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Evolution of Mesozoic fluvial systems along the SE flank of the West Siberian Basin, Russia

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ABSTRACT

The Mesozoic stratigraphy in the subsurface of the West Siberian Basin contains prolific hydrocarbon accumulations, and thus the depositional environments of marine and marginal marine Jurassic and Cretaceous age sediments are well-established. However, no information is currently available on strata of equivalent age that crop out along the SE basin margin in the Mariinsk–Krasnoyarsk region, despite the potential of these exposures to supply important information on the sediment supply routes into the main basin. Detailed sedimentological analysis of Jurassic–Cretaceous clastic sediments, in conjunction with palaeo-botanical data, reveals five facies associations that reflect deposition in a range of continental environments. These include sediments that were deposited in braided river systems, which were best developed in the Early Jurassic. These early river systems infilled the relics of a topography that was possibly inherited from earlier Triassic rifting. More mature fluvial land systems evolved in the Mid to Late Jurassic. By the Mid Jurassic, well-defined overbank areas had become established, channel abandonment was commonplace, and mudrocks were deposited on floodplains. Coal deposition occurred in mires, which were subject to periodic incursions by crevasse splay processes. Cretaceous sedimentation saw a renewed influx of sand-grade sediment into the region. It is proposed that landscape evolution throughout the Jurassic was driven simply by peneplanation rather than tectonic processes. By contrast, the influx of sandstones in the Cretaceous is tentatively linked to hinterland rejuvenation/ tectonic uplift, possibly coeval with the growth of large deltaic clinoform complexes of the Neocomian in the basin subsurface.

1. Introduction

This paper presents new data and interpretations of Jurassic and Cretaceous clastic sedimentary rocks that crop out at the southeastern flank of the West Siberian Basin, Russia (Fig. 1). This basin, which is bounded by the Urals to the west, the Kara Sea to the north, the Siberian Craton to the east and the Altai–Sayan folded area to the south, is Earth's largest continental sedimentary basin (Peterson and Clarke, 1991) and contains ~60% of Russian hydrocarbon reserves (Kontorovich et al., 1997). Because of hydrocarbon exploration, there exists extensive subsurface data north of the outcrops that has helped to reveal aspects of the Mesozoic geology of this basin in some detail. These studies have included seismostratigraphy (Rudkevich et al., 1988), source rock and petroleum system analysis (Kontorovich et al., (1997), and sequence stratigraphic study of specific parts of the Jurassic and Cretaceous systems (Pinous et al., 1999, 2001). These latter authors (2001) focussed on the Upper Jurassic–Lower Cretaceous interval because over much of the West Siberian Basin subsurface, Volgian black shale of the Bazhenov Formation is a prolific hydrocarbon source rock (Kontorovich et al., 1997). This shale forms the bottomsets for Neocomian deltaic clinoforms, which are also the principal hydrocarbon reservoir target in the basin (Rudkevich et al., 1988) (Fig. 2).

In contrast to a tradition of detailed and thorough research in the subsurface of the West Siberian Basin, very little is known about the Mesozoic geology of the basin margins, and their exist no publications on Jurassic and Cretaceous outcrops in the international literature. What is known about them is written in the Russian language, mostly in memoirs and geological maps of research organisations such as the Krasnoyarsk Geological Survey (Berzon and Barsegyan, 2002). One possible explanation for this is that the study of Jurassic and Cretaceous rocks at the basin margins has been neglected deliberately. Unlike their oil-bearing counterparts in the basin subsurface, numerous versions of palaeogeographic maps (Nesterov 1976 and others) suggest that sand-dominated continental sediments with little hydrocarbon potential crop out in the Mariinsk–Krasnoyarsk region.

There are several good reasons why continental deposits should be studied at the margins of the West Siberian Basin. The first is that

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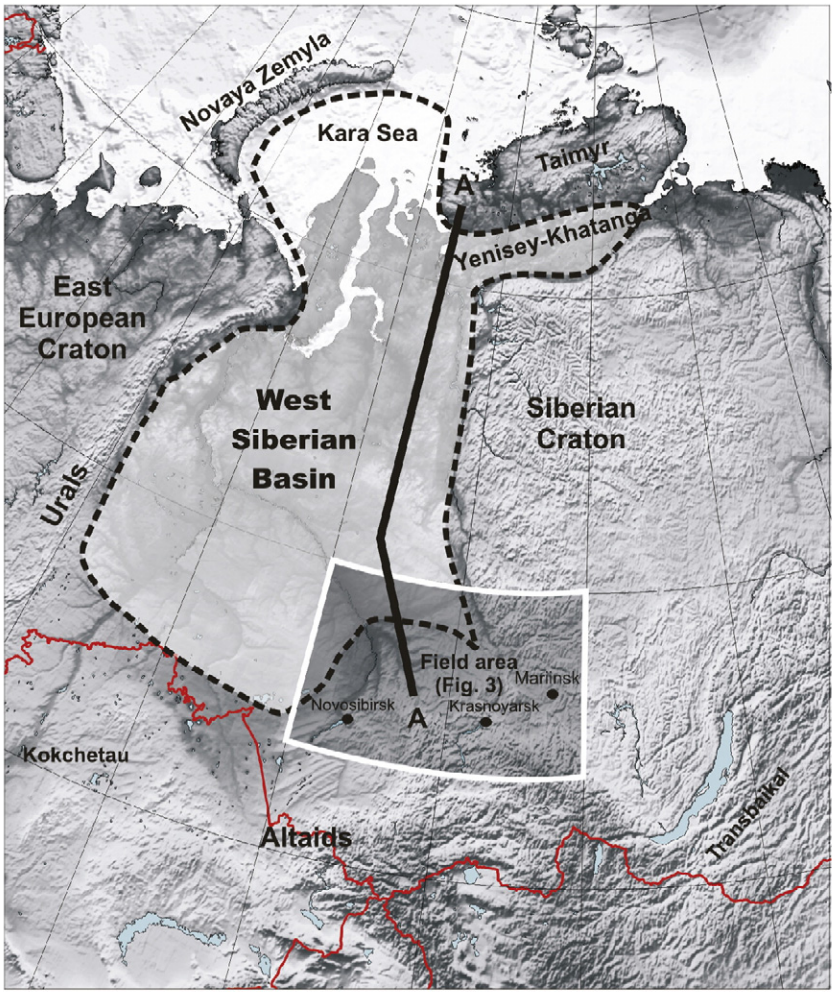


Fig. 1. Location map of the West Siberian Basin (inset) to the west of the Siberian craton, to the east of the Urals, and to the north of the Altaid Mountains. Large map shows location of study sections in the Mariinsk–Krasnoyarsk region at the southern flank of the basin (see Fig. 3).

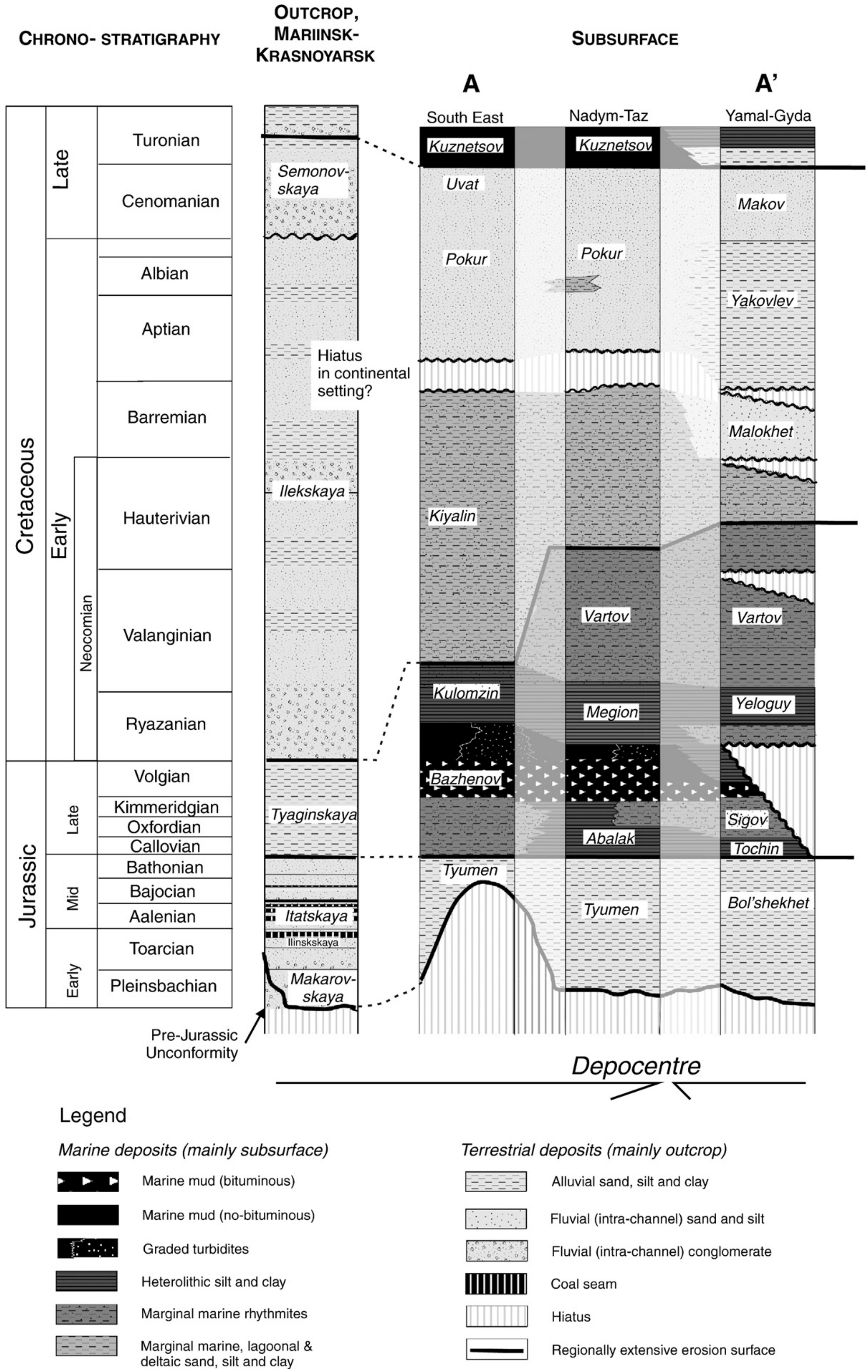
basin-flanking deposits tend to be situated in greater proximity to regional uplifts, and hence might provide the opportunity to better unravel tectonic events that influence stratigraphic architecture in the basin subsurface. The second is that basin-flanking sediments are ultimately a sediment source for strata of equivalent or slightly younger age in the subsurface of sedimentary basins. Lithological description of sediments, and the types of clast in coarser-grained sediments, provides valuable information on the likely quality of potential reservoir facies. Thirdly, the palaeo-drainage network during Jurassic and Cretaceous times should be characterised in order to predict the patterns of sediment distribution in the basin subsurface. Palaeocurrent analysis of outcrops potentially provides clues as to whether the evolution of palaeo-drainage network was moderated by tectonism or passive subsidence. The simple objective of this paper, therefore, is to characterise the sedimentology of Jurassic and Cretaceous sedimentary rocks at the SE basin margin for the first time in the international literature. The results of this paper are thus relevant to the petroleum exploration community, to scholars of Mesozoic palaeogeographic reconstructions of Asia, and to sedimentologists engaged in researching basin-flanking sedimentary architectures.

2. Sedimentology of Jurassic–Cretaceous strata

2.1. Exposure quality and data quality issues

In West Siberia, the outcrop area of the Mesozoic is extensive (Fig. 3). However, it is also densely vegetated, and consequently characterised by low-lying, poorly exposed sections. Regionally, dip angles are low (2° N). Cretaceous strata are conformable to disconformable on Jurassic rocks, overstepping them to the north of the Angara River and to the south of the Bolshoy Kemchuk River (Fig. 3). Good quality exposures occur in three situations. Firstly, large open cast coal mines expose high quality sections of coal and its overburden together with limited stratigraphic sections beneath large coal seams. The thickest coal accumulations occur within the Middle Jurassic (Bajocian–Bathonian), and thus the database in this paper is inevitably skewed towards rocks of this age. Data recovered from Lower and Upper Jurassic intervals, and also Lower Cretaceous strata, are less comprehensive. The second type of exposure occurs on outer meander bends of modern rivers, such as the Bolshoy Kemchuk, Chulym and Yenisey (Fig. 3). In such settings, outcrop quality is good, but the low dip angle and distance between exposures means that constructing accurate vertical profiles is difficult without recourse

Fig. 2. Chronostratigraphic chart for Jurassic–Cretaceous rocks in the West Siberian Basin, Russia. The chart attempts to link the stratigraphy of the outcrop area in this paper (Mariinsk–Krasnoyarsk region) with the subsurface of the basin from the Vasyugan region in the south-east to the Yamal–Gyda peninsula regions in the north. Stratigraphic charts are after Berzon and Barsegyan (2002): outcrop, and Rudkevich et al. (1988): subcrop. Correlation between outcrop and subsurface regions is difficult although four tentative regionally developed erosion surfaces are proposed: for details see the text.


Chrono- stratigraphy
Outcrop, Mariinsk-Krasnoyarsk
Subsurface
A
A'
South East
Nadym-Taz
Yamal-Gyda
Cretaceous
Late
Early
Neocomian
Turonian
Cenomanian
Albian
Aptian
Barremian
Hauterivian
Valanginian
Ryazanian
Jurassic
Late
Mid
Early
Volgian
Kimmeridgian
Oxfordian
Callovian
Bathonian
Bajocian
Aalenian
Toarcian
Pleinsbachian
Semonov-skaya
Hiatus in continental setting?
Ilekskaya
Tyaginskaya
Itatskaya
Ilinskskaya
Makarov-skaya
Pre-Jurassic Unconformity
Kuznetsov
Uvat
Pokur
Kiyalin
Kulomzin
Bazhenov
Tyumen
Kuznetsov
Pokur
Vartov
Megion
Abalak
Tyumen
Makov
Yakovlev
Malokhet
Vartov
Yeloguy
Sigov
Tochin
Bol'shekhet
Depocentre
Legend
Marine deposits (mainly subsurface)
Marine mud (bituminous)
Marine mud (no-bituminous)
Graded turbidites
Heterolithic silt and clay
Marginal marine rhythmites
Marginal marine, lagoonal & deltaic sand, silt and clay
Terrestrial deposits (mainly outcrop)
Alluvial sand, silt and clay
Fluvial (intra-channel) sand and silt
Fluvial (intra-channel) conglomerate
Coal seam
Hiatus
Regionally extensive erosion surface

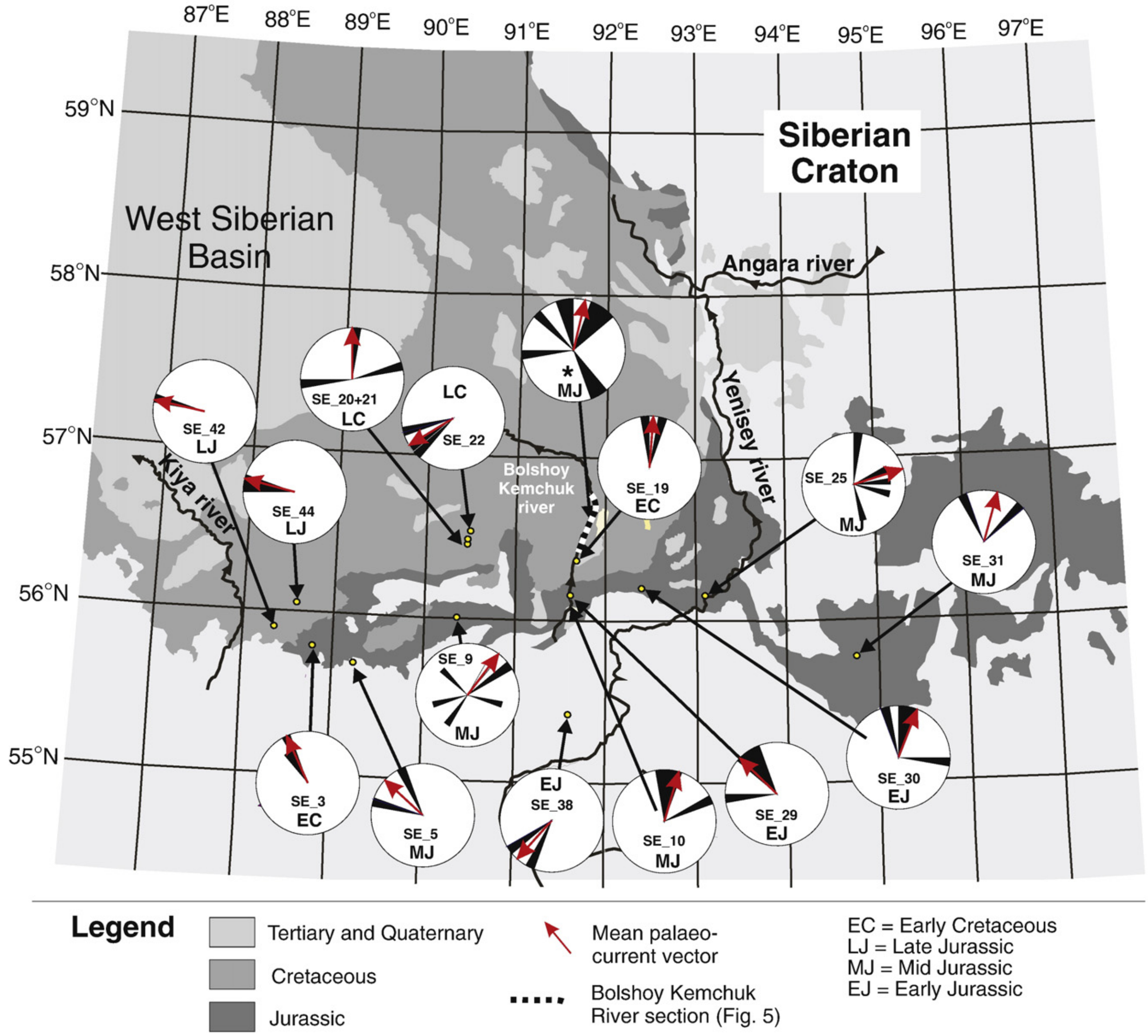


Fig. 3. Palaeocurrent data collected from Mesozoic dune-scale cross-bedded sandstone (Lower Jurassic to Upper Cretaceous). The palaeocurrent data were collected from both the fine- to medium-grained sandstone facies association and the coarse-grained sandstone facies association.

to biostratigraphic data. The third type of high quality exposure occurs in road cuttings.

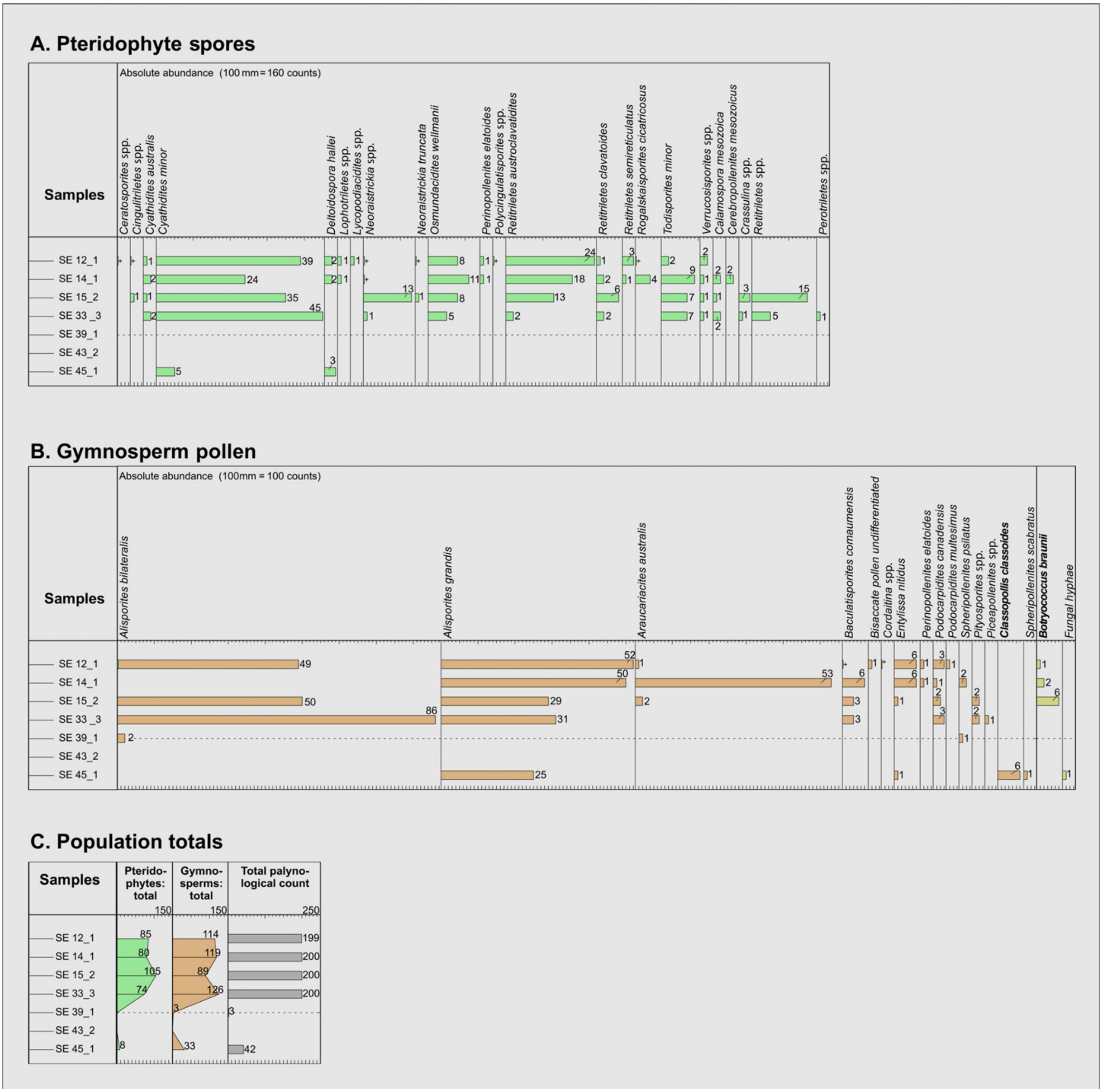
2.2. Age determination and stratigraphy

The study area shown in Fig. 1 comes under the remit of investigation of the Krasnoyarsk Geological Survey. Research published in Russian by this organisation has included the results of outcrop investigations by Berzon and Barsegyan (2002). These workers undertook comprehensive palaeo-botanical analyses of samples from outcrops along the Bolshoy Kemchuk River, and integrated these results with data from shallow boreholes in order to establish a chronostratigraphy for the outcrops that we describe in this paper. Despite obtaining >90 samples, we were not able to establish a detailed biostratigraphic zonation for Jurassic–Cretaceous deposits (Table 1). We attribute this to 1) over-representation of sandstone samples with respect to mudstones (from which recovery of palynological material is much better) and 2) the tendency of organic materials to oxidise in contact with air and water on present day outcrops. Nevertheless, in certain samples palynological recovery is good (Table 1), providing data that are valuable for palaeo-environmental analysis.

In the Mariinsk–Krasnoyarsk region, Mesozoic sedimentary deposits rest unconformably upon variably-aged basement (Fig. 2) which includes Devonian and Carboniferous mixed clastic successions and Devonian granite. According to previous research documented in the Russian literature, Russian workers have constructed a lithostratigraphic framework for the Jurassic and Cretaceous stratigraphy (Berzon and Barsegyan 2002). In Russian terminology, the basic lithostratigraphic unit is the *свита* (*svita* or suite). This is commonly mis-translated as formation, but the concepts are different, since the word "suite" contains an implication that the unit has a particular age range. To emphasise this difference, we have used the word suite throughout when referring to stratigraphic units. For clarity, we have omitted the feminine adjectival ending (*-ская* -skaya), which is a formal part of every suite name.

The Early Jurassic succession comprises coarse-grained sandstones and conglomerates of the Makarov Suite, and is overlain by sandstones of the finer-grained Ilinsk Suite (Fig. 2). The overlying Mid Jurassic Itats Suite is notably coal-bearing (Fig. 2); extraction of coals from this suite

Table 1
Palynological data from the Mesozoic samples of the Mariinsk–Krasnoyarsk region



15 samples were prepared but only 6 contain enough palynomorphs to provide reliable results. Two principal types of palynomorphs can be identified within mudstones of Jurassic and Cretaceous age, namely 1) pteridophyte spores and 2) gymnosperm pollen. Of particular interest are the occurrences of *Classopolis classoides* and *Botryococcus braunii*: see section on the mudrock facies association for details.

includes those of the Borodino Quarry, Asia's largest open cast coal mine. Sediments of the upper Mid Jurassic and the Late Jurassic belong to the Tyagin Suite, a siltstone and mudstone-prone deposit lacking coal. Cretaceous rocks, which disconformably overlie the Jurassic, are locally referred to a three-fold stratigraphic subdivision. These are the Ileks Suite (Early Cretaceous) and the overlying Semonovs and Smes Suites (Fig. 2). For the sake of clarity, the present paper refers to Early, Mid and Late Jurassic rocks, and to Early and Late Cretaceous rocks, rather than referring to individual Suite names.

In this study, nine detailed sedimentary logs were produced, representing various stratigraphic levels ranging from Early Jurassic to Late Cretaceous (Berzon and Barsegyan, 2002). Eight of these belong to relatively narrow stratigraphic intervals (Fig. 4), but the ninth spans a >700 m thick succession from Mid Jurassic (Aalenian) through Early Cretaceous (Neocomian) age (Fig. 5). The latter represents a discontinuous section compiled from river exposures accessible by boat along the Bolshoy Kemchuk River.

2.3. Facies analysis

Facies associations, of which five are recognised, are shown to the right of each log. These include mudrock, coal, silty sandstone, fine to

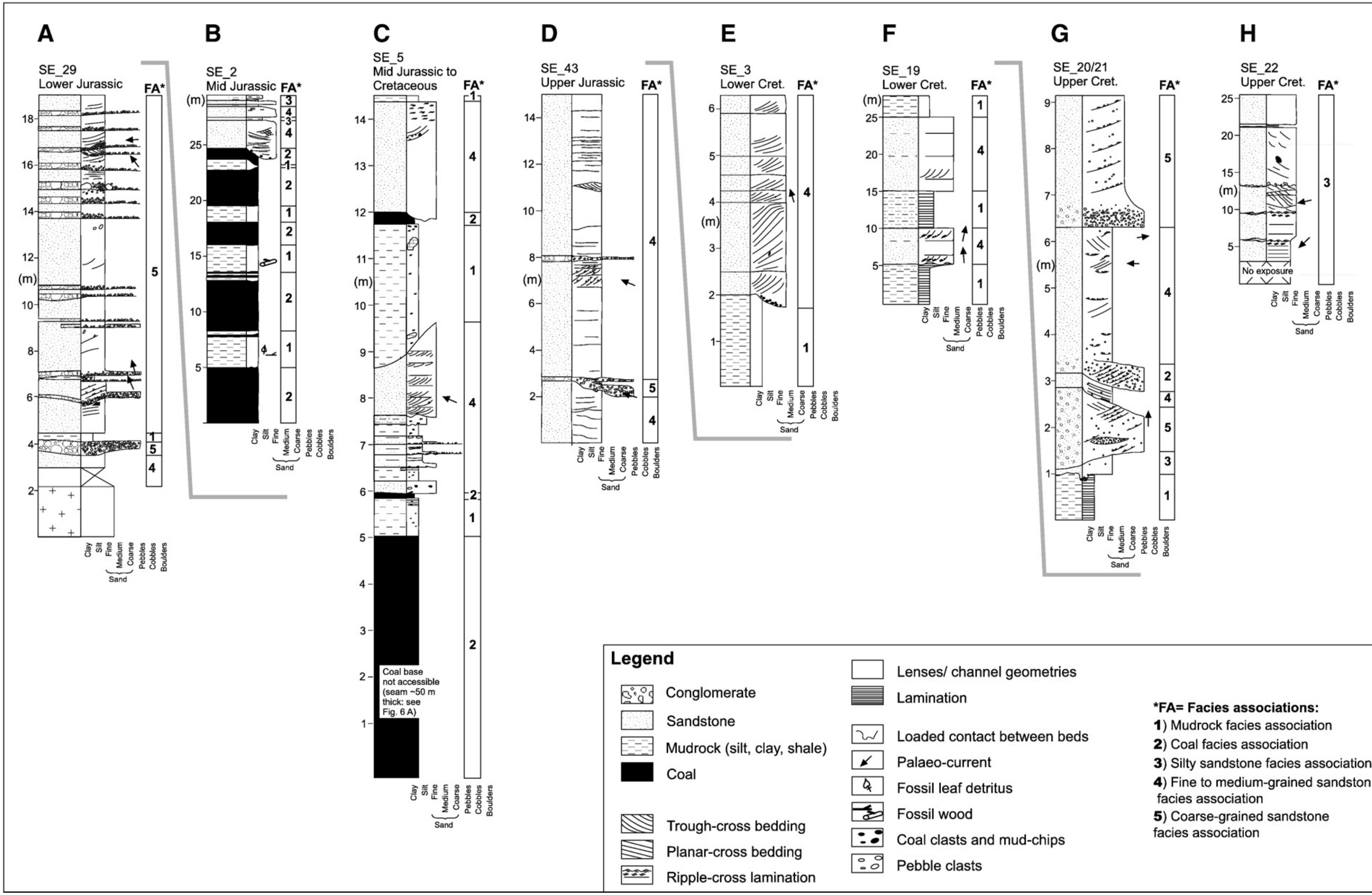


Fig. 4. Sedimentary logs constructed from eight separate localities and used to define the five facies associations that are recognised in Jurassic and Cretaceous rocks across the Mariinsk–Krasnoyarsk region. The logs span Lower Jurassic to Upper Cretaceous intervals. The facies associations identified on each measured section are shown to the right of each log. Palaeocurrent data are indicated by the arrows on the side of each log. Note that the vertical scale varies significantly from log to log. Co-ordinates for each of the localities are as follows. Log A (SE_29), 56° 08.627'N 91° 36.427'E; Log B (SE_2, Kaichak Quarry), 55° 44.707' N 88° 35.479'E; Log C (SE_5), 55° 40.516'N 89° 13.140'E; Log D (SE_43), 55° 52.641'N 88°19.127'E; Log E (SE_3) 55° 46.169'N 88°45.530'E; Log F (SE_19), 56° 21.698'N 91° 40.354'E; Log G (SE_20 & 21) and Log H (SE_22) correspond to detailed sections along the Bolshoy Kemchuk River north and eastwards of 56° 21.698'N 91° 40.354'E.

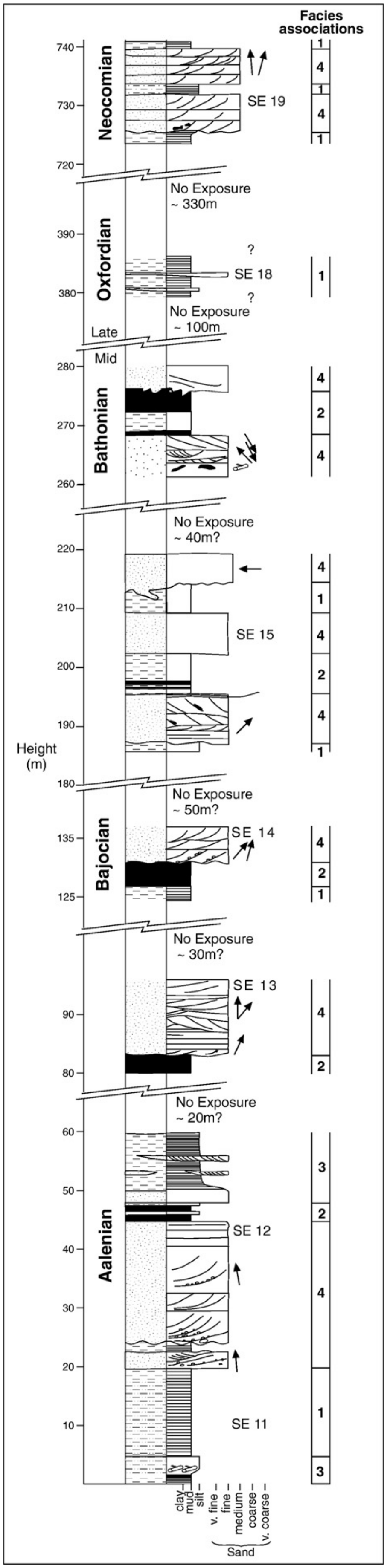


Fig. 5. Discontinuous profile (log) of Middle Jurassic to Cretaceous sedimentary rocks cropping out along the Bolshoy Kemchuk river. The sections were accessed by rubber dinghy. The degree of up-section non-exposure was determined by GPS waypoints combine with regional dip measurements. Large sections are non-exposed, particularly in the Upper Jurassic. Palaeocurrent measurements were restricted to metre-scale trough cross-beds in sandstone and are shown to the right of the log. The vertical arrangement of facies associations is partly cyclic and this is interpreted to record phases of major and far-reaching avulsion of the river system (see text for details). For legend see Fig. 4.

medium-grained sandstone, and coarse-grained sandstone facies associations. Information on the external geometry of facies associations including their lateral extent is provided wherever possible to enhance the interpretations. However, in some cases where this is not possible, e.g. due to isolated exposure, analogues are drawn from the appropriate literature. In the following section, these facies associations are described and interpreted before their stratigraphic and lateral relations are considered.

2.3.1. Mudrock facies association: description

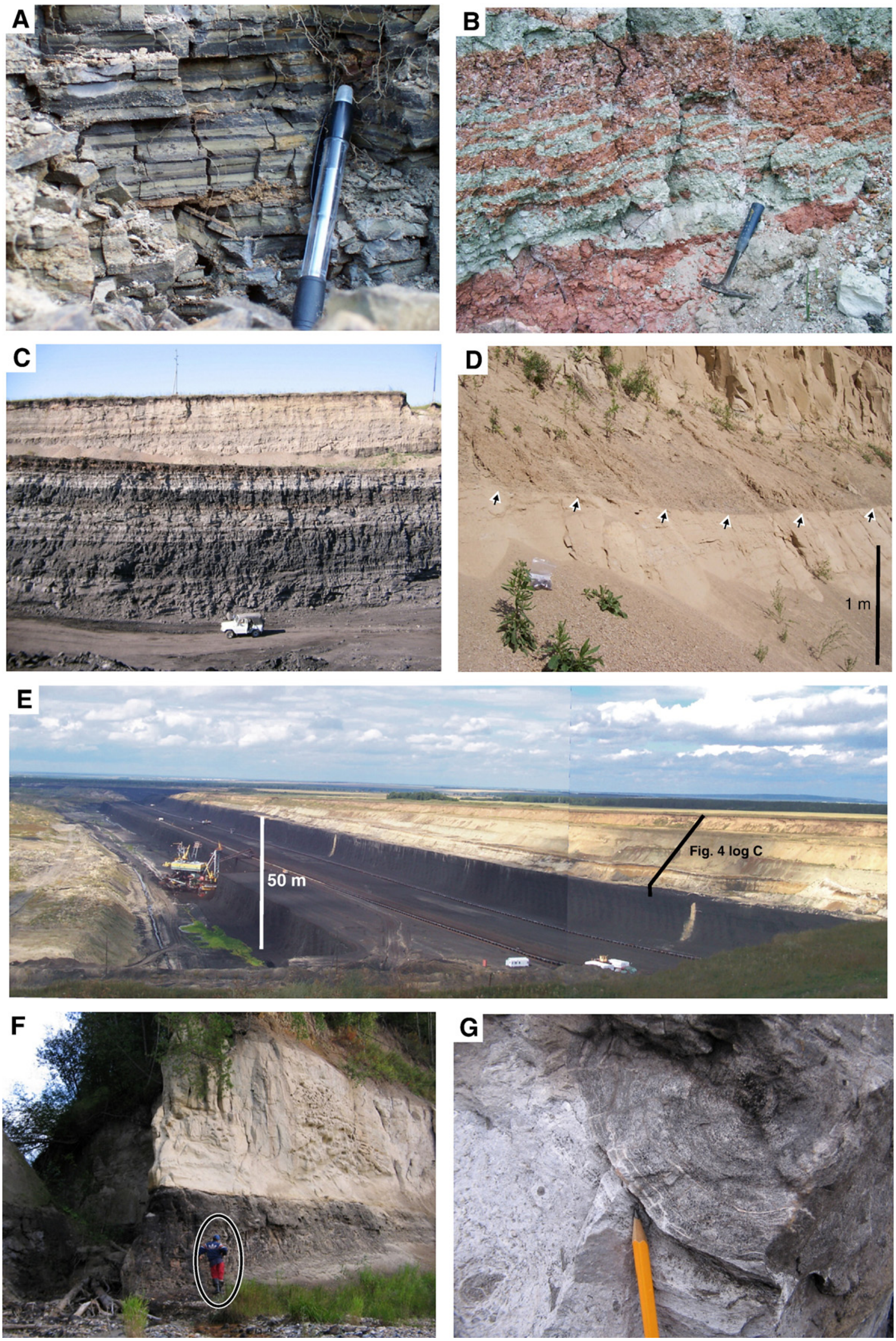
The mudrock facies association encompasses shale (laminated clay-grade sediments: Fig. 6A), mudstone (non-laminated clay-grade sediments: Fig. 6B), minor siltstone and subordinate coal material. Mudstones and shales are grey, dark grey, red or green in colour, and form metre to tens of metre thick units (Fig. 4, log B) that can be traced laterally for >200 m (where they are bounded above and below by coal; Fig. 6C) and >100 m (where they are bounded by sandstone facies). The lateral extent of this facies association is potentially much greater but limited by outcrop continuity. The measured thickness of mudrocks may be under-representative because they are commonly truncated by overlying sandstone beds (Fig. 4: log E, 0–2 m; log G, 0–1 m). Laminae in both shale and siltstone are defined by organic material, whereas mudstones contain scattered coal fragments. In the thickest accumulations of these latter facies, the content of organic materials (coal fragments) typically increases up-section, particularly where these rocks underlie coal (Fig. 4: log C, 8.7–11.8 m). Mudrocks locally rest sharply on other lithofacies such as sandstone (Fig. 6D), where they infill channels on the scale of 1–3 m deep and 5–30 m wide.

The mudrock facies association yields a diverse assemblage of both Pteridophyte spores and Gymnosperm (conifer) pollen (Table 1). Notably among these, green algae (*Botryococcus braunii*) occur in Mid Jurassic mudstones and *Classopolis* sporomorphs are represented within Late Jurassic mudstones (Table 1).

2.3.2. Mudrock facies association: interpretation

The mudstone facies association records low energy suspension fallout of silt and clay in non-agitated waters within a terrestrial environment. The vari-coloured nature of this facies association is attributed to an admixture of different clay mineral species, in variable states of oxidation, and with differing contents of organic matter. The significant thickness of this facies association, and its lateral extent, raises two main interpretive possibilities. These interpretations are firstly a lacustine depositional setting and secondly an overbank fluvial setting. The first interpretation is less likely because of the homogenous nature of mudrocks and lack of interstratified sandstones and associated turbidites that might indicate the progradation of deltas into a lake (e.g. Etienne et al., 2006). The small-scale thickness variations of the facies association, and its occurrence directly above channel scours is more indicative of its deposition within formerly active channels that became filled with overbank deposits (e.g. Plint, 1988). Commonly, overbank flow processes play an important part in the infilling of such channels following avulsion (Nichols and Fisher, 2007).

The occurrence of green algae (*B. braunii*) in association with fern spores in Mid Jurassic mudrocks strongly supports the fluvial interpretation given above. This alga is a freshwater variety (Guy-Ohlson, 1998) and hence indicates accumulation of plant material in settings such as oxbow lakes and floodplains. Likewise, the occurrence of *Classopolis* sporomorphs within mudrocks of the Upper Jurassic section also supports continental (floodplain) deposition of rocks of this interval. *Classopolis* is typical of Late Jurassic and Cretaceous intervals across central Asia, including the Tien Shan in neighbouring Mongolia (Hendrix et al. 1992).



This genus derives from a now extinct drought-resistant conifer (Pocock and Jansonius, 1961).

2.3.3. Coal facies association: description

This facies association includes anthracitic/bituminous coal and subordinate interbedded mudstone and shale. Coal seams reach 40–50 m thick (Fig. 4, log C; Fig. 6E), and are up to tens of kilometres in lateral extent. Rootlets are absent. The thickest seams often exhibit sharp and flat upper surfaces (Fig. 6F), and are most commonly overlain by sandstone facies associations. Coal seams also occur at the smaller scale (several cm to dm thick) and these are interbedded with 3–4 m thick shale deposits (Fig. 4, log B). Pyrite commonly occurs as mm-scale crystals and aggregates. Thin seams (<1 m thick), containing fossil tree material and with a crystalline texture also occur (Fig. 6G).

2.3.4. Coal facies association: interpretation

The coal facies association is interpreted as the accumulation and preservation of plant material over a prolonged period in a swamp on a poorly drained floodplain. According to Fielding (1987), three principal conditions are required to form peaty organic residues, namely (1) sufficient vegetation growth, (2) reduced oxidation and suppression of bacterial reduction probably by an elevated water table and (3) reduced clastic input. With these conditions in mind, the absence of rootlets in this facies association may be indicative of peat sourced from mires, or alternatively introduction of plant material by fluvial processes. A swamp of considerable depth is required to produce a coal seam some 40–50 m thick, which assuming a compaction ratio of 1.2:1 to 2.2:1 (Nadon, 1998) would indicate a peat mire some 60–110 m deep for these thickest seams. The smaller-scale (cm to dm thick) coal seams that occur interbedded with shale indicate the development of mires on a much smaller scale, within shallower bodies of standing water. The associated shale records the intermittent influx of oxygenated fresh water into the mire. In overbank settings, crevasse splay processes may provide a suitable mechanism for such an influx of fresh water into an otherwise stagnant mire (Farrell, 2001).

2.3.5. Silty sandstone facies association: description

This facies association comprises siltstones and very fine-grained sandstones (e.g. Fig. 4, log H). These deposits are dominated by parallel laminated facies with a common upward transition into ripple cross-laminated facies. Massive siltstones also occur, containing organic-rich streaks (Fig. 7A). Siltstones are also interlaminated with centimetre-thick coal seams (Fig. 7B) and drape current ripple foresets. Typically, this facies association has a limited vertical extent in any given section (30–50 cm thick), and can be traced laterally for ~5–10 m. Siltstones and sandstones of this facies association typically rest in flat concordant contact upon underlying facies associations (Fig. 5, 48 m).

2.3.6. Silty sandstone facies association: interpretation

Siltstones and very fine-grained sandstones of this facies association, are relatively fine-grained sediments, and were deposited during intervals of low depositional energy. In a fluvial setting, such deposits record low stream power (lower flow regime parallel lamination: Ashley 1990), typically in low capacity streams or overbank conditions such as crevasse splays (Farrell, 2001). The generally flat contacts at the base of this facies association favour the latter interpretation. The upward transition from parallel to ripple cross-laminated deposits indicates flow deceleration, resulting from flow expansion over the alluvial plain during waning flow events. Previous detailed study of the products of avulsion processes has likened crevasse splay deposits to small-scale delta complexes, where ~3 m thick distributary mouth bars and reworked marginal to distal mouth bars can be recognised in exceptional exposures (Farrell, 2001). By comparison, the low thickness (30–50 cm) and restricted extent (5–10 m) of the silty sandstone facies association in our current paper points to small-scale, localised crevasse splay deposits.

2.3.7. Fine to medium-grained sandstone facies association: description

This facies association is dominated by fine to medium-grained sandstones, with a generally low overall concentration of pebble-sized clasts. At least ten stratigraphic occurrences of this facies association can be observed along the Bolshoy Kemchuk river (Fig. 5). The base of the facies association is typically channelised, with well-defined channels 10–20 m wide (Fig. 7C) that are lined at their bases with mudstone, siltstone and to a lesser extent chert clasts 0.5–15 cm diameter. The channels form the most conspicuous erosional features within a 15 m thick sand sheet, the lateral extent of which is impossible to demonstrate owing to the limited extent of most exposures to small quarries. Trough cross-stratification is common in these deposits, with foresets 0.1–1 m high (Fig. 7D) that are lined with abundant coal, fossil wood fragments and millimetre-scale clay clasts. Bedsets are typically amalgamated and stacked (Fig. 4: log D, 3–14 m). Horizontal parallel lamination (Fig. 7E) also occurs in fine to medium-grained sandstone successions of 2–3 m thickness, with laminae incorporating a high percentage of organic matter (including wood fragments 40 cm length) and siltstone. Moderate amplitude ripple cross-stratification (ripple crests 1–2 cm high; Fig. 7F), cap both the trough cross-bedded facies and the parallel laminated sandstones. Uppermost contacts of the fine to medium-grained sandstone facies association are typically irregular or channelised, and it is commonly overlain by the mudrock facies association (e.g. Fig. 4, log F).

2.3.8. Fine to medium-grained sandstone facies association: interpretation

The fine to medium-grained sandstone facies association is interpreted to record deposition within a fluvial intra-channel setting in a mixed load system that was characterised by a minor component of bedload transport (exemplified by pebble lined channels). The stacked nature of trough cross-bedding indicates high rates of sediment aggradation (e.g. Leclair et al., 1997; Mack and Leeder, 1999). Significant cannibalisation and reworking of underlying deposits is implied by the pebble trains at the bases of channels and the mud clasts. Together, the occurrence of trough-cross beds and channels amalgamated into a sand sheet bears some resemblance to fluvial sandsheets from the Permian of Queensland (Allen and Fielding 2007). The presence of coal fragments and wood fragments within parallel laminated sandstones suggests deposition of organic matter along the bedding surfaces. The scale of preserved foresets (0.1–1 m) suggests initial dune bedforms in the range 0.5–1 m height to a maximum of 5 m (Leclair et al., 1997; Ashley, 1990). The vertical transition from parallel laminated to current rippled sandstones is interpreted as a typical waning flow signature. This waning flow signature may be attributed to either overtopping of river banks with sediment (i.e. intra-channel equivalents to crevasse splay deposits; Farrell, 2001) or alternatively reduced discharge during lowering of river water levels.

2.3.9. Coarse-grained sandstone facies association: description

These deposits comprise coarse-grained sandstones that are associated with gravels, pebble and cobble-grade conglomerates (Fig. 8A–D),

Fig. 6. Fine-grained sedimentary facies in Jurassic and Cretaceous strata. Photos A–D depict aspects of the mudrock facies association. A: Shale showing variably grey and brown laminae. B: Mudstone showing alternating pink (oxidised) and green (reduced) intervals, and no fissility. C: View of the mudstone facies association (grey) interbedded with the coal facies association (black) in Middle Jurassic deposits at Kaichak quarry, (log B, Fig. 4). D: Mudstones (brown) capping an abandoned channel that is cut into sandstone (buff colour). Photos E–F show aspects of the coal facies association. E: Berezovsky open cast mine (log C, Fig. 4). The coal seam is ~50 m in thickness and has a lateral extent of ~3 km. Note the knife-sharp contact between coal and sandstone. F: Another example of a knife-sharp contact between a 4 m thick coal overlain by a medium-grained sandstone along the Bolshoy Kemchuk river. G: Fossil tree trunk within coal (log B, Fig. 4). This specimen exhibits a crystalline texture, a result of graphitisation in response to modern day autocombustion of the coal at outcrop.

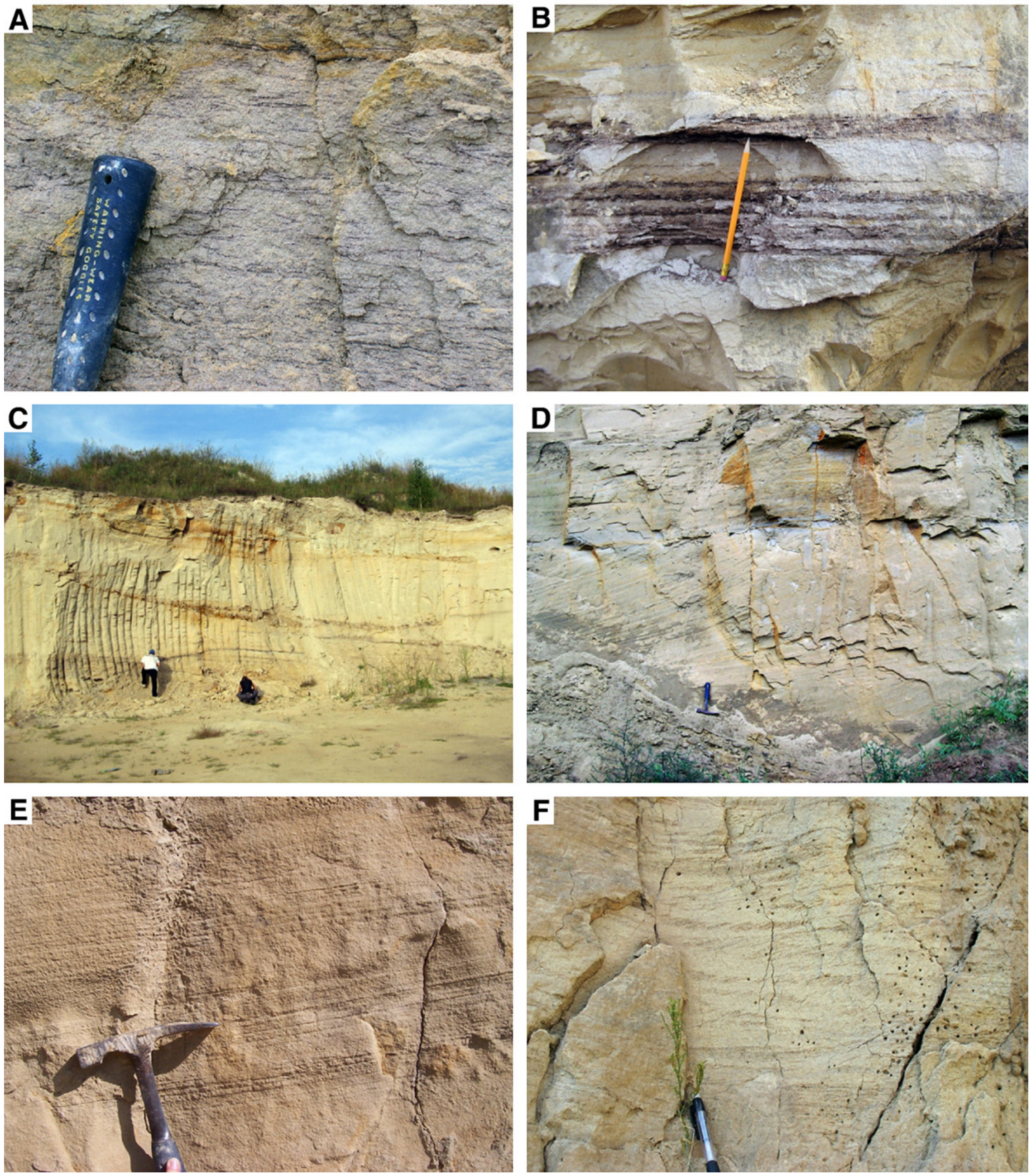


Fig. 7. Sandstones and siltstones of two facies associations in rocks of Jurassic and Cretaceous age. Photos A and B shows aspects of the silty sandstone facies association. A: Siltstones with a poor fissility. Bedding is horizontal. The laminae are defined by concentration of organic material (coal grains and granules). B: Interlaminated siltstone, shale and coal deposits. Pencil for scale. Photos C–E depict aspects of the fine- to medium-grained sandstone facies association. C: Large channels developed in fine- to medium-grained sandstone. The channels are identified by a zone of ferruginisation at their bases, and by pebble-sized conglomeratic material (including wood fragments, exotic clasts) above. D: A large trough-cross bed typical of this facies association, yielding excellent palaeo-current information. Note hammer for scale. The bedform is capped/ truncated by a metre-thick bed that contains the parallel lamination shown in (E). F: Stacked sets of ripple within fine-grained sandstone typically occur toward the top of fining-upward cycles, interpreted as a classic waning flow signature.

together with subordinate finer-grained sandstones (Fig. 4, log A). The base of this facies association is highly irregular to channelised where contact with pre-Mesozoic crystalline basement can be demonstrated (Fig. 9A). Clasts in the conglomeratic horizons range 0.5–6 cm in length, and include grey and green mudstone, green siltstone, black and red cherts, sandstone (locally deformed and metamorphosed), carbonate fragments, granite, granite pegmatites, tuffs, vein quartz, quartzite, andesite and coal. Clasts are typically moderately to well-rounded, although unusually large and angular clasts occur where this facies association rests directly upon crystalline or pre-Mesozoic basement (Fig. 8B). Lenticular sandstone beds are preserved within pebble conglomerates (Fig. 8C). The sandstone beds sharply overlie underlying conglomerates, and this latter lithofacies is characterised by both trough and planar cross beds (Fig. 8C), the sets of which exhibit normally graded bedding and well-developed imbrication of the pebbles (Fig. 8D). Low-angle ($<5°$) stratification also occurs. These sandstone lenses comprise 1–2 clast thick trains of pebbles and cobbles.

2.3.10. Coarse-grained sandstone facies association: interpretation

The coarse sediment calibre of this facies association points to deposition in an intra-channel, mixed load to bedload dominated fluvial system where moderate to high current velocities were commonplace (Miall, 1996). The irregular to channelised contacts typical of the base of this facies association, coupled with the predominance of large and

Fig. 8. Representative photographs of the coarse-grained sandstone facies association. A: 10 m thick succession of interstratified sand and gravel at locality SE 29 (log A, Fig. 4). B: Detail of conglomerate bed at the same locality 2 m above the lower contact between this facies association and Devonian granite. The large angular clast to the right of the pen is a clast of this Devonian granite. Conglomerate horizons show lateral pinching and swelling, and thin onto the Devonian granite basement, suggesting bedrock-confined river conditions. C: Complex facies relationships between conglomeratic intervals and medium-grained sandstone. The wedge/ lens of sandstone towards the top of the photo is interpreted as a sand-filled channel body. Beneath it, a pen is positioned for scale on forsets that are developed in granule to pebble-grade conglomerate. Photo D shows a close-up of these foresets, which are normally graded.

angular clasts where it is observed to overlie basement, is indicative of a high stream power. Some of these river channels appear to have been topographically constrained (Fig. 9A).

The coarse-grained sandstone facies association shares many characteristics with the deposits of modern braided rivers such as the Sagavanirktok River, Alaska (Lunt and Bridge, 2004). Analysis of such modern river deposits shows that gravelly braid bars are architecturally composed of large-scale cross-strata with a complex and composite internal structure reflecting medium scale cross- and planar strata (Lunt and Bridge, 2004), produced during the lateral migration or bifurcation of streams (point bars and mid-channel bars respectively). Pebble lags at the base of trough cross-beds are interpreted as traction deposits, whereas the matrix supported nature of conglomerates along other bedding surfaces, scour surfaces and cross bed forsets may signify grain-dispersive processes operating under the influence of gravity. Such matrix supported conglomerates are common features of deposits laid down in the lee of topographic scarps and may point to the development of hyperconcentrated flows in the immature fluvial land system (Mack and Leeder, 1999). The low angle stratification within some of these deposits is interpreted as the migration of low-profile bedforms along the riverbed. The similar size of the clasts, and their overall moderate to well-rounded character, indicates prolonged transport periods as river bedload. The relative abundance of chert and intermediate to acid intrusive and extrusive igneous rocks is compatible with their provenance from the Altaid region of northern Kazakhstan: in this region, the crystalline basement comprises island arcs, ophiolites and accretionary wedge complexes (Buslov et al., 2004). By comparison, the carbonate and sandstone clasts are suggestive of a more local source from Devonian mixed carbonate-clastic succession in the Mariinsk–Krasnoyarsk region (Berzon and Barsegyan 2002).

2.3.11. Lateral and vertical evolution of palaeoslopes

An extensive palaeocurrent database was compiled from 156 palaeocurrent measurements at >20 localities. Palaeocurrent data along the composite Bolshoy Kemchuk river section (Fig. 5) derive from five separate observation points. Data were collected from trough cross beds of ~1 m height from sandy deposits, namely the silty sandstone facies association, the fine to medium-grained sandstone facies association, and the coarse-grained sandstone facies association. These data were plotted on standard rose diagrams, which have been superimposed on a sketch geological map (Fig. 3). This figure does not discriminate between the three sand-prone facies associations, although since it was established above that all were deposited as fluvial bedload within Jurassic and Cretaceous river systems, the data can be considered together.

Fig. 3 separates data collected from Lower, Middle and Upper Jurassic intervals, and distinguishes between Lower and Upper Cretaceous rocks. Data from the Early Jurassic indicate the migration of dunes in several directions: those cropping out in the west of the study area (SE42, SE44, SE20 & 21) show predominantly westward dispersals, whereas those in the centre and east of the study area show southwestward (SE38) and a swath of northwest to eastward (SE29, SE30) directions. In the Middle Jurassic, north and northeastward vectors predominate in the western part of the study area (SE2, SE9, Bolshoy Kemchuk river section), but east to east–north-east dispersals are recorded for the centre and east of the

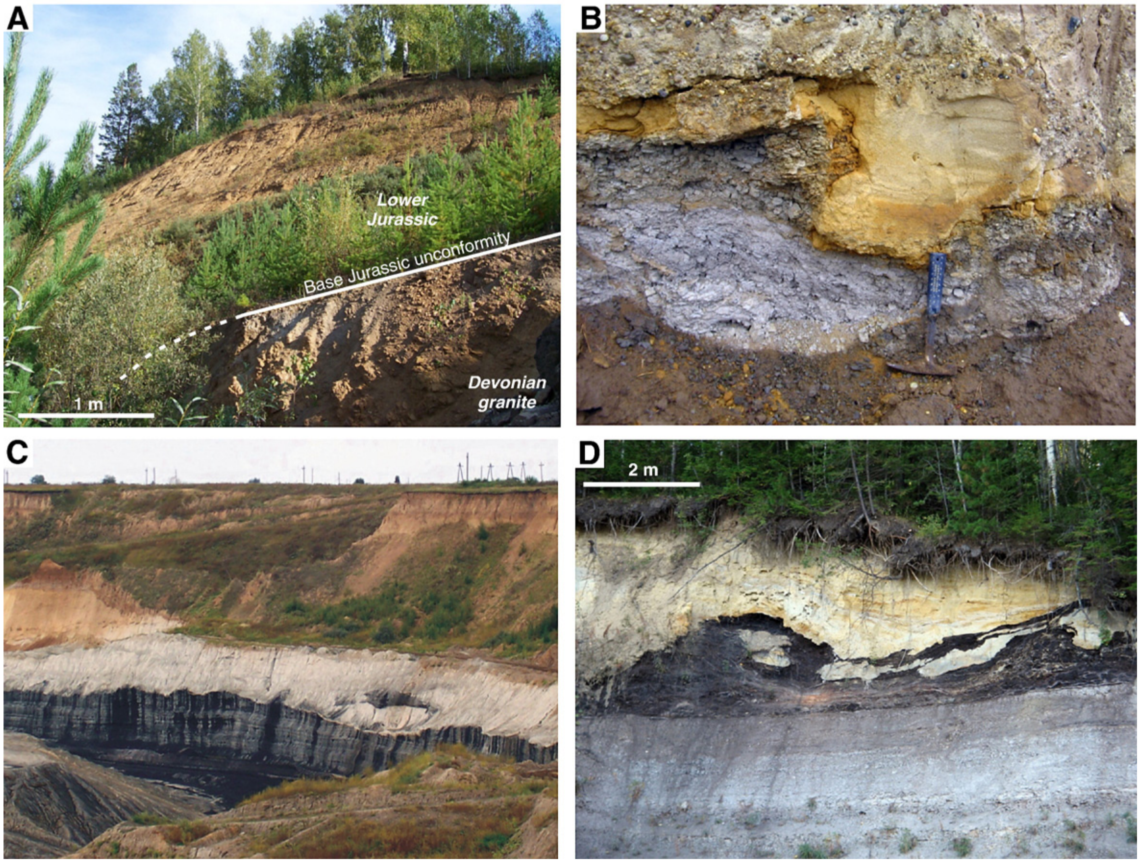


Fig. 9. Vertical relationships between facies associations in Jurassic and Cretaceous strata. A: Contact between Devonian granite basement and Lower Jurassic sands of the coarse-grained sandstone facies association (see Fig. 4, log A). B: Irregular contact between the mudrock facies association (brown/grey lithology: in the lower and middle part of the photo) and the coarse-grained sandstone facies association (buff yellow: above the hammer). This juncture is attributed to gravitational/load instability of the coarse-grained sands and gravels onto unconsolidated mudstones. C: Highly irregular contact between the coal facies association and the fine- to medium-grained sandstone facies association exposed as a result of coal mining at Periyaslovski Quarry. Note the enclosure of pods of coal by the sandstone. Coal seam is ~10 m thick. D: Similar irregular contact between coal and fine-grained sandstone in a section along the Bolshoy Kemchuk river. Note the development of isolated pods of sandstone beneath a load feature in the overlying sandstone bed, resulting in complete enclosure by the coal. The features in C and D stand in contrast to the localities shown in Fig 6E and F where lithological contrasts are sharp and well-defined, and might imply the presence of residual water within the peat before the coalification process was complete.

region (SE10, SE25, SE31). For the Upper Jurassic, no data are available. Lower Cretaceous sandstones were shed in a north (SE19) to north–westward (SE3) direction, and Upper Cretaceous dunes migrated in a range of directions from north to southwest (SE20 & 21, SE22).

In summary, these data suggest that the southeastern edge of the West Siberian Basin was characterised by a northwest to north-eastward dipping slope and that this slope did not vary significantly laterally or during the Jurassic and Cretaceous, although local south and southwestward dune migration is recognised. The spread of palaeocurrents observed in certain localities (e.g. SE9) probably reflects the tendency of intra-channel dune systems to infill hollows (such as scour pools produced by eddies etc.) which record local departure from the regional topographic gradient of the landscape.

3. Lateral and vertical relationships between facies associations

The sedimentary facies described and interpreted above show marked vertical and lateral changes, some of which are gradual, whilst other facies transitions are sharper. The most notable vertical and (and hence temporal) change in facies throughout the Jurassic is the progressive up-section appearance of mudstones. The Lower Jurassic sections are dominated by either the coarse-grained or medium-grained sandstone facies association (Fig. 4, log A; Fig. 8), whilst the mudrock facies association is conspicuously absent from this level. However, mudstones are well-represented within the Mid Jurassic and to a lesser extent in the Lower and Upper Cretaceous (Fig. 4). Vertical alternation between the mudstone facies association and the coal facies association is also apparent (Fig. 4B). These lithological changes are interpreted to record the transition from an immature fluvial landscape, dominated by a fluvial system that was locally influenced and confined by a bedrock topography (Fig. 9A) to a more mature palaeo-landscape characterised by stable meandering rivers with extensively developed overbank areas and mires. The overbank areas were subject to deposition of fine sand-grade materials (silty sandstone facies association) by the Middle Jurassic, probably in response to high discharge events.

In the Middle Jurassic, the sharp contact between the thickest developments of the coal facies association and overlying fine to medium-grained sandstone association (Fig. 6A) provides evidence that the mature fluvial system was episodically prone to avulsion. The remarkably planar, as opposed to channelised contact between these facies associations may be attributable to the elastic rheology of peat, which significantly reduces the potential for vertical erosion by avulsing rivers (McCabe 1984; Collinson 1996). The occurrence of fluvial channel deposits directly overlying coal may provide evidence of significant avulsion of a large fluvial system, at least at the scale of several kilometres. Such large-scale avulsion is a common for rivers of an anastomosing geometry (Makaske 2001). Additional evidence for channel abandonment and avulsion is provided by the occurrence of the mudrock facies association in channels on the upper surface of the fine to medium-grained sandstone facies association (Fig. 4C). These stratigraphic relationships indicate erosion and scouring on the upper surface of the fine to medium-grained sandstone facies association, bypass of bedload sediments, and deposition of slackwater mudrocks in the absence of traction currents. Therefore, these stratigraphic relationships imply an abandonment process analogous to the formation of oxbow lakes in meandering fluvial systems (e.g. Constantine and Dunne 2008).

The contact between coal and overlying sandstone is not everywhere sharp and planar, however. At several intervals along the Bolshoy Kemchuk river section (Fig. 5), the contact between coal and the fine to medium-grained sandstone facies association is characterised by a disrupted and irregular interface between these two contrasting lithofacies (Fig. 9B, C). The relationship varies between pods of coal enclosed by sandstone (Fig. 9B), and sandstone pods occurring within the upper portion of the coal (Fig. 9C). These features are compatible with the entrainment of rafts of peat by an overlying fluvial system. The more irregular coal pods and sands within the upper coals may be due to the liquefied nature of the peat during sand deposition and, in such instances, gravitational instability between the two lithologies would have been promoted more easily.

The facies associations discussed above were studied at widely separated outcrops between Krasnoyarsk and Novosibirsk, the ages of

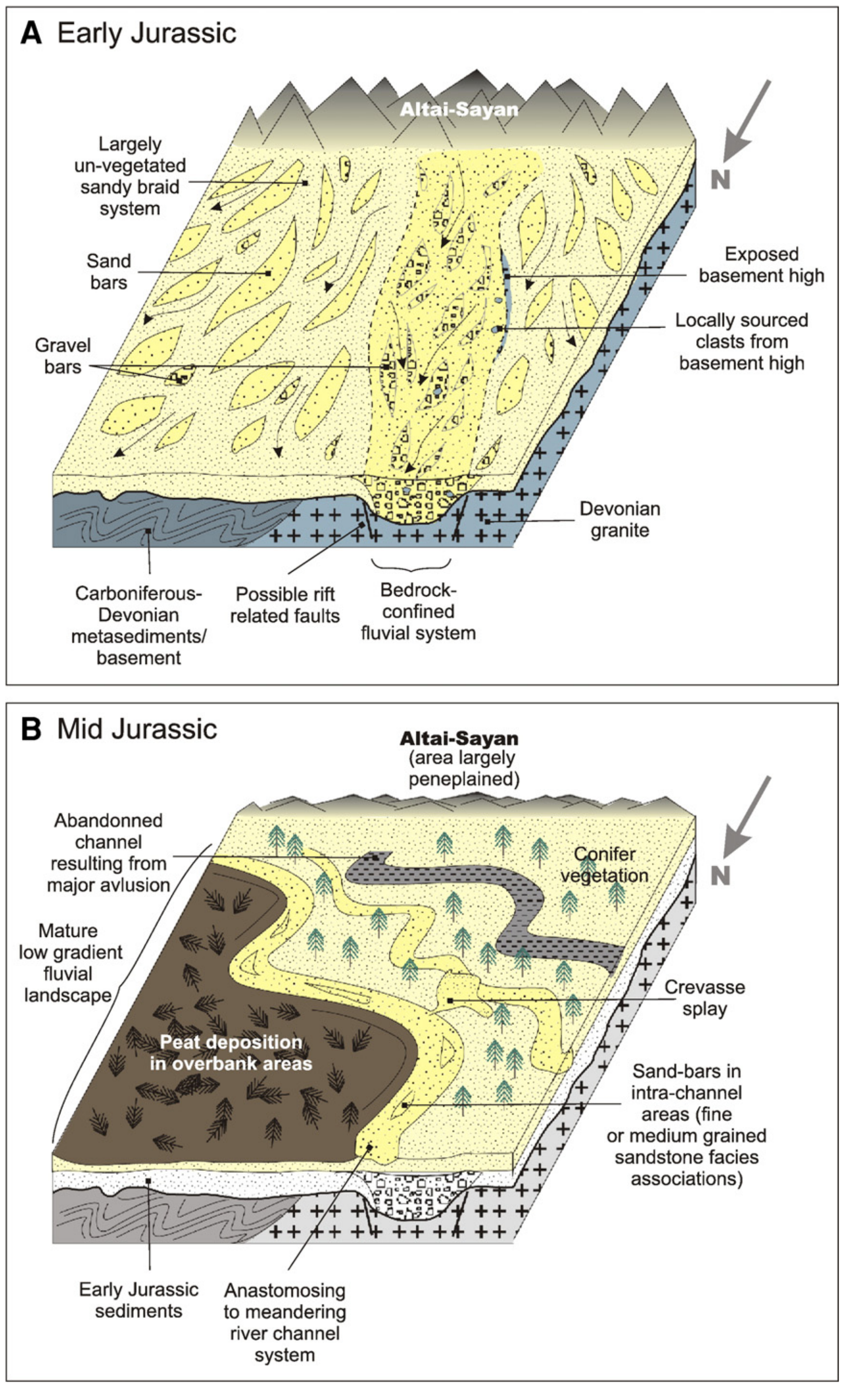


Fig. 10. Depositional model for continental sedimentary systems of the southeastern West Siberian Basin during the Jurassic, developed from outcrops in the Mariinsk–Krasnoyarsk region. A: Early Jurassic depositional environments, dominated by relatively immature fluvial environments, coarse bedload fluvial systems, and the continuing influence of bedrock topography upon sedimentary architecture. B: Cartoon summarizing depositional environments of the Mid Jurassic, which were characterised by a more mature/ evolved fluvial landscape system that included well-defined overbank areas. These overbank areas were the depocentres for peat accumulation (and hence economically significant coal accumulations). These coals may also contribute to a hitherto untapped source of natural gas in the southern part of the West Siberian Basin.

which were determined following consultation with Y. Berzon of the Krasnoyarsk Geological Survey. Consideration of outcrops in isolation, however, provides an understanding that is quite limited by lack of information on lateral and vertical relationships between facies associations. In order to reduce this problem, a composite log through Mid Jurassic to Cretaceous strata was compiled along the Bolshoy Kemchuk river (Fig. 5). This composite section, which is >700 m thick, is dominated by Middle Jurassic (Aalenian–Bathonian) strata but extents into the Lower Cretaceous (Neocomian) (Berzon and Barseg-yan 2002). The outcrops used to construct the composite section are spread over a ~26 km stretch of the river. Where they occur, the quality of exposures is very high. However, each outcrop is disconnected. Regional dips are low (always <10°), and there is little stratigraphic overlap from section to section. Therefore, the total thickness of the section presented herein (Fig. 5) may be an underestimate.

The log reveals a partly cyclic evolution of the depositional system as follows. The coal facies association is sharply overlain by either the silty sandstone or fine to medium-grained sandstone facies association. Sand injection structures, penetrating downward into coal, are observed at several intervals (Fig. 5, 46 m, 80 m, 127 m, 275 m). Above, a fining up occurs, culminating in the mudrock facies association. On the Bolshoy Kemchuk river section, four principal coal-bearing intervals are noted, all of which are restricted to the Middle Jurassic section. Exposures of the Upper Jurassic (Oxfordian) are poor and exclusively muddy (Fig. 5, 360 m), but overlying Lower Cretaceous deposits comprise the coarse-grained sandstone facies association with interbedded mudstones (Fig. 5, 720–740 m). In summary, in the Mariinsk–Krasnoyarsk area, most coal horizons are restricted to the Middle Jurassic (Figs 4 and 5).

4. Depositional model

The temporal evolution of the Mariinsk–Krasnoyarsk region in the Jurassic and Cretaceous can be summarised as follows. During the Early Jurassic, bedrock-constrained fluvial systems deposited bedload-dominated sediments including coarse-grained sands, gravels and conglomerates of both a local and regional (e.g. Altai–Sayan) provenance (Fig. 10A). These fluvial systems were probably ephemeral, and lacked the presence of well-defined overbank areas where mud deposition could occur (Fig. 10A). By Mid Jurassic times, progressive denudation of the landscape by high capacity rivers resulted in a low-profile alluvial plain that was characterised by anastomosing rivers and well-defined floodplains (Fig. 10B). Freshwater algae were able to populate standing water areas. During peak flow conditions, river banks were overtopped and crevasse splay sediments were deposited. Choking of older channel courses resulted in major avulsion, during which minor channels were also abandoned and filled with overbank fines in oxbow lakes. The extensive overbank areas were waterlogged and perhaps topographically depressed beyond the levees, allowing for thick peat accumulation in floating mires (Fig. 10B). These mires were also periodically subject to freshwater incursions that interbedded mudstones with peat.

By the Late Jurassic, coal deposition had generally ceased, but fluvial sedimentation continued. The deposition of coarser-grained sandstones during this interval may record subtle rejuvenation of the source area for these sediments by a process such as hinterland uplift/tilting or alternatively base level fall. The presence of *Classopolis* pollen in these deposits may provide a subtle indication of climatic change that accompanied the shift away from coal deposition: this genus is able to withstand desiccation (Pocock and Jansonius 1961), and may thus hint at subtle climatic changes in the Late Jurassic toward a slightly drier climate. By Cretaceous times, deposition of medium to coarse-grained sediments recorded a continued prevalence of bedload-dominated fluvial sedimentation, although mudstone sedimentation continued in overbank areas.

5. Discussion

5.1. Controls on sediment architecture at the margin of the West Siberian Basin

The data provided in this paper allow us to interpret the depositional history of a portion of the West Siberian Basin throughout the Jurassic and Cretaceous. In recent years, there have been intense efforts to investigate the sedimentary architecture of similar continental successions across the globe, many incorporating novel techniques such as laser-scanning and high resolution GPS studies to unravel the three-dimensional architecture of amalgamated sandstone deposits (e.g. Labourdette and Jones, 2007). In addition to technological advances, syntheses of outcrop data (e.g. Nichols and Fisher, 2007) and new angles on sequence stratigraphic models that may have value in coal-bearing successions (Yoshida et al., 2007), provide a valuable starting point from which to consider controls on sediment architecture.

It has long been known that the subsidence regime, and to a lesser extent sediment availability, play an important role in determining the architecture of coal-bearing successions, although a detailed understanding of the environment of deposition remains important (Fielding, 1987). Much emphasis has been placed upon coals by sequence stratigraphers, not least because they have the potential to form laterally continuous horizons readily interpreted as an “instant” reduction in clastic input. In the Permian of the Bowen and Galilee basins, Australia, 10–15 m thick fining upward cycles are interpreted as depositional sequences *sensu stricto* (Allen and Fielding, 2007). According to these authors, the base of an ideal sequence developed over low gradient basin margins is sharply flat though minimally erosional. This is because unlike areas of higher relief, extensive and flat coastal or alluvial plains tend to be cut by relatively shallow channels along the sequence boundary (Posamentier and Allen, 1999). In the study area of Allen and Fielding (2007), the sequence boundary is overlain by coarse to very coarse-grained, trough cross-bedded fluvial sandstone. Crucially, their sequence stratigraphic interpretation hinges on the recognition on the identification of such subtle palaeo-environmental indicators as a tidally reworked sandstones or bioturbation. As our sedimentological and palynological data failed to unveil any evidence for a marine influence on sedimentation, we prefer not to speculate as to plausible sequence stratigraphic interpretations of our data.

Integrating observations from large open cast coal mines and subsurface data, Fielding (1984) proposed a three-tiered hierarchy to explain sediment architecture in the Coal Measures (Upper Carboniferous) of NE England. For that area, Fielding (1984) envisaged that patterns of delta progradation and switching exerted large-scale controls, structural and compaction subsidence controlled medium-scale variation, whereas sedimentary processes and additional subsidence influenced local-scale variability. Compaction-related subsidence for these 900 m thick deposits was held accountable for the formation of sedimentary “basins” up to 8 m deep and several tens of kilometres wide. At the SE flanks of the West Siberian Basin, however, where our logging indicates a Jurassic through Cretaceous section >700 m in thickness (Fig. 5) the influence of compacting Middle Jurassic coals is likely to have been much more significant. Taking the compaction estimate above, a peat bed some 50 m thick may have created a sedimentary “basin” several tens of metres deep. Thus, the compaction of plant material to produce peat beds and ultimately coal seams may help explain the exceptionally sharp stratigraphic contact with overlying fine-grained sandstone (Fig. 6E).

5.2. Regional and global implications

A huge database on the Jurassic–Cretaceous succession is available from boreholes in the subsurface of the West Siberian Basin in the international literature (e.g. Kontorovich et al., 1997; Pinous et al., 1999, 2001). Here, attempts are made to link our new outcrop database, and the evolving fluvial depositional system of the Jurassic and Cretaceous, with disparate studies conducted across the extensive (3.5 M km^2) subsurface area of the basin.

Tentative correlation between surface (Berzon and Barsegyan, 2002) and subcrop (Rudkevich et al., 1988) is attempted in Fig. 2 to frame the present study in a regional context. It should be noted that no such correlation has been previously been attempted, and thus the correlation of the key unconformities and discontinuities should be regarded as preliminary, and to be confirmed in the course of future research. At outcrop, a significant unconformity occurs at the base of the Jurassic succession, a disconformity at the boundary between the Middle and Upper Jurassic, an irregular unconformity at the Jurassic–Cretaceous boundary, and a disconformity in the Upper Cretaceous (Fig. 2). These discontinuities can be traced into the subsurface and have been identified by various authors as follows. The first, at the base of the Jurassic, corresponds to the initial phase of stable sedimentation following rifting and the outpouring of the Siberian Traps (Reichow et al., 2002; Saunders et al., 2005; Allen et al., 2006). The second, at the base of the Callovian, corresponds to a major transgressive event that deposited marginal marine to lacustrine sediments over large areas: the Callovian source rock (Kontorovich et al., 1997; Pinous et al., 1999). The third is time-transgressive throughout the Neocomian and corresponds to the downlapping of large deltaic clinoforms shed from the Siberian Craton and to a lesser extent from the Urals (Pinous et al., 2001). The fourth discontinuity corresponds to a transgressive onlap of the Kuznetsov Suite and correlative lacustrine shales onto older deposits (Rudkevich et al., 1988; Fig. 2).

Many models of sedimentary basin formation invoke an active tectonic phase followed by a passive phase (Allen and Allen 1991). In the case of the West Siberian Basin, the active phase is attributed to rifting (and possibly dextral oblique-slip faulting: Allen et al., 2006), whilst the passive phase might be assumed to be represented by the post-Triassic sedimentary record. However, there are important stratigraphic reasons to question whether the phase of active basin formation ceased by the Early Triassic, with implications for the way in which we might view the Jurassic–Cretaceous sedimentary succession discussed in the present paper. In terms of stratigraphic architecture, Early to Mid Jurassic sedimentary rocks north of our outcrops in the Nyorlskaya depression are suitable for sequence stratigraphic analysis because they comprise marginal marine to shallow marine facies, including marine fauna and shales on maximum flooding surfaces: features which facilitate direct comparison to the international sea level curve (Pinous et al., 1999). These features enable Pinous et al. (1999) to link the creation of accommodation space in the basin (indicated by backstepping parasequence sets) to global sea level variation, effectively discounting active/ tectonic processes from basin evolution during the Early to Late Jurassic.

One of the key questions in the subsurface of the West Siberian Basin is the origin of enormous deltaic clinoforms of Neocomian age that were shed from the Siberian Craton and to a lesser extent from the Urals. Progradation of shallow marine and subaerial environments resulted in regional regression and the shift of shorelines basinwards by ~1000 km during the earliest Early Cretaceous (Pinous et al., 2001). In the Gydan Peninsula, in the northernmost extremity of the basin, seismic data show that Neocomian clinoforms offlap the fault-bounded Messoyakh Ridge system, hence providing evidence for uplift at the beginning of the Cretaceous (Kunin and Segalovich 1996). Furthermore, in the Altai–Sayan region of northern Kazakhstan, significant strike-slip deformation is thought to have occurred around the Jurassic–Cretaceous boundary (Buslov et al., 2004). According to De Grave et al. (2007), apatite fission track thermochronology suggests an uplift of the Altai–Sayan region between ~140 and 100 Myr BP, commencing 4 Myr into the Early Cretaceous. Additionally, Glasmacher et al. (2002) document a change in the regional stress field of the southern Urals during the Late Jurassic and Early Cretaceous. Therefore, these studies suggest that Early Cretaceous regression in the West Siberian Basin was potentially driven by uplift of the basin margins. As the present paper has shown, a fluvial system which reflects progressive landscape denudation and evolution from bedrock-confined fluvial channels to mature, anastomosing rivers characterised the Jurassic evolution of the south-east basin margin. Given the evidence for extensive and far-reaching Neocomian regression in the subsurface of the basin, the influx of coarser-grained clastics in the Cretaceous of the Mariinsk–Krasnoyarsk region are potentially explained by tectonically-related hinterland rejuvenation, although our data do not allow us to discount the possibility of regular fluvial avulsion processes.

Our outcrop dataset also contribute a valuable palaeoclimatic data point for the Jurassic and Cretaceous in a region that has never previously been studied outside Russia. As noted above, the loss of coal up-section from the Mid Jurassic into Late Jurassic times may be allied to a transition to a less humid climate, as might also the appearance of *Classopolis* as noted above, even if a hinterland rejuvenation event cannot be ruled out. The interval also spans the much elusive Late Jurassic–Early Cretaceous glaciation for which sedimentological evidence has never been found, although a global cooling in temperatures for this interval is recognised from the isotopic composition of belemnites collected previously from the Urals (Price and Mutterlose 2004).

6. Conclusions

- Jurassic and Cretaceous sediments cropping out at the SE flank of the West Siberian Basin in the Mariinsk–Krasnoyarsk region are exclusively clastic and comprise five facies associations.
- A coarse-grained sandstone facies association was deposited within an intra-channel setting where mixed load to bedload processes were dominant. A fine- to medium-grained sandstone facies association was also deposited within an intra-channel setting where mixed load sedimentation was dominant, characterised by migrating bedforms and waning flow processes. The finest sand component and silt, represented by the silty sandstone facies association, is interpreted to record overbrimming of channels and crevasse splay sedimentation. These processes interrupted the accumulation of a mudrock facies association in non-agitated waters, which took place on both the floodplain and within abandoned channels. Quiescent (low energy) sedimentation of the coal facies association, particularly in the thickest developed sections, took place in mires beyond channel levees.
- A clear vertical and hence temporal evolution of the fluvial system that deposited these facies associations is identified. Initial sedimentation during the Early Jurassic was restricted to bedrock-confined fluvial systems that cut into a range of Palaeozoic lithologies including crystalline basement. By Mid Jurassic times, a more mature fluvial landscape system had evolved, where well-defined overbank areas separated anastomosing river courses. Coal accumulation testifies to these extensive overbank areas and signifies humid climatic conditions. By Late Jurassic times, fluvial sedimentation continued with *Classopolis* pollen indicating a less humid climate. By the Cretaceous, a renewed influx of coarse clastic material indicates hinterland rejuvenation.
- Comparison between outcrop and subsurface stratigraphy of the West Siberian Basin suggests that the evolution of fluvial systems in the Jurassic took place during a period of tectonic quiescence. However, hinterland rejuvenation in the Cretaceous potentially corresponds to the progradation of major deltaic clinoform complexes in the basin subsurface during the Neocomian.

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