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Gradual onset of anoxia across the Permian–Triassic Boundary in Svalbard, Norway

Anna M. Dustira [a,*], Paul B. Wignall [b], Michael Joachimski [c], Dierk Blomeier [d], Christoph Hartkopf-Fröder [e], David P.G. Bond [b]

[a] *Department of Geology, University of Tromsø, Dramsveien 201, 9037 Tromsø, Norway*
[b] *School of Environment, University of Leeds, LS2 9JT Leeds, United Kingdom*
[c] *GeoZentrum Nordbayern, Friedrich-Alexander University of Erlangen-Nürnberg, Schlossgarten 5, 91054 Erlangen, Germany*
[d] *Norwegian Polar Institute, Fram Centre, Hjalmar Johansens gt. 14, 9296 Tromsø, Norway*
[e] *Geological Survey North Rhine-Westphalia, De-Greiff-Str. 195, 47803 Krefeld, Germany*

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ABSTRACT

The Permian–Triassic extinction event is considered to be the most devastating environmental crisis of the Phanerozoic. With many coinciding factors involved, the role of marine anoxia during the extinction is still poorly understood. In this study a boreal Permian–Triassic Boundary (PTB) section from Svalbard, Norway has been investigated with the aim of better understanding the timing and nature of local marine anoxia onset and extinction events across the PTB. The section comprises the Kapp Starostin and Vikinghøgda formations; $\delta^{13}C_{org}$ values indicate the PTB is located within the lower part of the Vikinghøgda Formation. Lag deposits at the top of the Kapp Starostin Formation indicate a marine hiatus and ensuing transgression during the Late Permian shortly before the extinction event, implying concurrence of major ecological changes and sea-level rise. Pyrite framboid size distributions and total organic carbon (TOC) were used to evaluate bottom water oxygen conditions, and show that changes in bottom water redox conditions and extinction are clearly linked. Oxic to dysoxic bottom water conditions prevailed during deposition of Kapp Starostin Formation sediments and changed to anoxic to euxinic conditions above the formation boundary. The onset of anoxia is not abrupt but rather shows a gradual increase within the Kapp Starostin Formation during the Late Permian. The tipping point where bottom waters reach a long-term state of anoxia to euxinia coincides with the final extinction event, though changes in biotic assemblages at the top of the Kapp Starostin Formation indicate a marine ecosystem crisis prior to this. Oxygen depletion in the boreal region, as seen in our study section and correlating to Greenland and Arctic Canada, seems to be consistently more severe than in lower latitude settings.

1. Introduction

Of the five great mass extinctions during the Phanerozoic, the Permian–Triassic Boundary (PTB) environmental crisis was the most devastating; approximately 90% of all marine species and 70% of terrestrial vertebrate families were eliminated (Erwin, 2006). Despite decades of research, a general consensus on the actual cause(s) of the extinction event remains elusive. A wide range of contributory factors has been suggested, such as (but by no means exclusively) hypercapnia, ocean acidification, nutrient input fluxes or increased sedimentation rates (Knoll et al., 1996; Payne et al., 2007; Algeo et al., 2010; Winguth and Winguth, 2012). Many researchers attribute the Permian–Triassic mass extinction events ultimately to greenhouse and toxic gas emissions from the Siberian trap eruptions, based on extensive and wide-ranging evidence linking volcanic activity to mass extinctions both on land and in the oceans (Vogt, 1972; Renne et al., 1995; Wignall, 2001; Beerling et al., 2007; Ganino and Arndt, 2009; Algeo et al., 2011). Oceanic anoxia is proposed to be the key factor in the marine PTB extinction, as evidence of widespread anoxic to dysoxic marine conditions has been established coinciding with this event (Wignall and Twitchett, 1996, 2002a; Bond and Wignall, 2010). The intensity and duration of anoxia in marine sediments at the PTB varies greatly on a global scale, making study and comparison of boundary sections from a range of different palaeolatitudes and environments important. While many of the lower-latitude sections have been well investigated in this respect, less information is available from Boreal and high latitude settings, which we address here.

The aim of this study is to better understand the timing and nature of Permian–Triassic marine anoxia onset in boundary sections in central Spitsbergen (Fig. 1). Previous work in the region (e.g. Wignall et al., 1998; Nabbefeld et al., 2009; Bond and Wignall, 2010) has been hampered by a lack of clarity concerning the position of the PTB, which can now hopefully be resolved. Wignall et al. (1998) provided modest organic carbon isotope data from the Festningen section in western

* Corresponding author. Tel.: +47 40721552.
E-mail address: anna.dustira@uit.no (A.M. Dustira).

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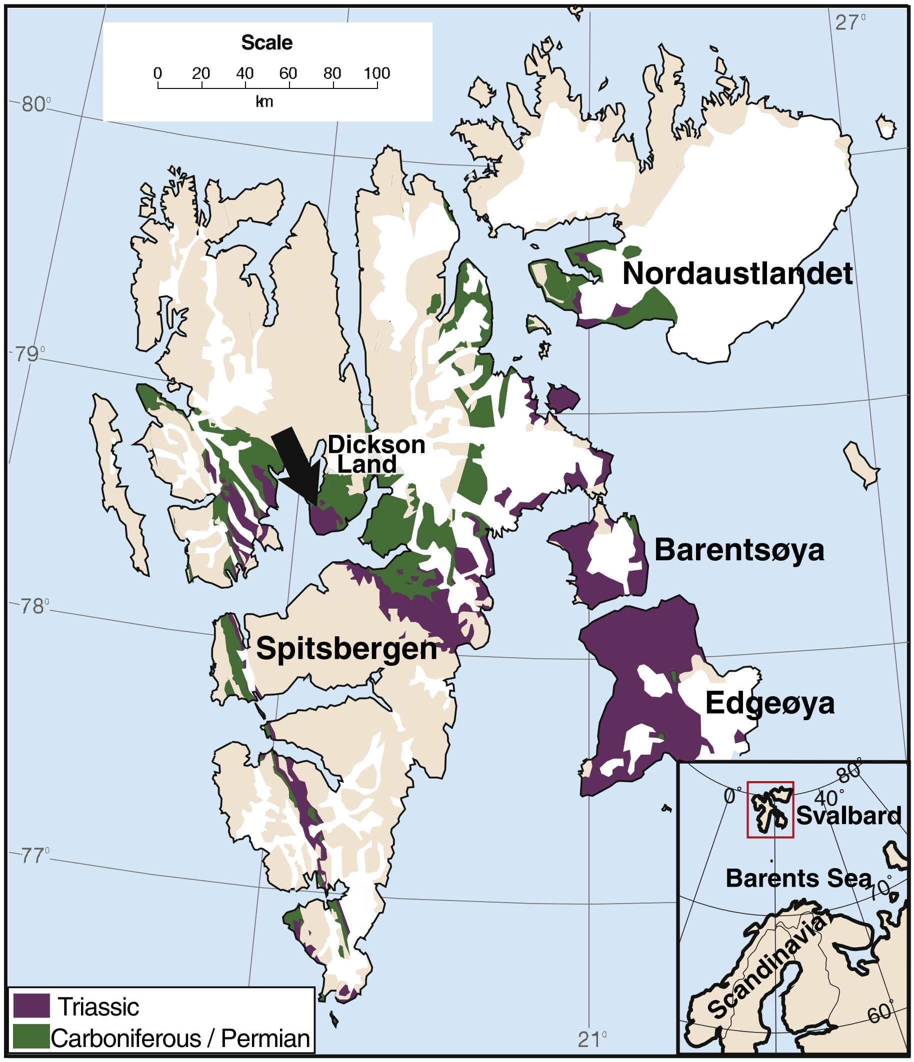

Fig. 1. Map showing the study area (arrow) at the contact between Permian and Triassic deposits on central Spitsbergen, Svalbard, Norway. Undifferentiated Carboniferous/Permian strata are marked in green, and Triassic deposits in purple. White indicates ice- and snow-covered areas.
Modified map courtesy of Norwegian Polar Institute.

Spitsbergen in an attempt to define the PTB, supplemented with a few datapoints from Tschermakfjellet in central Spitsbergen. Here the latter section is targeted with more detailed and high-resolution sampling of the $\delta^{13}C_{org}$ record that allows high-resolution correlation with other PTB sections. The presence of anoxic to euxinic bottom water conditions is established using the size distribution (diameter) of framboidal pyrite as the main proxy, supported by total organic carbon (TOC) and total sulphur (TS) data, and facies and palynological analyses.

Pyrite framboids occur in sedimentary deposits as raspberry-shaped collections of microcrysts, usually spherical or near-spherical, and are distinct from pyrite crystals and lumps formed during later diagenesis (Wilkin et al., 1996). Anaerobic sulphur-reducing bacteria produce H_2S (hydrogen sulphide); this reacts with iron to form an iron sulphide precipitate, and through a chain of transitions, the iron sulphide alters to pyrrhotite, greigite and then pyrite in the form of framboids (Sweeney and Kaplan, 1973; Wilkin et al., 1996). Because this is a redox-dependent process involving weakly oxidizing steps (Wilkin et al., 1996), pyrite framboids only form at the redox boundary where oxygen-bearing and hydrogen sulphide-bearing waters come in contact. Typically, in oxygenated bottom water settings, this is encountered in the upper sediment column, but in euxinic settings the redox boundary is within the water column. Framboids formed in the water column have a limited diameter range, as once they have grown to a certain extent (diameters of 5.0 ± 1.7 μm) they will sink out of the narrow redox interface zone and into oxygen-free bottom water and sediment, where further growth is not possible (Wilkin et al., 1996). The smallest mean diameters (3–5 μm) with very limited size range are indicative of euxinic conditions (sulphidic lower water column) (Bond and Wignall, 2010). Framboids forming within the sediment under oxic bottom water conditions attain greater diameters on average (7.7 ± 4.1 μm) as they grow within the sediment where they reside at the redox interface zone for a longer time (Wilkin et al., 1996). Framboid size distributions have been successfully applied as anoxia and euxinia indicators in ancient marine sediments, including PTB sections (Wignall et al., 2005; Shen et al., 2007; Bond and Wignall, 2010; Liao et al., 2010).

This paper presents pyrite framboid size distribution data coupled with stable carbon isotopes ($\delta^{13}C_{org}$), total organic carbon (TOC) and total sulphur (TS), facies analysis and palynological data from a high-resolution dataset from Svalbard that allows a detailed picture of the timing and development of the marine depositional environment during the PTB. In principle, this information should also enable the correlation to findings from comparable depositional basins within the region, e.g. East Greenland (Wignall and Twitchett, 2002b;