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Shelf hypoxia in response to global warming after the Cretaceous-Paleogene boundary impact

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ABSTRACT

The Chicxulub asteroid impact at the Cretaceous-Paleogene (K-Pg) boundary resulted in one of the most abrupt global warming events in the past 100 m.y., presenting an analogue to current global warming. Here, we present high-resolution geochemical, micropaleontological, and palynological records of the Brazos-1 (Texas, USA), Stevns Klint (Denmark), and Caravaca (Spain) K-Pg boundary sections to assess the rapid environmental changes during the global warming following the brief K-Pg boundary impact winter. Warming during the first millennia after the impact is associated with hypoxic bottom waters at the studied shelf sites, as indicated by molybdenum enrichments, causing major stress for benthic communities. We attribute this decline in dissolved oxygen to a combination of decreased gas solubility and ocean ventilation resulting from the warming of the sea water, and increased oxygen demand in shelf bottom waters due to increased nutrient inputs and associated high productivity.

INTRODUCTION

Anthropogenically forced global warming is expected to have large effects on global ecosystems (Pachauri et al., 2014). For instance, climate-change projections for the end of this century predict a 1%–7% decline in dissolved oxygen in the oceans, as a consequence of decreased ocean ventilation and oxygen solubility at higher temperatures (Keeling et al., 2010). Furthermore, anthropogenic nutrient input to coastal zones (e.g., fertilizers and sewage) results in increased primary productivity (Diaz and Rosenberg, 2008), inducing additional oxygen deficiency in coastal ecosystems (Breitburg et al., 2018). Past analogues, such as oceanic anoxic events (e.g., van Helmond et al., 2014) or hyperthermals (e.g., the Paleocene Eocene Thermal Maximum; Sluijs et al., 2014) provide insight into the long-term impact of global warming on dissolved oxygen concentrations in the ocean. However, most geological analogues represent a much slower and prolonged input of greenhouse gasses, over time scales of millennia (Zeebe et al., 2014); i.e., at least an order of magnitude slower than the current anthropogenic input (Solomon et al., 2009).

Perhaps the best analog in geological history, representing a near-instantaneous input of CO_2 into the atmosphere-ocean system, is provided by the Chicxulub asteroid impact at the Cretaceous-Paleogene (K-Pg) boundary, ca. 66 Ma (Schulte et al., 2010). This impact likely induced the most abrupt climate changes in the past 100 m.y. (Overpeck and Cole, 2006); a severe, short-lived global cooling in the years after the impact, followed by a rapid warming within hundreds of years after the impact (Vellekoop et al., 2016). Impact-generated shock waves induced volatilization of targeted continental crust, including the ~3-km-thick carbonate platform at the site of the impact (Hildebrand et al., 1991), suddenly releasing a large amount of climatically active gases into the atmosphere (Artemieva and Morgan, 2017). Estimates of the amount of CO_2 released from the targeted carbonate platform alone range between 425 Gt and 10,000 Gt (see the GSA Data Repository[1] for estimates). In addition, associations of mineral microspherules (Harvey et al., 2008), black carbon (Wolbach et al., 1990), and pyrolitic polycyclic aromatic hydrocarbons (Venkatesan and Dahl, 1989) provide compelling evidence for the combustion of large amounts of organic matter (hydrocarbon reservoirs and biomass), providing at least another 1000 Gt of CO_2 (Harvey et al., 2008; Wolbach et al., 1990) (see the Data Repository). Hence, the Chicxulub asteroid impact resulted in an exceptionally rapid (<10 yr; Artemieva and Morgan, 2017) release of a large amount (10^3–10^4 Gt) of CO_2. This huge input resulted in a rapid increase in atmospheric CO_2 concentrations in the earliest Paleocene, for example, indicated by pCO_2 reconstructions based on fossil leaf stomatal indices (Beerling et al., 2002). Such a strong increase in atmospheric pCO_2 would have resulted in rapid global warming.

Indeed, a TEX_{86} sea-surface temperature (SST) record from Brazos-1 (Brazos River, Texas, USA), shows that the K-Pg boundary impact winter (Vellekoop et al., 2014, 2016) was followed by climate warming within the first thousands of years of the Paleocene. This warming phase is characterized by temperatures ~1.5–2 °C above end-Cretaceous values, which fall within the same range as the warming projected by the most recent Intergovernmental Panel on Climate Change (IPCC) report (Pachauri et al., 2014) to occur before the end of this century (1.5–4.8 °C). Hence, the rapid climate change resulting from the Chicxulub impact at the K-Pg boundary represents an analog to current, anthropogenically forced global warming. The Brazos-1, Stevns Klint (Denmark) and Caravaca (Spain) K-Pg boundary sections enable us to evaluate the long-term impact of rapid global warming, following the K-Pg boundary impact, on dissolved oxygen concentrations in early Paleocene coastal regions.

MATERIAL AND METHODS

During the earliest Paleogene, mid-shelf Brazos-1 and Stevns Klint sections (Culver, 2003), experienced relatively high post-impact sedimentation rates (1–3 cm/k.y., see the Data Repository for materials and methods) compared to deep-sea K-Pg boundary clay deposits (usually <0.5 cm/k.y.; e.g., Mukhopadhyay et al., 2001). This allows for a more-detailed assessment of the rapid environmental changes following the K-Pg boundary impact. In contrast, the Caravaca K-Pg boundary section represents a more offshore, bathyal setting (Culver, 2003), characterized by lower sedimentation rates (0.2–0.5 cm/k.y.; see the Data Repository). Combined, these sites represent perfect locations to evaluate the long-term

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[1] GSA Data Repository item 2018232, detailed age models, methods, and estimations; Figures DR1–DR4; and Tables DR1–DR3, is available online at http://www.geosociety.org/datarepository/2018/ or on request from editing@geosociety.org.

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impact of rapid global warming on dissolved oxygen concentrations on the shelf (Brazos-1 and Stevns Klint) and further offshore (Caravaca).

Concentrations of redox-sensitive trace elements in sediments, in particular molybdenum (Mo), constitute excellent tools to evaluate changes in the paleo-redox state of bottom water and seafloor sediments (e.g., Scott and Lyons, 2012) (see the Data Repository). Benthic foraminiferal assemblages are good indicators for the biotic responses to changes in food flux and bottom-water oxygenation (Jorissen et al., 2007). In shallow marine settings such as Brazos-1 and Stevns Klint, organic-walled dinoflagellate cysts (dinocysts) provide a powerful tool to assess changes in nutrient availability in the water column (Sluijs et al., 2005; see the Data Repository). Therefore, we conducted high-resolution combined geochemical, micropaleontological, and palynological studies on the K-Pg boundary transition, employing the Brazos-1 and Stevns Klint shelf sections (Fig. 1), to assess rapid environmental changes during the warming phase following the Chicxulub impact. These data are complemented with geochemical analyses on the bathyal Caravaca section, to enable comparison between shallow and deeper marine sites. Concentrations of Mo and aluminum were measured using inductively coupled plasma–optical emission spectrometry following digestion of the sediment (see the Data Repository for details).

RESULTS AND DISCUSSION

Our Mo and benthic foraminiferal data confirm that the latest Cretaceous marine environment was fairly stable at all three sites (Fig. 2). Directly below the post-impact tsunami and/or storm deposit at Brazos-1, Mo shows somewhat elevated levels (~5–7 ppm; Figs. 2 and 3), suggesting slightly reducing conditions at the sediment-water interface (Scott and Lyons, 2012), perhaps related to the rapid burial of the seafloor by the tsunami-backwash sediments (Smit et al., 1996). Within the tsunami/storm deposit, Mo shows an anomalously high peak value of ~25 ppm (Figs. 2 and 3), suggesting stronger reducing conditions (Scott and Lyons, 2012). As the sediment of the tsunami/storm deposit was transported to the Brazos site as backwash material (rich in plant debris, wood, and other organic matter transported from land; Smit et al., 1996), the reducing conditions resulting from the partial degradation of this organic matter may have led to Mo sequestration.

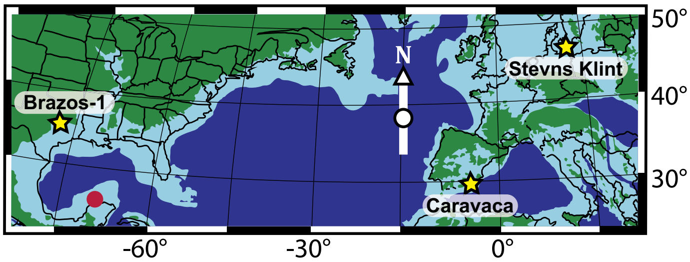

Figure 1. Earliest Paleocene paleogeography of the North Atlantic region (modified after Scotese and Dreher, 2012).

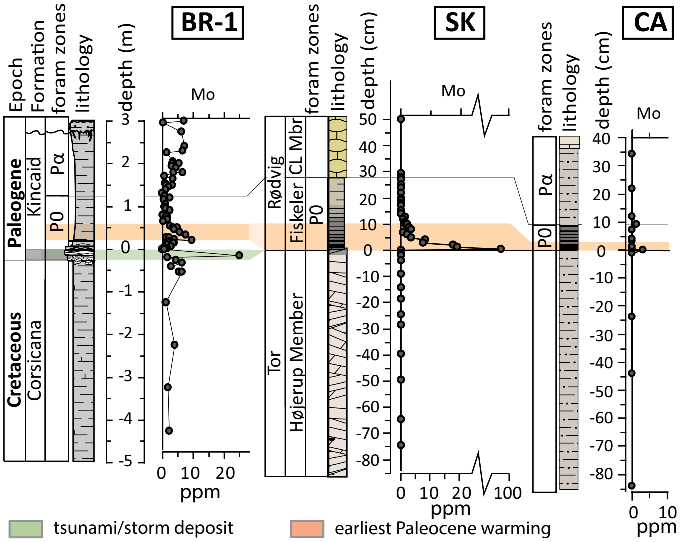

Figure 2. Molybdenum records of Brazos-1 (BR-1; Texas, USA), Stevns Klint composite (SK; Denmark) and Caravaca (CA; Spain). For the sampling and age models, see the Data Repository (see footnote 1).

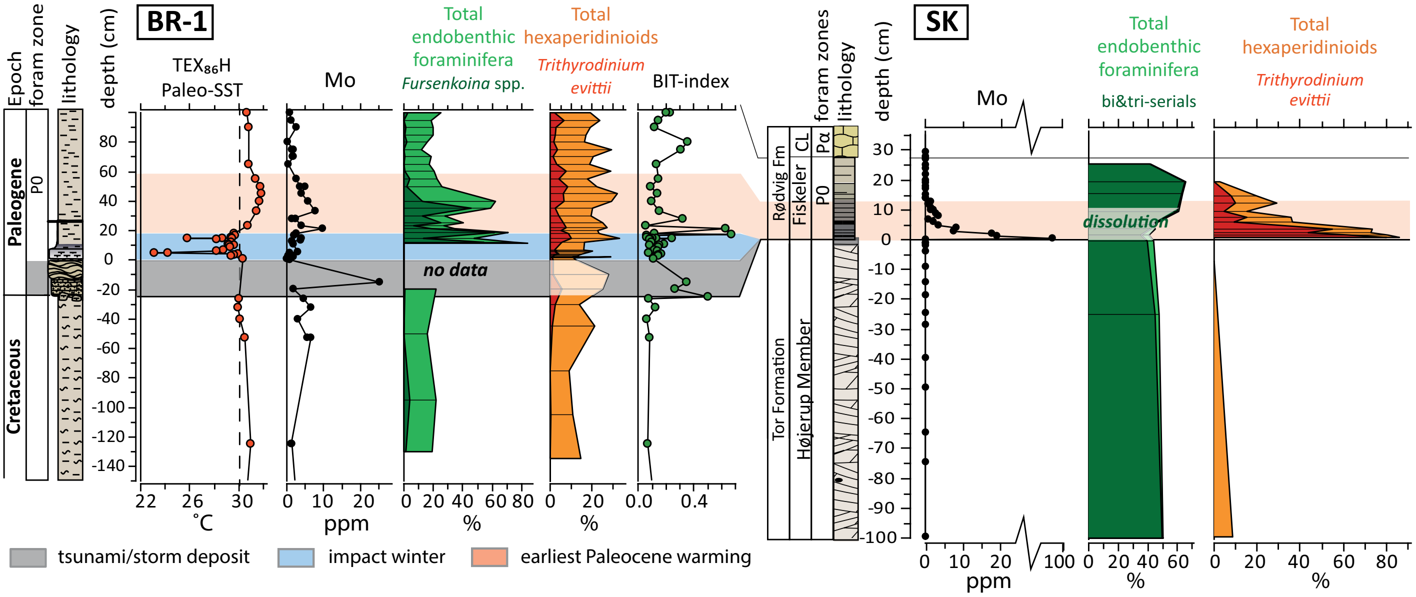

Figure 3. K/Pg boundary molybdenum, benthic foraminiferal, and palynological records of Brazos-1 (BR-1; Texas, USA) and Stevns Klint (SK; Denmark) composite. Biostratigraphy, TEX_{86} sea-surface temperature (SST) and branched and isoprenoid tetraether (BIT) index records are from Vellekoop et al. (2014). For the total records, see the Data Repository, and figures therein (see footnote 1).

Directly above the tsunami/storm deposit (Hart et al., 2012; Vellekoop et al., 2014), the TEX_{86}-based SST record of Brazos-1 displays a millennial-scale warming event following the short-lived impact winter (Vellekoop et al., 2014) (Fig. 3). In this earliest Paleocene interval, the trace elemental, benthic foraminiferal, and palynological records of both Brazos-1 and Stevns Klint show large variations (Figs. 2 and 3), reflecting rapid environmental perturbations and ecological change. Within the first millennia following the impact, represented by the basal 10 cm above the impact-winter deposits at Brazos-1 and the basal 4 cm above the ejecta layer at Stevns Klint (see the Data Repository for details on the age models), the concentration of Mo reached up to ~10 ppm at Brazos-1 and >95 ppm at Stevns Klint. These enrichments persist when expressed as Mo/Al ratios to correct for changes in detrital input (Fig. 4). Given that the background values at these sites are <2 ppm and the crustal average is ~1–2 ppm (McLennan, 2001), the Mo peaks at Stevns Klint and Brazos-1 reflect sedimentary enrichment of Mo, indicating that bottom waters in the earliest Paleocene were characterized by hypoxic conditions at Brazos-1 and euxinic conditions at Stevns Klint (Scott and Lyons, 2012). Within the same interval, a peak of native sulfur up to ~10 ppm, interpreted to have been produced by sulfate-reducing bacteria, has been recorded at Brazos-1 (Heymann et al., 1998). The enrichment in Mo and the presence of abundant bacterially reduced sulfur indicate bottom-water deoxygenation during earliest Paleocene warming. In contrast, while the benthic foraminiferal and geochemical records of the more offshore Caravaca site also show perturbations (Coccioni and Galeotti, 1994; Kaiho et al., 1999), no coeval Mo enrichment was observed there (Figs. 2 and 4). This suggests that further offshore, hypoxic conditions were likely very brief, as also argued by Rodríguez-Tovar and Uchman (2006) and Sosa-Montes de Oca et al. (2013, 2016), based on trace-fossil and trace-elemental analyses.

Benthic foraminiferal assemblages at Brazos-1 and Stevns Klint display a strong response to this early Paleocene bottom-water deoxygenation (Figs. 2 and 3). At the onset of the warming, impoverishment of the benthic community and a large increase in the relative abundance of endobenthic taxa occurred. In the basal 5 cm of the boundary clay at Stevns Klint, the foraminiferal assemblages are strongly affected by dissolution, likely caused by remineralization of organic matter (cf. Jahnke et al., 1994). At Brazos-1, the endobenthics maximum of >80% is almost entirely dominated by *Fursenkoina* spp. (Fig. DR1 in the Data Repository). Modern *Fursenkoina* is considered stress-tolerant; especially resistant to low-oxygen conditions (Kaiho, 1994). A highly impoverished community, dominated by only a few endobenthic taxa, is typical for bottom-water hypoxia or anoxia related to eutrophic conditions (Jorissen et al., 2007).

Therefore, our combined geochemical and benthic foraminiferal records suggest that the rapid onset of the earliest Paleocene warming was associated with hypoxic bottom-water conditions in widely separated open marine marginal basin sites, severely affecting the benthic communities. At deeper and more offshore sites such as Caravaca and Bidart (France), hypoxic conditions were brief, limited to the first few hundred years following the impact (Rodríguez-Tovar and Uchman, 2006; Sosa-Montes de Oca et al., 2013; Alegret et al., 2015). While previous studies indicated a very brief interval of bottom-water deoxygenation during the earliest Paleocene at bathyal sites (e.g., Kaiho et al., 1999; Sosa-Montes de Oca et al., 2013; Alegret et al., 2015; see the Data Repository for an overview), our study indicates that deoxygenation in shelf settings lasted much longer. The higher sedimentation rates at these more-proximal sites also permits assessing the earliest Paleocene deoxygenation in much more detail. The records from Brazos-1 and Stevns Klint provide a direct link to controlling mechanisms; i.e., global warming and enhanced nutrient input. The initial decline in dissolved oxygen in the first centuries after the impact is possibly related to the mass mortality on land, resulting in a short-lived flux of organic matter to the seas (Alegret et al., 2015). A peak of soil-derived organic matter recorded at Brazos-1 (branched and isoprenoid tetraether [BIT] index; Figs. 3 and 4) supports such influx of land-derived material. The continuous hypoxic conditions in the following millennia might be a direct consequence of the decrease of oxygen solubility and ocean ventilation resulting from higher sea-water temperatures (Keeling et al., 2010). Yet, the relative increase of peridinioid dinocysts across the K-Pg boundary, from ~10%–20% to up to ~30% of the dinocyst assemblage at Brazos-1 and from <10% up to >85% at Stevns Klint (Fig. 3), suggests that this time interval was also characterized by increased nutrient input, as this inferred heterotrophic dinoflagellate group generally flourishes during episodes of abundant food supply (Sluijs et al., 2005). This resulting increase in primary productivity created additional demand for oxygen in bottom waters. At both sites, the increase in relative abundance of peridinioids is largely due to a marked increase of the taxon *Trithyrodinium evittii* (Figs. 2 and 3), further signifying that the biotic changes at these widely separated locations are likely driven by similar environmental factors.

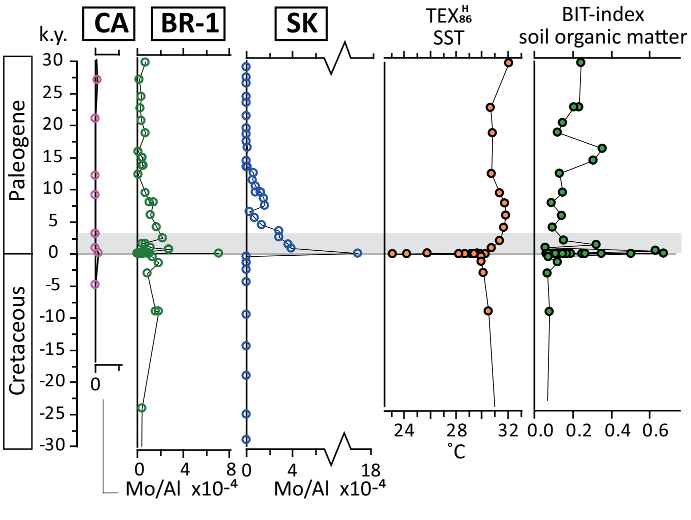

Figure 4. Mo/Al records of the first ~30 k.y of the Paleocene, correlated to the TEX86 sea-surface temperature (SST) and branched and isoprenoid tetraether (BIT) index soil organic-matter records of Brazos-1 (BR-1, Texas, USA; Vellekoop et al., 2014). For details on the age models, see the Data Repository (see footnote 1). CR—Caravaca (Spain); SK—Stevns Klint (Denmark).

SUMMARY AND IMPLICATIONS

Geochemical, benthic foraminiferal, and palynological records of Brazos-1 and Stevns Klint reflect increased nutrient input, seafloor hypoxia, and severe benthic community disruption at continental shelf sites. We attribute the decline in dissolved oxygen during the first millennia after the K-Pg impact to decreased gas solubility and ocean ventilation resulting from the warming sea water, combined with an increased oxygen demand in shelf bottom waters due to the higher nutrient inputs and resulting enhanced productivity. At deeper marine sites, these effects were more short-lived. The K-Pg boundary analog demonstrates the risk of long-term expansion of hypoxia along shallow continental margins due to the combination of anthropogenic global warming and eutrophication.

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