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Global perturbations of carbon cycle during the Triassic–Jurassic transition recorded in the mid-Panthalassa

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ABSTRACT

To examine environmental changes in the biosphere during the Triassic–Jurassic transition, with a particular focus on the global carbon cycle related to Central Atlantic Magmatic Provinces (CAMP) volcanism in the mid-Panthalassa, we established stratigraphic $\delta^{13}C_{org}$ variations using Rhaetian (Late Triassic) to Hettangian (Early Jurassic) shales interbedded within deep-sea cherts in the Katsuyama section in the Mino-Tanba belt, SW Japan. High-resolution record of Rhaetian to Hettangian $\delta^{13}C_{org}$ values in the mid-Panthalassa contain three distinct negative carbon isotopic excursions (NCIEs) before and across the Triassic–Jurassic boundary (TJB): the Rhaetian NCIE1 and NCIE2 show a deviation of 5.0‰ from *ca.* −24.0‰ to *ca.* −29.0‰, whereas NCIE3 across the TJB shows a 3.5‰ deviation from *ca.* −23.5‰ to *ca.* −27.0‰. Our newly obtained NCIEs in the deep mid-Panthalassa can be correlated with the $\delta^{13}C_{org}$ records in the shallow-marine Tethyan regions (i.e., precursor, initial, and main CIEs), suggesting that three NCIEs in the Tethys and mid-Panthalassa likely reflected the global perturbations of the carbon cycle. Three NCIEs before and across the TJB can be interpreted as the consequence of the multiple CAMP volcanic episodes; i.e., the release of thermogenic methane from organic-rich sediments by CAMP intrusive rocks for NCIE1 and large-scale volcanically derived carbon species for NCIE2 and NCIE3. In addition, progressive increase of atmospheric pCO_2 throughout three NCIEs was possibly attributed to accumulation of volcanically derived CO_2 from multiple CAMP eruptions, which resulted in the development of ocean acidification across the TJB. On the other hand, in view of the oxic conditions in the deep mid-Panthalassa during three NCIEs, the development of coeval oceanic anoxic–euxinic conditions was restricted solely to shallow-marine regions. Therefore, ocean acidification together with localized shallow-marine anoxia acted as environmental stresses on the biosphere, which eventually resulted in the severe biotic crisis at the end of the Triassic.

1. Introduction

The biodiversity crisis across the Triassic–Jurassic boundary (TJB; *ca.* 201 Ma) has been regarded as the one of the biggest mass extinctions in the Phanerozoic history of life (e.g., Sepkoski, 1997; Alroy, 2010). The emplacement of the Central Atlantic Magmatic Province (CAMP), which was associated with the breakup of Pangea, has been considered as a main trigger for the extinction-related environmental changes; i.e., an increase in atmospheric pCO_2 (McElwain et al., 1999; Bonis et al., 2010a; Steinthorsdottir et al., 2011), an Oceanic Anoxic Event (OAE) in the shallow-marine regions (Tethys—Bonis et al., 2010b; Richoz et al., 2012; Jaraula et al., 2013; Eastern Panthalassa—Kasprak et al., 2015), and ocean acidification in the shallow-marine Tethys (Hautmann, 2004) and deep mid-Panthalassa (Abrajevitch et al., 2013; Ikeda et al., 2015). Of these environmental changes, the development of ocean

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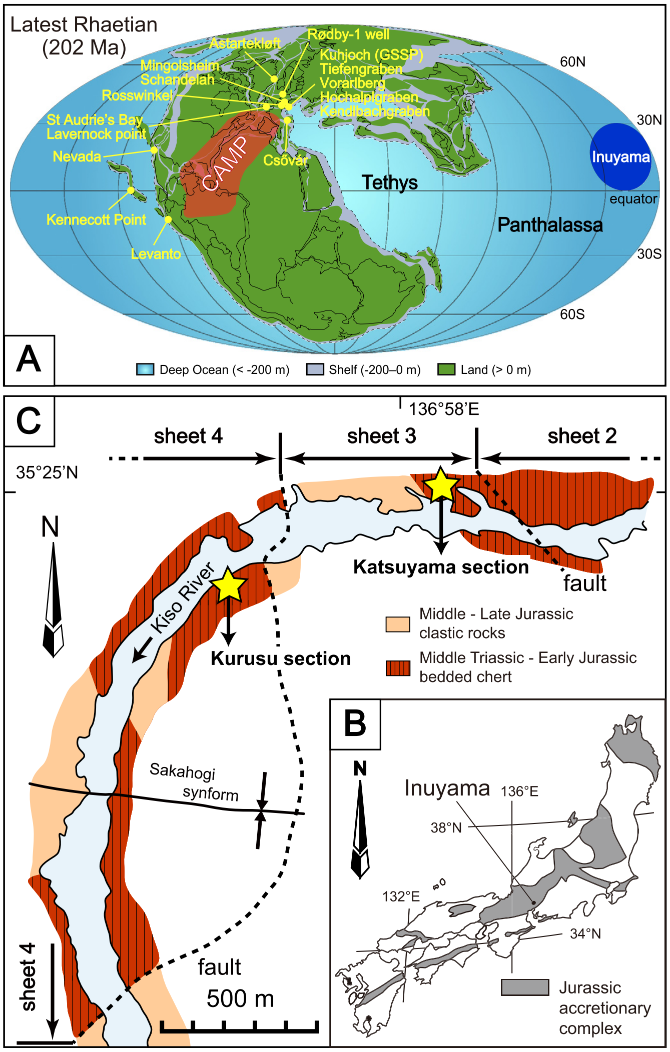

Fig. 1. (A) Latest Rhaetian paleogeography (modified after Abrajevitch et al., 2013) with ancient location of deep-sea bedded cherts exposed in the Katsuyama section. CAMP volcanism is illustrated in red color. (B) A simplified geological map of the Japanese Islands and the location of the Inuyama area. The Jurassic accretionary complexes are denoted by shaded areas. (C) Geological map of the Inuyama area in the Mino-Tanba belt, which is one part of the imbricated Jurassic accretionary complexes (modified after Fujisaki et al., 2016). The stars represent the locations of the Katsuyama and Kurusu sections. White areas show post-Jurassic cover sediments. (For interpretation of the colors in the figure(s), the reader is referred to the web version of this article.)

acidification and anoxia was proposed as a possible cause for the mass killing at the end of the Triassic. In addition, these environmental changes occurred alongside significant carbon-cycle perturbations, as shown by a complex pattern of positive and negative carbon isotope excursions during the Triassic–Jurassic transition in fossiliferous shallow-marine strata deposited along the continental margins of Tethys (Pálfy et al., 2001, 2007; Hesselbo et al., 2002; Kürschner et al., 2007; Ruhl and Kürschner, 2011) and Eastern Panthalassa (Ward et al., 2001, 2004; Williford et al., 2007). These investigations during the Triassic–Jurassic transition emphasized the causal relationships between CAMP volcanism and perturbations of the carbon cycle (e.g., Hesselbo et al., 2002; Ruhl and Kürschner, 2011), but the number and duration of perturbations still remain unclear. In addition to these studies on continental shelf sediments, information from the mid-Panthalassa, which accounted for a major portion of the Triassic to Jurassic global ocean (Fig. 1A), is indispensable for reconstructing changes on the global carbon-cycle related to CAMP volcanism during the Triassic–Jurassic transition.

Deep-sea bedded cherts in the Mino-Tanba belt in SW Japan are appropriate for obtaining paleo-environmental information in the deep mid-Panthalassa because of the successive occurrence of the extinction-related intervals in the Middle Permian to Early Jurassic (Matsuda and Isozaki, 1991). To clarify extinction-related environmental changes in the deep mid-Panthalassa during the Triassic–Jurassic transition, Kuroda et al. (2010) determined organic carbon isotope ($\delta^{13}C_{org}$) values and Os isotopic compositions from deep-sea cherts in the Kurusu section in SW Japan (Fig. 1C). They detected a signature of CAMP volcanism during the Rhaetian based on the negative $^{187}Os/^{188}Os$ excursion. The existing $\delta^{13}C_{org}$ profile, however, may not trace the carbon cycle around the Triassic–Jurassic transition in detail, possibly due to the low sampling resolution. Therefore, more information is needed about carbon cycle variations, with high resolution, to identify the extinction-related perturbations in the mid-Panthalassa that are relevant to environmental changes at the end of the Triassic, and especially to understand the linkage with CAMP volcanism.

To examine possible links between CAMP volcanism and perturbations of the carbon cycle in the mid-Panthalassa during the Triassic–Jurassic transition, we established $\delta^{13}C_{org}$ variations in Triassic to Jurassic shales (siliceous claystones) interbedded within deep-sea cherts in the Katsuyama section in the Inuyama area, Mino-Tanba belt. Shales have an advantage over cherts in terms of monitoring fluctuations in the long-term carbon cycle because of their low sedimentation rates (Hori et al., 1993). In addition, we measured the abundances of major, trace, and rare earth elements (REEs) to constrain redox conditions in the deep mid-Panthalassa. Based on the newly obtained $\delta^{13}C_{org}$ values, trace element (i.e., molybdenum and uranium) abundances, and REE patterns (i.e., cerium anomalies), we discuss the multiple carbon isotopic fluctuations, their possible association with CAMP volcanism, in combination with the redox conditions in the mid-Panthalassa during the Triassic–Jurassic transition.

2. Geological setting

2.1. *Jurassic accretionary complex in the Mino-Tanba belt*

The Mino-Tanba belt is a large part of a Jurassic accretionary complex that was developed along the East Asia margin from the Late Triassic to the earliest Cretaceous, as constrained by detailed macrofossil records (Fig. 1B; e.g., Matsuda and Isozaki, 1991). The Katsuyama section in the Inuyama area is characterized by Early Triassic to Middle Jurassic bedded cherts and Middle to Late Jurassic mudstones and sandstones repeated in thrust sheets (Yao et al., 1980). The metamorphic grade in the Mino-Tanba belt is pumpellyite–actinolite to prehnite–pumpellyite facies or lower, constrained by the mineral assemblage of basaltic rocks (Hashimoto and Saito, 1970).

2.2. *Katsuyama section in the Inuyama area*

The bedded cherts in the Katsuyama section have been thoroughly investigated through geological, structural (Fujisaki et al., 2016), and paleontological studies (Fig. 1C; Hori, 1992; Carter and Hori, 2005). In the Katsuyama section, rhythmically-bedded cherts that exhibit a cyclic pattern corresponding to Milankovitch cycles (Ikeda and Tada, 2014) were deposited from the Middle Triassic to the Early Jurassic without a major hiatus. The bedded cherts strike mostly N–S with a vertical or sub-vertical dip to the west, and show several colors (i.e., black, gray, white, green, red, and purple). Triassic to Jurassic red and purple bedded cherts in the study interval have a total thickness of 3.5 m (Fig. 2A). The thickness of