The continental Permian–Triassic boundary in the Netherlands: Implications for the geomagnetic polarity time scale

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Abstract

In Central and NW Europe, the transition from the Permian to the Triassic (i.e., the Zechstein–Buntsandstein boundary interval) is developed mainly in red bed facies. This continental sedimentary succession is marked by relatively high sedimentation rates providing a high temporal resolution favorable for magnetic polarity stratigraphy. Here, we present a Zechstein to Lower Buntsandstein magnetostratigraphy obtained from the c. 100 m thick Everdingen-1 core from the Netherlands. Seven magnetozones (EV1n to EV4n) and five sub-magnetozones (EV1n.1r to EV3r.1n) have been delineated. The Everdingen-1 magnetostratigraphy has been integrated into the well-established high-resolution Zechstein–Buntsandstein stratigraphic framework, and verifies the geomagnetic polarity record from Central Germany. This confirms the hypothesis of nearly synchronous base-level cycles within the interior of the Central European Basin. These cycles are related to solar-induced ~100 ka eccentricity cycles. The most distinctive feature of the Everdingen-1 magnetostratigraphy is a transition from a thin reverse to a thick dominantly normal magnetic polarity interval. This reversal predates both the terrestrial mass extinction, which is indicated by a palynomorph turnover and a major sediment provenance change at the base of the Buntsandstein, and the marine Permian–Triassic Boundary (PTB). The PTB is located within the lowermost Buntsandstein and is approximated by the last occurrence of the conchostracan Fabisica postera and a negative excursion in the carbon isotope record. According to the Buntsandstein cyclostratigraphy, the R/N reversal predates the marine end-Permian extinction event by about 0.1 Ma and the marine biostratigraphic PTB by about 0.2 Ma. The thick normal magnetozone is estimated to have lasted c. 700 ka, and roughly coincides with the main phase of Siberian Trap volcanism.

1. Introduction

The transition from the Permian to the Triassic is indicated by the most severe mass extinction of the entire Phanerzoic, strongly affecting both marine and terrestrial biota (Erwin, 1993; Retallack, 1995). Despite intensive studies, its cause remains controversial (Knoll et al., 2007). Suggested explanations include a bolide impact (Becker et al., 2001), a large-scale flood basalt volcanism (e.g. Reichow et al., 2002), anoxia in the oceans (Wignall and Twitchett, 1996), and various combinations of these processes (Benton and Twitchett, 2003). Crucial to the multiple hypotheses for the end-Permian ecosystem collapse is a precise temporal framework. This is a prerequisite to establishing a causal link between possible triggers and kill mechanisms for the extinction event.

Another key issue in resolving the current debate on the possible scenarios for the end-Permian biotic crisis is a precise correlation of events in the sea and on land. A direct biostratigraphic comparison of continental and marine PTB successions is ecologically limited by different paleoenvironmental conditions. The key to successful correlation lies with linking biostratigraphy to other less facies-sensitive methods, such as carbon isotope stratigraphy or magnetic polarity stratigraphy. The global synchronous character of polarity reversals makes magnetic stratigraphy a powerful tool for precise facies-independent correlation between different depositional environments. In the last two decades, significant progress has been made in constructing an integrated bio-magnetostratigraphy for the PTB interval in both marine and continental settings (Glen et al., 2009; Heller et al., 1995; Hounslow and Muttoni, 2010; Hounslow et al., 2008; Li and Wang, 1989; Nawrocki, 1997; Ogg and Steiner, 1991; Scholger et al., 2000; Szurlies, 2007; Szurlies et al., 2003; Ward et al., 2005 and references therein). Across the PTB interval, virtually all magnetostratigraphic records display a distinctive polarity pattern. A transition from a thin reverse to a relatively thick dominantly normal polarity interval that straddles the biostratigraphic PTB, plays an important role in marine to non-marine correlations (Metcalfe and Nicoll, 2007; Szurlies et al., 2003).
For the continental PTB in Central Germany (i.e., the Zechstein–Buntsandstein boundary interval), the above-mentioned magnetostratigraphic association with this boundary is further supported by conchostracan biostratigraphy (Bachmann and Kozur, 2004 and references therein), palynology (e.g. Kürschner and Herngreen, 2010) and carbon isotope data (Korte and Kozur, 2005). All indicate the PTB to be within the lower part of a thick normal polarity interval (CG3n-CG4n of Szurlies, 2007) within the lowermost Buntsandstein. The Zechstein–Buntsandstein boundary interval, however, is characterized only by one magnetostratigraphic record (Schlierbachswald-4 core, Szurlies et al., 2003). Thus, there is need to verify this magnetic polarity sequence elsewhere in Central Europe.

Here, we report a magnetostratigraphy for the continental PTB interval from the about 100 m long Everdingen-1 core, the Netherlands (Fig. 1). Tied to an integrated high-resolution gamma-ray log- and cyclostratigraphy, this record enables to (a) verify the magnetic polarity stratigraphy established for Central Germany (Szurlies et al., 2003) and (b) test the hypothesis of synchronous sedimentary cycles within the Buntsandstein (Clemmensen et al., 1994; Geluk and Röhling, 1997; Menning et al., 2005; Szurlies, 2007). Moreover, a multi-disciplinary approach that combines biostratigraphy (Bachmann and Kozur, 2004; Kürschner and Herngreen, 2010 and references therein), carbon isotope data (Korte and Kozur, 2005) and cyclostratigraphy (Szurlies, 2007), contributes to calibrating the duration of bio- and magnetozones across the PTB that remains unresolved by radio-isotopic dating (Mundil et al., 2004).

2. Geological setting

Traditionally, the Zechstein and Buntsandstein groups are subdivided on lithological criteria (Boigk, 1959; Richter-Bernburg, 1955; Fig. 1). In Central and NW Europe, the transition from the Zechstein Group to the Buntsandstein Group (i.e., the continental Permian-Triassic boundary interval) is developed mainly in red bed facies. These sediments were deposited in the large WNW–ESE trending intracratonic Central European Basin (CEB) that evolved essentially on the former Variscan foreland in the latest Carboniferous to Early Permian (Doornenbal and Stevenson, 2010; Ziegler, 1990). During latest Permian to Early Triassic times, the CEB was subdivided into a complex system of NNE–SSW trending highs and lows (Fig. 1), with tectonic pulses occasionally affecting the sedimentary succession. The effects of such pulses were particularly recorded on “paleohighs” by unconformities, e.g., the Bröckelschiefer unconformity within the uppermost Zechstein or the Volpriehausen unconformity at the base of the Middle Buntsandstein (Br and V unconformities in Fig. 1).

In Germany, the Zechstein is subdivided into seven evaporite cycles (Z1 to Z7 formations), whereas in the Netherlands, the topmost two cycles (Z6 and lower Z7) are combined, forming the Zechstein Upper Claystone Formation (e.g. Peryt et al., 2010). The up to 1500 m thick evaporite cycles exhibit a typical succession of marine clastics and carbonates, followed by sulfates and chlorides. Modeling of Late Permian climates has revealed a pronounced impact of monsoonal circulation patterns on Pangea (Kutzbach and Gallimore, 1989), which together with periodic glacio-eustatic sea-level change may have favored the development of these stacked cycles (cf. Stolhøfen et al., 2008). The entire Zechstein displays an overall regressive trend from dominantly marine to widespread sabkha environments, with only the lower three evaporation cycles (Z1–Z3) having the full evaporite facies inventory. The overlying cycles (Z4–Z7) mainly consist of red brittle evaporitic shales (so-called Bröckelschiefer facies), sandstones and sulfates. Halites occur only occasionally and are confined to the interior of the CEB (e.g. Best, 1989).

In Germany the Zechstein–Buntsandstein boundary, is placed at the base of the first prominent (oolitic) sandstone above the Z7 Formation (Röhling, 1993 and references therein). This corresponds to the base of the Calvörde Formation (Fig. 1). In the Netherlands, however, the Upper Z7 Formation is considered to form the base of the Buntsandstein, i.e., the base of the Main Claystone Member (e.g. Geluk and Röhling, 1997; Fig. 1). The base of the Buntsandstein in Germany is characterized by a marked palynofloral turnover, from...
pollen-dominated assemblages of the Zechstein, with Permian markers such as Lueckisporites sp. and Vitratina, to spore-dominated assemblages within the Buntsandstein, with typical Triassic forms, e.g. Densoisporites sp. and Lundbladispora sp. (e.g. Kürschner and Herngreen, 2010 and references therein). Within the lowermost Buntsandstein, the last occurrence of the conchostracan Falsisca postera within the uppermost Grey Bed Interval some 15 m above the base of the Buntsandstein is proposed to be a proxy for the marine PTB (e.g. Bachmann and Kozur, 2004). This is supported by carbon isotope stratigraphy (Korte and Kozur, 2005) and magnetostratigraphy (Szurlies, 2007; Szurlies et al., 2003).

The 300 to 400 m thick sedimentary succession of the Lower Buntsandstein (Fig. 1) was deposited mainly in fluvo-lacustrine environments, with the fluvial influx originating principally from the massifs at the southern margin of the CEB (e.g. Paul et al., 2008). In the Netherlands and Northern Germany, the Lower Buntsandstein is further subdivided into fining-upward cycles. The most obvious cycle is the 10 to 20 m thick so-called small-scale cycle, which is ascribed to changes in lake level (base-level). Commonly, these base-level cycles are composed of three divisions, recording a phase of lake level rising (wet phase) and subsequent lake level falling (dry phase), in which the lateral and vertical fluctuation of lake level controlled the facies pattern (Paul and Klarr, 1988; Szurlies, 1999). The first unit of such a cycle mainly consists of fluvial red-brown and gray-brown sandstones witnessing wetter, i.e., more humid climates. Within the interior of the CEB, this unit is followed by oolitic limestones and interbedded gray and green-gray shales with abundant fossils, such as palynomorphs, conchostracans (bivalved crustaceans) and stromatolites (e.g. Paul and Klarr, 1988; Szurlies, 1999). The topmost division of a typical base-level cycle consists mainly of red-brown shales and few fluvial sandstones that often increase in number and thickness toward the top, indicating the onset of the next wet phase. The shales were deposited in playas that were frequently dry, as indicated by abundant mud cracks. These base-level cycles reflect variability in precipitation (wet–dry cycles) within the CEB, which is most probably related to solar-induced ~100 ka eccentricity cycles (Bachmann and Kozur, 2004; Clemmensen et al., 1994; Geluk and Röhl, 1997; Menning et al., 2005; Szurlies, 2007).

In this paper, we follow the German nomenclature for two reasons. Firstly, the prominent (oolitic) sandstones at the base of the Calvörde Formation represent an excellent low radiation marker in the gamma-ray logs, which can be correlated over large parts of the central CEB (Best, 1989; Geluk, 2005; Geluk and Röhl, 1997; Szurlies, 1999; Fig. 2). Secondly, the onset of the Calvörde Formation marks a strong increase in humidity and freshwater discharge, resulting in an increased influx of sands transported mainly by braided river systems. This distinct climatic change was accompanied by a complete shift in sediment sources and transport directions (Bachmann and Kozur, 2004; Hug and Gaupp, 2006), assumed to be a proxy for the end-Permian ecological crisis (Bachmann and Kozur, 2004).

3. Integrated wireline log- and cyclostratigraphy

The continental PTB sections from Central Europe are characterized by consistent and relatively high rates of sedimentation of 10 to 20 cm/ka (Szurlies, 2007; Szurlies et al., 2003). This has the potential for high temporal resolution within the Lower Buntsandstein, what is favorable for integrated stratigraphy. In this paper, we focus on the c. 100 m thick Zechstein–Buntsandstein boundary interval from the Everdingen-1 core and apply an integrated...
high-resolution gamma-ray log-, cyclo- and magnetostratigraphic approach (Fig. 1). The Everdingen drill site was situated on the Central Netherlands Swell close to the western margin of the CEB in latest Permian to Early Triassic times. The Everdingen-1 core recovered about 28 m of the uppermost Zechstein and about 72 m of the lowermost Buntsandstein. Gamma-ray log and lithostratigraphy combine to give a detailed subdivision of the Zechstein–Buntsandstein (Fig. 3).

The Zechstein formations can be correlated in detail throughout the interior of the CEB by means of wireline logs (Figs. 2 and 3; Best, 1989; Geluk, 2005; Käding, 2000; Peryt et al., 2010). At the base of the core, the marine Z3 Carbonate (so-called Platy Dolomite) of the Z3 Formation is indicated by extremely low gamma-ray (or GR) values, providing a prominent marker for regional correlation (e.g. Geluk, 2005; Käding, 2000; Peryt et al., 2010). The overlying upper Zechstein (Z4 to Z7) is of reduced thickness, due to the more marginal position of the Everdingen site on the Central Netherlands Swell in Late Permian to Early Triassic times. Overall, the uppermost Zechstein consists mainly of red brittle evaporitic shales, with two discrete sandstone intervals, which correspond to the base of the Lower and Upper Fulda Formation, respectively (Figs. 2 and 3).

Based on wireline logs, the Buntsandstein fluvio-lacustrine cycles can be traced over distances of several 100 km (Geluk, 2005; Geluk and Röhling, 1997; Fig. 2). These cycles are considered to represent synchronous basin-wide events. The fining-upward cycles of the

Fig. 3. Sediment log, lithostratigraphy and gamma-ray log of the Zechstein–Buntsandstein boundary interval in the Everdingen-1 core. Arrows indicate sampling horizons for magnetostratigraphic investigation.
Lower Buntsandstein are widely used for correlation in outcrops, cores, and wireline logs (Best, 1989; Geluk, 2005; Geluk and Röhl, 1997; Paul and Klarr, 1988; Röhl, 1993; Szurlies, 1999; Szurlies et al., 2003). GR logs are particularly useful. In the Buntsandstein, they mainly indicate the content of 40K, which is particularly present in clay minerals. Accordingly, the sandy-oolitic lower part of a base-level cycle is indicated by low GR values, whereas the subsequent mainly pelitic unit displays significantly higher radioactivities.

In the Everdingen-1 core, the recovered 72 m of the Buntsandstein encompass most of the lower 8 fining-upward cycles of the Calvörde Formation (Figs. 2 and 3). The sandy division of these cycles is characterized by low GR values, e.g., the Gray Bed Interval or the Thale Beds (Fig. 3), whereas the pelitic division is indicated by rather high radioactivities. Consistent with GR logs from Northern Germany, the base of cycle 3 (so-called Thale Beds of Szurlies, 1999) in the Everdingen-1 core displays markedly low radioactivities (Fig. 3), thus providing a prime marker for regional correlation (Best, 1989; Geluk and Röhl, 1997; Szurlies, 1999). The Lower Buntsandstein of the Everdingen-1 core can be correlated with confidence throughout the interior of the CEB, based on regional GR log transects. This complements the already well-defined high-resolution stratigraphic framework for the CEB (Geluk, 2005; Geluk and Röhl, 1997; Szurlies, 2007; Szurlies et al., 2003; Fig. 2).

4. Magnetic properties

4.1. Material and methods

Standard paleomagnetic samples were drilled perpendicular to the core axis of the c. 100 m long Everdingen-1 core. They were inscribed in the upcore direction and sliced into 22 mm long cylindric (25 mm) specimens. Following previous experience, fine-grained sandstones, siltstones and carbonates were preferentially sampled. Sampling yielded a total of 80 specimens.

At first, isothermal remanent magnetization (IRM) acquisition experiments were performed on selected samples using a 2 G Enterprises 660 pulse magnetizer and measured with a Molyneux MiniSpin fluxgate magnetometer (noise level 0.2 mA/m). Samples were exposed stepwise to a set of peak fields in the range of 10–2700 mT, enabling a separation of the magnetic spectra into low-coercivity components, such as (titanio) magnetite, and high-coercivity magnetic minerals, such as hematite and goethite. For the subsequent demagnetization treatments, the specimens were divided into red-brown samples (rich in high-coercivity components) and gray lithologies (rich in low-coercivity components). Progressive thermal treatment of the red-brown and some selected gray lithologies was carried out with an ASC Scientific TD48 oven. Alternating field (AF) demagnetization of the remaining gray lithologies was performed using a 2 G Enterprises automatic DC-SQUID 755SRM cryogenic magnetometer (noise level 1 × 10⁻⁵ mA/m).

4.2. Rock magnetism

Routinely, a representative subset of specimens was selected for IRM experiments (Fig. 4). The behavior of the gray and red-brown lithologies revealed significant differences (cf. Szurlies, 2007). Usually, the gray samples are dominated by a low coercivity fraction, acquiring the majority of IRM in the range of 20–200 mT (Fig. 4a), which is ascribed to most probably magnetite. Commonly, most of the IRM is reached in ambient fields of less than 300 mT. The red-brown lithologies however reflect the further presence of a high coercivity mineral (Fig. 4c–d) that is saturated between 300 and 2000 mT, which is attributed to hematite. Additionally, most of the red-brown lithologies and some gray samples are not entirely saturated at maximum field of 2700 mT (Fig. 4b–d), indicating the presence of the high-coercivity mineral goethite.

4.3. Paleomagnetic properties

Most paleomagnetic samples carry either one or two geologically significant components of remanent magnetization. These are: (a) a viscous remanent magnetization (VRM), which allows direct determination of present-day geographic north that is useful for paleomagnetic re-orientation of bore cores, and (b) a primary magnetization (hereafter referred to as the characteristic remanent magnetization, ChRM), which is acquired at, or close to, the time of formation of
the rock, thus providing a record of the geomagnetic polarity at that time.

The average natural remanent magnetization (NRM) intensity of the Everdingen samples is 2.09 mA/m, with individual values ranging from 0.13 to 10.88 mA/m (Fig. 5a), in which the red-brown lithologies (Fig. 5c) clearly display higher NRM intensities than the gray sediments (Fig. 5b). Either progressive thermal demagnetization up to 680 °C or AF demagnetization up to 100 mT were used to successfully demagnetize the NRM of the samples. These procedures revealed that most of the samples carry two different components of remanent magnetization, a low temperature/low coercivity component and a high temperature/high coercivity component, respectively.

A coherent low temperature/low coercivity component of remanent magnetization suitable for paleomagnetic core re-orientation (cf. Hailwood et al., 2010) was defined in 64% of the samples. The remaining samples appear to represent spurious magnetizations, most probably associated with plugging or drilling. The low temperature/low coercivity magnetic component was typically isolated by thermal treatment up to 300 °C and by alternating fields of less than 15 mT, representing relatively steep positive inclinations mostly in the range of +50° to +80°. These values are reasonably consistent with the present-day mean inclination of the geomagnetic dipole field in the Netherlands and Central Germany (D = 0°, I = +66°; Finlay et al., 2010). Thus, this viscous overprint makes it possible to re-orientate most core intervals of the Everdingen-1 core with respect to geographic north, including those individual intervals for which the VRM is not well-defined, by using the mean VRM per core section. This procedure further enables to re-orientate the ChRM directions identified in most of the samples (Fig. 6). After core re-orientation, the mean normal and reverse ChRMs slightly deviate from being antipodal with the normal directions having a tendency to be somewhat steeper and better grouped than the reverse directions (Fig. 6). This is most likely due to residual contaminations from overprint magnetizations and the precision of the core re-orientation procedure, which in any case do not influence interpretation of magnetic polarity.

Thermal demagnetization treatment revealed ChRMs in about 90% of the samples, referred to as type I magnetization. The remarkably high rate of success is most likely due to the fact that only those lithologies have been sampled that have already been proven in former studies to carry a ChRM (Szurlies, 2004, 2007; Szurlies et al., 2003). Depending on the perceived reliability of the ChRM identification in the samples from the Everdingen-1 core, the behavior of the specimens during demagnetization was divided into two main categories (classes 1 and 2). This categorization of type I magnetizations was based on visual qualitative assessment of the linear trajectory isolated during incremental thermal or AF demagnetization and displayed in the vector end-point diagrams (Fig. 7).

For each sample, the directions of the ChRM components were calculated from the demagnetization data using principal component analysis (Kirschvink, 1980). Its determination is typically based on three to five demagnetization steps. These type I magnetizations are suitable for establishing a Late Permian–Early Triassic magnetic polarity stratigraphy for the Everdingen-1 core. In all, c. 90% of the samples exhibit such type I magnetizations. These specimens were assigned a quality factor based on the noisiness of the principle component analysis, in which class 1 behavior (maximum angular deviation, MAD <10°) was assigned to 44 samples and class 2 behavior (MAD >10°) to 30 samples, respectively. The remaining c. 10% of the samples exhibit exclusively a VRM or show highly variable directional behavior during demagnetization (referred to as type II magnetizations). Thus, no identifiable characteristic remanence of Permian–Triassic origin is apparently present in these samples.

After paleomagnetic core-re-orientation, the ChRM component yielded two antipodal groups of directions: northerly (southerly) declinations with shallow to moderate positive (negative) inclinations (Figs. 6 and 7). In the gray lithologies, this direction is isolated over a temperature range of 300–580 °C (Fig. 7c, f) by or alternating fields of 30–100 mT (Fig. 7d–e), ascribable to (titano)magnetite as main carrier of remanence. In the red-brown samples, this direction is substantially demagnetized over a temperature range of 300–675 °C (Fig. 7a–b), indicating hematite as main carrier of remanence. The obtained inclinations from the Everdingen-1 core are fully consistent with ChRM inclinations of 10–50° obtained from coeval Zechstein–Buntsandstein sections in Germany (Szurlies et al., 2003). Thus, these ChRMs carried by either (titano)magnetite or hematite are regarded as primary components.

5. Magnetostratigraphy

The paleomagnetic signal from type I magnetizations of c. 90% of the specimens preserves a dual-polarity magnetization with shallow
to moderate either positive or negative inclinations. These results are consistent with previous data from Zechstein and Buntsandstein sediments (Hounslow and McIntosh, 2003; Nawrocki, 1997; Szurlies, 2004, 2007; Szurlies et al., 2003) and close to the expected Late Permian geomagnetic field direction for the Netherlands (Van der Voo and Torsvik, 2004). The overall mean paleomagnetic direction for the

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Fig. 6. Stereoplots of ChRM (characteristic remanent magnetization) directions (i.e., all type I magnetization) in the Everdingen-1 core, before (left) and after (right) re-orientation to geographic north using the low-temperature VRMs (viscous remanent magnetizations). Solid symbols lower hemisphere, open symbols upper hemisphere. Large symbols refer to mean directions. Class 1 refers to ChRMs with a maximum angular deviation (MAD) of <10°, but mostly of <5°; class 2 refers to ChRMs with an MAD of >10°.

Fig. 7. (a–f) Vector end-point diagrams and normalized intensity decay curves illustrating thermal and alternating field demagnetization of NRM for six representative samples with the demagnetization results assigned to type I (a–e) and type II (f) magnetizations, respectively.
Everdingen-1 core, using all type I magnetizations after core re-orientation is $D = 1.7^\circ$, $I = 27.2^\circ$, $\alpha_95 = 8^\circ$ (Fig. 6). This represents a paleolatitude of about 14.4°N, which is equivalent to paleolatitudes of 15–20°N previously derived from coeval sections in Central and Northern Germany (Szurlies et al., 2003). Since the Netherlands were located in the northern hemisphere during Late Permian to Early Triassic times, shallow negative (positive) inclinations indicate reverse (normal) magnetic polarity (Fig. 7).

A magnetostratigraphy was constructed using all polarity determinations from type I magnetizations from the Everdingen-1 core (Fig. 8). Results from three or more successive samples of the same polarity are defined as a magnetozone (depicted as full bars) and those from only one or two successive samples as submagnetozones (depicted as one- or two-thirds of a bar). The magnetozone couplets (i.e., successive normal-reverse pairs) are labeled EV for Everdingen. From the Everdingen-1 core, in all, seven magnetic polarity intervals (EV1n to EV4n) and further four submagnetozones (EV1n.1r to EV3r.1n) have been delineated (Figs. 2 and 8). The upper Zechstein (Z3 to Z7) is indicated by normal polarity (EV1n) and further four submagnetozones (EV1n.1r to EV3r.1n) have been delineated (Figs. 2 and 8). The upper Zechstein (Z3 to Z7) is indicated by normal polarity (EV1n) and further four submagnetozones (EV1n.1r to EV3r.1n) have been delineated (Figs. 2 and 8). The upper Zechstein (Z3 to Z7) is indicated by normal polarity (EV1n) and further four submagnetozones (EV1n.1r to EV3r.1n) have been delineated (Figs. 2 and 8).

6. Correlation within the Central European Basin

The Zechstein and Buntsandstein have been the focus of several paleomagnetic studies in Western Europe (England: Hounslow and McIntosh, 2003), and Central Europe (Poland: Nawrocki, 1997; Germany: e.g. Soffel and Wippern, 1998; Szurlies, 2007; Szurlies et al., 2003). The between-site correlation of these magnetostratigraphies with the magnetic record from the Everdingen-1 core reveals close similarities concerning the number of magnetozones, their relative thickness as well as the overall polarity pattern (Figs. 9). Moreover, the magnetostratigraphic comparison is consistent with the GR log- and cyclostratigraphic correlation of the Zechstein and Lower Buntsandstein (Fig. 2; Geluk, 2005; Geluk and Röhl, 1997; Szurlies et al., 2003).

In the Everdingen-1 core, the lower Z3 Carbonate (Figs. 3 and 9) is indicated by normal polarity (EV1n), whereas the uppermost Z3 Carbonate belongs to the following reverse magnetozone EV1r, which is correlated with CG1r from the Schlierbachswald-4 core in Central Germany (Figs. 2 and 9). In the Schlierbachswald-4 core, CG1r ranges from the upper Z3 Formation into the lower Z4 Formation. Further support for this correlation comes from the Jaworzna IG-1 core from SE Poland, where Nawrocki (1997) studied two samples from the Z3 Carbonate (PZ3 Formation). The lower sample exhibits normal polarity equivalent to EV1n and the upper sample reverse polarity, what is equated with EV1r. In the Schlierbachswald-4 core, the overlying Z5 and Z6 formations are characterized by normal polarity (CG2n), what is consistent with EV2n in the Everdingen-1 core (Fig. 9). However, magnetozone CG2n starts already in the Z4 Formation. The
suggested discrepancy is most probably due to the low-resolution sampling of the Z4 Formation in the Schlierbachwald-4 core (Szurlies et al., 2003). In Poland, the PZ4a suggested discrepancy is most probably due to the low-resolution field, concerning the number and relative length of magnetozones. The most distinctive feature of global paleomagnetic data from both marine and terrestrial sections is a magnetic polarity transition from a thin reverse to a remarkable thick dominantly normal magnetic polarity interval that predates the PTB (e.g. De Kock and Kirschvink, 2004; Glen et al., 2009; Hounslow et al., 2008; Li and Wang, 1989; Scholger et al., 2000; Szurlies et al., 2003; Fig. 10). Although, there is a good agreement of magnetic records from marine and non-marine PTB sections, correlation details are still lively debated, mainly because of the absence of marine index fossils in the continental successions (Glen et al., 2009; Hounslow and Muttoni, 2010; Steiner, 2006; Szurlies, 2007).

Following on this, the relatively thick EV3n interval is equivalent to CG3n in Germany and Tbn1 in Poland, which is in full agreement with GR log- and cyclostratigraphy (Figs. 2 and 9). In all these sections, this thick normal magnetozone spans the Zechstein–Buntsandstein boundary, representing a prime marker for basin-wide correlation. In the Everdingen-1 core, EV3n ranges into the uppermost cycle 4 of the Calvörde Formation, whereas in the Schlierbachwald-4 core it ends somewhat later in the lowermost cycle 7 (Fig. 9). There are two likely explanations for this discrepancy. Firstly, the sampling resolution in the Schlierbachwald-4 core, where, for instance, the CG3n–CG3r transition is marked by a sampling gap of about 3 m (Szurlies et al., 2003). Secondly, the concept of base-level cycles postulates time intervals of non-deposition or erosion associated with the base-level fall, i.e., the dry phase of the fluvo-lacustrine cycles of the Buntsandstein. On a regional scale, this has a direct effect on the agreement of sedimentary cycles and magnetozones, in that theyreveal a nearly synchronous base-level cycle pattern.

The uppermost part of the Everdingen-1 core is indicated by a thin interval of reverse polarity (EV3r) spanning cycle 7 and a following normal magnetzone (EV4n) that begins in cycle 8. Both magnetic polarity intervals are equivalent to polarity intervals CG3r and CG4n in Germany and Tbr1 and Tbn2 in Poland, respectively (Fig. 9). In both, the Schlierbachwald-4 and Everdingen-1 cores, the base of EV4n and CG4n fall together with the base of cycle 8 of the Calvörde Formation.

Overall, the detailed magnetostratigraphy from the Everdingen-1 core verifies the magnetic polarity record from Central Germany (Szurlies, 2007). Moreover, the good agreement of magnetozones and base-level cycles strongly supports the assumption of nearly synchronous sedimentary cycles within the Lower Buntsandstein (Bachmann and Kozur, 2004; Geluk and Röhling, 1997; Menning et al., 2005; Szurlies, 2007; Szurlies et al., 2003).

In contrast, the comparison with the Obernsees magnetic record from the southern margin of the CEB reveals a strong diachronity of the lithostratigraphic units (cf. Szurlies, 2007). This is most probably due to tectonic and autocyclic processes dominating the alluvial and fluvial facies development at the margin of the CEB. Consequently, the characteristic nearly synchronous fluvo-lacustrine cycles are confined to the large interior of the CEB.

Through integration with Buntsandstein cyclostratigraphy, the duration of the magnetozones from the Everdingen-1 core can be estimated. The thick normal polarity interval CG3n, which straddles the Zechstein–Buntsandstein boundary, spans seven base-level cycles (i.e., seven ~100 ka eccentricity cycles), yielding a duration of c. 700 ka. The following intervals CG3r and CG4n, each encompassing one base-level cycle, lasted c. 100 ka each (Fig. 9).

### 7. Global correlation and discussion

The integration of the Everdingen-1 results with the earlier established magnetostratigraphy of the Schlierbachwald-4 core from Central Germany (Szurlies et al., 2003) establishes a robust stratigraphic framework for the Zechstein–Buntsandstein transition and the continental PTB in the CEB, allowing a thorough comparison with the global data.

In the last two decades, a considerable number of magnetostratigraphic studies have focused on the PTB interval and the Early Triassic (cf. Hounslow and Muttoni, 2010 and references therein), which provide excellent independent evaluation of the behavior of the Earth magnetic field, concerning the number and relative length of magnetozones. The most distinctive feature of global paleomagnetic data from both marine and terrestrial sections is a magnetic polarity transition from a thin reverse to a remarkable thick dominantly normal magnetic polarity interval that predates the PTB (e.g. De Kock and Kirschvink, 2004; Glen et al., 2009; Hounslow et al., 2008; Li and Wang, 1989; Scholger et al., 2000; Szurlies et al., 2003; Fig. 10). Although, there is a good agreement of magnetic records from marine and non-marine PTB sections, correlation details are still lively debated, mainly because of the absence of marine index fossils in the continental successions (Glen et al., 2009; Hounslow and Muttoni, 2010; Steiner, 2006; Szurlies, 2007).

At the global stratotype section and point (GSSP) at Meishan (China), the biostratigraphic PTB is placed at the first occurrence of the conodont *Hindeodus parvus* (Yin et al., 2001), which falls within the lower part of a thick normal magnetzone (Li and Wang, 1989). This boundary postdates the end-Permian extinction event, which is located at the base of the preceding *Clarkina meishanensis–Hindeodus praeparvus* Zone (= base of the Boundary Clay) at the GSSP Meishan (Jin et al., 2000). Due to the absence of *H. parvus* in continental successions, the location of the PTB requires other stratigraphic indicators. In the Karoo Basin (South Africa), the last occurrence of the vertebrate *Dicynodon* is proposed to be a proxy for the PTB (Ward et al., 2005). In the CEB, the PTB is placed at the last occurrence of the conchostracan *Falsisca postera*, since its disappearance coincides with the last occurrence of *Dicynodon* (Bachmann and Kozur, 2004). This biostratigraphic correlation is consistent with global paleomagnetic data, in that the last occurrence of both *Dicynodon* and *F. postera* falls within the lower part of a thick normal polarity interval (CG3n of Szurlies et al., 2003; N1 of De Kock and Kirschvink, 2004; Ward et al., 2005; Fig. 10).

Further constraint for the continental PTB is provided by carbon isotope stratigraphy. Both, the last occurrence of *Dicynodon* (Karoo...
B. Fm = Bellerophon Formation, T = Tesero Oolite, A = Andraz Horizon, CHANGH. = Changhsingian.

In the CEB, the base of the Buntsandstein is characterized by a marked palynofloral turnover, from pollen-dominated assemblages of the Zechstein, with Permian markers such as {\em Lueckisporites} sp. and {\em Vittatina} sp. to spore-dominated assemblages within the Buntsandstein, with typical Triassic forms, such as {\em bladispora} and {\em Vittatina} sp. (Kürschner and Herngreen, 2010 and references therein). Besides, the onset of the Buntsandstein is indicated by a strong increase in humidity and freshwater discharge, resulting in an increased influx of sands into the CEB (e.g. Best, 1989) transported mainly by braided river systems. This distinct climatic change was accompanied by a major shift in sediment sources and transport directions (Bachmann and Kozur, 2004; Hug and Gaupp, 2006). Such radical change in depositional environment toward braided river systems is also known from other possibly coeval end-Permian continental records (Michaelsen, 2002; Ward et al., 2000), probably indicating a decrease in the coherence of riverbank sediments after a vegetation gap due to a terrestrial extinction event (Sephton et al., 2009). This major sediment provenance change and the palynofloral turnover at the base of the Buntsandstein constitute important proxies for the terrestrial extinction event, which falls within the lowermost part of CG3n. Such a negative carbon isotope shift is a well-documented feature approximately at the PTB in both marine and continental environments (Korte and Kozur, 2010 and references therein). It falls within the lowermost part of a thick normal magnetozone and postdates the extinction event (Korte and Kozur, 2010).

In virtually all studied sections, the PTB falls within a thick normal magnetozone (e.g. Fig. 10). However, the Shangsi (China) record reveals a further thin reverse magnetozone somewhat above the \textit{H. parvus}-calibrated boundary (Glen et al., 2009 and references therein). Such a reverse interval occurs probably at about this level in the Deltadalen section on Svalbard (Hounslow et al., 2008). Consequently, Hounslow et al. (2008) proposed CG3n to be equivalent to only the lower LT1n and CG4n to the upper LT1n, what is at odds with previous cyclo-magnetostratigraphic correlation of the Buntsandstein (Szurlies, 2007). However, a thin reverse polarity interval postdating the PTB is not well-defined elsewhere or even absent in most PTB sections (Fig. 10). For the Southern Alps composite, Hounslow et al. (2008) therefore propose the lower LT1n to be removed by erosion at the basal Werfen Formation unconformity. However, the proposed unconformity (Farabegoli et al., 2007) has recently been denied by other authors (Brandner et al., 2009; cf. discussion in Horacek et al., 2010). Brandner et al. (2009) correlate the current event (i.e., the marine extinction event) in the Southern Alps with the major provenance change at the base of the Buntsandstein. Moreover, a revision of the erroneously misplaced current event by Scholger et al. (2000), placed this event 30 cm higher within the lower Tesero Oolite of the Werfen Formation has recently been closed, showing a further thin normal magnetozone that straddles the boundary between CG4n and CG5n to the upper LT1n, what is at odds with previous cyclo-magnetostratigraphic correlation of the Buntsandstein (Szurlies, 2007).
correlation (Metcalfe and Nicoll, 2007; Szurlej et al., 2003; Fig. 10). However, we have currently no explanation for the presence of a further thin reverse interval splitting this thick normal magnetozone in the Shangsi section and arguably in the Deltadalen section and its absence in virtually all the other PTB sections. For the Deltadalen section, we consider the correlation of magnetozones Vh2 with CG2n from the Central Europe composite as more likely (Fig. 10).

Magnetostatigraphic data from the Siberian Traps reveal a simple polarity pattern comprising a thin reverse, an overlying thick normal and a following reverse magnetozone (Gurevitch et al., 1995) that spans most of the Siberian Traps and may be equivalent to the polarity pattern across the PTB, thus predating the extinction event (e.g. Glen et al., 2009). The duration of the main phase of Siberian flood basin volcanism has been estimated by radio-isotopic ages as less than 1 Ma (Kamo et al., 2003). The Buntsandstein cyclostratigraphy offers good potential for dating events around the PTB or the length of magnetic polarity intervals, such as the thick normal magnetozone across the PTB. Szurlej (2007) estimated c. 0.7 Ma for CG3n and further c. 0.1 Ma for each of CG2r and CG3r. This gives a duration of c. 0.9 Ma for the assumed coeval main phase of Siberian flood basin volcanism. Recently, the Buntsandstein cyclostratigraphy has been questioned by Hounslow and Muttoni (2010) for two main reasons. Firstly, Szurlej (2007) obtained lower numbers of cycles for some Buntsandstein formations then other authors (Geluk and Röhl, 1997; Röhl, 1993) that according to Hounslow and Muttoni (2010) may reflect a non-basin central focus of Szurlej (2007). However, this apparent discrepancy in cycle numbers is because of different stratigraphic approaches (cf. section 2). For the Calvörde Formation all authors derived 10 cycles (Geluk and Röhl, 1997; Menning et al., 2005; Paul and Klarr, 1988; Röhl, 1993; Szurlej, 1999; Szurlej et al., 2003), giving duration of c. 1 Ma for this formation. Secondly, Hounslow and Muttoni (2010) pointed out that the thin reverse interval CG3r is too short with a length of c. 50 ka, because it spans 1.5 ammonoid zones. Apart from the fact that biozones are far from being time-indicative, CG3r spans at least c. 100 ka. Following the assumption that the base of the Olenekian is located within the upper to uppermost Lower Buntsandstein (e.g. Bachmann and Kozur, 2004), the Buntsandstein cyclostratigraphy gives duration of 1.2 to 1.8 Ma for the Induan stage.

According to Mundil et al. (2010) and Galfetti et al. (2007) the Induan spans c. 1.0 Ma and 1.4 Ma, respectively, which is in accordance with c. 1.5 Ma obtained from Buntsandstein cyclostratigraphy (Szurlej, 2007). Using time-series analysis of the Tesero to Seis members of the Werfen Formation, Rampino et al. (2000) received duration of the Induan of c. 1.4 to 1.6 Ma. However, there are uncertainties related to the final position of the Induan–Olenekian boundary within the marine and continental sections, which has an effect on duration of the Induan and Olenekian (cf. Tong and Zhao, 2011).

8. Conclusions

The paleomagnetic signal from about 90% of the specimens from the c. 100 m thick Everdingen-1 core preserves a Late Permian–Early Triassic dual-polarity magnetization. The consistent lateral correlation of sedimentary cycles and magnetozones on a scale of some 500 km supports an early acquisition of the ChRM in both, the magnetite-bearing gray sediments and the hematite-bearing red-brown lithologies. The further presence of a VRM enables re-orientation of ChRM directions, giving a mean paleomagnetic direction of D = 17.7°, I = 27.2° (α95 = 8°; Fig. 6). This represents a paleolatitude of about 14.4°N, which is consistent with results from previous coeval sedimentary successions in Central Europe (Nawrocki, 1997; Szurlej et al., 2003). However, because of inclination shallowing in these sedimentary rocks, the derived paleolatitude is most probably somewhat to low (see also Dominguez et al., 2011). From the Everdingen-1 core, in all, seven magnetic polarity intervals (EV1n to EV4n) and further five submagnetozones (EV1n.1r to EV3r.1n) have been delineated.

The two main outcomes of the integrated cyclo-magnetostratigraphy from the Everdingen-1 core are: (a) the verification of the geomagnetic polarity record from Central Germany, and (b) the confirmation of the hypothesis of nearly synchronous base-level cycles. The terrestrial extinction event is placed at the base of the Buntsandstein. It is indicated by a palynofloral turnover and a major provenance change. Tied to palynology, conchostracan biostratigraphy, carbon isotope data, and cyclostratigraphy, the magnetic polarity sequence across the PTB provides a reliable marine to non-marine correlation. A transition from a thin reverse to a thick normal magnetozone that predates the biostratigraphic PTB represents a prime marker for global correlation that enables to correlate the Buntsandstein cyclostratigraphy with the marine Triassic stages. The continental PTB is located within the Gray Bed Interval of cycle 2 of the Lower Buntsandstein.

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