changes of biological organization (Condie and Sloan, 1997; Payne et al., 2009), redox states of Fe, Eu and Ce in deep sea, and shallow marine carbonate through time (Kato et al., 2006; Canfield et al., 2007; Komiya et al., 2008), and the change in sulfur isotope ratio analyses (Fike et al., 2006; McFadden et al., 2008; Xiao et al., 2012).

These major environmental changes strongly perturbed the carbon cycle in the ocean. In fact, strong depletion events (excursions) of carbon-13 are reported in the late Ediacaran ocean, recorded in platform sediments almost simultaneously around the world (Burns and Matter, 1993; Narbonne et al., 1994; Kaufman and Knoll, 1995, 1997, 2006; Saylor et al., 1998; Myrow and Kaufman, 1999; Yang et al., 1999; Calver, 2000; Walter et al., 2000; Jiang et al., 2002, 2007; Wang et al., 2002a,b; Condon et al., 2005; Fike et al., 2006; Le Guerroué et al., 2006; Zhou and Xiao, 2007; Zhu et al., 2007; Tahata et al., 2013). This drop in carbon-13 is referred to as the Shuram excursion.

The stable isotope ratios $\delta^{13}C_{carb}$ and $\delta^{13}C_{org}$ are believed to reflect the change in the global status of photosynthesis, since biological organisms preferentially use light carbon during photosynthesis. When the biological mass with light-carbon content becomes large, the inorganic carbon (mantle CO_2) in the atmosphere and ocean become heavier. Rothman et al. (2003) first modeled the behavior of the carbon cycle and the stable isotope ratios with a simple one-zone model, which has two reservoirs of carbon: dissolved organic carbon (DOC) and dissolved inorganic carbon (DIC). They also suggested that the reservoir of DOC in the early Ediacaran Ocean was 100 times larger than that of DIC in the modern ocean. The transition from such a dark and nontransparent Precambrian ocean to the modern blue and transparent ocean must have taken place in the late Ediacaran period. Knoll and Carroll (1999) suggested that the appearance of multicellular metazoans might have contributed to the clear up of the DOC in the ocean. However, the discussions so far remain qualitative.

In order to promote quantitative studies, we performed a new line of observational and theoretical investigations. First, we conducted chemostratigraphic investigation of carbonate carbon isotope ratios ($\delta^{13}C_{carb}$) and organic carbon isotope ratios ($\delta^{13}C_{org}$) using the drill-core samples collected at the Three Gorges, South China (Fig. 2; Ishikawa et al., 2008; Kikumoto et al., 2014; Tahata et al., 2013). These data are much more reliable than those in previous studies (Zhou and Xiao, 2007; Zhu et al., 2007; McFadden et al., 2008; Jiang et al., 2010; Guo et al., 2013), because drill-core samples of these data have little diagenesis weathering not to expose. Our new data offers the best proxy of changes in the carbon cycle from the Ediacaran period through early Cambrian period, since: (1) no major unconformities, (2) a much finer resolution with 731 points (organic carbon isotope values: 342 points) from 635 to 510 Ma, and (3) pristine drilling-core samples lacking weathering or contamination.

These data collection of $\delta^{13}C_{carb}$ and $\delta^{13}C_{org}$ are compared with results of the numerical simulations of an one-zone model of the carbon cycle proposed by Rothman et al. (2003) and Ishikawa et al. (2013); by fitting numerical data to observational ones, we constructed a Bes Fit Model (referred to hereafter as BFM) which reproduced, the time histories of $\delta^{13}C_{carb}$ and $\delta^{13}C_{org}$, adding much greater detail of the fluctuations of the carbon cycle compared to the previous investigations. The BFM, therefore, forms the basis for quantitative investigation of the evolution of the carbon cycle from the Ediacaran period through early Cambrian period (635–510 Ma).

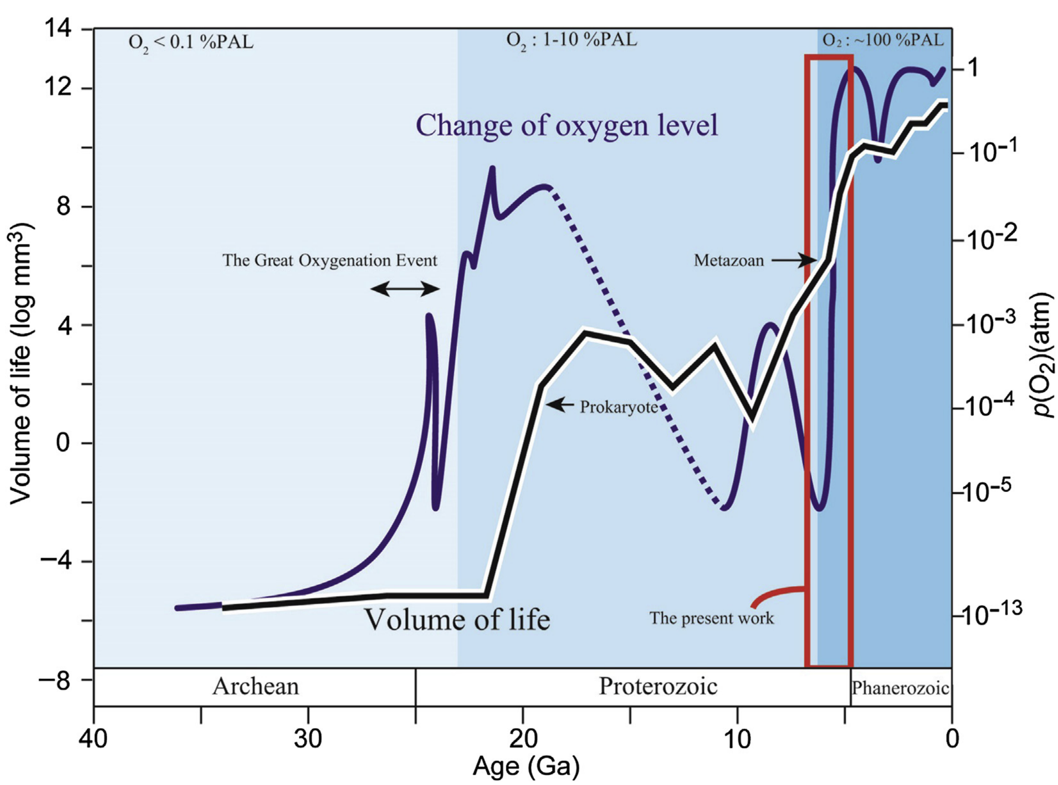

Figure 1. The history of the size of biological organization and oxygen level on the Earth (modified after Condie and Sloan, 1997; Kato et al., 2006; Komiya et al., 2008; Payne et al., 2009; Maruyama et al., 2014). The size of biological organization and the oxygen level are represented by black and blue curves, respectively. The red rectangle shows the period (ca. 635 to ca. 510 Ma) in which we consider in the present paper. This period is one of the most important periods in history of life when oxygen level and the size of biological organization drastically increased at the transition from Proterozoic to Phanerozoic Ocean.