Intensifying aeolian activity following the end-Permian mass extinction: Evidence from the Late Permian–Early Triassic terrestrial sedimentary record of the Ordos Basin, North China

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ABSTRACT

Sedimentary successions provide direct evidence of climate and tectonics, and these give clues about the causes of the mass extinction around the Permian–Triassic boundary. Terrestrial Permian-Triassic boundary strata in the eastern Ordos Basin, North China, include the Late Permian Sunjiagou, Early Triassic Liujiagou and late Early Triassic Heshanggou formations in ascending order. The Sunjiagou Formation comprises cross-bedded sandstones overlaid by mudstones, indicating meandering rivers with channel, point bar and floodplain deposits. The Liujiagou Formation was formed in braided rivers of arid sand bars interacting with some aeolian dune deposits, distinguished by abundant sandstones where diverse trough and planar cross-bedding and aeolian structures (for example, inverse climbing-ripple, translatent-ripple lamination, grainfall and grainflow lamina-tions) interchange vertically and laterally. The Heshanggou Formation is a rhythmic succession of mudstones interbedded with thin medium-grained sandstones mainly deposited in a shallow lacustrine environment. Overall, the sharp meandering to braided to shallow lake sedimentary transition documents palaeoenvironmental changes from semi-arid to arid and then to semi-humid conditions across the Permian–Triassic boundary. The die-off of tetrapods and plants, decreased bioturbation levels in the uppermost Sunjiagou Formation, and the bloom of microbially-induced sedimentary structures in the Liujiagou Formation marks the mass extinction around the Permian–Triassic boundary. The disappearance of microbially-induced sedimentary structures, increasingly intense bioturbation from bottom to top and the reoccurrence of reptile footprints in the Heshanggou Formation reveal gradual recovery of the ecosystem after the Permian–Triassic boundary extinction. This study is the first to identify the intensification of aeolian activity following the end-Permian mass extinction in North China. Moreover, while northern North China continued to be uplifted tectonically from the Late Palaeozoic to Late Mesozoic, the switch of sedimentary patterns across the Permian–Triassic boundary in Shanxi is largely linked to the development of an arid and subsequently semi-humid climate condition, which probably directly affected the collapse and delayed recovery in palaeoecosystems.
Keywords Aeolian, fluvial, mass extinction, North China, palaeoclimate, palaeoecology, Permian–Triassic, recovery.

INTRODUCTION

The Permian–Triassic extinction event wiped out over 90% of marine species and about 70% of continental vertebrate and plant families on Earth (Raup, 1979; Erwin, 1994; Bond & Grasby, 2017). The Earth underwent drastic environmental and ecological collapse across the Permian–Triassic boundary (PTB) in the sea and on land (Ward et al., 2000; Benton & Newell, 2014; Shen et al., 2019b). Numerous studies on terrestrial PTB conditions have focused on significant shifts in palaeoenvironment and palaeoclimate (Newell et al., 1999; Ward et al., 2000; Twitchett, 2006; Benton & Newell, 2014; MacLeod et al., 2017), as well as on ecological collapse (Visscher et al., 1996; Chu et al., 2015a; Yu et al., 2015; Zhang et al., 2016a,b; Bernardi et al., 2017) in representative sections. A large number of models have been established to identify the causes of the mass extinction, including volcanism (Renne et al., 1995; Reichow et al., 2009; Burgess et al., 2017; Shen et al., 2019a), impact (Becker et al., 2001), anoxia (Wignall & Twitchett, 1996), environmental changes (Newell et al., 1999; Ward et al., 2000) and multiple causes among these (Baresel et al., 2017). The widely accepted killing model involves increased mass wasting (Newell et al., 1999; Ward et al., 2000; Sephton et al., 2005; Algeo & Twitchett, 2010) and aridity in climate and the input of greenhouse gases (Benton & Twitchett, 2003; Huey & Ward, 2005; Algeo et al., 2011; Benton & Newell, 2014; Xu et al., 2017a,b) resulting from massive volcanic eruptions in Siberia (Sanei et al., 2012; Burgess et al., 2017; Shen et al., 2019a,b). The coincidence of the mass extinction with synchronous extensive volcanic emplacement of the Siberian Traps Large Igneous Province (LIP) which generated large volumes of sulphate aerosols and carbon dioxide within a short period of time across the PTB indicates that volcanism was the most important trigger (Reichow et al., 2009; Burgess et al., 2017; Black et al., 2018; Shen et al., 2019a,b).

Previous studies have suggested that the collapse of terrestrial ecosystems co-occurred with the decline in marine diversity during the Permian–Triassic transition (Twitchett et al., 2001; Shen et al., 2011). However, little is known about the specific palaeoclimatic changes coupled with the devastation and delayed recovery of ecosystems across the PTB. To a large extent, research on palaeoclimate across the terrestrial PTB is limited because complete sections are not common and the vast inland arid areas often preserve little of the fossil record, in which only occasional studies have focused on a detailed sedimentary facies analysis across the PTB. However, the continental record, particularly the sedimentological and palaeovegetation signal, is predicted to be most strongly affected by future climate change and is most relevant to human society, so has attracted increasing attention (Newell et al., 1999; Ward et al., 2000; Algeo & Twitchett, 2010; Benton & Newell, 2014; Benton, 2018; Fielding et al., 2019). Previous work on the terrestrial PTB in China has focused on diversity and abundance changes of preserved fossils, such as tetrapods, plants and invertebrates (Young & Yeh, 1963; Qu, 1982; Zhou & Zhou, 1983; Wang & Wang, 1986, 1990; Liu, 1995; Liu et al., 2011, 2014, 2015, 2017; Xu et al., 2014; Chu et al., 2015a,b, 2018; Yu et al., 2015; Benton, 2016; Zhang et al., 2016b). Little attention has been paid to the evolution of sedimentary environments and the drastic collapse and delayed recovery of ecosystems. However, sedimentation patterns in basins are directly connected with climatic change and tectonic activity (Mountney et al., 1999; Leeder et al., 2010; Jolivet et al., 2017), which is vital to understanding palaeoclimate and palaeogeography across the terrestrial PTB.

Interacting fluvial–aeolian depositional systems can illuminate the effects of climatic change and variations of source areas related to tectonic events and relative sea-level changes (Chakraborty & Chaudhuri, 1993; Mountney, 2006; Bourquin et al., 2009; Jordan & Mountney, 2010; Rodríguez-López et al., 2014; Al-Masrahy & Mountney, 2015; Han et al., 2016; Bállico et al., 2017), and such systems are of course core in reconstructing palaeoenvironments. The identification of ancient aeolian deposits has been mostly based on their large-scale, high-angle cross-bedding and hierarchical bounding
surfaces (Thompson, 1970; Walker & Harms, 1972; Day & Kocurek, 2017), but some small-scale, low-angle cross-bedding features are indicative of aeolian deposition, i.e. planebed lamination and inverse climbing-ripples (Hunter, 1977a), translatant-ripple lamination (Hunter, 1977b), sand-drift surfaces (Clemmensen & Tirsgaard, 1990) and pin-stripe lamination (Fryberger & Schenk, 1988). In an arid climatic setting, particularly in ancient vegetation-free landscapes, exposed parts of the bar, sandflat or floodplain in a sand-dominated fluvial system are commonly subjected to wind reworking during periods of low flow (Rust, 1972; Cant & Walker, 1976; Chakraborty & Chaudhuri, 1993). Reworking of the exposed parts of sandy, braided alluvial tracts by wind often appears as thin aeolian deposits interlayered with channel deposits, which is, however, a rare but significant indicator in palaeoenvironmental analysis (Chakraborty & Chaudhuri, 1993). Although it is not easy to differentiate between aeolian and fluvial cross-bedded strata all of the time, the identification can be convincing when combined with unequivocal aeolian sedimentary structures (for example, pin-stripe lamination, grainfall and grainflow lamination and inverse-graded climbing ripples). Further, these structures can be examined with other indicators such as geochemical proxies, clay minerals and morphology of grain surfaces.

The terrestrial PTB in North China is complete and well-constrained by the extinction event, marked by the extinction of tetrapods, ostracods and conchostracans, the die-off of plants and decreased bioturbation (Institute of Geology, Chinese Academic of Geological Sciences, 1980a,b; Chu et al., 2015a, and references therein), and geochemical evidence of organic δ13C (Cao et al., 2008; Shen et al., 2012). The successions are comparable to Permian–Triassic strata in north-western China and South China (Institute of Geology, Chinese Academic of Geological Sciences, 1980a,b), which provides great opportunities for detailed sedimentological studies on representative terrestrial sedimentary sections. The aim of this work is to explore climate change by investigating how the sedimentary pattern changed across the terrestrial PTB in Shanxi, North China (Figs 1 and 2). Two representative sections were measured where the outcrop is well-exposed and palaeontological evidence is well-constrained. Through this, it was possible to identify the intensification of aeolian activity following the end-Permian mass extinction. Moreover, by comparing the sedimentary environmental changes with palaeoecological evolution (extinction and subsequent delayed recovery) across the PTB, the authors suggest that the change of climate to dry and then humid should be linked with the mass extinction and subsequent recovery across the PTB in North China.

GEOLOGICAL BACKGROUND

Outcrop location and methods

Two sections were measured in Baode County (39°00′30.23″N, 111°02′30.23″E to 39°00′07.75″N, 111°00′51.87″E) and Dongzhai Town (38°45′59.60″N, 112°04′50.22″E) in northern Shanxi Province, located approximately 500 km west of Beijing in north-east China. The section located at Baode County along the Yellow River was selected because here a mass burial of Shihtienfenia par-eiasaur fossils (Young & Yeh, 1963; Benton, 2016), comprising several complete skulls and over 100 scattered fossils, was discovered in 2015 by the Shanxi Museum of Geology. A 300 m logged section was made through the Sunjiagou and Liujiagou formations, comprising strata of Late Permian and Early Triassic age (Fig. 3A). The second section is near Dabeigou and Chenjiabangou villages, parts of Dongzhai Town in the Luliang Mountains. This section is located 120 km south-east of the Baode section and was selected because of near-continuous rock exposure across strata that extend from the earliest Late Permian Shihezi Formation to the Middle Triassic Ermaying Formation, comprising a total of ca 570 m of logged section. Further, the measured section in Dongzhai Town is 1 km, 3 km and 16 km distant from the locations of the standard sections for the Sunjiagou, Heshanggou and Liujiagou formations, respectively (in Sunjiagou, Heshanggou and Liujiagou villages). The lithofacies and sedimentary characteristics of the measured sections show nearly the same conditions as noted in their primary definitions.

Both sections form an important part of the Ordos Basin (also named Shan’ganning Basin) in North China where there are a complete Permian–Triassic sedimentary succession and well-preserved abundant fossils (Institute of Geology, Chinese Academic of Geological Sciences, 1980a,b; Chu et al., 2015a,b, 2017; Zhu et al., 2019a). Together, both sections provide relatively thick
successions across the PTB, and the recorded fossils enable dating and provide evidence of pre-extinction and post-extinction life.

**Basin setting**

The logged sections are located in the north-eastern part of the Ordos Basin, the largest cratonic basin on the North China Craton which covers an area of 400 000 km² and is bordered to the north, east, south and west by the Yin, Lülüang, Qinling, Liupan and Helan mountains, respectively (Yang et al., 2005; Sun et al., 2017). The Ordos Basin was developed on rigid Archean granulites and early Proterozoic green-schists (Yang et al., 2005), and is a broadly rectangular structure with a largely undeformed interior bounded by linear fold and fault belts around the margins, which switched from being convergent in the early Palaeozoic to convergent in the late Palaeozoic and Mesozoic (Yang et al., 2005). Multi-directional compression was particularly intensive in the Middle to Late Jurassic with thick syntectonic deposits in the foreland zones of the western Ordos thrust–fold belt and along the Yinshan–Yanshan belt (Zhang et al., 2008).

The Palaeozoic to Cenozoic stratigraphy of the Ordos Basin is around 4 to 6 km thick and dips gently to the west at an angle of less than one degree. Rocks of Cambrian to Tertiary age are present, with a significant gap corresponding to the Silurian, Devonian and early Carboniferous when there was an uplift of the North China Craton (Li et al., 2010). Early Palaeozoic marine platform carbonates, evaporites and mudstones are unconformably overlain by an alternating succession of Carboniferous to Late Jurassic fluvial, deltaic and lacustrine deposits which accumulated during a remarkably sustained episode of close to sea-level deposition in this stable cratonic setting. Coal deposits are an important component of the stratigraphy, being present in Lower Permian, Upper Triassic and Jurassic successions, but notably absent from those of Mid Permian to Mid Triassic age (Yang et al., 2005).

The Permian and Triassic rocks described in this study crop out in a north–south trending linear belt along the eastern margin of the Ordos Basin, parallel to the Yellow River which flows south across the basin. Much of the Permo–Triassic stratigraphy, such as that described here from Dongzhai, is preserved within the cores of synclines developed within the Lülüang (or

![Fig. 1. Investigated localities and generalized terrestrial Permian–Triassic strata in China. The studied sections (marked by red stars) are located in Baode and Dongzhai of Shanxi Province, North China. The generalized terrestrial Permian–Triassic strata in China modified after Inst. Geol., Chin. Acad. Geol. Sci. (1980a,b). The black dotted line on the right shows the Permian–Triassic boundary. Fm, Formation; g, gravel; m, mudstone; PTB, Permian–Triassic boundary; si, siltstone; s, sandstone.](image-url)
Shanxi) fold and fault belt. Fission track analysis indicates that uplift and deformation of the Lüliang Mountains mainly occurred after the late Early Cretaceous (Zhao et al., 2016) and would therefore not have exerted any control on Permo-Triassic sedimentation. Around the PTB, the Ordos Basin was part of a stable cratonic foreland that received sediment from the Yinsan–Yanshan tectonic belt to the north and passed southward into shallow marine

Fig. 2. Map of the study area. (A) Structural map of the northern margin of the North China Craton (modified after Zhang et al., 2009). The inset figure (modified after Benton & Newell, 2014) shows the palaeogeographic map and climate zones of the Permian–Triassic Pangaea and locations of typical terrestrial Permian–Triassic sections: (1) West Siberian/Kuznetsk Basin; (2) Precaspian/Urals foreland basin/Russian Platform; (3) Central European Basin; (4) Iberian Basin; (5) South China; (6) Karoo Basin, South Africa; (7) Satpura/Ramigunj basins, central India; (8) Bowen Basin, Western Australia; (9) Victoria Land and the central Transantarctic Mountains, Antarctica. The numbered circles with orange indicate the presence of alluvial fans and yellow for no alluvial fans. (B) Regional geological map of Baode county where the pareiasaur Shitienfenia mass burial in the Sunjiagou Formation was found within the measured section. (C) Regional geological map of Dongzhai Town in Ningwu Basin. Measured sections are marked with black bars and red stars.

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environments along the eastern seaboard of the Pangea supercontinent (Sun et al., 2017).

Permian–Triassic lithostratigraphy

Late Permian to Middle Triassic strata in the Shanxi region are a continental red-bed succession divided into the Shihezi, Sunjiagou, Liujiagou, Heshanggou and Ermaying formations, in succession upward (Figs 1 and 3). As described in detail below, each formation has a characteristic assemblage of facies that represents a distinct shift in the depositional environment. The Late Permian to Early Triassic Sunjiagou Formation (Fig. 3) is typically around 100 to 200 m thick and consists of cross-bedded, coarse-grained pebbly sandstone bodies interbedded with dark red mudstone which often contains carbonate nodules. The Early Triassic Liujiagou Formation unconformably overlies the Sunjiagou Formation and is a mixed fluvial and aeolian deposit typically around

Fig. 3. Measured stratigraphic sections of Permian–Triassic transitional sequences in northern Shanxi show the environmental change. The Permian–Triassic boundary (PTB) was located in the uppermost Sunjiagou Formation. Fm, Formation. Detailed interpretation of facies codes (for example, Sp, Sh, Gpt, etc.) are shown in Table 1. The Baode section revised from Zhu et al. (2019a) with more details based on further fieldwork.
200 m thick composed of laterally and vertically variable cross-bedded medium–coarse-grained sandstone. The late Early Triassic Heshanggou Formation, by contrast, is a fine-grained lacustrine deposit characterized by rhythmic alternations of mudstone, siltstone and occasional thin medium-grained sandstone layers (Institute of Geology, Chinese Academy of Geological Sciences, 1980a,b; Hu et al., 2009).

Permian–Triassic strata in Shanxi are comparable to other PTB sequences across North China which are preserved in various isolated synclinal basins such as the Qinshui Basin, the Ningwu–Jingle Basin and Rayuan Basin (Institute of Geology, Chinese Academy of Geological Sciences, 1980a,b; Zhang et al., 2009). All show a similar terrestrial fluvial to lacustrine fining-upward transition (Institute of Geology, Chinese Academy of Geological Sciences, 1980a,b; Chu et al., 2015a).

**Biostratigraphy and dating**

Dating of the terrestrial succession across the PTB is based on a range of biostratigraphic and sedimentological evidence. The common Late Permian plants *Ullmannia* and *Lepidopteris* were discovered in the upper part of the Sunjiagou Formation in the Dayulin, Sugou and Baode sections (Zhang et al., 2012; Chu et al., 2015a), coupled with abundant spores and pollen such as *Reduviasporites* (Liu et al., 2015) that confirm the age of the Sunjiagou Formation as Late Permian. The PTB is identified at a horizon ca 20 m below the top of the Sunjiagou Formation by the occurrence of the *Lundbladispora–Aonitisporites–Taeniaesporites* assemblage (Ouyang & Zhang, 1982), which is a typical earliest Triassic palynomorph assemblage (Krassilov & Karasev, 2009). The PTB transition near the top of the Sunjiagou Formation was also identified by an abrupt decrease in the abundance of plant material (Zhou & Zhou, 1983; Wang & Wang, 1986; Chu et al., 2018) and bioturbation (Chu et al., 2015a), evidence from continental conchostracan assemblages (Chu et al., 2017), and the last occurrence of Late Permian tetrapods including the pareiasaurs *Shihthienfenia*, *Huanghesaurus* and *Sanchuansaurus* (Young & Yeh, 1963; Gao, 1983, 1989; Benton, 2016). The Liujiagou Formation has an extremely sparse fauna and flora, but an Early Triassic age is supported by common microbially induced sedimentary structures (MISS) in the mudstones, which globally are a common feature formed after mass extinctions (Bottjer & James, 1999; Sheehan & Harris, 2004; Chu et al., 2015a, 2017; Tu et al., 2016). The MISS disappear in the Heshanggou Formation. Bioturbation intensifies from bottom to top of the Triassic beds. Plants such as *Pleuromeia* sp. (cf. *Pl. sternbergi*), *Pleuromeia* sp. (cf. *Pl. rossica*), *Neocalamites* sp. (cf. *Neuropteridium intermedium*), *Yuccites* sp. and *Voltziaceaesporites heteromorpha* zone, etc., were confirmed in the Yushe area, Shanxi Province (Institute of Geology, Chinese Academy of Geological Sciences, 1980a,b). Vertebrate fossils reoccurred in the Heshanggou Formation (for example, *Ceratodus heshanggouensis*, Temnospondyli, Capitosauridae, etc.) (Institute of Geology, Chinese Academy of Geological Sciences, 1980a,b; Shu & Norris, 1988). These fossils are part of the gradually recovering ecosystem after the PTB extinction and confirm its age as late Early Triassic (Institute of Geology, Chinese Academy of Geological Sciences, 1980a,b; Shu & Norris, 1988; Ouyang & Norris, 1999; Nesbitt et al., 2010; Feng et al., 2017; Shu et al., 2018).

**EVOLUTION OF DEPOSITIONAL SYSTEMS ACROSS THE PERMIAN–TRIASSIC BOUNDARY**

**Sunjiagou Formation**

The predominantly Late Permian Sunjiagou Formation comprises two main facies associations defined on texture, sedimentary structures, lithofacies, lithological alternations, sequence stratigraphic architecture and stratal geometry: (i) conglomerates and sandstones: fluvial channel and bar deposits (Table 1; Figs 4 and 5); and (ii) mudstone with calcrite and thin sandstones: floodplain deposits (Table 1; Figs 6 and 7). The conglomerates and sandstones range from 1 to 25 m thick, separated by mudstones which range from 1 to 20 m thick. The two facies associations occur in approximately equal proportions.

**Conglomerates and sandstones: fluvial channel and bar deposits**

**Description**

This facies association (Table 1) is characterized by massive or cross-bedded sandstones (i.e. St, Sp, Sh, Sr and Sdl facies; Table 1) and conglomerates (i.e. Gm, Gpt and Gci; Table 1), which are characteristic of the Sunjiagou Formation (Figs 4
<table>
<thead>
<tr>
<th>Facies code</th>
<th>Lithology</th>
<th>Sedimentary structures</th>
<th>Depositional process</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gm</td>
<td>Coarse-grained sandstones to cobbles (centimetre, rarely decimetre), angular to sub-rounded</td>
<td>Trough cross-bedded (decimetre to metre), imbricated structure, erosive basal boundary (Fig. 4)</td>
<td>Active current (Postma, 1990)</td>
<td>Arid alluvial fan debris flow, bypass</td>
</tr>
<tr>
<td>Gpt</td>
<td>Coarse-grained sandstones to cobbles (centimetre, rarely decimetre), sub-rounded, siliceous and some gneiss and volcanic extraformational clasts, poorly sorted</td>
<td>Planar to trough cross-bedded (decimetre to metre), maybe faint, erosive basal boundary (Figs 4 and 5A)</td>
<td>Channel lag deposits under conditions of lower flow regime (Miall, 1996; Ghazi &amp; Mountney, 2009)</td>
<td>Transverse to linguoid bedforms, or sinuous-crested</td>
</tr>
<tr>
<td>Gci</td>
<td>Coarse-grained sandstones to pebbles (thin bedded or lenticular), sub-rounded, silt and mud intraformational clasts</td>
<td>Planar to trough cross-bedded (decimetre to metre), maybe faint, erosive basal boundary (Fig. 5D). Lower contacts of these sets are erosional and sharp</td>
<td>Channel lag deposits derived from erosion of the base of the channel or from the bank collapse (Miall, 1977; Medici et al., 2015)</td>
<td>Sinuous-crested or linguoid bedforms</td>
</tr>
<tr>
<td>St</td>
<td>Sand, fine to coarse arenites, some clay chips</td>
<td>Trough cross-bedded (Figs 4, 5B and 5E)</td>
<td>The upper part of lower flow regime (Miall, 1978)</td>
<td>Sinuous-crested or linguoid bedforms</td>
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<tr>
<td>Sp</td>
<td>Sand, fine to coarse arenites</td>
<td>Planar cross-bedded (Figs 5A to F and 6)</td>
<td>Medium part of the lower flow regime (Miall, 1978)</td>
<td>Transverse bedforms</td>
</tr>
<tr>
<td>Sh</td>
<td>Sand, fine to coarse-grained</td>
<td>Planar or subplanar lamination, sharp base and top boundaries, current lineations, normal-graded (Figs 5A, E and F)</td>
<td>Tractive current, high-flow regime, sometimes underwent wave reworking (Miall, 1978; Horton &amp; Schmitt, 1996; Clemmensen et al., 1998)</td>
<td>Transverse to linguoid bedforms or sand-sheet</td>
</tr>
<tr>
<td>Sm</td>
<td>Sand, fine to coarse, sometimes coupled with scattered gravels</td>
<td>Massive bedding, sharp basal and top boundaries, sometimes with desiccation cracks at the top (Fig. 4)</td>
<td>Subaerial hyper-concentrated density flow or subaqueous high-density turbidity current (Lowe, 1982; Mulder &amp; Alexander, 2001)</td>
<td>Alluvial fan debris flow, bypass</td>
</tr>
<tr>
<td>Sr</td>
<td>Sand, fine to coarse arenites</td>
<td>Ripple cross-laminations</td>
<td>The lower part of the lower flow regime (Miall, 1978; Postma, 1990; Horton &amp; Schmitt, 1996)</td>
<td>Asymmetrical current ripples, climbing-current ripples</td>
</tr>
<tr>
<td>Sbi</td>
<td>Sand, fine-grained to siltstone, massive bioturbated</td>
<td>Massive laminations, sometimes with desiccation cracks at the top (Figs 11 and 12)</td>
<td>A reworking of sand deposits by biological activity</td>
<td>Sand-sheet, shallow lake, or floodplain reworking in a subaqueous environment</td>
</tr>
<tr>
<td>Facies code</td>
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<tr>
<td>Sdl</td>
<td>Fine to medium-grained sandstone</td>
<td>Deformed laminations, characterized by disharmonic folds. These sets overlie planar cross-bedded sandstone and are overlain by massive mudstone (Figs 8C, 10A and 10C)</td>
<td>Soft sediment deformation due to sudden water escape and bedform collapse (Owen et al., 2011; Owen &amp; Santos, 2014)</td>
<td>Overbank or migrating of sand dune deposits</td>
</tr>
<tr>
<td>Sgf</td>
<td>Coarse to medium to red sand, well-sorted and rounded, intense grading lamination</td>
<td>Planebed lamination and inverse climbing-ripple (inverse grading is common within these sets, which are 0.5 to 2.0 cm thick), translatent-ripple lamination, sandflow, grainfall laminations (Figs 8 to 10)</td>
<td>Avalanches on dune lee sides and grainfalls in the zone of flow separation (Brookfield, 1977; Hunter, 1977a; Clemmensen &amp; Abrahamsen, 1983; Clemmensen &amp; Tirsgaard, 1990), subcritical climbing translatent stratification (Hunter, 1977a,b)</td>
<td>Aeolian dune</td>
</tr>
<tr>
<td>PB</td>
<td>Sand, fine-grained, pink and white interchange, well-sorted</td>
<td>Horizontal laminations or low-angle cross-laminations (millimetre), inverse climbing ripples (Fig. 9E)</td>
<td>Tractional deposition by high wind velocity (Hunter, 1977b; Clemmensen &amp; Abrahamsen, 1983) and SCTS by decreasing wind velocity (Clemmensen &amp; Abrahamsen, 1983)</td>
<td>Aeolian sand-sheet</td>
</tr>
<tr>
<td>HL</td>
<td>Sand, fine to coarse, white to flesh pink, aeolian quartz sandstone interbedded within silt and red mudstone</td>
<td>Horizontal laminations (millimetre to centimetre), the sharp basal boundary with adhesion warts, adhesion ripples and adhesion plane beds, wind ripples (Fig. 9F)</td>
<td>Wind-blown sand to a wet or damp surface (Kocurek &amp; Nielson, 1986)</td>
<td>Interdune deposits, under sand-saturated conditions, or aeolian sand-sheets within low wind regime or low sand supply, or wet interdune</td>
</tr>
<tr>
<td>SE</td>
<td>Coarse to fine-grained sandstone</td>
<td>An aeolian trough or planar cross-bedded sandstone which often interchanged with grainfall and pin-stripe lamination (Fig. 10B and C)</td>
<td>Migration of sinuous or straight-crested aeolian dunes (Hunter, 1977a)</td>
<td>Migration of aeolian dunes</td>
</tr>
<tr>
<td>Fl</td>
<td>Red mudstone to siltstone and/or interbedded with medium to thin-bedded sandstone, bioturbated</td>
<td>Horizontal lamination, which is overlain by massive mudstone (Fig. 11B)</td>
<td>The low-flow regime, suspension settling during the waning stage of the flood in an overbank setting, frequent emergence and desiccation (Miall, 1978)</td>
<td>Overbank or waning flood</td>
</tr>
</tbody>
</table>
In the field, the units of sandstone and conglomerate range from a few metres to 25 m thick and often show major lateral changes in thickness. Concave-up basal erosion surfaces (Figs. 4 and 5) are common and are variably overlain by coarse-grained sandstones or cobble-grade conglomerates. The conglomerates are typically poorly to moderately sorted and are composed of angular to sub-rounded clasts which include gneiss and volcanic extrabasinal material.

Table 1. (continued)

<table>
<thead>
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<th>Depositional process</th>
<th>Interpretation</th>
</tr>
</thead>
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<td>Massive or horizontal lamination, mud-cracks, lenticular or ripple cross-laminated, bioturbated (Figs. 11 and 12)</td>
<td>Suspension during waning flows within a fluvial channel or in an overbank setting or floodplain distal to the main channel (Miall, 1996; Ghazi &amp; Mountney, 2009)</td>
<td>Overbank or waning flood or within a permanent water body</td>
</tr>
<tr>
<td>Fm</td>
<td>Siltstone/mudstone</td>
<td>Massive or laminated, sometimes with desiccation marks (Fig. 6)</td>
<td>Deposition from suspension, with some events of emersion (Miall, 1978)</td>
<td>Overbank or waning flood within a permanent water body, or elliptical scour downstream of a bar</td>
</tr>
</tbody>
</table>

Interpretation

An abundance of concave-up erosional surfaces

and 5). In the field, the units of sandstone and conglomerate range from a few metres to 25 m thick and often show major lateral changes in thickness. Concave-up basal erosion surfaces (Figs. 4 and 5) are common and are variably overlain by coarse-grained sandstones or cobble-grade conglomerates. The conglomerates are typically poorly to moderately sorted and are composed of angular to sub-rounded clasts which include gneiss and volcanic extrabasinal material.

Table 1. (continued)

<table>
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Mudstone with calcrite and thin sandstones: floodplain deposits

Description

This facies association (Table 1; Fig. 6) occurs mainly in the Late Permian Sunjiagou Formation and is characterized by laminated to massive thick red claystone and siltstone in units 4 to 20 m thick that are variably interbedded with thin to medium beds of medium-grained sandstone (facies Fl, Flb, Fm and Sdl; Table 1). The mudstones can be traced laterally for distances exceeding 1500 m, both parallel and perpendicular to major channel sandstone bodies. The thin to medium beds of sandstone that occur within the mudstones are tabular, with no evidence for channelization, and show unidirectional current ripples. Casts of desiccation cracks developed on the top of underlying mudstone units are sometimes preserved on the base of sandstone interbeds.

Three types of claystone and siltstone are distinguished in the field based on the colour, texture and style of occurrence: (i) massive red mudstone with carbonate nodules; (ii) laminated red mudstone without carbonate nodules but occasional grey mottling; and (iii) greenish-grey mudstone occasionally bioturbated, sometimes with massive blocky structure and a few rootlets. Massive red mudstones show a range of features including bioturbation at different intensities. Calcareous nodules of 3 to 8 cm in diameter (Fig. 6D) occasionally occur, either scattered throughout the mudstone or concentrated in discrete horizons. Ferruginous concretions are also observed. Macrofossils preserved within the mudstones include the plant Lepidoteras baodensis and the Pareiasaur tetrapod Shihitianfenia (Fig. 6B and C). Bedding surfaces at the tops of fine sediments sometimes preserve rain imprints. Laminated red mudstone commonly bears no carbonate nodules but occasional grey mottling, mostly preserved near the top of the fine sediments, bounding the overlying grey-greenish sandstones. Furthermore, thin greenish-grey mudstones were confirmed near the top of the Sunjiagou Formation, along with the last appearance of tetrapod fossils and bioturbation (Figs 3 and 7A, layer 51).

Interpretation

Mudstones (facies Fl, Flb, Fm and Sdl; Table 1) are a characteristic lithology of the Sunjiagou Formation (Figs 3, 6 and 7) and their sheet-like geometry and close association with channel belt conglomerates and sandstones suggests that they represent floodplain deposits (Mrinjek et al., 2006). The occasional presence of horizontal lamination indicates deposition from static, mud-laden flood-waters but the presence of mudcracks and rain-drop impressions shows frequent subaerial exposure without the development of long-lived lakes (Plummer & Gostin, 1981; Ghazi & Mountney, 2009). Thin, flat-based sandstones that interbed with the mudstones and show unidirectional current ripples probably represent unconfined overbank flows relatively proximal to channel belts.

The massive, destratified, character of much of the mudstone together with the presence of bioturbation, rootlets and calcareous nodules suggests extended periods of subaerial exposure and the development of palaeosols under low rates of floodplain accretion (Kraus & Gwinn, 1997). An almost continuous vertical profile of multiple, overlapping palaeosol horizons can develop...
Fig. 5. Outcrop of meandering channel-belt sandstone bodies in the Sunjiagou Formation. (A) Large-scale planar cross-bedded pebbly coarse-grained sandstone (Sp) overlies red mudstone (Flb), bounded by an uneven erosional surface, from the middle part of the Sunjiagou Formation in Baode. (B) Large-scale planar cross-bedded coarse to medium-grained sandstone (Sp) and the overlying horizontal laminated sandstone (Sh), showing the lateral accretion of a migrating point bar deposit, from the middle part of the Sunjiagou Formation in Baode. The length of the hammer is 28 cm. (C) Large-scale uneven erosional surfaces in the middle part of the Sunjiagou Formation in Baode, where normally graded bedding and large-scale trough cross-bedding are developed, and sandy filled lentillar conglomerate interbedded in the trough cross-bedded coarse-grained sandstone (Gpt). (D) Large-scale uneven erosional surfaces in the middle part of the Sunjiagou Formation at Baode, where normally graded bedding and large-scale trough cross-bedding (Gci) are developed and interbedded with red fine-grained sandstone (Sdl). (E) Large-scale planar cross-bedded medium-grained sandstone (Sp) in the middle part of the Sunjiagou Formation in the measured Baode section. (F) Large-scale planar and trough cross-bedded medium-grained sandstone (Sp) with scour-like bounding surfaces truncating cosets in the upper part of the measured Baode section.
under the typically thin incremental accretion of floodplain sediments formed by episodic overbank flooding (Bridge et al., 2000; Ghazi & Mountney, 2009). The predominant red colouration of the mudstones of the Sunjiagou Formation in association with the presence of soil carbonate (or calcrete) suggests a relatively well-drained floodplain environment under a semi-arid or monsoonal climate with pronounced wet and dry seasons (Nadon & Middleton, 1985; Sheldon, 2005). Rarely observed desiccation cracks may reveal the drying of mud or clay that had previously been water saturated (Wilkins et al., 2018).

The only exception to this generally well-drained and oxidised floodplain environment occurs at the top of the Sunjiagou Formation close to the Permo–Triassic boundary. Here an interval of greenish-grey mudstones linked to the presence of iron in a ferrous state may indicate a waterlogged, relatively hypoxic environment (Besly & Fielding, 1989). It is notable that comparable evidence for a short period of hypoxic conditions at the end of the Permian is also seen in the Karoo Basin of South Africa where they have been linked to global climatic events around the end-Permian mass extinction event (Retallack et al., 2003; Gastaldo et al., 2009).

**Liujiagou Formation**

The Early Triassic Liujiagou Formation represents a major change in the stratigraphy relative to the underlying mudstone-rich Sunjiagou Formation. The Liujiagou Formation is dominated by sandstone that can be subdivided into three major facies associations: (i) coarse to fine sandstones: braided river deposits; (ii) coarse to fine sandstones: aeolian sand dunes; and (iii) medium to fine sandstones: aeolian
sand-sheets (Table 1; Figs 7 to 10). The top of the Liujiagou Formation is marked by an abrupt return to the mudstone-dominated stratigraphy of the Heshanggou Formation. As shown in the logged section (Fig. 3), the Liujiagou Formation is approximately 230 m thick in total and is dominated by intervals of fluvial sandstones and conglomerates that are generally around 10 to 30 m thick. Fluvial deposits are separated by thinner intervals of aeolian sandstone (i.e. Sgf, PB, HL and SE facies; Table 1) which generally do not exceed more than 15 m in thickness. A few mudstone deposits (i.e. facies Fl, Flb, Fm and Sdl; Table 1), which generally do not exceed more than 1 m thick, occur throughout the fluvially-dominated parts of the formation.

Coarse to fine sandstones: braided river deposits

Description

This facies association (Table 1) is mainly distributed in the Early Triassic Liujiagou Formation and is characterized by a range of cross-bedded, laminated and massive sandstone facies (i.e. St, Sp, Sh, Sm, Sr, Sbi and Sdl; Table 1) (Fig. 8). The sandstones are fine to coarse-grained, and mostly poorly sorted. Conglomerates are represented only by maroon intraformational mudrock clasts which occur above irregular scour surfaces. Conglomerates with extraformational clasts of the type seen in the underlying Sunjiagou Formation are not present. This facies association of the Liujiagou Formation is characterized by numerous stacked cycles of planar tabular, trough and horizontally laminated sandstone abruptly overlain by thin red mudstones. Cycles are typically less than 5 m thick and are floored by undulating erosion surfaces locally overlain by reworked mudstone clasts. Convolute lamination and deformed foreset laminae are common features of the sandstones. The red mudstones which form the tops of cycles are generally less than 1 m thick and are often horizontally laminated, lacking carbonate nodules and bearing no rootlets or any fossils. Mudstones in the Liujiagou Formation differ from those in the underlying Sunjiagou Formation where bioturbation and carbonate nodules are common and occasionally bear rootlets and grey mottling.
Interpretation

The presence of numerous erosion surfaces, cross-bedded sandstones showing a unidirectional flow towards the south-east, and fining-upward cycles capped by red mudstone indicate a fluvial origin for this part of the Liujiagou Formation. The relatively small vertical thickness of the fluvial cycles and the predominance of

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planar–tabular cross-bedding is in marked contrast to the underlying Sunjiagou Formation and might indicate the development of transverse bars in broad, shallow channels (Miall, 1977; Bridge et al., 2000). Such channels may have had a braided pattern during low flow stage.
when bar tops became emergent (Cant & Walker, 1976, 1978; Miall, 1977, 1996; Allen, 1983). Abrupt transitions in the erosive-based fluvial cycles from sandstone to mudstone may indicate rapid falling stages. Most of the massive mudstones probably represent channel plugs and thicker intervals of overbank mudstone, and show well-developed pedogenic features (bioturbation, rootlets and carbonate nodules) of the type seen in the Sunjiagou Formation which are absent from the Liujiagou Formation (Fig. 8D). Coupled with the close association with aeolian

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deposits, the generally variable small-scale of planar tabular cross-bedding in the Liujiagou Formation probably indicates deposition on an arid, sandy alluvial plain with numerous shallow channels that have a high lateral migration rate (Bourquin et al., 2010).

Coarse to fine-grained sandstone: aeolian sand dunes and sand sheets

Description
This facies association (Table 1; Figs 9 and 10) mainly occurs in the Early Triassic Liujiagou Formation and is characterized by a number of facies (i.e. Sgf, PB, HL and SE facies; Table 1) developed in fine to coarse-grained, well-sorted sandstone. Units of aeolian facies association occur at intervals throughout the Liujiagou Formation and are typically 2 to 8 m thick. Aeolian strata normally overlie a sharp ‘sand-drift’ surface developed on underlying fluvial strata (Fig. 10A and C). The tops of aeolian intervals are commonly eroded by overlying fluvial deposits and laterally aeolian deposits may be entirely cut out. Sandstones of the aeolian facies association show a range of horizontal, low angle and high-angle stratification types (Figs 9 and 10).

Horizontal to low angle aeolian stratification is characterized by sets of parallel laminae which are typically 1 to 10 mm thick and show distinct segregation of sand grains into thin fine-grained layers and thicker medium-coarse grained layers. The effect is to give the sandstones a pin-stripe appearance (Fig. 9A, C, D and E; Fryberger & Schenk, 1988). Intervals of sandstone showing horizontal to low angle pin-stripe lamination range up to 1 m thick and they are the repository of small but persistent very fine sand and silt populations within the fine–medium-grained sands (Fig. 9A and B). High-angle stratified aeolian sandstone is developed as sets of trough and planar-tabular cross-bedding. Individual cross-bed sets range up to 1 m thick and form cosets up to 4 m thick, with pink and white variable colour. Foresets are variably developed as millimetre-scale, fine-grained laminae and as centimetre-thick laminae in medium to coarse-grained sand which may have an erosional base. Moreover, the inverse-graded climbing ripples in the Liujiagou Formation are separated into subcritically and supercritically climbing translatent stratification, often sloping at an angle of 10 to 26°, thin-intermediate in thickness (mostly 1 to 15 mm) and with gradational contact with the plane bedded sandstone at the bottom.

Interpretation
Aeolian sand-sheet and aeolian dune deposition in the Liujiagou Formation are suggested by an abundance of horizontal to low-angle cross-bedding and inverse graded pin-stripe laminations, grainflow and rare preserved grainfall laminations, some translatent-ripple lamination and small-scale of low to high-angle aeolian climbing ripples and a few sets of trough and planar-tabular cross-bedded sandstone. Pin-stripe laminations are very common and characterize most aeolian deposits (Fryberger & Schenk, 1988). They probably result from the downward settling of fine sand and silt within the moving avalanche at the interface of moving and unmoving sands (Fig. 9A, C, D and E in avalanche strata) or form in grainflow deposits (Fig. 9E). Aeolian planebed lamination is formed by tractional deposition on smooth surfaces at high wind velocities. The overlying inversely graded climbing ripples probably form at relatively high or supercritical angles, and are typically accompanied by planebed lamination, which comprises wavy layers parallel to rippled depositional surfaces (Fig. 9A and B; Hunter, 1977a). Translatent-ripple lamination in the Liujiagou Formation represents the translational movement of an aeolian depositional surface and is formed as wind ripples migrate under conditions of bed accretion and each individual lamina is generated by the translation of a single wind ripple (Fig. 10A; Hunter, 1977b). Sand-drift surfaces are an important type of bounding surface, formed by periodic sub-aerial exposure during fluvial deposition, and they mark environmental transitions from subaqueous to aeolian depositional processes in the Liujiagou Formation (Clemmensen & Tirsgaard, 1990). Well-preserved sandflow cross-strata are formed by avalanching of non-cohesive sands on dune slip faces, while occasionally preserved grainfall laminations in the Liujiagou Formation are formed on smooth surfaces, largely by grainfall deposition in zones of flow separation (Figs 9D, 9E, 10B and 10C; Hunter, 1977a).

Aeolian sand sheets in the Liujiagou Formation are areas of aeolian sand where dunes with slip faces are generally absent, creating aeolian deposits dominated by low-angle stratification (Kocurek & Nielson, 1986). Beds with horizontal to low-angle planar cross-bedding with inverse graded climbing ripples are interpreted as subcritical climbing translatent strata resulting from
migration, climbing and accumulation of wind ripples over a dry substrate (Hunter, 1977a; Kocurek, 1981; Basu et al., 2014). Aeolian dunes that cross strata or underlie floodplain and ephemeral channel deposits are often consistent with deflation surfaces, which may be a response to the migration of ergs or climatic changes (Kocurek, 1988). The depositional cycle of aeolian sand-sheets and waterlain deposits succeeded by aeolian dune and interdune deposits indicates a drying-upward trend (North & Prosser, 1993; Bálico et al., 2017).

Overall, the well-preserved aeolian deposition in the Liujiaogou Formation is an important marker of arid conditions, which could provide valuable information for environmental reconstructions and short-term and long-term climate changes. It can also be compared with similar fluvial–aeolian deposits identified in the Jurassic Tianchihe Formation of the Ningwu–Jingle Basin, North China (Xu et al., 2019) and on Mars (Grotzinger et al., 2005; Edgar et al., 2018).

Heshanggou Formation: claystone and mudstone – shallow lacustrine deposits

Description
This facies association (Table 1; Figs 11 and 12) mainly occurs in the late Early Triassic Heshanggou Formation, which is an important marker of the trend towards a humid depositional environment. The succession mainly comprises cycles of red mudstone to siltstone and/or interbedded with a few thin medium-grained sandstone layers (facies Fl, Flb and Fm; Table 1). While massive beds are common, others show horizontal lamination (Fig. 11A and B), mud cracks (Fig. 11C) and lenses of ripple cross-lamination. Vertebrate (tetrapod) and invertebrate trace fossils are observed (Fig. 12). Further, bioturbation in the Heshanggou Formation becomes more frequent from the base of the formation to the top.

Interpretation
The fine grain size and near absence of current-generated structures in the Heshanggou Formation (facies Fl, Flb and Fm; Table 1) indicate deposition from suspension in temporary bodies of standing water (Fielding, 1984; Scherer et al., 2007), that were subject to wave currents and occasional bedload deposition of sand. Casts of shrinkage mudcracks found within the sequence are diagnostic of environments periodically subjected to subaerial exposure (Plummer & Gostin, 1981). Some of the shallow lake deposits alternate with well-drained floodplain or mudflat facies and these may have developed periodically in parts of the basin. They are affected by the balance between water input from surrounding river systems and evaporative loss; similar alternations of dry mudflat and shallow lake environments have been identified in the modern Lake Eyre Basin, Central Australia (Magee et al., 2004).

Abundant trace fossils (for example, Plano- lites, Psilonichnus, Scoyenia, Skolithos and Taenidium) were observed in the field and have also been reported from other sections in the Heshanggou Formation (Hu et al., 2009; Chu et al., 2017). They suggest that the Heshanggou Formation was deposited in a shallow lacustrine environment under a semi-arid climate. Besides, many trace fossils from reptiles were observed on the surface of intercalated greenish medium-grained sandstones (Fig. 12) and plenty of gravel scattered in massive siltstone. These suggest that the Heshanggou Formation was deposited in an overbank or shallow lacustrine environment that was periodically subjected to subaerial exposure and underwent periodic flooding.

SEDIMENTARY FACIES CHANGE THROUGH THE PERMIAN–TRIASSIC TRANSITION

The five facies recognized in the Permian–Triassic sections at Baode and Dongzhai can be grouped into three larger facies associations; meandering river, braided river-aeolian deposits and shallow lacustrine deposits (Fig. 13). Larger channel and point bar, as well as floodplain meandering sequences, were mainly developed in the Late Permian Sunjiagou Formation (Fig. 13A). The Early Triassic Liujiaogou Formation is characterized by braided rivers of arid sand bars interacting with some preserved aeolian dunes and a few floodplain deposits (Fig. 13B). Shallow lacustrine deposits occur in the late Early Triassic Heshanggou Formation (Fig. 13C). The meandering sequences in the Sunjiagou Formation are characterized by sequences of light grey, greenish, coarse sandstone and overlying dark red mudstone (1 : 1 ~ 1 : 2 in thickness), most of which were deposited in point bar and floodplain environments as a result of lateral accretion of meandering streams. The braided–aeolian deposits in the Liujiaogou Formation are characterized by a high
proportion of sandstones where diverse trough and planar cross-bedding ranging from low-angle to high-angle alternate vertically and laterally. The shallow lacustrine deposits of the Heshanggou Formation are characterized by cycles of siltstones and/or mudstones interbedded with a few thin, fine to medium-grained sandstone layers.

DISCUSSION

Increasingly aridity in palaeoclimate around the terrestrial Permian–Triassic boundary in the eastern Ordos Basin, North China

The sedimentary facies analysis has shown a transition from meandering rivers in the Sunjiagou Formation to braided river–aeolian interactions in the Liujiagou Formation in the eastern Ordos Basin, which may reveal a palaeoenvironmental change from semi-arid to arid conditions around the PTB. In particular, the intensification of aeolian activity in the Liujiagou Formation probably reveals an increasingly arid palaeoclimate and depression of palaeoecosystems in the Early Triassic, which is supported by several lines of evidence.

First, the sedimentary patterns of the Liujiagou Formation support an increasingly arid palaeoenvironment. In an arid climatic setting, particularly for ancient vegetation-free landscapes, the preservation of wind reworking of the exposed parts of the sandy, braided alluvial tracts often showed as thin aeolian deposits interlayered with channel deposits (Clemmensen, 1978; Kocurek, 1981; Kocurek & Nielson, 1986; Chakraborty & Chaudhuri, 1993; Clemmensen et al., 1998). The Early Triassic Liujiagou Formation is mainly associated with braided stream and linguoid and
transverse bar facies, which is best matched with a distinctly arid climatic setting. Therefore, the preservation of aeolian–braided river interactions in the Liujiagou Formation is a significant indicator of an increasingly arid palaeoenvironment in the Early Triassic. Further, the aeolian facies association (St, Sp, Sh, Sgf, PB, HL and SE; Table 1) in the Liujiagou Formation probably reveal oscillating arid conditions (Hunter, 1977b; Clemmensen & Tirsgaard, 1990; Clemmensen et al., 1998). Similar arid braided–aeolian deposition was also confirmed in other places, such as the Upper Jurassic–Lower Cretaceous Kalaza Formation in Central Asia (Jolivet et al., 2017), Mars (Grotzinger et al., 2005; Edgar et al., 2018) and so on.

Second, the similar tectonic setting across the PTB in North China suggests that palaeoclimate was the main control on sedimentary facies changes, recording increasing aridity in the Early Triassic. Climate, sedimentation and tectonics are three important factors that have an impact on the preservation of sedimentary systems (Olsen & Larsen, 1993; Péron et al., 2005; Bourquin et al., 2009, 2010; Xu et al., 2019; Zhu et al., 2019b). In the Ordos Basin, Late Permian to Early Triassic sedimentary environmental conditions varied significantly with increasing aridity, as indicated by the transverse bar facies, which is best matched with a distinctly arid climatic setting. Therefore, the preservation of aeolian–braided river interactions in the Liujiagou Formation is a significant indicator of an increasingly arid palaeoenvironment in the Early Triassic. Further, the aeolian facies association (St, Sp, Sh, Sgf, PB, HL and SE; Table 1) in the Liujiagou Formation probably reveal oscillating arid conditions (Hunter, 1977b; Clemmensen & Tirsgaard, 1990; Clemmensen et al., 1998). Similar arid braided–aeolian deposition was also confirmed in other places, such as the Upper Jurassic–Lower Cretaceous Kalaza Formation in Central Asia (Jolivet et al., 2017), Mars (Grotzinger et al., 2005; Edgar et al., 2018) and so on.

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Fig. 13. Sedimentary environment evolution across the Permian–Triassic transition in eastern Ordos Basin of northern Shanxi Province, North China. (A) Meandering river deposits in the Late Permian Sunjiagou Formation. (B) Braided river-aeolian deposits in the Early Triassic Liujiagou Formation. (C) Shallow lacustrine deposits in the late Early Triassic Heshanggou Formation.
changes and sediment accumulation rate were controlled by a combination of eustatic sea-level changes, local tectonics and global climatic change. Disentangling the effects of each is difficult. The persistent uplifting tectonics in northern North China as a response to the final closure of the Palaeo-Asian Ocean and collision between the Mongolian arc and North China Craton along the Solonker Suture Zone (Zhang et al., 2009) would provide a simple explanation for a change from meandering rivers to braided-aeolian high-energy depositional conditions across the PTB. However, such tectonics cannot explain the reversion to lacustrine conditions at the end of the Early Triassic. Further, all of the sandstones through the Permian–Triassic succession show similar provenance (Yang et al., 2005; Zhou et al., 2017; Zhu et al., 2019a) based on palaeocurrent analysis, petrographic analysis, detrital zircon ages and geochemical proxies (for example, Ti/Al). Together, these observations suggest that the sedimentary environmental transition across the PTB was largely linked to palaeoclimatic change rather than changes in sand provenance. Therefore, it is reasonable to conclude that the intensification of aeolian activity in the Liujiagou Formation suggests some dramatic changes around the PTB that triggered increasing aridity.

Third, palaeontological evidence supports increasing aridity from the end-Permian to Early Triassic in North China. Based on detailed investigations on the palaeovegetation of the Upper Permian and Lower Triassic, Wang (1985) identified the main flora types across the PTB, and pointed out that the so-called ‘Cathaysian floras’ in the Late Permian to Early Triassic in North China actually represent a mixed association of Euramerican elements (arid indication) with some Cathaysian components. Therefore, the palaeovegetation suggests an overall arid palaeoclimate in the Late Permian–Early Triassic strata. Abundant spores and pollen from the Middle–Late Permian in North China reveal a wet-hot palaeoclimate, but with increasing drying conditions. The identification of MISS in the Liujiagou Formation proves an arid and lowland environment in the Early Triassic (Chu et al., 2015a).

Fourth, previous researches on other terrestrial PTB sections identified the same pattern of increasing aridity in the Early Triassic, strongly suggesting that the change cannot readily be explained in each case by regional tectonics. The remarkable change in fluvial pattern (meandering river to braided river) at the terrestrial PTB has been identified in the Karoo Basin of South Africa (Smith, 1995; Ward et al., 2000; Viglietti et al., 2017), Russian Platform (Newell et al., 1999, 2010), Ranigaj Basin in India (Sarkar et al., 2003), Bowen Basin in Australia (Michaelsen, 2002), Brazil (Zerfass et al., 2003), Kuznetsk Basin in Siberia (Davies et al., 2010) and Spain (Arché & López-Gómez, 2005; Mujal et al., 2018). In each case, local tectonic and basin subsidence (accommodation space, sediment supply and hydrodynamics) might be involved, but the fact that the switch seems to be nearly global in occurrence suggests that it was probably triggered by global changes in aridity and plant cover of soils. By analysing the similar fluvial transition on the Russian Platform and the Karoo Basin of South Africa, both Newell et al. (1999) and Ward et al. (2000) pointed out that the meandering to braided fluvial shift across the PTB cannot be explained by local tectonic activity. These authors noted that high rates of erosion following the rapid and extensive die-off of rooted plant life and mass wasting of landscapes and wash-off of soils into the oceans, marked the beginning of a 10 Myr ‘coal gap’; in other words, the global loss of forests (Retallack, 1995). Therefore, it is reasonable to assume that the sedimentary mode switch (increasing aeolian activity and fluvial pattern changes) across the PTB in North China is largely linked to global climatic change against a background of global regression (Millne et al., 2009; Yin et al., 2014; Baresel et al., 2017) when the simultaneous environmental changes (for example, increasing aridity) and the onset and aftermath of the mass extinction across the PTB are combined. The remarkable change in fluvial pattern across the PTB in Shanxi supports previous results from other terrestrial Permian–Triassic sections around the world (e.g. Newell et al., 1999, 2010; Ward et al., 2000).

In addition, the intensifying weathering and aridity through the terrestrial Permian–Triassic strata in North China are confirmed by geochemical data (Cao et al., 2019; Zhu et al., 2019a). Multiple weathering indexes (for example, Chemical Index of Alteration (CIA), Chemical Index of Weathering (CIW) and Plagioclase Index of Alteration (PIA)) and clay minerals all suggest increasingly intense weathering (a major excursion towards higher values) around the PTB in North China (Cao et al., 2019; Zhu et al., 2019a) and South China (Xu et al., 2017a,b). A similar greater intensity in weathering and increasing aridity were also confirmed in the Karoo Basin of South Africa (Ward et al., 2000; Retallack et al., 2003), Russia (Newell et al.,
Mass extinction and delayed recovery across the terrestrial Permian–Triassic boundary in North China

North China is one of the best investigated palaeontological study areas across the terrestrial PTB in the world (Institute of Geology, Chinese Academic of Geological Sciences, 1980a,b; Grauvogel-Stamm & Ash, 2005; Nesbitt et al., 2010; Chu et al., 2015a, and references therein; Chu et al., 2015b, 2017, 2018; Benton, 2016) where the Permian–Triassic sequences are thick and complete (Institute of Geology, Chinese Academic of Geological Sciences, 1980a,b), which provides a great opportunity for detailed palaeontological and sedimentological study. Previous analysis and comparison to shifting diversity and morphology among fossil plants (Ouyang & Zhang, 1982; Qu, 1982; Wang & Wang, 1982, 1986, 1990; Zhou & Zhou, 1983; Wang, 1984, 1989, 1993, 1996; Wang & Zhang, 1998; Chu et al., 2015a, 2018), tetrapods (Young & Yeh, 1963; Gao, 1983, 1989; Liu et al., 2011, 2014, 2015, 2017; Xu et al., 2014; Benton, 2016) and bioturbation (including MISS) (Liu, 1995; Bottjer & James, 1999; Sheehan & Harris, 2004; Hu et al., 2009; Chu et al., 2015a, 2017; Tu et al., 2016) identified that the mass extinction and delayed recovery did occur across the PTB in North China. In particular, both of these phenomena were confirmed by the succession of plant communities through the Permian–Triassic interval in North China (Wang & Wang, 1982, 1986, 1990; Wang, 1984, 1989, 1993, 1996; Wang & Zhang, 1998). Based on previous palaeontological evidence through the PTB and the newly identified MISS in the Liujiagou Formation, Chu et al. (2015a) recognized the mass extinction near the boundary of the Sunjiagou and Liujiagou formations and delayed recovery in the Heshanggou Formation.

In this study, abundant tetrapod fossils (bones and skeletons of the pareiasaur Shihtienfenia; Figs 3 and 6C) were discovered in the Sunjiagou Formation, a number of fossil traces of tetrapods were discovered in the Heshanggou Formation (Figs 3 and 11) and bioturbation with different intensities (greatly decreased in the Sunjiagou Formation and gradually recovered in the Heshanggou Formation; Fig. 12) was confirmed in the field. Coupled with previous palaeontological evidence (e.g. Chu et al., 2015a; Benton, 2016), the ages of strata (Shihezi, Sunjiagou, Liujiagou and Heshanggou formations) were well-constrained. The mass extinction around the PTB and the delayed recovery of palaeoecosystems in the late Early Triassic were also identified in outcrop.

Implications for possible causes of the mass extinction and delayed recovery

The sedimentary transition from meandering rivers to braided river–aeolian interactions around the PTB and then to a shallow lacustrine environment in the late Early Triassic in the eastern Ordos Basin reveal a palaeoenvironmental change from semi-arid to arid conditions across the PTB, and then to semi-humid conditions. Significantly, the environmental transition shows contemporaneous changes with the mass extinction and delayed recovery. Similar conditions were also identified around the Jurassic–Cretaceous boundary (Yi et al., 2019).

All observations of terrestrial PTB sections from North China as well as from other sections worldwide should be integrated into a coherent ‘cause and effect’ model. The onset of the mass extinction around the PTB coincided with an abrupt change in emplacement style of the contemporaneous Siberian LIP (Burgess et al., 2017), which may have been an effective trigger (Shen et al., 2019a,b). The associated emissions of greenhouse gases caused warming of land and oceans, stagnation and ocean floor anoxia, associated with acid rain (sulphur volatiles), that
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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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