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Evaluating Late Cretaceous OAEs and the influence of marine incursions on organic carbon burial in an expansive East Asian paleo-lake

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ABSTRACT

Expansive Late Cretaceous lacustrine deposits of East Asia offer unique stratigraphic records to better understand regional responses to global climate events, such as oceanic anoxic events (OAEs), and terrestrial organic carbon burial dynamics. This study presents bulk organic carbon isotopes ($\delta^{13}C_{org}$), elemental concentrations (XRF), and initial osmium ratios ($^{187}Os/^{188}Os$, Os_i) from the Turonian–Coniacian Qingshankou Formation, a ~5 Ma lacustrine mudstone succession in the Songliao Basin of northeast China. A notable $\delta^{13}C_{org}$ excursion (~+2.5‰) in organic carbon-lean Qingshankou Members 2–3 correlates to OAE3 in the Western Interior Basin (WIB) of North America within temporal uncertainty of high-precision age models. Decreases in carbon isotopic fractionation ($\Delta^{13}C$) through OAE3 in the WIB and Songliao Basin, suggest that significantly elevated global rates of organic carbon burial drew down pCO_2, likely cooling climate. Despite this, Os_i chemostratigraphy demonstrates no major changes in global volcanism or weathering trends through OAE3. Identification of OAE3 in a lake system is consistent with lacustrine records of other OAEs (e.g., Toarcian OAE), and underscores that terrestrial environments were sensitive to climate perturbations associated with OAEs. Additionally, the relatively radiogenic Os_i chemostratigraphy and XRF data confirm that the Qingshankou Formation was deposited in a non-marine setting. Organic carbon-rich intervals preserve no compelling Os_i evidence for marine incursions, an existing hypothesis for generating Member 1's prolific petroleum source rocks. Based on our results, we present a model for water column stratification and source rock deposition independent of marine incursions, detailing dominant biogeochemical cycles and lacustrine organic carbon burial mechanisms.

1. Introduction

Upper Cretaceous marine strata preserve evidence for greenhouse warmth on a planet with high pCO_2 (e.g., Pagani et al., 2014) and lacking sustained ice sheets (MacLeod et al., 2013). Oceanic anoxic events (OAEs) are superimposed on this stratigraphic record of excessive warmth, as relatively brief intervals (<1 Ma) of enhanced organic carbon burial in many basins globally (Jenkyns, 2010 and references therein) accompanied by positive stable carbon isotope excursions (CIEs) (Scholle and Arthur, 1980). Precise correlations of terrestrial and marine records are critical for developing a unified Late Cretaceous paleoclimate reconstruction and understanding the terrestrial response to OAEs, as well as for testing hypotheses for the causal mechanisms of OAEs. However, such correlations are complicated in terrestrial basins due to the common occurrence of hiatuses, lateral heterogeneity in lithofacies, and limited biostratigraphic age control. Despite challenges, some workers have employed carbon isotope ($\delta^{13}C$) chemostratigraphy to identify Mesozoic OAEs in terrestrial strata and assess local paleoclimate responses (e.g., OAE2, Barclay et al., 2010; OAE1a, Ludvigson et al., 2010). Although comparatively rare in the geologic record, lacustrine facies offer promise in reconstructing robust ter-

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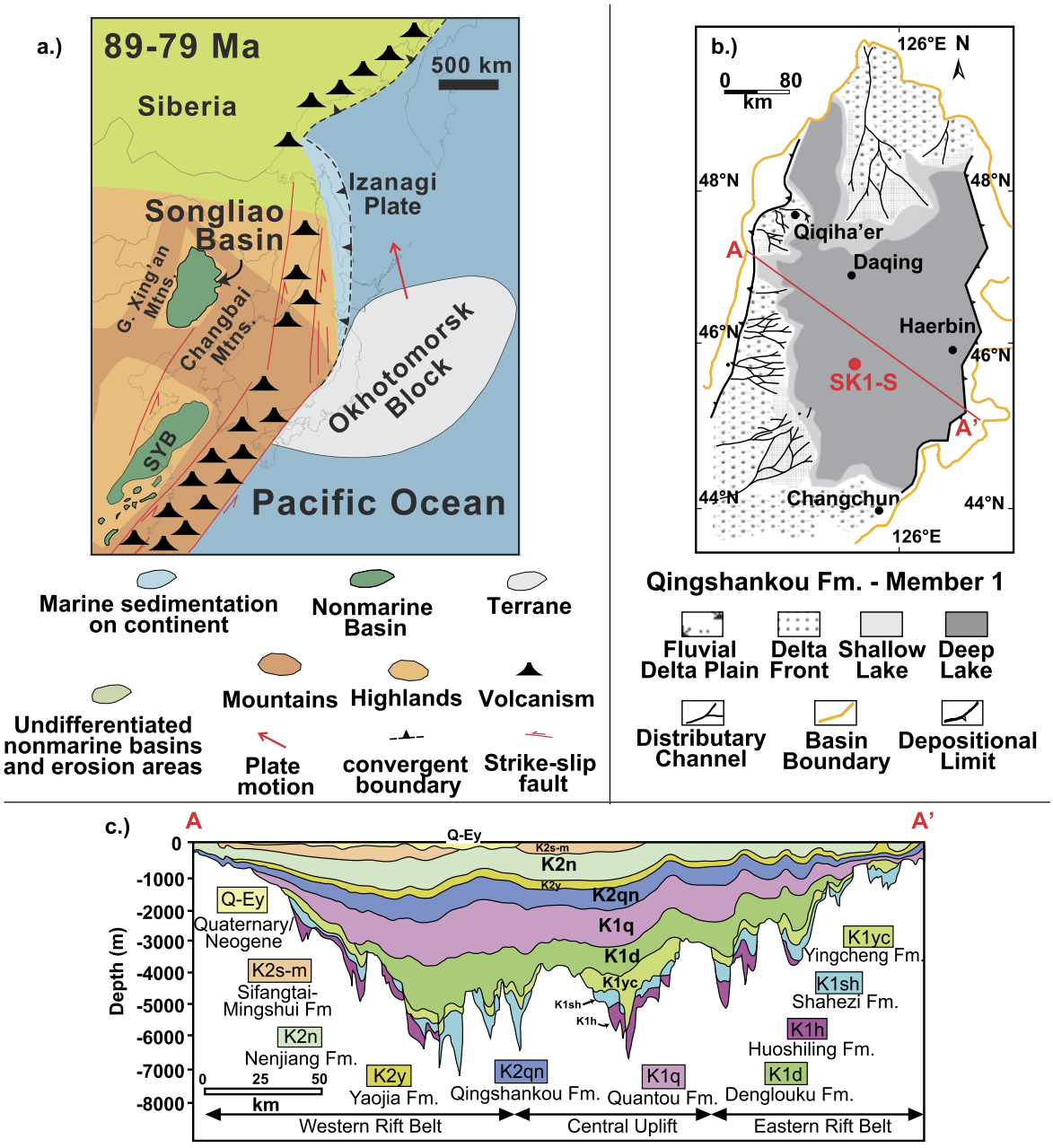

Fig. 1. a.) Palinspastic map of East Asia during the Coniacian-E. Campanian, including the studied Songliao Basin and surrounding physical geographic and plate tectonic features (SYB = Subei–Yellow Sea Basin; modified from Yang, 2013). **b**.) Map of SK1-S core and facies during deposition of Qingshankou Member 1 (modified from Feng et al., 2010). **c**.) Cross section A–A′ from Wang et al. (2013) depicting Cretaceous lithostratigraphic units of the Songliao Basin including the Qingshankou Formation (dark blue). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

restrial paleoclimate records given relatively continuous, expanded mudstone successions. Paleo-lakes are also suitable for testing hypotheses about OAEs' triggering mechanisms, such as accelerated weathering, and for better resolving regional environmental responses (e.g., Toarcian OAE: Xu et al., 2017).

In the non-marine Songliao Basin of northeast China, the SK1-S core provides a relatively continuous Late Cretaceous stratigraphic record from lacustrine and fluvial units influenced by local tectonic and climatic conditions (Fig. 1) (Wang et al., 2013). In addition, the organic carbon-rich mudstones of the Turonian–Coniacian Qingshankou Member 1 are primary petroleum source rocks in China's largest and longest producing non-marine oil and gas basin (Feng et al., 2010). As a result, the depositional history of the Qingshankou Formation has been heavily studied and debated, with some authors arguing that episodic incursions of marine waters during Member 1 drove water column stratification in the basin creating conditions favorable to preservation of organic carbon (e.g., Hou et al., 2000). More recently, the sporadic presence of biomarkers typical of marine algae and sponges in Member 1 and lowermost Members 2 and 3 (Hu et al., 2015), and pyrite sulfur isotopic records in Member 1 of SK1-S (Huang et al., 2013) have been interpreted as evidence for transient or even prolonged marine connections. However, the marine incursion hypothesis for source rock deposition in Qingshankou Member 1 remains controversial, as paleogeographic reconstructions note considerable distances to the nearest marine waters (>500 km; Yang, 2013) (Fig. 1) and because no well-preserved uniquely marine micro- or macrofossils have been reported from the Qingshankou Formation in