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A multistratigraphic approach to pinpoint the Permian-Triassic boundary in continental deposits: The Zechstein–Lower Buntsandstein transition in Germany

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A B S T R A C T

The Central European Basin is very suitable for high-resolution multistratigraphy of Late Permian to Early Triassic continental deposits. Here the well exposed continuous transition of the lithostratigraphic Zechstein and Buntsandstein Groups of Central Germany was studied for isotope-chemostratigraphy ($\delta^{13}C_{org}$, $\delta^{13}C_{carb}$, $\delta^{18}O_{carb}$), major and trace element geochemistry, magnetostratigraphy, palynology, and conchostracan biostratigraphy. The analysed material was obtained from both classical key sections (abandoned Nelben clay pit, Caaschwitz quarries, Thale railway cut, abandoned Heinebach clay pit) and a recent drill core section (Caaschwitz 6/2012) spanning the Permian-Triassic boundary. The Zechstein–Buntsandstein transition of Central Germany consists of a complex sedimentary facies comprising sabkha, playa lake, aeolian, and fluvial deposits of predominantly red-coloured siliciclastics and intercalations of lacustrine oolitic limestones. The new data on $\delta^{13}C_{org}$ range from −28.7 to −21.7 ‰ showing multiple excursions. Most prominent negative shifts correlate with intercalations of oolites and grey-coloured clayey siltstones, while higher $\delta^{13}C_{org}$ values correspond to an onset of palaeosol overprint. The $\delta^{13}C_{carb}$ values range from −9.7 to −1.3 ‰ with largest variations recorded in dolomitic nodules from the Zechstein Group. In contrast to sedimentary facies shifts across the Zechstein-Buntsandstein boundary, major element values used as a proxy (CIA, CIA*, CIA-K) for weathering conditions indicate climatic stability. Trace element data used for a geochemical characterization of the Late Permian to Early Triassic transition in Central Germany indicate a decrease in Rb contents at the Zechstein-Buntsandstein boundary.

New palynological data obtained from the Caaschwitz quarry section reveal occurrences of Late Permian palynomorphs in the Lower Fulda Formation, while Early Triassic elements were recorded in the upper part of the Upper Fulda Formation. The present study confirms an onset of a normal-polarized magnetozone in the Upper Fulda Formation of the Caaschwitz quarry section supporting an interregional correlation of this crucial stratigraphic interval with the normal magnetic polarity of the basal Early Triassic known from marine sections in other regions. Based on a synthesis of the multistratigraphic data, the Permian-Triassic boundary is proposed to be placed in the lower part of the Upper Fulda Formation, which is biostratigraphically confirmed by the first occurrence date of the Early Triassic *Euestheria gutta-Palaeolimnadiopsis vilujensis* conchostracan fauna. Rare records of conchostracans reported from the siliciclastic deposits of the lower to middle Zechstein Group may point to its potential for further biostratigraphic subdivision of the Late Permian continental deposits.

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1. Introduction

The sedimentary successions of the Zechstein and Buntsandstein Groups in Central Germany were the focus of numerous recent studies (e.g., Szurlies et al., 2003; Bachmann and Kozur, 2004; Korte and Kozur, 2005; Kozur and Weems, 2010; Hiete et al., 2006, 2013; Szurlies, 2013; Scholze et al., 2016) examining both the position of the Permian-Triassic boundary and the palaeoenvironmental changes during the end-Permian mass extinction. As known from previous studies, the end-Permian mass extinction event has been linked to oceanic anoxia (e.g., Song et al., 2014) or enhanced volcanism events (e.g., Reichow et al., 2002). Controversially, global cooling was interpreted as potential mechanism for climate perturbation (e.g., Roscher et al., 2011), while more recently global warming is discussed to serve as a pace increasing catalyst but not as the initial reason of the end-Permian extinction (e.g., Joachimski et al., 2012; Schobben et al., 2014; Chen et al., 2016). Additionally, asteroidal or cometary impact (e.g., Becker et al., 2001), or a combination of the above mentioned processes (e.g., Benton and Twichett, 2003) were discussed as a cause of the end-Permian extinction.

In the South-Chinese marine Meishan GSSP section the stratigraphic position of the Permian-Triassic boundary defined by the first appearance date of the conodont *Hindeodus parvus* is interpolated at 251.902 ± 0.024 Ma (Burgess et al., 2014). The end-Permian extinction was calibrated by radiometric dating of volcanic ash beds in marine deposits to occur in an interval of 0.061 ± 0.048 Ma (Burgess et al., 2014). However, the exact position of the Permian-Triassic boundary in continental deposits is still under discussion, since these deposits can not be correlated with marine index fossils to the marine Standard Global Chronostratigraphic Scale. Additionally, the lack of radiometric age determinations due to rare volcanic ash beds in the Zechstein–Buntsandstein transitional beds of the study area in Central Germany is challenging the search of alternative time markers for regional to interregional correlation such as magnetostratigraphy (e.g., Taylor et al., 2009; Glen et al., 2009; Langereis et al., 2010), carbon isotope stratigraphy (e.g., Cao et al., 2008; Shen et al., 2011; Zhang et al., 2016; Cui et al., 2017), or abrupt facies changes (e.g., Ward et al., 2000; Newell et al., 2010). The exact position of the Permian-Triassic boundary serves as a prerequisite in order to contribute with multidisciplinary studies of continental deposits to the recent discussions on the causes of the extinction and associated environmental changes.

In the present study, we conducted a multistratigraphic analysis of the crucial stratigraphic interval in continental deposits of the Zechstein-Buntsandstein transition in Central Germany integrating new $\delta^{13}C_{org}$, $\delta^{13}C_{carb}$, $\delta^{18}O_{carb}$ data, magnetostratigraphy, and biostratigraphy with palynomorphs and conchostracans (Crustacea: Branchiopoda). Major/trace element analyses are used to document the palaeoclimatic conditions as previously performed in continental Permian-Triassic boundary sections such as in the Bogda Mountains in NW-China (e.g., Thomas et al., 2011), western Guizhou and eastern Yunnan in South-China (e.g., Yu et al., 2007), the Karoo Basin in South Africa (e.g., Gastaldo et al., 2014), and northern Germany in the Central European Basin (e.g., Hiete et al., 2006, 2013). This interdisciplinary study was performed on classical and new sections of the Zechstein-Buntsandstein transition in Germany (Thuringia, Saxony-Anhalt, and Hesse; Table 1). The work differs from previous studies in Central Germany (e.g., Bachmann and Kozur, 2004; Korte and Kozur, 2005; Kozur and Weems, 2010, 2011) by the following aspects: (1) more dense sample intervals for $\delta^{13}C_{carb}$ and $\delta^{18}O_{carb}$ analyses; (2) studies of new key sections (i.e., Caaschwitz quarry at the Galgenberg hill, drill core Caaschwitz 6/2012); (3) use of latest published conchostracan biostratigraphic correlations for Late Permian–Early Triassic continental deposits in Central Russia (Scholze et al., 2015) and Central Germany (Scholze et al., 2016).

Table 1
Location, outcrop situation and coordinates of studied Late Permian–Early Triassic sections in Central Germany.

Section	Outcrop situation	Coordinates
Caaschwitz 6/2012 drill core	Drill site at the Lerchenberg hill; 700 m south of Seifartsdorf	50°56′24.1″ N, 11°57′40.8″ E
Caaschwitz quarry	Abandoned quarry at the Galgenberg hill; north of the road Caaschwitz–Seifartsdorf	50°57′6.59″ N, 11°58′ 23.61″E
Heinebach	Abandoned clay pit; 700 m northwest of Hergershausen	51°01′ 58.71″N, 9°41′07.46″ E
Nelben	Abandoned clay pit; 500 m north of Georgsburg at the Saale bridge between Nelben and Könnern	51°40′18.4″ N, 11°44′36.1″ E
Thale	Southern railway cut at the Kirchberg hill	51°45′ 18.34″N, 11°01′ 37.94″E

2. Geological setting

2.1. Palaeogeography, lithostratigraphy, and facies

During the Late Permian–Early Triassic, the study area was located in the Central European Basin (also known as "Southern Permian Basin", "Germanic Basin", or "Northwest European Basin"; e.g., Ziegler, 1990; Beutler and Szulc, 1999; Doornenbal and Stevenson, 2010). This basin extended from England in the west to eastern Poland in the east, the Scandinavian Shield in the north and the Brabant, Armorican and Vindelician-Bohemian Massifs in the south. In the Late Permian, the sedimentation of the arid to semi-arid Zechstein Group deposits was governed by evaporitic cycles of marine ingressions from the Arctic Sea (e.g., Legler et al., 2005; Legler and Schneider, 2008). The Zechstein Group composes seven evaporitic cycles (z1–z7) used for its litho- and cyclostratigraphic subdivision (e.g., Richter-Bernburg, 1955; Käding, 2000) (Fig. 1). The study area was located at about 15°–20° N (e.g., Stampfli and Borel, 2002) in the southern part of the Central European Basin, where these marine evaporitic cycles of the Zechstein Sea were partially replaced by siliciclastic equivalents. In particular, the higher part of the Zechstein Group (z4–z6) consists almost without exception of haloturbated sandstones and pedoturbated siltstones deposited in a siliciclastic sabkha system. In the directly overlying Lower Fulda Formation (lower z7; upper part of the Zechstein Group), this facies gradually changes from decreasing palaeopedogenically overprinted sabkha deposits to lenticular- and flaser-bedded silt- and sandstones indicating a gradual shift towards a playa lake facies. The overlying Upper Fulda Formation (upper z7; uppermost part of the Zechstein Group) is marked at its base by an about 4 m thick sandstone with horizontal to irregular wavy bedding and occasionally intercalated small-scale channels representing a prominent facies change towards shallow subaquatic deposits of a fluvial to fluvio-lacustrine environment (Scholze in Schneider et al., 2014: p. 77–79). The overlying part of the Upper Fulda Formation (upper z7; Fig. 1) is composed of playa lake deposits consisting of mm- to cm-thick alternating claystones to sandstones with internal lenticular and flaser bedding (e.g., Scholze et al., 2016).

The lithofacies of the Early Triassic sections of the Buntsandstein Group in the Central European Basin strongly differ from one another, depending on the respective palaeogeographic position within the basin. Sections located in more marginal parts of the basin consist predominantly of variously-coloured, fine- to coarse-grained siliciclastics of alluvial, fluvial, fluvio-lacustrine, and aeolian deposits, while a playa lake facies is present in more central parts of the basin (Fig. 2). In