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 laminations) 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-Permain 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, palaeoclima, palaeoecology,
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 change 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, H. et al., 2016; Zhang, Y. et al., 2016; 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 and 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, 2015b, 2018; Yu et al., 2015; Benton, 2016; Zhang, Y. et al., 2016). 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, et al., 2010; Rodríguez-López et al., 2014; Al-Masrahy & Mountney, 2015; Han et al., 2016; Bálico 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), translatent-ripple lamination (Hunter, 1977b), sand-drift surfaces (Clemmensen & Tirsgaard, 1990) and pin-stripe lamination (Fryberger & Schenk, 1988). In an arid climatic setting, particularly in

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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, 1978; 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 the time, the identification can be convincing when combined with unequivocal aeolian sedimentary structures (for example, pin stripe lamination, grainfall and grain flow 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; Qu, 1980; Chu et al., 2015a, and references therein), and geochemical evidence of organic δ13C (Cao et al., 2008; Shen et al., 2012). The succession is 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* pareiasaur 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 Lüliang 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., 2015, 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
This cratonic basin on the North China Craton which covers an area of 400 000 km\(^2\) and is bordered to the north, east, south and west by the Yin, Lüliang, 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 greenschists (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 divergent 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 Lüliang (or 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 Yinshan–Yanshan tectonic
belt to the north and passed southward into shallow marine 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 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 Academic 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 Ruyuan basin (Institute of Geology, Chinese Academic of Geological Sciences, 1980a, b; Zhang et al., 2009). All show a similar terrestrial fluvial to lacustrine fining-upward transition (Institute of Geology, Chinese Academic 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.
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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 calcrete 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 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 (Fig. 4) 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 extraformational material. Conglomerates show horizontal bedding or planar and trough cross-bedding on a range of scales from decimetre to metre. These typically pass upward into sheets of planar-tabular cross-bedded sandstone (facies Sp unit; Figs 4 and 5), normal-graded coarse to fine-grained sandstone or ripple cross-laminated sandstone. Lateral accretion bedding composed of inclined beds of sandstone showing climbing ripple or horizontal lamination alternating with beds of dark red mudstone are occasionally preserved, usually where the sandstone and conglomerate bodies transition upward into overlying mudstones. Sets of lateral accretion lateral bedding often terminate laterally in a lenticular body of mudstone.

Interpretation. An abundance of concave-up erosional surfaces, unidirectional cross-bedded sandstones and conglomerates, and associated terrestrial plants and tetrapod fossils indicates a fluvial origin for the Sunjiagou Formation (Figs 4 to 7). The erosively amalgamated units of
cross-bedded sandstone and conglomerate represent the deposits of channel fills and bars within a channel belt where there were multiple episodes of deposition and erosion (Zhu et al., 2019a).

Medium to large-scale planar-tabular and trough cross-bedded sandstone was probably deposited on the lower parts of migrating bars (Fig. 5). Lateral accretion bedding composed of alternating sandstone and mudstone was deposited on bar tops during alternating phases of flood and falling stage flow. These deposits might indicate the development of point bars in a meandering channel system and typically transition into dark red mudstones and thin fine-grained sandstones that represent floodplain deposition adjacent to channel belts. Lateral accretion bedding passes laterally into channel plugs composed of mudstone which may have formed following channel abandonment by processes such as neck cut-off (Fig. 5A to F; Bridge et al., 2000).

**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: massive red mudstone with carbonate nodules; laminated red mudstone without carbonate nodules but occasional grey mottling; 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 *Lepidotris baodensis* and the Pareiasaur tetrapod *Shihtienfenia* (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, 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 under the typically thin incremental accretion of floodplain sediments formed by episodic overbank flooding (Bridge, 2006; 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 these 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 water-logged, relatively hypoxic environment (Besly, 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 seen. This
The 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 motting.

Interpretation. The presence of numerous erosion surfaces, cross-bedded sandstones showing a unidirectional flow toward 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 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; Allen, 1983; Miall, 1977, 1996). 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 showing well-developed pedogenic features (bioturbation, rootlets and carbonate nodules) of the type seen in the Sunjiagou Formation are absent from the Liujiagou Formation (Fig. 8D). Coupled with the close association with aeolian 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 & Christopher, 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.
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 important types of bounding surface, formed by periodic subaerial 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 indicate a drying-upward trend (North & Prosser, 1993; Bálico et al., 2017).

Overall, the well-preserved aeolian deposition in the Liujiagou 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., 2018) 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, *Planolites*, *Psilonichnus*, *Scyenia*, *Skolithos* and *Taenidium*) were observed in the field and have also been reported from other sections in the Heshanggou Formation (Chu et al., 2017; Hu et al., 2009). 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

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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 Liujiagou 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 Liujiagou 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; Clemmensen et al., 1998; Chakraborty & Chaudhuri, 1993). 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) 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, 1993; Péron et al., 2005; Bourquin et al., 2009, 2010; Xu et al., 2018; Zhu et al., 2019b). In the Ordos Basin, Late Permian to Early Triassic sedimentary environmental 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 provenances (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 floral 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; Newell et al., 2010), Raniganj 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 et al. 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 (Milne 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., 1999, 2010), the Iberian Ranges of Spain (Mujal et al., 2017, 2018) and the North Sea (Péron et al., 2005; Bourquin et al., 2011; Wilson et al., 2019). Moreover, previous studies of marine successions across the PTB consistently show evidence of intensified chemical and physical weathering conditions and wash-off of terrestrial silica-rich and organic-rich sediments into the ocean (Algeo & Twitchett, 2010; Shen et al., 2015; Song et al., 2015; Xie et al., 2017).
It is worth noting that active aeolian sand sheets in the Askja region of north-east Iceland (Mountney & Russell, 2004) prove that aeolian systems are not restricted to hot environmental conditions. The authors therefore propose that the palaeotemperature across the PTB in North China may not have been the dominant part of the climate change. A relatively stable temperature is also supported by palaeontological evidence of pre-crisis and post-crisis plants from western Europe, Siberia and North China (Grauvogel-Stamm & Ash, 2005).

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 (Grauvogel-Stamm & Ash, 2005; Qu, 1980; 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 (Wang, 1984, 1989, 1993, 1996, Wang & Wang, 1982, 1986, 1990; Ouyang & Zhang, 1982; Qu, 1982; Zhou & Zhou 1983; 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) (Bottjer, 1999; Sheehan & Harris, 2004; Liu, 1995; 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, 1984, 1989, 1993, 1996, Wang & Wang, 1982, 1986, 1990; 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 paracisaur 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, Ljiugou 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 stripped the landscape of plants and soils and acidified the oceans (Benton & Twitchett, 2003; Huey & Ward, 2005; Algeo et al., 2011; Burgess et al., 2017; Black et al., 2018). Massive soil erosion may have followed the destruction of land vegetation by volcanogenic disturbance of atmospheric chemistry (acid rain), increasing aridity and intensity in weathering. The excessive supply of soil materials to the oceans may provide a direct link between terrestrial and marine ecological crises, suggesting that ecosystem collapse on land could have contributed to the
end-Permian marine extinctions (Sephton et al., 2005; Algeo & Twitchett, 2010; Algeo et al., 2011; Benton & Newell, 2014; Benton, 2018). At this turnover, the increasing aridity of palaeoclimate and the mass extinction (including the die-off of plants) may have contributed to the meandering river to braided river and interacting aeolian environmental transition. At the beginning of the late Early Triassic Heshanggou Formation, the palaeoenvironment transited from semi-arid to humid conditions. A warm and relatively humid palaeoenvironment was suitable for the recovery of ecosystems. The relatively developed palaeoecosystem provided sufficient living space and food sources for the recovery and subsequent prosperity of life.

CONCLUSION

This study has identified an intensification of aeolian activity in the Liujiagou Formation in the eastern Ordos Basin of Shanxi Province, North China, which is an important indicator of an increasingly arid palaeoclimate in the Early Triassic. The environmental transition from meandering rivers in the Sunjiagou Formation to braided river–aeolian interactions in the Liujiagou Formation and then to shallow lacustrine environments in the Heshanggou Formation reveal increasingly arid conditions around the Permian–Triassic boundary (PTB) and a shift to semi-humid and humid palaeoclimates in the late Early Triassic in North China. These suggest that the contemporaneous changes in sedimentary environments associated with the mass extinction and delayed recovery of palaeoecosystems across the PTB in Russia, South Africa, Australia and Europe. The increasingly arid and then semi-humid and humid palaeoclimate changes may have been triggered by the sharply rising temperatures and acid rain associated with the eruption of the Siberian Traps.

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Table Caption

Table 1. Summary of lithofacies types observed in the Permian–Triassic strata.

Figure Captions

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. Abbreviations: Fm, Formation; PTB, Permian–Triassic boundary; m, mudstone; si, siltstone; s, sandstone, g, gravel.

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/Raniganj 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 Shittenfenia 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.

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. Abbreviations: 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. (2019) with more details based on further fieldwork.

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Fig. 4. Transverse outcrop of braided channel-belt sandstone bodies overlying floodplain in the middle part of the Sunjiagou Formation. Note: Flags (circled) in the photograph provide the scale and line A–A’ indicates the measured location. Abbreviations of facies are explained in the Fig. 4 caption.

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 surfaces, 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 an 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 lenticular 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 scoured-like bounding surfaces truncating cosets in the upper part of the measured Baode section.

Fig. 6. Outcrop of meandering floodplain sediments in the Sunjiagou Formation. (A) Typical meandering sequences of light grey greenish coarse sandstone (Sp) and overlying dark red mudstone (Fbl, Fm) in the Sunjiagou Formation. The geologist in the figure is 1.70 m tall. (B) Outcrop of the latest Permian pareiasaur Shihtienfenia fossil quarry, located in a floodplain environment of the middle part of the Sunjiagou Formation in Baode County; several complete
skulls and hundreds of scattered fossils were excavated. (C) Skulls and scattered fossils of pareiasaur *Shihtienfenia* fossils in the fossil quarry. (D) Calcareous nodules that occasionally occur in disorder or as thin interlayers in the Sunjiagou Formation. The length of the pencil is 12 cm.

**Fig. 7.** Outcrop photographs and field sketch of the Permian–Triassic boundary (PTB) in Shanxi, North China. (A) Terrestrial PTB from Baode County. The last appearance of the pareiasaur *Shihtienfenia*, bioturbation and synchronous negative excursions of soil carbonate $\delta^{13}$C, $\delta^{18}$O and geochemical proxies were confirmed at the PTB. The geologist in the figure is 1.70 m tall. (B) Terrestrial PTB at Dongzhai Town. They both show a meandering to braided–aeolian environmental switch across the PTB: (B) is from Zhu et al. (2019a).

**Fig. 8.** Outcrop of braided river deposits in the Liujiagou Formation. (A) Variable planar cross-bedding and parallel bedding that formed in a transverse to linguoid bedform environment. (B) Deformed laminations in braided sand bars or overbank due to sudden water escape and bedform collapse. (C) The interaction of transverse to linguoid bars and aeolian sand dune deposits. (D) Shifting trough cross-bedded coarse-grained sandstone and overlying parallel bedding that maybe deposited in a braided channel environment. (E) Variable cross-bedding formed in aeolian sand dunes incised by aeolian sand-sheets. (F) Fluvial floodplain and upper part aeolian sand dunes, distinguished by a sand-drift surface; grainflow lamination planebed lamination are developed in the sand dunes and inverse climbing ripples often represent the migrating aeolian bar deposit formed by high-speed wind: (F) is revised from Zhu et al. (2019a).

**Fig. 9.** Outcrops of aeolian deposits in the Liujiagou Formation. (A) Planebed lamination and the overlying inverse climbing ripples formed at high speed wind (migrating aeolian bar deposition) overlying pin stripe laminated sandstone (B) Planebed lamination and inverse climbing ripples formed at high speed wind in migrating aeolian bars. (C) Typical aeolian pin stripe lamination, indicated by the white arrow. (D) Pin stripe lamination and migrated planar cross-bedding that
formed in aeolian dune deposition. (E) Typical aeolian sand-sheet; where horizontal to low-angle inclined, parallel laminated medium to fine-grained sandstone contains well-sorted, sub-angular to sub-rounded grains. These sets are inversely graded and range from 1 to 5 cm thick. Pin stripe, grainfall and grainflow laminations are also well-preserved. The length of the hammer is 28 cm. (F) Aeolian wind ripples along the base of aeolian dunes.

Fig. 10. Typical sedimentary structures of aeolian deposits in the Liujiagou Formation. (A) Braided sand bars incised by aeolian sand-sheet and aeolian dune deposit in the lowermost Liujiagou Formation in the Baode section; translatent-ripple lamination form as wind ripples migrate under conditions of bed accretion and each individual lamina is generated by the translation of a single wind ripple; sand-drift surface formed by periodic subaerial exposure of fluvial deposits. The length of the notebook is 18 cm. (B) Planar cross-bedded coarse–medium-grained sandstone in the lower part of the Liujiagou Formation in the Dongzhai section, where aeolian grainflow lamination and sand-drift surfaces were also developed. The geologist in the figure is 1.75 m tall. (C) Soft-deformed medium-grained sandstone overlain by planar cross-bedded fine–medium-grained sandstone; the braided sandbar and overlying aeolian dune deposit were bounded by a sand-drift surface, and massive grainfall and grainflow lamination was developed in the upper part of an aeolian sand dune.

Fig. 11. Outcrop of shallow lake deposit in the Heshanggou Formation. (A) Lithological association from the late Early Triassic (Spathian) Heshanggou Formation. The standing in the figure is 1.75 m tall. (B) Horizontally laminated siltstone-mudstone in the Heshanggou Formation, where worm-trail fossils are developed. (C) Mud-cracks in the Heshanggou Formation, indicating intermittent exposure to the surface. (D) Gravel scattered in massive siltstone.

Fig. 12. Fossil evidence for ecological recovery in the late Early Triassic (Spathian) Heshanggou Formation. (A) and (B) Overview of footprint fossils formed by a tetrapod such as a pareiasaur. They are preserved on the surface of a greyish green medium-grained sandstone layer. (C) and (D)
Close-up of possible tetrapod footprints. (E) and (F) Various ichnofossils preserved in greyish green medium-grained sandstone interlayers, deposited in a shallow-shore lake palaeoenvironment. The length of the hammer is 28 cm.

**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.
<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>
</tr>
<tr>
<td>Sp</td>
<td>Sand, fine to coarse arenites</td>
<td>Planar cross-bedded (Figs 5A to 5F and 6)</td>
<td>Medium part of the lower flow regime (Miall, 1978)</td>
<td>Transverse bedforms</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
<td>Sedimentary Structures and Processes</td>
<td>Depositional Environment</td>
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<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, 5E and 5F)</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>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</td>
<td>Soft sediment deformation due to sudden water escape and bedform collapse (Owen et al., 2011, Owen and Santos, 2014)</td>
<td>Overbank or migrating of sand dune deposits</td>
</tr>
<tr>
<td>Acronym</td>
<td>Description</td>
<td>Remarks</td>
<td>Location</td>
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<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.), translent-ripple lamination, sand flow, 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, 1990), subcritical climbing translent stratification (Hunter, 1977a, 1977b)</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</td>
<td>Migration of sinuous-or straight-crested</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>
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| Flb  | Red mudstone to siltstone, bioturbated                                                                 | Massive or horizontal lamination, mud-cracks, lenticular of ripple cross-laminated, bioturbated (Figs 11 and 12) | Suspension during waning flows within a fluvial channel or in an overbank setting or floodplain distal to the main channel (Miall, 1996, Ghazi & Mountney, 2009) | Overbank or waning flood or within a permanent water body |
| Fm   | Siltstone/mudstone                                                                                  | Massive or laminated, sometimes with desiccation marks (Fig. 6)         | Deposition from suspension, with some events of emersion (Miall, 1978) | Overbank or waning flood within a permanent water body, or elliptical scour downstream of a bar |
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