Magnetostratigraphy of Permian/Triassic boundary sequences in the Cis-Urals, Russia: No evidence for a major temporal hiatus

Graeme K. Taylor a,⁎, Christopher Tucker a, Richard J. Twitchett a, Timothy Kearsey a, Michael J. Benton b, Andrew J. Newell c, Mikhail V. Surkov d, Valentin P. Tverdokhlebov d

a School of Earth, Ocean and Environmental Sciences, University of Plymouth, Drake Circus, Plymouth PL4 8AA, UK
b Department of Earth Sciences, University of Bristol, Bristol BS8 1RJ, UK
c British Geological Survey, MacLean Building, Wallingford OX10 8BB, UK
d Geology Institute of Saratov State University, Astrakhanskaya 83, 410075 Saratov, Russia

A R T I C L E   I N F O

Article history:
Received 6 June 2008
Received in revised form 3 February 2009
Accepted 6 February 2009
Available online 5 March 2009

Editor: R.D. van der Hilst

Keywords:
Magnetostratigraphy
Permian–Triassic boundary
Russia
Tatarian

A B S T R A C T

During the last five years there has been considerable doubt over the age of the continental uppermost Permian Russian stages, the Kazanian and Tatarian. Traditionally they have been regarded as Late Permian but were re-dated as Middle Permian in the 2004 international time scale, despite fossil evidence that the Tatarian, at least, is Late Permian. These debated ages are tested by magnetostratigraphic study of five sections spanning the Permian Triassic Boundary (PTB) of the SE Urals in the Orenburg region of Russia. The Upper Permian and Lower Triassic of this region have a well documented vertebrate fauna whose evolution has a significant bearing on our understanding of the PTB mass extinction event. If the Tatarian is viewed as Mid Permian, then the Late Permian in Russia is marked by a 9–10 Ma stratigraphic gap. The palaeomagnetic data yield a distinct series of polarity zones that provide clear local and regional correlation and are readily tied to a recently compiled global magnetostratigraphic record. On the basis of this correlation the sampled sections span the upper Guadalupian to Induan stages without any obvious break, so confirming the traditional view that the Tatarian is Late Permian in age. Anomalies in the magnetic inclination are consistent with sediment compaction (inclination shallowing, a common phenomenon of red beds) but declination anomalies between these sites and elsewhere in Russia may suggest localised vertical axis rotation.

© 2009 Elsevier B.V. All rights reserved.

1. Introduction

The Late Permian mass extinction event is regarded as the greatest single extinction event in geological history with an estimated loss of 80–90% of marine species (Benton, 2003). Our knowledge of this event has grown significantly in recent years (Twitchett, 2006) following stratigraphic research of marine Permian–Triassic strata associated with identification of the base-Triassic GSSP (Global Boundary Stratotype Section and Point), which is accepted as the first appearance datum of the conodont Hindeodus parvus, in Meishan, South China (Yin et al., 2001). Our understanding of the extinction event in the terrestrial realm is, however, relatively poor. A key problem is the dating and correlation of the terrestrial deposits. Hitherto, the main correlative tool for Permian continental successions has been a fossil vertebrate-based biostratigraphic scheme derived from the study of the Karoo Supergroup in South Africa (Rubidge, 1995; Lucas, 2006). However, these biozones cannot be directly correlated with marine stratigraphy, and phylogenetic problems with some of the key zonal taxa (e.g. Dicynodon), may limit their use in global correlation (Angielczyk and Kurkin, 2003). Attempts to establish a stratigraphic system based on carbon isotopes have proved difficult because of the non-global nature of some carbon isotope excursions (Tabor et al., 2007). Magnetostratigraphy is an attractive alternative to these approaches as it utilises the globally synchronous nature of magnetic reversals and is, essentially, a facies-independent technique. It does however rely upon the construction of a coherent and composite magnetostratigraphic record, linked to biostratigraphy, and significant progress has been made toward a global, composite Permian/Triassic boundary (PTB) record (Gallet et al., 2000; Scholger et al., 2000; Molostovskii, 2005; Steiner, 2006; Szurlies, 2007).

Most studies of the late Permian mass extinction event in the terrestrial realm have focussed on the southern palaeohemisphere, in particular South Africa, Australia and Antarctica (Smith and Ward, 2001). To test whether trends and patterns of extinction recorded in these studies are truly global, we have studied the Permian–Triassic record of northern palaeohemisphere sections in Russia (Benton, 2003; Tverdokhlebov et al., 2005). However, in order to integrate the rich and diverse fossil tetrapod assemblages of this region (Tverdokhlebov et al., 1997; Tverdokhlebov et al., 2002; Tverdokhlebov et al., 2005; Surkov et al., 2007) into global estimates of species loss at this critical extinction event, it is necessary to demonstrate how the Russian sequences correlate with the global stratigraphic scheme. It
was assumed that the Russian Tatarian was equivalent to the Late Permian (i.e. Lopingian) e.g. (Efremov, 1937; Olson, 1957; Chudinov, 1965; Tverdokhlebov et al., 1997; Benton et al., 2004; Tverdokhlebov et al., 2005). However, in the most recent definitive edition of the international timescale (Gradstein et al., 2004) the entire Lopingian and the PTB was deemed to be missing in European Russia. Instead the Tatarian and Kazanian were compressed and correlated with the Guadalupian (middle Permian) rather than with the Lopingian (Wardlaw et al., 2004). If correct, this implies a significant 9–10 Ma gap in the Russian stratigraphic record that has major stratigraphic and palaeontological implications.

Since 2004 some additional stratigraphic studies of the Russian Kazanian and Tatarian have been undertaken. Menning et al. (2006) postulated a pre-PTB gap corresponding to the Changhsingian, with the Vyatkian being equivalent to the Wuchiapingian and the Severodvinian being equivalent to the Capitanian. In contrast, some Russian authors have presented palaeontological evidence that the Vyatkian (Vyazniki) units in the Moscow Basin correspond to the very latest Permian (i.e. Changhsingian) (Sennikov and Golubev, 2006). Following biostratigraphic work in the Kanin Peninsula in the north of Russia, Grunt (2006) correlates the Vyatkian to the whole of the Lopingian, and the Severodvinian to the Capitanian. In a recent revision of the international timescale (Ogg et al., 2008) the Russian Ufimian, Kazanian and Tatarian are equated with the Guadalupian and Lopingian, and the top of the Tatarian coincides with the end of the Permian. Thus, there are at least three mutually exclusive hypotheses: (a) that the Vyatkian and Severodvinian are Guadalupian in age, and the entire Lopingian and PTB are missing (Gradstein et al., 2004; Wardlaw et al., 2004); (b) that the Vyatkian corresponds to the lower Lopingian (i.e. Wuchiapingian), the Severodvinian is upper Guadalupian (i.e. Capitanian) in age, and the upper Lopingian (Changhsingian) is missing (Menning et al., 2006); or (c) that the Vyatkian spans the entire Lopingian, the Severodvinian is Capitanian in age (Grunt, 2006), and that there can only be, if at all, a short stratigraphic gap around the PTB in this region.

The magnetostratigraphy of Permian–Triassic sections in Russia has a long history of study commencing in the 1950s and includes the work of Khramov, Molostovskii, Borisov, Burov and their colleagues. However, much of the work remains difficult to access. Furthermore, there have been significant concerns about the demagnetization techniques employed (Bazhenov et al., 2008). The most comprehensive and recent information (in English) is that for the Volga and Kama areas (Burov et al., 1998) some 600–700 km N–NW of our study area. In addition to a complete magnetostratigraphic section, this summary of the available information also presents basic data for many individual sections, which helps to assess the reliability of the measurements and their interpretation.

Our study of the Permian–Triassic strata of the southern Cis-Urals therefore aims to (a) resolve the issue of whether or not there is a major temporal gap below the PTB in this part of Russia, and (b) contribute to the regional and global correlation of the magnetostratigraphic record of this crucial interval in Earth history. This study therefore has focussed upon sampling across the supposed PTB, concentrating in particular on the uppermost Tatarian deposits of the Vyatkian Gorizont immediately below the locally recognised PTB.

2. Geological setting

The three principal sections sampled are located at Boyevaya Gora (51.30°N, 54.91°E), (locality 59 in Tverdokhlebov et al., 2005) Sambullak (51.88°N 56.21°E) (locality 53 in Tverdokhlebov et al., 2005) and Tuyembetka (51.92°N 56.34°E) in the Orenburg region of the southern Cis-Urals (Fig. 1). These sections were chosen for study primarily on the basis that they could provide reasonably long (260, 80 and 190 m respectively) and well exposed (generally >75%) sections plus their previous history of investigation by Russian workers (see Tverdokhlebov et al., 2005). Two further shorter sections were sampled at Krasnogor (51.56°N, 56.08°E) and Vozdvizhenka (51.71°N, 56.38°E) (locality 76 in Tverdokhlebov, 2005). Four of the five sections lie some 80 km east of the city of Orenburg close to the town of Saraktash and the Sakmara and Ural rivers, while the fifth section, Boyevaya Gora lies some 50 km south of Orenburg (Fig. 1).

The Tatarian stratigraphy of the study area comprises, in ascending order from oldest to youngest, the Urzhumian, Severodvinian and Vyatkian horizons, which are defined primarily on their palaeontological characteristics (Table S1). The horizons are further subdivided into svitas, which are lithostratigraphic units that are also defined partly on their fossil assemblages (Tverdokhlebov et al., 2005). In the study area,

![Outline location map of the Orenburg study area. Individual section localities are BG, Boyevaya Gora, Kr, Krasnogor, S, Sambullak, T, Tuyembetka, and V, Vozdvizhenka. Also shown are the Ural and Sakmara rivers and the border with Kazakhstan in the extreme south (light dashed line).](image-url)
the Vyatkian Gorizont, represented by the Kulchumovskaya Svita, is dominated by meandering river flood-plain deposits, including channels, overbank fines, ephemeral lakes and paleosols (Newell et al., 1999; Tverdokhlebov et al., 2005; Surkov et al., 2007). Freshwater habitats of the Kulchumovskaya Svita were home to ostracods such as *Suchonellina trapezoida*, *S. compacta* and *Wjatkellina fragilina*; fishes including *Toye-mia blumentalis*, *Isadia aristoviensis* and *Saurichthys*; and anthracosaurs including *Uralerpeton* and *Chroniosuchus* (Tverdokhlebov et al., 2005) (Table S1). Vyatkian terrestrial tetrapods include *Dicynodon*, which has been used to provide a correlation with the latest Lopingian Permian *Dicynodon* biozone of South Africa (Tverdokhlebov et al., 2005).

The Vyatkian Gorizont is overlain by the Early Triassic (Induan) age Vokhmian Gorizont, comprising the Kopanskaya Svita (Tverdokhlebov et al., 2002) (Table S1). In all five sections the local PTB has been recognised on the basis of lithostratigraphy and/or biostratigraphy (Tverdokhlebov et al., 2002; Tverdokhlebov et al., 2005). Of particular importance is the occurrence of the small temnospondyl amphibian *Tupilakosaurus*, which first appears in the coarse sandstones and conglomerates of the lower Kopanskaya Svita rocks (Tverdokhlebov et al., 2002). *Tupilakosaurus* also occurs in well-dated Lower Triassic (Induan) marine strata of East Greenland (Shishkin, 1961), providing one of the few biostratigraphic tie-points between the terrestrial

![Fig. 2. Example demagnetization diagrams for samples from the Boyevaya Gora section. Circles are on the horizontal and diamonds on the vertical projection respectively. Examples A, B, and E are normal and C, D and F reverse polarity ChRMs respectively. The ChRM unblocks over temperatures that span the titanomagnetite–hematite range (200°–670 °C). The grey arrows on examples B, D and E represent the removal of the low temperature (75–300 °C), present-day directed, component.](image-url)
Russian Permian–Triassic sections and marine sections worldwide. In the upper half of the Kopanskaya Svita, larger temnospondyls such as *Wetlugosaurus samariensis* appear (Tverdokhlebov et al., 2002).

The local PTB is also marked by a major facies change (Newell et al., 1999; Tverdokhlebov et al., 2002; Surkov et al., 2007). In several sections, e.g. Sambullak and Tuyembetka, the meandering flood plain facies of the Vyatkian Kulchumovskaya Svita become significantly coarser towards the top of the Vyatkian and include a number of channelized granule and pebble conglomerates that may reach a few metres in thickness. At the (locally erosional) boundary between the Vyatkian and Vokhmian horizons, however, there is an even more dramatic increase in grain size with the deposition of stacked conglomerates and coarse sandstones, deposited in a braided alluvial fan setting, which may reach 15+ m in thickness (e.g. at Sambullak) and which form a significant feature in the modern landscape (Newell et al., 1999).

Although Newell et al. (1999) recognised that the provenance and transport direction of these major braid plain conglomerates were very similar to the thinner, finer and more localised conglomerates of the upper Vyatkian, they suggested that the step change upward in grain size was too large to be the result of a simple progradation of the alluvial fan system. Citing sedimentary evidence of widespread aridity, they suggested that the facies change was caused by a combination of tectonic uplift and climate change (Newell et al., 1999; Smith and Ward, 2001; Sephton et al., 2003; Diéguez and López-Gómez, 2005) and have also been interpreted as reflecting a change in climate, increased aridity, seasonal rainfall and widespread loss of vegetation cover (Newell et al., 1999; Smith and Ward, 2001; Sephton et al., 2005).

The facies changes and faunal records provide a robust regional stratigraphy that enables correlation between sections. Coarse correlation with other sections worldwide is perhaps possible by stratigraphy that enables correlation between sections. Coarse correlation with other sections worldwide is perhaps possible (Ward et al., 2000; Michaelson, 2002; Sarkar et al., 2003; Tupilakosaurus

3. Methodology

Samples were collected using a portable gasoline-powered drill and orientated using a combination of sun and magnetic compasses. While every attempt was made to collect all lithologies present, often the mudstones could not be successfully sampled because they were too friable. In contrast, well developed paleosols tended to provide good core samples. In comparison to the mudstones and sandstones, they are over represented in terms of numbers of samples and each horizon sampled probably reflects a much longer period of time than an equivalent thickness of clastic material. At Boyevaya Gora and Sambullak sampling was essentially of a single continuous logged section, while in Tuyembetka the section is a composite of multiple individual overlapping subsections. These individual subsections were readily correlated in the field on the basis of numerous, laterally persistent, paleosol horizons which provided clear visual markers.

Where possible, multiple samples were taken from individual horizons but, with the exception of some of the very thickest paleosols of Tuyembetka, they are always presented as a single directional result.

All samples were cut into standard 22 mm lengths and their remanences measured using a Molspin spinner magnetometer. Nearly all samples were demagnetized using a Magnetic Measurements MMTD1 thermal demagnetiser using between 13 and 17 steps to a maximum temperature of 680 °C although the most typical demagnetization sequence was NRM, 100, 150, 200, 300, 400, 450, 500, 530, 560, 580, 610, 640, 670 °C. In order to monitor thermochemical changes, all samples had their bulk susceptibilities measured after every demagnetization step. On a limited number of samples we undertook AF demagnetization, using an Agico LDA 3a demagnetizer, followed by thermal demagnetization, but this was found to be less effective in most cases than the standard thermal demagnetization at resolving individual components. Directional analysis was undertaken using a combination of PCA analysis (Kirschvink, 1980) and, in a few cases, remagnetization circles (McFadden and McElhinney, 1998). In order to quantify the reliability of the individual directional analyses, a simple quality factor scheme (Hounslow and McIntosh, 2003) has been adopted based on the

![Fig. 3. Stereoplots of the isolated LTC (A–C) and ChRM (D–F) directions for Boyevaya Gora, Tuyembetka and Sambullak respectively. Closed (open) symbols are on the upper (lower) hemisphere. Lines represent remagnetization circles where, in a limited number of cases, individual remanence directions could not be isolated for the LTC.](image-url)
noisiness of the principal component fits such that Q1 has a MAD (maximum angular deviation, Kirschvink, 1980) ≤5°, Q2 ≤10°, Q3 ≤15° and Q4 >15° or endpoint(s).

4. Results

Well over 70% of the samples collected yielded stable magnetization directions that could be used for further analysis. We found no correlation between lithology and stability of remanence, although there is a weak correlation between inclination and lithology such that the sandstones tend to show steeper inclinations. In practice, this is thought to be an artefact of sandstones being concentrated in the upper, younger parts of the sections.

4.1. General magnetic behaviour

Most samples show very simple demagnetization behaviour. After a marked directional change at the first demagnetization step, almost all samples carry a well defined Low Temperature Component (LTC) that is typically removed on treatment to 150–200°C, although in some it may persist until 300°C (Fig. 2A, B, D, E, grey arrows). The LTC is clearly directed toward the present-day geocentric field and is typically removed on treatment to 150–200°C, although in some it may persist until 300°C (Fig. 2A, B, D, E, grey arrows). The LTC direction is recovered above demagnetization temperatures of 300°C and persists up to 630°C (Fig. 2A–E). There is no apparent difference between directions recovered above and below 570°C, suggesting that this remanence was acquired by both haematite and titanomagnetite at, or shortly after, the time of deposition. Furthermore, there is no apparent tendency for the polarity to change with changes in lithology, which is particularly important given the relatively high permeability of the sandstones and conglomerates in comparison to the paleosols and mudstones.

In the field we also noted that several of the paleosols, especially at Tyumembetka, were markedly pink in colour suggesting large amounts of haematite may have been present, but in practice the magnetic behaviour of these units was found to be identical to their more grey-white-coloured counterparts. Cross plotting of Total NRM intensity versus bulk susceptibility shows the same linear trends for all lithologies and the only notable difference is that paleosols, at the local PTB, have a weak correlation between inclination and stability of remanence, although there is a weak correlation between lithology and stability of remanence such that the sandstones tend to show steeper inclinations. In practice, this is thought to be an artefact of sandstones being concentrated in the upper, younger parts of the sections.

Table 1

<table>
<thead>
<tr>
<th>Section</th>
<th>n (N)</th>
<th>DEGc</th>
<th>INCg</th>
<th>DECs</th>
<th>INCs</th>
<th>k</th>
<th>α95</th>
<th>Rev</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boyevaya Gora (51.30°N, 54.91°E)</td>
<td>29</td>
<td>44.4</td>
<td>47.3</td>
<td>33.5</td>
<td>44.2</td>
<td>11.6</td>
<td>8.2</td>
<td></td>
</tr>
<tr>
<td>R</td>
<td>43</td>
<td>213.5</td>
<td>38.0</td>
<td>206.3</td>
<td>33.3</td>
<td>8.6</td>
<td>7.7</td>
<td></td>
</tr>
<tr>
<td>R+</td>
<td>31</td>
<td>211.9</td>
<td>44.5</td>
<td>203.1</td>
<td>39.4</td>
<td>8.7</td>
<td>9.3</td>
<td></td>
</tr>
<tr>
<td>N+ R</td>
<td>72 (97)</td>
<td>37.7</td>
<td>42.8</td>
<td>28.9</td>
<td>38.7</td>
<td>10.7</td>
<td>5.4</td>
<td></td>
</tr>
<tr>
<td>N+ R+</td>
<td>60 (97)</td>
<td>37.9</td>
<td>46.0</td>
<td>28.0</td>
<td>41.9</td>
<td>9.8</td>
<td>6.2</td>
<td></td>
</tr>
<tr>
<td>Tyumembetka (51.92°N 56.34°E)</td>
<td>22</td>
<td>27.5</td>
<td>50.7</td>
<td>30.8</td>
<td>39.2</td>
<td>15.0</td>
<td>8.3</td>
<td></td>
</tr>
<tr>
<td>R</td>
<td>65</td>
<td>204.7</td>
<td>48.3</td>
<td>206.2</td>
<td>37.0</td>
<td>10.0</td>
<td>5.9</td>
<td></td>
</tr>
<tr>
<td>N+ R</td>
<td>87 (107)</td>
<td>25.4</td>
<td>49.0</td>
<td>28.9</td>
<td>37.6</td>
<td>11.1</td>
<td>4.7</td>
<td></td>
</tr>
<tr>
<td>Sambulak (51.88°N 56.21°E)</td>
<td>14</td>
<td>33.0</td>
<td>50.6</td>
<td>8.1</td>
<td>56.2</td>
<td>5.1</td>
<td>19.6</td>
<td></td>
</tr>
<tr>
<td>R</td>
<td>13</td>
<td>214.0</td>
<td>25.4</td>
<td>204.2</td>
<td>33.5</td>
<td>10.1</td>
<td>13.7</td>
<td></td>
</tr>
<tr>
<td>N+ R</td>
<td>27 (43)</td>
<td>36.0</td>
<td>34.9</td>
<td>21.9</td>
<td>43.1</td>
<td>6.4</td>
<td>11.9</td>
<td></td>
</tr>
</tbody>
</table>

The abbreviations are: n(N) is the number of samples, N the total number of samples demagnetized; DEGc(s) and INCg(s) the declination and inclination of the isolated ChRM in n (tilt corrected) coordinates; k and α95 the precision parameter and cone of 95% confidence of standard Fisher statistics and Rev the results of the reversal test (see text). a Excludes data from the N2P polarity sub-zone (see text).

4.2. Boyevaya Gora

This long section is divided into three main parts. The lower 52 m crops out above the Elshanka River and comprises fluvialite sandstones and mudstones that are considered to be Severodvinian in age (Tverdokhlebov et al., 2005). The middle part of the section outcrops 800 m NE and comprises 94 m of fluvialite sandstones, overbank mudstones and paleosols that are assigned to the Kulchumovskaya Svita on the basis of the lithology and associated fauna of ostracods and vertebrates (Tverdokhlebov et al., 2002; Tverdokhlebov et al., 2005). A 27 m stratigraphic gap separates the lower and middle parts of the section. The middle section, informally termed Korolki Ravine, has recently yielded large therapsid footprints (Surtov et al., 2007), which occur 124.3 m above the base of the section. The upper part of the section comprised a series of trenches and semi-continuous natural outcrop extending from the top of the Korolki Ravine section (204 m above base). In total, 103 separate sampling intervals cover a total stratigraphic thickness of 260 m, of which 46 m was not exposed.

The boundary between the Vyatkian and Vokhmian horizons (the local PTB) occurs 173 m above the base of the studied section, at a major facies change between red mudstones and trough-cross-bedded pebbly sandstones and conglomerates. The basal Vokhmian strata at this locality have yielded the tetrapods Wettugasaurus and Tipilikosaurus, characteristic of the upper Kopanskaya Svita (Tverdokhlebov et al., 2002). The youngest Permian (Vyatkian) vertebrate assemblage occurs 151 m above the base of section, and 22 m below the local PTB, and comprises tetrapods (e.g. Scutosaurus and Chroniosuchus) and fishes (e.g. T. blumentalis and I. arisifoniensis) (Tverdokhlebov et al., 1997; Tverdokhlebov et al., 2005). The highest Vyatkian ostracods (e.g. W. fragilina) have been recorded in the mudstones ‘a few metres’ beneath the local PTB (Tverdokhlebov et al., 2005).

The observed directions, VGP latitudes and inferred polarity zones are shown in Fig. 4. The polarity of each zone is typically readily identified from multiple consecutive samples of the same polarity, occasionally, single samples show opposing or intermediate directions and these are denoted by thin, half-width bars in the polarity column.
Samples show no particular changes in magnetic characteristics with stratigraphic position, other than multiple polarities.

4.3. Tuyembetka

The main section, comprising mudstones, paleosols and sandstones, is 116.5 m thick, including a 6 m covered interval near the base, and yielded 89 samples. The tops and bottoms of some of the thickest paleosols were sampled to ensure that they were of the same polarity. The highest beds comprise coarse sandstones and fine conglomerates and were previously regarded as marking the PTB at this locality. A stratigraphically higher, upper, section, some 33 m thick and comprising spectacularly trough-cross-bedded medium-coarse sands and conglomerates, is separated by a stratigraphic gap of some 38.5 m from the main section and yielded a further 15 samples.

Tuyembetka has not yielded any vertebrate or ostracod remains and there is an absence of biostratigraphic data. During our field study, plant remains were documented for the first time, including cordaitalean leaves 1.8 m above the base of the section and common, silicified stems and branches of large, arborescent gymnosperms in a fluvial conglomerate between 4.5 and 7 m above the base of the section. The section is underlain by fluvial and lacustrine deposits with halite pseudomorphs that crop out some 6 km to the SW near the village of Kul’chumovo. These evaporitic horizons characterize the tops of sedimentary cycles within the Vyazovskaya Svita of the Severodvinian Gorizont, and are not found within the overlying Vyatkin Gorizont (Tverdokhlebov et al., 2005). A Severodvinian age for the Kul’chumovo locality is confirmed by the vertebrate fossils it has yielded (Tverdokhlebov et al., 2005). It is therefore likely that the base of the Tuyembetka section does not extend significantly into the Severodvinian, and on this basis it is primarily assigned to the Vyatkin (Table 1).

At the top of the section, the coarse, braided channel deposits between 155 and 188 m above the base of section are assumed to belong to the Vokhmian Gorizont (Kopanskaya Svita). Below the covered interval between 116.4 and 155 m sandy granule to pebble conglomerates, at least 5 m thick, are recorded at the top of the main section. In the absence of any biostratigraphic data, these conglomerates had previously been regarded as belonging to the Kopanskaya Svita, thus placing the local PTB immediately below these beds at 111.4 m above base of section.

The remanence is dominated by reverse polarity directions (Fig. 5) throughout the main section (0–116.5 m) with only relatively narrow normal polarity zones. In contrast the upper section (155–188 m) is predominantly of normal polarity. The putative PTB, located at the top of the main section based purely on lithological variation (i.e. a change from mud dominated to conglomerate dominated facies), falls within a clearly reverse polarity section which continues through at least the underlying 15 m of section. Given the continuity of this reverse polarity interval it is impossible that these conglomerates at the top of this section do in fact mark the actual PTB. Instead the magnetic polarity data indicate that the PTB is likely to be located within the unexposed interval between the two sections (Figs. 5 and 8). Therefore these conglomeratic beds are in fact Permian and comparable with similar facies present at the Sambullak locality (see below) and lie close to but not at the top of the Permian sequence.

Paleosol samples have remanence and susceptibility characteristics comparable to other lithologies with a slightly lower than average total NRM intensity. Both the intensity of remanence and magnetic susceptibility show an overall tendency to decrease with increasing stratigraphic height with both parameters becoming distinctly less scattered in the lithologically more uniform Triassic sediments (Fig. 5).

4.4. Sambullak

This section forms part of a prominent hill overlooking the Sakmara River. The total thickness of the studied section was over 140 m, but only the upper 90 m of the section yielded samples; 43 in total (Fig. 6). Sampling was particularly difficult here as the majority
of the lower part of the section comprised fine, blocky mudstones that proved to be very fragile and fragmentary. Furthermore, of the three principal studied sections, Sambullak also yielded the lowest number (~50%) of reliable data points, although there is no obvious reason for this discrepancy, with remanence and susceptibility characteristics very similar to the previous sections (cf. Figs. 4–6).

A Vyatkian-age vertebrate assemblage including *Karpinskiosaurus ultimus* and *Uralerpeton tverdokhlebovae*, has been recovered from the lower, unsampled, mudstone-dominated part of the section (Tverdokhlebov et al., 2005). The bulk of the section, dominated by mudstones, siltstones and paleosols with occasional lenses of sand and finer (granule to small pebble) conglomerates in the upper part, is thus interpreted as belonging to the Kulchumovskaya Svita of the Vyatkian Gorizont. The uppermost 14 m of section consists of a stacked sequence of very coarse sandstones to pebble conglomerates, which are referred to the Vokhmian Gorizont. These coarse sandstones have not yielded fossils, but ostracods and tetrapod fossils from stratigraphically equivalent nearby localities confirm an Induan age for this unit (Tverdokhlebov et al., 2002). The base of the coarse conglomerates, overlying the uppermost red mudstone at 76 m above base of section, therefore marks the boundary

Fig. 5. Composite log for the Tuyembetka section. Nomenclature as in Fig. 4.

Fig. 6. Composite log for the Sambullak section. Nomenclature as in Fig. 4.
between the Vyatkian and Vokhmian horizons and the local PTB. Field observation indicates that only very limited and localised erosion occurs beneath the massive earliest Triassic conglomerate, so suggesting the absence of a significant stratigraphic gap.

The lower, Upper Permian, part of the section shows a well defined R–N–R sequence of polarity zones, with the Vyatkian–Vokhmian boundary falling within the next higher N polarity interval. This normal polarity zone extends from below this boundary into the pebble conglomerates of the Vokhmian horizon and includes within it a single sample indicating an R polarity at the very top of the section (Fig. 6).

4.5. Krasnogor and Vozdvizhenka sections

The two short sections of Krasnogor and Vozdvizhenka (21 m and 33 m respectively) were sampled as they were presumed to span the PTB. As elsewhere, the PTB was taken to be marked by a facies change from mud-dominated to sand-dominated facies but without any obvious stratigraphical breaks. However, the Lower Triassic sandstones of Krasnogor have yielded the remains of *Benthosuchus* and have been assigned to the Staritskaya Svita of the Rybinskian Horizon (Tverdokhlebov et al., 2003). This would appear to imply that the lowermost Triassic, the Vokhmian horizon, may be condensed or absent at this locality. The Krasnogor section outcrops as a small continuous cliff of several hundred metres length and is a prominent feature in the landscape. Despite the limited thickness it yielded a relatively large number of samples, principally from sandstone units, but the directions found are rather dispersed (Table 1, Fig. S1) and overall are notable for their markedly low inclination despite the strata being essentially horizontal. The magnetic polarity is, however well defined and shows a simple R–N transition but the limited length of section and the gaps in sampling preclude any definitive confirmation of the age of the section but it is magnetostratigraphically consistent with the PTB observed elsewhere.

5. Pole position

The mean pole position (55.2°N, 190.1°E, α95 = 6.1; Fig. 7) for the tilt-corrected combined Boyevaya Gora, Tuyembetka and Sambullak sections is little changed by the inclusion of the two weaker results from Krasnogor and Vozdvizhenka. However, these latter results were excluded from the mean calculation on the basis of their high dispersion/low numbers. During the Late Permian the Cis-Urals formed part of the eastern margin of the Eurasian–Baltic plate and hence pole comparisons need to be made with comparable European poles from this plate. However, there has been considerable ambiguity in the location of Permian pole positions within the European palaeomagnetic record, leading in part to various suggestions including alternative reconstructions for Pangaea, and the existence of quadrupole and octupole contributions to the Earth’s magnetic field etc. (e.g. Torsvik et al., 2001; Van der Voo and Torsvik, 2004; and references therein). In particular, it has been shown that the pole position depends very much on the type and quality of data included in its calculation (Van der Voo and Torsvik, 2004) and it is clear that inclination shallowing (the reduction in the observed inclination angle of the remanence due to burial compaction) plays a significant role in creating the ambiguity over the pole positions and the
Apparent Polar Wander Path (APWP). Comparison of our pole with a current European APWP (Torsvik et al., 2001) clearly shows (Fig. 9) that it falls well beyond the expected pole position (i.e. it is “far sided” relative to the collection site) which is consistent with the inclination having been significantly reduced by ~10° or more by compaction.

In a recent paper, Bazhenov et al. (2008) report a new pole (OK) of “Upper” Permian age from sampling sites that extend across a large area up to 300 km west of Orenburg. These authors argue that only three previous poles from Russia should be regarded as having been demagnetized sufficiently in detail to be deemed reliable. Two of the three have already been referred to as they include the magnetostratigraphic section from the Sukhona River (SH) (Khramov et al., 2006) and the Monastirskoye section (GI) from the Volga-Kama region (Gialanella et al., 1997) and a recent update from the same region (TA) (Shatsillo et al., 2006). These poles are also shown in Fig. 9. It is clear that they all show inclination shallowing in that they are far sided with respect to their sampling sites and the reference 250 or 260 Ma poles. However Bazhenov et al. (2008) reject Gialanella et al.’s (1997) pole for the Monastirskoye section because of the lack of agreement in pole longitude (or declination in terms of direction) with their, and the other, poles. They argue that the difference between the GI pole and the SH, TA and their OK pole is possibly a function of incorrect correction of the magnetic orientation at the time of collection. However our new pole (OR) shows the same deviation, even though our sample orientations were primarily referenced to the sun rather than oriented magnetically. In both the Monastirskoye section (Gialanella et al., 1997) and our own (Fig. 3) studies the present-day component is well defined and close to the expected direction which would not be expected had the suggested ~20° in orientation error implied by Bazhenov et al. (2008) been made. The discrepancy between these results is in essence a declination anomaly and so we would suggest, given the limited availability of data, that, it is not impossible that these might be explained by, as yet unspecified, block rotations at the eastern margin of the Eurasian plate. Indeed, even within the data of Bazhenov et al. (2008) there is a near 10° declination discrepancy between the two sampling groups (Orenburg and Kinel River) of sites that form the OK pole, and this further suggests to us that these anomalies in declination require further study.

6. Composite section and global comparison

The polarity sequences for the five sections have been integrated into a single composite section (Fig. 8). Boyevaya Gora provides the stratigraphically longest section and the other sections are, in essence, correlated with this one. With the exception of Tuyembetka, the locally postulated PTB (defined on facies and fossil evidence) falls close to a polarity transition from R to N polarities, but always within the lower part of the N interval. This positioning is consistent with previous Russian studies and present global correlations (Burov et al., 1998; Gallet et al., 2000; Molostovskii, 2005; Steiner, 2006; Szurlies, 2007). The PTB is recognised to fall in the lower part of this N polarity chron and beneath a short R event within the N chron (Steiner, 2006). This short-lived R event (t1 of Fig. 8) is present in the Boyevaya Gora,
Tuyembetka and Krasnogor sections and may also be present in the other two sections where reversed polarity was detected in isolated samples at or near the top of the sampled sections. Only at Boyevaya Gora is the sampled section sufficiently continuous stratigraphically upward to detect the next clear R polarity chron.

The Permian part of the section is correlated simply on the basis of the start and end of significant N or R chrons defined from consecutive samples and to a lesser extent short-lived events marked by one or two individual samples. Perhaps the biggest issue is that there appears to be significantly less representation of the N polarity in the Tuyembetka section than might be expected. This is believed to be a function of the highly non-linear nature of the sedimentation/accumulation rate at Tuyembetka where paleosols make up such a large proportion of the section and, consequently, the samples. The normal polarity events detected in this section tend to coincide with some of the thickest/most mature paleosols and hence they may well be under-represented in stratigraphic thickness terms. The major sampling gap in the lower part of the Boyevaya Gora section appears to correlate with an interval dominated by R polarity in the Tuyembetka section, and hence we believe that this interval is also of R polarity.

The composite section is strikingly similar to Russian composites from the Volga–Kama region (Burov et al., 1998) some 700 km to the NNW and is also readily comparable to the global composite, showing not only correlation of the main chrons but also some of the minor events (Steiner, 2006) (Fig. 8). In correlative terms, the Boyevaya Gora section commences in N1P and extends upward to R1T using the Russian nomenclature (Burov et al., 1998; Molostovskii, 2005) or in global terms from the Capitan N to the first reversal of the Diener R–N chron (Steiner, 2006). Despite the sampling gaps in the Boyevaya Gora and Tuyembetka sections, we believe this correlation is robust. During fieldwork, no evidence of any obvious erosional unconformity was encountered in any of the sections, and, although we recognise the potential for non-deposition during thick paleosol formation, we believe that the paleosols continued to record a true, if highly compressed, record of the prevailing geomagnetic field. The base of the Tuyembetka section is estimated to be some 6 Ma older than the PTB (based on estimates of paleosol maturity, time for formation and frequency; see Table S2; after Retallack, 2001). This is consistent with the observed Reverse polarity of the lowermost samples and with the timescale of Steiner (2006) which dates the lowermost part of this section to be Lopingian in age. The base of the Boyevaya Gora section is slightly older and falls within the upper part of the Guadalupian marked by the Capitan N interval (Steiner, 2006).

7. Discussion

Any hypothesis that implies a major time-gap at or below the Russian PTB, if correct, would cause a number of significant problems for studies of the Late Permian mass extinction event and for global correlation of Permian–Triassic continental sequences. For example, much of our understanding of the Late Permian extinction of tetrapods derives from studies of the Karoo Supergroup in South Africa (e.g. Ward et al 2000) and numerous shared genera between the tetrapod-bearing units of Russia and South Africa. These link, for example, the South African Tapinocephalus Assemblage Zone with the Russian Urzhumian Gorizont, and the South African Dicynodon Assemblage Zone with the Russian Vyatkian Gorizont. Moving the Vyatkian down to the Middle Permian would either imply that (a) the South African units also need to be reassigned an older age, or (b) that taxa that are used to define biozones for international correlation are perhaps too long-
ranging to be used in this way. If so, then the regional and global studies of extinction and recovery based on these correlations and assumptions (e.g. Ward et al., 2000; Benton et al., 2004) would perhaps be spurious. Note, however, that the implied Lopingian gap would suggest that numerous genera, and even species, of tetrapods that cross the PTB in South Africa and Russia were astonishingly long-lived; closing the gap removes this anomaly. Our new magnetostratigraphic data and their correlation to the global composite (Steiner, 2006) demonstrate, unequivocally, that the PTB is indeed present in the Russia sections and there is no significant hiatus. The upper part of the Vyatkian Gorizont is undoubtedly Changhsingian in age and we reject the correlation presented in the 2004 international timescale (Wardlaw et al., 2004) and subsequently that of Menning et al. (2006). The lower Vyatkian is Wuchiapingian in age, and the upper part of the Severodvinskian is Capitanian, supporting previous palaeontological correlations (Grunt, 2006; Sennikov and Golubev, 2006). The Russian sections span this crucial time period in Earth history with no significant hiatus or stratigraphic gap and provide an important record of the Late Permian mass extinction interval in the terrestrial realm.

8. Conclusions

The Permian–Triassic sediments of the Orenburg area provide a high-fidelity, composite, magnetostratigraphic section extending from the Capitan N to Diener R–N polarity chron (Steiner, 2006), which equates to the upper part of the Capitanian Stage of the Guadalupian in the Permian to the Griesbachian subsurface of the Induan in the Triassic. The data show a high correspondence with the recent global composite (Steiner, 2006) and are consistent with previous Russian composites (Burov et al., 1998; Molostovskii, 2005). The data provide no evidence for a major stratigraphic gap at the Permian Triassic Boundary and instead indicate that there is no major unconformity at this boundary as has been previously proposed. This conclusion clearly indicates the validity of including the extinction record of the vertebrate fauna of the Tatarian in discussions of mass extinction events at the PTB.

Like many other red bed studies marked inclination shallowing to MJB and RJT. The laboratory measurements undertaken by CT is tentatively suggested to be a possible re...