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Notes

The petroleum potential of the Riphean–Vendian succession of southern East Siberia

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Abstract: The Siberian Platform covers an area of *c.* 4.5 million km^2 in the East Siberia region of Russia, up to 3.5 million km^2 of which is prospective for hydrocarbons. We review the Archaean to Neoproterozoic evolution of the Siberian Platform and the potential oil and gas resources of Riphean, Vendian and Infracambrian sediments. The Riphean was dominated by passive margin sedimentation and was intensely deformed during the Baikalian orogeny. Vendian strata record a clastic transgressive sequence and the eventual re-establishment of carbonate platform sedimentation. The late Vendian–early Cambrian is characterized by carbonate deposition including thick salt horizons, which form a regional seal. Hydrocarbon maturation and migration from Riphean and Vendian source rocks occurred during the late Neoproterozoic and Early Palaeozoic, indicating that hydrocarbon reservoirs on the Siberian Platform may have hosted their reserves over a remarkable period of geological time. Despite many years of hydrocarbon exploration in East Siberia, many regions remain under-explored, and aspects of the proven hydrocarbon systems are poorly understood. There are undoubtedly more major discoveries to be made in the region, and the Infracambrian succession of the southern Siberian Platform therefore represents an irresistible target for further hydrocarbon exploration.

Infracambrian sedimentary basins are a major source of hydrocarbons in many parts of the world, including Australia, India, Pakistan, Oman, Mauritania, the USA and East Siberia. Oil shows were noted in East Siberia more than 200 years ago, and since then East Siberia has become a world-class hydrocarbon province. Oil and gas in-place estimates are 4 billion barrels of oil (Bbbl) (Nakashima 2004) and >38 trillion cubic feet (TCF) of gas (Ulmishek 2001*a*, *b*; Nakashima 2004). Oil in East Siberia is of high quality, with a density of 31°API, sulphur content of 0.1–1.3% and low paraffin content (*c.* 1%) (Poussenkova 2007). The East Siberian gas reserves differ from the gas fields of West Siberia in that they have a particularly high helium content (0.2–0.6%) (Poussenkova 2007). Total helium reserves in East Siberia are estimated to be between 1.9 and 2.5 TCF, exceeding the helium reserves of the USA, which is currently the world's largest producer (Poussenkova 2007).

Predicted values of the total volume of hydrocarbon reserves in East Siberia vary substantially depending on the source of the data. Resource estimates by Nakashima (2004) suggest that oil reserves range from 18.9 Bbbl (standard case) to 67.2 Bbbl (upside case), representing 13% of in-place Russian reserves (Dobretsov *et al.* 2007). Gas reserves are estimated at 386 TCF, or 18% of in-place Russian reserves (Nakashima 2004; Dobretsov *et al.* 2007). Estimates of maximum oil and gas production also vary significantly (Tables 1 & 2), especially those provided by the Siberian Academy of Sciences and Gazprom (Tables 1 & 2). For East Siberia, peak oil production is estimated to be 188 Mbbl/yr by Gazprom and 450 Mbbl/yr by the Academy, while peak gas production is estimated to be 4.7 TCF/yr by Gazprom and 4.2 TCF/yr by the Academy (Poussenkova 2007). Such differences probably reflect the limited scale of exploration in East Siberia as well as political factors. Current estimates of hydrocarbon reserves in southern East Siberia indicate the relative importance of the three oil and gas plays as follows: Riphean carbonates (3%), Vendian clastics (67%) and Vendian–early Cambrian carbonates (30%). However, Shemin (2007) concludes that the distribution of these reserves reflects the focus of earlier exploration, not the actual potential of each oil and gas complex. The opening of the ESPO (East Siberian Pacific Ocean) pipeline is likely to further stimulate exploration in the region.

Geology

The Siberian Platform occupies an area of *c.* 4 500 000 km^2 and is bound by the Enisey–Khatanga trough to the north, the Enisey and Lena rivers to the west and east respectively and by the

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Table 1. *Oil production (million barrels/yr)*

2010	2020	2030	Reference	Region
	750–788	900–990	Kontorovich (2007)	Yakutia, Krasnoyarsk, Irkuksk
81.6	351.6	375	Dobretsov *et al.* (2007)	East Siberia
225			Poussenkova (2007)	East Siberia
		450 (peak – Russian Academy of Sciences)	Poussenkova (2007)	Yakutia, Krasnoyarsk, Irkuksk
		188 (peak – Gazprom)	Poussenkova (2007)	Yakutia, Krasnoyarsk, Irkuksk

Central Asian Orogenic belt to the south (Fig. 1). The platform comprises Archaean basement overlain by a platform succession consisting of four sedimentary 'megacomplexes' deposited in Riphean, Vendian–Silurian, Devonian–Carboniferous and Jurassic–Cretaceous time. The platform margins are characterized by a thick Riphean passive margin succession.

The southern part of the Siberian Platform, which contains numerous proven and potential Infracambrian hydrocarbon fields, forms the focus of this paper. In this section we outline the geological evolution of six geological regions – the Baykit Anticlise the Khatanga Saddle, the Cis-Sayan Syneclise, the Angara-Lena Step, the Nepa-Botuoba Anticlise, and the Cis-Patom Trough, which together form a substantial part of the Lena-Tunguska oil and gas province (Fig. 1; Kontorovich *et al.* 1976). The Riphean platform succession and passive margin sediments deposited along the platform margins during the Mesoproterozoic and Neoproterozoic contain organic-rich intervals interpreted to have been the source of most of the hydrocarbons on the platform. Thus, the problem of long-term preservation of Infracambrian hydrocarbons, which is common to Infracambrian hydrocarbon plays elsewhere, may be complicated by the need to establish long-distance migration pathways from the platform margins onto the platform itself.

The region remains under-explored away from known fields, and correlation of Riphean and Vendian strata is hampered by rapid lateral facies changes, limited biostratigraphic data and an incomplete understanding of geological structures (Egorov *et al.* 2003). Correlation of well-exposed Riphean platform margin successions, interpreted as deepwater deposits, with the shallow marine platform succession observed in boreholes is especially problematic (Frolov *et al.* 2010).

Tectonic evolution of East Siberia

The Siberian Craton formed by the accretion of 11 Archaean and 2 Palaeoproterozoic crustal blocks in the period 2.1–1.8 Ga (Rosen *et al.* 2006; Gladkochub *et al.* 2006). The subsequent tectonic evolution of the Siberian continent, and its location and orientation with respect to other continents, has been the subject of much debate and research. It is assumed that the Siberian continent formed part of the supercontinent Rodinia; however, its position with respect to Laurentia and the timing of its separation remain unclear. The lack of reliable palaeomagnetic data from cratonic basement has led to a number of different reconstructions for the two continents (Pisarevsky & Natapov 2003). Frost *et al.* (1998) and Rainbird *et al.* (1998) point out that stable platform sedimentation from 1.8 Ga combined with the lack of Grenville age deformation (1.25–0.98 Ga) implies that the Siberian continent was on the northeastern periphery of Rodinia. It is believed that during Neoproterozoic time Siberia was located at equatorial/subtropical latitudes, south of the palaeoequator (Pavlov *et al.* 2002; Cocks & Torsvik 2007). At the beginning of

Table 2. *Gas production (TCF/yr)*

2010	2020	2030	Reference	Region
	2.5–2.8	2.6–3	Kontorovich (2007)	Yakutia, Krasnoyarsk, Irkuksk
1.7	3.5	4	Dobretsov *et al.* (2007)	East Siberia
1.8			Poussenkova (2007)	East Siberia
		4.2 (peak – Russian Academy of Sciences)	Poussenkova (2007)	Yakutia, Krasnoyarsk, Irkuksk
		4.7 (peak – Gazprom)	Poussenkova (2007)	Yakutia, Krasnoyarsk, Irkuksk

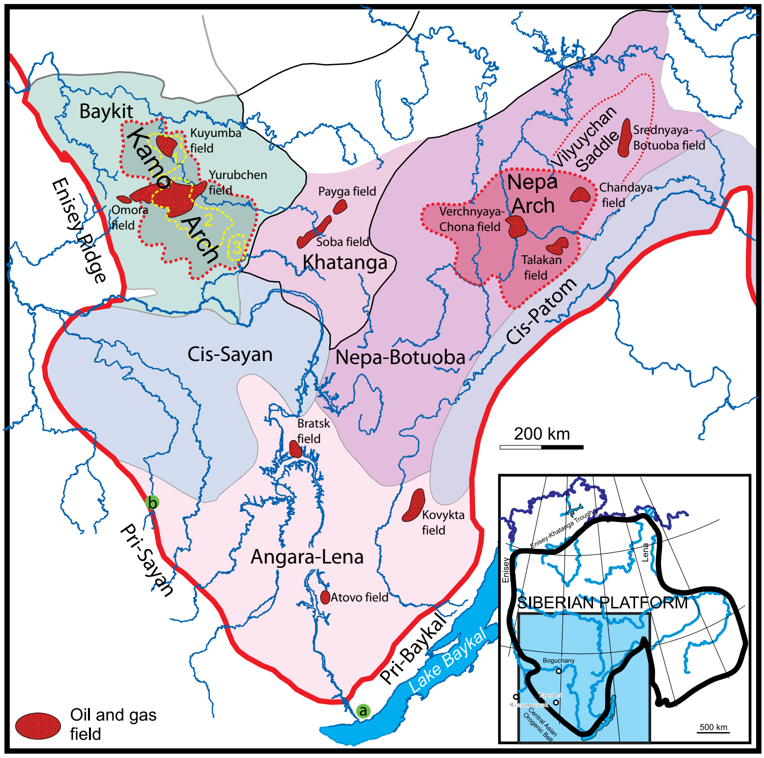

Fig. 1. Tectonic regions in the southern part of the Siberian Platform (based on Mikulenko & Starosel'tsev 1979). Only oil and gas fields indicated in the text are shown. Inset map shows the platform margins and the area covered by the main map. Uplifts on the Kamo Arch: 1, Kuyumba Uplift; 2, Tayga Uplift; 3, Chadobets Uplift. Sections described in the text indicated by green dots: a, Goloustnaya; b, Biryusa and Tagul rivers.

the early Cambrian the Siberian Platform began to drift slowly north (Shatsillo & Pavlov 2006).

The three main areas of basement outcrop in East Siberia are the Aldan Shield (the Stanovoy Block), the Anabar Shield and the Olenek Uplift. A number of smaller uplifts exist along the southern and southwestern margins of the Siberian Platform. The rest of the platform is covered by Riphean, Vendian and Phanerozoic sedimentary successions.

Following the accretion of the Siberian Craton, a phase of regional extension resulted in the formation of several intracratonic rifts (e.g. the Irkineeva-Chadobets and Urik-Iya rifts). A recent seismic line (Rudnitskaya *et al.* 2008) indicates that these may be more extensive than previously thought. This line shows evidence for an elongate Riphean basin, named the Angara-Kotul Rift Basin, containing up to 15 km of Neoproterozoic to Mesozoic sediment stretching from the Angara River (e.g. Irkineeva-Chadobets Rift) north across the craton (Fig. 2) (Rudnitskaya *et al.* 2008; Starosel'tsev 2009).

Passive margin sedimentation appears to have been established along the southeastern (Pri–Baikal–Patom) and western (Enisey) margin of the craton by the Mesoproterozoic time, whereas the onset of sedimentation along the southern and southwestern margins (Pri-Sayan) of the craton appears to be younger, established in Neoproterozoic times (Gladkochub *et al.* 2006). Gladkochub *et al.* (2006) propose that the onset of passive margin sedimentation in the SW records the breakup of Rodinia and the opening of the Palaeo-Asian Ocean.

Passive margin sedimentation continued into mid-Neoproterozoic times (between 850 and 760 Ma), but by late Neoproterozoic times, both the southwestern and southern platform margins had transformed into active margins. Island arcs and ophiolites formed along the margins of the Siberian Craton between 750 and 650 Ma and were obducted onto the platform margins by 600 Ma, prior to deposition of the Vendian (Vernikovsky *et al.* 2004). These events are collectively referred to as the Baikalian orogeny; however, as discussed in Vernikovsky *et al.* (2004), the accretionary events along the margins of Siberia did not occur simultaneously or have the same duration. Two fold

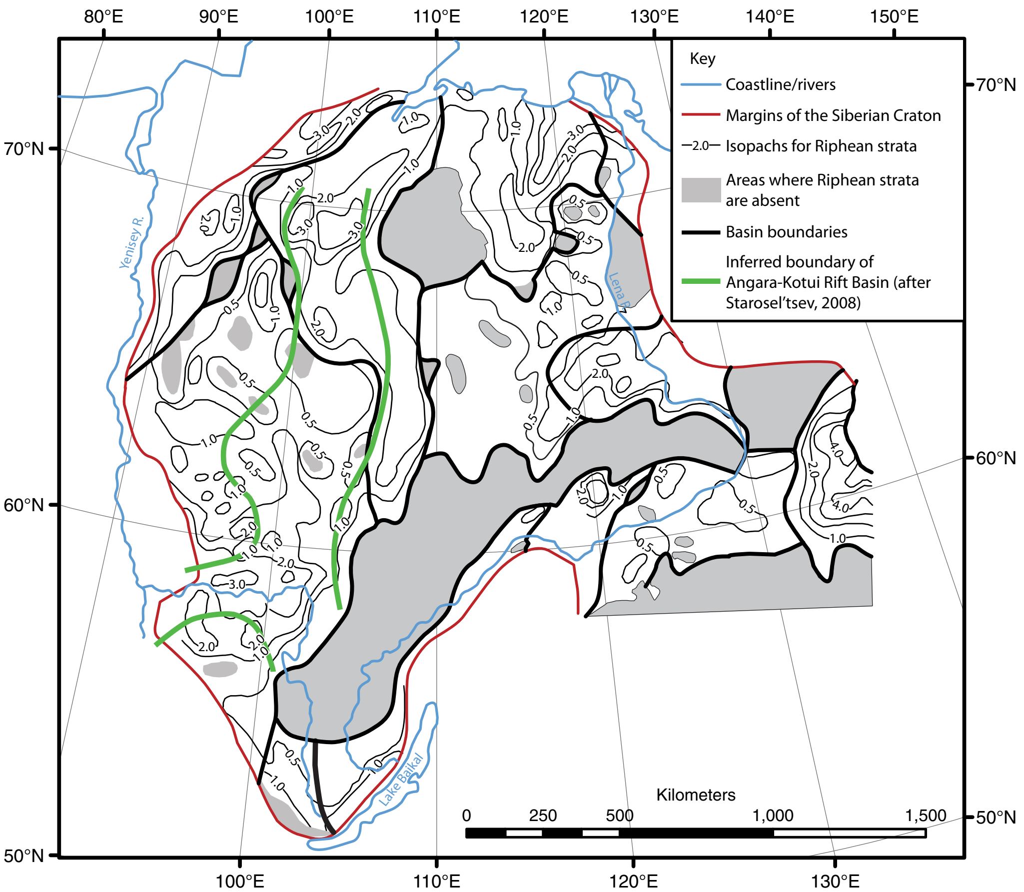

Fig. 2. Isopach map showing the distribution of Riphean sediments on the Siberian Platform, modified after Surkov *et al.* (1991). The thickness of Riphean sediments increases to 10–14 km along the platform margins (Khomentovsky *et al.* 1972). Inferred boundaries of the Angara-Kotul Rift Basin, after Starosel'tsev (2008), are also shown.

belts containing Neoproterozoic complexes crop out on the southern margin of Siberia: the Enisey Ridge and Baikal–Vitam fold-and-thrust belt (Fig. 3).

The Enisey Ridge

The Enisey Ridge is a complex fold-and-thrust belt that contains five terranes (East Angara, Central Angara, Isakov, Predivinsk and Angara-Kan; Fig. 3). The transformation from passive to active margin occurred at *c.* 760 Ma and was followed by several accretion events. The Central Angara Terrane collided with Siberia between 750 and 720 Ma. The Predivinsk island arc terrane was thrust eastwards onto the Angara-Kan between 660 and 630 Ma, and the Isakov island arc was obducted onto Siberia at 620–600 Ma (Vernikovsky *et al.* 2004).

The Baikal–Vitam fold-and-thrust belt

The Baikal–Vitam fold-and-thrust belt resulted from the collision between the Barguzin microcontinent and the Siberian continent. This collision event occurred over a prolonged period and was preceded by the accretion of island arcs and ophiolites (the Baikal–Muya complex) to Siberia. Siberia's southeastern passive margin transformed into an active margin during the Late Riphean, and the Baikal–Muya island arcs accreted to the margin of Siberia during the latest Riphean or early Vendian (Khain *et al.* 1997). However, the main phase of deformation occurred when the Barguzin microcontinent collided with Siberia during the Early–Middle Palaeozoic. This collisional event resulted in gentle folding of Cambrian–Silurian sediments across the platform and, probably, the reactivation and uplift of the

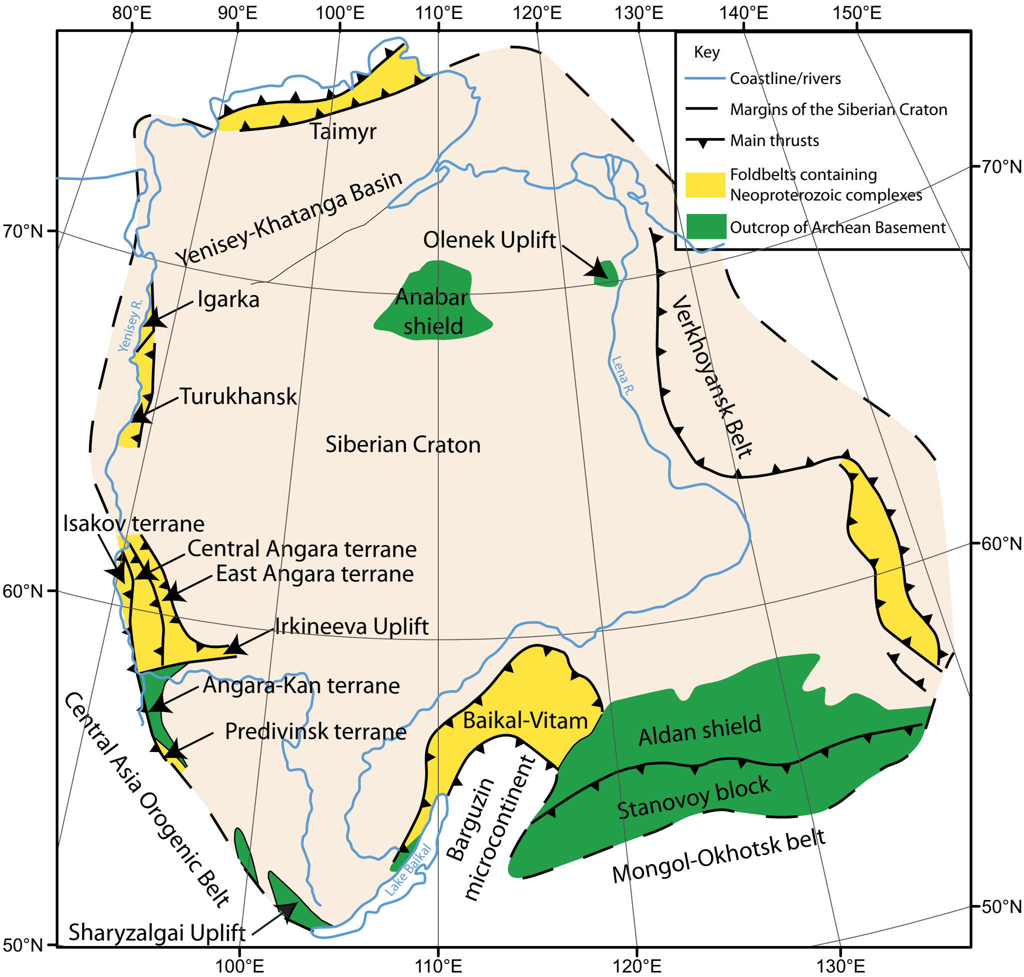

Fig. 3. Tectonic sketch map of Siberia modified after Vernikovsky *et al.* (2004) and Gladkochub *et al.* (2006). Areas of Precambrian exposure are indicated, together with the location of the main Baikalian faults.

Khatanga Saddle during the Late Silurian (Mel'nikov 1994).

Continental collisions around the platform margins during the Neoproterozoic are associated with significant deformation of the interior of the Siberian continent, including rift inversion and block uplift. Riphean strata are more heavily faulted than the overlying Vendian–Palaeozoic strata (Frolov *et al.* 2011). The modern structural framework of the Siberian Platform was established during the Vendian and the most significant of these structures form the boundaries of the hydrocarbon provinces shown in Figure 1.

Palaeozoic deformation on the platform is characterized by broad folding and vertical movements of large basement blocks. For example, the Khatanga Saddle underwent uplift and reactivation during the Silurian and subsequent subsidence during the Middle Carboniferous–Triassic (Mel'nikov 1994). Smaller uplifts have also undergone phases of Palaeozoic deformation; for example, in the Baykit region the Chadobets and Irkineeva Uplifts were active during the early Palaeozoic. At the end of the Palaeozoic, West Siberia underwent regional extension in response to the impact of a mantle plume and eruption of the Siberian traps.

Stratigraphy of the Siberian Platform

Five phases of sedimentation can be recognized on the Siberian Platform: Riphean, Vendian–Silurian, Devonian–Lower Carboniferous, Middle Carboniferous–Triassic and Jurassic–Cretaceous (Surkov 1987). Up to 70% of the preserved thickness of the sedimentary cover of the Siberian Platform is represented by Vendian–Silurian rocks. In this section we summarize the stratigraphic evolution of the Siberian Platform.

Riphean

Where Riphean strata crop out (Fig. 3) they have been widely studied, and detailed stratigraphic descriptions have been published (Semikhatov & Serebryakov 1983; Khomentovsky 1996; Podkovyrov *et al.* 2002). However, relatively little is known about the thickness and distribution of Riphean strata across the platform where they are overlain by Vendian and Palaeozoic strata. The exceptions to this rule are the Kamo Arch and Khatanga regions, where extensive drilling is supported by seismic data. The present-day distribution of Riphean sediments represents original depositional geometries, the effects of Baikalian deformation and subsequent erosion prior to deposition of Vendian strata (Figs 2 & 4).

Riphean sediments are not preserved in the central parts of the Nepa-Botuoba High or on the Angara-Lena Step, and are much less abundant on their flanks in comparison with adjacent areas (Fig. 2). Elsewhere, Riphean strata range from 1 to 4 km thick on the platform, but increase in thickness to 10–14 km along the platform margins (Khomentovsky *et al.* 1972). Early models predicted that substantial thicknesses of Riphean strata preserved on the platform were restricted to rifts (e.g. the Irkineeva-Chadobets and Urik-Iya rifts), but more recent studies have increasingly recognized that Riphean sediments are more widespread on the platform. Rudnitskaya *et al.* (2008) and Starosel'tsev (2008) propose an elongate Riphean basin, named the Angara-Kotul Rift Basin, extending across the centre and west of the platform (Fig. 2), while Mel'nikov *et al.* (2005) describe the Chunya sedimentary basin that is bounded by the Baykit and Khatanga highs to the SW and SE, respectively, and Frolov *et al.* (2011) suggest a series of broad Riphean basins developed above early Riphean rifts. Regardless of their names, these Riphean depocentres occupy the same positions and, based on seismic lines, are thought to contain almost continuous and thick (usually several kilometres) successions (Frolov *et al.* 2011). Consequently, these platform basins may be of great importance as a source of hydrocarbons.

Along the southeastern margin of the platform in the Cis-Patom region, early Riphean strata are represented by fluvial sediments associated with volcanic material, which are overlain by middle–late Riphean sediments interpreted as continental shelf and slope deposits. The succession increases in thickness from 2800 m in the north to 8000 m in the south and is interpreted to record deposition on a passive margin (Sovetov *et al.* 2007). This passive margin succession was subsequently deformed into a fold-and-thrust belt during the Baikalian orogeny.

On the southeastern part of the Angara-Lena Step, Riphean strata are 140–545 m thick and comprise interbedded claystones, sandstones, black shales and grey to black dolostones and limestones (Kontorovich 1995). These sediments thicken to the south, and on the flanks of the Angara-Lena Step up to 3000 m of Riphean sediments unconformably overlie basement. These sediments consist of basal dolomites overlain by greywackes, sandstones, black shales and, in the upper part, breccias (Maslov & Kichko 1985; Flecker & Voronova 1999). These sediments are interpreted to record deposition in shelf and slope environments and are interpreted as late Riphean in age (Postnikov 2001). Gladkochub *et al.* (2006) considered these marginal sediments as part of the Siberian Platform sequence; however, a marked change in palaeocurrent orientations at the base of the late Riphean Kachergatskaya Suite exposed in the Goloustnaya section indicates that the sediment was derived from the south and east (Fig. 1; Flecker & Voronova 1999). This implies sediment was shed into the evolving fore-arc basin, probably from the approaching Baikal–Muya island arcs, and the abrupt coarsening of sediment in the latest Riphean probably records the onset of collision.

Along the southwestern margin of the platform in the Cis-Sayan region, some of the most complete late Riphean successions crop out along the Biryusa and Tagul rivers near Tayshet (Figs 1 & 5). Riphean strata are up to 5100 m thick (Mel'nikov 2005). The succession has a basal clastic unit and becomes increasingly carbonate-dominated upward, and is interpreted as a passive margin succession (Fig. 5). This interpretation is supported by clinoforms observed in a recent deep seismic profile across Cis-Sayan (Mandelbaum *et al.* 1999).

The Enisey Ridge, to the west of the Baykit region, contains the most complete Precambrian sequences, reaching up to 12 km thick, from the Palaeoproterozoic to the Vendian (Mel'nikov 2005). This clastic, carbonate and volcanic-sedimentary succession exposed in the East Angara Terrane was deformed between 750 and 720 Ma during the collision between the Central Angara Terrane and the Siberian continent (Vernikovsky *et al.* 2004). It is difficult to reconstruct the depositional geometry; however, the westward thickening of the succession and an increase in deepwater facies to the west supports a continuation of

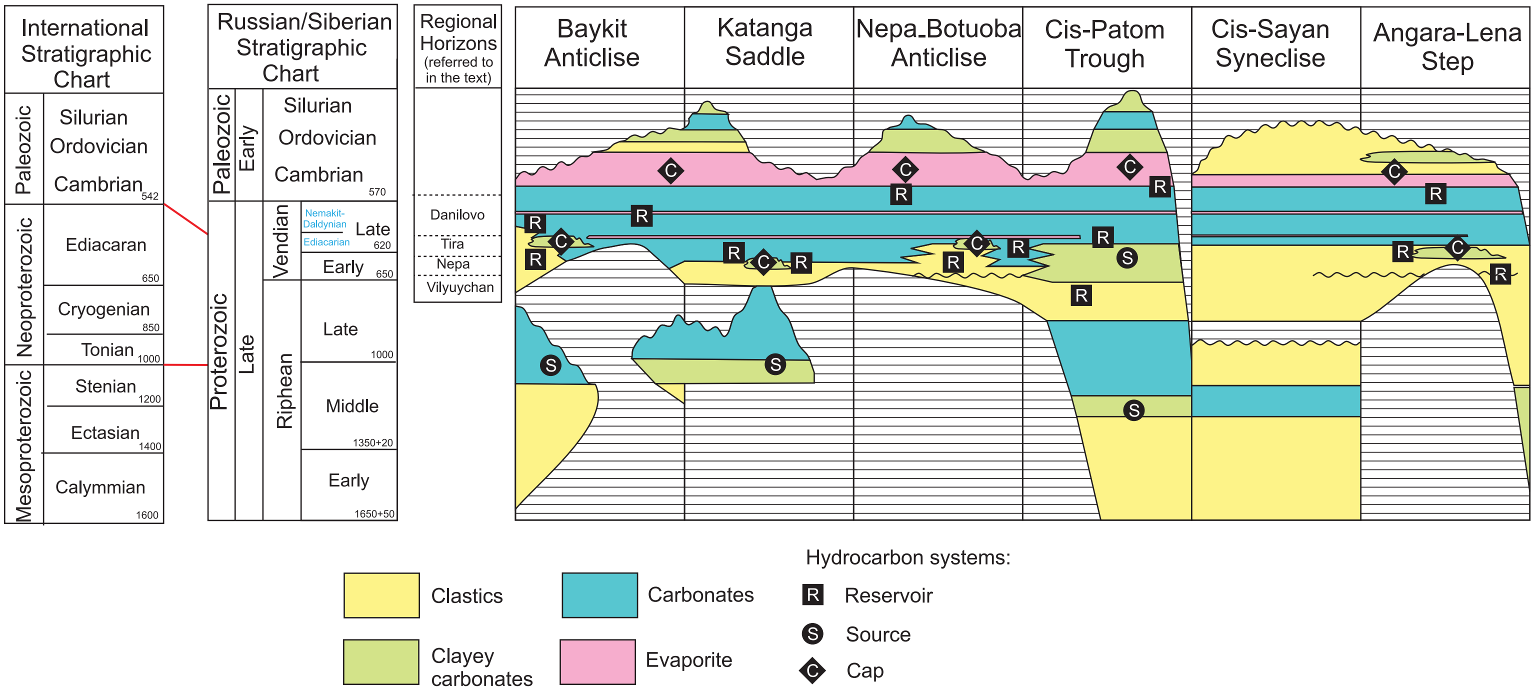

Fig. 4. Neoproterozoic to Early Palaeozoic sedimentary succession of the southern Siberian Platform (after Mel'nikov 2005, modified based on the author's field observations). Hydrocarbon systems are shown only for the Neoproterozoic–early Cambrian. Russian stratigraphic nomenclature is simplified (accepted Siberian regional stages are shown in blue), and correlation with the International Chart is provisional. Note the limited lateral extent of the Riphean strata, in part due to erosion during the pre-Vendian unconformity. Vendian strata progressively onlap the unconformity and become increasingly widespread, recording a marine transgression. The stratigraphy of the Cis-Sayan region remains uncertain. The Riphean stratigraphy of the Cis-Patom trough and the Cis-Sayan Syneclise contains numerous poorly constrained unconformities that are not included in this figure.

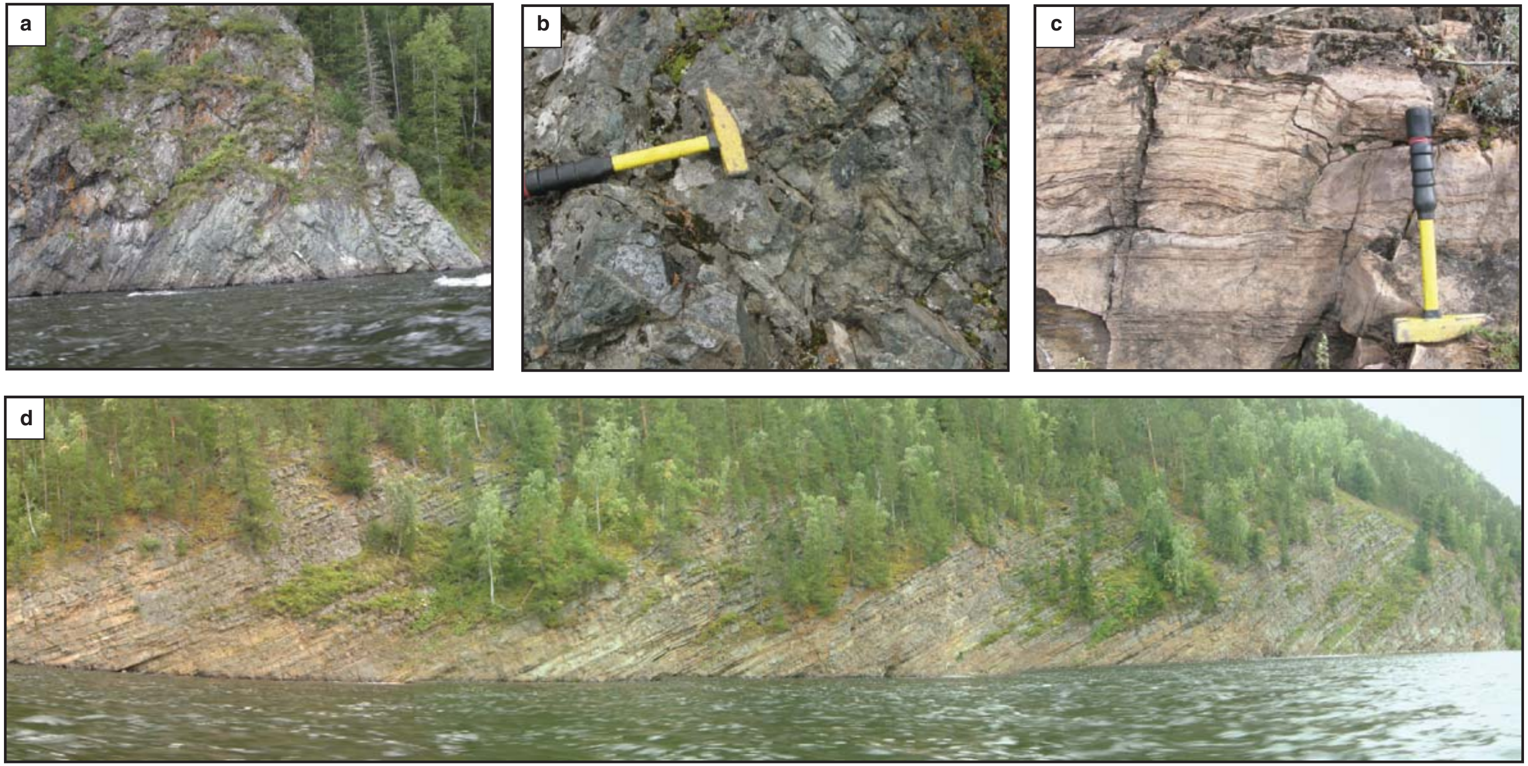

Fig. 5. Photographs showing representative features observed in the basement and Riphean strata exposed along the Tagul River near Tayshet. (**a**) Deformed metamorphic basement to the SE of a major suture zone on the Tagul River. (**b**) Basaltic breccias of the Mesoproterozoic Subluk Formation. (**c**) Finely laminated stromatolitic dolostone of the late Riphean Karagas Group. (**d**) General view of the monotonous thinly bedded clastic succession of the late Riphean Oselok Group along the Tagul River.

passive margin sedimentation into this region (Gladkochub *et al.* 2006).

On the Baykit Anticlise, east of Enisey Ridge, Riphean strata are absent in the north but reach up to 4000 m thick in the south based on seismic and drilling data (Kraevsky *et al.* 1991). The total thickness of Riphean rocks on the Khatanga Saddle is 2000 m (Mel'nikov 2005). Riphean sediments crop out on the Chadobets Uplift, one of the smaller structures complicating the anticlise (Fig. 1), and in the Irkineeva Uplift (Fig. 6a–d), a Riphean rift thought to have been inverted during the late Riphean (Fig. 3), but are elsewhere buried under younger strata. Riphean sediments on the Baykit Anticlise are dominated by interbedded carbonate and fine clastic beds and are interpreted to record passive margin sedimentation during early Neoproterozoic time (Vernikovsky *et al.* 2004; Kochnev *et al.* 2007). The Enisey Ridge began to deform during the late Riphean, and passive margin sediments in the Baykit region are overlain by late Riphean molasse (Vernikovsky *et al.* 2004).

At the end of the Riphean time, Siberia was an uplifted landmass from which clastic molasse material was transported into surrounding basins (Mel'nikov *et al.* 2005). Uplifted collisional highs around the platform margins provided a further source of clastic sediment. Riphean sediments were deformed in many areas and were partially and, in some areas (e.g. central Nepa-Botuoba), completely removed by erosion (Fig. 2).

Vendian

The Vendian succession records an overall transgressive regime with older formations restricted to the platform margins and successively younger formations increasingly widespread across the craton (Fig. 4). Vendian sediments rest unconformably on various levels of the Riphean sediments and on crystalline basement (Shenfel 1991).

During the Vendian, the Baykit and the Nepa-Botuoba basins are thought to have been located on the flanks of an uplift that occupied the central part of the Siberian Platform (Mel'nikov 1994). Between them was a less intensively subsiding region, the Khatanga Saddle, which was inverted in the Late Silurian when the Barguzin microcontinent collided with Siberia. This collisional event resulted in deformation across the platform and has important implications for petroleum migration and trapping (see discussion of hydrocarbon potential). The interpreted extent of these uplifts and their duration as topographic highs varies between publications (compare maps of Karnyushina *et al.* 2008 and Mel'nikov 1994). The thickness of Vendian strata ranges from 160 m in the northern Baykit Anticlise to 1600 m in the southern and southwestern Baykit Anticlise (Timoshina 2005) and the Nepa-Botuoba region (Mel'nikov 2005).

Vendian strata can be divided into four lithostratigraphic units: the Vilyuychan, Nepa, Tira regional horizons, which are clastic-dominated, and the Nemakyt–Daldynian Danilovo Regional Horizon, which is characterized by carbonate deposition (Fig. 7; Mel'nikov 1994; Kochnev *et al.* 2007). Some progress has been made towards establishing a regional chronostratigraphy based on integrated $\delta^{13}C$ chemostratigraphy and establishing a tentative sequence stratigraphic framework (e.g. Knoll *et al.* 1995; Pelechaty 1998); however, the older terminology is well established in the literature and is preferred here.

Vilyuychan Regional Horizon

Strata belonging to the Vilyuychan Regional Horizon are of uncertain age and lie between strata of known Riphean and Vendian age (i.e. the latest Riphean–early Vendian *sensu* Mel'nikov 2005). The sediments represent a post-Riphean molasse and are preserved only in marginal parts of the platform (e.g. Nepa-Botuoba) where foreland depressions formed adjacent and parallel to collisional belts formed by accretion of the Baikal–Muya ophiolites and island arcs during the latest Riphean and Vendian time (Vernikovsky *et al.* 2004). Clastic sediment was derived both from the platform and the surrounding orogens. Vilyuychan strata are dominated by clastic strata everywhere except in the NE Cis-Patom region where marls and shallow marine limestones and dolomites dominate the succession (Fig. 7). Karnyushina *et al.* (2008) use well data to reconstruct the distribution of clastic facies across the platform. Their map indicates that broad, conglomerate-dominated alluvial fans formed a fringe around uplifted areas and fed sediment onto a broad alluvial and lacustrine plain (Fig. 8a). Most of the clastic strata deposited on the Angara-Lena Step, Cis-Sayan and parts of the Nepa-Botuoba regions were eroded prior to deposition of the Nepa Regional Horizon (Mel'nikov *et al.* 1989).

Nepa Regional Horizon

Sediments belonging to the Nepa Regional Horizon are preserved over a much broader area than those of the underlying Vilyuychan Regional Horizon and extend into most parts of the southern Siberian Platform (Figs 7 & 8; Mel'nikov *et al.* 1989; Karnyushina *et al.* 2008). Erosional highs such as the Kamo Arch, central Siberia and parts of Nepa-Botuoba are fringed by sandstone-dominated successions that fine laterally into fine-grained alluvial plain and shallow marine successions (Figs 7 & 8). The marked decrease in grain size combined with

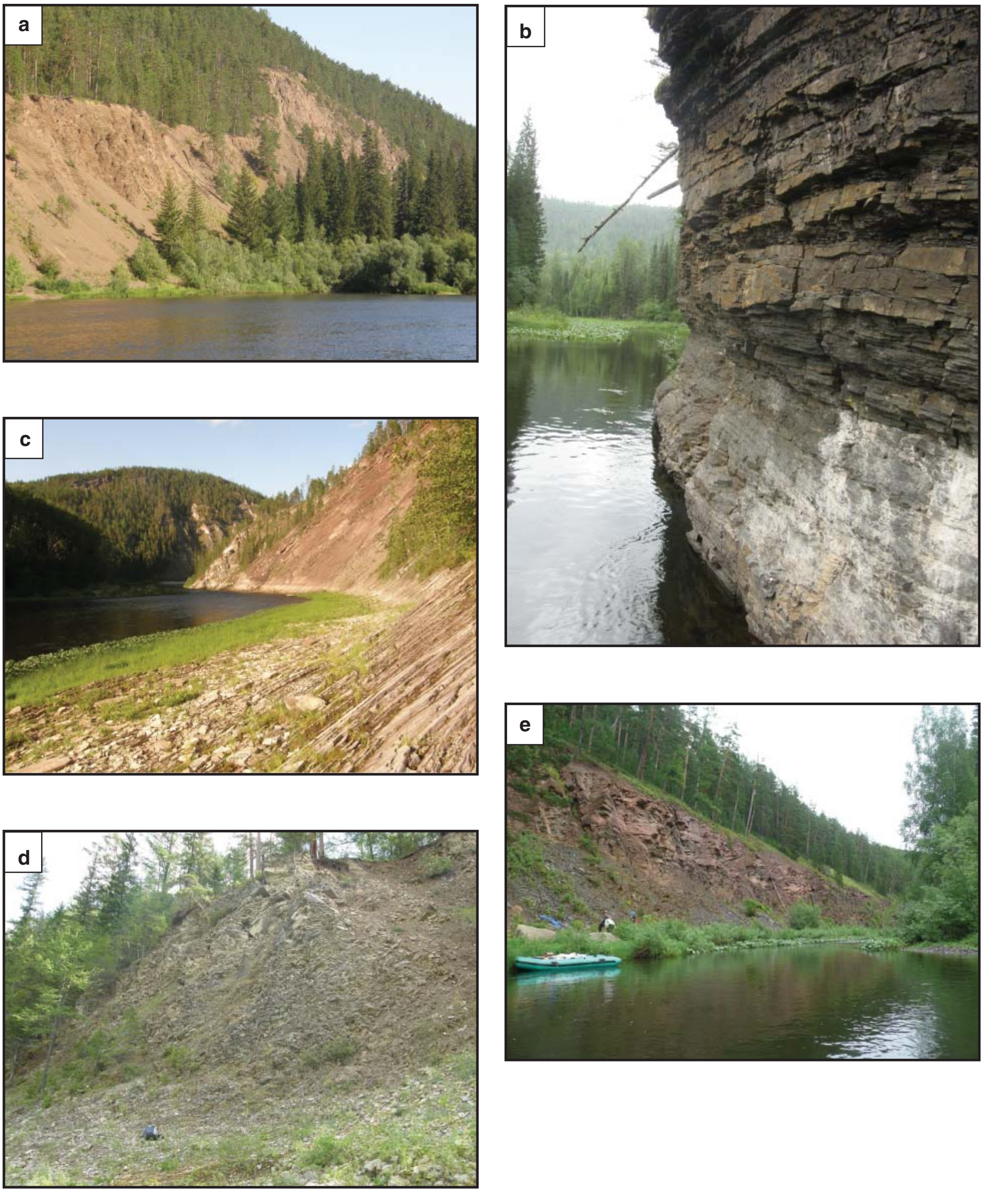

Fig. 6. Field photographs showing outcrops of late Riphean and Vendian strata exposed on the Irkineeva Uplift at the southern margin of the Baykit Anticlise. (**a**) Thinly bedded black shales of the middle Riphean Uderey Formation exposed on the Irkineeva River. In the subsurface this unit is a potential source horizon for the Baykit Anticlise. (**b**) Interbedded black sandy shales and sandy dolostones of the Upper Riphean Pogoryuy Formation exposed on the banks of the Nizhnyaya Terya River. (**c**) Thick succession of thinly bedded dolomites, sandstones and siltstones from the late Riphean Kartochka Formation exposed on the banks of the Irkineeva River. (**d**) Organic-rich dolostones and small reef bodies of the late Riphean Potoskuy Formation exposed on the Irkineeva River. This interval provides another potential source of hydrocarbons to the Baykit Anticlise. (**e**) Outcrop of the Vendian Chistyakov Formation on the Irkineeva River. Vendian strata overlie the Baikalian unconformity and are dominated by clastic strata. These coarsening-upward, sandstone-dominated deposits are interpreted as a prograding clastic delta sourced from the Enisey Ridge. Late Vendian carbonate units are not exposed in the Irkineeva Uplift.

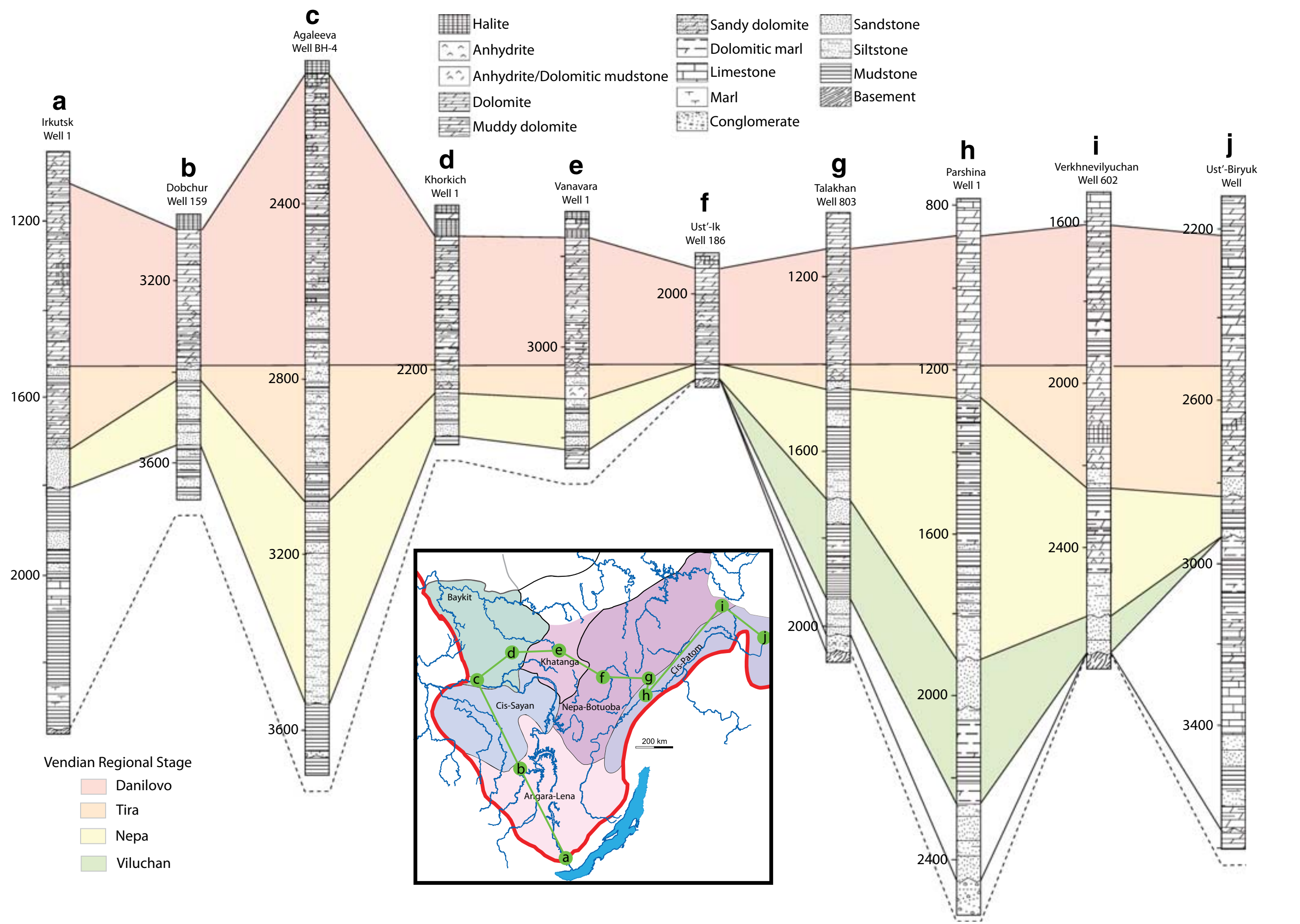

Fig. 7. Correlation panel for Vendian strata observed in wells across the southern Siberian Platform. Inset map shows well locations and the line of correlation. Wells (**a**), (**b**), (**d**), (**e**), (**f**), (**g**), (**h**), (**i**) and (**j**) modified after Mel'nikov (1994); well (**c**) modified after Kochnev *et al.* (2007).

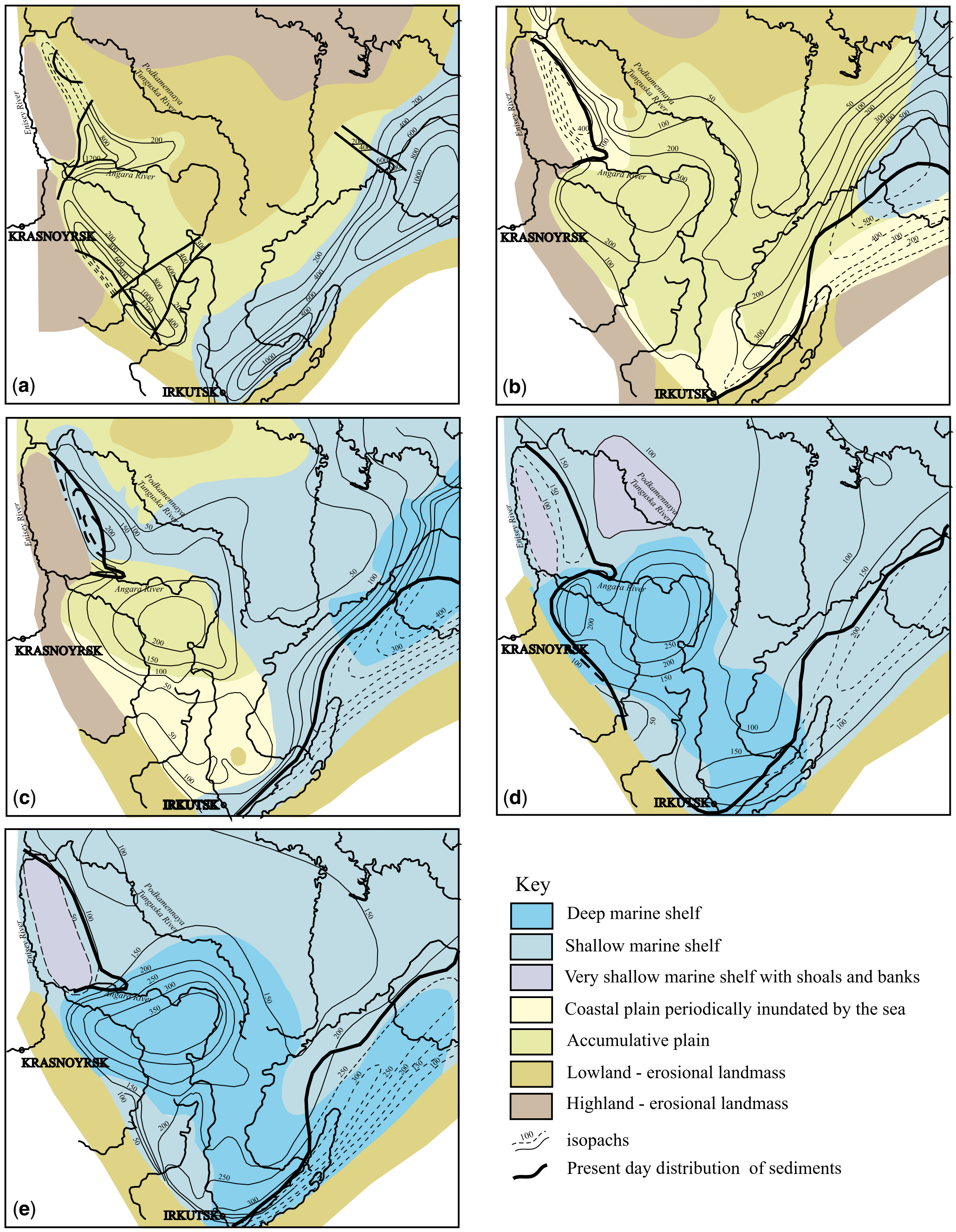

Fig. 8. Palaeogeographic maps showing the southern Siberian Platform during Vendian time modified after Mel'nikov (1994). (**a**) Vilyuchan, (**b**) Nepa, (**c**) Tira, (**d**) Danilovo (Lower–Middle), (**e**) Danilovo (Upper). Maps are based on a review of well and outcrop data too numerous to show on the maps.

evidence for denudation of source areas (e.g. 60 m cliffs incised into Riphean strata on the Kamo Arch; Mel'nikov 1994) indicates that uplift of the source areas had slowed or migrated further inland. Isopach data indicate that the subsidence along the southwestern platform margin had migrated eastwards into the Cis-Sayan region (Mel'nikov 1994). In contrast, the Baykal–Patom depression (in the Cis-Patom region) underwent continued subsidence in response to the ongoing collision between the Baikal–Muya island arcs and Siberia and up to 600 m of sediment accumulated in an open shelf environment. The Cis-Enisey Foredeep (east of the Enisey Ridge) also remained active and underwent periodic marine incursions (Fig. 8b). This final phase of subsidence occurred in response to the accretion of the Isakov and Predivinsk island arc terranes to Siberia (Vernikovsky *et al.* 2008).

Tira Regional Horizon

In the Tira Regional Horizon, the ongoing marine transgression inundated large parts of the Siberian Platform and only isolated land areas remained (e.g. Khatanga, Fig. 8c). Subsidence continued across the Cis-Enisey and Cis-Patom foredeeps and on the Angar-Lena Step and Cis-Sayan regions. Sediments belonging to the Tira Regional Horizon are widely preserved across the platform and are characterized by a broad mix of lithologies including clastics, carbonates, sulphates and salt (Fig. 7). The margins of the platform are again dominated by sandstones sourced from the now denuded source areas in the SW and SE and from the Enisey Ridge. In western areas, away from the clastic sources, much of the platform was dominated by deposition of mud-grade sediment. Eastern Nepa-Botuoba and the Cis-Patom depression are characterized by interbedded clastic and carbonate successions. Sulphate and carbonate rocks occur in the deepest part of the Cis-Patom depression. Salt deposits up to 50 m thick were deposited in the western margin of the platform (e.g. Angara River) in late Tira time, and coeval anhydrite and anhydritic dolomites formed in the hypersaline shallow sea that dominated the central and eastern parts of the platform (Mel'nikov 2005).

Danilovo Regional Horizon

The Danilovo Regional Horizon overlies a disconformable or unconformable basal contact with the Tira Regional Horizon sediments (Fig. 7). In the Danilovo Regional Horizon the marine transgression finally inundated the platform and, apart from low-lying land areas along the platform margins, sedimentation occurred across the whole of the area (Figs 7 & 8d). The thickest sediments accumulated in the Cis-Sayan where total thicknesses reach 600 m, and thick successions may also have accumulated in the Cis-Enisey Trough and Cis-Patom Depression. The lower part of the Danilovo succession is dominated by sandstones derived from highs at the platform margins (Sovetov *et al.* 2007). Anhydrite or salt occur in all areas at the end of early Danilovo time. Carbonates were deposited across much of the platform during middle–late Danilovo time. The central part of the platform was dominated by shallow-water, salt-bearing carbonates, whereas deeper-water conditions prevailed in the southern part of the platform (Mel'nikov 1994, Fig. 8e).

Post Vendian stratigraphy

Following deposition of the Vendian, subsidence greatly increased during Cambrian and Early Ordovician time and a 2200–3600 m thick succession of evaporites and carbonates accumulated (Mel'nikov 1994). Subsidence rates decreased during the Middle Ordovician–Silurian, when a mixed clastic and carbonate succession accumulated and parts of the platform underwent periodic uplift in response to the collision of the Barguzin Terrane with southern Siberia. Nepa-Botuoba, Angara-Lena and the northern Cis-Patom regions were exposed sources of clastic sediment by late Silurian time. The Khatanga region was also inverted during the Late Silurian. Vendian–Silurian successions reach 2700–3100 m in Nepa-Botuoba, Baykit and Khatanga, 3900–4000 m in the Cis-Patom and Angara-Lena regions, and up to 6000 m in the Cis-Sayan region (Mel'nikov 1994).

During the Devonian and Early Carboniferous, sedimentation was localized; up to 250 m accumulated in the northern flanks of the Kamo Arch, 200 m in the Cis-Sayan region and 150 m in the Cis-Patom regions. The succession is dominated by clastic sediments eroding from exposed highs at the margins of the platform and also within the platform, for example, in the Khatanga region.

The Middle-Carboniferous–Triassic time was characterized by widespread uplift and erosion of Carboniferous and Silurian sediments. Subsidence increased in the south of the platform during the Permian when 300–500 m of coal-bearing clastics were deposited in the Cis-Sayan region. The Cis-Patom and Angara-Lena regions continued to act as an uplifted sediment source at this time. The latest Permian and Early Triassic of northern Siberia is dominated by deposition of the Siberian traps, and during Middle–Late Triassic time the whole of southern Siberia was uplifted and underwent erosion with the removal of 150–300 m of Early Palaeozoic sediments (Mel'nikov 1994).

During Early–Middle Jurassic, Late Cretaceous and Early Palaeogene times, thin sediments accumulated across the southern part of the Siberian Platform; however, Mel'nikov (1994) suggests that, on balance, erosion outstripped sediment accumulation in the southern Siberian Platform.

Petroleum potential

The Lena Tunguska oil and gas province contains 99 known hydrocarbon fields, of which 29 are oil and gas fields and 60 are gas condensate fields (Nakashima 2004). Most of these fields are located in the Nepa Arch and Kamo Arch, including the five largest oil and gas fields, which together account for 85% of the proven oil reserves in East Siberia. The remaining fields are located in the Khatanga Saddle and Angara-Lena Step (Fig. 1).

These fields are hosted in Riphean–Cambrian strata, which, based on regionally distributed reservoirs and seals at several stratigraphic levels, may be subdivided into three distinct oil and gas plays, each with their own reservoir and top seal. These are (i) a Riphean play in which carbonate reservoirs are sealed by early Vendian clastic sediments; (ii) a Vendian play consisting of four clastic reservoirs in the Vilyuychan, Nepa and Tira Regional Horizons with a muddy carbonate seal in the lower part of the Danilovo Regional Horizon; (iii) a Vendian–Cambrian play with two carbonate reservoirs in the Middle and Upper Danilovo and Lower Cambrian succession. A regional seal is provided by salt bearing dolomites.

In this section we summarize potential source and reservoir units for each of the hydrocarbon plays before outlining the likely maturation history. The exploration potential for each region of the southern Siberian Platform is also discussed.

Source rocks

Riphean strata are recognized by most authors as a primary source for hydrocarbons on the Siberian Platform, with some estimating that they account for up to 90% of known hydrocarbon reserves (Drobot 1988). Riphean source rocks are known both on the platform and in the deformed remnants of foreland basins and back-arc basins around the platform margins. In the platform succession, good source rock intervals occur at the base of depositional cycles at several levels on the Kamo Arch and Khatanga saddle, where Riphean strata have been widely studied in wells. Highly prospective intervals include the Lower–Middle Riphean Vedreshev and Madra formations (mean TOC 1.2%), the Late Riphean Iremeken Formation (mean TOC 8.27%) on the Kamo Arch, and the late Riphean Ayan Formation (mean TOC 1.45%) on the Khatanga Saddle (Filiptsov *et al.* 1998; Timoshina 2005). These source rocks are characterized by great lateral and vertical variability, leading to a very irregular distribution of organic matter (Frolov *et al.* 2011). The source potential of Riphean platform sediments deposited in deeper basins (e.g. the Angara-Kotul Rift Basin/Chunya Basin and the Cis-Sayan Syneclise) that have not been drilled is uncertain. However, based on the presence of good source intervals on their margins, and the trend to deep marine depositional environments in the basin centres, they must be considered good candidates for source rock deposition. Riphean successions preserved at the deformed platform margins include thick intervals with excellent source potential and great lateral extent. In the Cis-Patom Trough, Middle–Late Riphean carbonaceous mudstones have TOC values >10% (Khabarov 1995). In the Cis-Enisey Trough, thick accumulations of black shale, subsequently deformed and uplifted as part of the Enisey Ridge, contain source rock intervals with TOC values of 5–10%, occasionally as high as 20% (Voronova & Tull 1993).

Potential hydrocarbon source rock intervals are also known from Vendian strata. Early Vendian sediments on the Siberian Platform are dominated by continental red beds that have low organic content. However, mudstones in the Middle Vendian Oskoba Formation have TOC values up to 14% on the Kamo Arch (Timoshina 2005). Vendian sediments on the Cis-Sayan region have not been widely drilled; however, it seems likely that intervals with source potential were deposited in this deep basin during late Vendian time (Fig. 8). The Cis-Patom Trough remained a marine basin throughout the Vendian and contains two potential source intervals. Vendian black mudstones with TOC values of 4–5% are reported and, in a 10 m thick black mudstone unit at the top of the Nepa Horizon, mean TOC reaches 5.6% (Drobot 1988; Mel'nikov 1994). This suggests that Vendian source rocks, despite being less rich in TOC than Riphean source rocks, are probably widespread in the overthrust zone of the Patom Highlands (Mel'nikov 1994).

Palaeozoic source rocks are not reported in southern Siberia, although Silurian strata are considered important in the Tunguiska Basin to the NW.

Reservoirs

The three hydrocarbon plays are distinguished based on the assessment of probable reservoir units. In this section we discuss the reservoir potential of each of these plays in general terms; mechanisms of trap formation vary from region to region and are discussed later.

Riphean clastic and carbonate units have generally low reservoir potential across the platform due to depositional heterogeneity and subsequent alteration during millions of years of deformation and fluid flow. There are, however, two situations where alteration of Riphean strata increases porosity and permeability to the point that they become viable reservoirs. Reservoirs are reported within the Riphean succession where tectonic fracturing of carbonate units leads to leaching and cavernous porosity. The Bysykhtakh Field in the eastern Siberian Platform is the only example of this field type. The future potential of such reservoirs is uncertain; some authors (e.g. Surkov *et al.* 1991) consider them important while others (e.g. Frolov *et al.* 2011) dismiss them as exploration targets. In contrast, the potential of reservoirs developed by karstification of exposed Riphean strata prior to deposition of the Vendian is undisputed following discovery of the Yurubchen and Kuyumba Fields on the Kamo Arch. On the Kamo Arch the palaeo-karst developed below the unconformity and penetrated up to 500 m below the top of the succession (Voronova & Tull 1993). The porosity is largely the result of leaching during exposure and, combined with later fracturing, has produced cavernous reservoirs with porosities as high as 10% (Kuznetsov & Skobeleva 2005). Riphean strata were eroded over wide areas of the Siberian Platform; consequently, karstified Riphean reservoirs are predicted around the margins of the Baykit Anticlise, Khatanga Saddle and around the Angara-Lena Step (Fig. 2).

Where preserved, Vendian clastic reservoirs are considered the most important target for hydrocarbon exploration on the southern Siberian Platform. Sandstone reservoirs occur at several stratigraphic levels and are usually named according to local stratigraphic schemes. They are commonly stratigraphically sealed by interbedded siltstone and evaporite beds, and a regional seal is provided by muddy carbonates in the lower part of the Danilovo Horizon. Correlation of sandstone reservoirs between fields is problematic due to an absence of regional seismic data and a paucity of fauna.

Late Vendian–Cambrian reservoirs are most significant in areas where the clastic Vendian is absent, such as in Central Nepa-Botuoba, where cavernous algal dolomites with porosities between 7 and 9% occur, and the Vilyuychan Saddle (in northeastern Nepa-Botuoba), where limestone and dolomite reservoirs have porosities of 10–25% (Mel'nikov 1994). Particularly high porosities occur where carbonates were sub-aerially exposed, leading to karstification; examples are the trap forming reefs in the basal part of the early Cambrian Osa Formation in the Talakan–Verkhnyaya–Chona field (Mel'nikov *et al.* 2005). In the Khatanga saddle, Vendian carbonates of the Soba, Tetre and Oka formations are sealed by salt in the upper Usolka Formation, although these reservoirs have generally low permeability (Mel'nikov *et al.* 2008).

Maturation and migration

The importance of Riphean source rocks in the hydrocarbon systems of East Siberia presents a huge span of geological time for hydrocarbon maturation and migration to occur. The literature is dominated by two migration models, one invoking Vendian–Cambrian maturation and the other proposing Early Palaeozoic maturation. The difference between these models lies in the significance attached to Riphean source rocks on the platform margins.

If Riphean strata in the Pre-Enisey Trough and the Cis-Patom Trough are an important source of hydrocarbons to reservoirs on the platform, then a model invoking early generation, migration and trapping must be invoked, because these source regions were substantially deformed during the Baikalian orogeny.

Most authors agree that source intervals in the Pre-Enisey Trough passed into the oil window (and possibly into the gas window) during the Riphean, and that the hydrocarbons generated would have migrated up dip onto the platform. There is, however, significant disagreement as to the potential for early hydrocarbons to be trapped and preserved on the platform. Trapping and preserving early hydrocarbons through the Baikalian orogeny and subsequent deformation events present significant problems. In particular, the processes of karstification and structuration that created the Riphean reservoirs on the Kamo Arch occurred during the Baikalian orogeny, and the seals are provided by the basal Vendian strata. Consequently, it seems likely that hydrocarbons generated during the Riphean must have been destroyed by erosion during the creation of the pre-Vendian unconformity (Frolov *et al.* 2011). Bitumens resulting from the weathering of hydrocarbons are seen in Riphean–Triassic strata across the Siberian Platform and are testimony to the volume of hydrocarbons lost during the long evolution of the hydrocarbon systems (Bazhenova & Tull 1995). Other authors suggest that although a substantial proportion of the early generated hydrocarbons were destroyed, there is the potential for some of them to have been trapped within the Riphean succession, and from there they may have subsequently migrated into the present reservoirs (Surkov *et al.* 1991). Timoshina (2005) recognized two distinct hydrocarbon families on the Siberian Platform, one of which was restricted to the Riphean fields on the Kamo Arch. Kontorovich *et al.* (1988) established that organic material of Riphean age was the source of hydrocarbons discovered in Riphean clastic reservoirs by tracing abnormally high contents of 12–13-mono-methylalkanes present in oils from the Yurubchen field and also in bitumen extracts from Riphean source rocks, which implies a Riphean source unique to this region.

In the Cis-Patom Trough the main stage of collisional deformation occurred during the Palaeozoic;

consequently, there is greater potential for hydrocarbons generated in this basin to be preserved. Generation of hydrocarbons from Riphean source rocks is thought to have begun during the Riphean and to have been completed during the Vendian but, as discussed above, much of the early generated hydrocarbons are likely to have been lost during formation of the pre-Vendian unconformity (Mel'nikov 1994). The main stage of migration from Riphean source rocks into Vendian and Vendian–Lower Cambrian reservoirs on the Siberian Platform occurred during late Vendian–early Cambrian time, after the formation of the regional seals (Mel'nikov 1994). Vendian source rocks in the Cis-Patom Trough began to generate hydrocarbons in the late Cambrian, and peak generation and migration was reached during the Silurian (Kontorovich *et al.* 1981).

Riphean source intervals deposited in basins on the platform (Cis-Sayan and Angara-Kotul Rift/Chunya Basin) underwent less pre-Vendian erosion and, due to the increasing Vendian overburden, they probably passed through the oil window during the Vendian. Ultimately, Riphean and Vendian source intervals were buried deep enough during the Palaeozoic to exhaust their hydrocarbon potential (Frolov *et al.* 2011). The hydrocarbons produced in these basins will have been destroyed by thermal alteration unless they migrated to shallower stratigraphic positions. Cambrian salt inhibits upward movement, so lateral migration to the basin margins is the only pathway available. This has clear implications for targeting hydrocarbon exploration in these basins.

The timing of hydrocarbon generation from Riphean source rocks on the Kamo Arch is well constrained. Lower–Middle Riphean source rocks of the Vedreshev and Madra formations, which underlie the pre-Vendian unconformity, are late or post mature. They are directly overlain by Vendian sediments that are within peak maturity for organic matter (Filiptsov *et al.* 1999; Timoshina 2005). This categenic unconformity suggests Lower–Middle Riphean units reached maximum maturity during pre-Baikalian time. In contrast, a gradual increase in kerogen maturation is recorded between Late Riphean source rocks (e.g. the Iremeken Formation) and Vendian source rocks, suggesting they reached maturity post Baikalian time (Filiptsov *et al.* 1999). Frolov *et al.* (2011) show that Late Riphean source intervals on the Kamo Arch began to generate oil in the Vendian and peaked during the upper Cambrian or Ordovician. Peak gas generation followed during the Ordovician–Silurian, and the main phase for gas migration probably occurred in the Triassic, related both to emplacement of the Siberian Traps and cracking of earlier oil.

Regional hydrocarbon potential

Cis-Patom Trough

The Cis-Patom Trough can be traced along the eastern boundary of the Siberian Platform (Fig. 1), and is 1000 km long and up to 150 km wide. This depression formed in response to collisions during the Baykalian orogeny and contains thick Early–Middle Riphean passive margin sediments overlain by a Late Riphean–Vendian active margin and foreland basin succession that contains known source intervals. Sediments in the Cis-Patom Trough were intensely deformed during the collision of the Barguzin microcontinent and Siberia during the Silurian, and the inner slope and base of the depression are buried beneath thrust sheets that tectonically juxtapose Vendian outer shelf and slope deposits on coeval sabka evaporites (Pelechaty 1998).

The Cis-Patom Trough is considered to be an important regional kitchen from which hydrocarbons generated in Riphean and Vendian source intervals charged oil, gas and gas condensate fields on the Nepa-Botuoba Anticlise and Angara-Lena Step. The Cis-Patom Trough underwent continued subsidence from Riphean to Silurian times, and hydrocarbon generation probably began in the late Riphean and continued until the Silurian when the basin closed.

The charging of reservoirs in the Nepa Arch and Angara-Lena Step from source rocks in the Cis-Patom Trough requires a lateral migration of up to 300 km. The architecture of the Siberian Platform during the Vendian–Cambrian was favourable to such long-distance migration, because the thick carbonates and clastic successions deposited on the platform margins provided a fairway for up-dip migration onto the elevated flanks of the platform.

The Bysykhtakh gas field in the northern part of the foredeep probably formed in a thrust-related anticline (Ulmishek 2001*a*). No other hydrocarbon fields are known from this area and it has low exploration potential due to the intensity of Silurian deformation.

Nepa-Botuoba Anticlise

The Nepa-Botuoba Anticlise, located in the SE of the platform, is 800 km long and 380 km wide and is covered by early Vendian–early Palaeozoic clastic units. Following Baikalian uplift, Riphean strata were eroded from the crest of the Nepa-Botuoba Anticlise, and clastic Vendian strata onlap the margins of the high. A number of small structures, including the Nepa Arch and Verkhnyayan Chona Uplift, formed on the crest of the anticlise during this deformation event. Successful exploration in Nepa-Botuoba has focused on oil and gas deposits hosted in Vendian sandstone reservoirs. Several large fields have been discovered, mainly located on the Nepa Arch. These include the four largest oil fields in East Siberia; Verkhnyaya-Chona (1220 Mbbl, 1.1 TCF), Chayanda (730 Mbbl, 5.6 TCF), Talakan (570 Mbbl, 1 TCF) and Srednyay Chandayaa Botuoba (440 Mbbl, 5.5 TCF) (Nakashima 2004). Carbonate reservoirs are less important in this region, and only in the Vilyuchansk region have hydrocarbons been found in dolomite reservoirs (Mel'nikov 1994; Drobot *et al.* 2004).

The most important reservoirs on the Nepa-Botuoba Anticlise belong to the clastic Vendian play. Sandstone reservoir units occur at several horizons, but most have limited lateral extent. They commonly wedge out as they onlap the high and shale out to the SE. Abrupt changes in the reservoir properties of the sandstones result from diagenesis, including silicification, halitization and sulphatization, which are irregular and unpredictable. Diagenesis is thought to have occurred after the first phase of hydrocarbon migration and to have sealed existing reservoirs, protecting them against subsequent tectonic movement (Vinogradov 1978).

Hydrocarbon fields in the Nepa-Botuoba region can be divided into anticlinal and sheeted types. Anticlinal traps, which drape over basement highs, characterize hydrocarbon fields on the crest of the Nepa-Botuoba Arch (Ulmishek 2001*a*). These folds deform Vendian and often early Cambrian sediments and are interpreted to have formed during the Early Palaeozoic in response to terrane accretion along the southern margin of Siberia. The timing of their formation is critical to the viability of the early hydrocarbon migration model. Lithological variation in reservoir properties forms the main trapping mechanism in non-anticlinal fields on the Nepa-Botuoba Anticlise, where traps due to simple stratigraphic pinchouts are rare (Mel'nikov 1994). Many fields, particularly those in the Mirnin area in northeastern Nepa-Botuoba are affected by faults that compartmentalize reservoirs. These faults probably formed during Early Palaeozoic compressional deformation and represent a significant risk to a Vendian–Cambrian hydrocarbon charge. However, the combination of significant reservoir heterogeneity and the presence of Cambrian salt, which forms a self-sealing trap, provides protection to early hydrocarbon accumulations.

Hydrocarbon accumulations in the Vendian–Cambrian play generally occur where the clastic Vendian play is thin or absent. The Vendian–Cambrian play forms important reservoirs in two areas: (i) in central Nepa–Botuoba, where cavernous algal dolomites occur with porosities between 7 and 9% (slightly reduced by secondary halite); (ii) the Vilyuychan Saddle in northeastern Nepa-Botuoba, where limestone and dolomite reservoirs are less affected by secondary halite, resulting in porosities of 10–25% and more continuous lateral extent (Mel'nikov 1994). Particularly high porosities occur where carbonates were sub-aerially exposed, leading to karstification, such as the trap-forming reefs in the basal part of the early Cambrian Osa Formation in the Talakan-Verkhnyaya Chona field (Mel'nikov *et al.* 2005). Accumulations in such reservoirs clearly require a late Cambrian or younger charge. It is possible that reservoirs of the Vendian–Cambrian play were charged by secondary migration of hydrocarbons from reservoirs in the Vendian play on the flanks of the Nepa-Botuoba Anticlise, for example, when older reservoirs overflowed or where seals were breached during Palaeozoic faulting.

The main phase of hydrocarbon maturation and migration from Riphean source rocks in the Cis-Patom Trough into the Nepa-Botuoba Arch is thought to have occurred during the Riphean–early Cambrian (Mel'nikov 1994). Owing to the age of the reservoirs (Vendian–Cambrian) and the later structuration, the preservation potential of these hydrocarbons appears low. Maturation and migration of Vendian hydrocarbons began in the Vendian and continued into the Silurian; consequently, these hydrocarbons have a much greater preservation potential. However, geochemical studies suggest a Riphean source for the majority of the hydrocarbons on the Nepa-Botuoba Anticlise, with Vendian source rocks providing only around 30% of the total (Drobot *et al.* 2004). The problems inherent in preserving hydrocarbons derived from the Cis-Patom Trough lead us to suggest that there may be a contribution from Riphean source rocks on the platform that were less deeply buried and consequently matured later. Riphean strata are absent across the Nepa-Botuoba region, but are widespread to the west and NW (Fig. 2).

Angara-Lena Step

The Angara-Lena Step (Fig. 1) lies at the southern end of the Siberian Platform, covering a territory of *c.* 350 000 km^2, and it shares many geological characteristics with the Nepa-Botuoba Arch (Ulmishek 2001*a*). Three giant gas condensate fields, thought to have been charged from source rocks in the Cis-Patom Trough, have been discovered on the Angara-Lena Step: the Kovykta, Bratsk and Atovo fields (Fig. 1).

The Vendian Chora Formation (equivalent to the Nepa and Tira regional horizons) contains four productive sandstone beds: Bokhan, Shaman, Parfenov and Bratsk (Mel'nikov *et al.* 2005). The sandstones are grey/red and separated by siltstone and anhydrite, and range from 3 (Bokhan) to 80 m thick (Parfenov). The major reservoir in all three fields is the Parfenov bed, which lies in the upper part of the clastic Vendian play, although commercial gas flows have been achieved from the older horizons in some wells.

Traps in the Angara-Lena Step are simple anticlines in which Vendian and Cambrian strata drape basement blocks, with minor faulting (e.g. Bratsk and Atovo fields) or stratigraphic traps in tilted fault blocks (Kovykta field). The anticlines and faulting are presumed to have formed during the Early Palaeozoic collisional events in the Baikal–Vitam Fold-belt. The resources of the giant Kovykta gas-condensate field are estimated to contain up to 1.9 TCF gas, plus 450 Mbbl of gas condensate. The gas from the Kovykta field contains 0.28% helium, 37–42% of Russia's total helium reserves (Poussenkova 2007). Reservoir thickness ranges from 5 to 30 m and it is possible that the Kovykta field might not simply be a field, but may instead form part of a huge condensate reservoir up to 200 km in diameter. Recoverable resources of this greater Kovykta reservoir could be as high as 10 TCF (Poussenkova 2007).

Overlap in the timing of hydrocarbon migration from the Cis-Patom Trough and the formation of reservoirs and traps on the Angara-Lena Step, the long migration distances required and subsequent deformation all suggest that the preservation potential of Riphean–Vendian hydrocarbons is low. However, the high helium content of the Kovykta gas field on the Angara-Lena step (0.28%) is significant. Helium may be derived either from uranium decay in Vendian reservoir lithics or from basement rocks, and to reach such high concentrations requires a long-lived, efficient trap that would also protect an early hydrocarbon charge.

Khatanga Saddle

The Khatanga Saddle is between 125 and 225 km wide and 200 and 400 km long, and lies between the Nepa-Botuoba Anticlise and the Baykit Anticlise. The Khatanga Saddle contains part of the Riphean–Vendian Chunya sedimentary basin (Mel'nikov *et al.* 2008; coincident with part of the Angara-Kotul Rift Basin) but was inverted in late Silurian–Early Carboniferous time. It underwent further subsidence during the Middle Carboniferous–Early Triassic.

Two producing oil and gas fields exist within the Khatanga Saddle: the Payga and Soba fields (Fig. 1). Commercial quantities of oil have also been obtained from individual wells in other areas of the saddle. The Payga and Soba fields lie on the eastern margin of the Chunya Basin where Riphean strata eroded on the flanks of the Nepa-Botuoba Anticlise subcrop Vendian sandstones of the Vanavara Formation (Nepa Regional Horizon). These sandstones form reservoirs with porosities ranging from 2.3 to 22% (in the Soba field) that are sealed by anhydritic dolomite of the overlying Oskoba Formation. The trap is an anticline that has been complicated by faulting producing three separate block structures (Bitner *et al.* 1990). The timing of the faulting remains uncertain, but it is likely to postdate trapping and relate to block uplifts in Silurian–Early Carboniferous time.

The primary source rocks in the Khatanga Saddle are considered to be Riphean strata preserved in the Chunya Basin (Mel'nikov *et al.* 2005). Upper Riphean sediments beneath the Soba field contain highly carbonaceous rocks (Filiptsov *et al.* 1998) that occur in the 140 m thick Ayan Formation as black mudstone with marl interbeds with a mean TOC of 1.45%. As discussed above, hydrocarbons produced within the Chuna Basin cannot migrate vertically due to Cambrian salt, so instead migrate laterally into fields at the margins of the basin (i.e. the Khatanga Saddle and the Baykit Anticlise).

The Khatanga Saddle is the focus of renewed exploration, particularly within the Ilimpeya petroleum zone to the north of the Soba and Payga fields. The main prospects are (i) late Riphean karstified carbonates sealed by Vendian mudstones (analogous to the Yurubchen–Tokhoma petroleum accumulation zone), (ii) the Vendian play recognized in the Soba and Payga fields, and (iii) late Vendian carbonates of the Vendian–Cambrian play, although these suffer from low porosity and permeability in the area (Mel'nikov *et al.* 2008).

Cis-Sayan Syneclise

South of the Baykit Anticlise is the Cis-Sayan Syneclise (Fig. 1), which covers an area of *c.* 192 000 km^2. Its western and southwestern margins are formed by the eastern Sayan and Enisey Ridge fold-belts. To the west it is bounded by the Angara-Lena Step. The Cis-Sayan basin is a deep Early Palaeozoic depression in which the basement occurs at depths of 5–7 km (Mel'nikov 1994).

No hydrocarbon fields have yet been discovered in the Cis-Sayan Syneclise; however, the area contains a thick Riphean and Vendian succession that has been buried to sufficient depths for hydrocarbon maturation to occur during Vendian–Early Palaeozoic time. The Riphean succession is likely to include potential source units similar to those in the Chunaya Basin to the north and there is particular interest in late Vendian strata exposed SW of the Biryusa River where the clastic succession (Shaman Formation) contains bitumen (Zolotov 1969; Mel'nikov *et al.* 2005; Samsonov & Larishev 2008). Hydrocarbons generated within the Cis-Sayan

Syneclise may have migrated into the surrounding highs in the Angara-Lena Step, Baykit Anticlise and southern Nepa-Botuoba Anticlise, but there is great potential for stratigraphic, lithological (e.g. reefs) and structural traps around the margins of the syneclise itself and therefore good potential for hydrocarbon exploration in the region.

Baykit Anticlise

The Baykit Anticlise lies in the western part of the platform, east of the Enisey Ridge and north of Cis-Sayan Syneclise. It occupies an area of 155 000 km^2. The major structures of the Baykit Anticlise have been mapped using seismic surveys: Central Kamo Arch, Kuyumba Uplift, Tayga Uplift and Chadobets Uplift (Fig. 1). Several large oil and gas fields are known in the Baykit Anticlise, mainly located on the Kamo Arch in the Yurubchen–Tokhoma Petroleum Accumulation Zone (PAZ).

Riphean strata on the Baykit Anticlise are up to 3000 m thick and are unconformably overlain by thin Vendian deposits. The clastic Vendian is thin or absent, so the Riphean play is the main focus of exploration in the region.

The structure of the petroleum reservoirs is well understood based on extensive well data (Kontorovich *et al.* 1994; Kuznetsov 1997). Riphean strata consist of a deformed succession of 12 alternating clay–carbonate, carbonate and clay units. The reservoir interval is a fractured Riphean dolostone represented by stromatolitic, intraclastic and microgranular varieties. Riphean strata were subaerially exposed for a long period during the early Vendian, and an extensive palaeo-karst has developed below the unconformity. Leaching during exposure, combined with later fracturing, produced cavernous reservoirs with porosities as high as 10% (Kuznetsov & Skobeleva 2005). Oil and gas have only been found in areas of well-developed palaeokarst and subsequent fracturing, so the boundaries of the Yurubchen–Tokhoma PAZ are largely defined based on the distribution of the palaeo-karst (Voronova & Tull 1993; Mel'nikov *et al.* 2008). High-quality seals are provided by mudstones in the overlying Vanavara Formation (Vendian), sulphate- and carbonate-bearing clastics of the Oskoba Formation (Vendian) and widespread lower Cambrian salt (Voronova & Tull 1993).

The Vendian succession, represented by mudstones interbedded with sandstones and siltstones, is thin (160–200 m) in the north and central part of the Baykit Anticlise and thick (750–1400 m) in the south and the SW, close to its boundaries (Timoshina 2005). Exploration in Vendian strata focuses on the Vanavara Formation (where its thickness exceeds 30 m, Mel'nikov *et al.* 2008) and the overlying Oskoba Formation. The Vanavara Formation contains five levels of oil- and gas-bearing sandstones sealed with a thick sulphate member of the Oskoba Formation. The Oskoba Formation contains a highly radioactive sandstone bed that has provided an economic gas flow in the Omora field (Mel'nikov *et al.* 2008). Late Vendian–Early Cambrian potential reservoirs are found in the Soba, Tetere and Osa carbonates, with the salt-bearing upper part of the Usol'e Formation acting as a regional seal. However, these carbonates have low porosity and permeability, limiting their potential. The Vendian–Cambrian boundary is conformable; however, its exact stratigraphic position has not been identified.

There are four hydrocarbon source regions with the potential to charge reservoirs in the Baykit Anticlise: the Cis-Enisey Trough to the west, the Cis-Sayan Syneclise to the south, the Chunya Basin to the NE and the Baykit Anticlise itself.

Timoshina (2005) and Kontorovich *et al.* (1988) established that fields hosted by Riphean sediments on the Kamo Arch belong to a distinct hydrocarbon family, implying a distinct source that has not charged fields in adjacent regions. The Chunya Basin is a source of hydrocarbons to the Khatanga Saddle so is unlikely to be the source of a unique hydrocarbon family on the Baykit Anticlise. Hydrocarbons sourced from the Chunya Basin do, however, represent a major play (the Chunku-Uchami Petroleum Accumulation Zone) along the northeastern flanks of the Bakyit Anticlise (Mel'nikov *et al.* 2008). Source intervals in the Cis-Enisey Trough, Cis-Sayan Syneclise and on the Baykit Anticlise itself therefore represent potential sources for hydrocarbons in known fields.

As discussed earlier, the preservation potential for hydrocarbons generated in the Cis-Enisey Trough is low because maturation occurred prior to formation of both the karst reservoir and Vendian seal. Riphean and Vendian sources on the Baykit Anticlise are mature (Frolov *et al.* 2011), but the distribution of organic matter is patchy and their potential is therefore uncertain. The Cis-Sayan Syneclise has very good source potential, assuming a similar maturation history to that proposed for the Chunaya Basin (Mel'nikov *et al.* 2008). However, migration of hydrocarbons from the Cis-Sayan Syneclise onto the Baykit Anticlise may have been impeded by deformation along the Irkineeva Uplift, which was repeatedly reactivated in early Palaeozoic time.

In addition to the Riphean source rocks discussed above, there are Vendian source rocks, including the late Vendian Oskoba Formation, which has TOC values of up to 14% on the Kamo Arch (Timoshina 2005). These Vendian source rocks are likely to be the source of oil and gas reserves in the Kuyumba field that are genetically distinct from hydrocarbons found in Riphean reservoirs (Bazhenova & Tull 1995).

Discussion

The recent interest in hydrocarbon exploration in East Siberia has supported increased levels of geological research in the region. The results of this research have revealed the geological complexity of this region by highlighting, and beginning to resolve, problems in our understanding of East Siberia's tectonic history, stratigraphy and hydrocarbon systems. Recent research has proven the potential for Riphean source rocks on the platform and mapped the depocentres in which hydrocarbon maturation and migration from these sources has occurred.

The potential for widespread Riphean and Vendian source intervals on the Siberian Platform provides an alternative to models invoking early maturation and migration from the platform margins. However, despite problems reconciling the timing of maturation and migration with the timing of trap formation in the Baykit Anticlise and the problems inherent to preserving hydrocarbon reservoirs filled during Neoproterozoic–Cambrian time, it remains likely that some fields in East Siberia have achieved this longevity. The main factors supporting the preservation of ancient hydrocarbon reserves in East Siberia are as follows.

- Since the development of the base Vendian unconformity when substantial loss of early hydrocarbons occurred (Mel'nikov 1994), some areas of the platform have not been substantially deformed. Palaeozoic deformation, particularly during the Silurian (uplift) and Permian (extension), was mainly localized at the edge of basement blocks, and over much of East Siberia Neoproterozoic and Early Palaeozoic strata are deformed only into long-wavelength folds. Faulting within these blocks is not intense, and although it probably breached early seals in some fields (e.g. Yurubchen), many fields remain largely unfaulted.
- The high helium content found in gas reserves on the Angara-Lena Step (Kovykta field) indicates that excellent trap integrity was sustained over extended periods of geological time. Such traps would also be capable of preserving an early hydrocarbon charge.
- Late Vendian argillaceous evaporate-rich carbonate beds, together with early Cambrian salts, form excellent regional seals. These are a major factor contributing to the preservation of hydrocarbon pools in Riphean and Vendian reservoirs over very long time periods, because salt formations are self-sealing and consequently difficult for faults to breach. The presence of this regional seal increases the chance of re-trapping hydrocarbons leaking from early accumulations breached by later deformation events.
- Widespread secondary mineralization in Nepa-Botuoba is thought to post-date the early hydrocarbon charge. Secondary mineralization reduces porosity around hydrocarbon fields, improving the seal and making the fields less susceptible to breaching by subsequent folding, tilting or faulting.
- Organic-rich Riphean and Vendian sediments in the Cis-Patom Trough represent the only known source rock capable of charging reservoirs in eastern Nepa-Botuoba. Hydrocarbons sourced from these rocks migrated during the Vendian–Cambrian.
- The composition of oil in reservoirs on the Siberian Platform indicate it is derived predominantly from Riphean source rocks. In most regions Riphean source rocks were producing hydrocarbons during Vendian–Early Palaeozoic times. The large reserves discovered suggest some of the early hydrocarbons must have been preserved.
- The influence of magmatic rocks on Infracambrian strata is not very well understood; however, it appears to have been minimal. The Siberian Platform has undergone several phases of extensive intrusive and extrusive volcanism culminating in the Permian–Triassic eruption of the Siberian traps (Mel'nikov *et al.* 1995). In some areas, magmatic rocks are thought to comprise large volumes of the preserved section (e.g. up to 20% in the Baykit region; Shemin 2007). However, the effects of these intrusions on the hydrocarbon systems are likely to be limited because in most cases intrusions are hosted in strata of Cambrian and younger age and are rarely found in Infracambrian strata. Magmatic episodes also post-date the main phases of hydrocarbon maturation and migration, so the effects of high heat flow associated with the impact of a mantle plume on the base of the Siberian Craton are not a major influence on hydrocarbon maturation in the region. The high heat flow may have resulted in cracking of oil in reservoirs increasing the volume of gas (Frolov *et al.* 2011).

Hydrocarbon exploration on the Siberian Platform has largely focused on the Vendian clastic succession with the exception of the Baykit region where the Riphean play is the primary target. Despite extensive drilling and seismic surveys, much of the southern Siberian Platform remains unexplored and many geological questions remain. The discovery of a major Riphean basin covering $>40\,000$ km^2

with significant potential for hydrocarbon generation, as recently as 2003–2005 (Mel'nikov *et al.* 2008; Rudnitskaya *et al.* 2008; Starosel'tsev 2008), indicates the potential gaps in our current geological understanding of the region. Further biostratigraphic and chemostratigraphic work is required to refine stratigraphic correlations across the platform and to accurately locate key boundaries within the succession. Only when strata can be accurately correlated across the region can the relationships of hydrocarbon systems from different areas be fully understood.

Our existing knowledge of Infracambrian hydrocarbon resources on the Siberian Platform reflects the narrow focus of past exploration. By expanding the search for hydrocarbons into new areas such as the NW Baykit Anticlise, the northwestern Nepa-Botuoba Arch and the Cis-Sayan Syneclise, and increasing the targeted succession to include the promising regional Riphean and Vendian–Cambrian play, there are probably more large discoveries to be made in the region.

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