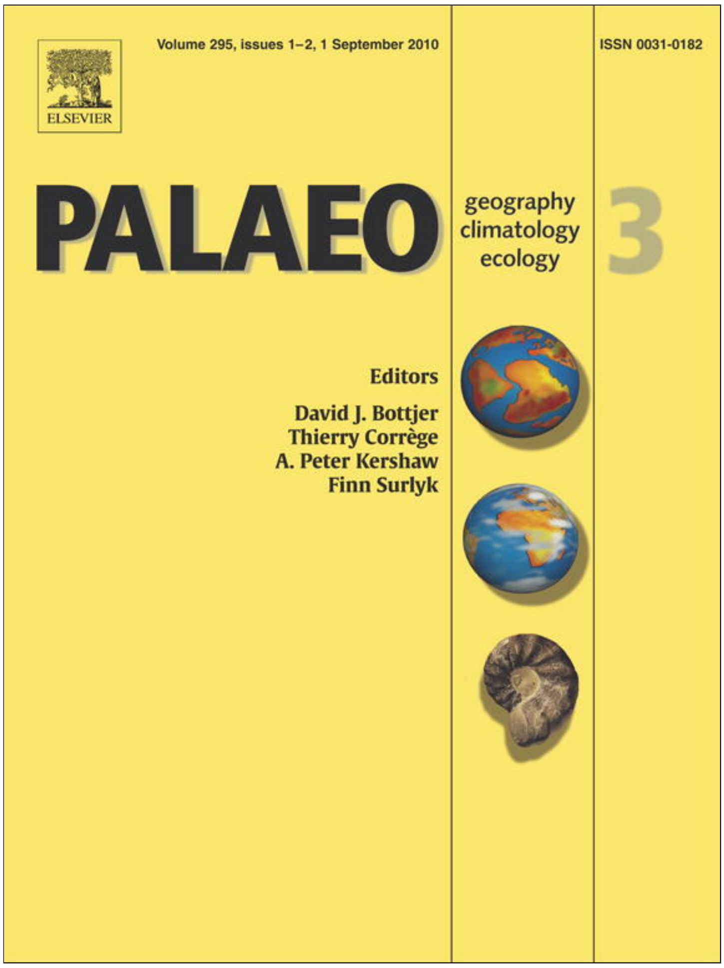
Volume 295, issues 1–2, 1 September 2010
ISSN 0031-0182
ELSEVIER
PALAEO
geography
climatology
ecology
3
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Palaeogeography, Palaeoclimatology, Palaeoecology 295 (2010) 307–322

Contents lists available at ScienceDirect

Palaeogeography, Palaeoclimatology, Palaeoecology

journal homepage: www.elsevier.com/locate/palaeo

Deposition in the Kuznetsk Basin, Siberia: Insights into the Permian–Triassic transition and the Mesozoic evolution of Central Asia

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ARTICLE INFO

Article history:
Received 3 August 2009
Received in revised form 25 May 2010
Accepted 14 June 2010
Available online 22 June 2010

Keywords:
Permian–Triassic transition
Jurassic
Siberia
Central Asia
Fluvial

ABSTRACT

This paper describes the Permian–Mesozoic stratigraphy of the Kuznetsk Basin, southern Siberia, which is adjacent to the vast and hydrocarbon-rich West Siberian Basin and on the edge of the Siberian flood basalts. The basin fill is Permian to Cretaceous in age, and is dominated by non-marine siliciclastics up to ~7 km thick. Palaeocurrent indicators show dominant flow to the north/northeast during the Permian to Jurassic. Fourteen lithofacies are grouped in three facies associations: fluvial channel belt, overbank and floodplain/floodplain pond. Coal-bearing Permian siliciclastics are interpreted as meandering river deposits in a foreland basin, with subsidence generated by thrust-sheet loading from at least three basin margins. These sediments pass abruptly but conformably upwards into coal-barren sandstones and conglomerates and siltstones, interpreted as braided river deposits. Two basalt flows occur within the coal-barren succession. A recently-published, precise Ar-Ar age of 250.3 ± 0.7 Ma for the lower of these basalts, <50 m above the sedimentary transition, suggests that the Permian–Triassic boundary occurs just above this flow. We relate the loss of coal-producing flora and the increase in mean sediment grain size to vegetation loss, in turn triggered by the eruption of the Siberian flood basalts to the north. End-Permian and Lower Triassic(?) strata are overlain by Lower Jurassic fluvial siliciclastics via a gentle angular unconformity. Conglomerates punctuate a sandstone-dominated succession that continues in to the Middle Jurassic. Both the basal unconformity and the rejuvenation in sedimentation may result from intracontinental thrusting at the basin margins and beyond; this thrusting was triggered by orogenies at the Eurasian margin. Lower and mid Cretaceous siliciclastics are poorly exposed and crop out only locally: field relations indicate an angular unconformity at their base. The end-Permian stratigraphy in the Kuznetsk Basin documents the environmental crisis at the time of the Siberian flood basalts, and reinforces the link between these eruptions and climatic and environmental deterioration. The Mesozoic sedimentary record highlights how episodic deformation influenced sediment supply to the West Siberian Basin, and is an example of the record of Eurasian assembly and deformation preserved within the continental interior.

1. Introduction

This paper concerns the sedimentary fill of the Permian-Cretaceous Kuznetsk Basin (Kuzbass) in southern Siberia, Russia (Fig. 1). The study has three main implications, beyond the basin itself. 1) The geology includes examples of sedimentation at the Permian–Triassic transition, in an area affected by Siberian trap volcanism — itself held responsible for the mass extinction between the Permian and Triassic (Wignall (2001) and references therein). 2) Sediment pulses, folds and unconformities within the Kuznetsk Basin are a record of tectonic events during the Permian–Mesozoic evolution that affected a much wider area of Central Asia. 3). Part of our observations is that north-flowing palaeo-drainage systems in the Kuznetsk Basin formed part of the sediment transport system for the nearby West Siberian Basin (area $>2\times10^6$ km^2) and so give insights into its evolution and likely basin fill. The West Siberian Basin has economic as well as academic importance, as it is one of the world's main hydrocarbon producing areas (Peterson and Clarke, 1991; Vyssotski et al., 2006).

Our approach is to describe the regional geology first, then to document the Permian–Mesozoic stratigraphy (mainly from our fieldwork in open-cast coal mines, quarries and road and river sections; other natural exposures are rare) and then to discuss the implications of the stratigraphy for each of the three lines of study listed above.

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doi:10.1016/j.palaeo.2010.06.008

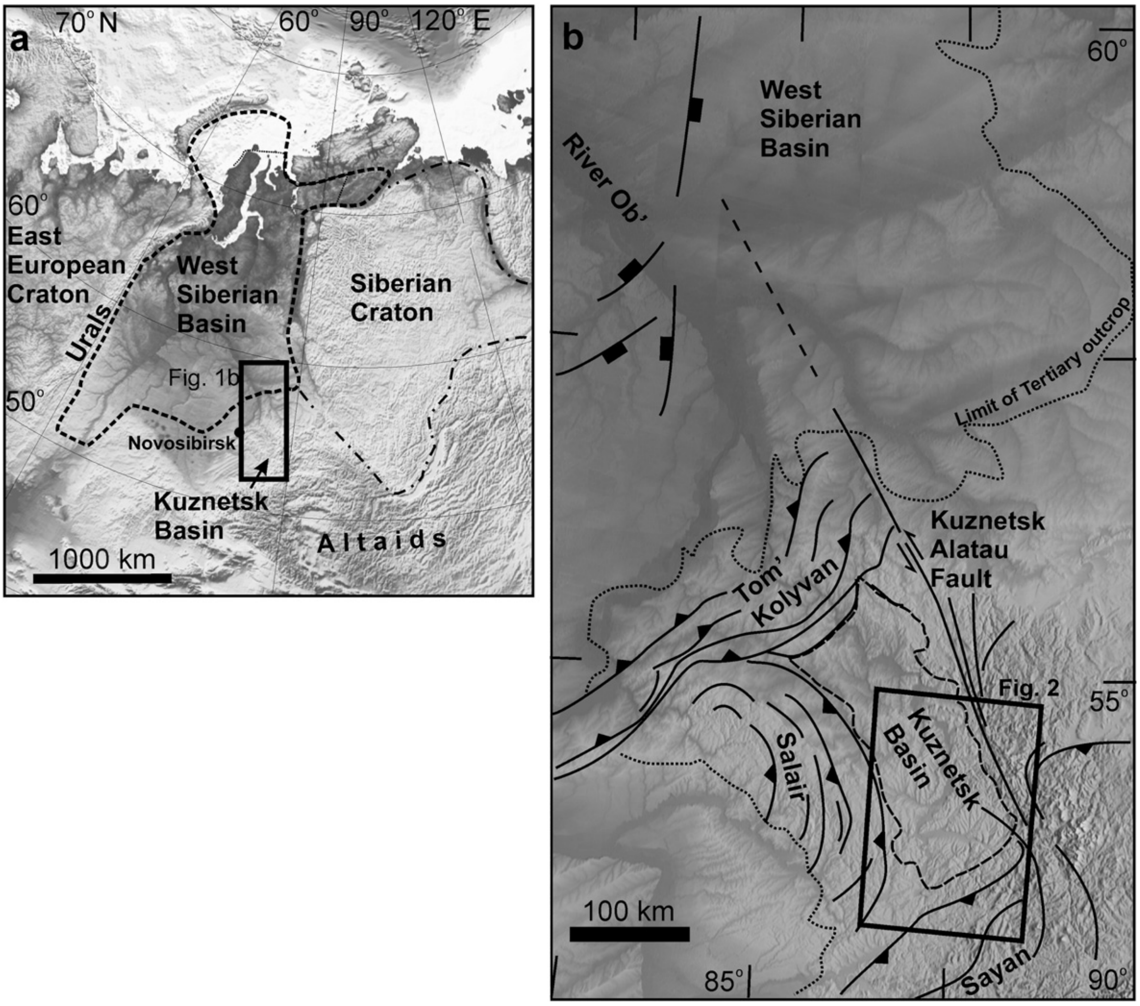

Fig. 1. a) Location map of the Kuznetsk Basin, showing its proximity to the West Siberian Basin to the north. Shaded digital topography from the GTOPO30 dataset. b) Structural framework of the Kuznetsk Basin, showing its proximity to marginal fold and thrust belts, and location south of the main West Siberian Basin. Fault locations adapted from Zonenshain et al. (1988) and Allen et al. (2006).

2. Geological background

2.1. Regional geology

The Kuznetsk Basin has an area of 20,000 km^2, and is located ~300 km to the south of the West Siberian Basin, and east of Novosibirsk (Fig. 1). The basin is bordered on all four margins by fold and thrust belts and shear zones that deform Palaeozoic rocks and generally verge towards the basin interior (Fig. 2). From the north, clockwise, these are the Tom'-Kolyvan, the Kuznetsk Alatau, the Western Sayan/Gorny Altai and the Salair Range. All four regions form part of the vast Altaid collage, which is the orogenic belt that constructed much of the basement of Central Asia during the Palaeozoic (Şengör and Natal'in, 1996; Buslov et al., 2004). Many of the Palaeozoic units are volcanic, volcaniclastic, or immature siliciclastics derived from these protoliths. The unexposed and undrilled basement to the basin presumably consists of similar rocks. In contrast, the Carboniferous succession is carbonate-dominated, which is exposed along much of the Kuznetsk Basin margin. These carbonates form part of a widespread Upper Devonian–Carboniferous platform across southern Central Asia (e.g. Cook et al., 1995; Gutak et al., 2008): no distinct Kuznetsk Basin was present at this time. The Carboniferous carbonates pass conformably upwards into an Upper Carboniferous–Permian non-marine clastic succession.

The exposed fill of the Kuznetsk Basin is mainly Permian in age (Fig. 2), and consists of up to 5 km of Permian non-marine siliciclastics. These are notable for the coal seams they contain: the Kuznetsk Basin is one of Russia's main coal-producing areas. Production is largely from open-cast mines, creating superb exposures of the Permian succession, and, in places, overlying Mesozoic strata.

Geological maps show the Triassic as everywhere conformable onto the Permian (Kurtigeshev et al., 2008; Lavrenov et al., 2008), with a mapped thickness in the order of hundreds of metres, and including at least two basalt units (probably both lavas, several metres thick, although some Russian geologists believe they are sills). Recent Ar-Ar determinations on these basalts (Reichow et al., 2009) give precise ages of 250.3 ± 0.7 Ma and 250.7 ± 0.6 Ma, placing them and the adjacent sediments most likely in the latest Permian: the Permian–Triassic boundary at the global section and stratotype at Meishan, China, lies between tuffs dated at 249.25 ± 0.14 Ma and 249.83 ± 0.15 Ma (Renne et al., 1995; Reichow et al., 2009). This makes it uncertain exactly where the Permian–Triassic boundary lies in the Kuzntesk Basin succession, and what thickness of Triassic strata is present below the Jurassic succession. The uppermost coal seam lies below these basalts, therefore for simplicity we refer to the rocks previously mapped as Triassic as the end-Permian/Triassic succession, allowing that the rocks above the basalts probably include some Permian deposits. However, biostratigraphic frameworks for the Kuznetsk Basin conventionally place the Permian–Triassic boundary

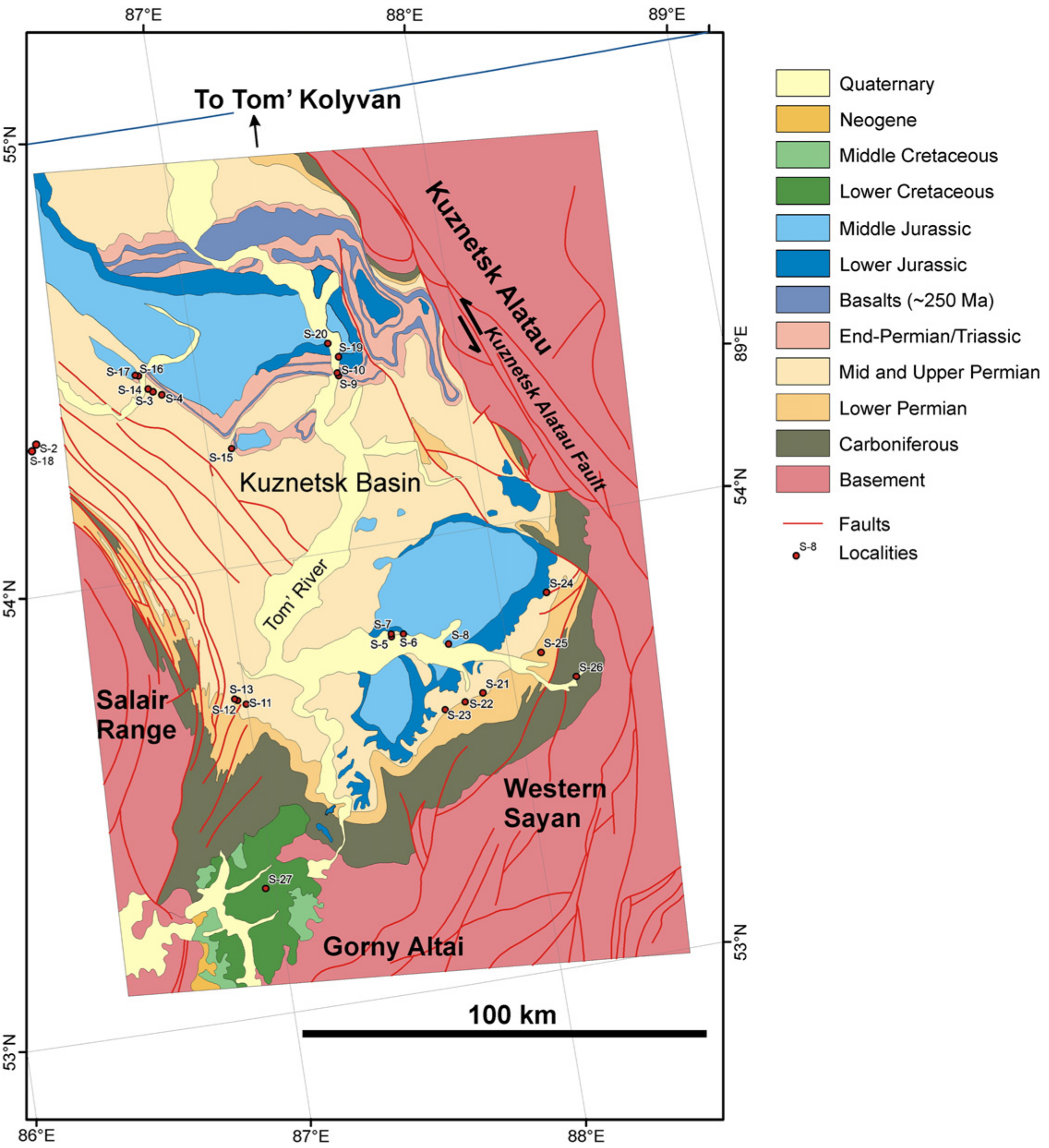

Fig. 2. Geology map of the Kuznetsk Basin (Buslov et al., 2007; Kurtigeshev et al., 2008; Lavrenov et al., 2008).

at the top of the coaliferous deposits (Mogutcheva and Krugovykh, 2009), based on changes in floral, ostracode, conchostracan, bivalve and charohpyte assemblages.

The Jurassic succession overlies the Permian (and any Triassic, if present) with a gentle angular unconformity (Fig. 2). The total succession is nowhere more than ~1000 m thick, comprising non-marine siliciclastics, mainly of Early Jurassic age. The upper part of the succession is mapped as Middle Jurassic (Buslov et al., 2007), but the non-marine nature of the rocks makes precise age determinations difficult. Lower Cretaceous strata are only present in the southwest of the Kuznetsk Basin and in small, somewhat speculative outliers in the basin interior. There are no Late Cretaceous or Paleogene strata preserved in the basin, consistent with much of Central Asia being a peneplain through this time (Allen et al., 2001).

All the Mesozoic strata are folded to some degree, although nowhere mapped as faulted. At present the basin is being incised, and lateral shifts in drainage imply gentle, active deformation, interpreted as a long-distance effect of the India–Asia collision (Allen and Davies, 2007).

2.2. Stratigraphy and age determinations

There is a long history of stratigraphic study and mapping in the Kuznetsk Basin (Yavorskiy and Butov, 1927; Usov, 1937) that continues to this day (Kurtigeshev et al., 2008; Lavrenov et al., 2008; Mogutcheva and Krugovykh, 2009). Fig. 3 summarises the stratigraphic units; and Fig. 4 is a summary log of the strata. The standard Russian division is the suite, which is roughly equivalent to the formation of international usage. Suites carry a connotation of time, as well as lithological equivalence. Two or more suites may be grouped to form a series.

The following summary and Fig. 3 are adopted from the review in Buslov et al. (2007). The Balakhonskaya Series spans the Carboniferous–Permian boundary and is the oldest suite of the Kuznetsk Basin proper. It is sub-divided in to three suites: Ostrogskaya, Nizhnebalakhonskaya (Lower Balakhonskaya) and Verkhnebalakhonskaya (Upper Balakhonskaya). The Ostrogskaya Suite begins with a thin basal conglomerate, but is apparently conformable over underlying strata in the basin interior. The unit is thinner towards the west and east and absent in the north of the basin. The

Age	Series (Group)	Suite (Formation)	Sub-suite
Lower-Middle Jurassic	Tarbaganskaya	Tersyukskaya	-
		Osinovskaya	-
		Abashevskaya	-
		Raspadskaya	-
Lower-Middle Triassic	Abinskaya	Yaminskaya	-
		Sosnovskaya	-
		Mal'tsevskaya (T_1m_1)	-
Upper Permian	Kol'chuginskaya	Yerunakovskaya (P_2er)	Tailuganskaya (P_2t) Gramoteinskaya (P_2gr) Leninskaya (P_2Ln)
		Il'inskaya (P_2il)	Uskatskaya (P_2usk) Kazankovo-Markinskaya (P_2k-m)
		Kuznetskaya (P_1kuz)	-
Lower Permian	Balakhonskaya	Upper Balakhonskaya (P_1bl)	Usyatskaya (P_2us) Kemerovskaya (P_1km) Ishanovskaya (P_1i) Promezhutochnaya (P_1pr)
Carboniferous		Lower Balakhonskaya ($C_{2\text{-}3}bl$)	Alykaevskaya ($C_{2\text{-}3}al$) Mazurovskaya ($C_{2\text{-}3}mz$)
		Ostrogskaya ($C_1{}^3ostr$)	-
	"Lower Carboniferous"		

Fig. 3. Stratigraphic table for the Kuznetsk Basin. From Buslov et al. (2007) and earlier sources, e.g. Yavorskiy and Butov (1927).

Nizhnebalakhonskaya Suite is the lowermost coal-producing unit in the basin. In general, the coal-bearing suites begin with coal-free successions which become coal-bearing with thicker seams up-section. The overlying Verkhnebalakhonskaya Suite is sub-divided in to four sub-suites, from bottom to top Promezhutochnaya, Ishanovskaya, Kemerovskaya and Usyatskaya. Esaulova (1997) placed the international Lower–Upper Permian boundary (base of the Ufimian Stage) at the base of the Usyatskaya Sub-suite, which is slightly different from the scheme used by others (Buslov et al., 2007). Note that Russian stratigraphic nomenclature includes a formal Middle Permian division. The Kemerovskaya and Usyatskaya sub-suites include coal seams 20–30 m thick. The Kolchuginskaya Series overlies the Verkhnebalakhonskaya Suite conformably, and is taken to represent a second major cycle within the coal-bearing succession. It is sub-divided in to three suites, the oldest of which, the Kuznetskaya Suite, contains fewer coals and more coarse siliciclastics than the overlying Il'inskaya and Yerunakovskaya suites.

Triassic strata are conventionally defined as the Lower–Middle Triassic Abinskaya Series (sub-divided in to the Mal'tsevskaya, Sosnovskaya and Yaminskaya suites), with the Permo-Triassic boundary located at the transition from coal-bearing to coal-barren strata (Mogutcheva and Krugovykh, 2009). As noted above, a basalt flow within the lower part of these rocks is most likely to be end-Permian (Reichow et al., 2009), such that the Permian–Triassic boundary must lie at an unknown point higher within the coal-barren succession (Fig. 4). These end-Permian/Triassic strata are also non-marine, making correlation difficult. The upper unit (Yaminskaya Suite) is placed in the Middle Triassic.

Jurassic strata are grouped as the Tarbaganskaya Series, sub-divided into the Raspadskaya, Abashevskaya and Osinovskaya suites (Lower Jurassic) and the Tersyukskaya Suite (Middle Jurassic, possibly Toarcian and Aalenian; Mogutcheva, 2009). Although dominated by sandstones and conglomerates, the Jurassic succession also includes coals in all four suites. Age determinations and regional correlations are done largely on the basis of palynology (Mogutcheva, 2009). A thin (>50 m) Cretaceous succession is present in the southwest of the Kuznetsk Basin (Fig. 2), where it directly overlies the Carboniferous and Devonian rocks. The age range is uncertain; it is mapped as Lower and mid Cretaceous, and supposed to be marine. As only one, poor-quality, outcrop was observed during fieldwork the depositional environment is not analysed in any detail in this paper.

3. Sedimentology of Permian and Mesozoic strata

3.1. Facies associations

Fourteen lithofacies have been identified within the Permian–Mesozoic succession of the Kuznetsk Basin and are summarised in Table 1 (with the majority illustrated in Fig. 5). Localities are shown on Fig. 2, and latitudes and longitudes for each locality are given in Table 2. Representative logs are shown in Fig. 6A–F (arranged in ascending stratigraphic order). The lithofacies form three recurring facies associations, which are interpreted as representing different fluvial environments. A summary of the three facies associations is given below.

3.1.1. Fluvial channel belt facies association

This facies association includes facies with the following lithologies: parallel laminated sandstone, trough cross-bedded sandstone, planar cross-stratified sandstone, ripple cross-stratified sandstone, massive sandstone, massive conglomerate and planar cross-stratified conglomerate (respectively Sl, St, Sp, Sr, Sm, Gm and Gp in Table 1). It comprises planar and trough cross-stratified, very fine to coarse grained sandstones, and clast and matrix supported conglomerates (Fig. 5F–I). The sandstones generally occur in sets of 0.5–1 m scale with either a flat base where they overlie coal (due to the resistant nature of peat to erosion (McCabe, 1984; Collinson, 1996)) or a scoured base and pebble lags where the underlying unit is siliciclastic in origin (Fig. 6A and F). The fluvial systems were channelised. Individual fluvial sand bodies are commonly stacked and amalgamated, forming laterally extensive, uniformally thick (up to 20 m) sandstone units. The conglomerates, commonly clast supported, contain rounded to subrounded clasts of 0.5–10 cm, maximum 60 cm in diameter. Conglomerate beds can be single or amalgamated events from 1 to 10 m thick (maximum 20 m thick) and internally contain foresets (Fig. 5I).

Permian sandstones commonly contain preserved foresets (0.5–1 m) whose scale suggests initial large dune bedforms in the order of 3–5 m in height (Leclair et al., 1996; Ashley, 1990). This indicates channels in the order of 18–50 m deep (Bridge, 2003). Stacked, laterally extensive uniformally thick sandstones are interbedded with the coal seams in the coal-bearing Permian succession (Figs. 5G, H and 6B). The presence of several examples of large scale, 6–10 m high, sandstone sets indicates lateral bar migration of large in-channel barforms, either bank attached or mid channel bars.

End-Permian/Triassic cross-stratified, fine-grained sandstones were deposited in 50–80 cm high foresets (locality S-14; Fig. 6C). These can be estimated to have formed as medium–large scale dune bedforms, 1.5–3 m in height (Leclair et al., 1996; Ashley, 1990) infilling channels 9–30 m in depth (Bridge, 2003).

Jurassic sandstones were deposited in 15–20 cm high foresets estimated to have formed small–medium dune barforms 60–80 cm in height (Leclair et al., 1996; Ashley, 1990) infilling channels in the order of 3.5–8 m deep (Bridge, 2003) to form massive to cross-stratified and parallel laminated sandstone bodies (Fig. 6D).

Evidence for high energy sediment transport and high sediment supply comes from the large scale dune bedforms, coupled with the substantial clast sizes within this facies association. These features suggest a mixed and bedload transported material in high energy braided fluvial (to possible meandering) system across an extensive floodplain.

3.1.2. Overbank facies association

This facies association is composed of massive or parallel laminated to ripple cross laminated siltstone to fine-grained parallel laminated or cross-stratified sandstone (Fig. 6A, D and G). Facies Fm, Fl, Fr, Sl and Sp (Table 1) are represented (Fig. 5A–E). Bed sets commonly show an erosive base with an overall fining upward trend

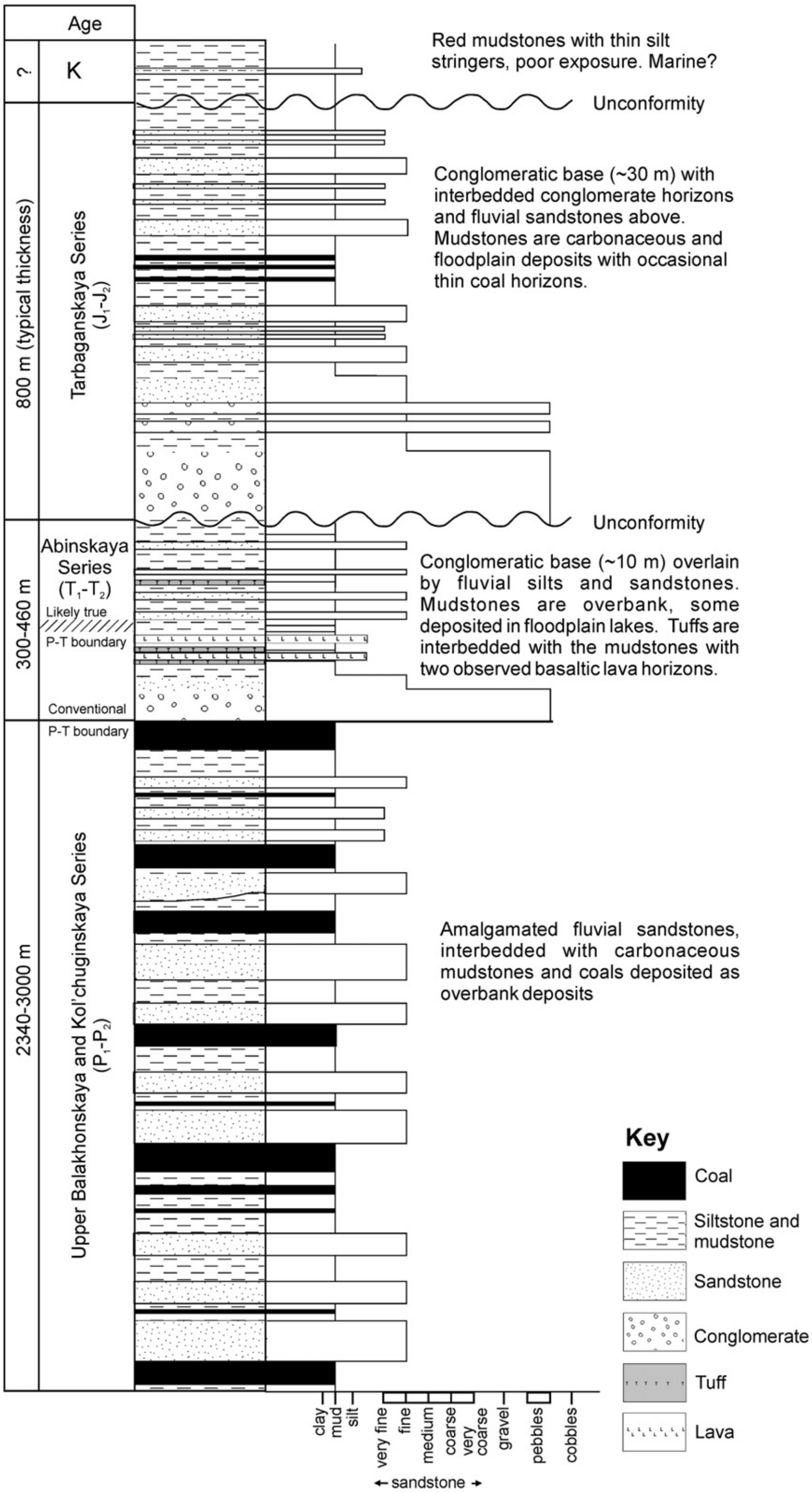

Fig. 4. Summary log for the Kuznetsk Basin. From Buslov et al. (2007) and our field observations.

and also record bedform evolution from massive through parallel laminated to ripple laminated facies. These siltstones and fine-grained sandstones are interpreted to record deposition within crevasse splays and crevasse channels, with parallel lamination to ripple lamination within a bed indicating flow deceleration resulting from flow expansion. Sandstone deposition also occurs in 30 m wide crevasse splay channels. Carbonaceous material and wood fragments are found draping ripples and along laminations. These fine-grained overbank deposits, which are interbedded with the mudstone, carbonaceous mudstone and thin coal layers, indicate distal floodplain environments (Collinson, 1996).

3.1.3. Floodplain/floodplain pond facies association

This facies association is composed of massive and laminated mudstones (facies C and Cl), coal (facies D), massive, laminated and ripple cross-stratified siltstones (facies Fm, Fl and Fr) and tuff (facies

Table 1
Facies divisions for the Kuznetsk Basin.

Lithology	Code	Sedimentary structures	Bioturbation/palaeoflow	Occurrence	Interpretation
Massive mudstone	C	Structureless. Colouration varies from red-brown, grey, black.		1–2 cm thick mudstone beds occur between coal seams, both laterally continuous for ~100 m. Grey msts grade upwards over 5 cm to become black and carbonaceous with coal layers above.	Suspension fallout from standing bodies of water following overbank flows or from channel abandonment.
Laminated mudstone	Cl	Mudstone with cm-scale parallel laminations, well-cemented to friable. Friable mudstone contains carbonaceous material on laminations. Can consist of paper laminations. Colouration varies from red-brown, grey, black, green.	Green paper laminated mudstones occur with monospecific bivalve casts and mm thick tuffaceous layers.		Suspension fallout from standing bodies of water following overbank flows or from channel abandonment. Carbonaceous material within the mudstone is preferentially aligned along surfaces during deposition, making it laminated. The well-laminated green mudstones with monospecific bivalves suggest deposition within sediment starved, environmentally stressed lacustrine environment.
Coal	D	Structureless and blocky, range in thickness from 1–2 cm up to a max thickness of 20 m. Large seams are laterally continuous for 100 m.	No evidence of rootlets or soil formation, therefore coal may have formed from transported organic material.	1–2 cm thick coal layers occur within mudstones. Thicker coal seams (>2 m) contain ~40 cm thick, laterally continuous, mudstones.	Vegetated floodplain areas, some of which were waterlogged (high water table), reducing conditions in floating, low-lying or raised mires. Mires are periodically inundated with mudladen floodwater (part of a distal crevasse splay).
Massive siltstone	Fm	Structureless siltstone. Beds laterally continuous up to 50 m, commonly erosive at base.		Interbedded with mudstone, carbonaceous mudstone and thin coal layers. Often fines upwards into mud-prone intervals.	Deposition by crevasse splay sheetfloods and minor crevasse channel environment in a distal floodplain environment.
Laminated siltstone	Fl	Parallel laminated siltstone. Carbonaceous material and wood fragments drape laminations.		Interbedded with mudstone, carbonaceous mudstone and thin coal layers. Grades from bed parallel lamination to ripple lamination upwards in a bed.	Deposition by crevasse splay sheetfloods and minor crevasse channels in a distal floodplain environment. Parallel lamination indicates decreasing flow velocities due to flow expansion and deceleration away from the main fluvial system.
Ripple cross-stratified siltstone	Fr	Uni-directional ripple cross laminated siltstone with rare climbing ripples. Carbonaceous material and wood fragments drape ripple foresets.	Ripples NW–SE, NE–SW, dominated to the NE and NW.	Interbedded with mudstone, carbonaceous mudstone and thin coal layers. Occur at the top of parallel bedded siltstone intervals.	Deposition by crevasse splay sheetfloods and minor crevasse channels in a distal floodplain environment. Ripple lamination also indicate decreasing flow velocities due to flow expansion and deceleration away from the main fluvial system.

Parallel laminated sandstone	Sl	Uni-directional low angle planar cross-stratified sandstone. Carbonaceous material and wood fragments drape foresets.	Uni-directional flow to east.	Interbedded with mudstone, carbonaceous mudstone and thin coal layers.	Deposition by crevasse splay sheetfloods and minor crevasse channel environment in a distal floodplain environment. Low angle cross-stratification indicates decreasing flow velocities due to flow expansion and deceleration away from the main fluvial system.
Planar cross-stratified sandstone	Sp	Uni-directional, planar cross-stratified, v. fine to coarse grained sandstone with normal grading. Cross-set preservation thickness of varies from 0.15–1 m up to 6–10 m. Cm-scale coal clasts occur along forests.	0.5–1 m high foresets (Permian? — Loc. S-21) and indicate palaeoflow to North. Similar scale foresets at Loc. S-18 show palaeoflow to the East. Larger 6–10 m foresets show palaeoflow to the NW (Permian? — Loc. S-21 and S-22).15–20 cm high sets at S-14 show palaeoflow to N–NE.	Mudstone intervals, cm in thickness, are interbedded with this facies.	Intra channel setting of mixed and bedload transported material, possibly within a meandering system. Large in-channel bar forms are preserved.
Trough cross-bedded sandstone	St	Uni-directional, trough cross-stratified fine to medium? Grained sandstone with common rounded to well rounded pebble grade material (0.2–6 cm in length) forming lags. Silicified and carbonised wood up to 1 m in length and 20 cm in diameter occur at the base of channels and flakes of carbonised material occur along laminations. Cm-scale angular coal clasts at base of beds.	Palaeoflow measurements from wood aligned in channels indicate a flow northwest–southeast and northeast–southwest (S-6).	Pebbles are composed of Quartz, granite, black chert, limestone and sandstone, pink rhyolite, green tuff.	Intra channel setting of mixed and bedload transported material, possibly within a meandering system.
Ripple cross-stratified sandstone	Sr	Uni-directional, ripple cross-stratified, fine to medium grained sandstone.	Jurassic–Palaeocurrent indicators to the northeast or northwest. Cm-scale ripples (Loc. S-11 and S-13) show palaeoflow to the NE and NW respectively.	.	Intra channel to overbank setting of mixed and bedload transported material, possibly within a meandering system.
Massive sandstones	Sm	Structureless fine–coarse grained sandstone, forming beds up to 5 m in thickness.			Intra channel setting of mixed and bedload transported material, possibly within a meandering system.
Massive conglomerate	Gm	Massive, matrix to clast supported conglomerate with clasts from gravel to cobble in size.		Up to 10 m thick intervals from multiple events.	Fluvial intra channels setting with bedload transported material in a high energy system.
Planar cross-stratified conglomerate	Gp	Uni-directional, planar cross-stratified coarse, matrix to clast supported conglomerate composed of well rounded–sub rounded, poor to well sorted gravel to cobble clasts. Rare angular clasts occur. Sets are up to 20 m high (Loc. S-16) and clasts range in size from 0.5 to 10 cm, max 60 cm in length.	Palaeoflow to SE, E at Loc. S-16. foresets are seen to abruptly down lap onto coal seams below (Loc. S-16).	Clasts are grey sandstone, red and black chert, siltstone, mudstone, rhyolite and possibly Basite. Some indication of clast imbrication. Within the conglomerates, decimetre to metre scale channels are infilled with fine to coarse grained sandstone and are often incised by later events filled with conglomerate deposits.	Fluvial intra channel setting with bedload transported material in a high energy system.
Tuff	T	White, very fine-grained sediment, occurs as mm to cm thick laterally continuous horizons.		Tuff layers are interbedded with well-laminated green mudstones. Tuff horizons increase in thickness up-section (Loc. S-4) until a basaltic lava occurs.	Formed by fallout from volcanic eruptions. Likely to be deposited and preserved in a lacustrine environment where reworking did not occur.

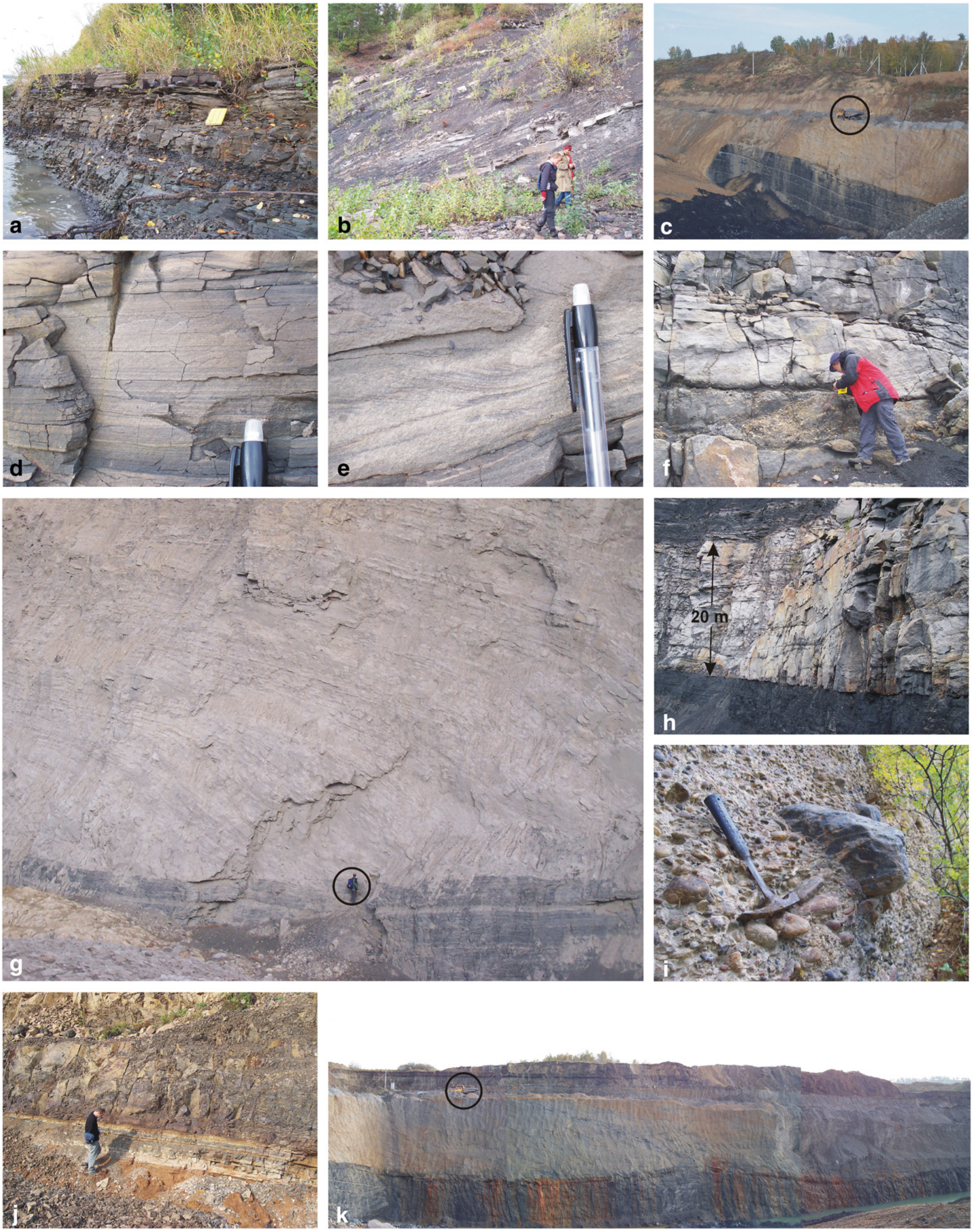
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Table 2
Locality information for this study. Some of these localities are in active open-cast coal mines, such that the outcrop appearance may have changed since this study was carried out.

Locality	Latitude (decimal degrees north)	Longitude (decimal degrees east)	Stratigraphy
S-1	53.79	83.54	Modern river
S-2	54.35	86.10	Carboniferous/Permian
S-3	54.42	86.83	Modern river
S-4	54.41	86.86	Triassic
S-5	53.79	87.58	Permian/Jurassic
S-6	53.80	87.62	Jurassic
S-7	53.80	87.58	Permian/Jurassic
S-8	53.76	87.78	Jurassic
S-9	54.39	87.54	Triassic
S-10	54.39	87.53	Permian/Triassic basalt
S-11	53.70	87.00	Permian
S-12	53.71	86.97	Permian
S-13	53.71	86.96	Permian
S-14	54.42	86.81	Permian/Triassic
S-15	54.26	87.09	Triassic
S-16	54.45	86.78	Permian/Triassic
S-17	54.46	86.77	Permian/Triassic
S-18	54.34	86.08	Permian
S-19	54.43	87.55	Jurassic
S-20	54.46	87.52	Jurassic
S-21	53.64	87.88	Permian
S-22	53.62	87.81	Permian
S-23	53.61	87.73	Permian
S-24	53.83	88.18	Permian/Jurassic
S-25	53.71	88.12	Permian
S-26	53.64	88.24	Modern river
S-27	53.28	86.97	Cretaceous
S-28	52.42	85.10	Modern river
S-29	52.53	85.23	Modern river

T; Table 1). They occur generally as laterally continuous sheets formed following the decrease in bedform size from ripple scale cross-lamination to the floodplain mudstone and/or coal facies (Fig. 6B, E and G). These deposits occur in low energy settings on the floodplain.

3.2. Depositional environments

3.2.1. Coal-bearing Permian strata

All three identified facies associations are present within the coal-bearing Permian succession. We did not identify any significant differences between outcrops from the five Permian and Upper Carboniferous suites, although the latter was only studied at one outcrop. The sedimentology of the coal-bearing Permian sections suggests environments of fluvial channels, with extensive overbank areas. Mires within these overbank areas allowed peat deposition. Fining upward packages (localities S-21 (Fig. 6B) and S-22), are interpreted to represent channel avulsion, although they could also result from lateral channel migration. The occurrence of coal facies directly overlain by fluvial sandstones is considered unusual by McCabe (1984) and suggests extreme, far reaching avulsion. Such large scale avulsion may be a characteristic of anastomosing systems (Makaske, 2001). Fielding (1984) noted that compaction of peat deposits in the Carboniferous Northumberland Basin could produce "basins" tens of kilometres wide, with sharp contacts with overlying sandstones. The association of overbank environments and coal deposition indicates stagnant, long-lived, low relief flood plains. These suggest that the overall system had a meandering planform.

3.2.2. End-Permian/Triassic strata

All three facies associations are also present within the end-Permian/Triassic succession, but significant coal seams are not present; coal is reduced to discontinuous millimetre-scale laminae. The abrupt sedimentary contact between the Permian coal measures and overlying sandstones and conglomerates is interpreted to represent the rapid change from peat formation in a floodplain swamp to deposition from large in-channel barforms following avulsion with an increase to a high energy bedload, fluvial system (Fig. 7b). The initial sand grade deposition occurs in foresets with a preserved set thickness of at least 20 m indicating lateral barform migration. The current geometry of the beds, which appear over steepened (Fig. 5G), and 'doming' above the underlying coal, are due to compaction effects (Fielding, 1984). There appears to be no change in foreset steepness upwards, indicating no preservation of topsets, therefore suggesting that bedforms were at least 20 m in height, with an even deeper channel. A cross section through a similar sized bar form, composed of sand grade material at locality S-14 (Fig. 6C), indicates that the main fluvial flow direction was to the northeast. The width of the channels forming these bars is harder to quantify. The lateral extent of the sand grade barform is at least 150 m and so the channel width may have been in the order of several kilometres wide. The enormous lateral scale of the barforms and the fluvial systems in which they formed suggests a major increase in the rivers' capacity at this time, despite a possible decrease in-channel depth in comparison to the underlying coal-bearing Permian sediments. The dominant coarse grain size of these systems indicates deposition from high velocity flows over the floodplain and a likely braided planform. The depositional setting for the finer sandstones and gravel sediments is within a mixed load system, and within an overbank setting derived from crevasse splays, crevasse channels and long-lived floodplain lake environments in the fluvial floodplain (Fig. 7c), and indicates that these systems were meandering.

3.2.3. Jurassic and Cretaceous strata

All three facies associations are also present within the Jurassic succession. The observed sedimentology in the exposed Jurassic sections in the Kuznetsk Basin indicate deposition from a mainly mixed to bedload dominated fluvial system. This system resulted in the deposition of laterally extensive sheets of conglomerates with channels containing sands, indicating periods of lower flow velocities,

Fig. 5. Examples of sedimentary facies from the Permian, end-Permian/Triassic and Jurassic of the Kuznetsk Basin. (a) The base of the outcrop is dominated by dark grey massive (*C*) to laminated mudstones (*Cl*) grading to carbonaceous rich laminated mudstones (*Cl*) with millimetre thick coal beds above (*D*), before further grey mudstones are deposited on top. Notebook for scale. Locality S-7; Jurassic. (b) Interbedded mudstone and carbonaceous mudstone (*Cl*), siltstone (*F*, *Fl*) and very fine-grained massive and parallel laminated sandstones (*Sm*, *Sl*) are interpreted as alluvial overbank deposits. The bedding dip is structural in origin. Locality S-7; Jurassic. (c) Laterally continuous massive mudstone (*C*) layers commonly occur within the thick coal (*D*) units. The truck (circled) is ~4 m high. Locality S-16; Permian. (d) Parallel laminated siltstone (*Fl*) and very fine-grained sandstones (*Sl*) occur with black organic fragments highlighting the lamination surfaces. Pencil top is ~2.5 cm. Locality S-7; Permian. (e) Ripple foresets within the siltstones (*Fr*) and very fine-grained sandstones (*Sr*), with foresets highlighted by organic fragments, some ripples are possibly climbing. Pencil is ~9 cm. Locality S-7; Permian. (f) Planar and trough cross-stratified sandstones (*Sp*, *St*) contain varying amounts of rounded to well rounded pebbles, 0.2–6 cm in length, aligned along foresets and along scoured channel bases. Set thickness is 0.5–1 m. Locality S-21; Permian. (g) Apparent downlap of a 30 m thick section of interbedded sandstones (*Sl*, *Sr*) and mudstones (*C*, *Cl*) onto the underlying coal unit (*D*). Person (circled) for scale. This apparent geometry is likely to be due to over-steepening of the overlying beds during compaction of peat into coal. Locality S-14; Permian. (h) Abrupt basal contact of a 20 m thick amalgamated fluvial sand body (*Sm*, *Sp*, *St*) overlying a thick, uniform coal deposit (*D*). Locality S-21; Permian. (i) Clast supported conglomerate (*Gm*), with rounded to subrounded clasts usually 0.5–10 cm in length, maximum clast size is 30 cm. Hammer is 30 cm. Locality S-6; Jurassic. (j) Green coloured laminated mudstone (*Cl*) containing white layers of tuff (*T*) overlain by a 2 m thick brown weathered basalt layer. Locality S-4; end-Permian/Triassic. (k) 20 m high large scale foresets composed of well rounded clast conglomerate (*Gp*) deposited with a sharp, non-erosive loaded contact onto the underlying coal horizon (*D*). The truck (circled) is ~4 m high. Locality S-16; Permian and end-Permian/Triassic.

deposited in shallow water depths of several metres. Channel abandonment is recorded by the overall fining up of sediment from conglomerates, through sandstone and siltstones to mudstone and eventually the accumulation of organic matter now preserved as minor coal (Fig. 6F). Overbank environments can also be seen within the Jurassic section with crevasse splay deposited sands interbedded with mudstones and coals (Fig. 6G). The Jurassic section contains the largest clasts (60 cm) and also the thickest conglomeratic succession (several 10s of metres) of the entire basin stratigraphy. This implies that during deposition of the Jurassic strata, river gradients and stream power were greater than during earlier deposition, in turn implying closer and/or greater source area relief. These coarse clastic, higher energy systems are likely to have had a braided planform (Fig. 7d). The localised finer-grained parts of the stratigraphic interval indicate a reduction in fluvial energy, either lateral to the main trunk system or by channel abandonment.

It is not possible to be certain of the relevant facies association(s) for the Cretaceous strata because of the limited nature of the outcrop in the southwest corner of the basin (Fig. 2). Mudstones are laminated, brick red in colour and have occasional silty laminations and are

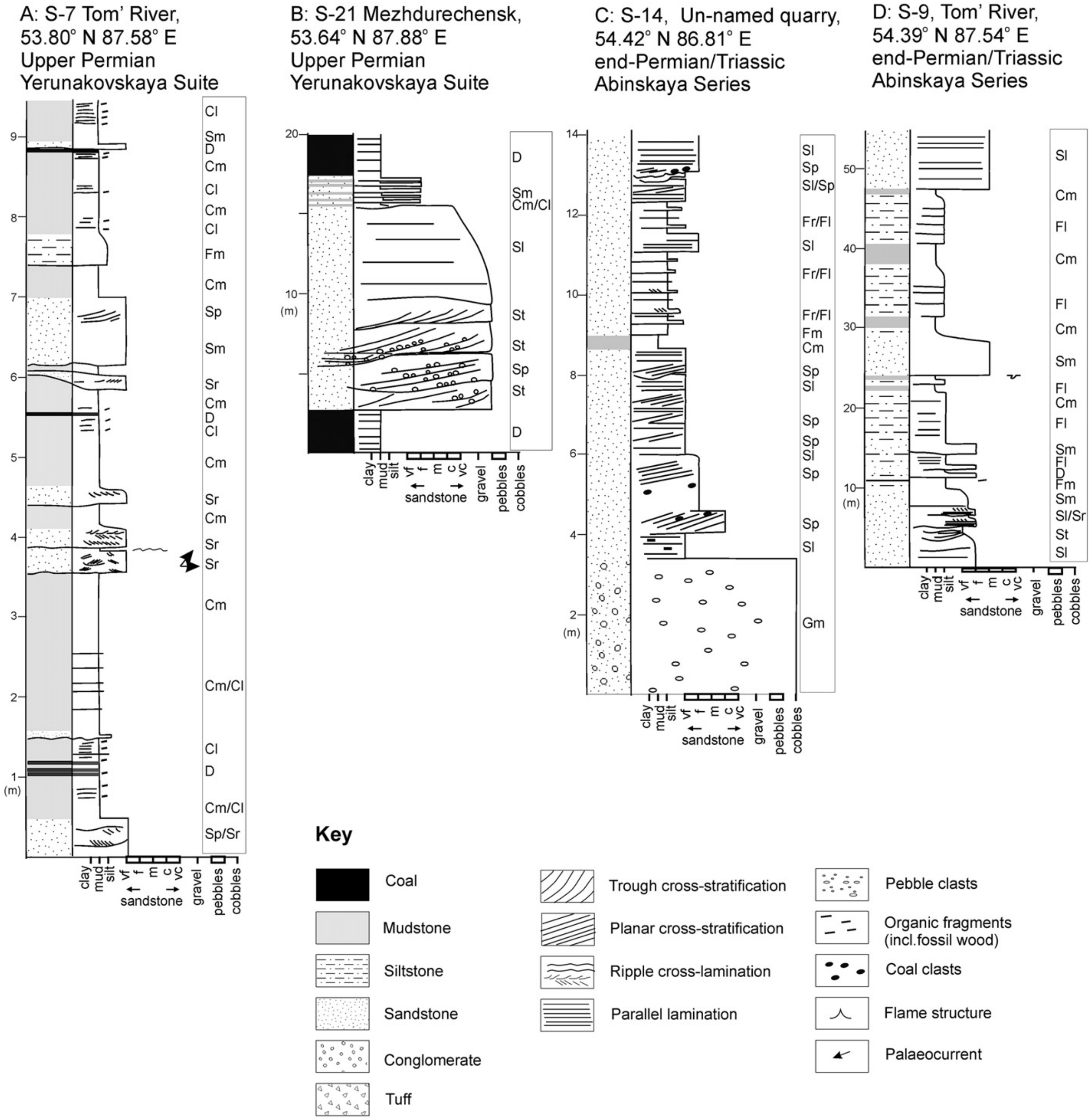

Fig. 6. Measured sedimentary logs constructed from seven separate localities where the facies were identified for the Permian, Triassic and Jurassic in the Kuznetsk region. The logs consist of a lithological column, a grainsize/sedimentary structure column, arrows which indicate any measured palaeocurrents and the identified facies for each section. Detailed facies descriptions are in Table 1. Note that the vertical scale varies significantly from log to log. Localities are shown on Fig. 2.

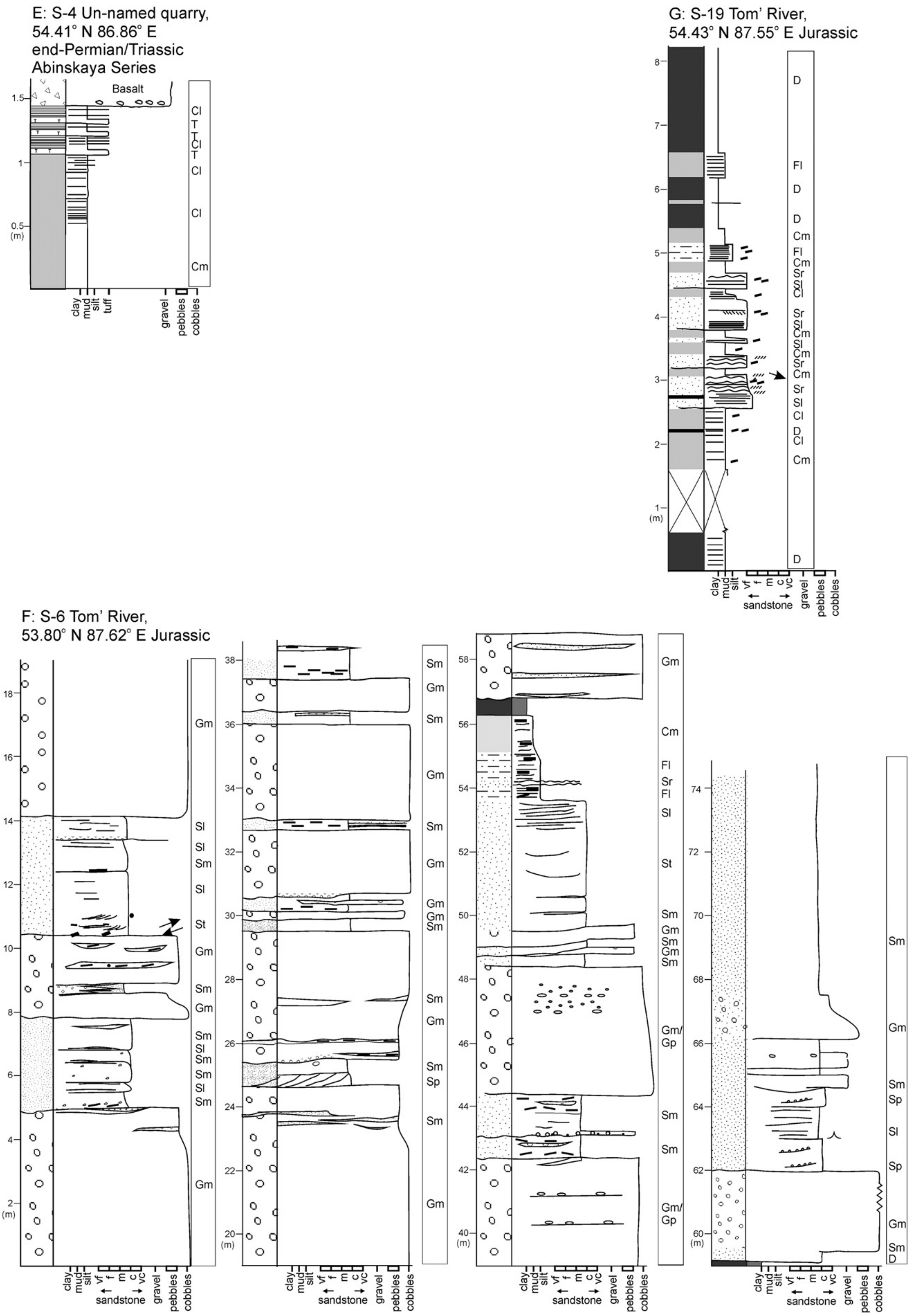

Fig. 6 (*continued*).

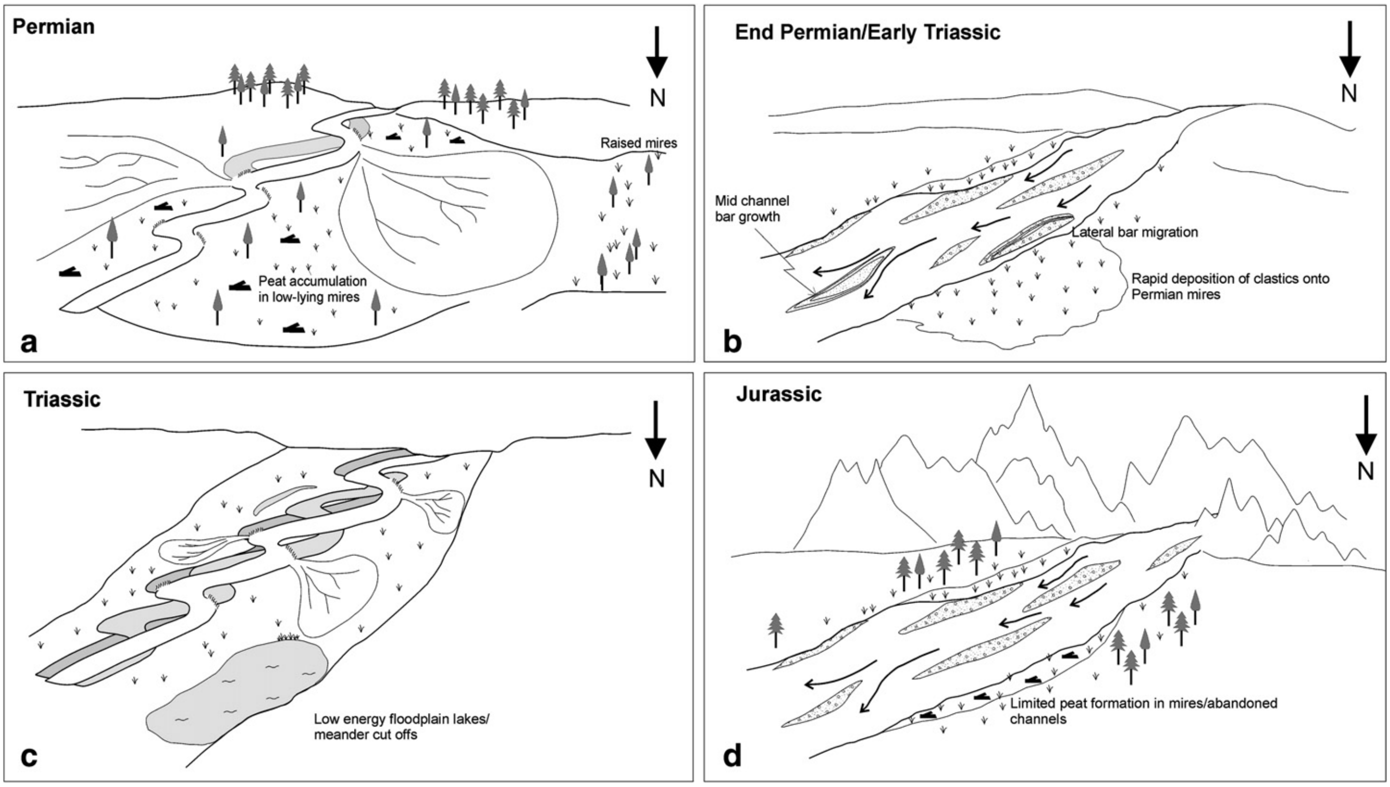

Fig. 7. Palaeogeographic illustrations for the interpreted depositional systems of the Kuznetsk Basin during the Permian to Jurassic. The Permian contained mixed to bedload dominated fluvial systems, possibly meandering with extensive overbank environments where peat accumulation occurred in low-lying and/or raised mires. The end-Permian/Early Triassic environments underwent a rapid change to bedload dominated, probably braided systems following the climatic crisis resulting in increased runoff due to lack of vegetation. The later end-Permian/Triassic environment indicates a wide fluvial plain containing mixed load fluvial systems, probably meandering, with overbank deposits and lakes. The Jurassic environment contained bedload dominated, possibly braided fluvial systems. The thick conglomeratic succession suggests greater uplift of the Altai/more proximal position of the encroaching thrust sheets than at any other time in the Mesozoic. Coals show the re-colonisation of the floodplain and surrounding areas following the climatic crisis.

occasionally interbedded with parallel to ripple cross laminated very fine-grained sandstone. Vertical burrows, 0.5–1 cm in diameter, are formed in the sandstone and infilled with mudstone.

3.3. Palaeocurrent analysis

3.3.1. Coal-bearing Permian

Palaeoflow directions derived from the Permian fluvial channel belt deposits show that the dominant sediment transport direction was to the northwest, northeast and east, depending on the position within the Kuznetsk Basin (Fig. 8). Rivers flowed towards the interior of the West Siberian Basin. This implies a possible source area from the terranes of the Gorny Altai to the south and maybe some sediment derived from the Salair Range to the west. Within the overbank facies of Permian age, ripples indicate dominant flow directions to the northeast and northwest (Fig. 8). Uni-directional ripples also clearly show palaeoflow to the east (locality S-7).

3.3.2. End-Permian/Triassic

The end-Permian/Triassic rocks show a palaeoflow to the north and northeast, with a likely sediment source area in the Gorny Altai, as seen for the coal-bearing Permian (Fig. 8). Clast compositions of tuff, basalt, chert and limestone are also consistent with derivation from the Gorny Altai to the south. Palaeoflow directions from the large scale foresets in the conglomerates at locality S-16 and the sand grade material at locality S-17 record cross channel migration of bar margin slipfaces (Best et al., 2003), resulting in the lateral migration of these large bar forms, to the southeast or east, allowing an assumption that the main fluvial system trended roughly NE–SW. The end-Permian/Triassic strata contain ripples with a probable dominant flow to the southwest.

3.3.3. Jurassic

Jurassic palaeocurrent indicators in fluvial channel belt deposits record flow dominantly towards the northeast or northwest, again indicating a source area to the south of this region (Fig. 8). This is confirmed by the clast lithologies, which appear to be derived from the Gorny Altai, to the south of the Kuznetsk Basin. Within the finer-grained Jurassic strata, a ripple crest orientation of northwest–southeast and a slight asymmetry, indicates a dominant flow direction of these low energy currents to the northeast (Fig. 8). We have no robust dataset for the Cretaceous rocks.

Overall, there are no significant compositional changes in clast-type found in the Permian, Triassic or Jurassic strata. The clast compositions suggest that the volcanics, low grade metasediments and melanges of the Gorny Altai sourced the observed sediments. This is in contrast with the modern Tom' River through the Kuznetsk Basin, where many granitic clasts occur, derived from the basement of the Kuznetsk Alatau to the east of the basin.

4. Deformation

This section considers the structures, boundaries and sedimentology of the Kuznetsk Basin strata in terms of what they reveal about the timing and nature of regional deformation. The >5 km thick Upper Carboniferous–Permian succession of the basin interior appears to have been deposited without major internal unconformities or syn-sedimentary faulting. The deposits lie between the fold and thrust belts at the basin margins (Fig. 2). Permian strata at the western basin margin are folded in to a sub-vertical orientation. Although the movement history on the marginal thrusts is not well-constrained, it is feasible that they operated during the Late Carboniferous and Permian to create accommodation space in their forelands — i.e. the

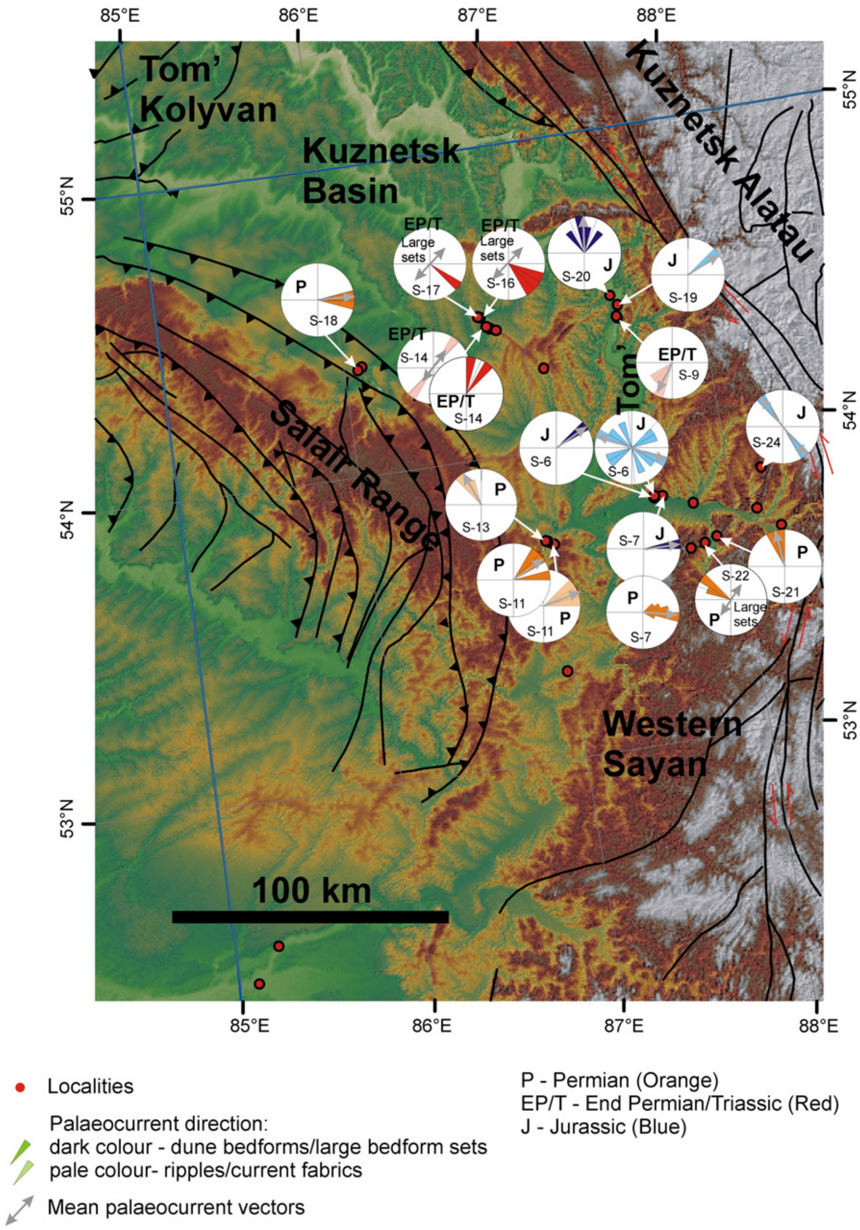

Fig. 8. Palaeocurrent measurements from the Kuznetsk Basin. There is no correction for any later tectonic tilt.

Kuznetsk Basin. This timing is the late stage of assembly of the Altaid orogenic collage, including the collision of the Tarim Block along its southern margin. There is no evidence of Early Permian rifting, reported for parts of northwest China (Wartes et al., 2002).

There is no indication of any local tectonism associated with the end-Permian basalts, such as regional uplift or rifting. As they are only a few metres thick, it is likely that they represent the extreme edge of the Siberian flood basalt magmatism, which reaches a thickness of ~3 km in the northwest of the Siberian Craton near Noril'sk (~1700 km north of the Kuznetsk Basin), but only ~50 m at the southeast of the outcrop limit on the craton (~700 km from the Kuznetsk Basin basalts; Lightfoot et al., 1993; Reichow et al., 2009). Therefore there is no local evidence for a tectonic event (tilting, faulting and abrupt provenance shifts) at the Permian–Triassic boundary changing the depositional regime in the Kuznetsk Basin, but an environmental crisis caused by the Siberian flood basalts is plausible.

The Jurassic succession lies unconformably over the end-Permian and Triassic(?) rocks. This implies folding and erosion of the basin interior before the deposition of the Jurassic strata. The amount of erosion was in places enough to remove most of the Permian succession, implying several kilometres of erosion (Fig. 2). Nowhere is any Late Triassic mapped, but it is not clear if this reflects later erosion, original non-deposition, or the difficulties in dating a non-marine clastic succession. The base of the Jurassic may be either a disconformity, without a discordance in bedding or an angular unconformity with a discordance of a few degrees (Fig. 9). The earliest Jurassic strata are conglomeratic in the localities studied, indicating that there was considerable relief in the sediment source areas and high stream power at this time. Jurassic strata are themselves folded (Fig. 2), so that there is clearly also deformation that postdates this period.

The timing of the deformation recorded below the base of the Jurassic is constrained to post-date at least part of the Middle Triassic, which is the age assigned to the youngest Triassic preserved, and to pre-date at least part of the Early Jurassic, which is the age of the oldest Jurassic strata. More precise constraints are not available from the field relations or the current knowledge of the age of the affected

Fig. 9. Field evidence for deformation within the Kuznetsk Basin from locality S-24: angular unconformity at the base of the Jurassic succession. Arrows highlight a fracture set within the Permian strata that predates the unconformity.

stratigraphy. The age of the deformation that post-dated the Jurassic strata is less well-constrained. It is plausibly around the Jurassic–Cretaceous boundary, for two reasons. First, the sparse Cretaceous outcrops are in a completely different part of the Kuznetsk Basin to the Jurassic, in the southwest (Fig. 2). This may imply a reconfiguration of the basin at or before this time. Second, to the northeast of the Kuznetsk Basin, on the southern side of the West Siberian Basin, there is a minor angular unconformity mapped between Jurassic and Early Cretaceous strata. As Cretaceous strata are themselves tilted at up to 50° in the southwest of the Kuznetsk Basin, there has clearly been deformation after this time too, although this is not discernible as a discrete phase in the structure of the Triassic and Jurassic outliers. This later deformation event may have taken place in the Late Cretaceous, as much of Central Asia was reduced to a peneplain at the end of this period (Allen et al., 2001). It could be Cenozoic, although the Kuznetsk Basin is not seismically active. There is geomorphologic evidence for subtle young or active deformation, in the form of systematic lateral shifts of drainage (Allen and Davies, 2007).

End-Permian and Triassic(?) and Jurassic strata within the basin interior are preserved in three major outliers and a small number of adjacent outliers. The central and southern outliers are very open synclines, with half wavelengths in the order of 10s of kilometres (Fig. 2). They are associated with smaller, parasitic, folds on wavelengths of the order of kilometres to hundreds of metres. Dips associated with Jurassic strata on these local structures reach ~40°.

The largest Mesozoic outlier lies in the centre of the Kuznetsk Basin and is aligned roughly northwest–southeast, i.e. roughly parallel to the main axis of the basin, and to the thrusts of the Salair Range. The second largest outlier is in the south, and is aligned roughly northeast–southwest, sub-parallel to the structural trends in the Permian and older rocks to its south, at the basin margin. The third outlier was not studied during our fieldwork, and lies at the intersection of the Salair and Tom' Kolyvan ranges to the north of the study area, trending roughly east–west. Unlike the other two, it is not synformal, but all strata appear to be tilted to the north, beginning with strata mapped as Upper Triassic (an age not found further south), which lie unconformably over folded older rocks.

The "bullseye" appearance of the Mesozoic synclines in map view resembles folds produced by Type 1–2 refolding, i.e. the basins of dome-and-basin refolds (Ramsay and Huber, 1987), but there is no positive evidence that this has taken place, in the form of overprinting of structures. It is also plausible that the present structural patterns result from synchronous or near-synchronous compression from more than one basin margin, in the manner of the active tectonics of the South Caspian Basin (Jackson et al., 2002).

5. Discussion

5.1. End-Permian environments

Deposition in the Kuznetsk Basin spanned the Permian–Triassic transition and included basalts of the Siberian Traps large igneous province. Therefore the basin fill provides a record of terrestrial environmental changes during the greatest global mass extinction event, in a region affected by the magmatism commonly interpreted as the cause of the environmental and biotic crisis (Wignall, 2001). The top of the Permian coal measures is marked by an abrupt transition to coal-barren, sand dominated large scale foresets of a laterally accreting barform, before being overlain by conglomeratic beds interpreted as the deposits of a high energy bedload fluvial system. Features include downlap geometries on to the underlying coals, but are likely sedimentary/compaction in origin, and not an angular unconformity or other indication of tectonic activity.

The disappearance of coals some 50 m below the lowest basalt (dated at 250.3 ± 0.7 Ma by Reichow et al., 2009) indicates that the environmental crisis in the Kuznetsk Basin occurred slightly before the first flood basalt magmatism affected this area. Given that many precise age determinations for the Siberian Traps are slightly older than the Kuznetsk basalts (Reichow et al., 2009) it is still feasible that the Siberian Trap magmatism caused the global environmental crisis and mass extinction. This is in keeping with the type Permo-Triassic boundary section at Meishan, China, where the extinction peaked at the top of Bed 24 (Jin et al., 2000), below the bio-stratigraphical Permo-Triassic boundary at the base of Bed 27c (defined by the first appearance of the conodont *Hindeodus parvus*; Nicoll et al., 2002).

The nature of the crisis is similar to other terrestrial regions at the time, including the Urals foreland (Newell et al., 1999; Benton, 2008) and the Bowen Basin, Australia (Michaelsen, 2002): catastrophic loss of vegetation and a presumed increase in aridity (reflected in the disappearance of coal measures), followed by an increase in sediment grade (presumably erosion was enhanced by the widespread loss of vegetation). The energy of the depositional systems fluctuated above this environmental crisis, but the extensive vegetation cover did not return until the Jurassic, based on the record of coal seams. The Kuznetsk Basin succession is therefore consistent with the global Early–Middle Triassic coal gap (Retallack et al., 1996), given that there are no coal seams in the end-Permian–Triassic strata, which are supposed to extend up to the Middle Triassic (Mogutcheva and Krugovykh, 2009). It is more extreme than other areas where Middle Triassic coal is recorded. As no Upper Triassic strata are reported from the Kuznetsk Basin it is not known whether coal-forming conditions recovered in the Late Triassic.

5.2. Implications for Central Asian tectonics

The Permian–Triassic succession in the Kuznetsk Basin shows no evidence for the extensional faulting that created the West Siberian Basin. It may be that the southern margin of the Kuznetsk Basin was beyond the rifting limit. The Triassic is relatively thin (300–460 m) in the Kuznetsk Basin, and suggests lower subsidence rates than during the Permian. This is consistent with a regional switch-off of compressional tectonics during the end-Permian rifting of the West Siberian Basin and the eruption of the Siberian Traps (Allen et al., 2006).

Compressional deformation affected all of the Permian–Triassic sediments within the Kuznetsk Basin, indicated by folding of the end-Permian/Triassic deposits and the angular unconformity at the base of the Jurassic succession. The Late Triassic–Early Jurassic was a time of regional deformation across much of Central Asia, associated with the Palaeo-Tethyan collision of Gondwana-derived microcontinents with the southern margin of Asia. This has left a widespread record of angular unconformities, fold and thrust belts and exhumation (Hendrix et al., 1992; Allen and Vincent, 1997; Vincent and Allen, 2001; De Grave et al., 2007). An unconformity is also present at the base of the Jurassic section in the Mariinsk–Krasnoyarsk region to the east of the Kuznetsk Basin (Le Heron et al., 2008).

It is likely that the deformation below the basal Jurassic unconformity in the Kuznetsk Basin represents part of this regional tectonics, and the overlying Jurassic strata relate to rejuvenation of marginal thrust belts, and a resultant flexural loading. The Jurassic strata initially dominantly contain conglomeratic beds, but no further unconformities or laterally extensive sedimentary pulses. The succession generally fines upwards, with the reappearance of coal measures, possibly at the end of the Early Jurassic or in the Middle Jurassic. This pattern differs from other Central Asian basins such as Junggar, where there are several unconformities and sedimentary pulses within the Jurassic (Hendrix et al., 1992; Vincent and Allen, 2001; Greene et al., 2005), related to the further Tethyan orogenies at the evolving Eurasian continental margin.

Folding of the Jurassic strata (Fig. 2) has taken place in the Late Jurassic or Early Cretaceous, because Upper Jurassic strata are not known from the basin. De Grave et al. (2007) produced fission track data for extensive uplift in Central Asia in the time range 140–100 Ma, i.e. Late Jurassic to mid Cretaceous.

Thin Cretaceous deposits may represent a short-lived record of transgression during some part of this period. The 50° bedding dip in one outcrop in the study area indicates tectonism post-dating deposition, but there are no good time constraints.

5.3. Implications for the West Siberian Basin

The Kuznetsk Basin is ~300 km from the southern edge of the West Siberian Basin, so that its evolution can shed light on this major hydrocarbon province, in particular in the identification of sediment transport pathways. The sediments during and immediately after the end-Permian environmental crisis are composed of coarse clastic conglomerates deposited from high stream power bedload systems. These systems had higher stream power when compared to the rest of the Permian, and sediment is likely to have been bypassed into the West Siberian Basin interior, at the very time rifting was underway. The rest of the end-Permian and Triassic(?) is finer-grained fluvial and overbank deposits from lower energy systems, with less chance of these later sediments being exported to the West Siberian Basin interior.

The basal Jurassic unconformity represents sediment erosion (of the Triassic and Permian strata) and its possible transfer into the West Siberian Basin. The deformation associated with this feature presumably led to the uplift of the hinterland (Gorny Altai) and a renewed pulse of coarse clastic sediment input into the Kuznetsk Basin by shallow, high stream power, fluvial systems. This implies a likely pulse of Early Jurassic siliciclastics into the West Siberian Basin from the south. These sediments are unlikely to make good hydrocarbon reservoir sandstones: Altaid lithologies are commonly slates, other low grade metamorphics and basic volcanics.

The fining-up nature of the Jurassic succession implies that it would have been a decreasing source of sediment for the West Siberian Basin over time. The thin, fine-grained Cretaceous succession in the Kuznetsk Basin suggests no uplift in the surrounding hinterland, in contrast to the southeast flank of the West Siberian Basin (Le Heron et al., 2008). This tallies with the ~800–1000 m thick main Neocomian reservoir unit of the West Siberian Basin prograding in to the basin interior from the east and west, with little sediment input from the south (Peterson and Clarke, 1991).

6. Conclusions

Permian and Mesozoic sediments within the Kuznetsk Basin are non-marine siliciclastics deposited in fluvial environments. They are grouped in three facies associations: i) fluvial channel belt, ii) overbank and iii) floodplain/floodplain pond. The latter association includes extensive coal deposits, particularly in the 5 km thick Permian succession. Permian sedimentation is interpreted as a response to thrust-sheet loading from the basin margins. An environmental crisis at the end of the Permian led to the loss of the vegetation that produced the coal seams, and is interpreted as part of the global biotic catastrophe near the Permian–Triassic boundary. Sediments immediately above the coals are thicker and coarser siliciclastics, probably produced when source areas were rapidly eroded once they had lost their vegetation cover. Basalt flows within the basin are part of the Siberian Traps, and occur just above the environmental change. A precise Ar-Ar age from the lower flow of 250.3 ± 0.7 Ma (Reichow et al., 2009) indicates that the adjacent sediments are Late Permian, and that the Permian–Triassic boundary lies some way above this flow, and therefore slightly later than the environmental change.

A gentle angular unconformity at the base of the Jurassic succession plausibly correlates with Late Triassic–Early Jurassic deformation recorded from elsewhere in Central Asia, related to Palaeo-Tethyan closure and continental collision at the southern Eurasian margin. Overlying Jurassic strata are themselves folded, but the timing and nature of this event is more obscure. The Cretaceous is represented by thin, poorly exposed strata, that are difficult to place in a regional context. There is a marked contrast between the Cretaceous evolution of the Kuznetsk Basin and the Mariinsk–Krasnoyarsk region to the east and the West Siberian Basin to the north (Le Heron et al., 2008). Both of the latter areas are marked by a resurgence of sedimentation in the Early Cretaceous. Some deformation postdates the Cretaceous deposits in the Kuznetsk Basin: they are at least locally tilted at 50°, while the modern basin has lateral drainage shifts indicative of subtle, long wavelength deformation at the edge of the India–Asia collision (Allen and Davies, 2007).

Acknowledgements

This study was carried out when two of the authors (CD and MA) were at CASP, Department of Earth Sciences, University of Cambridge, and CASP are thanked for permission to publish. We also thank the industrial sponsors of the West Siberian Basin Project. The Institute of Geology and Mineralogy, Russian Academy of Sciences, Novosibirsk, provided support. We also thank Nikolai Semakov and Lena Soloboeva for their assistance during the field campaign. Two anonymous referees provided helpful reviews.

References

Allen, M.B., Alsop, G.I., Zhemchuzhnikov, V.G., 2001. Dome and basin refolding and transpressive inversion along the Karatau Fault System, southern Kazakstan. Journal of the Geological Society, London 158, 83–95.

Allen, M.B., Anderson, L., Searle, R.C., Buslov, M.M., 2006. Oblique rift geometry of the West Siberian Basin: tectonic setting for the Siberian flood basalts. Journal of the Geological Society, London 163, 901–904.

Allen, M.B., Davies, C.E., 2007. Unstable Asia: active deformation of Siberia revealed by drainage shifts. Basin Research 19, 379–392.

Allen, M.B., Vincent, S.J., 1997. Fault reactivation in the Junggar region, northwest China: the role of basement structures during Mesozoic–Cenozoic compression. Journal of the Geological Society, London 154, 151–155.

Ashley, G.M., 1990. Classification of large-scale subaqueous bedforms: a new look at an old problem. Journal of Sedimentary Petrology 60, 160–172.

Benton, M.J., 2008. The end-Permian mass extinction events on land in Russia. Proceedings of the Geologists Association 119, 119–136.

Best, J.L., Ashworth, P.J., Bristow, C.S., Roden, J., 2003. Three-dimensional sedimentary architecture of a large, mid-channel sand braid bar, Jamuna River, Bangladesh. Journal of Sedimentary Research 73, 516–530.

Bridge, J., 2003. Rivers and Floodplains, Processes and Sedimentary Record. Blackwell Science Ltd. Oxford, UK, 504pp.

Buslov, M.M., Safonova, I.Yu., Fedoseev, G.S., Reichow, M., Travin, A.V., Babin, G.A., 2007. Plume-related basalts of the Kuznetsk Basin. In: Seltmann, R., Borisenko, A., Fedoseev, G. (Eds.), Magmatism and Metallogeny of the Altai and Adjacent Large Igneous Provinces with an Introductory Essay on the Altaids, IAGOD Guidebook Series 16. CERCAMS/NHM, London, pp. 121–135.

Buslov, M.M., Watanabe, T., Fujiwara, Y., Iwata, K., Smirnova, L.V., Safonova, I.Yu., Semakov, N.N., Kiryanova, A.P., 2004. Late Paleozoic faults of the Altai region, Central Asia: tectonic pattern and model of formation. Journal of Asian Earth Sciences 23, 655–671.

Collinson, J.D., 1996. Alluvial sediments. In: Reading, H.G. (Ed.), Sedimentary Environments: Processes, Facies and Stratigraphy. Blackwell Science, Oxford, pp. 37–82.

Cook, H.E., Zhemchuzhnikov, V.G., Buvtyshkin, V.M., Golub, L.Y., Gatovsky, Y.A., Zorin, A.Y., 1995. Devonian and Carboniferous passive-margin carbonate platform of southern Kazakhstan: summary of depositional and stratigraphic models to assist in the exploration and production of coeval giant carbonate platform oil and gas fields in the north Caspian Basin, western Kazakhstan. Pangea: Global Environments and Resources: Canadian Society of Petroleum Geologists Memoir, pp. 363–381.

De Grave, J., Buslov, M.M., Van den Haute, P., 2007. Distant effects of India–Asia convergence and Mesozoic intracontinental deformation in Central Asia: constraints from apatite fission-track thermochronology. Journal of Asian Earth Sciences 29, 188–204.

Esaulova, N.K., 1997. Correlation of Upper Permian deposits in the Volga-Urals region and Kuznetsk basin. Stratigraphy and Geological Correlation 5, 468–477.

Fielding, C.R., 1984. A coal depositional model for the Durham Coal Measures of NE England. Journal of the Geological Society, London 141, 919–939.

Greene, T.J., Carroll, A.R., Wartes, M., Graham, S.A., Wooden, J.L., 2005. Integrated provenance analysis of a complex orogenic terrane: Mesozoic uplift of the Bogda Shan and inception of the Turpan-Hami Basin, NW China. Journal of Sedimentary Research 75, 251–267.

Gutak, J.M., Tolokonnikova, Z.A., Ruban, D.A., 2008. Bryozoan diversity in Southern Siberia at the Devonian–Carboniferous transition: new data confirm a resistivity to two mass extinctions. Palaeogeography, Palaeoclimatology, Palaeoecology 264, 93–99.

Hendrix, M.S., Graham, S.A., Carroll, A.R., Sobel, A.R., McKnight, C.L.S., B.S., Wang, Z., 1992. Sedimentary record and climatic implications of recurrent deformation in the Tian Shan: evidence from Mesozoic strata of the North Tarim, South Junggar, and Turpan basins, northwest China. Bulletin of the Geological Society of America 104, 53–79.

Jackson, J., Priestley, K., Allen, M., Berberian, M., 2002. Active tectonics of the South Caspian Basin. Geophysical Journal International 148, 214–245.

Jin, Y.G., Wang, Y., Wang, W., Shang, Q.H., Cao, C.Q., Erwin, D.H., 2000. Pattern of marine mass extinction near the Permian–Triassic boundary in South China. Science 289, 432–436.

Kurtigeshev, V.S., Rodchenko, S.A., Mitrokhin, D.V., Tumanova, L.N., Tokarev, V.N., Babin, G.A., 2008. 1:200,000 State Geological Map of the Russian Federation Sheet N-45-X (Central Kuzbass). Kartfabrika VSEGEI, Saint Petersburg.

Lavrenov, P.F., Snezhko, B.A., Schigrev, A.F., Shelemeteva, N.V., Filippova, N.E., 2008. 1:200,000 State Geological Map of the Russian Federation Sheet N-45-XV (Leninsk–Kuznetsky). Kartfabrika VSEGEI, Saint Petersburg.

Le Heron, D.P., Buslov, M.M., Davies, C., Richards, K., Safonova, I., 2008. Evolution of Mesozoic fluvial systems along the SE flank of the West Siberian Basin, Russia. Sedimentary Geology 208, 45–60.

Leclair, S.F., Bridge, J.S., Wang, F.Q., 1996. Preservation of cross-strata due to migration of subaqueous dunes over aggrading and non-aggrading beds: comparison of experimental data with theory. Symposium on From Sandstone to Chaos at the Annual Meeting of the Geological Society of America, Northeastern Section. Geological Assoc Canada, Buffalo, New York, pp. 55–66.

Lightfoot, P.C., Hawkesworth, C.J., Hergt, J., Naldrett, A.J., Gorbachov, N.S., Fedorenko, V.A., Doherty, W., 1993. Remobilization of the continental lithosphere by a mantle plume — major element, trace element and Sr-isotope, Nd-isotope and Pb-isotpoe evidence from picritic and tholeiitic lavas of the Norilsk district, Siberian Trap, Russia. Contributions to Mineralogy and Petrology 114, 171–188.

Makaske, B., 2001. Anastomosing rivers: a review of their classification, origin and sedimentary products. Earth Science Reviews 53, 149–196.

McCabe, P.J., 1984. Depositional environments of coal and coal-bearing strata. In: Rahmani, R.A., Flores, R.M. (Eds.), Sedimentology of Coal and Coal-bearing Sequences: Special Publication of the International Association of Sedimentologists, pp. 13–42.

Michaelsen, P., 2002. Mass extinction of peat-forming plants and the effect on fluvial styles across the Permian–Triassic boundary, northern Bowen Basin, Australia. Palaeogeography, Palaeoclimatology, Palaeoecology 179, 173–188.

Mogutcheva, N.K., 2009. Problems of phytostratigraphy and the correlation of the Lower Jurassic continental sediments in West Siberia and Kuznetsk and Kansk–Achinsk basins. Stratigraphy and Geological Correlation 17, 283–290.

Mogutcheva, N.K., Krugovykh, V.V., 2009. New data on the stratigraphic chart for Triassic deposits in the Tunguska syneclise and Kuznetsk basin. Stratigraphy and Geological Correlation 17, 510–518.

Newell, A.J., Tverdokhlebov, V.P., Benton, M.J., 1999. Interplay of tectonics and climate on a transverse fluvial system, Upper Permian, Southern Uralian Foreland Basin, Russia. Sedimentary Geology 127, 11–29.

Nicoll, R.S., Metcalfe, I., Wang, C.Y., 2002. New species of the conodont Genus Hindeodus and the conodont biostratigraphy of the Permian–Triassic boundary interval. Journal of Asian Earth Sciences 20, 609–631.

Peterson, J.A., Clarke, J.W., 1991. Geology and hydrocarbon habitat of the West Siberian Basin. AAPG Studies in Geology No. 32. AAPG. 96 pp.

Ramsay, J.G., Huber, M.I., 1987. The techniques of modern structural geology. Folds and Fractures, 2. Academic Press, London. 309–700 pp.

Reichow, M.K., Pringle, M.S., Al'Mukhamedov, A.I., Allen, M.B., Andreichev, V.L., Buslov, M.M., Davies, C.E., Fedoseev, G.S., Fitton, J.G., Inger, S., Medvedev, A.Ya., Mitchell, C., Puchkov, V.N., Safonova, I.Yu., Scott, R.A., Saunders, A.D., 2009. The timing and extent of the eruption of the Siberian Traps large igneous province: implications for the end-Permian environmental crisis. Earth and Planetary Science Letters 277, 9–20.

Renne, P.R., Zichao, Z., Richards, M.A., Black, M.T., Basu, A.R., 1995. Synchrony and causal relations between Permian–Triassic boundary crises and Siberian flood volcanism. Science 269, 1413–1416.

Retallack, G.J., Veevers, J.J., Morante, R., 1996. Global coal gap between Permian–Triassic extinction and Middle Triassic recovery of peat-forming plants. Geological Society of America Bulletin 108, 195–207.

Şengör, A.M.C., Natal'in, B.A., 1996. Paleotectonics of Asia: fragments of a synthesis. In: Yin, A., Harrison, M. (Eds.), The Tectonic Evolution of Asia. Cambridge University Press, Cambridge, pp. 486–640.

Usov, M.A., 1937. The trap formation of the Kuznetsk Basin. Izvestia Akademia Nauk SSSR, Geology Series 4, 743–763.

Vincent, S.J., Allen, M.B., 2001. Sedimentary record of Mesozoic intracontinental deformation in the eastern Junggar Basin, northwest China: response to orogeny at the Asian margin. Memoirs of the Geological Society of America 194, 341–360.

Vyssotski, A.V., Vyssotski, V.N., Nezhdanov, A.A., 2006. Evolution of the West Siberian Basin. Marine and Petroleum Geology 23, 93–126.

Wartes, M.A., Carroll, A.R., Greene, T.J., 2002. Permian sedimentary record of the Turpan-Hami Basin and adjacent regions, Northwest China: Constraints on postamalgamation tectonic evolution. Bulletin of the Geological Society of America 114, 131–152.

Wignall, P.B., 2001. Large igneous provinces and mass extinctions. Earth-Science Reviews 53, 1–33.

Yavorskiy, V.I., Butov, P.I., 1927. Kuznetsk Coal-bearing Basin. Geolkom Publications, Leningrad. 244 pp.

Zonenshain, L.P. Mezhelovsky, N.V., Natapov, L.M., 1988. 1:2,000,000 Geodynamic map of the USSR and adjacent seas. Ministry of Geology of the USSR.