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Meso-Neoproterozoic petroleum systems of the Eastern Siberian sedimentary basins

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ABSTRACT

The elements of the petroleum systems of the Siberian platform have been formed in the course of geological evolution in Meso- and Neoproterozoic time and correspond to the supercontinent stage from assembly of Paleo-Mesoproterozoic Columbia to break-up of Neoproteorzoic Rodinia. Several large sedimentary basins were established within the Siberian craton during the Riphean. A number of passive continental margin basins (the Turukhansk, Cis-Patom basins and others) developed on the southern, western, and, probably, northern craton peripheries. Several other basins, such as the Irkineeva-Vanavara, Kotuy, Anabar-Kureika, and Udzha basins, were entirely intracratonic. The structural patterns of these basins and their petroleum systems were essentially affected by Baikalian orogeny events with intensive dislocations and erosion of Riphean series, especially along the margins of the continent. As a result, hydrocarbon accumulations formed by the source rocks, which have realized their potential in Riphean within the margin basins, were, most likely, completely destroyed. Vendian and Lower Cambrian deposits were the main source for present day oil fields of the central and northern parts of the Nepa-Botuoba Anteclise and the Turukhansk Uplift. The Upper Riphean source rocks of the intracratonic basins, on the contrary, are unlikely to be affected by the significant pre-Vendian erosion and, thus, could be a source for the oil fields of the Yurubchen-Tokhomo Zone and the Katanga Saddle. Such difference in petroleum system evolution for different basins is also supported by results of oil–source rock correlations based on biomarker studies.

A new mega-cycle of formation of the sedimentary cover started on the Siberian platform in the Vendian (Ediacaran). The initial fabric of all the main structural elements of the platform was established at this time. The large Vendian depressions (the "prototypes" of Paleozoic Kureika and Cis-Sayan-Yenisei syneclises and Cis-Patom Trough) were areas of mainly marine sedimentation where the high potential hydrocarbon source series could be deposited. Large elevated areas served as a terrigenous provenance in the Early Vendian resulting in a large amount of clastic material deposited along their flanks. The most promising areas for new discoveries of hydrocarbon fields are in the slopes of the Baikit, Nepa-Botuoba and Anabar anticlises faced towards the Kureika Syneclise.

1. Introduction

The supercontinent stage from the assembly of Paleo-Mesoproterozoic Nuna/Columbia to the break-up of Neoproterozoic Rodinia is known for its rich and diverse hydrocarbon resources (e.g. Craig et al., 2013). The cyclic evolution of the Proterozoic supercontinents is responsible for the set-up of petroleum systems of Siberia. The spatial distribution of hydrocarbon resources as well as a time of their formation is determined by tectonic, paleogeographic and biogeochemical history of Proterozoic supercontinents during accretion, amalgamation, and breakup (e.g. Craig et al., 2013).

Siberian craton was a promontory of Proterozoic supercontinents – Mesoproterozoic Nuna/Columbia and Neoproterozoic Rodinia (Li et al., 2008; Pisarevsky et al., 2008; Wingate et al., 2009). The geological structure of the Siberian basement and the tectonic history of the Siberian assemblage show some similarities with the Laurentian craton. However, reconstructions based on palaeomagnetic data place Siberia at a distance from Laurentia

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with its south facing Laurentia's north (Pisarevsky et al., 2008 and references therein). Since the late Palaeoproterozoic Siberia and Laurentia were cohered, but not tightly collided (e.g. Didenko et al., 2009; Wingate et al., 2009).

Most of Siberia's margins faced an open ocean in the Meso- and Neoproterozoic. Passive margin sedimentary successions deposited along the eastern, north-western, and possibly northern edges of the Siberian craton. Besides, after final stabilization of the Siberian basement at ~1.8 Ga, several intracratonic sedimentary basins were produced by series of extensional events (Pisarevsky et al., 2008).

Proterozoic series of East Siberia (Siberian Craton) are, probably, the most enriched in hydrocarbons among pre-Cambrian deposits of the world. Proven recoverable reserves in Meso- and Neoproterozoic siliciclastic and carbonate reservoirs are estimated to be about 600 million tonnes of oil and more than 2700 billion cubic metres of gas (Efimov et al., 2012). These deposits dominate in the Lena-Tunguska petroleum province, which occupies the major part of the Siberian craton, excluding only its shields and peripheral Upper Paleozoic–Mesozoic depressions to the north and to the east. Proterozoic sedimentary rocks of great volume extend over a large territory of East Siberia, reaching 5 km or more in thickness. They were formed during several cycles of deposition lasting more than one billion years (approximately 1650–1600 to 540–530 Ma).

Oil and gas fields of the Lena-Tunguska province have an irregular distribution. The majority are located in the southern (the Nepa-Botuoba Anteclise,[1] adjacent parts of the Angara-Lena Terrace and Cis-Patom Trough) and the western (the Baikit Anteclise and the Turukhansk Uplift) regions of the province (Fig. 1). This is partially due to the fact that the north of the province (the Kureika Syneclise[2] and the flanks of the Anabar Anteclise) is very poorly studied with only scarce and low-quality seismic lines and sparse wells, which rarely penetrate into deeper Upper Proterozoic and Lower Cambrian successions. The Lena-Tunguska province has significant differences in geology, which affects the distribution of oil and gas fields to a considerable extent.

Several separate sedimentary basins, differing in tectonic setting and depositional environments, have been developed on Siberian palaeo-continent during the Meso-Neoproterozoic, resulting in formation of a range of petroleum systems, each with specific characteristics.

In this paper we discuss how knowledge of the basin evolution can help in oil and gas prospecting in the many under-explored areas of the Siberian platform.

2. Data set

This work is based on analysis of logging data from more than 500 deep boreholes, interpretation of regional 2D seismic lines, and studies of rock samples from wells and natural outcrops, carefully collected by the authors of this paper for last three decades. Results of optical microscope petrography, SEM, micro-tomography, chromatography, Rock-Eval, GCMS, carbon isotope studies and petrophysics are integrated. Additionally, an extensive Russian literature and open industrial reports have been compiled and utilized in this review, which are normally difficult to access for most non-Russian scientists.

3. Geological setting and evolution

The term "the Siberian platform" (the Siberian craton) was introduced in 1923 by A.A. Borisyak to distinguish a large territory with pre-Cambrian basement in between Yenisei and Lena rivers (Kontorovich, 1981). The basement complex of the craton consists of an amalgamation of Achaean terrains, which sometimes also includes meta-sedimentary deposits of Palaeo-Proterozoic continental margins in its upper part. The terrains are merged by several orogenic belts formed 1900–1800 Ma ago (Rosen et al., 1994).

In the central part of the platform the sedimentary cover is composed mainly of Mesoproterozoic, Neoproterozoic and Palaeozoic deposits with total thickness of about 10 km or more, which are dominated by carbonate series (Fig. 2). In general, the platform sedimentary cover is formed during two mega-cycles separated by a long discontinuity in the middle Neoproterozoic. Several large basins, both intra-continental and marginal, were formed during the first Meso-Neoproterozoic (Riphean) mega-cycle. Sedimentary sections of Riphean are dislocated, weathered and eroded to different extents as a result of collisional processes along the southern, south-western, and north-western craton peripheries during the Baikalian Orogeny (850–630 Ma) (Nikishin et al., 2010).

The deposition on the platform (siliciclastic at the beginning and then carbonate) was resumed in Ediacaran time on top of the weathering crust formed during the break in sedimentation. The main structural highs (Anabar, Aldan, Nepa-Botuoba, and Baikit anteclises) and depressions (Kureika and Cis-Sayan-Yenisei syneclises) of the central part of the Siberian platform were established during this time. It is worth noting that the platform structural pattern of Ediacaran and Paleozoic differs significantly from the Riphean (Fig. 3).

Early Paleozoic evolution of the craton occurred under the influence of generally gentle submergence with prevalent carbonate (in Early-Middle Cambrian also with evaporates) sedimentation. Rifting occurred in the eastern region of the platform in the Late Devonian–Mississippian time. It was accompanied by large-scale basaltic effusions of the Yakutsk-Vilyuy Large Igneous Province (LIP) and formation of an evaporate-bearing series (Parfenov, 2001; Kiselev et al., 2012, 2014; Ernst, 2014). Rift-related nature of Upper Devonian–Lower Carboniferous deposits is well defined within the West-Vilyuy Depression (Fig. 4). The deposition on the platform changed from carbonate-dominated to siliciclastic since the beginning of Pennsylvanian time. The main depocentres were located on the northern and eastern margins of the platform as well as in the Kureika Syneclise.

The Permian-Triassic boundary on the Siberian platform was marked by a dramatic magmatic event of the Siberian Trap LIP (e.g. Ivanov et al., 2013; Ernst, 2014) and more than 2 km thick tuff-lava series were formed in the Kureika Syneclise during this time. Simultaneously, a number of sills and dykes were intruded into sedimentary cover of the platform. The majority of intrusive bodies penetrate the uppermost 1–1.5 km of the section, and their aggregate thickness in the northern areas of the platform can reach up to 1000–1200 m (Starosel'tcev, 1996).

Mesozoic sedimentary basins of the Siberian platform were located in peripheral depressions of various origins. The platform is partially overlapped by the West Siberia basin to the west with the Proterozoic and Palaeozoic sections often eroded by Mesozoic deposits. To the north-west, the large Jurassic-Cretaceous Yenisei-Khatanga Trough (up to 6–8 km deep) was superimposed on the junction of the Siberian platform and the Taymyr-Severnaya Zemlya orogene (Botneva and Frolov, 1995). The Palaeozoic series

[1] Anteclise is a positive structure of the continental platform; it is of broad, regional extent and is produced by slow crustal upwarp during the course of several geologic periods. The term is used mainly in the Russian literature (Neuendorf, 2005).

[2] Syneclise is a negative structure of the continental platform; it is of broad, regional extent and is produced by slow crustal downwarp during the course of several geologic periods. The term is used mainly in the Russian literature (Neuendorf, 2005).