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Late Permian–Middle Triassic magnetostratigraphy in North China and its implications for terrestrial-marine correlations

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Abstract

A detailed magnetostratigraphic study, linked to a new latest Permian U–Pb ID-TIMS age, was undertaken on the continental Shichuanhe section (SCH) in North China in order to provide a magnetic polarity scale for the Late Permian–early Middle Triassic interval. Tilt-corrected mean directions of the characteristic remanent magnetization pass the reversal test and correspond to a site paleolatitude of 18.1°N during the Early Triassic, consistent with previous results from the

North China Block. The magnetostratigraphy shows close similarity with previous studies, allowing interregional correlations with both marine and non-marine records. Normal magnetozone SCH3n, constrained by an absolute age of 252.21 ± 0.15 Ma from an ash bed 3.5 m below its base, is unambiguously correlated to the earliest Triassic normal magnetochron LT1n. Our newly established magnetostratigraphic framework and published carbon-isotope chemostratigraphy, indicate that the Permian–Triassic Boundary is ca. 8 m above the base of SCH3n (within the middle part of the Sunjiagou Formation) at SCH. The overlying reverse polarity dominated interval (SCH3r–SCH5r) ranges to the middle Liujiagou Formation, and straddles an interval from the mid-Griesbachian to mid-Smithian. The base of the Olenekian is provisionally located in the lower part of the Liujiagou Formation, near the base of magnetozone SCH5n. The succeeding thick normal magnetozone SCH6n persists into the upper Heshanggou Formation, with the inferred Smithian–Spathian boundary located in the upper part of the Liujiagou Formation. The transition from reverse magnetozone SCH6r to the overlying normal magnetozone SCH7n, coincides with a clear erosional contact with the base of the Ermaying Formation. Consequently, magnetozone SCH7n is matched to the Early Anisian magnetochron MT3n, with the Olenekian–Anisian boundary interval missing. Our new timescale provides additional magnetostratigraphic constraints on the timing of the terrestrial ecological crisis in North China, which is found to lie within reverse magnetozone SCH2r (equivalent with reverse magnetochron LP3r), a level some 270 ± 150 kyrs before the main marine extinction, that falls in the overlying normal magnetochron LT1n.

Key words: Magnetostratigraphy, marine-terrestrial correlation, ID-TIMS age, Permo–Triassic terrestrial extinction

1. Introduction

The Late Permian–Middle Triassic is a key interval in the history of life, which is marked by the Permian–Triassic mass extinction (PTME) at about 252 Ma, the most severe extinction of the Phanerozoic (e.g., Wignall, 2015; Benton, 2018). Harsh environmental conditions persisted through the Early Triassic (e.g., Payne et al., 2004; Sun et al., 2012; Wu et al., 2021), resulting in a delayed recovery of more than 5 Myrs after the PTME (Chen and Benton, 2012), with marine ecosystem recovery still underway in the latest Triassic (Song et al., 2018). Our understanding of the timing, magnitude and duration of the PTME and its aftermath are largely derived from marine records because they are stratigraphically most complete, can be more easily correlated using biostratigraphy and are better constrained by absolute ages (Chen and Benton, 2012; Burgess et al., 2014).

In contrast, a full understanding of the PTME and ecosystem restoration on land is more challenging, due to a less-than-continuous sedimentary record and typically rather poor age constraints. Recent studies have shed light on the timing of the terrestrial ecological crisis, which is suggested to have occurred anywhere between 50–640 kyr earlier than marine extinctions, with substantial variation of timing amongst continental basins (Fielding et al., 2019, 2021; Chu et al., 2020; Gastaldo et al., 2020). Despite these advances it's still difficult to study the relative timing of biotic and environmental events on land because a globally unified fine-scale chronostratigraphy is not available. Furthermore, causal links between unusual Early Triassic sedimentary structures, such as microbial mats and possible hurricanes, and abnormal environmental conditions are challenging to understand (Chu et al., 2017; Ji et al., 2021). An improved age framework for the Permo–Triassic and the Early Triassic, using magnetostratigraphy, is required for a better appreciation of the global evolution in both terrestrial and marine settings.

The global and nearly-synchronous nature of geomagnetic polarity boundaries have made magnetostratigraphy an important approach for precise correlation between successions, a tool which is independent of facies control. Significant progress has been achieved in establishing a comprehensive time-calibrated magnetostratigraphy during the Permian and Triassic, that provides a scale for interregional correlations (e.g., Steiner, 2006; Hounslow and Muttoni, 2010; Hounslow and Balabanov, 2018). A reliable Permo–Triassic Boundary (PTB) magnetostratigraphy has also been constructed in continental successions, including in Europe and eastern Australia (Szurlies, 2013; Belica, 2017), but a detailed continental-succession based magnetic stratigraphy through the entire Early Triassic is only available in the Central European Basin (Szurlies, 2007). In North China, magnetostratigraphic study of the Late Permian to Middle Triassic has rarely been undertaken and a detailed regional polarity reversal pattern is not available due to the coarse sampling and a lack of specific correlation anchors (e.g., using biostratigraphy or radioisotopic ages). Thus, regional lithostratigraphic templates have been widely used for correlation (Ma et al., 1992; Embleton et al., 1996).

We present a high resolution magnetostratigraphy from the Upper Permian through the Lower Triassic to the earliest Anisian (Middle Triassic) in central North China. A new U-Pb CA-ID-TIMS (chemical abrasion isotope dilution thermal ionization mass spectrometry) age from an ash bed within the middle part of the Sunjiagou Formation provides a geochronological anchor for our new magnetostratigraphic framework. Coupled to available biostratigraphy and carbon-isotope chemostratigraphy, our multi-disciplinary approaches enable us to establish a detailed Late Permian to the earliest Middle Triassic timescale in North China, to locate the PTB at Shichuanhe section and to understand the relative timing of the terrestrial PTME in North China and the marine extinctions.

2. Geological setting

The Ordos Basin was a large depocenter that formed part of the intracratonic central North China Basin, located at 10–20°N paleolatitude during the Paleozoic–Mesozoic transition, which was bordered by the Liupan-Helan-Yin-Lvliang uplands to the west and southeast and passed into further terrestrial basins to the east (Huang et al., 2018; Meng et al., 2019; Fig. 1A). In North China, sedimentation was interrupted by a major hiatus that began in the Middle Ordovician due to regional uplift, but restarted in the Pennsylvanian, with alternating marine and coal-rich terrestrial sequences (Yang et al., 2017). During the Permian the North China block was largely comprised of terrestrial systems, in which coal-forming environments ceased in the upper Shihhotse Formation. The succeeding Permian–Triassic Shiqianfeng Group is characterized by red beds, which contains rare body fossils that are inadequate to establish a detailed biostratigraphy (Tong et al., 2019). This interval is also poorly dated apart from few LA-ICP-MS ages obtained from detrital zircons (Zhu et al., 2019; Fig. 1C). However, a mixed terrestrial spinicaudatan-marine bivalve assemblage in the southern Ordos Basin, allows identification of the Permian–Triassic transitional interval at SCH (Chu et al., 2019).

The Shiqianfeng Group is divided, from base to top, into the Sunjiagou, Liujiagou and Heshanggou formations, and is overlain by the Ermaying Formation (Fig. 1C). The Sunjiagou Formation consists of green sandstone with interbedded mudstone in the lower part, containing a

Late Permian *Ullmannia bronnii-Pseudovoltzia* cf. *libeana* flora assemblage (Lu et al., 2020), and records fluvial channels and floodplain deposition (Zhu et al., 2019, 2020). However, this unit is poorly exposed at SCH and thus, the nature of the boundary with underlying strata is unclear. The overlying portion is characterized by a color change to a succession of dominantly red siltstone and minor sandstone horizons, with several paleosol horizons that formed on a floodplain (Yu et al., 2022; Zhu et al., 2020). This is followed by alternating thin beds of fine-grained sandstone, massive mudstone and marlstone, interpreted to be restricted coastal facies (Supplementary Data A). The age of the Sunjiagou Formation is somewhat controversial, with the supposed PTB, defined by tetrapods, organic carbon isotopes and a mixed marine-terrestrial biota, occurring somewhere between the middle to top of the Sunjiagou Formation (Chu et al., 2019; Zhu et al., 2019, 2020; Lu et al., 2020; Wu et al., 2020).

The mud-rich floodplain and coastal facies of the Sunjiagou Formation were replaced by the fluvial and shallow lacustrine-dominated, sandstone-rich Liujiagou Formation (Zhu et al., 2020; Ji et al., 2021). Conglomeratic intraclasts, concentrically-laminated concretions and microbial mats are found within the lacustrine facies of the Liujiagou Formation (Chu et al., 2017; Ji et al., 2021). Aeolian deposits are also reported in the northern part of the basin (Zhu et al., 2020). The Liujiagou Formation contains very rare fossils, with a few plants in the middle to upper parts attributed to the *Pleuromeia jiaochengensis* assemblage (Wang and Wang, 1990). The sharp base of the Liujiagou Formation has traditionally been considered conformable, although a disconformity has also been suggested (IGCAGS, 1980).

The overlying Heshanggou Formation is marked by a change to dominantly dark red mudstone and siltstone, which rest conformably on the underlying strata. Laterally persistent sandstone becomes prevalent at higher level and well-developed paleosols occur throughout the formation (Yu et al., 2022). Overbank and shallow lacustrine facies are considered to dominate deposition of the Heshanggou Formation (Zhu et al., 2020). Diverse fossils (e.g., vertebrates, ostracods and sporomorphs) indicate a late Early Triassic age (IGCAGS, 1980).

The conformably-overlying Ermaying Formation is characterized by massive green fluvial sandstone with interbedded green and red mudstone and conglomerate (IGCAGS, 1980). The basal sandstone of the Ermaying Formation at SCH contains imbricated pebbles and large mud clasts, implying an erosional contact and a possible hiatus (Supplementary Fig. S2). A *Parakannemeyeria* fauna and an U-Pb ID-TIMS age of 243.528 ± 0.069 Ma suggest the Ermaying Formation is Anisian (Middle Triassic) in age (Liu et al., 2018).

3. Materials and methods

3.1 Paleomagnetic methods and analysis

Magnetostratigraphic, sedimentological and geochronological analyses were undertaken at the Shichuanhe section (GPS: 35.03°N, 108.88°E), located near Tongchuan, 90 km north of Xi'an City, Shaanxi Province. Magnetostratigraphic samples were collected throughout the section, using both hand samples, oriented in situ by a magnetic compass, and oriented core-plugs made by a portable field drill. In total, 272 hand samples from fine-grained mudstones and marlstones, and 39 core plugs from sandstones, were collected, covering an interval spanning the inferred Late Permian to basal Middle Triassic (Supplementary Fig. S1). Sample spacing ranges from 0.5 to 2.5 m, depending on suitable lithologies. In the laboratory, 56 hand samples were excluded from paleomagnetic studies because they were too fractured and could not be prepared into specimens. Each of the remaining samples was cut into at least two 2 cm cubes or 2 cm long cylinders for paleomagnetic measurements.

All specimens were subjected to stepwise thermal demagnetization using 16–19 steps (up to 680°C) in a Magnetic Measurements ASC TD48 thermal specimen demagnetizer. Each heating was followed by cooling in a residual magnetic field ≤20 nT. Specimens were housed in a magnetically shielded room with ambient magnetic field ≤300 nT and measured on a 2G Enterprises 755-4K U-Channel magnetometer at the China University of Geosciences (Wuhan), China. Characteristic remanent magnetization directions (ChRMs) were isolated using principal component analysis, as implemented in the PuffinPlot software (Lurcock and Wilson, 2012). Both linear trajectory fits and great circles (remagnetization circles) were used in defining the paleomagnetic behaviors. The PMAGTOOL v5. software (Hounslow, 2006) was also used for calculation of mean directions, virtual geomagnetic poles (VGP) and performing the reversal tests. The isolated ChRM directions were classified into different categories based on their demagnetization behavior and quality, similar to the method of Hounslow et al. (2008). ChRMs displaying clear linearity or exhibiting great-circle trends were categorized into S-type or T-type behaviors, respectively. For S-type data, specimens were subdivided into three quality levels (S1, S2 and S3) based on the visual noisiness and length of colinear points, with S1 showing best quality and S3 the lowest quality. T-type data were also reclassified into three levels (T1, T2 and T3) according to the visual length and scatter of the demagnetization points about the great circle, with T1 having the best-quality great circle trend, which terminated near the expected Triassic direction, and T3 for the poorer results. Specimen demagnetization results were interpreted with a polarity quality rating on the basis of a semi-subjective judgment (e.g., for normal polarity, N = best quality, N? = intermediate quality and N??

= poorest quality). Specimens without an interpreted Permian–Triassic magnetizations are labelled as X quality. Poorer quality data (e.g., S3 and T3 demagnetization behaviors) were not used for mean direction calculations, but were used for VGP latitude calculations.

Representative specimens from green and red lithologies were selected to determine the main magnetic remanence carriers using magnetic susceptibility versus temperature experiments (K-T curves). Specimens were heated up to 700℃ in air at 10°C/min, and subsequently cooled at the same rate to room temperature. The K-T curves were measured using an AGICO, MFK1-FA Kappabridge, at the China University of Geosciences (Wuhan).

3.2 U-Pb geochronology

Zircons were separated from a ~1 cm thick ash bed in the middle part of the Sunjiagou Formation at SCH. Forty extracted zircons were initially analyzed by U-Pb LA-ICP-MS (Laser Ablation Inductively Coupled Plasma Mass Spectrometry) at the Mineral Rock Laboratory, Hubei Province Geological Experimental Testing Center, with an additional seven zircons analyzed by the U-Pb CA-ID-TIMS method at the Massachusetts Institute of Technology (MIT) Isotope Laboratory, USA. Details of U-Pb analytical methods are provided in Supplementary Data A.

Complete U-Pb isotopic data are given in Supplementary Data C. Calculated weighted mean ^{206}Pb/^{238}U ages are reported at 95% confidence interval and for the CA-ID-TIMS analyses is reported in the format ±x/y/z Ma, where x is the analytical (internal) uncertainty only, y includes the additional tracer calibration error and z includes the latter as well as the ^{238}U decay constant error of Jaffey et al. (1971).

4. Results

4.1 Rock magnetism

Susceptibility of most of the red specimens consistently reduces at around 700°C, which is attributed to hematite. One sample exhibits a large rise in susceptibility at 450°C (from thermal alteration), but subsequently decreases at 585°C and 680°C, suggesting the presence of both magnetite and hematite. The susceptibility of green lithologies generally shows curve inflexions at around 585°C, corresponding to the Curie temperature of magnetite. Therefore, magnetite and hematite appear to be the main magnetic remanence carriers of the magnetization in green and red sediments, respectively (Supplementary Fig. S4). A decline in susceptibility below 100°C in many samples may be due to goethite. The magnetization carriers are consistent with the thermal demagnetization behavior of the natural remanent magnetization (NRM) and previous investigations (Yang et al., 1991).

4.2 U-Pb geochronology

Fifteen grains from forty zircons analyzed by LA-ICP-MS that are less than 10% discordant, yield a weighted mean ages $^{206}Pb/^{238}U$ age of 252.9 ± 2.1 Ma (Supplementary Fig. S5 and Supplementary data C). Five CA-ID-TIMS analyses yielded overlapping $^{206}Pb/^{238}U$ dates, with a weighted mean of 252.21 ± 0.15/0.19/0.33 Ma and a mean square of weighted deviates (MSWD) of 0.45 (Fig. 5). One CA-ID-TIMS analysis produced a significantly younger Jurassic age (157.79 ± 0.74 Ma), which is in conflict with regional stratigraphy and LA-ICP-MS results, and is therefore rejected (see Supplementary Data A). The above CA-ID-TIMS weighted mean date serves as the best estimate for the (maximum) age of deposition of the corresponding ash bed.

4.3 Paleomagnetic properties

Commonly, the untreated NRM intensities range between 0.1–10 mA/m, with a few exceptions up to 30 mA/m (Fig. 4 and Supplementary Fig. S3). There was considerable variation in demagnetization behavior between different lithologies but usually, specimens showed two components, a low-temperature component (LTC) and a high-temperature component (HTC), which could be isolated during thermal demagnetization. More details about the demagnetization behavior and polarity interpretations are in Supplementary files A and B.

(a) A LTC was obtained in most specimens, which generally unblocked between NRM to ca. 200–450℃ (Fig. 2B–2E, 2H–2I). This LTC is generally northerly directed with a relatively steep inclination in geographic coordinates (Fisher mean of D=355.4°, I=55.3°, α95=5.1°, n=244; Fig. 3A). The direction is comparable to the present-day field at the site (D=355.9°, I=54.1°, World Magnetic Model 2019–2024), which is inferred to be a recently acquired or more likely a Brunhes-age overprint.

(b) The HTC is isolated by both line fit and great circle fit (Fig. 2). Red and some green colored sediments fully demagnetized at 600–680℃, indicating hematite is the main carrier of the NRM (Fig. 2A–2E). A third of the greenish specimens became directionally erratic above 600℃, suggesting hematite is less important in these specimens (Fig. 2H). Some 55% of specimens display stable endpoints with a linear segment towards the origin in orthogonal projections (i.e., S-type; Fig. 2A–2F), and 87% of line-fit results yield acceptable quality (S1 and S2) that could be used in a mean direction calculation (see Supplementary Table S1 for details). After tilt correction the mean normal-polarity HTC direction is concentrated in the NW with shallow positive inclination

(D=325.0°, I=34.0°, α_{95}=2.9°, n=93), and the mean reverse-polarity HTC direction is D=146.4°, I=-28.5°, (α_{95}=4.9°, n=31; Fig. 3B). The site paleolatitude of all the data converted to normal polarity is 17.7°N, regardless of potential inclination shallowing produced during later compaction (Table 1). Paleomagnetic mean directions pass the reversal test with class Rb (McFadden and McElhinny, 1990). A fold test is not possible due to the shallow bedding dips in the section.

(c) For the HTC, 37% of samples yield a great circle trend toward the characteristic directions. These were used for great circle fits to determine the unresolved directions (T-type; Fig. 2G–2I). About three-quarters of the T-type data display scatter terminating at around the observed mean S-class direction. T1 and T2 quality great circles were used in the mean direction calculation. A combination of line-fit ChRM directions and great circle poles (Fig. 3C), using the method of McFadden and McElhinny (1988), gave a combined mean direction for the HTC of D=325.6°, I=33.3° (α_{95}=1.9°, n=197), corresponding to a paleopole at 55.2°N, 359.0°E (dp/dm=1.23/2.16) and site paleolatitude of 18.1°N (Table 1). The combined mean directions have a positive reversal test with class Ra (McFadden and McElhinny, 1990).

The antipodal nature of the normal- and reverse-polarity subsets (Fig. 3B) and the statistically similar directions compared to previously published Lower Triassic direction in nearby regions (Yang et al., 1991; Ma et al., 1992; Table 1), suggest that the magnetization is primary and obtained near the time of deposition.

4.4 Magnetostratigraphy

The line-fit ChRM directions were converted to virtual geomagnetic pole (VGP) latitude using the combined great circle-fixed point mean direction as the reference pole. VGP latitudes reveal the polarity changes in the section with positive/negative values indicating normal/reverse polarity (Fig. 4). For specimens that display great circle trends, the point on the fitted great circle nearest the combined mean direction was used to calculate the VGP latitude (Hounslow et al., 2008). Major magnetozone normal and reverse couplets are labelled upward from the base of the section using the prefix SCH (Shichuanhe), with polarity magnetozones pairs comprising a lower predominantly normal-polarity ("N") and an overlying reversed-polarity "R". Intervals denoted by lowest quality and poorly defined directions (e.g., S3, T3 and X), are indicated with a gray bar to display uncertainly. Seven main magnetozones, from SCH1 to SCH7, are recognized based on at least three successive specimens with consistent polarity. Also present are a number of tentative submagnetozones (less than full width bars marked as .1r, .1n etc.), defined by a single specimen with acceptable quality (Fig. 4).

5. Discussion

5.1 Permian–Triassic boundary magnetostratigraphy in North China

The Permian–Triassic Boundary occurs in normal magnetochron LT1n, a position which has been well documented in both marine and non-marine successions (Hounslow and Balabanov, 2018 and references therein). At the Induan Global Boundary Stratotype Section and Point (GSSP) in Meishan, South China, the base of the Triassic is marked by the first occurrence (FO) of the conodont *Hindeodus parvus* in Bed 27c (Yin et al., 2001). However, magnetostratigraphic studies from Meishan display poor inter-study consistency, thus the exact relationship between the FO of *H. parvus* and magnetozones are unclear in the GSSP (Hounslow and Muttoni, 2010; Zhang et al., 2021). At the Shangsi section, the base of magnetochron LT1n coincides with the base of the

Feixianguan Formation (base of bed 28), within the *Clarkina meishanensis* conodont zone, and was estimated at 252.23 ± 0.08 Ma using a Monte Carlo statistical method (Yuan et al., 2019; Fig. 6 and 7). This is similar to the 252.2 ± 0.23 Ma age for the base of LT1n estimated using Bayesian methods in Hounslow and Balabanov (2018). Hence, at the SCH section, magnetozone SCH3n is equivalent to magnetochron LT1n, based on our new age of 252.21 ± 0.15 Ma obtained from an ash bed 3.5 m below the base of SCH3n (Fig. 6). Given the latest calibration of the PTB at 251.902 ± 0.024 Ma based on U-Pb CA-ID-TIMS geochronology (Burgess et al., 2014), our latest Changhsingian date provides independent, radioisotopic evidence to establish a robust PTB magnetostratigraphic framework for North China. The comparative age and the polarity stratigraphy indicate that the base of LT1n is a synchronous marker useful for global correlation, occurring ca. 0.3 Ma prior to the PTB (Fig. 7).

The correlation is also supported by biostratigraphic evidence from the mixed marine-terrestrial biota found at SCH. This fauna consists of a frashwater spinicaudatan (conchostracan) *Euestheria gutta-Magniestheria mangaliensis-Palaeolimnadiopsis vilujensis* assemblage and the marine bivalve *Pteria variabilis*, which is found about 1 m above the base of magnetozone SCH3n. This fauna is akin to the mixed terrestrial-marine biota in South China, which appears immediately after the demise of the Late Permian *Gigantopteris* flora (Chu et al., 2019). The *Euestheria gutta* assemblage with cooccurring marine bivalves has been considered an important marker for the Permian–Triassic transitional beds (Chu et al., 2019). A similar spinicaudatan fauna (*Euestheria gutta-Palaeolimnadiopsis vilujensis* assemblage) was also recognized in the lower Buntsandstein coeval with the Central German Composite magnetozone interval CG3n–4n, which is equivalent to magnetochron LT1n (Szurlies, 2007, 2013; Scholze et al., 2017; Fig. 6).

Compiled data from many marine carbonate successions have indicated a major minimum in $\delta^{13}C_{carb}$ around the PTB (e.g., Korte and Kozur, 2010), falling within the lower part of LT1n (Shen et al., 2019; Zhang et al., 2021). Such carbon isotopic excursions have also been suggested to be nearly synchronous with the changes in $\delta^{13}C_{org}$ in terrestrial facies (Wu et al., 2021). Thus, by combining the magnetostratigraphy and geochronology with the organic carbon isotope curve (Wu et al., 2020), the PTB at SCH is estimated to occur at a level about 8 m higher than the base of magnetozone SCH3n, around the largest negative excursion in $\delta^{13}C_{org}$, within the upper part of the middle Sunjiagou Formation (Fig. 7). Additionally, our new magnetostratigraphic data also allows a better constraint for the onset of the carbon isotope excursion (CIE) during the latest Permian. This was previously suggested to be located at ~27 m below the base of SCH3n on the basis of purely chemostratigraphic consideration (Wu et al., 2020); it is now placed ~3 m below the base of SCH3n, within the upper part of magnetozone SCH2r (i.e., magnetochron LP3r; Fig. 7).

Our results are also in good agreement with the age-constrained magnetostratigraphy from the Sydney Basin, eastern Australia. The Permian–Triassic transition of the Sydney Basin contains three normal magnetozones, with normal magnetozone C2n first detected in the base of the Coalcliff Sandstone (Belica, 2017; Fig. 7). Radioisotopic ages from the basal Bulli Coal (Metcalfe et al., 2015) and basal Coalcliff Sandstone (Fielding et al., 2019, 2021) allow a robust correlation of magnetozone C2n with LT1n. However, the position of the base of magnetozone C2n is unclear, since there is ~3.5 m unsampled interval that includes the underlying Bulli Coal bed (Fig. 7).

The Permian–Triassic magnetostratigraphy of the Karoo Basin, South Africa is equivocal. The integrated magnetic polarity stratigraphy of Ward et al. (2005) showed two reverse-to-normal couplets. The longer normal magnetozone of the lower couplet, has its base slightly preceding the vertebrate turnover, with an associated negative $\delta^{13}C_{carb}$ excursion, which was suggested to be equivalent with magnetochron LT1n. However, this situation has not been confirmed by subsequently studies. The *Daptocephalus–Lystrosaurus* transition is mostly within a normal magnetozone (see summaries in Gastaldo et al., 2021), which is, coupled to a U-Pb ID-TIMS age of 253.48 Ma from ~60 m below the vertebrate-defined PTB and is so considered to be early Changshingian (Gastaldo et al., 2015). This inconsistency could either be due to a local hiatus (Gastaldo et al. 2015) or difficulties in isolating the primary magnetization from Jurassic partial remagnetization (Belica, 2017).

Correlation of magnetozone interval SCH1–SCH2 to the Geomagnetic polarity timescale (GPTS) is not straightforward due to the lack of supporting fossil markers within this interval. Also, intrabasinal correlation with the nearby Hancheng section at this level is difficult owing to infrequent magnetostratigraphic sampling, which defines magnetozone O1 (Ma et al., 1992; Fig. 6). Overall, the relative thickness of magnetozones SCH1n–SCH2r is similar to magnetozone interval CG1n–CG2r in the Central German Composite (Szurlies, 2013; Fig. 6). In the Germanic Basin, magnetozones CG1n and CG2n were correlated to magnetozones IRA1n and IRA2n from the Abadeh section (Gallet et al., 2000; Fig. 6), corresponding to the late Wuchiapingian and early Changhsingian on the basis of the conodonts (*Merrillina divergens* and *Mesogondolella britannica*) and Re-Os dating from the Zechstein successions (Szurlies, 2013; Fig. 6). However, these conodonts occur throughout the Lopingian and do not provide a precise timescale (Henderson and Mei, 2000). Instead, magnetozone CG1n has been correlated to magnetochron LP2n.3n (equivalent to IRA2n), with its upper boundary at ca. 253.2 Ma, within the *Clarkina subcarinata* conodont zone at the Abadeh section and probably within the *C. changxingensis* zone at Shangsi (Hounslow and

Balabanov, 2018). Accordingly, magnetozone SCH1n is tentatively correlated to magnetochron LP2n.3n and SCH2n to LP3n (Fig. 6).

5.2 Lower Triassic magnetostratigraphy in North China

The two reference polarity scales for the remainder of the Lower Triassic, that from Buntsandstein (Szurlies, 2007, 2013) and the marine composite GPTS (Hounslow and Muttoni, 2010), are generally similar, but show a few differences in number and relative duration of the briefer magnetochrons (Fig. 6). The placement of the Induan–Olenekian Boundary (IOB) in the Buntsandstein composite also has some divergences of interpretation (Szurlies, 2007; Hounslow and Muttoni, 2010). In China, the IOB is informally defined by the FAD of *Novispathodus waageni* s.l. at the West Pingdingshan section, ~2.5 m from the top of reverse magnetozone WP4r and equivalent to the topmost part of magnetochron LT2r (Sun et al., 2009; Fig. 6). The *Densoisporites nejburgii* palynological assemblage from the Middle Buntsandstein, spans the late Dienerian to Smithian, suggesting that the IOB in Central Germany is within the lower part of the Middle Buntsandstein (Kürschner and Herngreen, 2010; Fig. 6), suggesting that CG6n is the equivalent to LT3n in the GPTS.

At SCH, the reverse polarity dominated interval SCH3r–SCH5r is correlated to the dominantly reverse magnetochron interval LT1r–LT4r and CG4r–CG7r, spanning from the mid-Griesbachian to mid-Smithian (Hounslow and Muttoni, 2010; Fig. 6). Correlation to the same lithostratigraphic interval at the Hancheng section reveals much similarity in the number and relative thickness of magnetozones. Crucially there are two major normal polarity magnetozones (SCH4n and SCH5n) with a third tentative normal submagnetozone SCH5r.1n in this interval at SCH, similar to that in the GPTS and Buntsandstein Composite which also have three normal magnetozones. The wide sample spacing at Hancheng probably missed the upper normal polarity magnetozone (SCH5r.1n) seen at SCH (Fig. 6). Overall, the relative thickness of magnetozones in the SCH3r–SCH5r is most similar to the Buntsandstein composite in the CG4r–CG7r interval. Thus, the IOB at SCH is placed at the base of SCH5n in the lower part of the Liujiagou Formation (Fig. 6). However, a hiatus could be present given that there is an abrupt change in depositional environments from the shallow lacustrine facies of the Sunjiagou Formation to the overlying channelized, conglomeratic sandstones of the basal Liujiagou Formation (see Supplementary data A for a sedimentological description). As a result, magnetozone SCH4n could be the equivalent of LT2n–LT3n and SCH5n=LT4n, suggesting that magnetochron LT2r is missing.

Like the underlying magnetozone interval SCH3r–SCH5, the succeeding thick normal SCH6n is more like the CG8n to CG10n interval in the Central German composite, than the marine-based magnetochrons LT5n to LT9n (Fig. 6), which range in age from the mid Smithian to late Spathian (Hounslow and Muttoni, 2010). Four reverse magnetozones within the LT5n–LT9n interval occur in Arctic Canadian and Norwegian sections (Ogg and Steiner, 1991; Hounslow et al., 2008), but their thicknesses differ greatly compared to the equivalent interval in the Central German Composite. Notably, only two major reverse magnetozones were recovered from this interval at the Majiashan section (South China; Li et al., 2016; Fig. 6). At Majiashan, the cyclostratigraphically-calibrated polarity stratigraphy can be readily matched with the Central German Composite, providing important constraints for marine to non-marine correlations (Li et al., 2016; Fig. 6). No major reverse polarity magnetozones were occurred within SCH6n, but three tentative submagnetozones SCH6n.1r–SCH6n.3r were detected (Fig. 4). However, in the nearby Hancheng section, reverse magnetozones O4r and O5r, straddling the Liujiagou and Heshanggou formations, were recognized (Ma et al., 1992; Fig. 6). The absence of such major reverse magnetozones at SCH could be related to local erosional loss. Sparse flora assigned to the *Pleuromeia sternbergii* assemblage in SCH6n interval suggests an Olenekian age (Wang and Wang, 1990), consistent with the magnetostratigraphic results. The Smithian–Spathian transition is marked by consistent normal polarity in the Arctic sections of Canada and Norway, and in South China. This interval is likely condensed in the upper part of magnetochron LT6n due to a major boreal transgression (Ogg and Steiner, 1991; Hounslow et al., 2008; Li et al., 2016). The well-defined reverse magnetozones O4r–O5r in Hancheng are probably equivalent to magnetozones MJ1r–MJ2r at Majiashan and LT6r–LT8r, CG8r–CG9n.2r in the reference sections (marked with blue correlated interval in Fig. 6; Li et al., 2016). Hence the base of the Spathian is interpreted to be in the middle of SCH6n, in the upper Liujiagou Formation at SCH (Fig. 6).

Magnetozone SCH6r represents the late Spathian magnetochron LT9r and CG10r from the Buntsandstein (Fig. 6). This late Spathian reverse magnetochron has been widely recognized and contains at least one normal submagnetochron (Hounslow and Muttoni, 2010). Only normal polarity is found in the overlying Ermaying Formation (SCH7n or upper part of O6n) and is likely correlative to MT3n of the early Anisian (Fig. 6). The formational boundary is represented by a distinct sedimentary facies switch: the conglomeratic fluvial sandstones of the basal Ermaying Formation resting with erosional contact on the underlying red, siltstone-dominated lacustrine facies of the Heshanggou Formation (Supplementary Fig. S1). The absence of a magnetozone equivalent to SCH6r in Hancheng is likely due to removal of the upper most Spathian LT9r. The brief magnetochrons MT1–MT 2 of the GPTS, which characterize the Olenekian–Anisian transition, appear to be missing in many Chinese sections, and in other continental successions (Hounslow and Muttoni, 2010). The occurrence of the *Sinokannemeyeria* fauna and a CA-ID-TIMS U-Pb age (243.528 ± 0.069 Ma), unequivocally place the Ermaying Formation within the Middle Triassic (Liu et al., 2018). Moreover, a diverse spinicaudatan *Protimonocarina-Euestheria* assemblage found in the lowermost part of the Ermaying Formation also indicates an early Middle Triassic age (Wu, 1991). Accordingly, the base of the Anisian is placed at the hiatus between the Heshanggou and Ermaying formations, with magnetochons MT1 and MT2 being removed at the hiatus.

5.3 Magnetostratigraphic implications for the timing of the end-Permian terrestrial crisis in North China

The Permian–Triassic GSSP section at Meishan is thought to record two pulses of marine biotic extinctions (Song et al., 2013) at 251.941 ± 0.037 Ma and 251.880 ± 0.031 Ma (Burgess et al., 2014), all within the lower part of LT1n and its equivalents (Zhang et al., 2021; Fig. 7). At Shangsi, the distinctive changeover of conodonts from *Clarkina*-dominated to *Hindeodus*-dominated faunas (FO of *Hindeodus changxingensis*) marks the extinction interval, starting in bed 28a, within the lower part of magnetochron LT1n (Metcalfe et al., 2007; Glen et al., 2009; Yuan et al., 2019; Fig. 7).

The timing of the terrestrial ecological crisis has been constrained by absolute ages or high-resolution chemostratigraphy (e.g., Fielding et al., 2019, 2021; Chu et al., 2020; Gastaldo et al., 2020). Detailed sedimentological investigations in the Sydney Basin (eastern Australia), have demonstrated that the Permian–Triassic transitional sequences are stratigraphically complete, and record the disappearance of a *Glossopteris* flora within the top of the Bulli Coal (Fielding et al., 2019, 2021). This floral extinction occurred ~160–600 kyrs before the marine biotic crisis, according to several ID-TIMS ages from the base of the Bulli Coal and the basal Coalcliff Sandstone (Fielding et al., 2019, 2021). However, the relationship between the extinction interval and magnetic polarity cannot be precisely confirmed owing to the sampling gap in the coal bed (Fig. 7).

In North China, the collapse of terrestrial palaeofloras was marked by the extinction of approximately 54% of plant genera within the Sunjiagou Formation (Chu et al. 2019). This floral extinction predated the latest Permian negative carbon-isotope excursion (Wu et al., 2020), and falls in magnetozone SCH2r (equivalent to magnetochron LP3r, immediately below LT1n; Fig. 7). According to our proposed magnetostratigraphic correlations, corroborated by our new absolute age (252.21 ± 0.15 Ma), the collapse of plant communities therefore occurred about 270 ± 150 kyrs earlier than the marine extinction (Fig. 7). Hence, our new magnetostratigraphic framework provides additional independent evidence that the terrestrial ecological crisis started before the marine mass extinction.

6 Conclusion

A detailed magnetostratigraphic investigation, spanning the early Changhsingian to early Anisian, was undertaken at the continental Shichuanhe section, yielding the first detailed Early Triassic non-marine timescale in North China. Results from the ~300 m thick red-bed dominated sequence exhibit dual polarity magnetizations, with the magnetic remanence mainly carried by hematite. The antipodal distributed directions are statistically indistinguishable to those expected in the Early Triassic (Yang et al., 1991), pass the reversal test, and indicate a paleolatitude for the Shichuanhe section of 18.1°N.

Seven main magnetozones are recognized and the relative thickness of magnetozones is comparable to those seen in the composite section from the Buntsandstein in Europe (Fig. 6). A new Late Permian CA-ID-TIMS U-Pb age of 252.21 ± 0.15 Ma, provides direct evidence for the correlation of magnetozone SCH3n at Shichuanhe to magnetochron LT1n of the GPTS. According to our multi-disciplinary approach, the PTB is placed at ca. 8 m above the base of SCH3n, around a minimum in the $\delta^{13}C_{org}$ record, within the middle part of the Sunjiagou Formation. The spinicaudatan fauna within SCH3n is identical to that found in Central Germany within magnetozones CG3n–CG4n (equivalent to LT1n), adding additional paleontological support for our correlations. According to our composite magnetostratigraphy, the base of the Olenekian is placed in the lower part of the Liujiagou Formation (base of SCH5n) and the Smithian–Spathian boundary is placed in the upper part of the Liujiagou Formation. Combined magnetic polarity and sedimentary facies analysis reveal that the Olenekian–Anisian transitional strata are absent.

Establishing a polarity timescale in North China enables us to show that the collapse of the terrestrial ecosystem during the Permian–Triassic transition started within the upper part of magnetochron LP3r, 270 ± 150 kyrs. This was before the onset of the marine crisis, which falls within the base of the overlying normal magnetochron LT1n. The Shichuanhe section preserves a complete terrestrial Permian–Triassic boundary record and is therefore an important reference section for terrestrial and marine stratigraphic correlation.

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Supplementary material

Supplementary files A, B, C

Figures and figure captions

Fig 1. Simplified paleotectonic map of the North China Block and its sedimentary basins (modified from Meng et al., 2019). The red star marks the studied Shichuanhe (SCH) section and the blue point indicates the Hancheng section. Inset B shows a detailed location of the SCH section. C. Permian–Triassic chrono- and lithostratigraphic framework in North China. ID-TIMS age is from Liu et al. (2018), LA-ICP-MS ages are from Zhu et al. (2019). The orange bar represents the studied interval.

Fig 2. Representative demagnetization behaviors with polarity interpretation of specimens from Shichuanhe section. A–F: Principal Component Analysis (PCA), steps used for ChRM line-fits are highlighted in red. A. A largely single component magnetization shows a stable end-point that is close to the expected Early Triassic direction in North China (polarity N; S1 class), Sunjiagou Formation. B. After removal of an eastward LTC below 400°C, specimen shows good linearity to the origin with the ChRM from 630–680℃ steps, polarity N (S1), Heshanggou Formation. C. Similar demagnetization behavior to B, but the ChRM direction is a little deviated from expected direction (N?, S2), Liujiagou Formation. D. Two component magnetizations with the ChRM 630°C to the origin (R, S1). Apparent mid-stable component is from blocking temperature overlap between the ChRM and the LTC, Sunjiagou Formation. E. Specimen shows good linearity above 600°C, but isolated ChRM is deviated from the expected direction (N??, S3), Liujiagou Formation. F. The last three steps show moderately linear ChRM component and the LTC is a composite LTC and Triassic reverse component (R??, S3), Sunjiagou Formation. Filled (open) symbols are lower (upper) hemisphere. G–I: Great-circle (GC) fits, red arc represents fitted great circle and blue indicates points used. Lower projection paths dashed and upper projection paths are solid. G. Great circle plane from 200–680℃, specimen shows a clear great circle trend towards the expected reverse direction (R, T1). LTC (100–500℃) is likely a composite component, Heshanggou Formation. H. Well-defined LTC 100–400 ℃ and a somewhat scattered trend (moderate arc length 100–540℃) towards Triassic reverse, with erratic directions above 600℃, due to thermal alteration (R?, T2), Sunjiagou Formation. I. Well-defined LTC NRM–400℃ and a trend towards expected Triassic reverse direction with the great circle fitted to the higher temperature steps (R??, T3), Liujiagou Formation.

Fig 3. Equal-area stereographic projection of the low-temperature components (LTC) and characteristic (ChRM) components of the Shichuanhe section. A. LTC in geographic coordinates, with the Fisher means (red star) close to the recent geomagnetic dipole field direction (orange star) at the SCH site (IGRF, computed from https://www.ngdc.noaa.gov/geomag/calculators/magcalc.shtml#igrfwmm). B. Dual polarity ChRM line fits (in stratigraphic coordinates), with calculated Fisher (dual) mean (only S1 and S2 data used) and Fisher means of all converted to normal (Blue star with 95% confidence ellipse). C. Poles to the great circle planes of T1 and T2 class data, along with the mean of the combined great circle and line-fits (McFadden and McElhinny, 1988). The single girdle plane (dotted) is the plane normal to the mean direction calculated using both the great circle poles and ChRM fits. Red star indicates the mean pole to the great circle girdle of points and its elliptical 95% confidence cone. The filled (open) circles refer to the lower (upper) hemisphere, respectively.

Fig 4. Magnetostratigraphy of the Shichuanhe (SCH) section with polarity quality ratings. Demagnetization behavior of S and T refer to ChRM line-fits (filled circles) and great circle fits (open circles), respectively, which are subdivided into S1, S2, S3 and T1, T2, T3 class (see text for details). Specimens with no Triassic magnetization are marked X. Half-width bars indicate a single sample with high quality (S1, S2 or T1, T2), showing opposite polarity interpretation with respect to adjacent samples. For the gray bar, one-quarter-width means single poorest quality or undetermined polarity (S3, T3 and X), whereas half-width indicates successive poorest or undetermined polarities.

Fig 5. Concordia diagram and ranked ^{206}Pb/^{238}U plot of the analyzed zircon grains by the CA-ID-TIMS method from the Shichuanhe ash bed (upper right inset marked by yellow arrow). Each vertical bar represents a single zircon analysis included in the weighted mean age and the bar height is proportional to the 2σ analytical uncertainty. The horizontal black line and gray band represent the calculated weighted mean age and its 2σ analytical uncertainty envelope, respectively. Two outlier analyses excluded from age calculation plot outside the diagram area and are not shown here. See Supplementary data C for complete U-Pb data.

Table 1. Permian–Triassic mean directions and virtual geomagnetic poles for the Shichuanhe section and other sections in North China. Paleolatitude and reversal test of Yang et al. (1991) were not provided in the original study.

Fig 6. Changhsingian–Anisian magnetic polarity stratigraphy of North China and comparison with other non-marine and marine successions. The geomagnetic polarity timescale (GPTS) is based on Hounslow and Muttoni (2010) and Hounslow and Balabanov (2018). Compiled Central German Composite and biostratigraphy (Szurlies, 2007, 2013; Kürschner and Herngreen, 2010; Scholze et al., 2017). Hancheng section (Ma et al., 1992). Distance between sampling sites >30 m is marked by a sampling gap. West Pingdingshan (Sun et al., 2009), Majiangshan (Li et al., 2016), Meishan (modified from Hounslow and Balabanov, 2018), Abadeh (Gallet et al., 2000; Szurlies, 2013), Guangdao (Lehrmann et al., 2006), Shangsi (Hounslow and Balabanov, 2018; Yuan et al., 2019). Desli Caira (Grădinaru et al., 2007). Question marks indicate uncertain correlations. *D.* Beds=*Deslicairites* Beds; *P.* Beds=*Paracrocordicera* Beds; *J.* Beds=*Japonites* Beds; *P. vilujensis–E. gutta*=*Palaeolimnadiopsis vilujensis–Euetheria gutta*; *L. virkkiae*=*Lueckisporites virkkiae* Zone.

Fig 7. Correlation of the Permian–Triassic interval at Shichuanhe with the GSSP at Meishan (Burgess et al., 2014), Shangsi (Yuan et al., 2019) and Australian sections (Belica, 2017; Fielding et al., 2019, 2021). Ages of ^{1}=calculated by Hounslow and Balabanov, 2018, ^{2}=Burgess et al., 2014, ^{3}=calculated magnetozone boundary ages by Yuan et al., 2019, ^{4}=Metcalfe et al., 2015, ^{5}=Fielding et al., 2019, ^{6}=Fielding et al., 2021. GPTS is from (Hounslow and Balabanov, 2018). Carbon isotope curve of Shichuanhe (Wu et al., 2020).

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