

Smithian-Spathian boundary event: Evidence for global climatic change in the wake of the end-Permian biotic crisis

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ABSTRACT

One of the most important carbon cycle perturbations following the end-Permian mass extinction event straddles the Smithian-Spathian boundary (SSB) (Olenekian, Early Triassic). This anomaly is characterized by a prominent positive carbon isotope excursion known from Tethyan marine rocks. Its global significance is established here by a new high paleolatitude record (Spitsbergen). Paleontological evidence, such as Boreal palynological data (Barents Sea, Norway) and global patterns of ammonoid distribution, indicates a synchronous major change in terrestrial and marine ecosystems near the SSB. The reestablishment of highly diverse plant ecosystems, including the rise of woody gymnosperms and decline of the formerly dominating lycopods, is interpreted as an effect of a major climate change. This hypothesis is supported by modeling of ammonoid paleobiogeography, the distribution patterns of which are interpreted as a proxy for sea surface temperatures (SST). The latest Smithian thus appears to have been a time of a warm and equable climate as expressed by an almost flat pole to equator SST gradient. In contrast, the steep Spathian SST gradient suggests latitudinally differentiated climatic conditions. We propose that this drastic climate change and the global carbon cycle perturbation were triggered by a massive end-Smithian CO₂ injection. The SSB event could therefore represent one of the causes for stepwise and delayed recovery of marine and terrestrial biotas in the wake of the end-Permian biotic crisis.

Keywords: late Early Triassic, climate change, extinction event, palynology, ammonoids, carbon isotopes.

INTRODUCTION

The end-Permian mass extinction event was the most severe in Earth history, and led to profound changes in terrestrial and marine ecosystems (e.g., Erwin, 2006). Carbon isotope profiles from the Tethys reveal that the C-isotope budget underwent large and short-lived fluctuations during the recovery phase following the extinction (e.g., Baud et al., 1996; Payne et al., 2004). Here we explore the relationship between a drastic modification in the Boreal terrestrial spore-pollen (S-P) assemblages with a major evolutionary turnover in ammonoid faunas, and a large, global C-isotope anomaly near the time of the Smithian-Spathian boundary (SSB). These coeval events are discussed in terms of climatic changes occurring in the wake of the end-Permian biotic crisis. The palynological record from the Svalis Dome (central Barents Sea, Norway), which has been discussed so far exclusively from the biostratigraphic point of view (Vigran et al., 1998), is compared with global ammonoid paleobiogeographic distribution patterns, which are used here as a proxy for sea surface temperatures (SST). C-isotope records comprise a new Boreal record (Spitsbergen) and a compilation of data from four Tethyan sections. Our proxies are of completely different nature and cover several latitudinally

oriented climatic belts (see GSA Data Repository Fig. DR1¹): coeval changes in these proxies necessarily reflect global signals.

OVERVIEW OF EARLY TRIASSIC LAND PLANTS AND PALYNOLOGY

The fossil record for terrestrial ecosystems of the Early Triassic is very fragmentary. Palynological and paleobotanical records of this epoch are sporadic and heterogeneous, especially for low latitudes. These poor records led some to speculate about extremely decimated Early Triassic floras (Looy et al., 1999), whereas others, ignoring macrofossil evidence and in situ S-P data, considered essential parts of the Early Triassic palynological assemblages as being reworked (Utting et al., 2004). The latter interpretation is based on the fact that numerous S-P groups dominating these assemblages originate in the Paleozoic, and on many shared fea-

¹GSA Data Repository item 2007072, materials and methods, Figure DR1 (Early Triassic paleogeography and location of the studied sections), and Table DR1 (organic carbon isotope results [Vikinghøgda Fm., Spitsbergen]), is available online at www.geosociety.org/pubs/ft2007.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

tures of Late Permian and Early Triassic floras. Grauvogel-Stamm and Ash (2005) reviewed the global paleobotanical record of the Early Triassic and demonstrated the relatively slow recovery of the terrestrial floras; they stressed the essential role of climate in this process. Boreal areas, with continuous and rapid sedimentation in marine environments, yield the best archives documenting the recovery of terrestrial floras during this interval. Considering the relatively high diversity of Boreal palynomorph assemblages, these areas might be regarded as the most likely refuges of plants and areas of early recovery after the Permian-Triassic boundary event.

DATA AND RESULTS

Boreal Organic Carbon Isotope Record

Here we present a new, ammonoid-constrained, late Early Triassic $\delta^{13}\text{C}_{\text{bulk OM}}$ data (OM: organic matter) from central Spitsbergen (Fig. 1, Table DR1 [see footnote 1]). The Early Triassic Vikinghøgda Formation (Mørk et al., 1999) in the Dicksonfjellet section is dominated by light gray to dark or black silty shales with thin siltstones, dolomite, and carbonate nodule interbeds. There are two members in the upper part of this formation, the Lusitaniadalen Member (Smithian) and the Vendomdalen Member (Spathian). A bulk organic C-isotope curve has been generated for the upper part of the Lusitaniadalen Member and the entire Vendomdalen Member. Samples from the Lusitaniadalen Member display the lowest $\delta^{13}\text{C}_{\text{bulk OM}}$, $\sim -33\text{‰}$. A prominent positive C-isotope excursion ($\leq 6\text{‰}$) in the Tardus Zone (latest Smithian) marks the transition between the two members. Peak values ($\sim -28\text{‰}$) measured within the Euomphala Zone (earliest Spathian) are followed by a gradual decrease until low and constant values ($\sim -32\text{‰}$) within the Subrobustus Zone (latest Spathian).

Tethyan Carbonate Carbon Isotope Records

Carbonate C-isotope records from the Tethyan realm (Pakistan and northern India: Atudorei, 1999; south and southeastern China: Payne et al., 2004; Tong et al., 2005) show that the composition of the carbon reservoir underwent a major change near the SSB. A prominent positive excursion ($\leq 4\text{‰}$) straddling the SSB begins

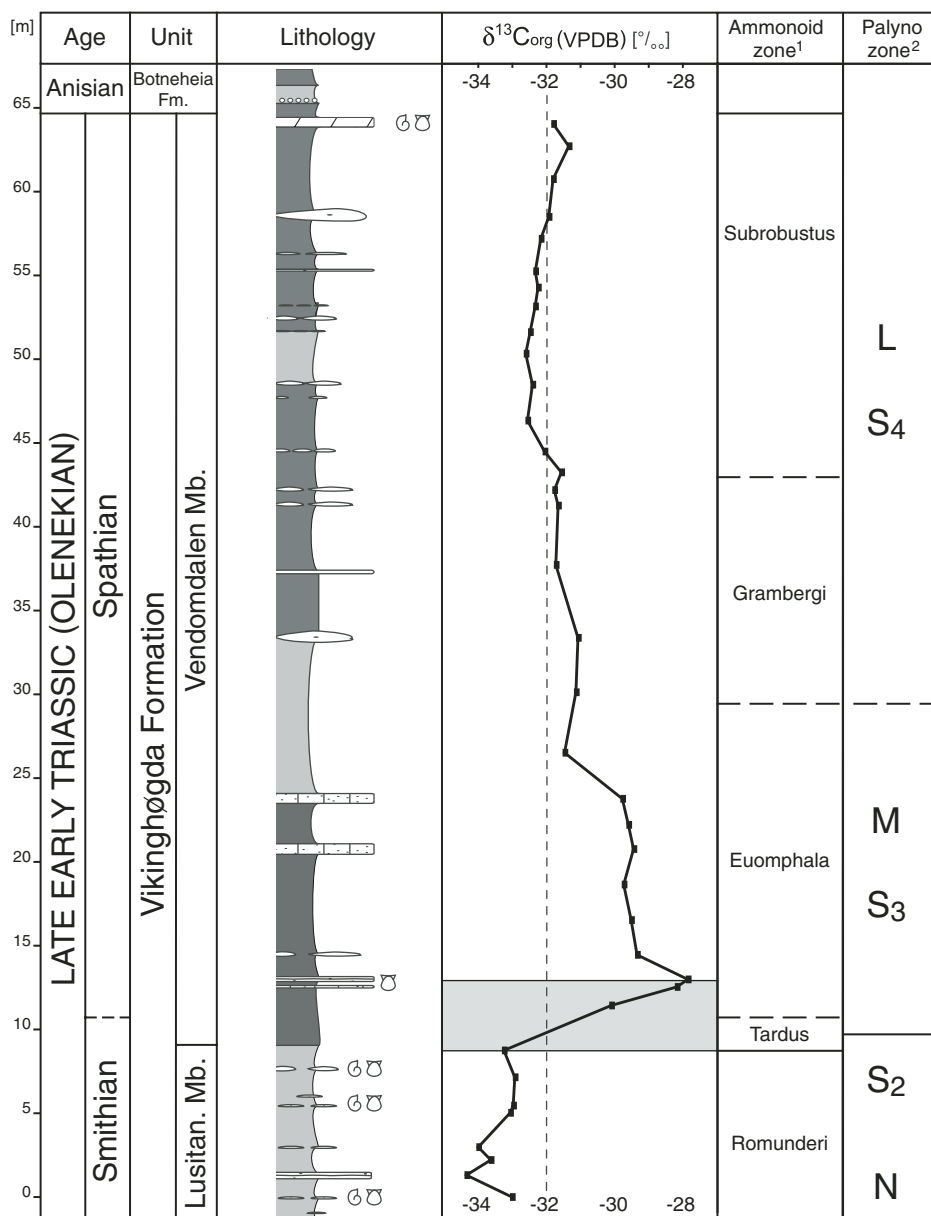


Figure 1. Lithology and bulk organic carbon isotope record of Dicksonfjellet section (Spitsbergen). Ammonoid zones (1) are after Weitschat and Dagens (1989); palynozons (2) are after Hochuli et al. (1989) and Vigran et al. (1998). VPDB—Vienna Peedee belemnite.

at the base of the Pluriformis Zone (correlative of high-latitude Tardus Zone) and ends within the earliest Spathian.

Palynological Record from the Boreal Realm and Climatic Implications

During the Early Triassic, the Barents Sea area was located ~50°N (Mørk et al., 1999). Its palynological record reflects the vegetation of a warm, relatively humid climatic zone. The studied area is at the boundary between zones of high and low evaporation, meaning that it was probably strongly affected by climatic changes (Ziegler et al., 2003).

Marine Early Triassic sediments of the Barents Sea area yield well-preserved palynological suc-

cessions that, based on the co-occurrence of ammonoids, are directly tied to the chronostratigraphic framework (Hochuli et al., 1989; Vigran et al., 1998). Cored sections subcropping in the Svalis Dome area provide the most continuous and best-dated palynological successions of that time. The data, originally represented in a semi-quantitative manner, have been transferred into a quantitative scheme by attributing figures to the semiquantitative classifications; 93 listed taxa have been assigned to 9 major S-P groups. The highly diversified S-P assemblages are comparable to those of Late Permian age in the same area (Mangerud, 1994). The number of species is extremely high compared to coeval assemblages from southern latitudes (Looy et al. 1999). The

quantitative distribution of the nine major groups (Fig. 2) shows consistent and homogeneous patterns within specific intervals. Similar to the procedure of Visscher and van der Zwan (1981), who inferred paleoclimatic trends from Late Triassic S-P assemblages by comparing ratios of major S-P groups, classified as hygrophytic or xerophytic elements, we regard variations in the distribution of the nine groups as paleoclimatic proxies, essentially reflecting availability of water for terrestrial ecosystems. However, only a few Early Triassic S-P species can be attributed to specific groups of plants with known paleoecological requirements. Thus, general ecological classifications of early Mesozoic S-P species are bound to include considerable uncertainties and simplifications. In this study the relative abundance of 9 major groups of S-P, classified as hygrophytes and xerophytes, are plotted for 53 assemblages for the late Smithian to late Spathian interval (Fig. 2).

Similar to the method of Visscher and van der Zwan (1981), we classify most pteridophytes as hygrophytes. As an exception the *Densosporites neburgii* group, attributed to *Pleuromeia* and known to show high abundances in arid or semiarid terrestrial environments of low latitudes, is regarded as a xerophytic element. With the exception of the *Cycadopites* group, all gymnosperms, essentially bisaccate pollen, are considered hygrophytic elements. Thus hygrophytes include the following S-P groups: (1) cavate trilete spores (herbaceous and arboreal lycopods, e.g., Isoetales), except *D. neburgii*; (2) *Aratrisporites* (herbaceous lycopods); (3) smooth trilete spores (mostly Filicales); (4) ornamented trilete spores (mostly Filicales); and (5) *Cycadopites* group (gymnosperms; Bennettiales, Cycadales, Ginkgoales, and Caytoniales).

The following groups are regarded as xerophytic elements: (1) taeniate bisaccate pollen (Coniferales); (2) bisaccate pollen (monolet, trilete, and alete forms, attributed to a wide range of taxonomic groups, like Coniferales, Voltziales, Ginkgoales, Caytoniales, and Peltaspermales); (3) *Ephedripites* (Peltaspermales and Gnetales); and (4) the only spore group, *D. neburgii* (Pleuromeiales).

The ratio between hygrophytic and xerophytic elements reflects a distinct change in plant assemblages in the interval between the late Smithian and the late Spathian (Fig. 2). Late Smithian assemblages are strongly dominated by spores, including those of herbaceous and arboreal lycopods as well as fern spores, and are marked by a slight increase in xerophytic elements. Among those, the dominant *D. neburgii* group is associated with taeniate pollen, occurring consistently and with rare bisaccate pollen and *Ephedripites*.

A distinct turnover in the S-P assemblages occurs at the SSB (S₂-S₃ palynozone boundary), changing from spore-dominated to gymnosperm-dominated assemblages (Fig. 2). Xerophytic elements, essentially dominated by taeniate

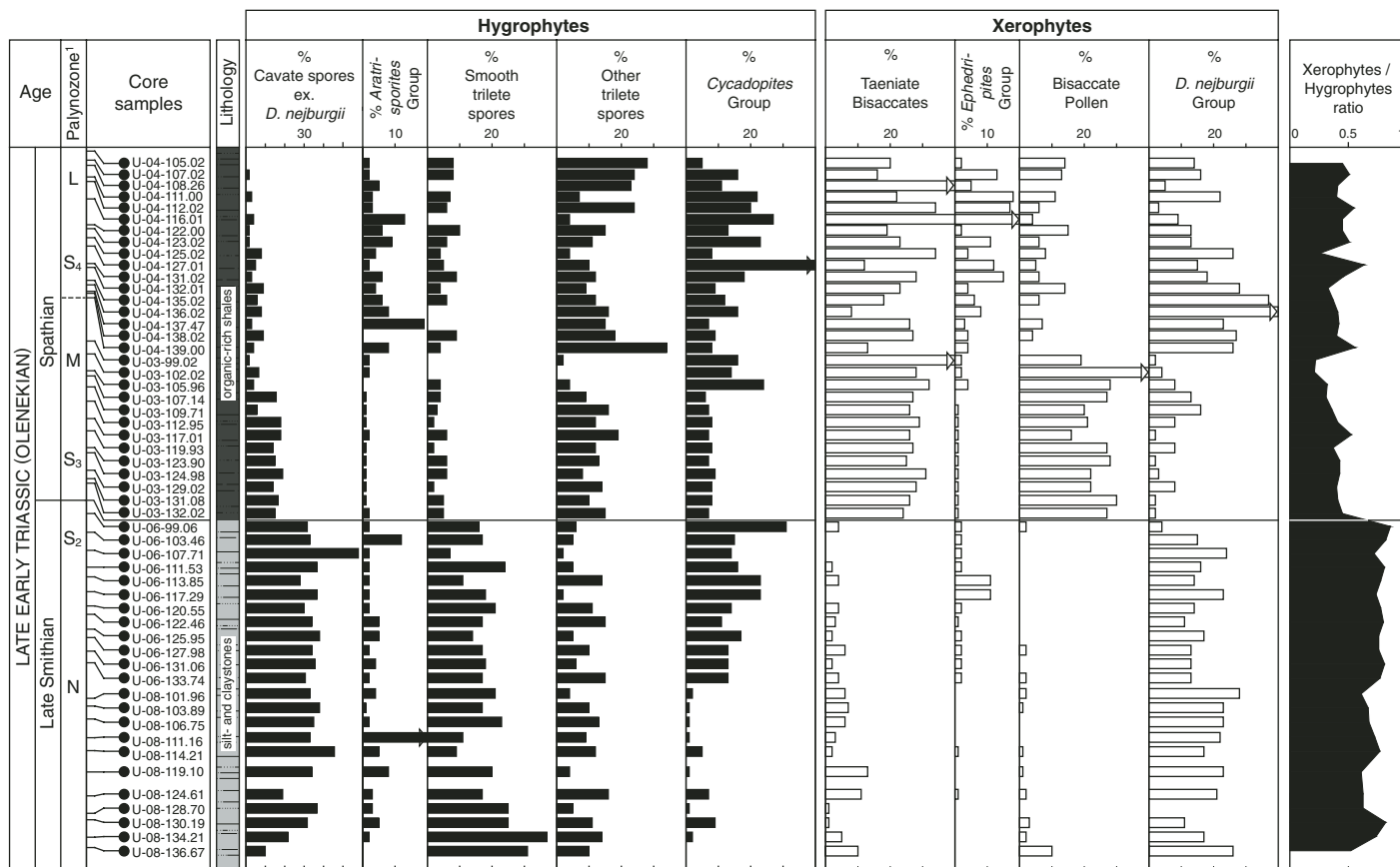


Figure 2. Late Smithian to late Spathian distribution of major floral elements of Svalis Dome (central Barents Sea, Norway) classified as hygrophytes and xerophytes and simplified lithology. Palynozones as in Figure 1.

and other bisaccate pollen, show a substantial increase in abundance. A slight decrease of the hygrophytic elements occurred during the early Spathian. Assemblages from the early part of the late Spathian are again dominated by spores, resulting in a slight increase of hygrophytic elements. In this part of the section, *D. nejburgii* shows its highest abundance and subsequently decreases rapidly during the latest Spathian; assemblages of this interval are strongly dominated by gymnosperms.

Global Distribution Patterns of Ammonoids and Climatic Implications

Several distinct turnovers in ammonoid faunas mark the recovery phase of the Early Triassic after their near extinction at the Permian-Triassic boundary. As first noticed by Tozer (1982), a major global ammonoid evolutionary turnover occurs near the SSB. This event is expressed by a major extinction at the base of the Pluriformis-Tardus Zone and is followed by a major radiation from the earliest Spathian onward. Ammonoid paleobiogeographic studies (Brayard et al., 2006) strongly support a close relationship between generic richness and climatic gradients, showing that the SST gradient is a crucial physical parameter controlling the shape of the latitudinal gradient of generic richness (LGGR), expressed for

the ammonoids by decreasing numbers of taxa from low to high latitudes.

The LGGR compiled from 20 Tethyan and Panthalassic basins (Fig. DR1; see footnote 1) indicates that biogeographic distributions and diversity changed considerably during the Early Triassic (Fig. 3). After an initial phase of low and flat LGGR characterizing the Griesbachian, the LGGR continuously increases during the Dienerian and the Smithian. This trend suggests the edification of contrasted SST gradients, which can be associated with latitudinally differentiated climatic conditions. The sudden end-Smithian ammonoid diversity collapse (Pluriformis-Tardus Zone) led to cosmopolitan and poorly diversified faunas. This event can be explained by a major and relatively brief climatic change, manifested by an almost flat SST gradient. In contrast to that, an extremely contrasted LGGR characterizes the Spathian, suggesting resumption of a steep SST gradient and latitudinally differentiated climatic conditions. Peak values of global diversity and pronounced biogeographic differentiation persisted throughout the Spathian.

DISCUSSION

Plant communities, as reflected by S-P assemblages from the earliest Triassic, were dominated by herbaceous and arboreal lycopods. In the

Boreal realm these plants are associated with numerous gymnosperm pollen and fern spores (Hochuli et al., 1989; Vigran et al., 1998). Typical earliest Triassic plant assemblages are documented here for the late Smithian. The distinct change from the spore-dominated to the gymnosperm-dominated assemblages occurs at the SSB, reflecting one of the major floral turnovers of the Mesozoic for the Boreal area. This distinct modification in the distribution of major floral elements is interpreted as a severe perturbation in the terrestrial ecosystem related to climatic evolution. Using ratios between hygrophytic and xerophytic elements, the following can be inferred: (1) spore-dominated late Smithian assemblages reflect relatively stable humid conditions; (2) the prominent change with a marked decrease of hygrophytes at the SSB indicates a rapid change to considerably dryer conditions, favoring reestablishment of conifer-dominated ecosystems.

Coeval changes in Boreal S-P assemblages and the global ammonoid evolutionary turnover coincided with rapid and global C-isotope shift near the SSB, suggesting a causal link between carbon system and biotic events (Fig. 3). Similar couplings between biotic turnovers and C-isotope perturbations (e.g., Early Cretaceous) have been explained by warming pulses triggered by an excess of atmospheric CO₂

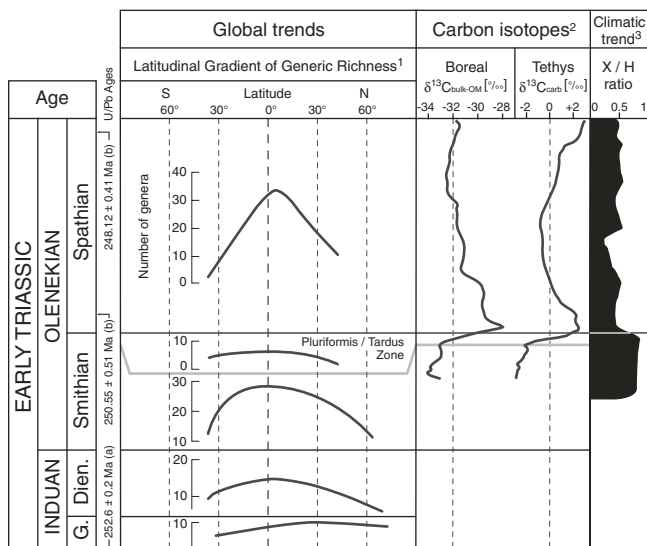


Figure 3. Summary of (1) global trends in ammonoid paleolatitudinal distribution (latitudinal gradient of generic richness, LGGR), after Brayard et al. (2006); (2) Boreal carbon isotope record (this study) and compiled records from Tethys (northern India, Pakistan, and southern China; see references in text); (3) climatic trend inferred from palynological data from central Barents Sea area; X/H: xerophytic/hygrophytic ratio. U/Pb ages are from Mundil et al. (2004) and Ovtcharova et al. (2006). G—Griesbachian; Dien—Dienerian.

(e.g., Weissert and Erba, 2004). The worldwide ammonoid collapse near the base of the latest Smithian coinciding with the beginning of the C-isotope excursion could thus be explained by a rapid shift toward a warmer and equable climate (i.e., flat LGGR-SST gradient) generated by an episode of increased CO₂ levels. This change in pCO₂ values would also lead to carbonate supersaturation levels in late Smithian oceans and to a biocalcification crisis (e.g., Wissler et al., 2003). We suggest that both temperature change and acidification of surface waters triggered the ammonoid extinction. Increasing C-isotope values register the response of the biosphere to altered pCO₂ levels. The trend to more positive C-isotope values is explained by increased burial rates of organic carbon. Continuous draw-down of CO₂ stimulated polar cooling (Knoll et al., 1996) from the SSB onward. Thus, latitudinally differentiated climatic conditions (i.e., steep LGGR) might have engendered global rediversification of marine and terrestrial biotas through the availability of more climatically contrasted habitats. However, the source of a possible CO₂ input remains unknown, although the Siberian igneous province appears to be a potential source area. Even if the main eruptive phase is supposed to have lasted no longer than 1–2 m.y. (e.g., Courtillot and Renne, 2003), igneous activity evidently continued for at least 6 m.y. (e.g., Ivanov et al., 2005). This leads us to speculate that the global climate change around the SSB was triggered by a massive CO₂ pulse originating from a short eruptive event near the base of the Pluriformis-Tardus Zone.

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