Latest Permian and earliest Triassic geomagnetic polarity timescale: A polarity reversal marks the greatest mass extinction

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Abstract

The establishment of the latest Permian geomagnetic polarity time scale has been inhibited by the inconsistent polarity patterns published by different teams for the section at Meishan, which hosts the Global Boundary Stratotype Section and Points (GSSPs) for the Permian-Triassic boundary (PTB) and base of the underlying Changhsingian Stage. We have analyzed the magnetostratigraphy of the Shangsi section, the former candidate for the PTB GSSP, and the alternate Chaotian section in South China to compile a reliable geomagnetic polarity timescale spanning the late Wuchiapingian and Changhsingian (Late Permian) to early Induan (Early Triassic). The late Wuchiapingian to early Changhsingian is dominated by normal polarity (chron "LP2n" of Hounslow and Balabanov, 2018) with three reversed-polarity subchrons (LP2n.0r to LP2n.2r) within the

Clarkina wangi conodont Zone. The mid to late Changhsingian is dominated by reversed polarity, with the onset of this chron “LP2r” in the *C. changxingensis* Zone. The biostratigraphic placement of the brief normal-polarity chron "LP3n" of the late Changhsingian is within the *C. yini* Zone. The reversed-polarity chron "LP3r" of the latest Changhsingian (late *C. yini* to *C. meishanensis* Zones) is succeeded by the normal-polarity chron “LT1n” that spans from the very latest Changhsingian into the early Griesbachian substage of the basal Triassic. The onset of this chron LT1n coincided with the lowest occurrence *of Hindeodus changxingensis*, which is just after the onset of the latest Permian mass extinction in South China and slightly prior to the PTB. The integration of conodont biozones, carbon isotope excursions and the revised magnetostratigraphy composite from the Shangsi and Chaotian sections produces a high-resolution consistent sequence of the latest Permian mass extinction (LPME), the onset of chron LT1n and then the PTB; thereby enabling high-resolution global correlation of these latest Permian to basal Triassic events.

Keywords: Latest Permian mass extinction; Permian-Triassic boundary; Shangsi; magnetostratigraphic timescale

1. Introduction

The latest Permian through the earliest Triassic was marked by mass extinction, the eruption of the Siberian Traps large igneous province, extreme temperature increases, carbon isotope excursions and other catastrophic events (e.g., Wignall, 2015; Dal Corso et al., 2022). The Paleozoic fauna was devastated at all ecological levels, with a two-episode extinction pattern (e.g., Yin et al., 2012; Huang et al., 2023). The first episode of mass extinction occurred during the latest Permian (1st pulse), while the second episode occurred during the earliest Triassic (2nd pulse). The first pulse witnessed the major biodiversity loss of the foraminifera, calcareous algae, brachiopods, rugose corals etc. (Song et al., 2013), whereas the second pulse accounted for the major destruction of marine ecosystems (Huang et al., 2023). The terrestrial crisis was likely to have been underway several tens to hundreds of thousands of years before the marine extinction (e.g., Chu et al., 2020; Gastaldo et al., 2020). However, the challenge has been to correlate the high-resolution marine records of dramatic events with the sedimentary successions from terrestrial basins in order to understand the relative timing and rates of responses of the land ecosystems and denudation to the climatic and other forcings (e.g., Dal Corso et al., 2022; Liu et al., 2023). The pattern of geomagnetic polarity chrons can provide high-resolution constraints on marine-terrestrial correlations. However, there is some remaining uncertainty in correlating the geomagnetic polarity pattern of the latest Permian (Changhsingian Stage) with the timing of the Permo-Triassic crisis because of the divergent interpretations of geomagnetic polarity time scales for the Changhsingian Stage (e.g., Steiner, 2006; Hounslow and Balabanov, 2018).

The main reference sections for Changhsingian through basal Triassic biostratigraphy, event stratigraphy and radio-isotopic dating are the relatively deep-water marginal-marine limestone strata with intercalated volcanic ash horizons of South China (e.g., Shen and Mei, 2010; Shen et al., 2013). Of these, the most important has been the Meishan D section (31° 4'47"N, 119° 42'21"E) in Changxing County, Zhejiang Province, which hosts the Global boundary Stratotype Section and Points (GSSPs) for the base of the Changhsingian Stage (Wuchiapingian-Changhsingian boundary, WCB) of uppermost Permian and for the overlying Induan Stage of basal Triassic (Permian-Triassic boundary, PTB) (Yin et al., 2001; Jin et al., 2006) (Fig. 1). This Meishan section has been intensively studied for its detailed record of the Latest Permian mass extinction and initial earliest Triassic partial recovery (e.g., Chen et al., 2015); for radioisotopic dating of the Permian-Triassic boundary (e.g., Burgess et al., 2014); for conodont and other biostratigraphic zonation of Late Permian to earliest Triassic (e.g., Jiang et al., 2007; Yuan et al., 2014); for stable isotope and other geochemical trends and signatures (e.g., Yin et al., 2012; Shen et al., 2013); and for cyclostratigraphy (e.g., Huang et al., 2011; Wu et al., 2013; Li et al., 2016). However, the various magnetostratigraphy interpretations published for the Changhsingian Stage at Meishan (Li and Wang, 1989; Liu et al., 1999; Meng et al., 2000; Zhang et al., 2021) have nearly no common features (reviewed by Yin et al. (2005) and by Hounslow and Balabanov (2018)) nor offered explanations of why their polarity data differ from the prior studies. Therefore, we initially did a very detailed resampling of one of the Meishan sections to independently derive its magnetostratigraphy (Fig. A-8, A-9). However, our results from Meishan, which are presented in the Appendix material (Fig. A-8, A-9), do not completely replicate (Fig. A-9) the interpreted geomagnetic polarity zones of another recent publication on the same section (Zhang et al., 2021). Nor do any of these different Meishan-derived polarity patterns appear to share much similarity to the rather more consistent polarity patterns published by three independent teams using the Shangsi section in northern Sichuan Province (Heller et al., 1988; Steiner et al., 1989; Glen et al., 2009).

That Shangsi section was a former candidate location for the GSSP of the base of the Triassic (Lai et al., 1996) and is unique in having an astronomical tuning of the integrated datasets of ammonoid-bivalve-conodont biostratigraphy, chemostratigraphy and chronostratigraphy datasets from the Changhsingian through the earliest Induan (reviewed by Yuan et al., 2019), thereby providing high-resolution integrative stratigraphic constraints and correlation potential for the latest Permian mass extinction (LPME) and PTB at the Shangsi section. Therefore, we performed a dense resampling of the Shangsi section to derive its magnetostratigraphy. An additional paleomagnetic study was made of the upper Changhsingian to lowest Induan at the nearby Chaotian section to test the reliability of polarity assignments (Fig. 1). Two important focuses of our study are to obtain an astronomically-tuned geomagnetic polarity time scale for the suite of Changhsingian conodont biozones and to determine the precise placement of the LPME horizons and of the Permian-Triassic boundary (PTB) relative to the composite geomagnetic polarity pattern.

2. Methods and Geological Background

The Shangsi section (32°20′19″N, 105°27′19″E) is situated on the slope of the northwestern margin of the Yangtze Platform (Fig. 1). It exposes continuous sedimentation of deep-water facies of the Dalong Formation (mudstones, cherts, siliceous limestones) and lowermost Feixianguan Formation (mudstones, thinly bedded limestones, micritic limestones) that span the late Permian through earliest Triassic (Li et al., 1989; Lai et al., 1996). Detailed investigations of conodont biozones (e.g., Jiang et al., 2011), ammonoids (Li et al., 1989), radiometric dating (e.g., Shen et al., 2011), bulk carbon isotopic fluctuations (e.g., Shen et al., 2013) and cyclostratigraphy (Wu et al., 2013) have been undertaken at Shangsi. The conodont zonation from Changhsingian to earliest Induan is: *Clarkina wangi* Zone of basal Changhsingian, followed by the *C. subcarinata* Zone, *C. changxingensis* Zone, *C. yini* Zone, *C. meishanensis* Zone, *Hindeodus changxingensis* Zone, *Hindeodus parvus* Zone of basal-Induan (early Triassic), *Isarcicella lobata* Zone, and *I. isarcica* Zone (Lai et al., 2018; Yuan et al., 2019). These zones can be correlated with the Meishan and other sections and enable dating of the WCB, LPME, and PTB relative to standardized bed numbering and biozones (Yuan et al., 2019). We took a total of 103 oriented minicores and 84 orientated blocks from 177 horizons for magnetostratigraphic study at Shangsi.

The Chaotian section (32°37′16″N, 105°51′35″E) is located ca. 50 km northeast of the Shangsi section (Fig. 1). It also has been well studied, including a detailed description of lithology (Isozaki et al., 2007), conodont biostratigraphy (Ji et al., 2007) and carbon isotopic stratigraphy (Wu et al., 2022), which have constrained the LPME and PTB at this location. A total of 82 oriented block samples were taken from this section.

All samples from the Shangsi and Chaotian sections underwent thermal demagnetization in an ASC TD-48 oven using progressive steps of 25°C steps until 550-600°C and were measured on a 2G 755-4K U-Channel magnetometer in a magnetically-shielded room (<200nT) at the Laboratory for Environmental Magnetism, School of Earth Sciences, China University of Geosciences (Wuhan). The characteristic remanent magnetization (ChRM) of the suite of demagnetization data from each sample was computed by a least-squares fitting technique (Kirschvink, 1980) using the software Paleomagnetic Analysis Program v.4.0 (Zhang and Ogg, 2003). The interpreted polarity and characteristic remanent magnetization (ChRM) directions of the samples were given a quality rating of ‘N(R)’, ‘NP(RP)’, ‘NPP(RPP)’, ‘N? (R?)’ or ‘INT’ according to a semi-subjective judgment of the behavior of the magnetic vectors through stepwise demagnetization and of the rotated VGP(rVGP) latitudes. The rVGP latitudes are the rotated latitude of the calculated virtual geomagnetic poles for the samples/specimens ChRM directions compared to the mean virtual geomagnetic pole position (Lowrie and Alvarez, 1984, and Lowrie and Lanci, 1994) of the South China Block during late Permian to the early Triassic (Paleolongitude= 219.18°E; Paleolatitude= 47.78°N; α95= 4.51°) (Table A-1).

The Appendix material contains (1) additional details on the methods of demagnetization, magnetic vectors during demagnetization, mean directions, examples of interpretation logic, magnetostratigraphic result of Meishan C, Shangsi, and Chaotian sections, and (2) an Excel file with all demagnetization steps (with those selected as the ChRM subset highlighted) for each sample, a brief explanation of the logic in assigning its polarity and the quality rating, and statistics and comparison of site mean directions and virtual geomagnetic poles (VGPs) from each section. Typical samples of different polarity-quality ratings are shown in Figs. A-2, A-3, A-4, A-5.

3. Results

3.1 Summary of magnetic behavior and interpretation of magnetic polarity

A total of 251 samples from 177 horizons in the Shangsi section and of 82 samples of 42 horizons in the Chaotian section from the upper Dalong Fm. to the lowest Feixianguan Fm. were thermally demagnetized. The natural remanent magnetization (NRM) of the samples from the Shangsi section is weak with a mean intensity of 0.4 mA/m, which is probably due to the very low concentration of ferromagnetic minerals in the depositional environment, whereas the mean intensity (1.1 mA/m) of samples from the Chaotian section are stronger than those from Shangsi.

Demagnetization data of the Shangsi section samples confirmed that the magnetizations often became unstable or trended towards anomalous directions above 450°C, as Glen et al. (2009) had also observed. Herein, we also limited our interpretation of the sample demagnetization data to the demagnetization temperature range below the onset of chaos magnetizations. Examples of typical samples from the Shangsi section with the corresponding selection of characteristic remanent directions (ChRMs) and interpreted quality rating for each polarity are presented in Fig. A-2. The typical trend for remanent magnetic vectors during the demagnetization process, which were interpreted as indicative of normal polarity (rated as N or NP), typically show a gradual clockwise or anti-clockwise shift towards a northeastern declination while becoming shallower in inclination. The temperature range for assigning ChRM vectors using stable directions is approximately 275°C to 350°C (Fig. A-2). Samples interpreted as reversed polarity (rated as R or RP) show a progressive movement of remanent magnetic vectors away from the north hemisphere to the south hemisphere accompanied by shifts of inclination toward an upward direction (Fig. A-2). The reversed-polarity samples typically display a stable vector direction from ca. 300°C to 400°C that was assigned as the ChRM, and these have a southwestern declination and negative inclination (Fig. A-2). These ChRM directions for the N/NP- and R/RP-rated samples are considered primary directions because they are antipodal (Fig. A-1) and are consistent with the mean directions derived from the previous paleomagnetic studies at the Shangsi sections and with the reference pole for the South China block during the late Permian to early Triassic.

The low-rated NPP samples of the Shangsi section show similar demagnetization trends as the N/NP- rated samples but do not reach the expected normal-polarity ChRM field before displaying unstable directions; therefore, the rVGP latitudes of their ChRMs are generally less than 60° (Figs. 2, A-2). The low-rated RPP samples presented similar demagnetization behaviors as the R/RP-rated samples, but their vectors either stabilized at a southeastern direction with a negative inclination or progressively shifted towards but didn't attain the expected reversed-polarity hemisphere; therefore, the rVGP latitudes of their ChRMs are generally greater than -60° (Fig. 2, A-2). The N?, R?, and INT-rated samples were discarded from the composites due their display of unstable magnetic vectors during demagnetization, overlapping secondary vectors, a remagnetization toward the present-day field that could not be removed, or because their intensities became too weak to be measured.

The samples from the Chaotian section display demagnetization behaviors (Fig. A-3) that are similar to those from the Shangsi section, but fewer samples were assigned a high rating (only 17 are NP- and RP-rated of the 82 measured samples). The mean ChRM of the higher-rated samples is consistent with the mean ChRM direction derived from the Shangsi suite and from other sections in the South China block of this age interval. The reversed- and normal-polarity directions from the Chaotian section are roughly antipodal (Fig. A-1). The low-rated NPP/RPP samples of the Chaotian section show similar demagnetization trends as the NP- or RP-rated samples; however, the secondary magnetic overprints of these samples were not completely removed, therefore, the rVGP latitudes of ChRMs are between -60° to 60° (Fig. A-3). The main secondary vectors that are removed during demagnetization of samples from both sections are close to the Brunhes to present age normal-polarity field direction (Decl: 360°; Incl: 50°). These secondary overprints of present field are typically removed upon heating to ca. 250°C.

The geomagnetic polarity zones in the Shangsi and the Chaotian sections are assigned to clusters of relatively higher-rated samples of similar polarity interpretation, although the precise boundary between some polarity zones has a degree of uncertainty owing to intermediate intervals with low-rated (N?/R?) or uncertain (INT) ChRMs (Figs. 2, A-6, A-7).

3.2 Shangsi magnetostratigraphy

The Shangsi section yielded three normal-polarity zones and two reversed-polarity zones through the study interval (Fig. 2). Our nomenclature for these composite polarity zones of Shangsi include a "SS" identifier, followed by an "n" or "r" to denote the polarity. Narrow polarity intervals are given a subzone designation of .1r/.1n/.2r, etc., after the main polarity zone designation (Fig. 2).

The lower through middle portion of the study interval at Shangsi is dominated by normal-polarity magnetozones (SS1n-SS2n), which span the uppermost *Clarkina transcaucascia* to the lower *C. changxingensis* conodont zones from 70m to 94.7m (uppermost Bed 14 to the upper part of Bed 20). This normal-polarity-dominated interval contains several potential reversed-polarity intervals, which are characterized by usually one reversed-polarity sample with several adjacent uncertain or intermediate samples (Fig. 2).

From 94.7m to 96.4m, the ChRM of the samples displayed a clustering with an eastward declination and positive inclination during the thermal demagnetization process (Appendix material). This suggests that our samples from this interval had undergone a pervasive remagnetization; therefore, an uncertain-polarity interval spans this transition between polarity magnetozones SS2n and SS2r (Fig. 2, 3).

The lower *C. changxingensis* zone to the basal *Hindeodus changxingensis* Zone (96.4m to 100.4m) is dominated by a reversed-polarity magnetozone (SS2r) (Fig. 2, 3).

This reversed-polarity interval contained a high-rated normal-polarity sample from 99.5m with several adjacent samples of questionable or intermediate polarity. This possible normal-polarity submagnetozone in the middle part of the *C. yini* Zone is designed as SS2r.1n (Fig. 2, 3).

In order to precisely assign an upper boundary to reversed-polarity magnetozone SS2r at the Shangsi section, we collected a near-continuous suite of oriented blocks for paleomagnetic sampling from Bed 25 of the uppermost Dalong Fm. to Bed 28 of lowest Feixianguan Fm. (Fig. 2, 3). Upon thermal demagnetization on the set of 28 samples from 18 horizons, the samples assigned as a high-rated reversed polarity ChRM exhibited a progressive shift of vectors from the east to the south accompanied by a shift of the inclination toward an upward direction (Sample 139-4, 99.7m, from Bed 25, rated as RP, with rVGP latitude = -86.16°), or stable ChRM vectors with a southwestern declination and negative inclination (Sample 145, 100.35m, from the top of Bed 28a, rated as R, with rVGP latitude = -71.40°). The samples assigned as a high-rated normal polarity displayed a minor clockwise drift in ChRM towards a northeastern declination while becoming shallower in inclination (Sample 147, 100.47m, from the middle of Bed 28b, rated as NP, with rVGP latitude = 68.97°; Sample 151 from Bed 28c, rated as N, with rVGP latitude = 78.66°). Therefore, the boundary between reversed-polarity magnetozone SS2r and the overlying normal-polarity magnetozone SS3n is well constrained as the basal part of Bed 28b at Shangsi. Normal-polarity magnetozone SS3n extends from the basal part of the *H. changxingensis* zone to beyond the top of the studied interval at Shangsi (Fig. 2, 3).

3.3 Chaotian magnetostratigraphy

The majority of Unit C of the Dalong Fm. to the lower Unit E of the Feixianguan Fm. in the Chaotian section is dominated by a reversed-polarity magnetozone CT1r. The lower boundary of CT1r was tentatively placed above a single high-rated normal-normal sample from Bed C1 (Fig. 4), which is at the upper part of the *C. changxingensis* – *C. subcarinata* Zone (Isozaki et al., 2007; Ji et al., 2007). A pair of normal-polarity samples from 1.8m (Bed D5) in the lower-middle part of CT1r suggests a brief normal-polarity submagnetozone (CT1r.1n). The submagnetozone CT1r.1r is at the upper part of the

C. postwangi - *C.* sp. B Zone (Isozaki et al., 2007; Ji et al., 2007) (Fig. 4), which corresponds to the middle and upper *C. changxingensis* Zone (Yuan et al., 2014; 2019). Above a 50 cm interval from ca. 2.5 m to ca. 3 m that did not yield useful paleomagnetic samples, the upper part of reversed-polarity magnetozone CT1r within uppermost Unit D of the Dalong Fm. is dominated by high-rated reversed-polarity ChRMs until just below the barren interval of the LPME. The lower part of conodont barren intra-zone in the lower Unit E of the Feixianguan Fm. (Bed E1 to Bed E7) yielded low-rated ChRMs of reversed polarity (RPP/R?), therefore is shown in the magnetic polarity column of Figure 4 as a less-certain reversed-polarity interval. The upper portion of conodont barren intra-zone from the middle part of Unit E (above 4.35m) through the upper part of Unit F of the Feixianguan Fm. at Chaotian is characterized by a normal-polarity magnetozone CT2n (Fig. 4). Magnetozone CT2n includes the lowest part of the *H. parvus* conodont Zone (Isoazki et al., 2007; Ji et al., 2007).

4. **Discussion**

4.1 Composite geomagnetic polarity pattern of the Shangsi section

The three previous magnetostratigraphic studies of the Shangsi sections (Heller et al., 1988; Steiner et al., 1989; Glen et al., 2009) have generally yielded similar geomagnetic polarity patterns (review by Hounslow and Balabanov, 2018). Our magnetostratigraphic results are based on a denser sampling (251 samples from 177 horizons) which yielded more conclusive polarity interpretations (53 N/NP- and R/RP-rated ChRMs, 52 NPP/RPP ChRMs) from the studied interval when compared to the previous investigations (e.g., 17 acceptable results from 37 samples from Steiner et al. (1989); 54 valid of 107 samples from Glen et al. (2009); 31 levels from Heller et al. (1988) which did not contain reliability information).

In order to attempt a consistent, integrated correlation of the different published magnetostratigraphies and other stratigraphic studies from the Shangsi section, we replotted all datasets relative to the main distinctive lithologic layers (e.g., dark, thinbedded organic-rich siliceous limestone Bed 17; claystone Bed 27 with volcanic tuff) in the detailed stratigraphic compilation by Lai et al. (1996) (Fig. 2). Most of the published polarity interpretations, when adjusted to this standardized stratigraphic scale, are consistent with our polarity pattern. Horizons or intervals having less-reliable paleomagnetic results were denoted by blocks with dual coloration of black/gray to denote N? or of white/gray for R? (Fig. 2).

In the lower normal-dominated interval (SS1n-SS2n), we observed several potential minor reversed-polarity intervals that were represented by single samples (Fig. 2). One of these, magnetozone SS1r, is also present in the re-interpreted data from Steiner et al. (1989) (Fig. 2). However, the duration of SS1r is still uncertain with only the horizon at 89.9m in the upper part of Bed 18 yielding reliable reversed-polarity samples in both this study and in Steiner et al. (1989) with other horizons in the 89m to 91m interval yielding mainly uncertain results (Fig. 2). Therefore, the upward transition between SS1n and SS1r is proposed to occur at approximately 89.8m, based on the normal-polarity samples below this level from Glen et al. (2009) and Steiner et al. (1989). However, the upper boundary of SS1r is within an uncertain interval from 89.9m to 90.7m (Fig. 2).

Within magnetozone SS2n, we propose a brief and poorly constrained reversed-polarity submagnetozone (SS2n.1r) from the topmost Bed 19 to the lowest Bed 20 spanning the uppermost *C. subcarinata* Zone to the *C. changxingensis* Zone of the Shangsi section (Fig. 2). This assignment of SS2n.1r is based on our sample in the topmost part of Bed 19 and another reversed-polarity sample by Glen et al. (2009) that is within the 92m to 94m interval of less-certain polarity in our dataset (Fig. 2), The boundaries of SS2n.1r are imprecise due to adjacent samples having uncertain polarity.

In our dataset, the upper boundary of SS2n falls within the interval of uncertain polarity from the middle of Bed 20 to the middle of Bed 21. However, Glen et al. (2009) and Steiner et al. (1989) obtained high-rated reversed-polarity results from samples in the lowest part of Bed 21 and just above the base of our uncertain interval (Fig. 2). Therefore, we assume that the highest reliable normal-polarity sample (94.6m at the middle of Bed 20) defines the upper limit of SS2n.

The magnetozone SS2r in the uppermost Dalong Fm. of late Changhsingian is generally well recognized by all the studies, although the exact placement of the upper boundary of SS2r varied slightly among the previous studies (Heller et al., 1988; Steiner et al., 1989; Glen et al., 2009). In our study, the denser sampling yielded a well-constrained boundary between the SS2r and SS3n at the lower part of Bed 28b (Fig. 2).

Within the magnetozone SS2r in the uppermost Dalong Fm, a brief normal-polarity interval indicated by a single high-rated normal-polarity sample from the upper part of Bed 24 (99.5m) in our dataset and by reliable normal-polarity samples from the top of Bed 22 by Glen et al. (2009), which is at the bottom of an uncertain interval in our study.

Therefore, we conclude that SS2r spans the lower *C. changxingensis* Zone (upper part of Bed 20) to the basal part of the *Hindeodus changxingensis* Zone (lower part of Bed 28b). It contains a brief submagnetozone SS2r.1n in the middle part of the *C. yini* Zone (top of Bed 22 to middle of Bed 24) (Figs. 3, 4).

4.2 Timescale for the geomagnetic polarity pattern of the Shangsi section

A suite of CA ID-TIMS radioisotopic dates have been obtained from the Shangsi section (Shen et al., 2011). An age calibration of the late Permian to earliest Triassic geomagnetic polarity chrons can be constructed by applying a Bayesian-based age model to these geochronological dates from the Shangsi section (Haslett and Parnell, 2008; Parnell et al., 2008) (Fig. A-10). However, U-Pb radiometric dates measured from the Meishan section using the EARTHTIME tracer calibration (Burgess et al., 2014) indicated offsets ranging from 200-400 kyr that are younger than the dates measured prior to the pre-EARTHTIME solution. It should be noted that these offsets may not be systematic when compared with some older pre-EARTHTIME calibrations (Hounslow, 2016).

To project an age model onto the composite geomagnetic polarity obtained in this study (Fig. 2)., we adopted the Milankovitch cyclostratigraphy interpretations of Wu et al. (2013), which provides a floating astronomical timescale (ATS) from the latest Wuchiapingian to the earliest Induan. We anchored that ATS on Bed 27 at the Shangsi section which correlates to Bed 25 at Meishan section that is dated as 251.941 ±0.037Ma (radioisotopic date using EARTHTIME tracer calibration; Burgess et al., 2014). The resulting calibrated ATS yields approximate ages for the polarity zones and first occurrences (FO) of marker conodonts. The overall composite geomagnetic polarity pattern from Shangsi is generally consistent with the synthesis by Hounslow and Balabanov (2018), and therefore the dates from this anchored ATS would apply to most of their associated LP and LT chron nomenclature:

251.89 Ma for the base of polarity zone SS3n (chron LT1n; duration of >0.3 Myr);

251.89 Ma for the FO of *H. changxingensis* (100.37m at Shangsi);

251.94 Ma for the FO of *C. meishanensis* (100.00m; marker for the LPME);

252.07 Ma for base subzone SS2r.2r (chron LP3r; 0.28 Myr duration at Shangsi);

252.28 Ma for base subzone SS2r.1n (chron LP3n; 0.21 Myr duration at Shangsi);

252.40 Ma for the FO of *C. yini* (98.14m at Shangsi)

252.75 Ma for base zone SS2r (chron LP2r; 0.47 Myr duration at Shangsi);

252.86 Ma for the FO of *C. changxingensis* (92.90m at Shangsi)

252.88 Ma for base subzone SS2n.1r (subchron LP2n.2r);

252.98 Ma for the FO of C. *subcarinata* (90.71m at Shangsi)

253.09 Ma for base zone SS1r (subchron LP2n.1r);

253.29 Ma for base subzone SS1n.1r (new subchron LP2n.0r)

253.46 Ma for the FO of *C. wangi* (86.70m at Shangsi; marker for the base of Changhsingian)

253.82 Ma for the FO of *C.* cf. *wangi* (84.20m at Shangsi).

No durations for the brief reversed-polarity magnetozones and submagnetozones (SS1n.1r, SS1r, SS2n.1r) within the SS1n-SS2n interval are provided due to their poorly determined thicknesses from Shangsi (Fig. 2, 6).

The anchored ATS in Meishan suggested the FAD age of *C. wangi* at the GSSP for the base of the Changhsingian Stage (WCB) is 253.76 Ma (Yuan et al., 2019), which is nearly identical within the uncertainty to the FO age of *C.* cf. *wangi* of 253.82 Ma at Shangsi in this study. However, both of these calculated ages for the base of Changhsingian are significantly different from the 255.4 Ma age based on the Bayesian age model by Hounslow (2016). In contrast, the International Chronostratigraphic Chart 2023 (ICS2023) proposed a 254.14 ±0.07 Ma age for the base of Changhsingian as derived from a different interpolation method of the U-Pb radioisotopic dating (pre-EARTHTIME solution) of the WCB interval in the Meishan and Shangsi sections (Shen et al., 2011).

The age model of the calibrated ATS method probably has a total uncertainty of about 100 kyr (ca. ±0.1myr) on these age assignments for the cycle-tuned magnetic polarity scale. There is a systematic external uncertainty of 0.04 Myr on the radioisotopic date (251.941 ± 0.037 Ma) used as the anchored age for the ATS. There are internal uncertainties in the placement of each polarity chron boundary within the 405-kyr long-eccentricity cycles as identified in the Shangsi section. Plus, there is likely an inherent variation of sediment accumulation rate through each of those lithologic cycles that locally distorts any linear relationship between meters and time within that cycle.

We also have constructed a Bayesian age-depth model using Bchron (Fig. A-10, Parnell et al., 2008) based on the radioisotope dates (pre-EARTHTIME) from Shangsi (Shen et al., 2011). This Bayesian age-depth model results in 252.15 ±0.14 Ma for SS3n (LT1n); 252.45 ±0.13 Ma for SS2r.2r (LP3r); 252.69 ±0.19 Ma for SS2r.1n (LP3n); 253.10 ±0.24 Ma for SS2r.1r (LP2r); 253.28 ±0.25 Ma for SS2n.2n (LP2n.3n); 253.32 ±0.25 Ma for SS2n.1r (LP2n.2r); 253.48 ±0.23 Ma for SS1r (LP2n.1r); 253.58 ±0.19 Ma for SS1n.1r (LP2n.0r); 253.72 ±0.23 Ma for FO of *C. wangi*, and 254.09 ±0.25 Ma for the FO of *C.* cf. *wangi* (Fig. A-10). These Bchron-derived ages are generally consistent with the ages derived from anchored ATS from the Shangsi section within the uncertainty between the two approaches.

4.3 Correlation among Changhsingian geomagnetic polarity reference sections of marine sediments

The overall composite geomagnetic polarity pattern from the Shangsi and Chaotian sections is generally consistent with the synthesis by Hounslow and Balabanov (2018) of important marine and non-marine reference sections for magnetostratigraphy of the Changhsingian (Fig. 5). In this section, we will briefly summarize the logic behind an updated correlation web as an array of numbered correlation lines among the main magnetostratigraphy reference sections.

Magnetostratigraphy and correlation to the are used as a synchronous correlation method, in which the geomagnetic reversals are recorded as time horizons regardless of biostratigraphic provincialism, and environmental conditions (marine, continental, lacustrine, etc.). The segments of the GPTS for time intervals preceding the Middle Jurassic has been meticulously constructed through the iterative process of integrating and validating magnetostratigraphic investigations from overlapping and contemporaneous stratigraphic reference sections (Laj et al., 2021; Langereis et al., 2010). The comprehensive synthesis by Hounslow and Balabanov (2018) of the Permian to the earliest Triassic magnetostratigraphic studies that had marine biostratigraphic control enabled the construction of a reference GPTS for that interval. Their numbered polarity chrons for GPTS of the late Permian and of the Early Triassic have prefixes of "LP" or "LT", respectively, and we have followed their nomenclature.

The detailed conodont biostratigraphic calibration on the composite magnetic polarity pattern from the Shangsi section enables a greatly improved calibration of the latest Wuchiapingian through earliest Induan portion of that part of the reference GPTS by Hounslow and Balabanov (2018). For example, their primary marine reference sections of Abadeh, Linshui, and Wulong for the Changhsingian GPTS lacked sufficient direct biostratigraphic data. Despite extensive studies on the conodont biostratigraphy of the Abadeh section from the late Permian to the early Triassic succession (e.g., IJRG, 1981; Shen and Mei, 2010), the conodont zonation of Changhsingian to earliest Induan, and the placement of the Wuchiapingian-Changhsingian (WCB) and Permian-Triassic (PTB) boundaries remained disputed (Kozur, 2005; Liu et al., 2013; Shen et al., 2013; Chen et al., 2020). The conodont zonation of the Linshui section was based on conodont occurrences at the nearby Daijiagou section (Yuan et al., 2015). Herein, approximate conodont zonations for the Abadeh and Linshui sections have been incorporated into the magnetostratigraphy using a regional-lithostratigraphy correlation (Fig. 5). The conodont zonation for the Abadeh section adopted the estimation from Shen and Mei (2010), except for the placement of the first occurrence (FO) of *C. wangi* for the WCB and of *H. parvus* for the PTB. The WCB of Abadeh was suggested to be constrained as ca.13.6 below the base of the Elikah Fm., as supported by a minor negative shift of $\delta^{13}C_{carb}$ and lower $^{87}Sr/^{86}Sr$ value of 0.7070-0.7072 (Liu et al., 2013). The base of the *H. parvus* Zone of Abadeh was placed at the top of the boundary clay (Basal Elikah Fm.), as suggested by Horacek et al. (2021) (Fig. 5).

The interval across the Wuchiapingian-Changhsingian transition (*C. orientalis* Zone to *C. wangi* Zone) into the lower *C. changxingensis* Zone at the Shangsi section is dominated by normal polarity (SS1n and SS2n). The middle portion of the upper Changhsingian (from *C. changxingensis* to *C. meishanensis* Zone) at the Shangsi section is dominated by a reversed polarity zone (SS2r), with submagnetozone SS2r.1n in the *C. yini* Zone. The overall Changhsingian polarity pattern of the Shangsi section closely resembles that of the Abadeh (Gallet al., 2000), Wulong, Linshui (Heller et al., 1995) and Nammal Gorge (Haag and Heller, 1991), based on projected conodont zonation and occurrences as demonstrated by Correlation Lines #3 (base of LP2r), #4 (base of LP3n), and #5 (base of LP3r) (Fig. 5).

The floating ATS in Shangsi for the geomagnetic polarity zones results in a duration of 0.96 ±0.1 myr for magnetozone SS2r, which fits the age model of Hounslow (2016) and Hounslow and Balabanov (2018) for the combined chrons of LP2r to LP3r (Fig. 5). However, the upper boundary of chron LP2n is within the *C. changxingensis* Zone at the Shangsi/Chaotian and Linshui sections, but it is within the *C. subcarinata* Zone at the Abadeh section (IRA2n) (Fig. 5). This inconsistent alignment of that conodont zonal boundary with polarity boundaries can be attributed to the known diachroneity in such transitional lineage conodont zones (Yuan et al., 2014; 2019).

The magnetozones of the earier Changhsingian at Shangsi below the well-documented lower boundary of chron LP3r (Correlation Line #3) of middle Changhsingian consist of submagnetozones SS1n.1r, SS1r, SS2r.1n within the interval SS1n to SS2n. These correspond to an interval with poorly resolved brief reversed-polarity subchrons (uncertain event "LP2n.ar" within LP2n.1n, and subchrons LP2n.1r and LP2n.2r) in the synthesis for the lower Changhsingian Stage by Hounslow (2016; also in Hounslow and Balabanov, 2018). The magnetostratigraphy from Linshui, Abadeh and Composite Central European Basin also display three reversed-polarity magnetozones in the lower Changhsingian (LS1r to LS3r; IRA1n.1r to IRA1n. 3r; CG1r to CG2n.1r and CG2n.2r), as in the Shangsi section as constrained by Correlation Lines #2 and #3 in Figure 5. The projected conodont zonations for the Linshui and Abadeh sections indicate that LP2n.2r falls within the *C. subcarinata* to the lowest *C. changxingensis* Zone, while LP2n.1r and LP2n.ar falls within the *C. wangi* Zone (Fig. 5). However, at Linshui, the lower reversed-polarity submagnetozone LS1r is exceptionally long (over 50m), which may be due to an anomalous high accumulation rate or a less reliable interpretation. Based on this observation, we propose upgrading the uncertain event "LP2n.ar" of Hounslow (2016) to a formal subchron, designated as LP2n.0r to avoid confusion, as it represents the earliest brief reversed-polarity subchron above the base of the Changhsingian stage.

The uppermost normal-polarity zone SS3n at the Shangsi section, which begins with the FO of *H. changxingensis* and continuously upward to the lowermost Induan stage, corresponds to polarity chron LT1n (first normal-polarity chron of the Early Triassic), as indicated by Correlation Line #5. Therefore, the latest Permian mass extinction (LPME) occurs slightly prior to the onset of the normal-polarity chron LT1n, while the Permian-Triassic boundary (PTB) occurs in its earliest portion. We explore the global correlations for the base of chron LT1n, the LPME and the PTB after examining continental records of Changhsingian magnetostratigraphy.

4.4 Correlation among Changhsingian geomagnetic polarity reference sections of continental sediments

The polarity column of Central European basin (right side of Fig. 5) was derived from the magnetostratigraphy in the Germanic Basin where the upper part of the Zechstein Group of latest Permian consists of hypersaline and sabkha sediments of seven evaporation cycles/formations (Z1-Z7): Werra (Z1), Staßfurt (Z2), Leine (Z3), Aller (Z4), Ohre (Z5), Friesland (Z6) and Fulda (Z7) formations (Szurlies, 2013). The Z3 cycle is dominated by a normal-polarity magnetozone CG1n, and the transition to the overlying lowest Z4 cycle-strata is magnetozone CG1r (Fig. 5). The Z4 to Z6 cycles are characterized by normal polarity magnetozone (CG2n) with two brief reversed-polarity submagnetozones (Soffel and Wippern, 1989; Szurlies, 2013).

The overlying reversed-polarity magnetozone CG2r spans the lower and middle parts of Z7 cycle (Fig. 5). The overlying normal-polarity-dominated interval of polarity magnetozones CG3n-CG4n spans the lower part of Z7u (upper Fulda Fm.) to the overlying Calvörde Fm. (Fig. 5, 6). The spinicaudatan biostratigraphy indicates that polarity zone CG3n is associated with *Palaeolimnadiopsis vilujensis* - *Euestheria gutta* assemblage (Scholze et al., 2017), and is equivalent to the normal polarity chron LT1n.

Therefore, the underlying reversed-polarity magnetozone CG2r could be correlated to the merged reversed-polarity chrons LP2r to LP3r, and the underlying normal-polarity magnetozones CG2n and CG1n are equivalent to chron LP2n (Fig. 5).

The Shichuanhe section in a terrestrial basin of North China has a high-precision U-Pb date of 252.21 ±0.15 Ma from a horizon in the upper part of magnetozone SCH2r and a *Palaeolimnadiopsis vilujensis - Euestheria gutta* spinicaudatan (conchostracan) assemblage was obtained from the lower part of magnetozone SCH3n (Guo et al., 2022; and reference herein). The radioisotopic date implies that reversed-polarity magnetozone SCH2r is correlated to chron LP3r of latest Permian; therefore the overlying magnetozone SCH3n is unambiguously equivalent to LT1n of earliest Triassic (Fig. 5). The normal-polarity magnetozone SCH2n that underlies magnetozone SCH2r could be correlative with chron LP2n (Fig. 5).

4.5 Global correlation of the latest Permian mass extinction (LPME) and the Permian-Triassic boundary (PTB) relative to geomagnetic polarity chrons

The global synchronous nature of geomagnetic polarity reversals has made magnetostratigraphy an important global correlation, especially for the correlation between marine and terrestrial successions (Laj et al., 2021). Beginning in the late 1980s, magnetostratigraphic research on PTB sections in different parts of the world had concluded that the latest Permian mass extinction (LPME) and the following PTB occurred at or within the basal part of the normal-polarity chron LT1n that extends through the lower part of the Griesbachian substage (e.g., Heller et al., 1988; Steiner et al., 1989; Hounslow and Muttoni, 2010; Li et al., 2016; Ogg et al., 2020). The LPME in the marine realm appears to coincide with a major catastrophe in terrestrial ecosystems with loss of plant diversity, increased wildfire activity and consequent enhanced soil erosion, which suggested a common causal mechanism for the marine and terrestrial crises (e.g., Algeo et al., 2011; Dal Corso et al., 2020). However, some studies indicate the terrestrial extinction phase in the Karoo basin (Gastaldo et al., 2020), in South China (Chu et al., 2020) and in North China (Lu et al., 2022) are not synchronous, thereby implying different causes. This suggested divergence in the timing of the LPME and PTB levels in the marine realm and the events in the terrestrial realm can be potentially resolved by compiling their high-resolution placement relative to the beginning of the normal-polarity chron LT1n.

However, at the PTB reference section (GSSP of Induan Stage) in Meishan, the interpreted assignment of the base of normal-polarity chron LT1n at Meishan varies among previous studies (Li and Wang, 1989; Liu et al., 1999; Meng et al., 2000; Zhang et al., 2021), which made it difficult to estimate the relative timing and placement of the LPME and PTB relative to that geomagnetic reversal. However, the integrated paleontological, stable isotope, cyclostratigraphy and magnetostratigraphy from Shangsi and from other marine reference sections allow a high-resolution placement of the LPME and PTB events relative to chron LT1n.

4.5.1 LPME and PTB placement within the magnetostratigraphy of Shangsi and Chaotian (South China)

The Shangsi section probably provides the most precise placement of LPME and a well-constrained placement of the PTB relative to the base of chron LT1n (Figs. 6, 7). At Shangsi, the LPME and the associated negative carbon-isotope excursion are observed at the base of Bed 27 (Shen et al., 2013; Yuan et al., 2019), which is at the base of *C. meishanensis* Zone. The base of normal-polarity magnetozone SS3n (= polarity chron LT1n) has been constrained to the lower part of Bed 28b (40cm above the LPME level), which is nearly coeval with the FO of *H. changxingensis*. The conodont *H. changxingensis* was considered as a disaster species that flourished over a wide region during a brief period of ecological stress after the LPME (Metcalfe et al., 2007).

However, the placement of the PTB within the Shangsi section is less direct. This is because the FO of *Hindeodus parvus*, which is the index marker coinciding with the PTB at the GSSP at Meishan, is only about 18 cm above the LPME at that GSSP Meishan (Cao and Zheng, 2007; Jiang et al., 2007), whereas it does not appear until >2 m above the LPME at the Shangsi section (Nicoll et al., 2002; Jiang et al., 2011). One interpretation is that this is a local delayed appearance of *H. parvus*, because several “new” Triassic species occur below the appearance of *H. parvus* at Shangsi (reviewed by Yuan et al., 2019). Therefore, other taxa in the PTB interval at the Meishan GSSP are used to place the PTB within the Shangsi succession.

Jiang et al. (2011) continuously collected samples for the conodonts from Beds 26 through 33 of the Shangsi section. Their sample, called "Bed 28a," actually spans Bed 28a to the basal 5cm of Bed 28c (100.15m to 100.6m). From this interval, the conodont fauna obtained from their study and a later study (Yuan et al., 2019) includes *Hindeodus changxingensis*, *Clarkina taylorae*, *Hindeodus praeparvus*, *Isarcicella huckriedei, I. turgida* and *H. eurypyge*. This conodont assemblage was considered as the Permian-Triassic transition fauna, which is found in Beds 26 through 28 at Meishan (Jiang et al., 2007). At a finer scale, the conodont biostratigraphy study conducted by Yuan et al. (2019), suggested that the turnover level from *Clarkina*-dominated to *Hindeodus*-dominated is in the base of Bed 28b at Shangsi. This conodont changeover is evident in multiple PTB sections located in South China, including the GSSP at Meishan (Lai et al., 2001; 2018; Yuan et al., 2014), Chaotian (Ji et al., 2007), Bianyang (Yan et al., 2013; Jiang et al., 2015). Earlier, Lai et al. (1996) had suggested the PTB at Shangsi be placed at the base of Bed 28c, which is 55cm above the onset of the LPME and 20cm above the base of zone SS3n/chron LT1n. Their placement had been based on the first occurrences of the early Triassic conodont species *I. turgida* and of *Ophiceras* ammonoids. However, later studies reported the presence of *Ophiceras* (?) in the middle of Bed 28b (Yuan et al., 2019). Thus, the combined later detailed study of conodont assemblages (Yuan et al., 2019) and the presence of ammonoids now agree that the PTB of the Shangsi section should be positioned in the middle of Bed 28b, which is slightly above the base of magnetozone SS1n (= chron LT1n).

The Chaotian composite magneto-chemo-biostratigraphy (Fig. 4) also suggests that the base of its normal-polarity magnetozone CT2n (equivalent to chron LT1n) is above the LPME and probably below the PTB. The LPME is placed at the base of Feixianguan Fm. (Unit D/E boundary) (Isozaki et al., 2007; Saitoh and Isozaki, 2021), therefore is in the uppermost part of reversed-polarity magnetozone CT1r (equivalent to chron LP3r) (Fig. 4). The conodont *H. parvus*, the index species for the PTB, has been obtained from the base of Unit F (Ji et al., 2007), which is within the overlying normal-polarity magnetozone CT2n (Fig. 4).

4.5.2 LPME and PTB placement within the magnetostratigraphy of Abadeh (Iran)

The reference section at Abadeh (Gallet et al., 2000; Hounslow and Balabanov, 2018) also shows similar relationships between the LPME, the base of chron LT1n and the PTB (Fig. 6). The uppermost sample with a high-rated ChRM of the reversed-polarity zone IRA3r, corresponding to chron LP3r, is located directly beneath the boundary clay of the Basal Elikah Formation, the lowest sample with a high-rated ChRM of the subsequent normal-polarity magnetozone IRA4n is positioned just above the boundary clay (Gallet et al., 2000). This suggests that the base of normal-polarity magnetozone IRA4n should be situated within the boundary clay. The mass extinction level (LPME) is placed at the base of boundary clay, where it is associated with a negative excursion of $\delta^{13}C_{carb}$ and major biotas losses, but the position of the PTB at Abadeh is debated (Chen et al., 2020; Horacek et al., 2021). In this study, we adopted the assignment of the PTB at the top of the boundary clay, which is based on the lowest occurrence of *H. parvus* (Richoz et al., 2010) (Fig. 6). This alignment between LPME, the onset of IRA4n, and PTB at Abadeh, Iran, is consistent with our observations from the Shangsi and Chaotian sections (Fig. 6).

4.5.3 LPME and PTB placement within the magnetostratigraphy from the Dolomite (Italy)

The Dolomites (Southern Alps, Italy) have long been considered as a key study area on the northwestern margin of the Paleo-Tethys Ocean for the Permian and Triassic successions and the biotic and environmental events of shallow-marine ecosystems. The main disappearances of late Permian marine taxa in the Dolomites is in the basal Werfen Fm. (Tesero Oolite Mbr.) marking the LPME (Posenato, 2019; Horacek et al., 2010). The base of chron LT1n (= magnetozone N2 in Scholger et al., 2000) is only 0.3m above the base of Tesero Mbr. and lowest occurrence of the PTB conodont marker *Hindeodus parvus* is at 1.3m above the base of Tesero Mbr. (Perri and Farabegoli, 2003), In summary, the base of chron LT1n (magnetozone N2) at the Dolomites reference sections is slightly above the LPME, and below the PTB (Fig. 6).

4.5.4 LPME and PTB placement within the magnetostratigraphy from the terrestrial realm (Central European Basin and North China)

The relative placements of the LPME, the base of chron LT1n and the PTB in terrestrial reference section follow the same relative placement in the marine successions (Fig. 6). The placements of the LPME and PTB in terrestrial reference sections are based on chemo-biostratigraphic evidence (Fig. 6).

In the Central European Basin, the magnetozone CG2r corresponds to chrons LP2r to LP3r, and the overlying magnetozone CG3n corresponds to chron LT1n (Fig. 5). A placement of the LPME at the boundary between the lower (Z7l) and upper (Z7u) of the Fulda Fm., is based on the highest occurrence of the late Permian spore *Lueckisporites virkkiae* and the termination of high $\delta^{13}C_{org}$ values (Scholze et al., 2017). The position of PTB has been proposed in the lower part of Z7u, slightly above the base of magnetozone CG3n, based on the first occurrence of the spinicaudatan (conchostracan) *Palaeolimnadiopsis vilujensis* - *Euestheria gutta* assemblage (Scholze et al., 2017). That assemblage has been considered as important marker for the Permian-Triassic transition beds in terrestrial settings (Chu et al., 2019). In summary, the LPME level is slightly lower than the base of LT1n and the projected PTB level is slightly higher than the base of chron LT1n in the Central European basin (Fig. 6).

At the Shichuanhe section, North China, the integrated chemo-bio-magnetostratigraphy indicate that the carbon isotope excursion, which has been considered as approximately synchronous with LPME, occurs at ~3m below the base of magnetozone SCH3n (= chron LT1n) (Fig. 6). The PTB was proposed to be placed at ~1m above the base of zone SCH3n (=chron LT1n), based on the lowest occurrence of *Euestheria gutta* - *Palaeolimnadiopsis vilujensis* assemblage (Chu et al., 2019). Therefore, the relative placements among the LPME, the base of LT1n and the PTB follow the same consistent pattern in North China (Fig. 6).

5. Conclusion

We have re-studied the magnetostratigraphy of the Shangsi section and recompiled the bio-chemo-magnetostratigraphy records of other reference sections. The revised composites verify the pattern for the main polarity chrons of the latest Permian through earliest Triassic and enable the more precise placement of the latest Permian mass extinction (LPME) and the Permian-Triassic Boundary (PTB) relative to the base of normal-polarity chron LT1n. The magnetostratigraphy of the lower Changhsingian (basal *C. wangi* to the lower *C. changxingensis* conodont zones) at Shangsi verifies the dominance of the normal-polarity chron LP2n. This chron LP2n contains three reversed-polarity subchrons in the *C. wangi* to lower *C. changxingensis* zonal interval. The polarity zones were also calibrated to the astronomical timescale of the Shangsi stratigraphy (Wu et al., 2013) that is anchored to the radioisotopic date (251.941 ±0.037 Ma; Burgess et al., 2014) for Bed 25 at the Triassic GSSP section of Meishan, which is coeval with Bed 27 at Shangsi. This timescale yields the onset ages for the polarity chrons and subchrons of 253.29 Ma (subchron LP2n.0r), 253.09 Ma (subchron LP2n.1r) and 252.88 Ma (subchron LP2n.0r). The overlying reversed-polarity chron LP2r begins about from 252.75 Ma to 252.65Ma and is within the *C. changxingensis* conodont zone. A brief (ca. 200 kyr) normal-polarity chron LP3n begins at 252.28 Ma within the lower half of the *C. yini* zone. The base of the major normal-polarity chron LT1n coincides with the lowest occurrence of conodont *H. changxingensis* at Shangsi and continues above through the lower part of the Griesbachian substage.

The integrated bio-chemo-magnetostratigraphy studies from a variety of marine and terrestrial paleoenvironments reveal a general agreement that the normal-polarity chron LT1n began after the onset of the LPME and prior to the PTB (beginning of the Triassic) (Fig. 6). Therefore, the base of LT1n is an important marker for recognizing and high-precision temporal correlation of the levels of the LPME and the PTB in non-fossiliferous successions (Fig. 6).

Appendix. Supplementary material

Supplementary materials related to this article include our Meishan magnetostratigraphy, details of methods of demagnetization, examples of interpretation logic, and an Excel table of all paleomagnetic demagnetization data with notes on the paleomagnetic analysis.

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Captions

Figure 1. Latest Permian paleogeography map. (A) Global reconstruction map showing the paleogeographic positions of South China during the Changhsingian (base map modified after Shen et al. (2013)). (B) Late Changhsingian paleogeographic map of South China during the *Clarkina meishanensis* conodont zone showing the settings of Meishan, Shangsi and other reference sections (base map modified from Yin et al. (2014)), Sections: MS = Meishan; SS = Shangsi; CT = Chaotian; LS = Linshui; WL = Wulong, Paleogeographic partitions: NMBY = North marginal basin of Yangyze Platform; HGG basin = Hunan-Guizhou-Guangxi basin; ZFG clastic Region = Zhejiang-Fujian-Guangdong clastic Region.

Figure 2. Comparison of our study to the published magnetostratigraphies of the Shangsi section (Heller et al., 1988; Steiner et al., 1989; Glen et al., 2009) after adjusting all studies to a standardized bed nomenclature and meter scale. The left columns include the lithologic stratigraphy (modified from Lai et al. (1996)), cyclostratigraphy (E: 405-kyr long eccentricity cycle) (Wu et al., 2013), radioisotopic date for the mass extinction level (Burgess et al., 2014), and conodont biostratigraphy (Jiang et al., 2011; Yuan et al., 2019). Polarity zones and subzones in the composite magnetic polarity pattern for Shangsi (leftmost polarity column) have a suggested "SS" nomenclature. Polarity ratings (N to INT to R) assigned to our samples are indicated by the red dots superimposed onto the magnetic polarity zones interpreted from clusters of similar polarity. The column of rVGP is only for the samples having assigned polarity of N to NPP or R to RPP. The rVGP latitudes approaching +90° and −90° signify normal and reverse polarity, respectively. The ticks on the 0° axis of the rVGP column are sampling levels that did not provide acceptable paleomagnetic data. Legend: A. siliceous limestone; B. carbonaceous siliceous rock; C. claystone with marl; D. marl with micritic limestone; E. limestone; F, G, H and I denote intervals of Uncertain polarity (gray), Reverse polarity (white); Normal polarity (black) and Unsampled gap (light blue), respectively. Abbreviations of conodont genera: *C. = Clarkina*; *H. = Hindeodus*; *I. = Isarcicella*.

Figure 3. Field photos from selected intervals in the Shangsi section with projected magnetostratigraphy interpretations (black-white bar, with the black/white/grey dots next to bar indicating the interpreted polarity of the sampled horizon), bed numbers (white front within black label and red lines), stratigraphic boundaries (white font within black label and white line), the latest Permian mass extinction level (LPME; yellow font and red line), conodont biozones (yellow font within red label and lines), radioisotopic dates from zircons (yellow font within black label), and cyclostratigraphy (black font in white circle with the span of each 405-kyr long-eccentricity (E) and ~100-kyr short-eccentricity (e) cycle denoted in yellow). (A) Exposure of the upper part of the Shangsi section from Bed 20 to Bed 26 of Dalong Fm. (B) Field photos of the Permian-Triassic transition interval in the Shangsi section. Datasets: bed numbers and lithological boundary (Lai et al., 1996), LPME and conodont biozones (Yuan et al., 2019), radioisotopic dates (Shen et al., 2011), and cyclostratigraphy (Wu et al., 2013).

Figure 4. Chaotian section magnetostratigraphic results with lithostratigraphy (Isozaki et al., 2007), conodont zones (Ji et al., 2007), bulk carbon isotopic values (Wu et al., 2022), magnetic polarity zones, polarity ratings, and rVGP latitudes. Legend: A: limestone; B: volcanic tuff; C: clayey limestone; D: Claystone; E, F, G, and H represent the same polarity legend as shown in Fig. 2.

Figure 5. Proposed correlation of our suggested composite ATS-tuned geomagnetic polarity timescale from the Shangsi section with conodont zones with other magnetostratigraphic studies of marine and terrestrial Changhsingian sections. Datasets: (1) Nammal Gorge: geomagnetic polarity pattern from Haag and Heller (1991); conodont occurrences are projected from the same regional study (Waterhouse, 2010). (2, 3) Wulong and Linshui sections: geomagnetic polarity patterns from Heller et al. (1995) with the right sub-columns after graying out intervals that had their low-quality-rated samples; conodont zones are modified projections from the adjacent Daijiagou section (Yuan et al., 2015). (4) Abadeh section: geomagnetic polarity pattern from Gallet et al. (2000), conodont zones proposed by Shen and Mei (2010) with estimated WCB placement by Liu et al. (2013), revised *H. parvus* Zone placement by Horacek et al. (2021). (5, 6) Chaotian and Shangsi sections: references see main text. (7) Optimized GPTS, adopted from Hounslow (2016). (8) Central European Basin: geomagnetic polarity pattern from Soffel and Wippern, (1998); Szurlies (2013); (9) Shichuanhe, North China: geomagnetic polarity pattern from Guo et al. (2022). Conodont genera abbreviations are the same as in Fig. 2. Conodont species

abbreviations: *C. l.* = *C. longicuspidata*; *C. w.* = *C. wangi*; *C. li.* = *C. liangshanensis*; *C. s.* = *C. subcarinata*; *C. ch.* = *C. changxingensis*; C. *y.* = *C. yini*; *C. m.* = *C. meishanensis*; *C. a.* = *C. abadehensis*; *C. h.* = *C. hauschkei*; *C. n.* = *C. nodosa*; *C. b.* = *C. bachmanni*; *H. c.* = *H. changxingensis*; *H. p.* = *H. parvus*.

Figure 6. Placements of carbon-isotope shifts, the latest Permian mass extinction (LPME) and Permian-Triassic boundary (PTB) levels selected global reference sections in various depositional environments relative to the magnetostratigraphy in the integrated geological timescale of this study. The level of LPME is indicated as the lowest red line. The level of the base of polarity chron LT1n is indicated by the continuous horizontal red line. The level of the estimated PTB is indicated by the upper red line. Datasets: (1) Integrated Geologic Timescale – age scale is the astronomical timescale (ATS) at Shangsi and Meishan (Wu et al., 2013) anchored to the radioisotopic dates from Meishan (Burgess et al., 2014); conodont biozones from Lai et al. (2018); geomagnetic polarity pattern is from this study; $\delta^{13}C_{carb}$ is a composite from several studies (Cao et al., 2002; Xie et al., 2007; Shen et al., 2013; Wei et al., 2020), trend median line of the $\delta^{13}C_{carb}$ is a locally weighted smoothing regression (LOWESS, 0.1Myr window) with 2SD confidence intervals, which are calculated using *ACycle* 2.4.1 (Li et al., 2019). Global trends (colored bars) - lethally high temperature from Joachimski et al. (2012); the increase of atmospheric CO_2 from Shen et al. (2022); two mass extinction pulses from Song et al. (2013) and Yin et al. (2012); Siberian Traps timing from Burgess et al. (2017). (2) Shangsi section, South China - conodont biozones from Jiang et al. (2011) and Yuan et al. (2019); $\delta^{13}C_{carb}$ from Shen et al. (2013); geomagnetic polarity pattern from this study. (3) Abadeh section, Iran - conodont biozones from Shen and Mei (2010); geomagnetic polarity pattern from Gallet et al. (2000); $\delta^{13}C_{carb}$ from Richoz et al. (2010). (4) Seis, Dolomites, Italy - conodont biozones are projected from nearby sections (Perri and Farabegoli, 2003); geomagnetic polarity pattern from Scholger et al. (2000); $\delta^{13}C_{carb}$ from Horacek et al. (2010). (5) Shichuanhe, North China - geomagnetic polarity pattern, estimated PTB and LPME from Guo et al. (2022) and references herein; $\delta^{13}C_{org}$ from Wu et al. (2020). (6) Central European Basin: geomagnetic polarity pattern from Szurlies (2013) and Scholze et al. (2017); $\delta^{13}C_{org}$ and estimated PTB from Scholze et al. (2017).