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Disruption of playa–lacustrine depositional systems at the Permo-Triassic boundary: evidence from Vyazniki and Gorokhovets on the Russian Platform

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Abstract: Permo-Triassic sections at Vyazniki and Gorokhovets provide evidence on terrestrial events at, or close to, the Permo-Triassic boundary, the time of the largest ever mass extinction. The sedimentary succession records the overrun of a muddy playa–lacustrine depositional system by major channel belts transporting sand-grade sediments. Biostratigraphy of sections at Vyazniki and Gorokhovets (Zhukov Ravine) shows that this event occurred either at the very end of the Permian or 8 m above in the sections. The timing and nature of this event, which records increased sediment flux from the Ural Mountains, is closely comparable with that from the Southern Uralian Foreland Basin. The Vyazniki and Gorokhovets sections are 800 km from the mountain front and in a separate depositional basin, which strengthens the case that increased sediment flux from the Urals at the Permo-Triassic boundary is related to devegetation of upland catchments (increasing sediment yield) and a switch toward low-frequency but high-magnitude discharge events (increasing sediment delivery). The interbedding of fluvial and aeolian deposits provides further evidence for climatic instability and extremes in the Early Triassic.

Supplementary material: Detailed reports on the ostracodes and fossil fish remains from the Zhukov Ravine sections are available at http://www.geolsoc.org.uk/SUP18402.

Permo-Triassic continental red beds cover 1.4×10^6 km^2 of European Russia (Fig. 1) and provide an important record of changes to terrestrial environments and ecosystems before, during and after the end-Permian mass extinction (Newell *et al*. 1999; Zharkov & Chumakov 2001; Tverdokhlebov *et al*. 2003, 2005; Benton *et al*. 2004; Sennikov & Golubev 2006; Shishkin *et al*. 2006; Shcherbakov 2008; Krassilov & Karasev 2009). Work on Permo-Triassic fluvial successions in the South Urals (Fig. 1) has shown that abrupt changes in sedimentary facies occur at the Permo-Triassic boundary, which could have resulted from climatic instability and loss of stabilizing vegetation in river catchments (Newell *et al.* 1999). These major environmental changes were associated with a devastating loss of life worldwide, the end-Permian mass extinction, responsible for the extinction of 80–95% of all species on Earth (Benton 2003; Benton & Twitchett 2003; Erwin 2006). Comparable changes in fluvial depositional systems at the Permo-Triassic boundary have now been recognized in other major basins such as the Karoo in South Africa (Ward *et al.* 2000) and the Bowen Basin in Australia (Michaelsen 2002). However, there is still a pressing need to examine other well-dated terrestrial boundary sections, (1) to eliminate the possibility that changes in fluvial system at the Permo-Triassic boundary are the result of local factors such as tectonic uplift rather than global climate change, (2) to understand the response of different types of depositional system (e.g. aeolian and playa–lacustrine) to end-Permian climate change, and (3) to document environmental changes through the latest Permian and across the Permo-Triassic boundary and how they relate to the extinctions.

Here we present for the first time a sedimentological study of Permo-Triassic boundary sections in the Zhukov Ravine and around Vyazniki town. Vyazniki is located 1000 km across the Volgo-Uralian Anteclise (Tatarian High) from boundary sections that have previously been examined in the Southern Uralian Foredeep (Newell *et al.* 1999) and they provide an opportunity to examine changes in terrestrial sedimentary environments and ecosystems on the Russian Platform at the Permo-Triassic boundary in an independent tectonic and depositional setting (Fig. 1).

The section in the Zhukov Ravine, near Gorokhovets, and other outcrops in the Vyazniki and Gorokhovets districts, were studied during geological mapping in the 1960s and 1970s by N. I. Strok, T. I. Gorbatkina, S. V. Alekhin and I. I. Molostovskaya but hitherto unpublished. Their work revealed definitive evidence, based on ostracodes and magnetostratigraphy for the Permo-Triassic boundary in the Zhukov Ravine, and we present this remarkable boundary succession here for the first time.

Vyazniki is historically important because Roderick Murchison first identified continental Permian in Russia here in 1841 (Benton *et al*. 2010), but the age, sediments and fossils from Vyazniki have been debated ever since. A renewed phase of collecting and study of the Vyazniki deposits by A.G.S. and V.K.G. from 1999 has expanded the fossil assemblages considerably, with evidence for two main fossiliferous horizons, first in dark grey laminated clays and fine sandstones in the lower part of the sequence (ostracodes, conchostracans, insects, bivalves, fishes, plants), and second in channelized coarse sandstones

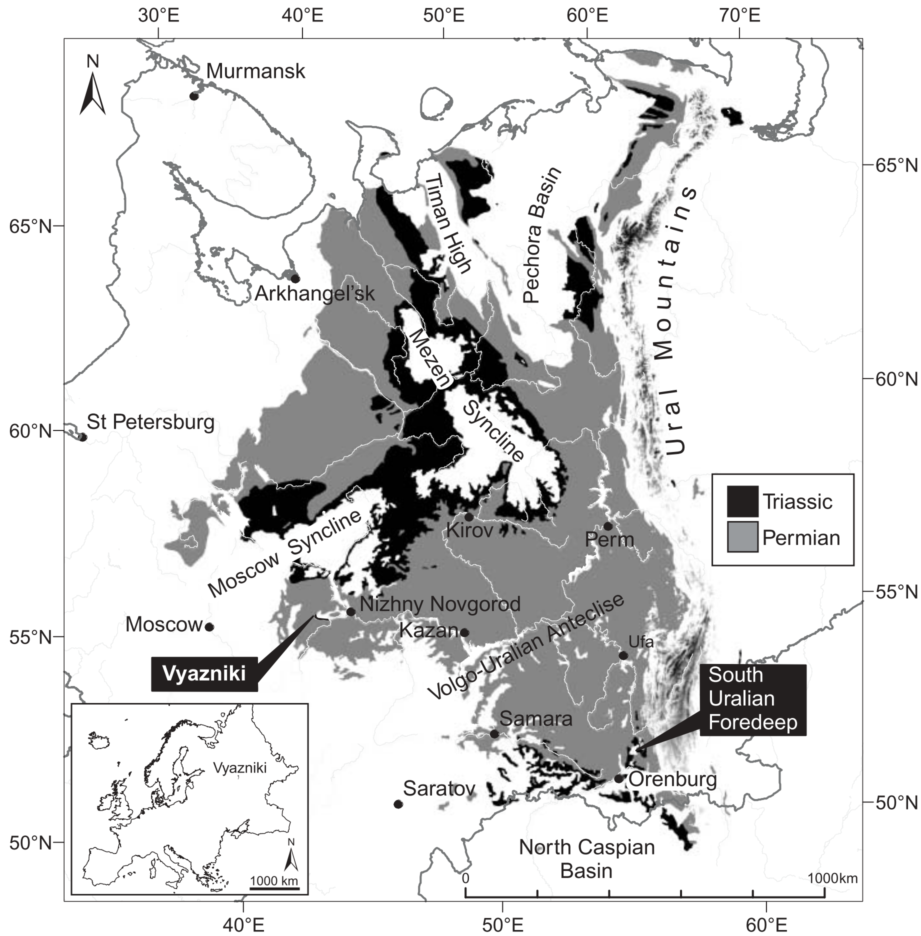

Fig. 1. Location map showing the distribution of Permian and Triassic outcrop on the Russian Platform. Major basins and structures are shown together with the location of this study at Vyazniki. Geology is derived from F. M. Persits, D. W. Steinshouer & G. F. Ulmishek, 20010600, fsu_geol.shp, Surface Geology of the Former Soviet Union, US Geological Survey, Denver, CO.

and conglomerates higher in the succession (bivalves, fishes, tetrapods, plants). The new work, including field visits by the coauthors in 2008 and 2009, allows a thorough investigation of the age and significance of the Vyazniki succession, and whether it terminates immediately below the Permo-Triassic boundary or passes through into the Triassic.

Geological setting

Permian deposits cover a large part of th**e Russian Platform in a north–south belt that extends from the Ural Mountains westward toward Moscow (Fig. 1). The overlying Triassic sequence has a less extensive distribution, with the main outcrops occurring along the flanks of the synclinal Moscow, Mezen' and Pechora basins in the north and the margin of the North Caspian Basin in the south (Fig. 1). Continental Permo-Triassic sequences in Russia range in age from the late Early Permian (Kungurian) to Middle Triassic (Ladinian), a span of some 35 Ma. This more or less matches the time span of the continental Permo-Triassic of the Karoo basin in South Africa, and most units can be equated in age by biostratigraphic and magnetostratigraphic evidence, although the Russian sequence is longer, including the Ladinian, a stage that is apparently missing in South Africa. The base of the Russian Urzhumian Gorizont marks the onset of widespread continental sedimentation on the Russian Platform, with the westward progradation of terrigeneous clastic deposits across underlying Kazanian shallow-marine carbonates and evaporites. A compilation of stratigraphic data for the Middle and Late Permian of the Russian Platform (Gorsky *et al.* 2003) shows that Tatarian red beds range in thickness from 100 to 400 m on the Russian Platform, increasing to 600–1500 m in the north–south-trending foredeep along the western margin of the Ural Mountains. The Urals are a linear, north–south-trending orogenic belt formed by the collision of the East European Platform and Siberian plate during the Carboniferous and Permian and they provided the major source of terrigeneous sediment for the westward-thinning Tatarian clastic wedge (Nikishin *et al.* 1996).

Vyazniki is located around 800 km west of the Ural Mountains on the southern limb of the Moscow Syncline (Fig. 1) and at the western extreme of the 'Perm' Facies Belt' as defined by Gorsky *et al*. (2003). Within this facies belt, Tatarian continental deposits thin from around 600 m in the Perm' area adjacent to the Urals to around 100 m at Vyazniki, which lies close to the western limit of Permian sedimentation on the Russian Platform (Fig. 1). Westward thinning is accompanied by a general westward reduction in grain size, with conglomerates interbedded with mudstones and sandstones in the Perm' area, passing laterally into mudstone-dominated successions with carbonate, gypsum and fine-grained sands in areas to the west. The generalized lithostratigraphic descriptions provided by Gorsky *et al.* (2003) suggest that the coarse, proximal facies belt expanded westwards throughout the Late Permian, with cross-bedded gravelly facies restricted to the proximal Perm' area in the Urzhumian (Urzhumskaya Svita), reaching the Vyatka area at the start of the Severodvinian (Slobodskaya Svita) and the area to the north of Nizhny Novgorod at the start of the Vyatkian (Zamochnikovskaya Svita). Vyazniki remained an area of fine-grained sedimentation until the latest Permian and early Triassic, at which time there was an abrupt basinward shift of sandy fluvial facies into the former playa–lacustrine basin. The nature and timing of this facies change and its possible relationship to major climate-change events at the Permo-Triassic boundary are discussed in following sections.

Detailed depositional models have yet to be devised for Upper Permian red beds of the Russian Platform, but it is probable that they were deposited in an interior continental basin that was closed, or had restricted connections to northern marine shelves. Gravelly and sandy river systems with catchments in the Ural Mountains transported water and sediment westwards across vast muddy floodplains on the Russian Platform before terminating in flood basins and playa lakes distal to the mountain front (Nalivkin 1973). The presence of calcretes, evaporites and aeolian sandstones within the predominantly fine-grained clastic wedge points toward a dryland environment for southern and central parts of the Russian Platform. However, Yakimenko *et al.* (2004) inferred sharp seasonal and longer-term fluctuations in precipitation based on the presence of reduction features in palaeosols shown by Upper Permian outcrops along the Suhkona River. In conclusion, therefore, the outcrops at Vyazniki and Gorkhovets discussed in following sections represent the distal part of an extremely large Late Permian fluvial distributary system developed to the west of the Ural Mountains in a dryland setting.

Stratigraphy of the Russian Permo-Triassic red beds

Background

The claim that the Vyazniki beds include some of the youngest Permian horizons in Russia, and that the Vyazniki and Zhukov sections straddle the Permo-Triassic boundary (Sennikov 1996; Modesto & Rybczynski 2000; Tverdokhlebov *et al*. 2005; Sennikov & Golubev 2006; Lozovskiy & Kukhtinov 2007; Kukhtinov *et al*. 2008; Krassilov & Karasev 2009) must be tested against the wider picture of the stratigraphy of the Permo-Triassic red beds of European Russia.

In the early phases of geological mapping of the continental Permian and Triassic of the Moscow and northern basins, up to 1930, Russian geologists defined svitas and noted fossil occurrences. As increasing numbers of fossil tetrapods (amphibians and reptiles) came to light (the history has been reviewed by Ochev & Surkov 2000), it became clear that a number of sequential tetrapod faunas could be identified, and these were named as Zones I–IV in the Middle and Upper Permian, and Zones V–VII in the Lower and Middle Triassic (Efremov 1941; Efremov & V'yushkov 1955). Subsequent comparisons with the Karoo tetrapod faunas from South Africa (e.g. Olson 1957) showed broad equivalences. From the 1930s to the present day, palaeontologists from the Paleontological Institute in Moscow (PIN) and Saratov State University Geological Institute (SGU) have continued to amass huge collections of tetrapod fossils, and to further refine these tetrapod-based zonal schemes (e.g. Ochev & Shishkin 1989; Sennikov 1996; Golubev 2000; Tverdokhlebov *et al*. 2003, 2005).

It is important to explain some fundamental differences between Russian and international stratigraphic terminology. According to the Russian system (Benton 2000; Zhamoida 2006), rock units, and geological time, are subdivided into svitas, gorizonts and other subdivisions (e.g. podgorizont, supergorizont). Sometimes these units are anglicized (e.g. Gorizont as Horizon and Svita as Suite) or the Russian divisions may be equated with international units (e.g. Gorizont with Horizon, and Svita with Formation). These approaches, however, mask fundamental differences between the Russian and the international approaches to stratigraphy, and we prefer to retain transliterated versions of the Russian terms to avoid confusion. Russian stratigraphy uses the concept of unified divisions of time, in which a specific time span, and the rocks of that age, are equated and treated as one. Gorizonts are the main regional stratigraphic units, identified primarily from their palaeontological characteristics, and they do not pertain to lithostratigraphic units. The gorizont may unite several svitas, or parts of svitas, or deposits of different facies in various districts but clearly contemporaneous on the basis of included fossils. Svitas, on the other hand, are largely lithostratigraphic units, given a locality name that is close to their characteristic exposure. The definition of a svita incorporates a mix of field lithological observations and biostratigraphic assumptions: 'In distinguishing a new svita, one ought without fail to establish at least an approximate, sufficiently proved correlation of it with the subdivisions of the unified [international] scale' (Zhamoida 2006).

Much of the detailed stratigraphic work on the Russian Permo-Triassic red beds, using a variety of fossil groups and magnetostratigraphy, is not well known outside Russia. This is partly because most of the key publications are in the Russian language, but more importantly because many are in conference volumes and field guides, and so are hard to obtain. Further, until 1990, much of the work was classified information. From the late 1950s to the 1980s, large field teams from Moscow, Saratov, Kazan', and other major geological institutes, worked on most of the Permo-Triassic basins, producing maps at 1:200 000 scale, and preparing detailed stratigraphic defences of their maps; almost none of this material is readily available. The maps were printed in runs of 100 copies or so, and the whereabouts of each was carefully monitored in Soviet days. The descriptive documents (memoirs) for each map were never published, but lodged at the offices of the Geological Ministry in Saint Petersburg. A series of field guides written by senior geologists from these Soviet surveys (e.g. Esaulova *et al*. 1998; Lozovskiy & Esaulova 1998; Goman'kov 2001; Molostovskiy & Minikh 2001), together with newer work (e.g. Golubev 2000; Grunt 2006), present detailed overviews of the astonishing field knowledge that had been acquired during the Soviet mapping campaigns.

Matching the Russian continental Permo-Triassic stratigraphic scheme to the international marine standard

The continental Permo-Triassic of European Russia is classified stratigraphically on the basis of schemes based on palynology, macroplants, charophytes, bivalves, ostracodes, conchostracans, fishes and tetrapods. The marine units of the Kazanian are subdivided based on foraminiferans, brachiopods, bryozoans, ammonoids and nautiloids. The summary scheme shown here (Fig. 2) presents information drawn from many recent Russian publications, as cited in the caption, and these provide full details, with illustrations, of the fossil species and their occurrences. The various biostratigraphic schemes have evolved through the past 50 years, and have been tested and retested against hundreds of sections throughout the major Permo-Triassic basins (Fig. 1). The degree of testing and validation has been intense because, from Soviet days, the Russian geological maps had to represent detailed information on svitas with precise age control.

This is why magnetostratigraphy was also explored as a dating

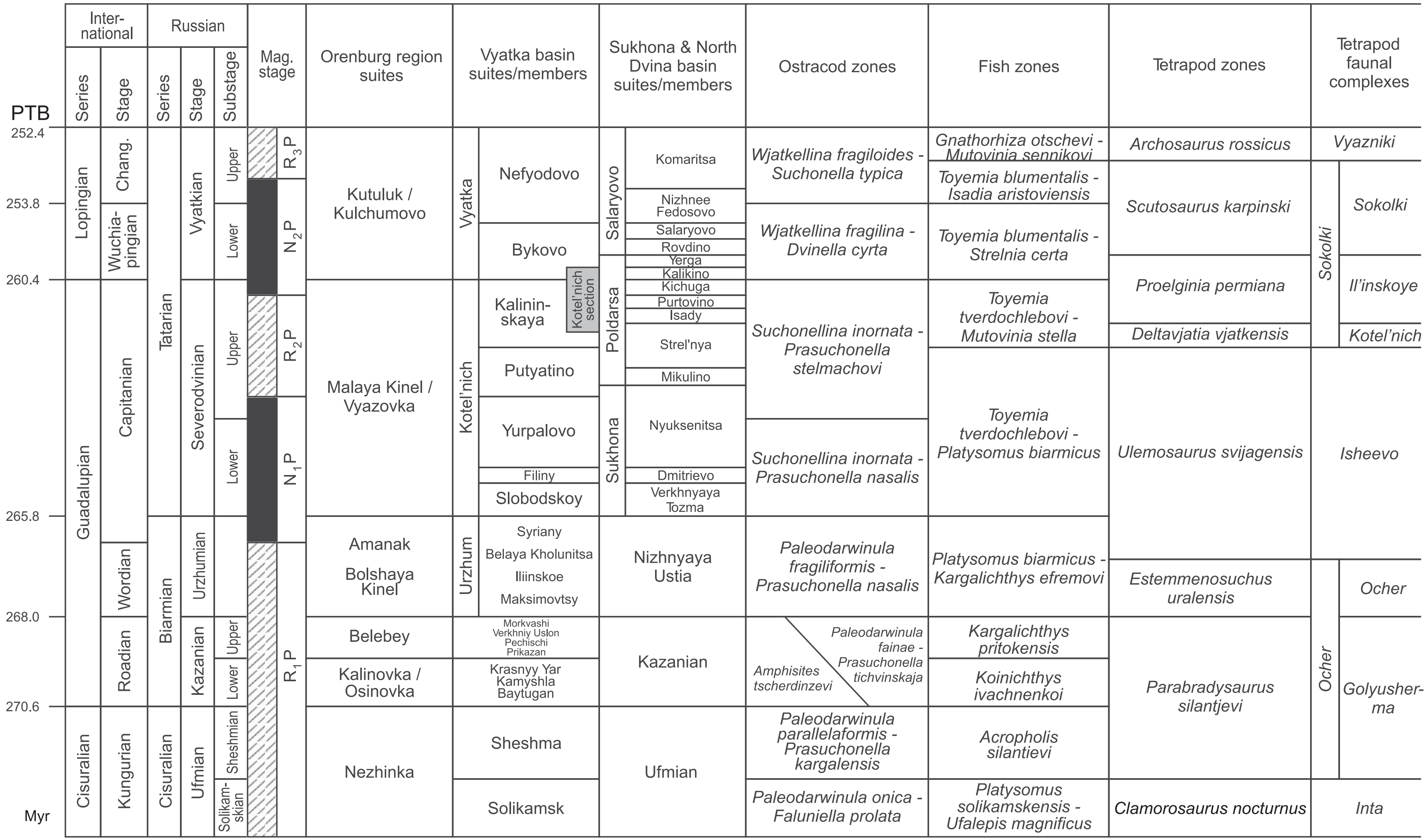

Fig. 2. Summary of the stratigraphy of the red beds of European Russia, showing the international (marine) stages and radiometric dates (from Gradstein *et al*. 2004; Ogg *et al*. 2008, with revised Permo-Triassic boundary date from Mundil *et al*. 2004), the global magnetostratigraphic scheme (from Muttoni *et al*. 2004; Steiner 2006), the Russian magnetostratigraphic zones (from Molostovskiy *et al.* 1998; Molostovsky 2005), the Russian marine and continental stages, the major gorizont names, major svitas in the South Urals (Molostovskiy *et al*. 1998; Molostovsky 2005; Tverdokhlebov *et al*. 2003, 2005), Vyatka Basin (Goman'kov 2001), Sukhona and North Dvina rivers (Golubev 2000), palynocomplexes (Yaroshenko & Goman'kov 1998; Golubev 2000), ostracode zones (Molostovskaya 2005; Kukhtinov *et al*. 2008), fish zones (Minikh & Minikh 1998; Yesin & Mashin 1998; Golubev 2000; Molostovskiy 2005), tetrapod zones and tetrapod faunal complexes (Golubev 2000; Ivakhnenko 2008). The Permo-Triassic boundary (PTB) runs across the top of the diagram.

method from early days (e.g. Khramov 1963). Since then, magnetostratigraphic studies have been made of hundreds of key sections in the Russian Permo-Triassic (reviewed by Molostovskiy 1983, 2005; Molostovskiy *et al*. 1979) and a detailed zonal scheme established (Fig. 2). Doubt had been cast on much of the older magnetostratigraphic work because of new methods and revised standards, but recent reanalyses of older work (e.g. Khramov *et al*. 2006) and new studies on freshly collected material (e.g. Gialanella *et al*. 1997; Bazhenov *et al*. 2008; Taylor *et al*. 2009) have confirmed the older work and allowed matching of the Russian chrons to the international scale (e.g. Muttoni *et al*. 2004; Steiner 2006). For example, in the Permian, the Russian stage N_1P is Capitan N (including P2), R_2P includes P3, N_2P is Chang N (including P4), and R_3P includes P5 (Steiner 2006; Taylor *et al*. 2009).

The key to the value of these recent correlations, from the Russian magnetostratigraphic scheme to the world, is that Russian magnetostratigraphic work on the Permo-Triassic red beds has always been tightly tied to biostratigraphic work (see, e.g. reviews by Molostovskiy 1983, 2005; and chapters in Esaulova *et al*. 1998; Lozovskiy & Esaulova 1998; Goman'kov 2001; Molostovskiy & Minikh 2001). These studies, where fossil samples and magnetostratigraphic plugs were collected on the same field trips, and matched to single measured sections, provide the basis of the schemes presented in Figure 2.

Magnetostratigraphy provides one direct link from the continental red beds of Russia to the marine standard stratigraphic stages, and further work will doubtless sharpen and improve those correlations. Further, studies of biostratigraphically significant fossils, and interfingering marine units, have provided further tie points. A common assumption is that such faunal resemblances are no better than the identification of tetrapod families shared between Russia and South Africa, as documented by Olson (1957), Modesto & Rybczynski (2000) and others, but this is far from the truth. Such comparisons are generally useful in establishing broad comparability between the patterns of faunal evolution in both areas, but because of regional differences among the genera, and because Karoo stratigraphy is still largely focused on the tetrapod assemblages, there is little point in attempting to make correlations from Russia to South Africa. In fact, it is much more useful to tie the Russian continental Permo-Triassic directly to the international marine stratigraphic scheme by comparison of magnetostratigraphy, shared fossils and interfingering marine deposits.

This is not the place to review all shared biostratigraphically significant fossils, but a few notes are offered on the ostracode schemes. Since the 1930s, numerous Russian biostratigraphers have studied the Late Permian ostracodes of the red beds across the Russian Platform, and they have published a substantial literature on the evolution of cytherocopine, volganellacean and darwinulocopine ostracodes. In parallel with magnetostratigraphic studies from the 1960s onwards, they have established a system of nine ostracode biozones that define Ufimian, Kazanian and Tatarian beds, so spanning the entire Middle and Upper Permian (Fig. 2; Molostovskiy *et al*. 1998; Molostovskaya 2005; Molostovskiy 2005; Molostovskaya, Horne & Benton, in prep). The ostracode biostratigraphy of the Permian has been embedded in official Russian stratigraphic synopses, and the zones have been checked and rechecked on hundreds of sections scattered through 10 major sedimentary basins, and over thousands of kilometres. The ostracode biostratigraphic scheme for the Triassic (Fig. 2) is less well established, and we show here the findings of E. M. Mishina, based on large collections of material from the western half of the Moscow Syneclise. The first biozone, *Darwinula mera–Gerdalia variabilis*, has been identified over the whole of the east of European Russia, but the later zones may be specific to the Moscow basin. Further, palynology (Goman'kov *et al*. 1998) and fossil fishes (Minikh & Minikh 1998) were also investigated in parallel with the ostracode and magnetostratigraphic work from the 1930s onwards to develop biostratigraphic schemes that were tested and retested against each other over wide areas of Permo-Triassic red beds between Moscow and the Urals, and around the Urals area. These are also shown in outline in Figure 2.

It is crucial here to establish biostratigraphic tie points that link the internally coherent Russian dating schemes (Fig. 2) to the rest of the world, and to the international marine standard. The base of the Russian succession has moved substantially downward in recent years. Until the 1990s, the Russian stages, the Ufimian, Kazanian and Tatarian, were the global standards, and they were termed 'Upper Permian'. With the introduction of a Middle Permian epoch, the Guadalupian, it became clear that the Russian succession spanned most of the newly delimited Middle and Upper Permian. The base has been much debated, and it seems clear that the Ufimian is in fact mostly, or perhaps all, Early Permian, and equates with the upper part of the international marine Kungurian stage (Gradstein *et al*. 2004; Menning *et al*. 2006; Lozovskiy *et al*. 2009). This is based on direct correlations using key marine species. For example, Leonova (2007) reported an ammonoid assemblage from the Verkhnekamyshlinskie Beds of the lower Kazanian Substage and lower part of the Prikazanskie Beds of the upper Kazanian Substage, from the Kremeshkie Quarry, 10 km south of the town of Sovyetsk, in the south of Kirov Region, in the heart of the Volga–Urals continental red beds successions. These ammonoids (abundant *Sverdrupites harkeri* and *S. amundseni*, and rarer *Biarmiceras* and *Medlicottia*) indicate a Roadian age: *Sverdrupites* is exclusively Roadian, and species of *Biarmiceras* and *Medlicottia* are known from the upper Kungurian and Roadian. Leonova's (2007) view has been supported in a comprehensive review of the age of the Ufimian by Lozovskiy *et al*. (2009), incorporating biostratigraphic evidence from foraminiferans, ammonoids, bivalves, brachiopods, ostracodes, conodonts, insects, fishes, tetrapods, macroplants and palynomorphs, in which the Ufimian, divided into a lower (Solikamian) and upper (Sheshmian) unit, correlates with the upper part of the Kungurian stage; whether the Kungurian, or this upper part of it, should be regarded as entirely Lower Permian (= Cisuralian) or as partly or wholly Middle Permian (= Guadalupian) is debated (Gradstein *et al*. 2004; Menning *et al*. 2006; Lozovskiy *et al*. 2009).

Higher parts of the Permian succession are also tied to the international scale. For example, the miospore assemblages of the Late Permian (Yaroshenko & Goman'kov 1998), may be correlated directly with those of Arctic Canada, Greenland, Europe, Pakistan, Australia and China (Utting *et al*. 1997; Lozovskiy 1998; Peng *et al*. 2006). Ammonoids from marine beds of the Kungurian, Ufimian and Kazanian correspond to those from North America (Bogolovskaya 2006), and brachiopods and ammonoids from marine beds interfingering with continental red beds in the Biarmian and Tatarian of the Kanin Peninsula, on the Arctic coast of European Russia, may be matched directly with species in Spitsbergen and Greenland (Grunt 2006), so providing a direct link to the standard marine stages of the Permian.

For the Triassic, Ochev & Shishkin (1989) and Shishkin *et al*. (2000, 2006) summarized tetrapod taxa, and other age-indicative fossils, that are shared between narrow stratigraphic units in Russia and marine units elsewhere. For example, the basal

Triassic unit in Russia, the Vokhmian Gorizont (Fig. 2), is equated with the marine Induan (*Glyptophiceras martini* to *Proptychites rosenkrantzi* ammonite zones) of East Greenland by the shared occurrence of the amphibians *Tupilakosaurus* and *Luzocephalus*. This is confirmed by a sporomorph assemblage that resembles those from the marine Induan of East Greenland, Canada and Pakistan, and the conchostracan *Vertexia tauricornis*, which is widespread, and provides a correlation with the Lower Buntsandstein of Germany and the upper Induan of East Greenland. The succeeding Rybinskian Gorizont is dated as early Induan on the basis of the presence of the lycopsid plant *Pleuromeia*, recorded nowhere before the Olenekian, the miospore assemblage that is shared with the Kumanskaya Svita of the eastern Caucasus, whose early Olenekian age is indicated by conodonts, and the occurrence of the amphibian *Benthosphenus* also in the Russian Far East accompanied by ammonites of the *Anasibirites nevolini* local zone of late early Olenekian age. As a third example, the Yarenskian Gorizont is typified by the amphibians *Parotosuchus* and *Trematosaurus*, known also from the Middle Buntsandstein of Germany, and from Upper Olenekian estuarine and coastal deposits of the Caspian Depression in association with ammonites of the *Tirolites cassianus* local zone and from Kazakhstan in association with the *Columbites karataucikus* ammonite fauna, both of which correlate with ammonite zones of the upper Olenekian Alpine standard zones. This age is confirmed further by miospore and charophyte assemblages shared with Germany, and the Gamskian Gorizont, representing the upper part of the Yarenskian Gorizont (Fig. 2), contains an *Atratisporites*-dominated miospore assemblage, common in the upper Olenekian worldwide. Plagiosaurs link the Donguz Gorizont to the marine Muschelkalk of Germany, and the procolophonid *Kapes* also links the Donguz to the upper Anisian Otter Sandstone Formation of England. Miospore assemblages indicate a late Anisian age for the lower part of the Donguz Gorizont, and a Ladinian age for the upper part. Finally, the amphibian *Mastodonsaurus* occurs both in the Bukobay Gorizont and the Lettenkeuper (upper Ladinian) of Germany (Ochev & Shishkin 1989), and the Bukobay also shares macroplants and a miospore assemblage with the Lettenkeuper (Shishkin *et al*. 2000).

There are some important issues concerning the Permo-Triassic boundary in Russia. This boundary in Russia has traditionally been set between the Vyatkian and the Vokhmian gorizonts (Fig. 2), but some doubt was cast on this correlation by a recent definitive edition of the international geological time scale (Gradstein *et al*. 2004) in which the entire Lopingian (Upper Permian) and the Permo-Triassic boundary were 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 would imply a substantial 9–10 Ma gap in the Russian record that has major stratigraphic and palaeontological implications. This 2004 conclusion had been preceded by a long debate among Russian stratigraphers about whether there was indeed a gap of 1–5 Ma at the end of the Permian and the beginning of the Triassic (e.g. Goman'kov *et al*. 1998; Lozovskiy 1998) or not (e.g. Tverdokhlebov *et al*. 1989; Afonin 2005; Sennikov & Golubev 2006; Krassilov & Karasev 2009). These researchers all agreed, however, that there was a substantial amount of Upper Permian in the Russian sections based on strong biostratigraphic and magnetostratigraphic evidence. This has been confirmed by revised magnetostratigraphic work (Taylor *et al*. 2009) and, independently, in the further revised international time scale (Ogg *et al*. 2008).

Further, recent work correlates the palynological assemblage at Vyazniki (Afonin 2005; Metcalfe *et al*. 2009; Krassilov & Karasev 2009; see below) with the lower *Otoceras* beds of East Greenland and the Canadian Arctic Archipelago, and the upper part of the Lower Guodikeng Formation of Xinjiang, China. This latter unit spans the Permo-Triassic boundary, and is correlated with the upper Changhsingian of the Permo-Triassic boundary Global Stratotype Section and Point (GSSP) at Meishan by the occurrence of the alga *Reduviasporonites chalastus* (Afonin 2005; Metcalfe *et al*. 2009).

Of course it would be wrong simply to claim that the Russian Vyatkian is identical in duration to the Changhsingian and the Vokhmian to the Induan. However, in that the Vyatkian is dated as exclusively Changhsingian and the Vokhmian as exclusively Induan, from fossils and magnetostratigraphy, we treat the boundary between the two Russian units as broadly equivalent to the Permo-Triassic boundary, whether marked with or without a meaningful gap in sedimentation.

In conclusion, the summary scheme (Fig. 2), compiled from many sources, and representing the work of hundreds of Russian geologists from 1960 to the present, appears to be internally coherent throughout the numerous separate sedimentary basins of European Russia. Further, the scheme may be tied to the international marine standard by two independent means, through magnetostratigraphy and through comparisons of assemblages and single species and genera of a broad range of fossils. This scheme will be used as a basis for dating the Zhukov and Vyazniki beds.

Previous work on dating the Vyazniki and Zhukov beds

Murchison (1841) and Murchison & de Verneuil (1842) presented brief reports on the Vyazniki red beds, which they had visited in 1840 (Benton *et al*. 2010), interpreting them as either latest Permian or early Triassic on the basis of fossils, and tending to prefer the Permian assignment. Little was done on these sections until the Russian geologist Sibirtsev (1896) restudied the Tolmachevo section, at the eastern end of Vyazniki town, as part of his geological mapping for the Geological Committee of Russia. Like Murchison, he identified the rocks as Upper Permian, and reported from Tolmachevo 'scales of *Palaeoniscus* and cytheriinins—*Estheria* sp. and *Bairdia* sp.' His *Paleoniscus* is a generalized term for thick, rhomboidal fish scales, his *Estheria* was a conchostracan, and *Bairdia* an ostracode. He also discovered Upper Permian sand outcrops near Bykovka village and at the west edge of Vyazniki town, as well as in the Zhukov Ravine section near Gorokhovets. In the Zhukov Ravine, Sibirtsev (1896) also reported woody plants, identified by him as *Araucarites*, *Arthropitys* and *Calamites*-like forms, as well as fish scales ('*Palaeoniscus*') and 'lizard' (= reptile) bones.

Interest was reawakened by the discovery of vertebrate fossils at the western end of Vyazniki town in 1951 by a local geologist, and subsequent excavations by the Palaeontological Institute of the Academy of Sciences of the USSR in 1952, 1955 and 1956, led by B. P. V'yushkov (Efremov & V'yushkov 1955). Finds included a range of fishes, amphibians and reptiles, mostly occurring as isolated bones in conglomerates and coarse sandstones, but with occasional more substantial remains, such as the complete skulls of the temnospondyl *Dvinosaurus* and the therocephalian *Moschowaitsia*. This tetrapod assemblage, representing an apparent mixture of latest Permian and earliest Triassic elements, led to the suggestion (Sennikov & Golubev 2006) that the Vyazniki beds might represent the very youngest Permian anywhere in the Russian basins, and the unit has even been made the type of a new latest Permian stratigraphic stage, the Vyaznikovian (Lozovskiy & Kukhtinov 2007; Kukhtinov *et al*. 2008), a term we do not use here, preferring to retain this unit as the uppermost part of the Vyatkian Gorizont (Fig. 2). It should be noted that Krassilov & Karasev (2009) accepted the Vyaznikovian as a distinct time unit, and inserted a further, and even younger, time division between it and the earliest Triassic Vokhmian, the Nedubrovian, based on the finding of plants, palynomorphs and the amphibian *Tupilakosaurus* at the Nedubrovo locality on the Yug river, at the head of the North Dvina river. The Vyazniki and Nedubrovo localities cannot be correlated by mapping as they lie too far apart, and their floras are partly shared and they both sit in the terminal Changhsingian reversed magnetic polarity zone (Krassilov & Karasev 2009; R_3P, Fig. 2), so it is not currently clear whether the two can be distinguished and characterized as successive time divisions.

Borehole information from the Gorokhovets–Vyazniki area presented by Strok *et al.* (1984) shows that a maximum of *c*. 130 m of Permo-Triassic red beds overlie Kazanian limestones (Figs 3 and 4). As recognized by Murchison, the red bed succession divides into two broad lithological parts, which should be named formally as formations (= svitas) at some point. The lower 60 m is dominated by reddish brown mudstones with thin beds of gypsum at the base and grey mudstones and thin sandstones at the top, whereas the upper part of the succession is predominantly sand and sandstone, which reaches a maximum preserved thickness of 70 m in the Vantino Borehole 10 km south east of Vyazniki (Strok *et al*. 1984). The sands and sandstones (Table 1) are an important aquifer in the region and the sharp contact with the underlying mudstone-dominated succession is commonly marked by springs along the foot of the escarpment adjacent to the Klyaz'ma River. Ravines cut into the face of the high escarpment between Vyazniki and Gorokhovets provide exposures of the Permo-Triassic succession in otherwise heavily vegetated terrain (Fig. 3). The sands and weakly consolidated sandstones are also exposed in several abandoned quarries around Vyazniki.

The Zhukov and Vyazniki sections

The Zhukov Ravine section

Description. Zhukov Ravine is located 2 km SW of Gorokhovets (Fig. 5). A composite 36 m section can be assembled from three correlative exposures at the base, middle and top of the 1 km long NW–SE-oriented ravine (Fig. 6). The basal 26 m of the section comprises predominantly massive, rooted, red mudstones with subordinate beds of laminated brown mudstone, massive or ripple cross-laminated sandstone and pale grey, well-cemented micritic limestones with root voids (Fig. 6). The limestones are distinctive marker beds in the published sections of Strok *et al*. (1984), a number of them occurring in our section 1, terminating with a major, 1 m thick rooted micritic limestone that provides a link to our section 2 (Fig. 6). A second substantial rooted micritic limestone occurs after a gap at the top of the cliff in our section 2, and provides a lateral marker to the base of a section logged by I.I.M., and the source of her ostracode samples (Fig. 6). Toward the head of the Zhukov Ravine a well-cemented intraclast conglomerate with fish remains marks an abrupt change from the mudstones and occasional limestones to a succession dominated by brown, fine- to medium-grained, cross-bedded, weakly consolidated sand and sandstone. Powerful springs emerge from the base of the sands and sustain perennial flow in the stream that flows down the heavily vegetated ravine. This overlying sandstone formation forms a deep channel when traced laterally, apparently cutting out the upper limestone bed (Fig. 6), and so lateral correlations must be performed with care.

Dating. The Permo-Triassic boundary in the Zhukov Ravine is determined by (1) regional comparisons, (2) magnetostratigraphy and (3) biostratigraphy. Regional comparisons presented by Strok *et al*. (1984) used the deep Vantino and Luknovo boreholes as guides, and a mix of ostracodes and conchostracans, as well as major lithological changes, to correlate from section to section.

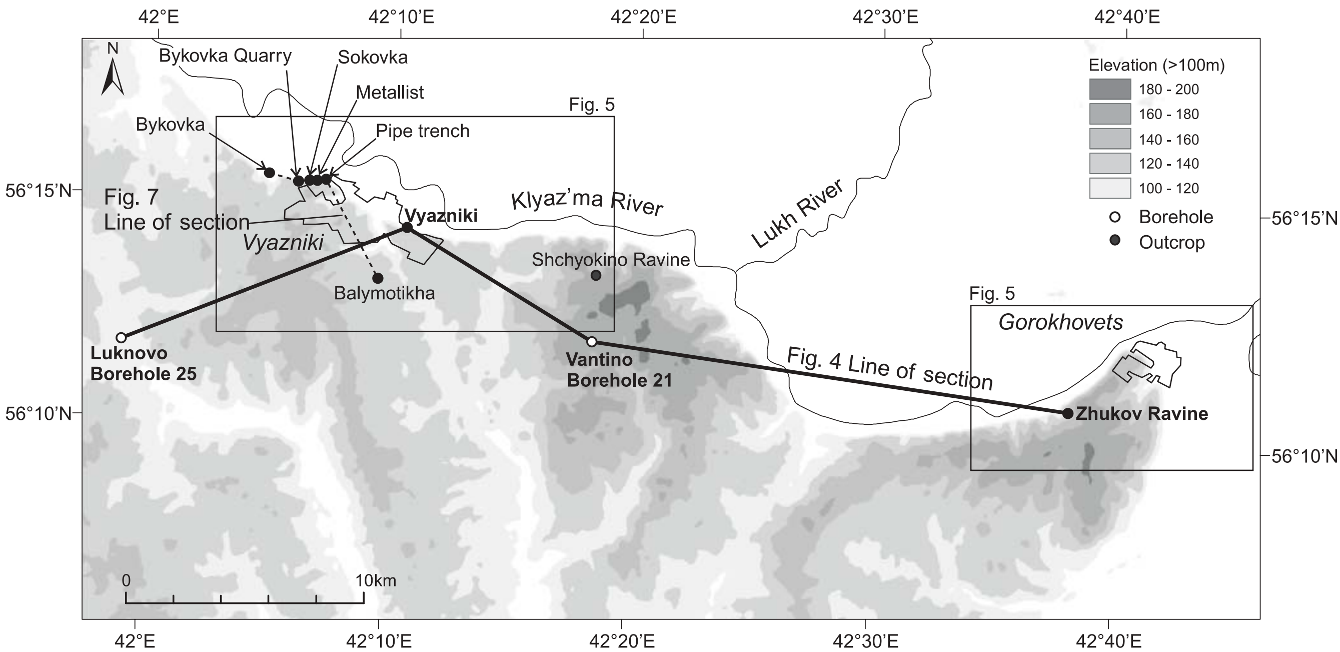

Fig. 3. Map showing the elevated terrain between Vyazniki and Gorkhovets and the steep escarpment to the south of the Klyaz'ma River. ●, Localities investigated around Vyazniki and the Zhukov Ravine; ○, borehole data. The bold continuous line shows the borehole and outcrop correlation shown in Figure 4, and rectangles show map areas in Figure 5. The finedotted line shows the correlation of outcrops shown in Figure 7.

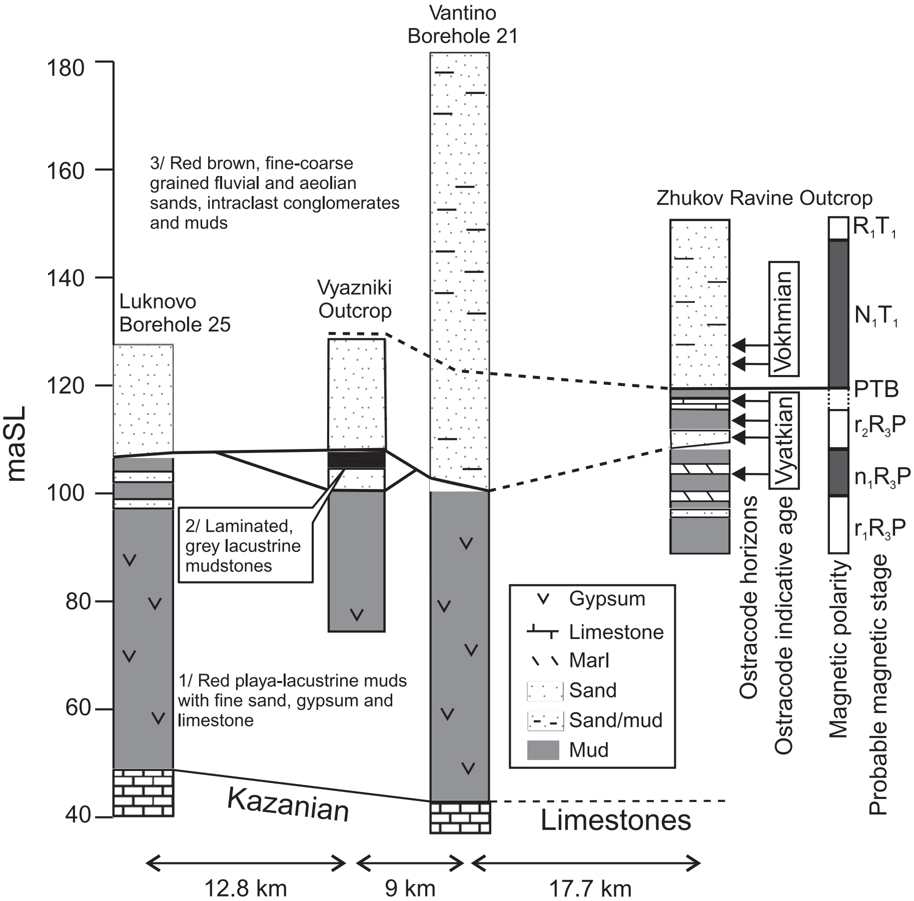

Fig. 4. Correlation of boreholes and logged sections in the Vyazniki–Gorokhovets area based on Strok *et al*. (1984), and other sources (see Fig. 3 for location of section). Approximately 130 m of Late Permian and Early Triassic continental strata overlie Kazanian limestones and divide into a lower mud-rich formation and an upper sandy formation. PTB shows the position of the Permo-Triassic boundary as discussed in the text; maSL, metres above sea level. Standard abbreviations for magnetic polarity chrons are indicated to the right (N, normal; P, Permian; R, reversed; T, Triassic).

Marine limestones of Kazanian age provide a clear marker for the base of the sections (Fig. 4).

A magnetostratigraphic study of the Zhukov Ravine by Molostovskiy (1983; Fig. 4) showed a reversed interval in the lower part of the succession, a short positive interval, followed by a short reversed interval, and a long positive interval spanning the upper sandstone unit, and reversing just below the top of the outcrop. This was interpreted (Molostovskiy 1983; Strok *et al*. 1984) as spanning part of the Urzhumian and Severodvinian (basal to mid-Tatarian) at the base, and the Vokhmian (lowest Triassic) through the upper sandstones. Strok *et al.* (1984) were mistaken in dating the lower mud units in the area as too ancient (see below), but the magnetostratigraphic record from the Zhukov Ravine matches recent determination of the Permo-Triassic boundary in Russian sections (Taylor *et al*. 2009). The long normal interval at the base of the sandstone unit is presumably N_1T_1, representing the very top of the Permian (uppermost Vyatkian) and much of the Vokhmian (basal Triassic), and perhaps passing into R_1T_1 at the top (Fig. 4). If this is correct, the Permo-Triassic boundary lies near the base of the N_1T_1 zone, some 19 m from the top of the section (Strok *et al*. 1984), or 22 m in our section (Fig. 6). The thick limestone bed at the base of section 2 and the top of section 1 is near the top of a reverse-polarity zone, presumably r_2R_3P, some 9 m thick (Strok *et al*. 1984), below which is n_1R_3P. Our section is 36 m thick, compared with a schematic log of a 43 m section of Strok *et al*. (1984), which presumably extends further downstream than ours, and so includes a lower negative-polarity zone, presumably r_1R_3P, all within the Vyatkian (Taylor *et al*. 2009; Fig. 4).

Ostracodes have been identified from six horizons in the

Table 1. *Qualitative X-ray diffraction analysis of heavy mineral separates from five sand samples whose location is shown on the logged sections (Figs 6 and 7)*

	Mineralogy		
Sample	Major	Minor	Trace
Hm1	Quartz, epidote*, haematite*, albite	Hornblende*, mica, chlorite, K-feldspar	Goethite*
Hm2	Quartz, zircon*, almandine*	Hematite*, rutile*, epidote*, grossular*, goethite*, magnetite*, albite	Staurolite*, chlorite
Hm3	Quartz, epidote*, haematite*, albite	Hornblende*, ferropargasite*, mica, chlorite, magnetite*, rutile*	Magnetite*, K-feldspar
Hm4	Quartz, epidote*	Rutile*, albite, chlorite, mica	K-feldspar
Hm5	Quartz, epidote*	Albite, hematite*, goethite*, mica, chlorite	K-feldspar

*Density >2.9 g cm^{-3}.

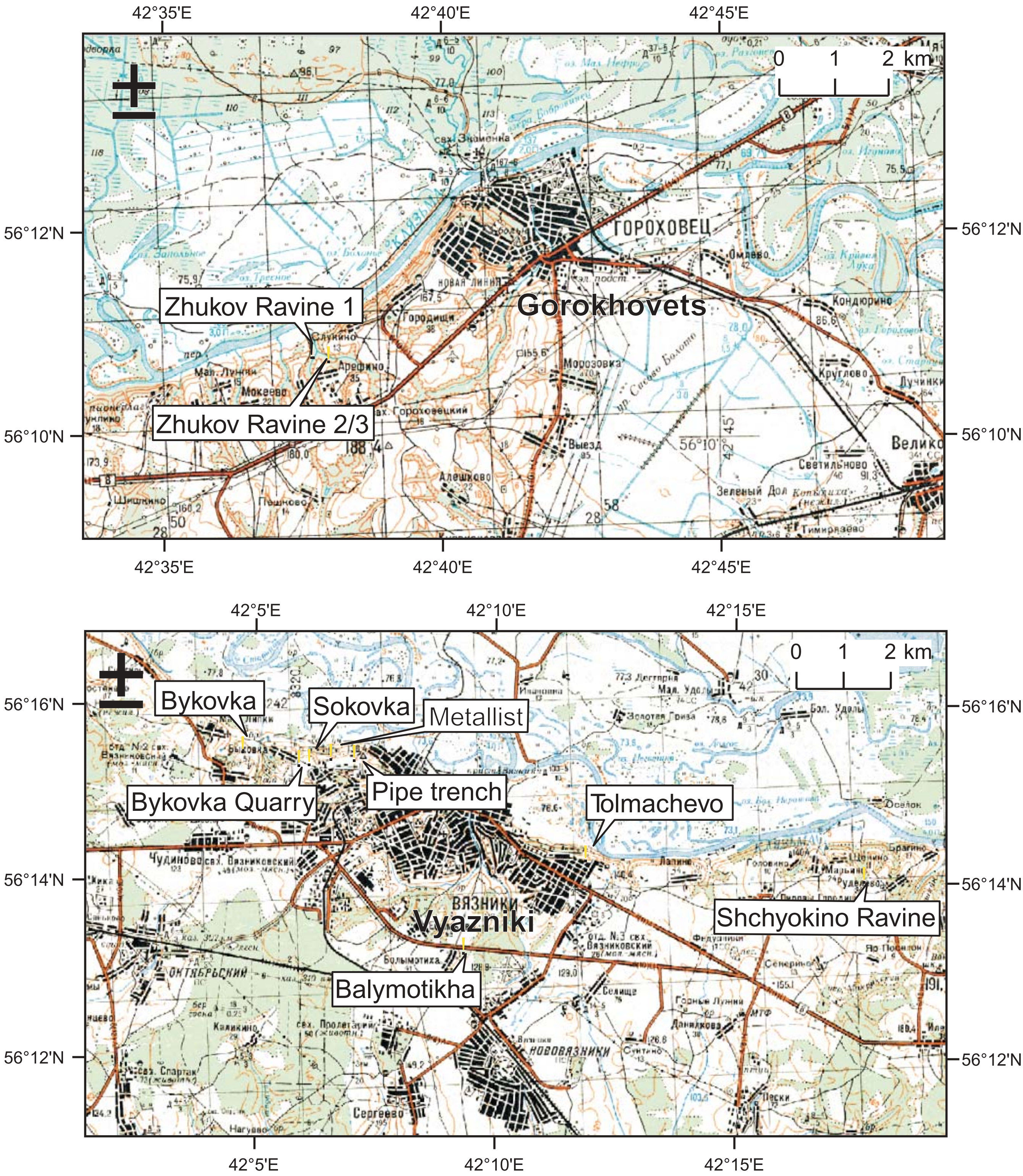

Fig. 5. Detailed topographic maps showing the locations of logged sections at Gorokhovets and Vyazniki. Global positioning system (GPS) readings for each named locality are given in Table 2.

Zhukov section, four below and two above the Permo-Triassic boundary. The uppermost Permian ostracode assemblage, from some 3–4 m below the Permo-Triassic boundary (Fig. 6) yielded *Suchonellina trapezoida* (Sharapova), *S. ignatjevi* (Zekina et Jan.), *S. anjugensis* Mishina and *Suchonella* ex. gr. *typica* Spizharskyi, all typical of terminal Vyatkian (latest Permian) age (the *Suchonellina inornata–Prasuchonella nasalis* ostracode zone, Fig. 2; Molostovskaya, cited by Sennikov & Golubev 2006;

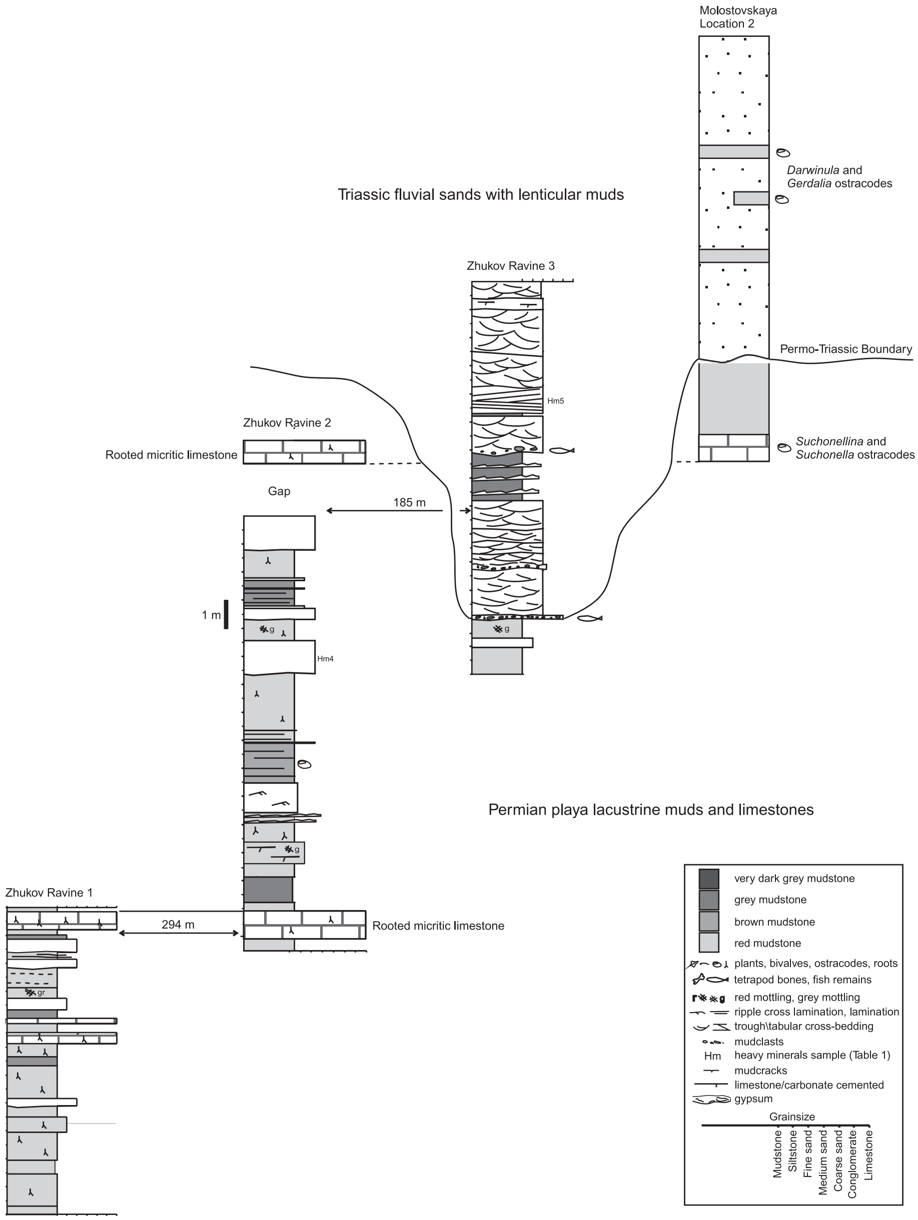

Fig. 6. Composite logged section at the Zhukov Ravine near Gorokhovets. Locations of Zhukov Ravine logged sections 1–3 are given in Figures 3 and 5, and exact GPS readings in Table 2. The stratigraphic log of Molostovskaya at her location 2, well upstream, is added. These show the position of the Permo-Triassic boundary as determined by ostracodes just above the conspicuous package of limestones and marls. The boundary occurs at, or below, the undulating erosional contact with the fluvial sands depending on the depth of incision. Molostovskaya Location 1 is located near Zhukov Ravine 1 and Molostovskaya Location 2 is located near Zhukov Ravine 3 (see Fig. 5).

Table 2. *Latitude and longitude of locations with sedimentary logs*

Locality	Latitude (N)	Longitude (E)	Reference
Bykovka	56.258467	42.085450	
Bykovka Quarry	56.256350	42.100183	Locality 4
Sokovka	56.256633	42.103350	Locality 5
Metallist	56.256900	42.107733	Locality 6
Pipe trench	56.257483	42.119250	
Balymotikha	56.221300	42.157167	Locality 10
Shchyokino Ravine	56.234783	42.296683	
Zhukov Ravine 1	56.180500	42.629933	
Zhukov Ravine 1	56.179817	42.634650	
Zhukov Ravine 1	56.180000	42.634650	

Positions are in decimal degrees; datum: WGS 1984. Reference locality numbers are from Sennikov & Golubev (2006).

Kukhtinov *et al*. 2008). The other three Permian ostracode assemblages from lower levels all confirmed Vyatkian age. The two ostracode assemblages from above the postulated Permo-Triassic boundary occurred in mudstones 7–8 m above the boundary, and higher, and I.M.M. identified species of *Darwinula* and *Gerdalia*, namely *Darwinula sima* Mischina, 1969, *D. acuta* Mischina, 1966, *D. cara* Mischina, 1969, *D. unzhica* Mischina, 1969, *D. media* Mischina, 1969, *D. regia* Mischina, 1969, *D.* cf. *prisca* Mischina, 1969, *D.* ex gr. *accuminata* Belousova, 1961, *Gerdalia clara* Mischina, *G.* ex gr. *variabilis* Mischina, 1966, *G. rixosa* Mischina, 1966, and G. dactyla Belousova, 1961. Both *Darwinula* and *Gerdalia* are extremely rare in the Permian, and this combination of species, with abundant representation of both genera, is typical of the Vokhmian *Darwinula mera–Gerdalia variabilis* ostracode zone, as recorded from many unequivocally basal Triassic localities across the Russian Platform (Fig. 2).

The basal Triassic (Vokhmian) age for the sandstones is confirmed by fish fossils recovered by A.G.S. and colleagues in 2003 from the thin rust-brown conglomerate at the top of a sand unit, seen at the base of section 3 (Fig. 6), and a further conglomerate unit at the base of a channel sand, some 7 m higher. The conglomerate contains fragments of fish bones and scales, less frequently with intact scales and teeth and plant remains, and very rarely with tetrapod bones. The only tetrapod material from the Zhukov Ravine in the PIN collection is an indeterminate temnospondyl femur. The fish remains include some teeth of large specimens of the palaeonisciform *Isadia aristoviensis* A. Minich, a dental plate fragment of the dipnoan *Gnathorhiza* sp., investing-bone fragments of *Mutovinia sennikovi* A. Minich, scales of *Strelnia* sp., an actinopterygian fish tooth vaguely resembling typical teeth of the genus *Saurichthys*, and numerous scales close to *Evenkia* (?) sp. *Gnathorhiza* is abundant in European Russia in the Lower Triassic and *Saurichthys* in the Lower and Middle Triassic, but these are very rare in uppermost Permian (Vyatkian) localities. *Evenkia* until now is known, and abundant, only in the Triassic of European Russia and Tunguska (Siberia). These three fishes confirm the evidence from magnetostratigraphy and ostracodes that the upper channel sandstones in the Zhukov Ravine are Early Triassic in age.

Vyazniki Bykovka–Sokovka–Balymotikha sections

Description. Permo-Triassic strata are exposed around Vyazniki in a number of temporary excavations on the escarpment at Sokovka, in eroded track sections, stream cuttings and disused quarry workings (Figs 3–5). Together, the sections show that the Permo-Triassic strata can be divided into three main parts (Fig. 7), as follows.

(1) The lowest part is seen in a poorly exposed track section at the western end of Vyazniki and comprises 18 m of reddish brown mudstone with two nodular gypsum beds in the basal 4 m. The reddish brown mudstones locally show grey mottling, contain the fibrous clay mineral palygorskite, and are interbedded with thin fine-grained sandstones that become more common toward the top. The lowermost mudstones exposed in this section are estimated to be 35 m above Kazanian limestone based on the regional borehole correlation of Strok *et al.* (1984). These red muds with palygorskite might even be Kazanian in age, based on regional lithological comparisons (Sennikov & Golubev 2006). This basal interval is not exposed at Vyazniki but boreholes indicate that it comprises red mudstones with gypsum (Fig. 4).

(2) Above the reddish brown mudstones is a 3–6 m thick interval of fine-grained greenish-grey sandstones, red mudstones and, most distinctively, laminated dark grey mudstones with ostracodes, fish debris and tetrapod remains. At Vyazniki this is sometimes referred to as the ‘lower fossil assemblage’. Laminated, dark grey mudstones are an unusual facies within the Tatarian of the Russian Platform. To the north of Vyazniki the mudstones crop out along the base of the River Klyaz’ma escarpment (Fig. 5).

(3) Sharply overlying the grey mudstone interval is a 20–25 m thick succession of brown and reddish brown, weakly consolidated, fine- to coarse-grained sand. The sands contain thin intervals of interlaminated mudstones and fine sandstones and well-cemented intraclast conglomerates that can contain vertebrate bones in what is sometimes termed the ‘upper fossil assemblage’. The sands and intraclast conglomerates are locally exposed on the main escarpment to the north of Vyazniki, where their sharp contact with the underlying muds is marked by springs. A disused quarry exposing the upper part of the sands is located at Bykovka (Fig. 5).

Dating. Several views have been expressed on the age of the Vyazniki beds. Originally, Strok *et al*. (1984) dated the Vyazniki red bed succession in its entirety as Severodvinian, thus lower to mid-Tatarian, and at the base of the Lopingian. This decision was made largely on the basis of regional mapping considerations, and it would imply a large temporal gap below the Permo-Triassic boundary. Most Russian researchers now accept that the Vyazniki beds are Vyatkian in age, broadly equivalent to the Changhsingian (Fig. 2), but there is a difference of opinion over whether they are mid-Vyatkian (Lozovskiy & Kukhtinov 2007; Kukhtinov *et al*. 2008), or late Vyatkian (Sennikov 1995, 1996; Ivakhnenko *et al*. 1997; Golubev 2000; Sennikov & Golubev 2006) in age. Elsewhere (Fig. 2), the youngest Permian tetrapod assemblages occur in the *Scutosaurus karpinskii* zone (Sokolki Assemblage); Kukhtinov *et al*. (2008) have argued that the Vyazniki tetrapods are exactly equivalent in age to the Sokolki Assemblage, whereas Sennikov & Golubev (2006) have argued that they are younger.

There are two main fossil-bearing horizons at Vyazniki: (1) the lower assemblage found in the grey clays (bed 2 of Kukhtinov *et al*. 2008); (2) the upper assemblage found in cemented intraclast conglomerates within the sand succession at the top (bed 3 of Kukhtinov *et al*. 2008). Each will be discussed in turn.

Fauna and flora of the lower grey clays. The lower fossil assemblage is dated securely as Vyatkian, based on fishes, insects, conchostracans, ostracodes, plant remains and the palynoassemblage. The fishes from the grey clays include the palaeonisciforms *Mutovinia sennikovi* A. Minich (investing bones and scales) and *Isadia aristoviensis* A. Minikh (rare teeth), both of which belong to the latest Vyatkian *Toyemia blumentalis*–*Isadia aristoviensis* ichthyoassemblage (Fig. 2). The insects include Gryllobatidae, Tomiidae, beetles, cockroaches and many other groups that are terminal Permian in aspect (D. E. Shcherbakov, D. S. Aristov & A. G. Ponomarenko, pers. comm.). The conchostracans include Limnadiopseidae gen. nov. and Lioestheriidae (*Sphaerestheria* sp. nov., *Pseudestheria suchonensis* Novojilov, *Pseudestheria* sp. nov. 1, *Pseudestheria* sp. nov. 2, *Loxomicroglypta* sp. nov., *Concherisma* sp. nov.), all taxa that are typical of the Tatarian (N. I. Novozhilov, pers. comm.).

The ostracodes from the lower fossil assemblage have been interpreted as either largely Triassic with some Upper Permian elements (Molostovskaya, cited by Sennikov & Golubev 2006; and herein), or as essentially Upper Permian with a few Triassic elements (Lozovskiy & Kukhtinov 2007; Kukhtinov *et al*. 2008). Kukhtinov *et al*. (2008) provided a revised list of ostracodes from the Vyazniki lower fossil assemblage. In summary, they noted that ‘Upper Permian species dominate, in particular *Suchonellina*, with the exception of the upper parts of the mudstone beds, which are poor in this genus and are rich in the genera *Darwinula* and rare *Suchonellina* and *Suchonella*. The genus *Gerdalia*, characteristic of the Lower Triassic . . . is not abundant here’.

Our revised summary of ostracodes from the Sokovka site in Vyazniki, collected in summer 2008, is that they consist of (1) definitively Permian ostracodes, (2) ostracodes that had appeared in the Permian and were widely common in the Triassic and (3) Triassic ostracodes.

(1) The Permian *Suchonellina*, *Wjatkellina* and *Darwinuloides* are crucial indicators of age. *Suchonellina*, represented by *S. trapezoida* (Sharapova in Schneider), *S. perelubica* (Starozhilova), 1968; *S. compacta* (Starozhilova), 1968, and *S.* ex gr. *lacrima* Starozhilova, 1968 typically occur throughout eastern Europe in the upper part of the Vyatkian (the Aristovo, Zabelino,

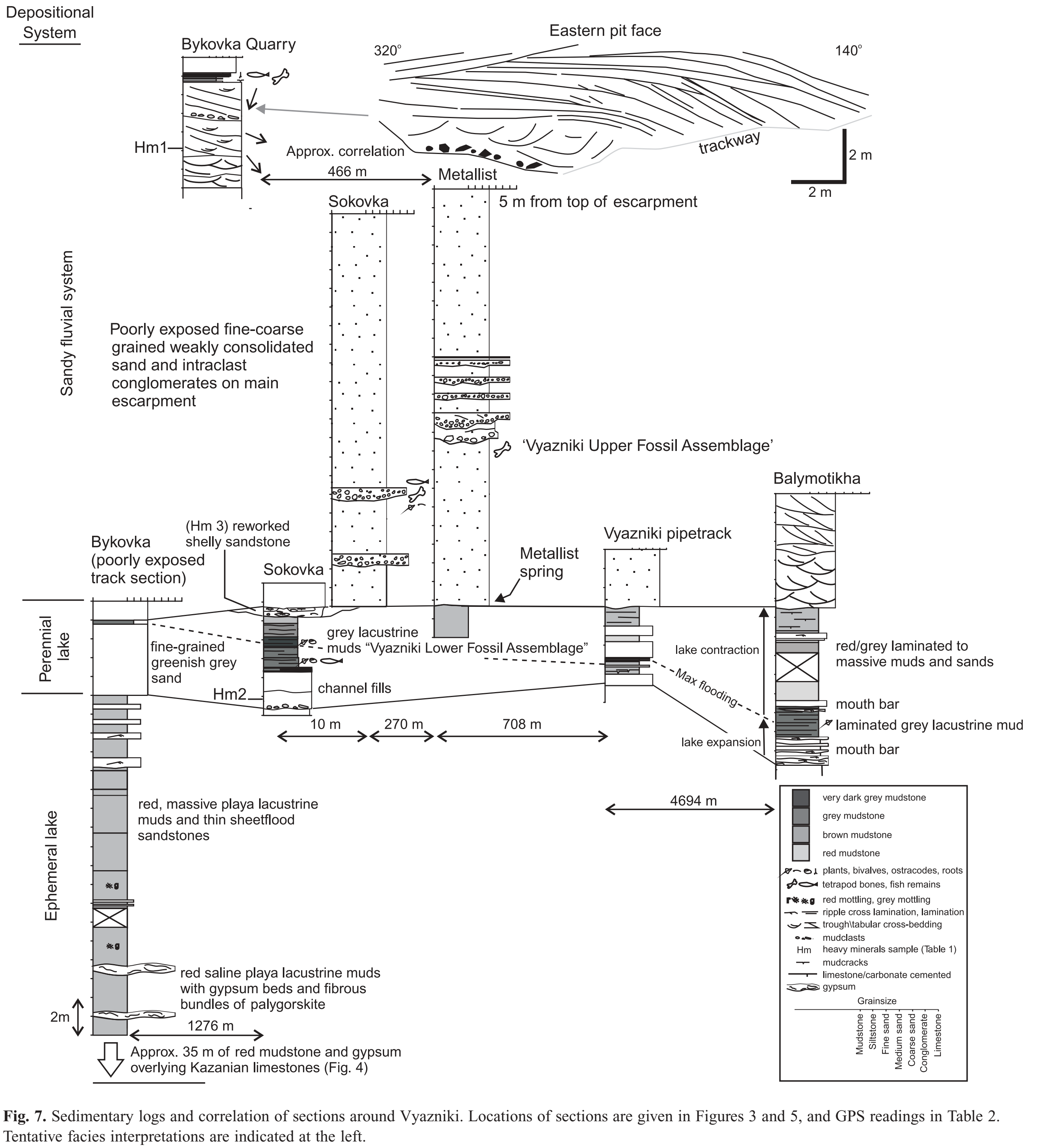

Fig. 7. Sedimentary logs and correlation of sections around Vyazniki. Locations of sections are given in Figures 3 and 5, and GPS readings in Table 2. Tentative facies interpretations are indicated at the left.

Sambulak, Vyazovka, Elshanka, etc. sections) and are absent, except for *S.* ex gr. *lacrima*, from the overlying Triassic beds. The genus *Wjatkellina* is represented by the species *Darwinula fragilina* Belousova, 1961, known otherwise from the Lower Triassic of the Volga basin, and *W. vladimirinae* (Belousova), 1963, typical of the Sarminskaya Svita (upper Tatarian), as well as *W.* ex gr. *vladimirinae* (Belousova), 1963, and *W.* sp. *Wjatkellina* appeared on the Russian plate at the beginning of the Vyatkian, and it increased in diversity and abundance in samples through that Gorizont, so that in the upper part (the Sambulak, Aristovo, Zabelino sections, wells in the Vyatka basin, etc.) samples show generally substantial and diverse occurrences. *Darwinuloides* is represented by the sole species ?*Darwinuloides svijazhicus* (Sharapova in Schneider), 1948, a fairly common and characteristic element of the Vyatkian ostracode complex from the Russian plate.

(2) *Suchonella* is represented by *S.* ex gr. *typica* Spizharskyi, 1939 (holotype from the upper Vyatkian of the Moscow basin) and *S. posttypica* Starozhilova, 1968, known also from the Lower Triassic of the Saratov region. *Darwinula* occurs in the Vyatkian, but became common in the Lower Triassic units, with most species regarded as typical of the Vetlugian Series: species from Sokovka include *D. regia* Mischina, 1969, *D. sima* Mischina, 1969, *D. accuminata* Belousova, 1961, *D. abscondida* Mischina, 1969 and *D.* ex gr. *pseudooblonga* Belousova, 1961. Holotypes of these species come from the Lower Triassic of the Moscow basin, except *D.* ex gr. *pseudooblonga*, whose holotype comes from the Lower Triassic of the Dnieper–Donets Depression. Single or rare tests are occasionally observed in the uppermost Permian Vyatkian Gorizont, jointly with *Suchonellina trapezoida* and *Suchonella typica* (the Sambulak, Vyazovka, Gryaznushka, Aristovo sections, etc.).

(3) *Gerdalia* is generally regarded as a purely Triassic ostracode (Molostovskaya, cited by Sennikov & Golubev 2006; Kukhtinov *et al*. 2008), but latest Permian examples occur. In the Sokovka samples, *Gerdalia* is represented by *G. wetlugensis* Belousova, 1961, *G. dactyla* Belousova, 1961, *G.* ex gr. *rixosa* Mischina, 1968, *G. secunda* Starozhilova, 1968, *G. analoga* Starozhilova, 1968 and *G.* sp. The first three species have been recorded before from the Lower Triassic units of the Moscow basin. Rare *Gerdalia* appear at the beginning of the Vyatkian Gorizont, and they become more frequent higher in the Gorizont, close to the Permo-Triassic boundary, after which the genus became most prosperous and widely distributed in the Early Triassic.

Similar ostracode complexes have been found in the upper part of the Upper Permian Vyatkian section of the Orenburg Cis-Ural Region (Vyazovka, Gryaznushka, Sambulak) in the Sukhona and the Malaya Severnaya Dvina basins (Aristovo, Zabelino), and in the basins of the Vyatka and the Vetluga (well core data).

The macroflora and palynoassemblages indicate a terminal Permian age. The key macroplant taxa are the peltasperm seed ferns *Pursongia* sp. nov., cf. *Lepidopteris* (al. *Callipteris*) *martinsii* Townrow (? gen. et sp. nov.), *Peltaspermum* sp. nov., and also the fern *Prynadaeopteris* (?) sp., the arthrophyte *Neocalamites* cf. *mansfeldicus* Weigelt, the ginkgophytes *Sphenobaiera* sp. nov. and *Ginkgoites* sp., and the conifer cf. *Ullmannia* sp. (Naugolnykh 2005; Krassilov & Karasev 2010). This macrofloral assemblage is new, so far unknown in Eastern Europe, and is generally similar to the Zechstein floral assemblage of the terminal Permian of the German Basin.

The Vyazniki Palynoassemblage includes elements characteristic of the Permian and of the Triassic, and a few taxa restricted to the Vyazniki bed. Spores are represented by rare *Calamospora* sp., *Punctatisporites* sp., *Retusotriletes* sp., *Lophotriletes novicus* Singh, *Apiculatisporis* sp. cf. *A. cornutus* Hoeg et Bose, *Apiculatisporis* sp., ?*Retitriletes* sp., *Limatulasporites fossulatus* Helby et Foster, *Kraeuselisporites* sp. and *Laevigatosporites* sp. Pollen grains include *Alisporites splendens* Foster, *Vitreisporites signatus* Leschik, *Klausipollenites schaubergeri* Jansonius, *Klausipollenites* sp. cf. *K. staplinii* Jansonius, *Platysaccus insignis* Ouyang et Utting, *Falcisporites* sp., *Potonieisporites*-like pollen grains, *Scutasporites* sp. cf. *S. unicus* Klaus, *Lueckisporites virkkiae* Clarke, *Protohaploxypinus* sp., ?*Lunatisporites* sp., *Vittatina connectivalis* Waryukhina, *Ephedripites* sp. and *Cycadopites* sp. cf. *C. follicularis* Wilson et Webster. Algae are represented by *Actinastrum* (= *Syndesmorion*) *stellatum* Fijalkowska, *Reduviasporonites chalastus* (= *Tympanicysta stoschiana* Balme), *Quadrisporites* sp., *Botryococcus* sp. cf. *B. braunii* Kutzing, *Veryhachium* sp. and *Leiosphaeridia* sp. (Afonin 2005).

The palynological assemblage is correlated (Afonin 2005; Krassilov & Karasev 2009) with the lower *Otoceras* beds of East Greenland and the Canadian Arctic Archipelago, both uppermost Permian, and new work (Afonin 2005; Metcalfe *et al*. 2009) shows close correlation with the upper part of the Lower Guodikeng Formation of Xinjiang, China, a more securely dated unit. The Permo-Triassic boundary lies within the upper Lower Guodikeng Formation (Metcalfe *et al*. 2009), characterized by the *Klausipollenites schaubergeri–Reduviasporonites chalastus–Syndesmorion stellatum* Palynoassemblage, dated by the alga *Reduviasporonites chalastus*, which is known from the upper Changhsingian of the Permo-Triassic boundary GSSP section at Meishan. There is little doubt that the Vyazniki Palynoassemblage is closely similar to the Lower Guodikeng Formation Palynoassemblage 2, sharing all three key taxa, and others (Afonin 2005; Metcalfe *et al*. 2009).

Fauna of the overlying sands. The upper fossil assemblage in the sands with intraclast conglomerates has yielded the only determinable bivalves, including *Palaeomutela oleniana* Amalitzky, *Palaeomutela plana* Amalitzky, *Palaeomutela* aff. *plana* Amalitzky, *Palaeomutela* cf. *solemyaeformis* (Netschajew), *Palaeomutela* (?) *concavocarinata* (Netschajew) and *Palaeomutela* sp. (V. V. Silantjev, pers. comm.). This bivalve assemblage is typical of the end-Permian (Tatarian) deposits of the Russian Platform (Sennikov & Golubev 2006).

Fishes from this upper level, based on collections made by B. P. V'yushkov in the 1950s, and by A.G.S., V.K.G., A.V.M. and M.G.M. since 2000, include the hybodont sharks *Hybodus* sp. and *Xenosynechodus* Glückman, a ctenacanth shark of the *Sphenacanthus* type, the palaeonisciforms *Mutovinia sennikovi* A. Minich, *Strelnia* sp., *Toyemia blumentalis* A. Minich, *Toyemia* sp., *Isadia* sp., *Isadia aristoviensis*, *Isadia* sp., *Geryonichthys* sp. nov. and (?) *Evenkia*, and the actinopterygian *Saurichthys* sp. This assemblage contains latest Permian and earliest Triassic elements.

Other localities around Vyazniki (Fig. 5) have recently produced fish remains. At Sokovka, the sand sequence has produced an operculum of a very large specimen of *Mutovinia sennikovi* A. Minich, up to 130 cm long, and other investing bones of the same species, scales of *Strelnia* sp., *Isadia aristoviensis*, and bones and scale of some other unknown fishes, including a possible lateral scale of the Triassic (?) *Evenkia*. At the Metallist locality, only some scales of *Mutovinia sennikovi* A. Minich and *Mutovinia* sp. have been determined. The Bykovka quarry has produced numerous fish bones and scales from upper sandy layers, including scales of *Toyemia blumentalis* A. Minich, *Toyemia* sp., *Strelnia* sp. and *Isadia* sp., as well as actinopterygian scales close to *Evenkia* (?) sp. Other fish fossils from Bykovka Quarry include teeth of *Saurichthys* (?) sp., a distal segment of the dorsal fin dermal armour and an investing bone of a new species of the genus *Geryonichthys*. At the head of a gully at the west end of Bykovka village (Fig. 5), scale fragments of actinopterygians close to *Varialepis stanislavi* A. Minich occur. In the Shchyokino Ravine (Fig. 3), in conglomerates from the upper part of the left wall of the gully and from the spring channel, a large jaw fragment of a probable discordichthyiform fish *Geryonichthys* sp. was found in 2008.

Of the fishes that offer stratigraphic information, *Xenosynechodus* is known so far only from the Tatarian of Russia. Further, *Varialepis stanislavi* A. Minich is at present known from the Severodvinian of the Sukhona basin, Monastyrskiy gully in Tatarstan, and other locations in the Orenburg Region (Tverdokhlebov *et al*. 2005). *Geryonichthys* sp. is known only from the

Severodvinian (Tverdokhlebov *et al*. 2005). It should be noted, however, that *Saurichthys* is generally a Triassic taxon, except for rare findings in the uppermost Permian units of Russia: isolated *Saurichthys* remains are known, for example, from the older Gorokhovets locality with the Sokolki Assemblage, definitively Vyatkian in age (Sennikov *et al*. 2003). Indeed, the Gorokhovets locality provides strong evidence to fix the age of the upper sand layer at Vyazniki as latest Permian because of comparable ichthyofaunas (Sennikov *et al*. 2003; Tverdokhlebov *et al*. 2005): teeth, a jaw fragment and other bones and scales of *Isadia aristoviensis* A. Minich, skull investing bones and scales of *Toyemia blumentalis* A. Minich, fin spines and dermal plates of *Geryonichthys* (?) *longus* A. Minich, *Geryonichthys burchardi* A. Minich, scales and cranial bones of *Mutovinia sennikovi* A. Minich, *Mutovinia stella* Minich, scales of *Strelnia* sp., scales of *Varialepis vitalii* A. Minich, numerous teeth and one scale of *Saurichthys* sp.

The upper fossil assemblage at Vyazniki is best known for its tetrapods. The tetrapods are: (1) the temnospondyl *Dvinosaurus egregius* Shishkin, 1968, known from a complete skull; (2) Microsauria (?) fam. indet., identified from vertebrae, limb bones and jaws (this rather startling late occurrence of a microsaur has been confirmed by M. A. Shishkin, pers. comm. to A.G.S., but is not yet published); (3) the kotlassiid anthracosaur *Karpinskiosaurus* sp., represented by vertebrae and skull fragments; (4) the bystrowianid anthracosaur *Bystrowiana permira* Vjuschkov, 1957, based on vertebrae and large skull fragments; (5) the chroniosuchid anthracosaur *Uralerpeton tverdochlebovae* Golubev, 1998, known from large fragments of skull and vertebrae; (6) the elginiid pareiasaurs *Obirkovia* sp. (PIN 1100/141, 142; nasal and osteoderm) and Elginiidae gen. indet. (PIN 1100/140, 500, osteoderms); (7) the proterosuchid archosaur *Archosaurus rossicus* Tatarinov, 1960, known from bones of the skull (premaxilla, frontal, parietal, squamosal), lower jaw (dentary) and skeleton (cervical vertebra, ribs, clavicle) (PIN 1100/55, 66-68, 78, 84, 85, 427); (8) the dicynodont Dicynodontidae gen. indet., known isolated cranial and postcranial bones; (9) the whaitsiid therocephalian *Moschowhaitsia vyuschkovi* Tatarinov, 1963, known from the anterior part of a skull (PIN 1100/20); (10) the whaitsiid *Megawhaitsia patrichae* Ivakhnenko, 2008, known from a maxillary fragment (PIN 1100/101).

Key tetrapod evidence that the Vyazniki upper fossil assemblage is Permian in age, and not Triassic, is the occurrence of ?Microsauria, Dvinosauridae, Kotlassiidae, Chroniosuchidae, Elginiidae, Dicynodontidae and Whaitsiidae (including Moschorhinidae), all groups that did not survive the end-Permian mass extinction elsewhere. The overall assemblage of tetrapods is also clearly Vyatkian, including as it does taxa known elsewhere only from the latest Permian (*Dvinosaurus*, *Karpinskiosaurus*, elginiid pareiasaurs). Taxa that are otherwise known only from the Triassic are the Bystrowianidae (known elsewhere only from the Olenekian to Ladinian) and the proterosuchid archosaur *Archosaurus* (archosaurs as a whole, and proterosuchids in particular, are known elsewhere only from basal Induan onwards).

Perspective on the dating of the Vyazniki sections. Whereas the upper portions of the Zhukov Ravine are Lower Triassic (Vokhmian), there is no evidence for definitively Triassic strata at Vyazniki. The debate remains whether the Vyazniki fossil assemblages are latest Vyatkian in age, and so presenting the youngest tetrapod assemblage in Russia (Sennikov 1995, 1996; Sennikov & Golubev 2006; Krassilov & Karasev 2009), or whether the unit is older, or represents the whole of the Vyatkian, and is a variant of the Sokolki tetrapod assemblage (Lozovskiy & Kukhtinov 2007; Kukhtinov *et al*. 2008). All the evidence favours the first of these options (Fig. 2), as follows.

(1) The ostracodes predominantly represent the *Suchonellina inornata–Prasuchonella nasalis* assemblage, and the fishes the *Toyemia blumentalis–Isadia aristoviensis* assemblage, both latest Vyatkian (Fig. 2).

(2) Gorgonopsians are absent at Vyazniki, and yet they are the key top carnivores of terminal Permian faunas elsewhere (e.g. the Sokolki fauna of Sokolki on the Dvina and Orenburg, as well as the *Daptocephalus* assemblage zone faunas of South Africa). It could be argued that a gorgonopsian fossil might be found any day, so negating this point, but so far thousands of isolated bones have been collected at Vyazniki, representing 10 tetrapod taxa, and the absence so far of gorgonopsian elements suggests they were either absent or played a very small role in ecosystems. Gorgonopsian bones are large and so should not be lost from an assemblage of small, medium and large fossils, and they can be found in all facies, whether as remains of *in situ* skeletons or as transported elements. In either case, their absence, or extreme rarity, is a major difference from the typical Sokolki subassemblage.

(3) The appearance of the new top predator, *Archosaurus*, a proterosuchid archosaur, typical otherwise of the Triassic, and the first occurrence of the thecodont-dicynodont type of community (typical of the basal Triassic). It should be noted that Kukhtinov *et al*. (2008, p. 725) referred to ‘the presence of thecodontid reptilians’ in the Zechstein 2 of Germany (Sues & Munk 1996) as evidence for correlation, but the German record is a mandible of ‘an unidentified *Protorosaurus*-like diapsid reptile’, a protorosaur with ‘thecodont’ tooth implantation, but not a basal archosaur (formerly called loosely ‘thecodonts’).

(4) The anthracosaur *Bystrowiana* is the first record of the otherwise Triassic family Bystrowianidae.

(5) The palynoassemblage in the lower grey shales is the same as the uppermost Molomian from Nedubrovo and other Russian locations (Yaroshenko 2005: Krassilov & Karasev 2009), and this is correlated with the upper part of the Lower Guodikeng Formation of Xinjiang, China, which is definitively Changhsingian in age (Metcalfe *et al*. 2009). Tetrapods have not been reported from Molomian palynoassemblage sites.

(6) The macrofloral assemblage is new, and represents the first evidence of mixing of eastern and western European floras, as Zechstein plants migrated into eastern Europe, and floras continued to be dominated by *Pleuromeia*, so showing mixed pan-European characteristics into the Early Triassic. Other Vyatkian floras lack these Zechstein-style elements.

Lithofacies and depositional environments

As recognized by Murchison during his 1841 visit, and in all subsequent studies (Strok *et al*. 1984), the major lithological feature of the Permo-Triassic red bed succession in the Vyazniki–Gorokhovets area is an abrupt switch from a succession dominated by reddish brown mudstones to one dominated by brown sand. As discussed in detail above, dating evidence for the sections shows that the switch from mud- to sand-dominated deposition occurs either at the Permo-Triassic boundary (Zhukov Ravine) or in the very uppermost part of the Permian succession (Vyazniki). The main lithofacies found within the mud- and sand-dominated successions at Vyazniki and the Zhukov Ravine are outlined below to elucidate the environmental significance of the lithological change.

Upper Permian mud-dominated lithofacies and environments

The Upper Permian mud-dominated succession contains seven main lithofacies.

Red mudstones with occasional grey mottling and rootlets. This is the most common lithofacies in the Upper Permian sequence at Vyazniki–Gorkhovets and comprises red and reddish brown silty clays and clayey silts, which are devoid of primary sedimentary structure such as bedding and lamination, but may show an angular blocky texture, slickensided clay coatings, downward branching root traces (often highlighted by greenish grey haloes) and irregular grey or greenish grey mottles.

Massive red mudstones were probably deposited from suspension in temporary bodies of standing water (ephemeral lakes or floodplains) but they retain little of their primary structure because of destratification by rooting and other pedogenic processes during frequent episodes of subaerial exposure. The local development of an angular blocky ped structure with slickensided clay coatings may have resulted from cracking around roots and shrink–swell on wetting and drying of the muds (Retallack 1997). The destratified and rooted muds represent weakly developed palaeosols that could be classified as protosols or vertisols under the scheme of Mack *et al.* (1993). They do not show the development of soil horizons or soil carbonate as described elsewhere on the Russian Platform (Yakimenko *et al.* 2004), which may indicate short breaks in sedimentation between accretion events and a relatively poorly drained low-relief landscape. Poor drainage is suggested by the presence of grey mottling, often associated with root traces, which might result from surface water gleying (Yakimenko *et al.* 2004), although it can also result from local reduction associated with organic material during soil burial (Retallack 1997). Although most of the fine sediment is likely to have been transported into ephemeral lakes and flood basins by water some of the silt fraction in the mudstones may have been contributed as wind-blown dust (Yakimenko *et al.* 2004). Aeolian entrainment, transport and deposition of silt are important processes in many modern dryland floodplain and playa lacustrine basins (Hesse & McTainsh 2003).

Red mudstones with gypsum and palygorskite. This lithofacies comprises massive, reddish brown mudstones, with structureless, irregular nodular beds of pinkish grey gypsum up to 20 cm thick and matted, felted masses of fibrous palygorskite clays.

Closely comparable associations of red muds, evaporites and palygorskite clays have been described from many modern and ancient examples of saline mudflats or playa lakes (Ingles & Anadon 1991), although the massive, nodular evaporites could equally represent pedogenic gypcrete developed in soils under arid, highly evaporative conditions, or indeed they may have a hybrid origin as salt lake precipitates later altered to massive gypcretes on subaerial exposure or in the shallow subsurface above the groundwater level (Chen 1997). Palygorskite is authigenic clay that typically forms by the alteration of illite or smectite and has been described from a broad range of saline mudflats and arid-zone soils where the groundwaters are Mg-rich (Ingles & Anadon 1991).

Red mudstones with thin sheet sandstones. Greenish-grey, very fine- to fine-grained sands occur interbedded with red mudstones. The sands have sharp bases and tops but do not show evidence for basal scour or channelization. Beds range up to several decimetres thick and mostly show no internal sedimentary structure.

The lack of evidence for channelization and close association with playa lacustrine mudstones suggests that these thin tabular sands may have been deposited from unconfined sheetfloods on a low-gradient, dry lake bed or floodplain. The lack of sedimentary structure could indicate bedform suppression by high concentrations of suspended sediment, rapid deposition of sediment out of suspension or post-depositional bioturbation (Fisher *et al*. 2008).

Cross-bedded sand with erosional bases. This lithofacies comprises beds of very fine- and fine-grained sand up to 2 m in thickness. The sands have irregular erosional bases, commonly overlain by reworked mudclasts, and may be structureless or show faint small-scale trough cross-bedding and ripple cross-lamination. These sands were probably deposited in fluvial channels cut into muddy substrates.

Rooted micritic limestone. A cluster of three pale grey limestone beds occurs at the base of the Zhukov Ravine section (Fig. 6). The limestone beds range up to 50 cm thick, have sharp tops and bases, and are laterally persistent over at least 300 m. The limestones are composed mostly of massive micrite with a clotted texture and contain numerous branching root moulds typically 4 mm in length and less than 0.5 mm in diameter. Rootlets occur throughout the limestone bed but are generally concentrated at several levels. The tops of limestone beds may show an undulating laminar structure.

These limestones probably represent lacustrine or palustrine carbonates deposited in shallow lakes or swamps and modified by rooting during intervals of subaerial exposure. Massive clotted textures are often described from palustrine limestones where carbonate precipitation is commonly mediated by microbial activity (Freytet & Verrecchia 2002). The lack of enclosed or displaced siliciclastic sediment and the absence of a brecciated fabric does not support a possible alternative interpretation for the limestones as primary pedogenic carbonate.

Dark grey laminated mudstone. This distinctive lithofacies comprises dark grey silty claystone with discontinuous centimetre-scale lamination (Fig. 8b). The lamination consists of pinch and swell, clayey, micaeous siltstone beds alternating with silty claystone. The mudstones contain plant material and common freshwater ostracodes, which are generally concentrated into millimetre-thick lenses within silty beds. The grey laminated muds can be correlated over a distance of *c.* 5 km from the escarpment north of Vyazniki to Balymotikha in the south (Fig. 7).

Intervals of grey laminated mudstones are up to 0.6 m thick and were probably deposited in perennial lakes. Pinch and swell silty lamination and lenticular concentrations of ostracode shells suggest relatively shallow lakes with wave-generated bottom currents. However, the uniform grey colour and lack of features indicating emergence such as desiccation cracks show that the lakes were perennial and of sufficient depth and longevity to accumulate deposits up to 0.6 m thick and develop a diverse ecosystem with ostracodes, conchostracans, insects, bivalves, fishes and plants (Sennikov & Golubev 2006).

Grey laminated mudstones and coarsening and thickening upward sandstone beds. At Balymotikha, grey laminated mudstones are associated with metre-thick packages of greenish-grey, micaeous, cross-laminated, fine-grained sands with abundant comminuted plant material (Fig. 7). Beds in the upper interval of

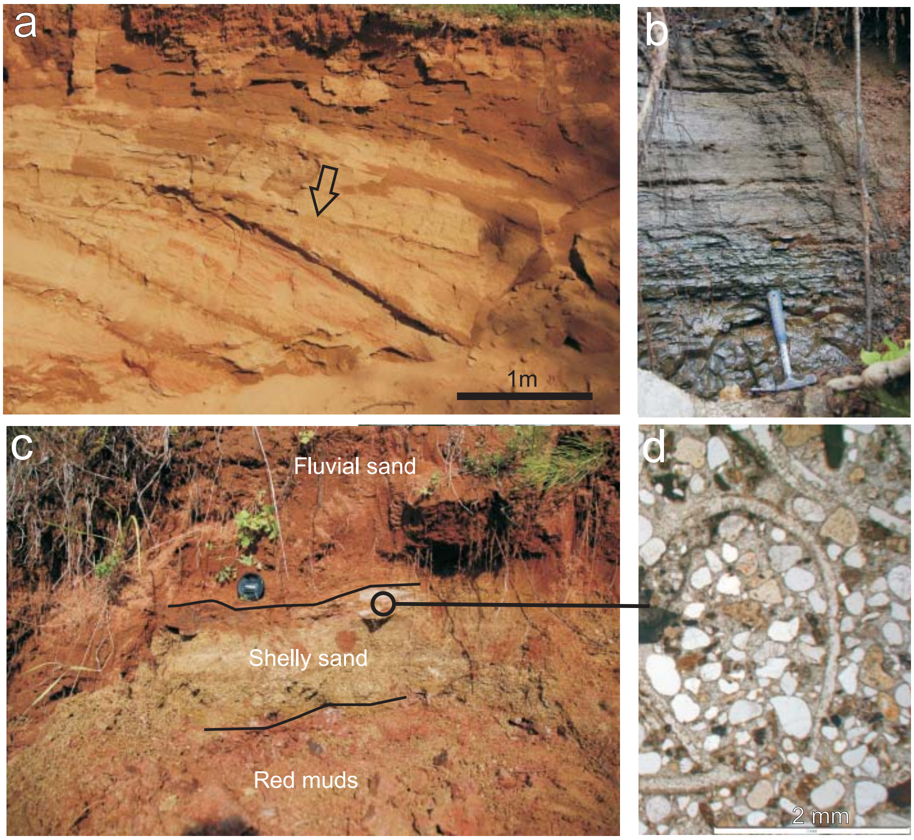

Fig. 8. Clastic facies in and around Vyazniki (see Fig. 5 for locations). (**a**) Fluvial sands in Bykovka Sand pit, showing truncated lateral accretion surfaces (arrow at example); (**b**) laminated dark grey lacustrine muds at Balymotikha; (**c**) brown fluvial sands overlying reworked shelly sands and red playa lacustrine muds in the Sokovka Ravine; (**d**) thin section of cemented, shelly sandstone. Shell fragments are mostly from the bivalve *Palaeomutela*.

cross-laminated sand coarsen and thicken upwards into a cap of red rooted mudstones. These sands probably represent the deposits of lacustrine deltas formed at lake margins where a river entered a shallow, perennial water body.

Depositional system

Lithofacies in the Upper Permian mudrock-dominated succession were deposited in a broad range of fluvial and lacustrine environments that ranged from ephemeral to perennial and saline to freshwater. The predominantly fine-grained character of the lithofacies and evidence for generally low relief and poorly drained conditions is consistent with the concept that the Vyazniki–Gorokhovets area formed part of the distal flood basin of large terminal fluvial distributary systems sourced from the Urals (Nalivkin 1973).

Most of the mudrocks were probably deposited in ephemeral lake or fluvial floodplain environments, but retain little of their primary structure because of frequent episodes of subaerial exposure and pedogenesis. The lack of well-developed soil horizons and presence of gley features suggest a landscape that was, at least seasonally, poorly drained. Incised channel fills are scarce and thin sands were probably dispersed across the dry flood basin by sheetfloods. Comparable thin-bedded, massive sands have been described from the distal parts of terminal splays in Lake Eyre, central Australia, where channelized flow from incoming channels becomes unconfined as it enters the dry lake basin (Fisher *et al*. 2008). There is local evidence for the development of shallow perennial lakes that are characterized by grey or dark brown coloration, the preservation of well-developed lamination, a diverse fauna and an association with coarsening-up sands interpreted as lake-margin deltas. Vyazniki is the only location where dark grey, laminated lacustrine mud was found, and in general this lithofacies has not been widely reported from the Upper Permian units of the Russian Platform (Gorsky *et al.* 2003). At Zhukov Ravine, dark brown laminated muds represent the nearest development of a perennial lake deposit (Fig. 6). Perennial lake deposits typically occur within sequences that record the growth and then infill of the lake. At the base, prior to lake development, channel or sheet sands with grey mottled red mudstones record increased fluvial activity accompanied by waterlogging and gleying of soils. Grey or brown laminated mudstone represent maximum lake depth and expansion, whereas overlying red, rooted massive mudstone records lake infill and conversion to an ephemeral playa (Fig. 7). Saline ephemeral lakes are distinguished by the presence of gypsum and palygorskite. At outcrop they are restricted to the lowermost beds exposed at Vyazniki (Fig. 7), although Strok *et al.* (1984) indicated a wider stratigraphic distribution within the basal 45 m of the Upper Permian sequence based on borehole evidence (Fig. 4). The upward shift from muds with gypsum to perennial lake deposits could indicate a positive shift in the balance between water input and evaporation throughout the Late Permian.

The Lake Eyre playa in central Australia could be a close modern analogue for these Late Permian flood-basin deposits because within this basin a broad range of environments develop (e.g. dry mudflats, saline pans, perennial lakes and spring-fed carbonates), depending on the balance between water input from surrounding river systems and evaporative loss (Dulhunty 1982; Magee *et al.* 2004). When lake beds are exposed, water and sediment input from surrounding river systems form terminal splays on the dry, low-gradient lake floor (Fisher *et al.* 2008). When water input greatly exceeds evaporation, the dry basin floods and becomes a shallow perennial lake with delta formation at lake margins (Lang *et al.* 2004) and an explosion of life. Longer-term wet and dry phases in the Lake Eyre sedimentary record have been correlated with Milankovitch-scale climate forcing (Magee *et al.* 2004).

Upper Permian and Early Triassic sand-dominated lithofacies

The Vantino borehole drilled midway between Vyazniki and Gorokhovets in an elevated position (Fig. 3) proved *c.* 70 m of uppermost Permian and early Triassic sand and mud, resting sharply on Upper Permian gypsiferous muds and truncated by overlying Quaternary deposits (Fig. 4). Outcrops of the sands at the Shchyokino Ravine (near the Vantino borehole), Zhukov Ravine, and around Vyazniki show that the sands differ significantly in colour, grain size and sedimentary structure from the thin, fine-grained, greenish grey sands associated with the underlying mud-dominated succession. At Vyazniki, there is a change in the major mineral assemblage from quartz–zircon–almandine in the underlying fluvio-lacustrine deposits (Sample Hm2 at Sokovka) to quartz–epidote in the overlying brown sands (Samples Hm1 and Hm3) (see Table 1 and Fig. 7). The sands are composed of four main lithofacies, as follows.

Cross-bedded sands. Fine- to coarse-grained, cross-bedded, brown and reddish brown sands occur in intervals up to 5 m thick separated by three types of major discontinuity: (1) intraclast conglomerates; (2) thin mudstones; (3) inclined erosion surfaces overlain by well-rounded, mudstone clasts up to 0.3 m in diameter. The sands mostly show small- to medium-scale trough cross-bedding, often with an upward decrease in set thickness and grain size within a single discontinuity-bounded sequence. Low-angle cross-bedding, horizontal bedding, and overturned or deformed foresets and laminae occur toward the top of sequences. Larger exposures, such as those seen at Bykovka Quarry, show that the sands can contain lateral accretion surfaces composed of decimetre-thick bedsets of small-scale cross-bedded and laminated sand (Fig. 7). The lateral-accretion bedding is distinctive in that it is commonly truncated by bedding disconformities, often draped by a thin veneer of mud (Fig. 8a). These sands contain many features typical of fluvial environments (trough cross-bedding, erosion surfaces, lateral accretion bedding), and they were deposited by the migration of sinuous-crested dunes within channels and the lateral expansion of point bars.

Intraclast conglomerate. Well-cemented intraclast conglomerates range up to 1 m thick. The conglomerates are composed mainly of well-rounded calcitic nodules and cemented red mudstone clasts set in a matrix of fine to coarse sand. Tetrapod bones form a minor component and a bivalve-rich cemented conglomerate (Fig. 8d) with many well-rounded and frosted quartz grains occurs at the base of the sands in the Sokovka section at Vyazniki (Fig. 7). Bed bases are generally erosional and irregular, and the internal structure is crude discontinuous horizontal bedding or low-angle cross-bedding. The association of intraclast conglomerates with fluvial sands suggests that they result largely from the cutting of river channels into pre-existing alluvium. Lateral migration and bank erosion, generally at the apex of a channel bend, provides a supply of reworked gravel-grade material (e.g. calcrete fragments, tetrapod bones, overbank muds) from adjacent floodplains that accumulates as a winnowed lag within the channel thalweg. The shelly conglomerates with reworked aeolian grains at Sokovka may have been reworked from lacustrine and aeolian deposits.

Interbedded sand and mud. Interbedded fine-grained sands and muds range up to 2 m thick and have sharp upper and lower boundaries with the enclosing cross-bedded sands. Large exposures at Bykovka Quarry show that the beds are laterally discontinuous (Fig. 7). Sand beds with these fine-grained intervals commonly thin and fine upwards, are massive or ripple cross-laminated and have mudcrack casts on their base. Muds and sandy muds are massive and rooted, particularly near the tops of sequences. Coprolites and fish remains (mainly scales) are locally abundant in this facies (e.g. the uppermost bed at Bykovka Quarry) and vertebrate fossils have also been found. This mud-rich lithofacies was probably deposited predominantly from suspension in a standing water body, although multiple, thin sands overlying desiccated muds indicate periodic incursions of tractional flows into a dry pond. The abundance of fish coprolites and scales suggests that the ponds concentrated and formed a refuge for aquatic fauna before eventual desiccation and infill with vegetation growth and rooting.

Thick sets of tabular cross-bedded sand. Friable, fine- to medium-grained sands with large-scale tabular cross-bedding were seen toward the top of the logged section at Shchyokino Ravine (Fig. 9). The sedimentary features of these sands differ from those of the fluvial sands seen lower in the section at Shchyokino Ravine and at Bykovka. The development of thick (10–20 mm) inversely graded foreset laminae, high foreset dips (30°), well-rounded and frosted quartz grains, and the general lack of mica and mudclasts within the sands suggest that they are aeolian in origin. They were probably deposited by flow-transverse, straight-crested dunes under conditions of low water table and an abundant supply of dry, fine- to medium-grained sand.

Late Permian and Early Triassic depositional system

The presence of unidirectional cross-bedding, scoured erosion surfaces and a freshwater fauna clearly indicate a fluvial environment for the bulk of this thick sandy succession. Applying the equations of Bridge (2003), the typical cross-set thickness of 0.2 m is likely to have been generated by dunes around 0.5 m in height, which scale to a maximum bank flow depth of 3–5 m. Given typical scaling relationships for sand-dominated rivers the channels could have been several hundred metres wide. Although the channels may have been large with deep flows, there is a range of evidence to suggest that discharge events were episodic and highly variable. Cross-cutting truncation surfaces within lateral accretion deposits are typical of channel belts with highly variable discharge (Willis 1993). Mudclast-lined erosion surfaces indicate multiple episodes of channel cut and fill. Desiccated and rooted muds with concentrations of fish are found in many dryland river systems where waters ponded in scours and abandoned channels are often the last refuge for aquatic animals (Unmack 2001). There are insufficient large 3D outcrops to determine precisely whether the channels within this sand-dominated river system had a braided or a meandering pattern. The presence of erosionally nested, multiple channel fills suggests a sandy braided river pattern, whereas lateral accretion bedding is more typical of point bars in meandering channels. Given the evidence for discharge fluctuation, it is possible that the rivers had the appearance of a sandy braided system at high

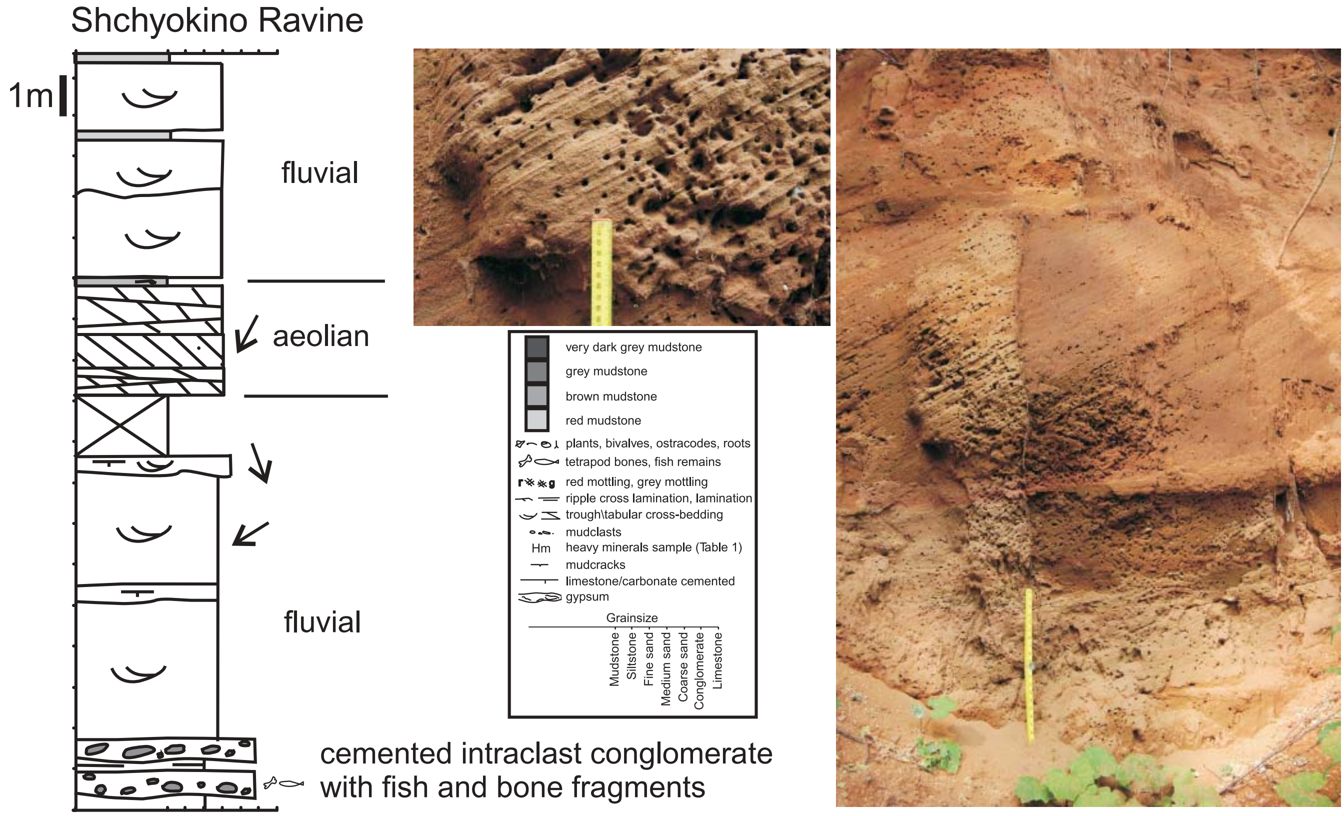

Fig. 9. Sedimentary log and photographs of aeolian sandstones at Shchyokino Ravine. The steeply cross-bedded friable sands are partly obscured by modern wasp borings.

flows and a single-thread meandering pattern at low flows. Such channels are sometimes described as compound, and are typical of sandbed rivers in dryland environments that have variable discharge (Baker *et al.* 1988).

It is generally assumed that drainage basins located within the Carboniferous–Permian Ural Mountains to the west formed the primary source of water and sediment feeding river systems on the Russian Platform (Nalivkin 1973). The occurrence of a complex suite of heavy minerals (Table 1) indicating a heterogeneous metamorphic and igneous source does not negatte the existing idea that fluvial sands in the Vyazniki area were sourced from the Urals (Sennikov & Golubev 2006). Given that the Urals are located 800 km east of Vyazniki in present coordinates this implies rivers of considerable length, but, given the scale of the Russian Platform, the possibility that more localized drainage systems were established on inactive parts of the depositional slope cannot be eliminated.

As described from other Early Triassic terrestrial deposits (Newell *et al.* 1999; Pace *et al.* 2009) the sands may provide evidence for apparent oscillations in climate in the earliest Triassic. Aeolian sands within the fluvial sequence have been identified at Shchyokino Ravine and these may have formed under arid conditions with reduced fluvial activity and depressed groundwater tables, although there are many known examples of coexisting aeolian and fluvial environments (Langford 1989). The presence of reworked calcrete clasts and intensely oxidized, rooted red mudclasts (Fig. 10) points towards the development of aridisols and calcisols on floodplains possibly under conditions of greater aridity. Comparable reworked calcrete conglomerates have been described from the Early Triassic sandy fluvial Katberg Formation of the Karoo, where they are interpreted as forming in soils under dry conditions, which are subsequently reworked into channel lags during periods of regional fluvial degradation under wetter conditions (Pace *et al.* 2009).

Independent dating evidence for sections at Zhukov Ravine and Vyazniki (see above) shows that the influx of fluvial sands occurs either at the Permo-Triassic boundary (Zhukov Ravine) or slightly earlier in the latest Permian (Vyazniki). Russian geologists (e.g. Nalivkin 1973; Ignat'ev 1976) have long pointed to a major shift in the source of these latest Permian sands, from a western Baltic source for the lower, quartz-rich sands, such as sample Hm2 from Sokovka, to a western, Ural Mountain, source for the upper sand unit, characterized by a diversity of heavy minerals. Cross-bedding directions and lithological comparisons tend to bear out the idea of two phases of sand influx, the first sampled at Vyazniki and the second at Zhukov Ravine (Fig. 4). A small number (38) of palaeocurrent measurements from fluvial trough cross-bedding of the lower sands at Vyazniki indicates flow toward the south or SE (e.g. Fig. 7), and the upper sands at Zhukov Ravine show evidence of flow toward the west. The switch from a western to an eastern sediment source could reflect renewed uplift of the Ural Mountains, the reason usually given by Russian geologists (Ignat'ev 1976), or perhaps more probably climatic and topographic change within the basin.

Significance of the change in depositional system

Facies analysis shows that the observation by Murchison (1841) of a major lithological change from red clays to sands at Vyazniki appears to represent an abrupt shift from a wet, muddy

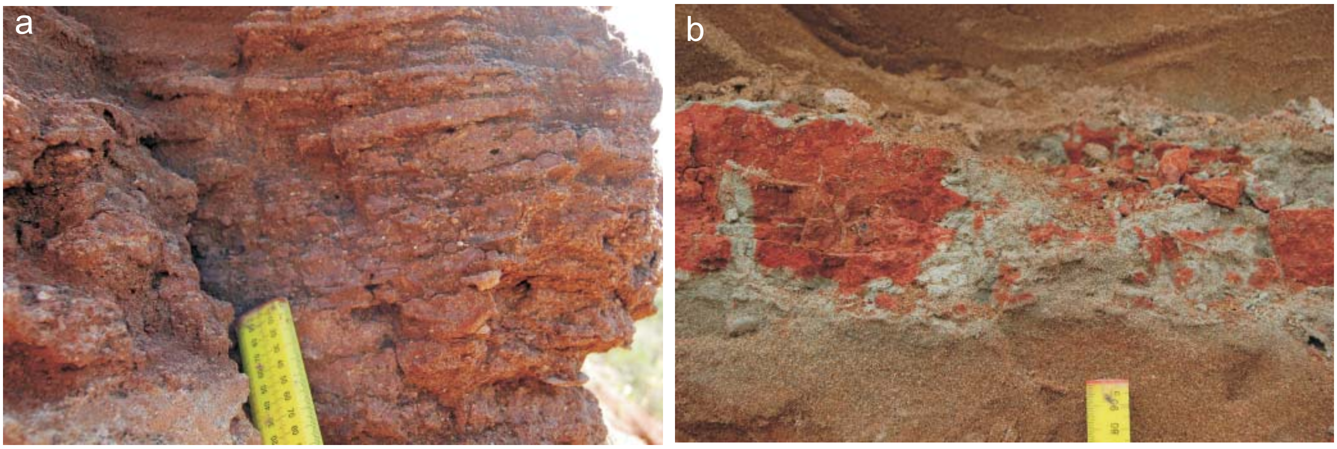

Fig. 10. (**a**) Cemented calcrete conglomerates in an abandoned quarry near Shchyokino Ravine and (**b**) intensely reddened, rooted mudstone clasts in Late Permian sands at Bykovka Quarry provide evidence for reworking of calcisols developed on semiarid floodplains.

lacustrine environment to major sandy channel belts and aeolian dunes. As discussed above, the basinward shift of sandy facies into the Vyazniki–Gorokhovets flood basin appears to occur within the context of a progressive westward migration of coarse gravelly and sandy facies away from the Ural source area throughout the Late Permian (Fig. 3). This long-term progradational trend probably relates to the steady reduction of thrust loading and basin subsidence adjacent to the Urals during the Late Permian, allowing continental sediments to overfill the foreland basin and spread across the Russian Platform (Newell *et al.* 1999). The stratigraphic successions at Vyazniki–Gorokhovets, however, do not suggest that the influx of fluvial sands into the Vyazniki flood basin around the Permo-Triassic boundary results exclusively from this long-term progradational trend. First, the switch from fine to coarse facies is not progressive but extremely abrupt and at Vyazniki superimposes thick fluvial sandstones on perennial lake deposits. Second, at Vyazniki–Gorokhovets it is a single event that represents a significant basinward shift of sandy facies several hundred kilometres from central parts of the Russian Platform toward the western limits of Permian sedimentation (Fig. 3). Third, and most significant, is the timing of the sand influx near the end of the Changhsingian stage, a time of mass extinction (Benton 2003), exceptional instability in terrestrial and marine and environments (Wignall 2007), and high-amplitude $\delta^{13}C$ oscillations that persisted into the Early Triassic (Corsetti *et al*. 2005). The start of these events, dated at 252.6 Ma (Mundil *et al.* 2004), is synchronous with, or slightly post-dates, the eruption of the Siberian Traps (Reichow *et al.* 2009) and may therefore be related to rapid global warming caused by the release of large amounts of CO_2, augmented by the associated release of methane (Retallack *et al.* 2006). A number of abrupt changes to terrestrial environments globally are now well documented at the end of the Permo-Triassic boundary, as follows.

(1) Major changes occurred in terrestrial vegetation at the Permo-Triassic boundary with an abrupt decrease in the proportion of arborescent plants (e.g. cordaite trees) relative to herbaceous pioneer communities (Rees 2002) and the loss of peat-forming plants creating an Early Triassic 'coal gap' (Retallack *et al.* 1996).

(2) Enhanced terrestrial weathering and erosion under greenhouse conditions at the Permo-Triassic boundary has been postulated based on geochemical evidence from earliest Triassic palaeosols in Antarctica (Sheldon 2006), pedoliths (redeposited soils) in Antarctica, eastern Australia and South Africa (Retallack 2005), and from an influx of land-derived organic materials into marine Permo-Triassic boundary sections in northeastern Italy (Sephton *et al.* 2005) and Meishan, China (Xie *et al.* 2007).

(3) Abrupt changes in fluvial style at the Permo-Triassic boundary toward coarser-grained, braided regimes have been documented by Newell *et al.* (1999) from the south Urals, Ward *et al.* (2000) from the Karoo Basin of South Africa, and Michaelsen (2002) from the Bowen Basin in Australia. Changes in fluvial regime may be related to the vegetation loss in upland catchments, increasing runoff intensity and sediment yield. Under Late Permian and Early Triassic global warming there may also have been a shift toward low-frequency but very high-magnitude discharge events that can increase rates of bedload movement (Molnar 2001). Channel belts and drainage networks may also become enlarged, as these tend to scale with the runoff volume and sediment grade of the largest flood event, even if these are infrequent (Patton & Baker 1977; Newell *et al.* 1999).

In conclusion therefore, there appears to be a sufficient body of independent evidence for major climatic and terrestrial geomorphological change at the Permo-Triassic boundary that this must be considered a possible mechanism whereby latest Permian and early Triassic fluvial sands could prograde rapidly across a fine-grained muddy flood basin in distal regions of the Russian Platform. The sudden loss of vegetation cover could have increased sediment yield, and an increase in the magnitude of discharge events related to intensified runoff and climate change could have increased sediment transport rates and caused an abrupt extension of drainage networks. The intercalation of aeolian sands and reworked calcrete conglomerates into the latest Permian and Early Triassic fluvial sands may provide further evidence (e.g. Pace *et al.* 2009) for climatic instability during this period of high-magnitude oscillations in $\delta^{13}C$ (Corsetti *et al.* 2005).

Conclusions

Permo-Triassic sections at Vyazniki and Gorokhovets on the Russian Platform played a key part in Murchison's original recognition of the Permian System and have now gained fresh significance as an important location to understand terrestrial events at the Permo-Triassic boundary, the largest ever mass extinction event. A body of work from across Pangaea provides evidence that abrupt global warming and climatic instability at the Permo-Triassic boundary produced major changes in terrestrial environments, which included loss of vegetation cover, increased rates of soil erosion and altered river morphologies (Benton 2003).

The first detailed sedimentological work undertaken on the Permo-Triassic sections at Vyazniki and Gorokhovets, as reported here, shows that they record the overrun of a muddy playa–lacustrine depositional system by major channel belts transporting sand-grade sediments over 800 km from the Urals to the distal parts of the Russian Platform. Independent work on the biostratigraphy of two sections at Vyazniki and Gorokhovets shows that this event occurred either at the very end of the Permian or 8 m above the putative Permo-Triassic boundary as determined by ostracodes.

The timing and nature of this event, which records increased sediment flux from the Ural Mountains, is closely comparable with that described from the Southern Uralian Foreland Basin, where the Permo-Triassic boundary is marked by the sudden appearance of coarse Uralian-derived fluvial conglomerates (Newell *et al.* 1999). The proximal setting of the south Urals depositional basin relative to the mountain source will always create some uncertainty as to the relative importance of tectonic uplift versus climate change in generating this abrupt fluvial response. However, the location of Vyazniki and Gorokhovets, 800 km from the mountain front and in a separate depositional basin, strengthens the case of Newell *et al.* (1999) that increased sediment flux from the Urals at the Permo-Triassic boundary is related to the devegetation of upland catchments (increasing sediment yield) and a switch toward low-frequency but very high-magnitude discharge events (increasing sediment delivery). In the Vyazniki–Gorokhovets area, the interbedding of fluvial and aeolian deposits may provide additional evidence for climatic instability and extremes in the early Triassic.

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