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Interplay of tectonics and climate on a transverse fluvial system, Upper Permian, Southern Uralian Foreland Basin, Russia

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Abstract

Late Permian (Tatarian) fluvial sediments accumulated during the final phase of orogenesis in the southern Uralian Foreland Basin (Russia). Four facies associations have been recognised which, in ascending stratigraphic order, are mudflat, sandy distributary, small gravelly-channel and large gravelly-channel. Fluvial processes were dominant, with the size of channels and grain size increasing upsection. Sediment provenance and palaeocurrents indicate an intraorogen source basin with transport to the west, across the basin axis. The highly gradational contacts between the mudflat, sandy distributary and small gravelly-channel associations suggest that these facies were part of a small (50–100 km long) prograding terminal fan characterised by downslope decreases in channel size caused by evaporation and infiltration. The overlying large gravelly-channel association is so out of proportion in terms of required discharge that it cannot be related to this small fan. It was deposited as part of a much larger terminal fan (900 km long) and represents an abrupt phase of drainage net enlargement at the Permo–Triassic boundary. A decline in thrust-related tectonic subsidence probably accounts for the overall development of the coarsening-upward succession. However, the abrupt emplacement of thick conglomerates at the top of this succession probably resulted from a change toward a more arid climate, with higher sediment yield and greater peak discharges in a drainage basin with reduced vegetation cover.

Keywords: Urals; Foreland Basin; fluvial; Permian

1. Introduction

The characteristics of a fluvial succession reflect the complex interaction between source-area properties such as size and erodibility, the rate and mechanism of sediment delivery, and patterns of accommodation within the basin (Bull, 1991; Frostick and Steel, 1993). Unravelling the relative importance of these factors on fluvial architecture is a complex task. In particular, a major difficulty results from the dual control of climate and tectonics on the production of sediment and its transport into a basin (Derbyshire and Owen, 1990). For example, the supply of sediment from a source area could be controlled by tectonic factors such as the emplacement of thrust sheets, or it could be related to climate via weathering rates and vegetation cover (Bull, 1991; Summerfield, 1991). Determining the relative importance of climate and tectonics on the development of a fluvial succession requires knowledge of how these variables changed through time.

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Fig. 1. Map showing location of study area.

In the Pre-Quaternary this is hampered by the lack of a detailed understanding of climate change. It is also difficult to escape circular reasoning, which can be based on erroneous assumptions such as an influx of conglomerates within a fluvial succession is always related to tectonic activity (Frostick and Steel, 1993).

This paper examines the effect of climatic and tectonic change on a Permian transverse fluvial system in the southern Urals (Fig. 1). The drainage basin for this system was rooted within the active Uralian mountain belt and it fed sediment into the adjacent foreland basin. The possible effect of climate on fluvial sedimentation is particularly interesting because, in Pre-Quaternary terms, the period over which the deposits accumulated is a well-constrained global climate change event. As described by Veevers et al. (1994), steady change from late Palaeozoic icehouse to early Mesozoic greenhouse conditions was accelerated around the Permian–Triassic boundary (250 Ma) by a surge in carbon dioxide levels caused by the eruption of flood basalts. Rapid global warming produced many environmental effects such as widespread deglaciation, loss of coals, increased aeolian activity, and a major change in terrestrial

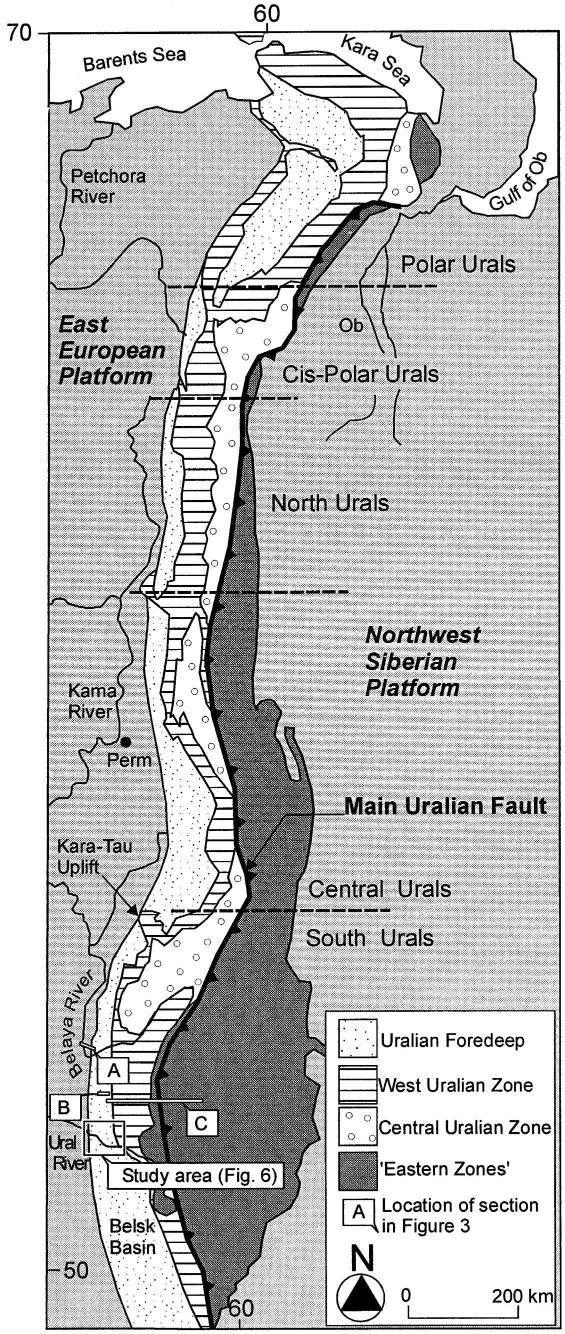

Fig. 2. Map showing the linear Uralian Orogen, and its structural zonation (details in Puchkov, 1997). The study area is in the Belsk Basin, in the southern part of the orogen (modified from Puchkov, 1997).

vegetation type. Some evidence of this event might also be expected in the fluvial record given the sensitivity of drainage systems to climate change.

2. Geological background

The Uralian Foreland Basin is a major N–S linear depocentre that extends for some 2500 km across mainland Russia from the Arctic Ocean to the Aral Sea (Fig. 2). It is an asymmetric structure formed by flexure of the European Craton in response to tectonic loading by the Uralian Orogen (Zonenshain et al., 1984) (Fig. 3). During its westward migration, it accumulated greater than 5000 m of synorogenic Middle Carboniferous to Early Triassic sediment. Collision was oblique, moving wave-like, from south to north along the orogen (Puchkov, 1997). Transverse (NW–SE) structural elements accommodated this oblique collision and subdivided the foreland into several semi-isolated basins. The most southerly of these basins, the Belsk Basin, is the subject of this research (Fig. 2).

The large-scale stratigraphy of the Belsk Basin records a classic deep marine to continental foreland basin transition (Covey, 1986). This can be described in terms of two major cycles (see Fig. 14) that are exposed along the Sakmara River in the southern Urals (Nalivkin, 1973). The first cycle rests on pre-orogenic platform carbonates and comprises around 1500 m of Middle/Late Carboniferous turbidites. These progressively shallow upwards into Early Permian mudstones, limestones and marls (Nalivkin, 1973). A chain of coeval carbonate reefs that developed along the western flank of the basin now form important hydrocarbon reservoirs. The second cycle also starts with deep-water turbidites (ca. 1000 m) (Fig. 4). However, this Artinskian phase was terminated abruptly in the Kungurian, when the deep-marine basin filled with 500 m of evaporites. This promoted a switch to fluvial sedimentation in the Ufimian. These deposits are around 200 m thick adjacent to the mountain belt, and extend as a westward-thinning and fining wedge across former shallow-marine areas of the European Craton (Fig. 4). Marine flooding in the Kazanian deposited 200 m of limestone, mudstone and halite across both basin and platform areas, before a return to continental conditions in the Tatarian. These fluvial clastics reach around 1000 m in thickness within the basin

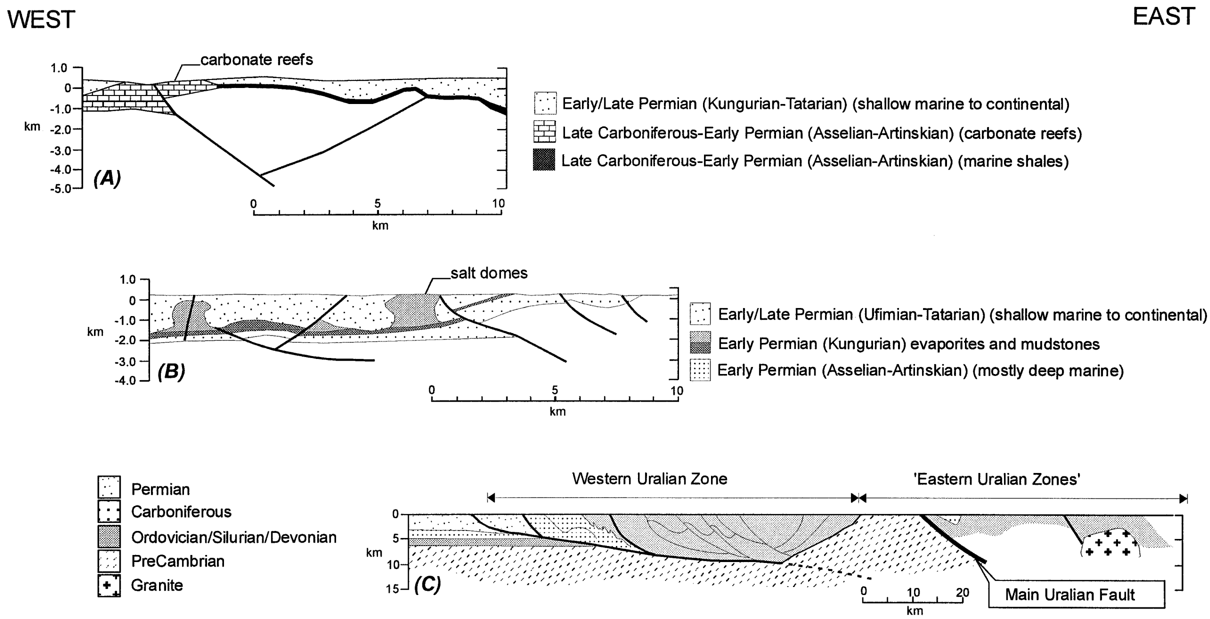

Fig. 3. Composite cross-section (located in Fig. 2) across the southern Uralian Orogen: (A) after Bush et al., 1984; (B, C) after Puchkov, 1997.

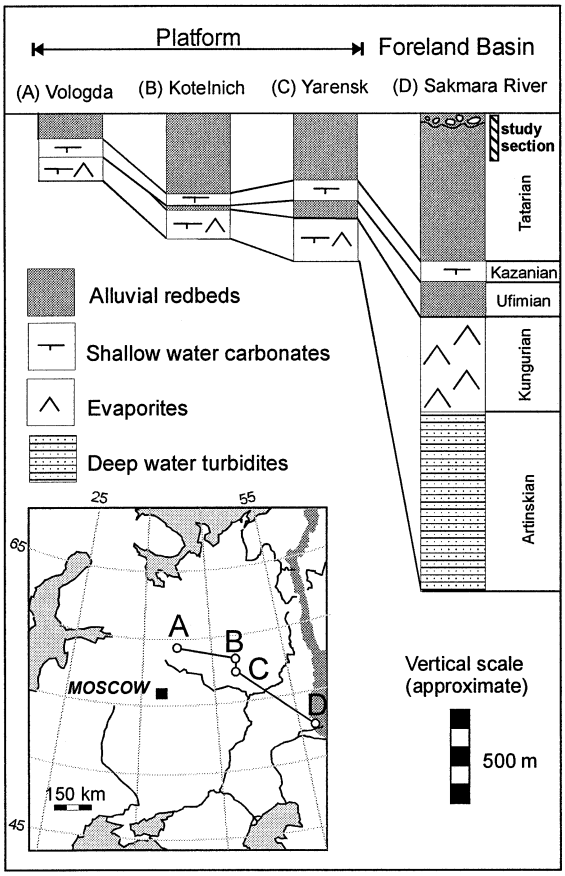

Fig. 4. Permian (Artinskian–Tatarian) stratigraphy of the Southern Uralian Foreland Basin and European Platform [compiled from data in Nalivkin (1973) and Puchkov (1997)].

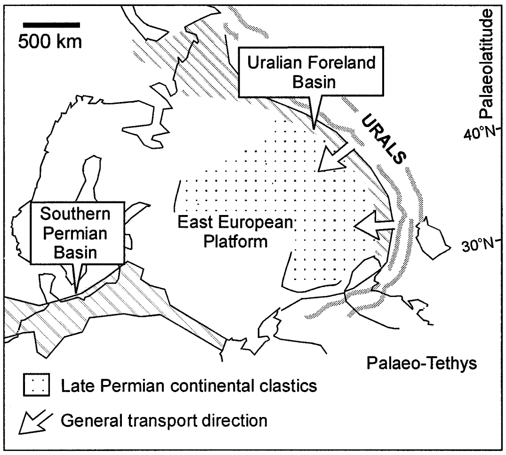

Fig. 5. Main palaeogeographical elements of the European continent in the Late Permian.

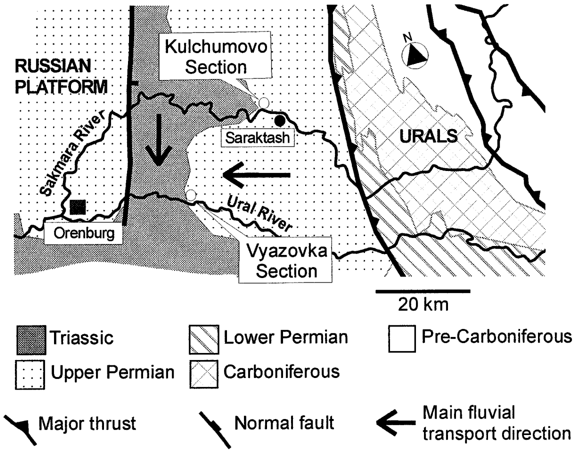

Fig. 6. Geological sketch map of part of the Belsk Basin to show the location of studied sections at Vyazovka and Kulchumovo. Triassic rocks are in a fault-bounded basin, and expand southward into the Caspian Basin.

and also extend as a westward-tapering and fining wedge across the East European Platform (Bush et al., 1984) (Fig. 5). During this time the southern Urals were at a palaeolatitude of around 30ºN and the fluvial sediments are red beds deposited under generally arid conditions. The uppermost 250 m of this Tatarian continental succession in the Belsk Basin is the subject of this research.

3. Section location and stratigraphy

Late Permian (Tatarian) rocks form a N–S outcrop belt in the western part of the Belsk Basin. Exposure is largely restricted to stream cuts in low-relief, grass-covered terrain. The best sections (details in Appendix A) are near the settlements of Vyazovka and Kulchumovo, approximately 60 km east of Orenburg (Fig. 6). Upper Permian rocks in this part of the foreland basin are largely unthrusted. However, post-depositional salt movement and extensional faulting complicate the geological structure, and dislocate Tatarian foreland-basin successions from coeval deposits on the platform (Fig. 6).

At Vyazovka and Kulchumovo, around 250 m of uppermost Permian (Tatarian) stratigraphy is exposed. Both sections show a comparable coarsen-

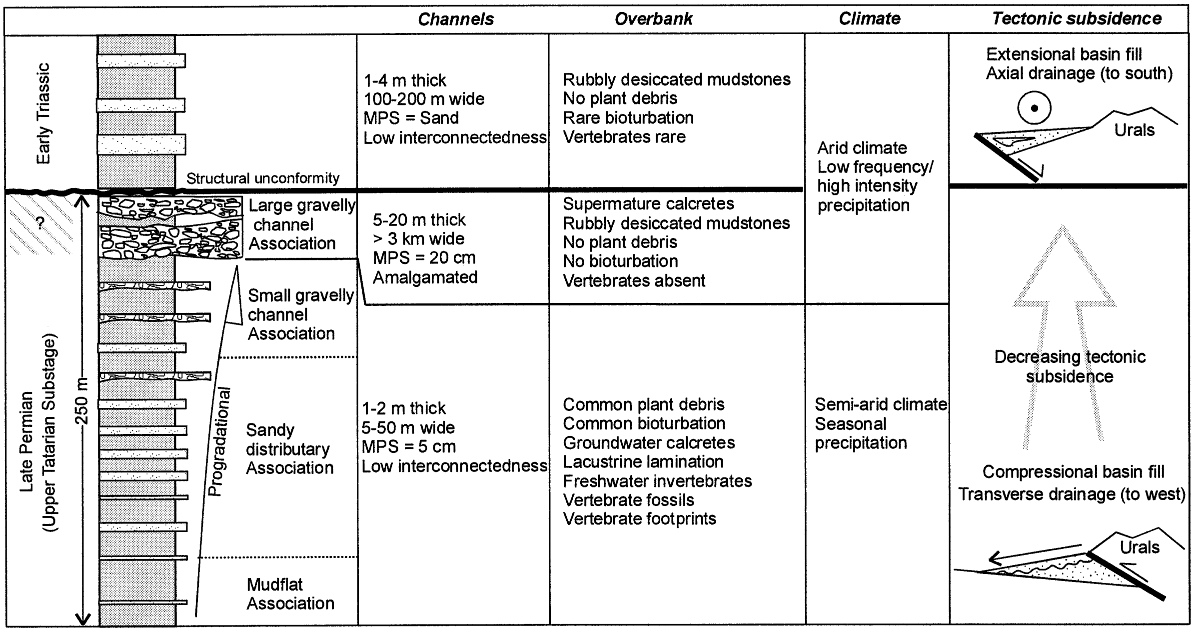

Fig. 7. General stratigraphy of the Upper Permian/Lower Triassic in the Belsk Basin, based on the sections at Vyazovka and Kulchumovo.

ing-upward trend, changing vertically through intervals dominated by mudstone, sandstone and thin conglomerates (up to 2 m thick) (Fig. 7). This succession is capped by 'thick conglomerates' (up to 15 m), which are laterally extensive and form a regional datum for correlation (Tverdokhlebov, 1976). As discussed by Tverdokhlebov et al. (1996), Russian workers do not apply formal lithostratigraphic terms to these rocks.

Rocks above and below the 'thick conglomerates' are firmly dated with fossil vertebrates and microfossils (see Anfimov et al., 1993; Tverdokhlebov et al., 1996). These data show that at the Kulchumovo and Vyazovka, rock exposed below the thick conglomerate is Late Permian (Upper Tatarian Substage) and rock above is Early Triassic. The thick conglomerate thus marks the position of the Permo–Triassic boundary. There is no direct evidence for the age of the conglomerates themselves. Until further evidence is obtained, they are included here within the Tatarian because they are below a structural unconformity with the Triassic, and are more closely related to the underlying Tatarian in terms of sediment provenance (intraorogen) and transport direction (westwards). Lower Triassic sediments in the Belsk Basin also comprise fluvial-channel sandstone and overbank mudstone. However, they were deposited by south-flowing rivers in a N–S extensional basin which formed during a phase of regional crustal tension in the southern Urals (Puchkov, 1997).

4. Facies associations

Upper Permian sediments in the Belsk Basin can be divided into thirteen facies (Table 1). These form four distinct facies associations, genetically termed the mudflat association, the sandy distributary association, the small gravelly-channel association and the large gravelly-channel association (Fig. 7). These form a vertical stratigraphic succession, described below in ascending order.

4.1. Mudflat association

The mudflat association (Fig. 8A) is dominated by massive red mudstone, laminated mudstone with desiccation cracks, and laminated grey mudstone. These facies interbed with thin sandstone sheets and heterolithic channel fills. This association occurs in

Table 1
Facies description and interpretation

Facies	Description	Interpretation
Facies G1. Multi-storey conglomerates	Thickness: 5–15 m. Width: >3 km. Concave-up basal erosion surface encloses amalgamated lenticular or tabular storeys 0.5–2 m thick. Granule to cobble size, moderately sorted, framework supported clasts. Abundant matrix of medium sand. Crude horizontal or tabular cross-bedding. Decimetre-thick wedges of massive or laminated sandstone at top of storeys.	Braided channel belt with gravel deposited as diffuse sheets or transverse bars. Laminated or massive sandstone deposited during falling stage.
Facies G2. Single-storey conglomerates	Thickness: 1–2 m. Width: 20–100 m. Basal erosion surface encloses crudely stratified or disorganised gravel and sandy gravel. Clasts from granule- to large-pebble size.	Broad shallow channels with gravel deposited as low-relief sheets.
Facies S1. Multi-storey sandstones	Thickness: 4 m. Width: 50–100 m. Concave-up basal erosion surface encloses 0.5–1.0 m thick tabular storeys. Fine- to medium-grained sandstone. Mostly tabular cross-bedded. Extensively bioturbated top.	Sandy channels cut and filled during repetitive flood events. Channel floors covered in straight-crested dunes or bars which may have been emergent at low-flow stage giving the channel a braided pattern.
Facies S2. Laterally accreted sandstones	Thickness: 2 m. Width: 20–50 m. Flat, erosional base with an irregular, undulating top. Fine- to medium-grained sandstone. Thick lateral accretion surfaces terminate in mud plug. Common root traces, desiccation cracks and bioturbation.	Broad, shallow, sinuous channels with point bars. Plug formed following abandonment.
Facies S3. Single-storey ‘winged’ sandstones	Thickness: 1–6 m. Width: 20–50 m. Central body with concave-up erosion surface flanked symmetrically by lenticular wings. Fine- to medium-grained sandstone. Bodies are massive or cross-bedded, and wings are thoroughly bioturbated.	Straight or slightly sinuous ephemeral channels. Wings form as levees during overbank flooding.
Facies S4. Interbedded sheet sandstones and mudstones	Thickness: 1–10 m. Width: >50 m. Tabular packages of fine-grained sandstone and mudstone. Sandstone beds (2–60 cm thick) are massive and bioturbated or show parallel lamination or small-scale cross-lamination. Mudstones (2–30 cm thick) are reddish brown and massive with desiccation cracks and root traces. Sandstone sheets can sometimes amalgamate without interbedded mudstone.	Deposition from sheetfloods or in channels where the perimeters are too low-angle to be readily distinguished. High-velocity, ephemeral flows.

Table 1 (continued)

Facies	Description	Interpretation
Facies H1. Inclined or concave-up heterolithic strata	Thickness: 1–2 m. Width: 10–20 m. Erosionally based hollows infilled with interbedded sandstone and mudstone (heterolithic strata). Symmetrical bodies are infilled concentrically, while asymmetric bodies show lateral accretion surfaces. Mudstone forms prominent plug.	Straight or sinuous channels. Heterolithic strata from alternating periods of sand deposition as migrating ripples and mud from suspension. Plug marks channel abandonment.
Facies M1. Massive to faintly bedded mudstone	Thickness: 0.01–20 m. Blocky, reddish brown, massive to faintly laminated mudstone. Often with comminuted carbonaceous organic matter, desiccation cracks and root traces.	Deposition from standing floodwaters, mudflows or bedload aggregates? Destratification by plant and animal activity and/or wetting and drying cycles.
Facies M2. Laminated, desiccated mudstone	Thickness: 1–3 m. Reddish brown alternations of claystone and siltstone laminae. Common desiccation cracks (concave-up curls), raindrop impressions and dewatering structures.	Low-salinity ephemeral lakes with deposition from suspension. Dewatering structures from burst-out of pressurised pore waters.
Facies M3. Laminated grey mudstone	Thickness: 1 m. Pale bluish grey laminated mudstone characterised by an absence of desiccation cracks, root traces and bioturbation.	Suspension fall-out in shallow perennial lakes. Depleted in oxygen but not anoxic.
Facies M4. Laminated mudstone with halite casts	Thickness: 0.1–0.5 m. Alternation of thin laminated grey mudstone and layers of salt hopper casts.	Saline pans. Deposition of fine siliciclastic mud after flooding and halite after evaporation. Possibly groundwater-fed.
Facies C1. Carbonates	Thickness: 0.1–0.2 m. Isolated nodules up to 10 mm in diameter, coalesced nodules, or massive tabular beds up to 0.2 m thick. Relic patches of clay and silicate grains.	Groundwater calcretes precipitated from shallow, alkaline groundwaters flowing along sandy or gravelly aquifers. Precipitation driven by evaporation.
Facies C2. Carbonates	Thickness: 0.5–1.5 m. Carbonate beds showing highly brecciated to laminar morphology. Clasts of cemented peloids and coated grains, with spar-filled circumgranular cracks.	Pedogenic calcretes, brecciation from subaerial exposure.

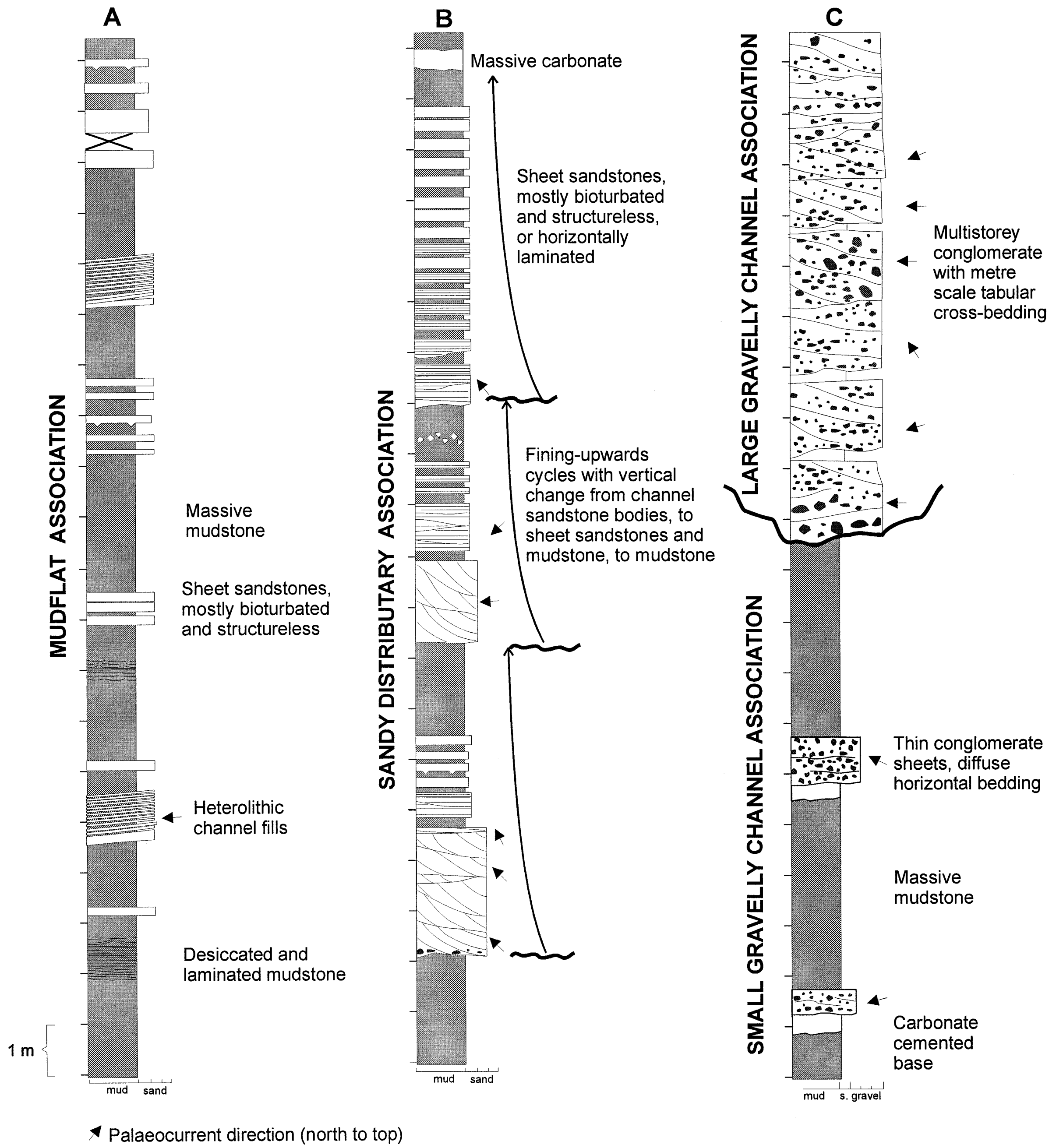

Fig. 8. Sedimentological logs showing typical example of facies and facies stacking patterns within: (A) the mudflat association (Kulchumovo), (B) the sandy distributary association (Vyazovka), and (C) the small and large gravelly-channel associations (Kulchumovo).

the lowest part of the measured sections and grades upwards into the sandy distributary association by the progressive introduction of more closely spaced and thicker sandstone units.

This facies association is interpreted as a low-gradient mudflat environment. Deposition was dominated by the settling of suspended sediment from shallow, ponded floodwaters. The lack of structure in much of the mudstone may reflect the post-depositional homogenising effects of plants and animals and seasonal wetting and drying cycles (Talbot et al., 1994). The presence of plant debris and vertebrate footprints (Tverdokhlebov et al., 1996) indicate that the mudflats were at least partially vegetated. Mudstone interlaminated with halite casts is a rare evaporite facies. This may reflect deposition on 'saline pans' which were normally dry except when storm flooding or rising groundwater levels turned them into temporary lakes. Deposition of fine siliciclastic mud occurred following flooding, while evaporation led to saturation with halite and a period of salt precipitation (Lowenstein and Hardie, 1985).

Fluvial processes deposited sandstone sheets and heterolithic channel fills. Palaeocurrent indicators (channel elongation and small-scale cross-lamination) indicate general westward transport, although dispersal is high. Sandstone sheets probably resulted from unconfined sheetflood events and are a typical facies of arid-zone mudflats (Tunbridge, 1984). The presence of channels with inclined and concentric heterolithic stratification (Fig. 9) is of greater interest because comparable facies have not previously been described from ancient examples of this type of environment (e.g. Hubert and Hyde, 1982). Channel fills of this type are more usually associated with tidally-influenced coastal settings (Thomas et al., 1987). This interpretation is rejected here on the basis that supporting evidence for tidal or marine influence (bi-modal palaeocurrents, marine organisms) is absent. The presence of inclined heterolithic stratification in this fully continental setting may reflect the low energy of discharge events. Rates of erosion could have been insufficient to cause significant reworking of previously deposited sand–mud bed couplets. The depth (1–2 m) and high sinuosity of channels (indicated by lateral-accretion bedding) compares with those described from low-gradient playa basins of the Mojave Desert. Such channels are numerous, extend far out into the playa and are thought to be the most important mechanism for distributing sediment (Handford, 1982).

4.2. Sandy distributary association

The sandy distributary association consists of isolated fluvial sandstone bodies supported within a matrix of red mudstone. The array of sandstone bodies is diverse and includes multistorey sandstone lenses (Fig. 10a), interbedded sandstone and mudstone sheets (Fig. 10b), laterally accreted sandstone sheets (Fig. 10c) and single-storey sandstone lenses with 'wings'. Thin conglomerate sheets are rare. The enclosing mudstones are mostly massive (with dispersed plant debris and carbonate), although laminated facies also occur. This association is continuously exposed at Vyazovka where it is 150 m in thickness.

This environment was dominated by fluvial processes. Flow ranged from fully confined (channel

Fig. 9. Heterolithic sandstone and mudstone body showing broad concave-up erosional base enclosing right- to left-dipping convex-up lateral accretion bedsets. Underlying, irregular sandstone bed may have controlled the depth of channel scour.

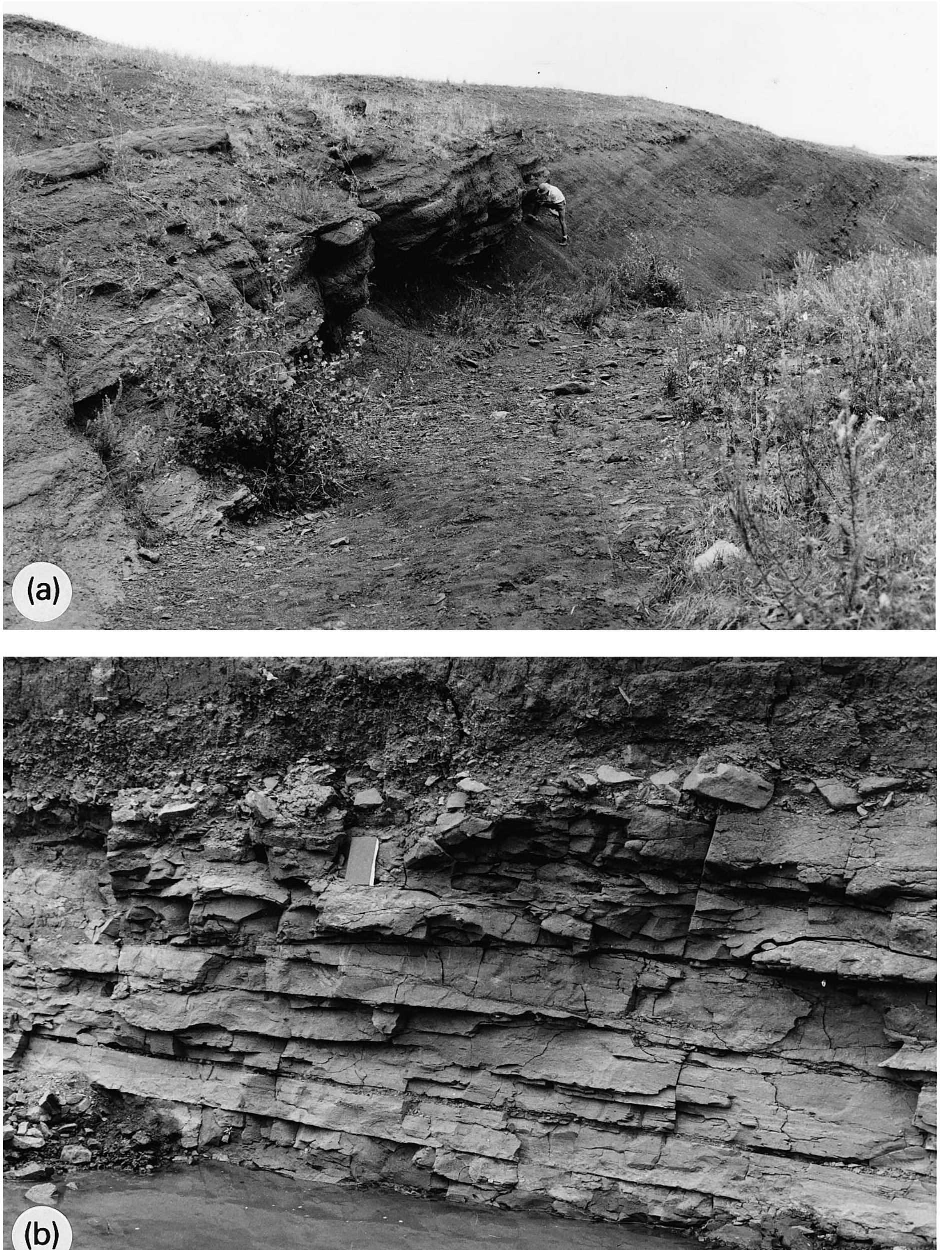

Fig. 10. Sandstone bodies of the sandy distributary association. (a) Lenticular sandstone body with thin (0.5 m) sheet-like storeys. (b) Interbedded sheet sandstones and mudstone (angular gravel overlying sheet sandstones is recent). Notebook is 0.2 m long.

sandstones), to fully unconfined (single sheet sandstones), or a combination of both (winged sandstone bodies, stacked sheets) (Friend, 1978). An abundance of horizontal lamination suggests that flows were of short duration and high intensity (Tunbridge, 1984). This type of run-off pattern is typical of modern semi-arid regions where high rainfall intensity rapidly exceeds the infiltration capacity of clay-rich,

Fig. 10 (continued). (c) Laterally-accreted sandstone sheet showing crude lateral-accretion bedding (inclined left to right) passing into a concentrically infilled mudstone plug.

dried surfaces (Hogg, 1982). Convex-up slopes, such as those found on alluvial fans, also encourage sheet flooding by preventing the concentration of flow and channel erosion (Horton, 1945).

Facies in this association are arranged in cyclic patterns, on a scale of 2 to 12 m (Fig. 8b). Cycles typically fine upwards, from a basal channel sandstone body, into sheet sandstones and mudstones, which grade into massive mudstone. Palaeocurrent measurements, although consistent within cycles, often show marked divergence (80º) across cycle boundaries. The small scale, dispersion pattern and facies stacking of these cycles are typical features generated by sediment distributary systems (e.g. delta plain or alluvial fan). In this case, the cycles probably resulted from the switching of active depositional areas across a low-gradient fluvial distributary fan, with flow being diverted from high-aggraded areas to adjacent low areas. This process is essentially autocyclic, with the fluvial system attempting to maintain even aggradation across the basin. However, it may be initiated by unusually large flood events, or by tectonically related changes in slope (Scott and Erskine, 1994). The dominance of channelised flow at the base of cycles may reflect the initially steep gradients (and thus high erosive power) of flows entering new areas (Kellerhals and Church, 1990). Upwards, the transition to sheet flooding may indicate a levelling in gradient, and a progressive loss of discharge as the active lobe aggrades and overspills. The dominance of mudstone toward the top of a cycle, could have resulted from a shift in the locus of sand deposition, with the area receiving only mud, possibly from the lateral margins of sheetfloods (Beer and Jordan, 1989). Comparable cycles have been described from many inferred examples of ancient semi-arid fluvial distributary zones (Hubert and Hyde, 1982; Tunbridge, 1984; Beer and Jordan, 1989).

Carbonate nodules and massive beds are an important component of the cycles, invariably occurring near the top, or just below the channelised facies of the following cycle. The lack of related pedogenic features, association with colour mottling, massive character of beds and absence of reworked carbonate in channel fills strongly suggests that most of these were precipitated from shallow alkaline groundwaters (Pimentel et al., 1996). Their position reflects the role of channel fills as aquifers, with groundwaters flowing along the channel–clay interface and percolating downwards into underlying muds.

4.3. Small gravelly-channel association

The small gravelly-channel association is characterised by single or multistorey conglomerates encased within massive mudstone. The association is approximately 30 m thick at Kulchumovo. It grades upwards from the sandy distributary association through the progressive loss of sandy facies. Conglomerates are usually 1–2 m thick and around 100 m in flow transverse width. They are tabular or lenticular in flow-transverse section, and contain thin (<0.3 m) sheet-like storeys. Clasts are composed mainly of well-rounded quartzite with subordinate limestone and marble. Maximum clast size is 5 cm.

This association is interpreted as a channel–floodplain complex characterised by broad, shallow low-sinuosity channels that transported a gravel load. Palaeocurrent measurements from clast imbrication show a low dispersion toward the west. This is consistent with a clast provenance which has been sourced to the central zones of the Ural Orogen (Tverdokhlebov, 1976). The lack of cross-bedding and thinness of storeys suggest relatively shallow flows with gravel being deposited as low-relief diffuse sheets rather than slip-faced bars (Hein and Walker, 1977). Mud was probably deposited on floodplains during periods of overbank flooding. Carbonate beds, which are invariably developed along the gravel–clay interface of channel fills, are interpreted as groundwater carbonates (Pimentel et al., 1996). They are generally thicker (0.3 to 0.5 m) than those of the sandy distributary association. This may reflect higher rates of groundwater flow and/or higher rates of evaporation.

Fig. 11. Single storey within the large gravelly-channel association. Storey is tabular cross-bedded with a thin wedge of sandstone at the top. Hammer is 1 m long.

4.4. Large gravelly-channel association

The large gravelly-channel association caps the Permian succession. At Kulchumovo, it comprises 15 m of erosionally-based conglomerate with an internal geometry of multiple broad, lenticular storeys (1–3 m thick). Storeys are tabular cross-bedded, with thin sandstone wedges and channel fills at the top (Fig. 11). Maximum gravel clast size is 20 cm, although is generally in the range 5–10 cm. In flow-transverse section the conglomerate body is lenticular with an estimated total width of around 3 km. At Vyazovka, this association also comprises sharp-based, multistorey, tabular cross-bedded conglomerate. However, the conglomerates are developed as two bodies each 5 m in thickness, separated by 4 m of massive mudstone. The maximum clast size is 7 cm. Both bodies appear tabular in geometry, exceeding 5 km in width. At both localities, foreset azimuths indicate flow to the west with low dispersion. Clasts are composed mainly of well rounded quartzite with subordinate limestone, marble, chert but also include a range of acid to basic igneous materials which have been sourced to the central zones of the Ural Orogen (Tverdokhlebov, 1976). The reddish brown mudstones that interbed and enclose the conglomerate bodies differ from those of the underlying facies associations in their total lack of dispersed organic material. They are generally

Fig. 12. Part of a 1.5 m thick carbonate in overbank mudstones of the large gravelly-channel association. The highly brecciated structure is closely comparable to the Mio–Quaternary supermature calcrete illustrated in Wright et al. (1993), fig. 10a)

massive, or totally brecciated, probably due to desiccation. Carbonates are absent from the base of the conglomerate bodies, but near Kulchumovo occur in mudstones which flank the conglomerate body. These carbonates differ from those of underlying associations in their greater thickness (up to 1.5 m), pervasive brecciation (circum- and intragranular cracks around cemented peloids) (Fig. 12), zones of irregular lamination, and silica-infilled voids.

Conglomerates within this association were deposited in a major fluvial conduit that transported sediment from an intraorogen source transversely across the basin axis. The multistorey geometry of conglomerates may have resulted from the activity of many coeval channels which formed part of a larger channel-belt (Bridge, 1993). This would probably have exhibited a braided pattern at low flows. Tabular foresets could have resulted from the migration of transverse bars (Hein and Walker, 1977). Minor sandstone filled channels and wedges could have formed during low and falling-stage flows. Massive mudstones, which encase the conglomerates are interpreted as overbank fines deposited on floodplains adjacent to the channel belt. This facies combination can be seen in present-day areas such as the Kosi Megafan (Gohain and Parkash, 1990). Wells (1983) and Schwans (1988) have described comparable ancient examples of this facies association. The thick laminated and brecciated carbonates developed in overbank mudstones compare closely with the supermature calcretes described by Wright et al. (1993). These profiles develop as secondary accumulations of calcium carbonate in soils. The brecciation may result from long periods of direct subaerial weathering, possibly related to periods of soil erosion or deflation (Wright et al., 1993).

5. Depositional systems: a two-phase terminal fan model

5.1. Terminal fan (Phase 1)

The mudflat, sandy distributary and small gravelly-channel associations have gradational stratigraphic contacts, a consistent westward transport direction, and show no change in provenance. These characteristics, in combination with the progressive coarsening-upwards trend, could indicate that they were part of a common prograding depositional system. The main characteristics of this depositional system would thus be: an intraorogen source, a dominance of fluvial processes, a radial drainage system-oriented transverse to the axis of the orogen, and a downslope reduction in sediment load and channel size terminating in a muddy floodbasin. These are typical features of terminal fans (Mukerji, 1976; Friend, 1978; Parkash et al., 1983; Abdullatif, 1989), or as termed by Nichols and Hirst (1998) fluvial distributary systems. The decrease in channel size and discharge is the result of channel splitting, runoff infiltration and evaporation (Abdullatif, 1989). Modern terminal fans are generally developed under semi-arid climates with seasonal rainfall (Kelly and

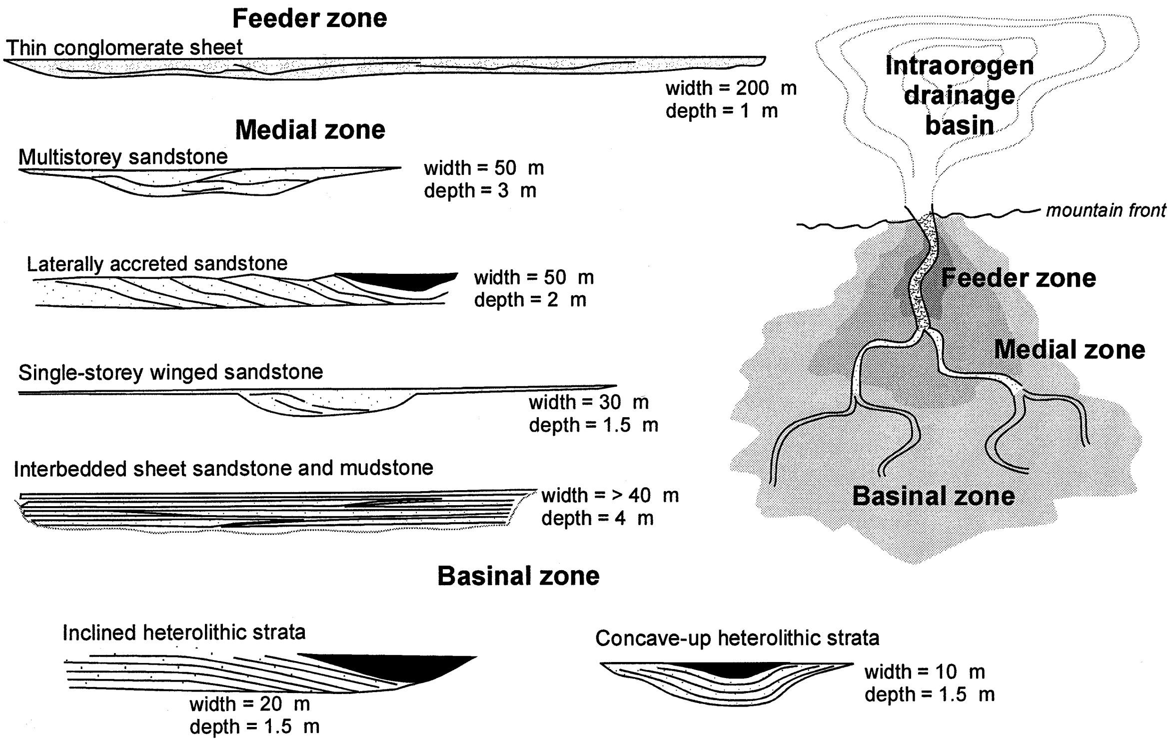

Fig. 13. Diagram summarising the architecture of conglomerate and sandstone channel bodies within the inferred terminal fan system (Phase 1). All channel bodies are supported in a matrix of overbank mudstone.

Olsen, 1993). The small gravelly-channel association can be compared to the proximal 'feeder channels' of modern terminal fans. These channels are generally straight, braided and transport a gravel bedload if material of this grade is available (Kelly and Olsen, 1993). Feeder channels emerge onto a lower gradient distributary zone where they bifurcate into a number of shallow, wide channels, typically with rectangular cross-sections and a sandy load (Mukerji, 1976). These channels undergo further division before terminating in a muddy floodbasin. In the terminal fan described here, the downslope decrease in gradient, discharge and sediment load produced a change in channel architecture from vertically-accreted conglomerate bodies in proximal zones, to laterally or vertically-accreted sandstone bodies in medial zones, to muddy heterolithic bodies in distal zones (Fig. 13). In addition to downslope changes in surface runoff, there is evidence for downslope changes in groundwater flow. The exclusive presence of groundwater calcretes in the gravelly-channel and sandy distributary associations, and halite in the mudflat association could result from a downslope increase in shallow groundwater salinity due to evaporation (Wright and Sandler, 1994).

5.2. Terminal fan (Phase 2)

A test of terminal fan models which are inferred from vertical sections (or physically unconnected time slices) lies in the scaling relationships of channels. On modern fans, discharge decreases downslope in a progressive manner resulting in relatively small, progressive decreases in channel dimensions (Abdullatif, 1989). This scaling relationship is tenable for channels within the associations which make up the first phase terminal fan. However, it is clear that channels within the uppermost 'large gravelly-channel association' are too out of proportion to be a part of this fan system. For example, at Kulchumovo, there is an abrupt increase in the cross-sectional area of channel bodies from around 400 m^2

(small gravelly-channel association), to an estimated 22,000 m^2 (large gravelly-channel association). A substantial increase in peak flow depth and velocity is also suggested by the increase in maximum clast size (5 cm to 20 cm), storey thickness (decimetres to metres) and storey structure (gravel sheets to tabular cross-bedding). The large gravelly-channel association must represent a much larger, superimposed fluvial system. The available evidence suggests that this was also a fluvial distributary system, but on a much larger scale. This is supported by the westward decrease in storey thickness and maximum clast size between Kulchumovo and Vyazovka and the splitting of channel bodies. Based on published accounts, this basinward decreasing grain-size trend extends across the European Platform to the western limits of Tatarian strata, some 900 km from the mountain front (Nalivkin, 1973) (Fig. 5). Given the scale of the feeder channels it is not unreasonable that these areas could have been the basinal zone for this terminal fluvial system. Nalivkin (1973) used analogues from the Gobi Desert to demonstrate that internally drained arid zones of this size can be traversed by large rivers. Tverdokhlebov (1976) has demonstrated that several major feeder channels emerged along the southern Uralian mountain front by mapping lateral variations in gravel composition.

6. Controls on fluvial system evolution

Considerations of channel size, grain size and the location of distal floodbasin deposits show that two very different scales of fluvial system are superimposed in the Upper Permian of the Belsk Basin. An initial system fed sediment for only a short distance (50–100 km) into the foreland basin and showed steady prograding behaviour. This is directly overlain by a fluvial system characterised by a much larger proximal gravelly-channel belt, and a distal floodbasin which could have been located 900 km from the mountain front. The possible causes of this switch are discussed below. Eustatic controls and intrinsic sediment redistribution processes are initially ruled out. Although there was a major eustatic fall at the end of the Permian, this should not have directly influenced Tatarian strata which were deposited within a hydrologically-closed basin (Nalivkin, 1973). The change between the two fluvial systems is also considered more abrupt and of higher magnitude than that normally produced by intrinsic sediment redistribution processes (Fraser and De Celles, 1992). Tectonic and climate change are considered the two main possible controls.

6.1. Tectonic change

Tectonic processes in foreland basins have a clear ‘first order’ control on the thickness of accumulated fluvial sediment, and on its gross facies distribution (Miall, 1981; Jordan et al., 1988). Other studies have suggested that tectonics may also exert a fine control on fluvial stratigraphy. For example, gravels may be emplaced into the stratigraphy, either in response to thrusting, or as a post-thrusting phenomenon (Burbank et al., 1988).

A range of evidence suggests that the rocks discussed here accumulated during a period of low tectonic activity. (1) Lower Permian rocks are generally the youngest in the southern Urals that are extensively thrusted. Upper Permian rocks can blanket thrusts and do not contain outcrop evidence of structural deformation or rotation. (2) Tatarian red beds occur at the top of the second major ‘shallowing-upward’ cycle that defines the basin fill (Fig. 14). (3) There are no major changes in transport direction or provenance within the fluvial succession that might be expected from thrust emplacement (Jordan et al., 1988). (4) The highly amalgamated multistorey character of the large gravelly channels, and the development of super-mature calcretes in overbank mudstones point towards low rates of thrust-related subsidence (Frostick and Steel, 1993). (5) The transverse orientation of the drainage system suggests that accumulation was outstripping the rate of subsidence. High rates of subsidence relative to sediment accumulation should capture streams within the foreland basin and result in longitudinal drainage (Burbank and Beck, 1991).

In sum, the available evidence suggests that the fluvial sediments accumulated under slow and declining rates of tectonic subsidence. This is consistent with the understanding that the main locus of compression had moved northwards into the central and northern Urals by the Late Permian (Puchkov, 1997). A decline in tectonic subsidence

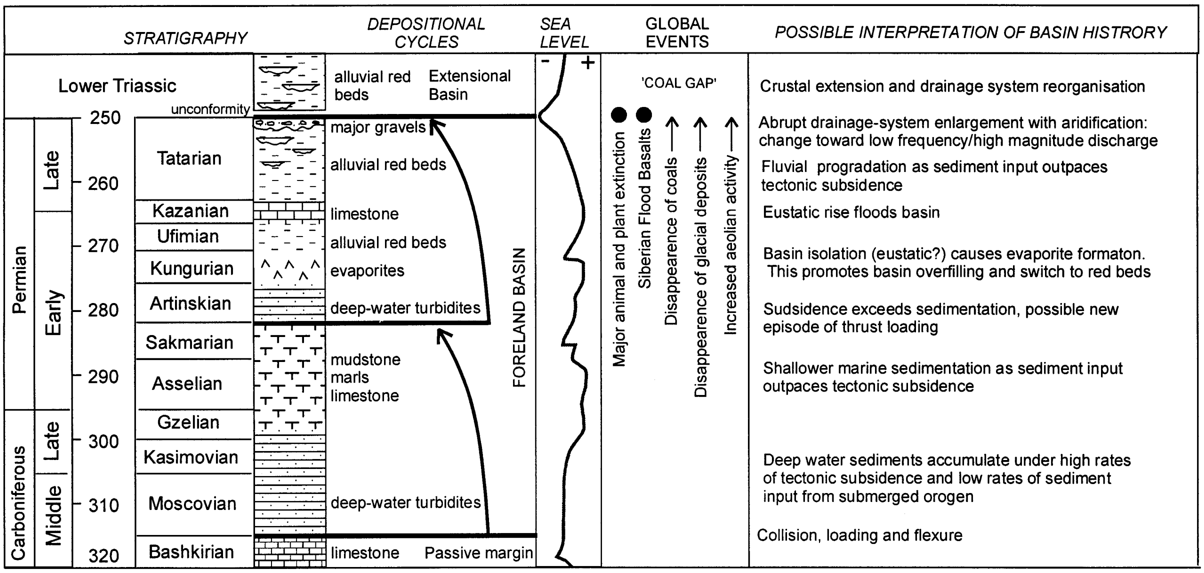

Fig. 14. Diagram summarising the stratigraphy of the Southern Uralian Foreland Basin, the development of major depositional cycles, the sea-level curve for Euramerican platform areas (from Veevers et al., 1994) and major global events (after Veevers et al., 1994).

may have caused the long-term progradation (coarsening-upward) of the fluvial system. Under these conditions, sediment accumulation can outstrip the creation of accommodation space within the basin (Burbank et al., 1988). However, it is uncertain whether declining subsidence could also have produced an abrupt enlargement of the drainage system.

6.2. Climate change

Over the Permian/Early Triassic there appears to have been a trend toward global warming and aridification, from the relatively humid Early Permian, to the arid Early Triassic (Veevers et al., 1994). The rate of global warming peaked at the Permo–Triassic (P–Tr) boundary with profound environmental effects including a major vegetation change and the largest animal mass extinction of all time (Benton, 1985). Many environmental changes preclude this event, including the disappearance of coals (including the Late Permian of the northern Uralian Foreland Basin), and the deglaciation of Gondwanaland (Veevers et al., 1994). Moore et al. (1990) using a General Circulation Model, attributed the P–Tr climate change to an increase in CO_2, CH_4 and other greenhouse gases caused by processes related directly to the formation of the Pangean Supercontinent. At the P–Tr boundary CO_2 levels and global warming were catastrophically accelerated by the eruption of Siberian flood basalts.

In general terms, the fluvial sediments described here appear to have accumulated in a relatively hot, dry climate. This is indicated by the terminal nature of the drainage systems, pervasive oxidation of overbank mudstones and the presence of calcretes. These features are consistent with the 30°N palaeolatitude. However, in detail, there would appear to be some evidence of change over the section examined. This is most apparent in the overbank mudstones. In facies associations that comprise the small terminal fan, mudstones show evidence of a reasonable supply of water, with metre-thick intervals of perennial lacustrine lamination, and an abundance of organic debris and rootlets in massive facies. Carbonates, which cement the base of channels, are interpreted as groundwater calcretes, which imply relatively high groundwater tables. There is also evidence of much animal activity, with tetrapod skeletons and footprints, pervasive bioturbation of sandstone beds, and common freshwater invertebrates. These features might indicate a semiarid/subhumid climate. They contrast sharply with the overbank mudstones of the overlying large gravelly-channel association. These are rubbly and desiccated, and contain no trace of plant debris or rootlets. Thin sandstone beds are generally non-bioturbated. Groundwater calcretes are absent, but thick brecciated pedogenic calcretes are developed. These features suggest a more arid climate.

If channel bodies are considered the results seem initially surprising because their dimension and grain size are inversely related to the degree of humidity indicated by their overbank deposits. The increase in channel size might be expected to result from a change toward an overall wetter climate. This interpretation is not favoured here on the strength of evidence from overbank mudstones and global events for an increase in aridity. In this case, the increase in channel size is interpreted in terms of a change in discharge regime toward one of low-frequency, but high-magnitude flood events. This interpretation is supported by Holocene studies which show that an increase in channel-belt size and drainage network can result from the more variable runoff associated with greater aridity (Patton and Baker, 1977). This reflects the fact that arid zone channels tend to adjust to the runoff volume and sediment grade of the largest flood events even if these are infrequent. This contrasts with humid climates where channels adjust to base flow.

Changes in precipitation pattern and a reduction in vegetation cover in the drainage basin could also have caused the abrupt influx of gravel at the P–Tr boundary. A reduction in vegetation cover would have two important effects (Bull, 1991). Firstly, it would increase sediment yield by releasing detritus that was previously locked in hillslope reservoirs. An input of second-cycle gravel is consistent with the dominance of well-rounded quartzite clasts. Secondly, reduced vegetation cover would increase the rate of surface runoff. This is a positive feedback process whereby uncontrolled overland flow erodes more rills and channels in the basin, increasing the drainage density, and thereby the efficiency of the drainage network for carrying runoff. This results in greater flood peaks. These low-frequency/high-magnitude events may achieve higher rates of gravel transport than high-frequency/low-magnitude events because most gravel is transported during major floods (although high-frequency events may transport a greater weight of sediment over time including suspended material) (Patton and Baker, 1977).

7. Conclusions

This study described a transverse fluvial system from the southern Urals that moved sediment and water from an intraorogen source into the adjacent foreland basin. Progressive discharge loss and decreasing gradient within the basin promoted downslope sorting of the sediment load into zones of gravel, sand and mud. The fluvial system developed over the final phase of mountain building in the southern Urals. Decreasing subsidence rates may have caused the overall coarsening-upward (prograding) character of the fluvial succession. However, an abrupt increase in channel size associated with a major influx of gravel around the Permo–Triassic boundary could be related to climate change. This climatic event is well constrained by global and local sedimentary/biological evidence. A switch from a semiarid/subhumid climate toward one of greater aridity can increase sediment yield by reducing vegetation cover (Bull, 1991). It may also result in higher rates of gravel transport under a regime of low-frequency but high-magnitude runoff events which favour the movement of coarse sediment. Under arid conditions, channel architecture will reflect the discharge of these rare flood events rather than background flow, which may be negligible (Patton and Baker, 1977). Channel dimensions may represent the least reliable means of determining palaeohumidity in ancient fluvial red beds.

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Appendix A. Details of localities

Vyazovka is a 4 km long stream cut which joins the main Ural River. The map reference for this locality, using the Soviet 'Sistema Koordinat 1942' is 10418857333 (longitude 55º55′E and latitude 51º43′N). A continuous 250 m section can be seen in strata which dip (and young) to the southwest. The second section lies near Kulchumovo just to the north of the Sakmara River (at map reference, 10449457505 (longitude 55º55′E and latitude 51º43′N). A detailed map showing this location can be found in Tverdokhlebov et al. (1996). Here, a discontinuous section can be examined starting in a stream cutting at Kulchumovo and finishing 3 km east at cliff exposures on Sambulla Hill.

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