# Anabar–Lena Composite Tectono-Sedimentary Element, northern East Siberia

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**Abstract:** The Anabar–Lena Composite Tectono-Sedimentary Element (AL CTSE) is located in northern East Siberia extending for *c.* 700 km along the Laptev Sea coast between the Khatanga Bay and Lena River delta. The AL CTSE consists of rocks from the Mesoproterozoic to Late Cretaceous in age with the total thickness reaching 14 km. It evolved through the following tectonic settings: (1) Meso-Early Neoproterozoic intracratonic basin; (2) Ediacaran–Early Devonian passive margin; (3) Middle Devonian–Early Carboniferous rift; (4) late Early Carboniferous–latest Jurassic passive margin; (5) Permian foreland basin; (6) Triassic to Jurassic continental platform basin; and (7) latest Jurassic–earliest Late Cretaceous foreland basin. Proterozoic and lower–middle Paleozoic successions are composed mainly of carbonate rocks, while siliciclastic rocks dominate upper Paleozoic and Mesozoic sections. Several petroleum systems are assumed in the AL CTSE. Permian source rocks and Triassic sandstone reservoirs are the most important play elements. The presence of several mature source rock units and abundant oil and gas shows (both in wells and in outcrops), including the giant Olenek Bitumen Field, suggests that further exploration in this area may result in economic discoveries.

The Anabar–Lena Composite Tectono-Sedimentary Element (AL CTSE) is located in northern East Siberia (Fig. 1, Encl. A, E). Studies of its geology and petroleum systems have a long history. The first reports about surface oil leaks in this area date back to the beginning of the nineteenth century. Systematic geological surveys started in the 1930s when the first deep boreholes were drilled. In 1932, the basin was determined, for the first time, to be an individual tectonic element named by Shatsky (1932) as the 'Khatanga Depression'. Kalinko (1958) specified its boundaries, indicating that the basin extends from an area east of the Khatanga River towards the Lena River mouth. He also identified the Anabar–Khatanga Saddle (AKhS) as a separate structural domain located between the Khatanga and Anabar rivers, later often referred to as the Khatanga Saddle. However, on more recent tectonic maps, the AKhS has been included in the Anabar–Lena Basin and not shown as a separate structure (Parfenov 1990; Bogdanov *et al.* 1998). Nowadays, both structures are usually separated from each other, and the area between the Anabar and Lena rivers is usually called the Anabar–Lena (or, sometimes, Lena–Anabar) Basin or Province, whereas the AKhS occupies the area between the Khatanga and Anabar rivers (e.g. Pogrebitsky and Shanurenko 1998; Prokopiev and Deikunenko 2001; Kontorovich *et al.* 2013, 2019; Proskurnin and Shkarubo 2017). In this chapter, both structural domains – the AKhS and the Lena–Anabar Basin – are combined in the Anabar–Lena CTSE (Fig. 2).

The exploration history of northern East Siberia started in the 1930s when liquid oil occurrences were found in Jurassic sandstones at the southern shore of Khatanga Bay. Results of these early works are summarized by Kalinko (1958, 1959), who also presented maps and cross-sections of the Nordvik and Yuzhno-Tigyan oil fields and pointed out the high potential of Permian rocks. Later, Ivanov (1979) reported the huge Olenek Bitumen Field in Permian rocks at the boundary between the Olenek Uplift and the Anabar–Lena Basin. More extensive exploration, accompanied by 2D seismic data acquisition and drilling, took place in the 1980s when potential source rocks and reservoirs were identified and studied. Recent exploration has been conducted by the Russian oil companies Rosneft and Lukoil in the western part of the AL CTSE and adjoining parts of the Yenisei–Khatanga CTSE (Deev *et al.* 2021). Although no significant discoveries have been made so far, the AL CTSE is commonly believed to have good potential for petroleum exploration (Botneva and Frolov 1995; Kalabin *et al.* 2013; Ulmasvay *et al.* 2017). The main goal of this chapter is to summarize the most recent data on the geology and petroleum habitat of the AL CTSE.

## Age

Lower Mesoproterozoic to Upper Cretaceous strata are documented within the AL CTSE both in natural outcrops and wells (Kontorovich *et al.* 2013; Proskurnin 2013; Proskurnin and Shkarubo 2014, 2017). However, numerous unconformities make the stratigraphic record incomplete, and a significant part of the Proterozoic and Paleozoic sections is absent or has a limited occurrence (Fig. 3). Lower Cretaceous strata are dominant at the surface in the central AL CTSE.

## Geographical location and dimensions

The AL CTSE is located within the eastern North Siberian Lowland, between the Khatanga River mouth in the west, the Lena River delta and Verkhoyansk Range in the east, the Central Siberian Plateau in the south and the Laptev Sea in the north (Fig. 1, Encl. A). It extends in a west–east direction for *c.* 870 km, and its width varies from a maximum of *c.* 290 km in the western part to 75 km in easternmost part

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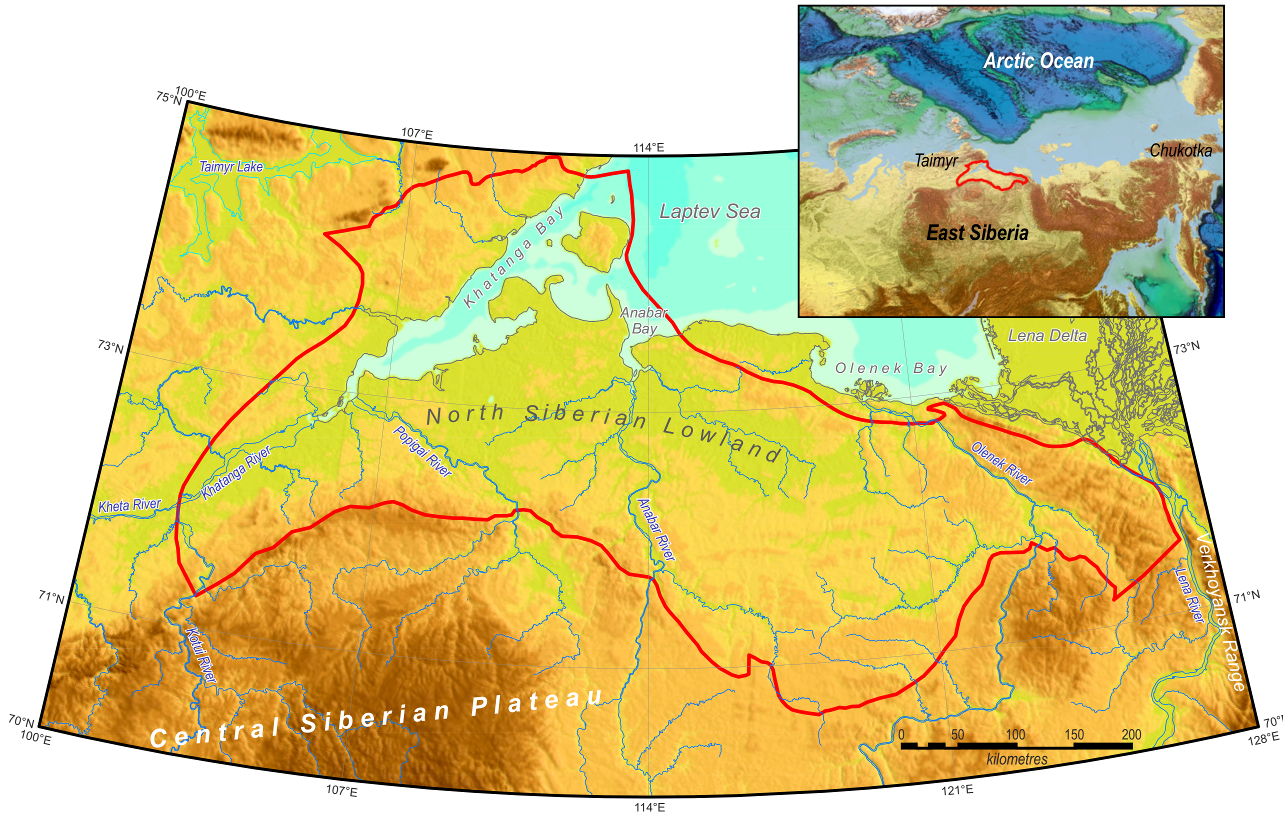


**Fig. 1.** Geographical setting of the Anabar–Lena CTSE (red outline) in northern East Siberia. IBCAO-3 map as background. Upper right map shows location of the AL CTSE within the Arctic.

where it transitions into the Priverkhoyansk Foredeep Basin. The area of the AL CTSE is *c.* 170 000 km$^2$.

## Principal datasets

### *Wells*

There are over 50 deep wells within the AL CTSE (Fig. 4, Encl. F). The majority of them were drilled between 1934 and 1953 in the western part of the CTSE (Anabar–Khatanga Saddle) by the Nordvik Expedition of the Chief Directorate of Northern Sea Route (Kalinko 1958). An additional 13 deep boreholes in the AKhS and 5 boreholes in the eastern part of the Anabar–Lena Basin were drilled in 1980–93 (Pronkin *et al.* 2012; Kontorovich *et al.* 2013, 2019; Proskurnin 2013; Proskurnin and Shkarubo 2017). Recently, several boreholes have been drilled in the western part of the basin in the coastal areas of Khatanga Bay by Rosneft and Lukoil in co-operation with the Polar Marine Geosurvey Expedition (PMGE), but their results are not yet publicly available.

### *Seismic data*

The first seismic surveys were carried out in 1934–53. In the following years, more than 10 000 km of 2D multichannel seismic profiles were acquired by the Taimyr Geophysical Expedition in 1960–90s (the western part of the basin), and by the Olenek Geophysical Party in 1977–93. Recently, seismic surveys have resumed in the northern part of the region, particularly in Khatanga Bay (Fig. 4, Encl. F). However, only a few profiles have been published (Pronkin *et al.* 2012; Kontorovich *et al.* 2013, 2019; Afanasenkov *et al.* 2016; Drachev and Shkarubo 2018).

### *Outcrop studies*

Outcrops of the AL CTSE sedimentary rocks are mostly limited to stream banks and shorelines, whereas unconsolidated Quaternary deposits and vegetation of low-lying plains obscure bedrocks across most of the CTSE area. The recent bedrock maps were compiled by Proskurnin (2013) and Proskurnin and Shkarubo (2014, 2017).

## Tectonic setting, boundaries and main tectonic/erosional/depositional phases

The AL CTSE occupies the northeastern periphery of the Siberian Craton (Fig. 2). Its basement consists of high-grade Archean and Paleoproterozoic metamorphic rocks amalgamated at *c.* 2000–1850 Ma (e.g. Rosen *et al.* 1994; Smelov and Timofeev 2007). The southern boundary of the AL CTSE approximately coincides with a regional unconformity at the base of the Permian, or base of the Upper Carboniferous–Permian sedimentary successions exposed along the northern slope of the Anabar Shield. To the east, the CTSE becomes narrower, and south of the Kelimyar–Kuogastakh Swell it transitions into the Priverkhoyansk Foreland Basin (Fig. 2). In the west, the Yenisei–Khatanga CTSE (Deev *et al.* 2021) adjoins the AL CTSE along the poorly defined boundary coinciding with a regional flexure expressed in westward thickening of Mesozoic strata (Fig. 2).

The northern boundary of the AL CTSE is obscured by the Olenek Fold Zone (Fig. 1; Drachev *et al.* 2022) and so is debatable. Several authors consider the Olenek Fold Zone to be an uplift on the margins of the Laptev Sea Rift coinciding with an inverted Mesoproterozoic or Late Paleozoic aulacogen (Vinogradov 1984; Ivanova *et al.* 1990). According to more

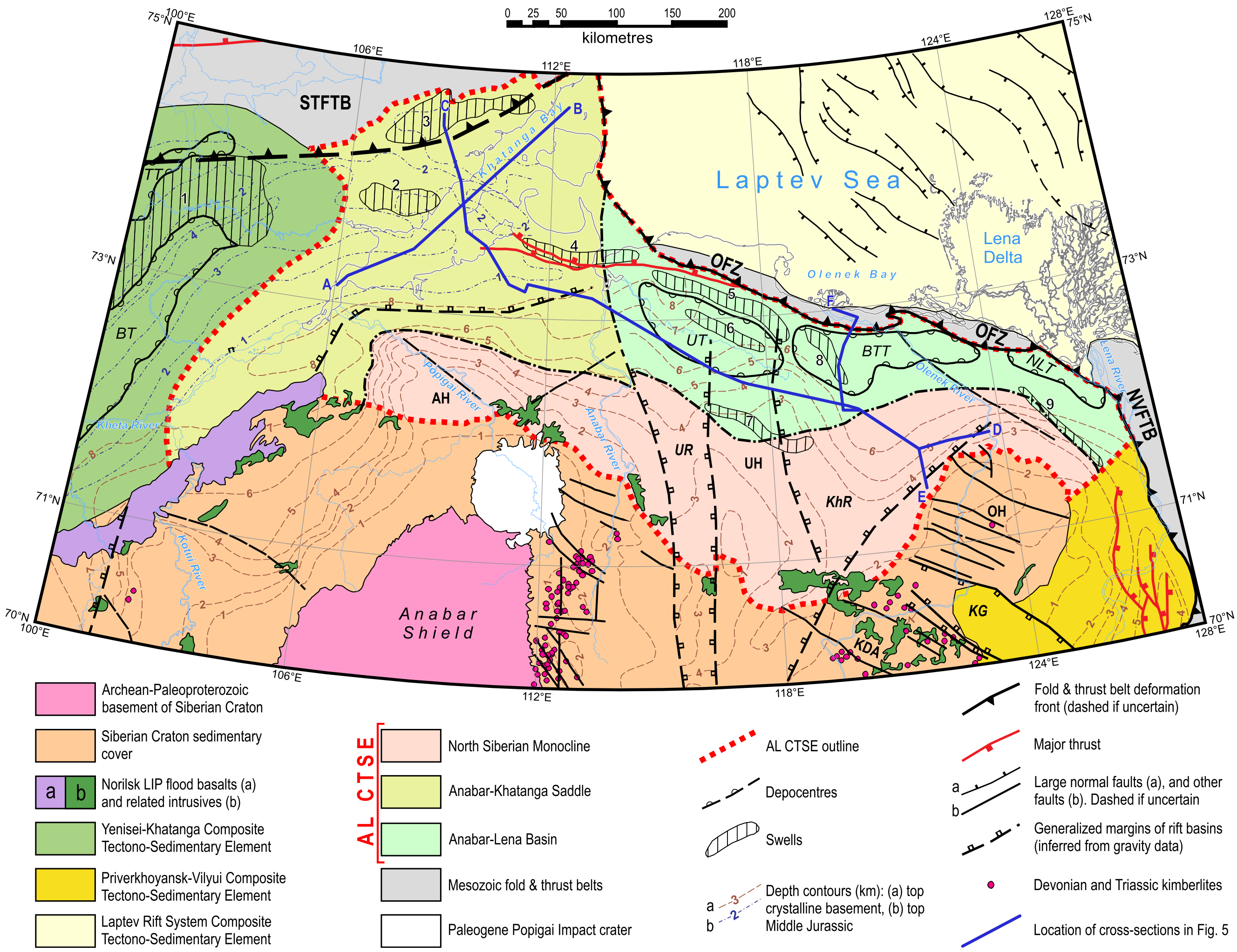


**Fig. 2.** Tectonic map of northern East Siberia. The map has been compiled using maps from Parfenov (1990) and Prokopiev and Deikunenko (2001). Inverted swells: 1, Balakhinski; 2, Belogorski; 3, Osipovski; 4, Tigyan-Anabar; 5, Kirenei; 6, Sasyl-Yuryakh; 7, Kangallakh-Uele; 8, Buolkalakh; 9, Kelimyar-Kuogastakh. Troughs: *BT*, Bogadinskiy Trough; *BTT*, Buolkalakh–Taimylyr Trough; *NLT*, Nizhne–Lena Trough; *TT*, Turovskiy Trough; UT, Uyelin Trough. Basement highs and arches: AH, Anabar High; KDA, Kuoisk–Daldynsk Arch; OH, Olenek High; UH, Udzha High. Rift basins: *UR*, Udzha; *KhR*, Khastakh; *KG*, Kyutingda Graben. Other tectonic labels: OFZ, Olenek Fold Zone; STFTB, South Taimyr Fold and Thrust Belt; NVFTB, North Verkhoyansk Fold and Thrust Belt. Red capital letters 'AL CTSE' in the legend denotes the Anabar–Lena Composite Tectono-Stratigraphic Element.

recent interpretations, the Olenek Fold Zone is a northwestern continuation of the Verkhoyansk Fold-and-Thrust Belt (FTB) (Vinogradov and Drachev 2000; Prokopiev and Deikunenko 2001; Vasiliev and Prokopiev 2012; Drachev and Shkarubo 2018).

The AL CTSE evolved since the Mesoproterozoic to Cenozoic. In most of this long geological history, the CTSE was part of the Palaeo-Siberian passive margin, which ceased to exist after two major collisions of the Siberian Palaeocontinent with the Kara and Kolyma-Omolon crustal blocks (microcontinents) in the Late Paleozoic (Taimyr Orogeny) and Late Mesozoic (Verkhoyansk–Kolyma Orogeny), correspondingly (Drachev *et al.* 2022 and references therein). The former orogeny mostly affected the western part of the region between the Taimyr Peninsula and the mainland, while the latter dominated over the eastern part adjacent to the North Verkhoyansk Fold Belt. The approximate boundary between the western and eastern domains coincides with the Anabar River.

The evolution of the CTSE can be represented as a sequence of tectonic settings, each of which formed accommodation space that hosts a correlative tectono-sedimentary element (TSE; see Fig. 3).

*Mesoproterozoic–Early Neoproterozoic*

During the Mesoproterozoic–Early Neoproterozoic, deposition occurred in an intracratonic setting along the margins of the Anabar Shield, Olenek Uplift and northern continuation of several basement troughs. These troughs were inferred based on interpretation of gravity and magnetic data (Enclosures B and C) and have been recently confirmed by 2D seismic data (Fig. 5b). Their origin is not clear. The only evidence for latest Paleoproterozoic (*c.* 1720 Ma) volcanic activity, which may be related to an intracontinental rifting, is provided by detrital zircon grains at the base of the Mesoproterozoic succession, whose euhedral shape points to their local provenance (Khudoley *et al.* 2015). However, available seismic data do not show clear evidence of the rift origin of troughs, perhaps due to low resolution of the data in the deeply subsided parts of the basins (Kontorovich *et al.* 2013; Frolov *et al.* 2017).

Although a short depositional event at *c.* 1000 Ma is documented on the eastern margin of the Anabar Shield (Kuptsova *et al.* 2015), and some Neoproterozoic rocks are recognized in deep wells and inferred by seismic interpretation in the eastern part of the Anabar–Lena Basin (Kontorovich *et al.* 2013),

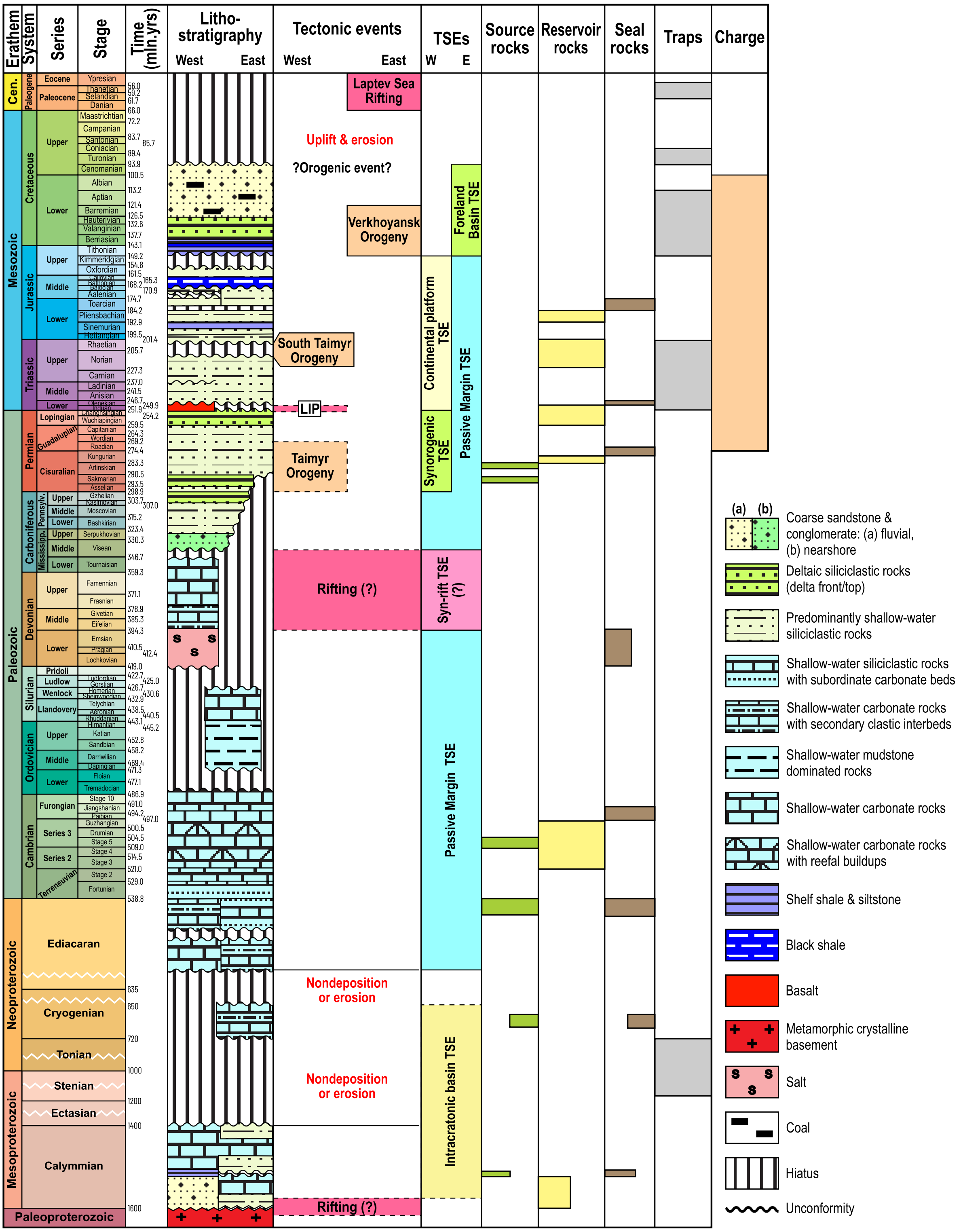


**Fig. 3.** Regional lithostratigraphy, tectonic phases and hydrocarbon play elements of the AL CTSE. Geological time-scale after Gradstein *et al.* (2020). 'LIP' in the 'Tectonic events' column denotes the Norilsk (Siberian) Large Igneous Province.

most of the Meso- and Neoproterozoic time interval corresponds to non-deposition and/or erosion (Fig. 3). According to regional stratigraphic correlations, more than 1 km of deposits was removed in the Udzha Basin by pre-Ediacaran erosion (Shishkin and Isaev 1999). Based on interpretation of seismic data, up to 6–7 km of pre-Ediacaran erosion could be inferred within the Anabar–Lena Basin (Kontorovich *et al.* 2021). Furthermore, the difference in maturation of organic matter in the Ediacaran and Mesoproterozoic source rocks on the western margin of the Siberian Craton points to more than 3 km of erosion (Frolov *et al.* 2011, 2015).

### *Ediacaran to Early Devonian*

The Ediacaran to Early Devonian is characterized by overall subsidence of the AL CTSE territory in a passive margin setting. Ediacaran rocks unconformably overlie various Archean

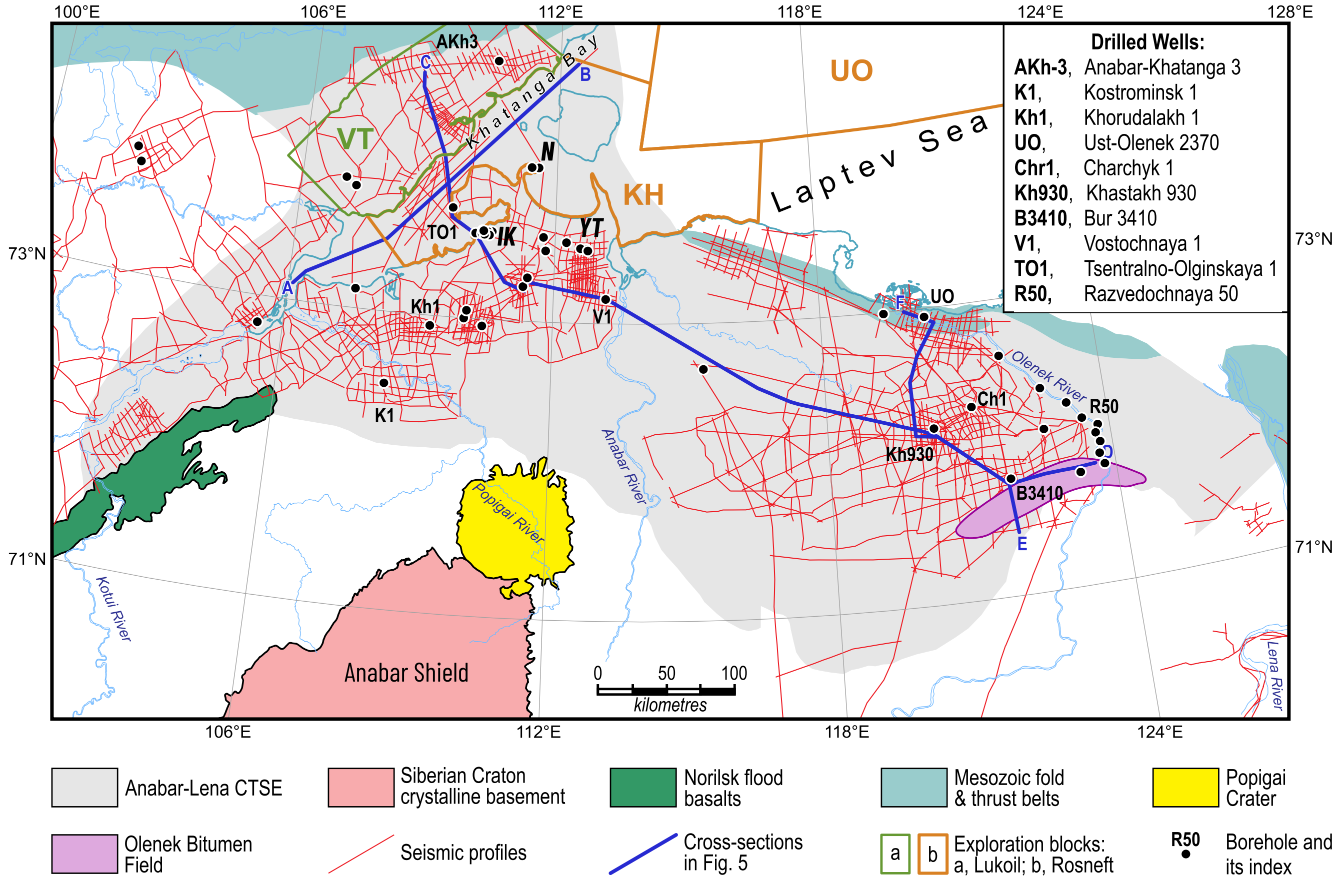


**Fig. 4.** Location of drilled wells, seismic profiles, and subsoil exploration blocks. Black bold italic capitals denote small oil fields: IK, Il'insk and Kozhevnikov; N, Nordvik; YT, Yuzhno-Tigyan. Exploration blocks: VT, Vostochno-Taimyrskiy; KH, Khatangskiy; UO, Ust' Olenekskiy.

to Neoproterozoic rock units and mark a craton-wide Ediacaran–Cambrian transgression (e.g. Shenfil 1991). Ediacaran and Cambrian predominantly shallow-water carbonate rocks were deposited throughout the CTSE. The palaeo-basin deepened northward (present-day coordinates). A rifting event that predated formation of the passive margin is documented along the east margin of the Siberian Palaeocontinent (Khudoley and Guriev 2003) but has not been recognized in the AL CTSE. An abundant occurrence of 750–550 Ma detrital zircons in the Ediacaran and Lower Cambrian rocks is likely linked to a Neoproterozoic accretion event at the northern margin of the Siberian Craton within the Central Taimyr accretionary belt north of the AL CTSE (Vernikovsky *et al.* 2004, 2018; Khudoley *et al.* 2015; Priyatkina *et al.* 2017; Vishnevskaya *et al.* 2017). The presence of *c.* 520 Ma zircons is likely related to a local magmatic event, although associated magmatic rocks have not been reported yet (Pasenko *et al.* 2020). However, no foredeep basin synchronous to the Neoproterozoic accretion has been documented.

Starting from the Ordovician, deposition occurred along the northern margin of the AL CTSE, similarly to the Taimyr and Verkhoyansk passive margins of the Siberian Palaeocontinent. Ordovician and Silurian rocks are documented only in the Ust-Olenek 2370 well at the most northeastern periphery of the CTSE (Prokopiev *et al.* 2001). There, correlative to the Ordovician and Silurian, carbonate rock seismic packages, pinching-out southwards, are interpreted on seismic profiles (Kontorovich *et al.* 2013, 2021). Ordovician and Silurian carbonate rocks probably form the same sedimentary basin in the Southern Taimyr FTB, with facies transitioning northward from shallow-water carbonates to deep-water graptolitic black shales (Pogrebitsky and Shanurenko 1998; Khudoley *et al.* 2018; Vernikovsky *et al.* 2018 and references therein).

Note that Lower Devonian rocks have not been identified in the AL CTSE but are inferred based on their presence in the adjacent Southern Taimyr FTB.

### *Middle Devonian to Early Carboniferous*

During the Middle Devonian to Early Carboniferous, an extensional tectonism affected the northern CTSE. It is inferred based on the occurrence of diapirs of Devonian evaporites on the Nordvik Peninsula (Pogrebitsky and Shanurenko 1998; Proskurnin 2013). Similar rocks are known to occur in rifted troughs along the eastern margin of the Siberian Craton (Vilyui Basin and Verkhoyansk FTB; see Parfenov 1991; Prokopiev *et al.* 2001, 2022); these are believed to mark a significant Middle Devonian to Early Carboniferous extensional episode that resulted in fragmentation of the Ediacaran to early Paleozoic passive continental margin and opening of a new small oceanic basin, the Oimyakon Ocean (Prokopiev *et al.* 2001; Oxman 2003). During this phase, most of the AL CTSE territory was affected by a prolonged uplift that resulted in a prominent stratigraphic hiatus and absence of most of the Paleozoic sediments in the eastern part of the CTSE. However, published seismic data (see Pronkin *et al.* 2012; Afanasenkov *et al.* 2016; Kontorovich *et al.* 2019, 2021) support the presence of the inferred Middle Devonian to Lower Carboniferous synrift succession in the NW part of the CTSE (Fig. 5b) and, thus, support the possible occurrence of Devonian rifting.

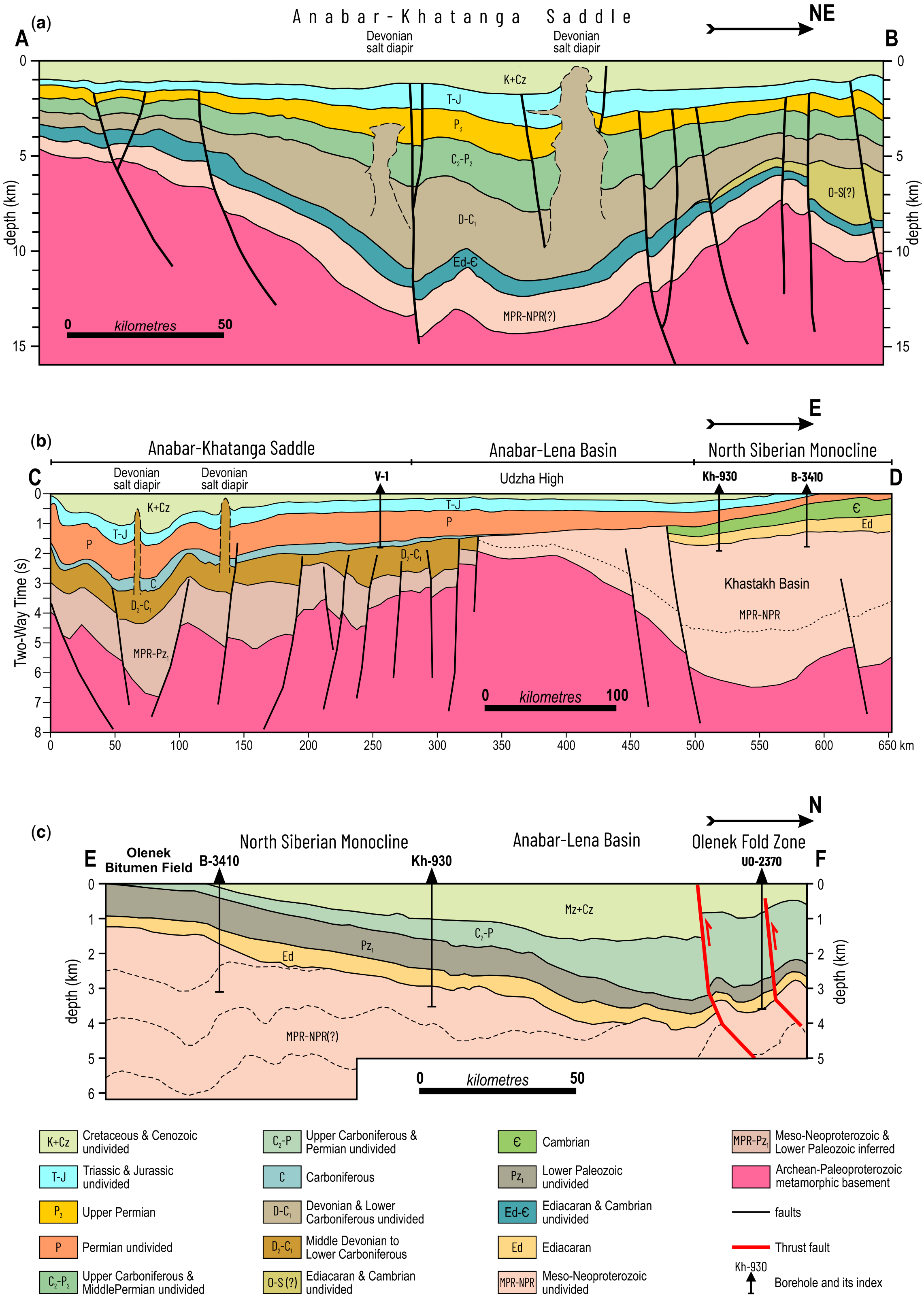

**Fig. 5.** Cross-sections based on 2D seismic profiles (location shown on Figs 2 & 4). (**a**) Cross-section along the YuzhMorGeo seismic profile 240802 (interpretation by S. Frolov). Original interpretation of the seismic profile is in Pronkin *et al.* (2012). (**b**) Cross-section along a composite seismic profile (interpretation by S. Drachev). Original interpretation of the seismic profile is in Kontorovich *et al.* (2021). (**c**) Cross-section along a composite seismic profile (modified from Kontorovich *et al.* 2013).

### *Late Early Carboniferous–latest Jurassic*

The beginning of late Early Carboniferous–latest Jurassic time is marked by a drastic change in palaeogeography and depositional environments that is manifested in the regional onset of the siliciclastic sedimentation throughout the CTSE territory and adjoining Yenisei–Khatanga CTSE and the Verkhoyansk FTB (Parfenov 1991; Pogrebitsky and Shanurenko 1998; Prokopiev *et al.* 2001; Proskurnin and Shkarubo 2014, 2017; Vernikovsky *et al.* 2018; Deev *et al.* 2021). There were two possible causes for this change: (1) the northern drift of the Siberian Palaeocontinent that entered a low-temperate climatic zone; and (2) growth of orogens along the western and northern margins of the palaeocontinent (Metelkin *et al.* 2012; Ershova *et al.* 2015, 2016*a*).

Timing of this event is poorly constrained by available flora and fauna remnants. In the northern Verkhoyansk FTB, siliciclastic sedimentation started in the Serpukhovian Stage of the Early Carboniferous (Prokopiev *et al.* 2001; Ershova *et al.* 2014) and, probably, the Upper Carboniferous–Permian succession of the AL CTSE contains rocks of Serpukhovian age as well.

A passive continental margin, which was part of a broader Verkhoyansk passive margin, dominated the eastern part of the CTSE. Detrital zircon ages from Carboniferous and Permian sandstones within and around the AL CTSE show a predominance of *c.* 800–260 Ma zircon grains, with only a minor portion of Paleoproterozoic and Archean grains. This points to the Taimyr Orogen, the Central Asian Orogenic Belt and Paleozoic basement of the West Siberia Basin as the main source areas, with minor addition from the Siberian Craton (Zhang *et al.* 2013, 2016; Ershova *et al.* 2015, 2016*a*).

The Permian–Triassic transition was marked by the Norilsk flood basalt magmatic event (Fig. 3). The earliest Triassic mafic sills intrude Permian and older sedimentary rocks throughout the AL CTSE. A rifting event, correlated with mafic magmatism, is inferred in the Yenisei–Khatanga CTSE and also within the AL CTSE (Talvirskiy 1976; Frolov 1990; Afanasenkov *et al.* 2016; Vernikovsky *et al.* 2018; Deev *et al.* 2021). However, available seismic data do not confirm the presence of typical extensional wedge-shaped sediment growth packages in the Triassic succession of the CTSE (Fig. 5; see Kontorovich *et al.* 2013, 2021; Afanasenkov *et al.* 2016).

Siliciclastic sedimentation continued in the Triassic, Jurassic and the beginning of the Cretaceous. Chemical and isotopic study of siliciclastic rocks shows that during the Triassic, the main provenance was from the Siberian Craton dominated by the lowermost Triassic mafic rocks and older sedimentary and crystalline rocks from local uplifts (Malyshev *et al.* 2016). Detrital zircons varying in age from 290 to 250 Ma are most widespread in Jurassic sandstones, pointing to continued erosion of the Taimyr Orogen and/or reworked Permian–Triassic sedimentary rocks (Vereshchagin *et al.* 2018).

A regional unconformity within the Upper Triassic is most likely related to a strong deformation event documented within the Taimyr Orogen and northern part of the Yenisei–Khatanga Basin (Khudoley *et al.* 2018; Vasiliev *et al.* 2018; Zhang *et al.* 2018). The age of this event is estimated as the end of the Triassic (Kazakov *et al.* 2002; Nikitenko *et al.* 2013) or, more recently, as Middle Norian–earliest Rhaetian (Lutikov *et al.* 2009; Polubotko 2010; Konstantinov *et al.* 2013). Apatite fission track (AFT) ages pointing to the timing of corresponding cooling and uplift vary from 215 to 185 Ma (Khudoley *et al.* 2018; Zhang *et al.* 2018).

The Jurassic and the lowermost Cretaceous siliciclastic rocks form an almost complete succession, although unconformities within the Aalenian in the western part of the AL CTSE and in Upper Oxfordian–Kimmeridgian stages in its eastern part have been documented (Nikitenko *et al.* 2013; Alekseev 2014).

### *Permian*

During the Permian, a thick siliciclastic succession accumulated south of the Taimyr Orogen, representing a foreland basin setting (Figs 3 & 5). Traditionally, the age of the foreland basin deposits is estimated as Late Carboniferous–Permian (Pogrebitsky and Shanurenko 1998; Vernikovsky *et al.* 2018; Deev *et al.* 2021). However, comparison of U–Pb zircon crystallization ages of granite intrusions and Ar–Ar mica ages of their cooling shows that the main deformation event, corresponding with collision of the Kara microcontinent and Paleao-Siberia, occurred in the Early Permian (Kurapov *et al.* 2021). Therefore, Upper Carboniferous rocks are interpreted as passive margin deposits throughout the AL CTSE, whereas deposition of syn-orogenic Permain rocks of the western AL CTSE occurred in a foreland basin tectonic setting. Eastwards, the foreland basin possibly merged into the Verkhoyansk passive palaeocontinental margin (e.g. Parfenov 1990; Prokopiev *et al.* 2001).

### *Triassic and Jurassic*

The tectonic setting of the Triassic and Jurassic successions in the western CTSE (AKhS) is not constrained. This sedimentary body was formed in an intracontinental setting but there is no evidence to suggest its association with a syn-orogenic or synrift deposition. It transitions into the easterly located passive margin sedimentary basin and, thus, might have formed in a shallow-marine embayment between the elevated terrains of Taimyr in the north and Anabar in the south. We tentatively consider it as a continental platform accumulation.

### *Latest Jurassic–earliest Late Cretaceous*

The latest Jurassic–earliest Late Cretaceous foreland setting was controlled by contractional tectonic deformations along the eastern and northeastern margin of the AL CTSE, where, at the end of the Jurassic and beginning of the Cretaceous, the Verkhoyansk FTB started to form (Parfenov 1991; Prokopiev and Deikunenko 2001). The northwestern continuation of the Verkhoyansk FTB is now buried below Cenozoic sediments in the southern part of the Laptev Sea (Drachev and Shkarubo 2018), and the Olenek Fold Zone is inferred to represent an exposed frontal deformation zone of the Verkhoyamsk FTB (Drachev *et al.* 2022). West of the Verkhoyansk FTB, however, almost continuous deposition of Upper Jurassic to lowermost Cretaceous marine sediments was taking place. In the Nordvik area, black shales accumulated during Oxfordian time and remained a common rock type until the late Berriasian (Kashirtsev *et al.* 2018). Within the northern Priverkhoyansk Foreland Basin, deposition of black shales occurred in the latest Jurassic (Tithonian) at the initial stage of foreland basin formation (Prokopiev *et al.* 2022). In the Early Cretaceous (Valanginian), deposition of shallow-water and continental siliciclastic sediments with coal interbeds dominated on the eastern margin of the AL CTSE (Rogov *et al.* 2011). A similar coarsening-upward succession is documented throughout the northern part of the AL CTSE in the foreland tectonic setting (Nikitenko *et al.* 2013, 2018).

No structural evidence of the latest Jurassic–earliest Cretaceous compressional deformation is recorded within the AL CTSE, although, to the west of it, in the Yenisei–Khatanga Basin, this time was a period of the most intense growth of inverted swells (Talvirskiy 1976; Baldin *et al.* 1997; Afanasenkov *et al.* 2016; Vernikovsky *et al.* 2018; Deev *et al.* 2021). According to AFT study, deformations and related uplift in the Olenek Fold Zone occurred at *c.* 120 and 85–75 Ma (Khudoley *et al.* 2018; Vasiliev *et al.* 2018). The main source of siliciclastic sediments in the AL CTSE and adjoining parts of the Priverkhoyansk Foreland Basin in the Cretaceous, most likely starting from the Hauterivian, was the Siberian Craton basement. This is indicated by a predominance of Paleoproterozoic and Archean detrital zircons, as well as results of heavy mineral and isotopic studies of siliciclastic rocks (Malyshev *et al.* 2016; Vereshchagin *et al.* 2018).

From the second half of the Cretaceous, the AL CTSE underwent uplift and denudation. AFT-based estimation of erosion shows removal of at least 2 km of sediments (Vasiliev *et al.* 2018). This estimation is also supported by the occurrence of pebbles with Upper Triassic (Carnian) fossils in the Albian sandstones (Proskurnin and Shkarubo 2017).

Based on the above descriptions, and in line with the volume framework, we consider the AL CTSE as consisting of seven individual TSEs (Fig. 3):

1. a Mesoproterozoic to Lower Neoproterozoic continental sag basin TSE;
2. an Ediacaran to Lower Devonian passive margin TSE;
3. a Middle Devonian to Lower Carboniferous synrift TSE (inferred);
4. an uppermost Lower Carboniferous to Upper Carboniferous (western CTSE) to latest Jurassic (eastern CTSE) passive margin TSE;
5. a Permian syn-orogenic TSE (western CTSE);
6. a Triassic to Jurassic continental platform TSE (?) (western CTSE); and
7. a latest Jurassic–earliest Late Cretaceous syn-orogenic TSE (eastern CTSE).

The question mark in the sixth TSE denotes uncertainty related to tectonic regime that created the accommodation space for the Triassic and Jurassic deposits of the western CTSE.

## Underlying and overlying rock assemblages

### *Age of underlying basement (consolidated crust), or youngest underlying sedimentary unit*

Throughout its extent, the AL CTSE is underlain by the Archean and Paleoproterozoic crystalline basement of the Siberian Craton (Encl. D).

### *Age of oldest overlying sedimentary unit*

The youngest consolidated rocks within the AL CTSE are Cretaceous clastic rocks. They are typically overlain by Quaternary fluvial, lacustrine or glacial-marine deposits that universally developed across the CTSE. The thickness of the Quaternary cover locally reaches 200 m.

## Subdivision and internal structure

Three major structural elements are recognized within the AL CTSE: the North Siberia Monocline, Anabar–Lena Basin, and the AKhS (Fig. 2).

### *North Siberia Monocline*

The North Siberia Monocline is a gentle northward-dipping monocline with dip angles less than 1–2°; steeper angles are documented locally only near fault zones. In some places, the monocline is complicated by gentle open folds (6–10 km in width and vertical amplitude less than 100 m) (Proskurnin and Shkarubo 2017). Sediment thickness is controlled by major basement highs (Anabar Shield, Udzha High and Olenek Uplift) and the intervening, possibly rift-related, Udzha and Khastakh basins (Fig. 2).

### *Anabar–Lena Basin*

The Anabar–Lena Basin is structurally asymmetrical, with a gentle (dip angles <1°) southern margin, which is a continuation of the North Siberia Monocline, and steeper northern margin where dip angles locally increase up to 5° along slopes of inverted swells (Egorov *et al.* 2001). The southern boundary of the Anabar–Lena Basin approximately coincides with the southern boundary of the distribution area of Cretaceous rocks (Fig. 2). The depocentre of the Anabar–Lena Basin has shifted to the north, towards its northern margin. The internal structure of the basin is complicated by a set of swells and troughs. Major swells are up to 150–180 km long and 15–20 km wide (Fig. 2). The direction of swells corresponds with the structural trend of the Olenek Fold Zone, which suggests the origin of these structures in the same stress field. No significant thickness variation is documented on the swells to imply their post-sedimentation origin. Troughs are wider and with more gentle bedding, with typical dip angles less than 1° (Fig. 2).

### *Anabar–Khatanga Saddle (AKhS)*

The Anabar–Khatanga Saddle (AKhS) separates the Anabar–Lena and Yenisei-Khatanga basins. It is a rather historical name, reflecting reduced Mesozoic sediment thickness in the saddle when compared with the adjoining Yenisei–Khatanga CTSE (Deev *et al.* 2021) and Anabar–Lena Basin. In basement topography, the AKhS is expressed as a deeply subsided Meso-Neoproterozoic and Paleozoic sedimentary basin (Fig. 5a, b) with a total thickness of Paleozoic sediments greater than in other parts of the AL CTSE. The southern slope of the saddle is gentle, transitioning northward into a deep sedimentary basin complicated by a number of salt-cored diapirs (Fig. 5a, b). The thickness of the Mesozoic succession in the saddle is approximately 1.5 times less than that in the Anabar–Lena Basin. By contrast, according to seismic data, the pre-Mesozoic succession of the AKhS is much thicker than that of the Anabar–Lena Basin, up to 11 km in total.

Diapiric domes formed by Devonian salt are another characteristic feature of the AKhS. On the surface, the diameter of domes is usually *c.* 2–3 km but may reach 10–12 km downward (Fig. 5a) (Kalinko 1959; Pogrebitsky and Shanurenko 1998; Pronkin *et al.* 2012; Kontorovich *et al.* 2021). Sedimentary rocks hosting the domes are affected by numerous faults and by steep to sub-vertical bedding at their contacts with salt and associated brecciated carbonate rocks. The top of the salt domes contains caprock (Kalinko 1958; Pogrebitsky and Shanurenko 1998).

## Sedimentary fill

### *Total thickness*

According to seismic data, the thickness of the sedimentary cover in the Anabar–Lena Basin reaches 9–9.5 km, and in the northern AKhS it is up to 12–15 km (Kontorovich *et al.* 2013; Frolov *et al.* 2017).

### *Lithostratigraphy and depositional environment*

*Mesoproterozoic*. Mesoproterozoic rocks crop out along the southern margin of the AL CTSE and form its base. They are also penetrated by wells further north (Kontorovich *et al.* 2021). The base contact of Mesoproterozoic rocks was penetrated only by the Kostrominsk-1 well in the western part of the CTSE (Fig. 6). In this well, a *c.* 500 m-thick section of Mesoproterozoic rocks correlates with a much thicker Mesoproterozoic section of the northern margin of the Anabar Shield located in the Anabar–Olenek CTSE (Ershova *et al.* 2022). In the Kostrominsk-1 well, the lowermost Mukun Group consists of red-coloured quartz to arkosic sandstones with conglomerate interbeds overlain by carbonate and shaly carbonate rocks of the Bilyakh Group. A 70 m-thick black shale unit with siltstone and sandstone interbeds (Ust-Iliya Fm) at the base of the Bilyakh Group on the northern margin of the Anabar Shield is not present in the Kostrominsk-1 well. In the eastern AL CTSE, the thickest Mesoproterozoic carbonate and clastic succession (1050 m) was penetrated by the Bur 3410 well. The section is traditionally correlated with coeval rocks exposed at the Olenek Uplift (Grausman *et al.* 1996; Kontorovich *et al.* 2013), although some palaeontological-based studies suggest a Neoproterozoic age for the succession in the Bur 3410 well (Nagovitsin *et al.* 2015).

The wide distribution of stromatolites points to carbonate sedimentation in a very shallow-marine environment, whereas cross-bedded reddish siliciclastic rocks occurring at the base of the western and eastern sections were likely deposited in fluvial environments. In contrast to the Anabar Shield and Olenek Uplift, the Mesoproterozoic succession exposed in the Udzha Rift contains tuffs and mafic volcanic rocks.

No reliable geochronological dating is available for the Mesoproterozoic rocks. In the adjacent Anabar–Olenek CTSE, the lowermost clastic unit of the Mukun Group contains detrital zircons as young as 1681 ± 28 Ma, whereas overlying carbonate units are cut by mafic sill with a U–Pb baddeleyite age of 1502 ± 2 Ma, constraining the age of deposition (Khudoley *et al.* 2015; Ernst *et al.* 2016 and references therein). Mesoproterozoic rock units on the Olenek Uplift and in the Udzha basin are likely to be similar in age (Khudoley *et al.* 2015; Malyshev *et al.* 2018).

*Lower to Middle Neoproterozoic*. Lower to Middle Neoproterozoic rocks are known to occur locally. An ∼120 m-thick unit of reddish cross-bedded quartz to arkosic sandstones deposited at *c.* 1000 Ma or earlier was documented at the eastern margin of the Anabar Shield (Kuptsova *et al.* 2015). In the eastern part of the AL CTSE on the Olenek Uplift and in wells Bur 3410, Khastakh 930, Charchyk 1 and Razvedochnaya 50, a sandstone–shale–carbonate unit of the Khaipakh Fm (up to 250 m thick) unconformably overlies Mesoproterozoic carbonate rocks and is inferred to have a Neoproterozoic age (Fig. 6).

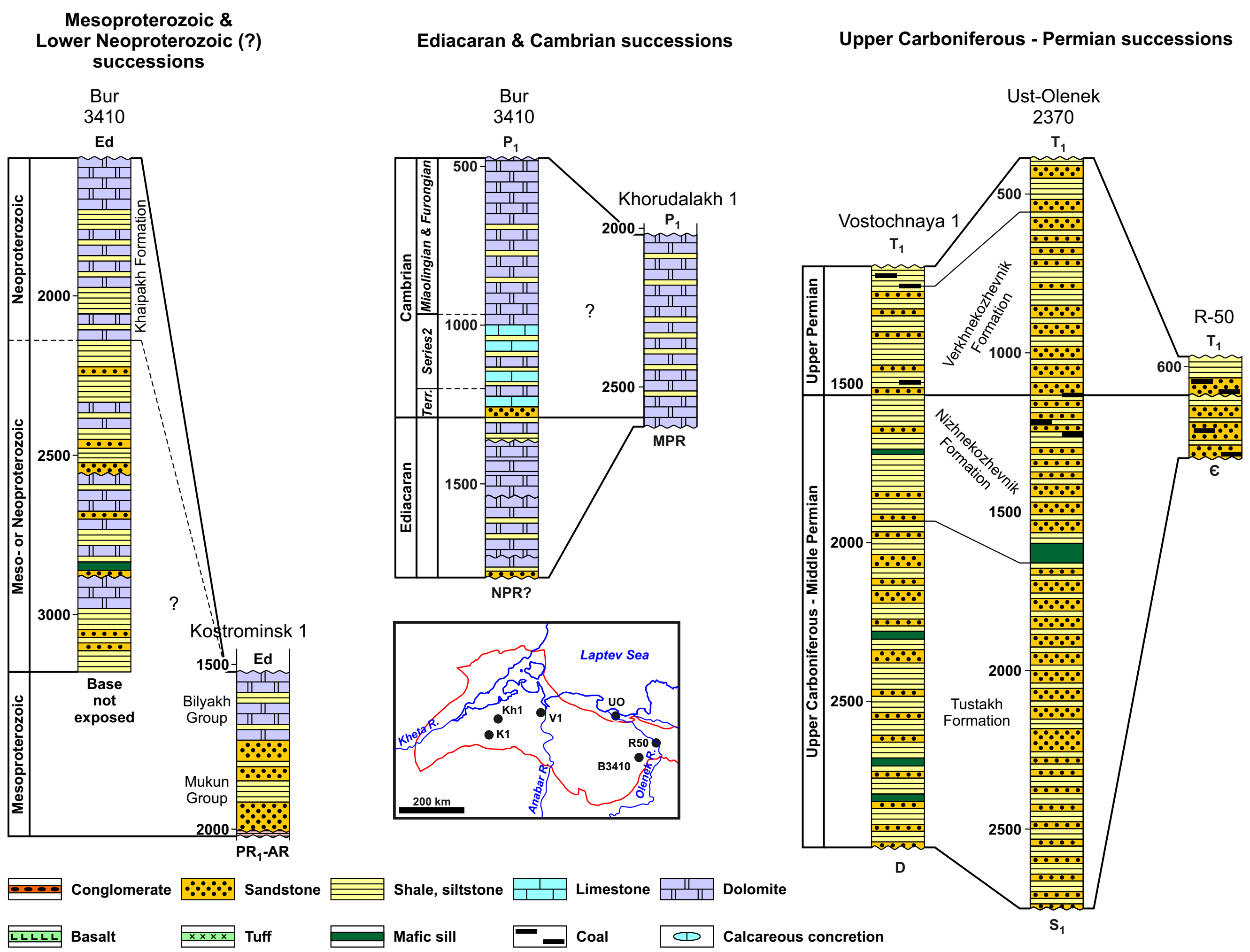


**Fig. 6.** Correlation charts for Mesoproterozoic, Neoproterozoic and Paleozoic rocks of the AL CTSE. Data sources for compiled sections are unpublished observations of authors with additional data from Egorov *et al.* (2001), Grausman *et al.* (1996), Kontorovich *et al.* (2013), Khudoley *et al.* (2015), Nagovitsin *et al.* (2015), Pogrebitsky and Shanurenko (1998), Prokopiev *et al.* (2001), Proskurnin (2013), Proskurnin and Shkarubo (2014) and Sukhov *et al.* (2016). Wells in the inserted map: **K1**, Kostrominsk 1; **Kh1**, Khorudalakh 1; **V1**, Vostochnaya 1; **UO**, Ust-Olenek 2370; **B3410**, Bur 3410; **R50**, Razvedochnaya 50. Note that the Ust-Iliya Fm, which is located at the base of the Bilyakh Group on the Anabar Shield south of the study area, is not found in the Kostrominsk-1 well. The red line shows the boundaries of the AL CTSE.

According to seismic data interpretation, undifferentiated Meso- and Neoproterozoic rocks within the Anabar–Lena Basin have a total thickness of up to 8 km (Kontorovich *et al.* 2013, 2021), which is much thicker than any succession measured in natural outcrops in northern Siberia (e.g. Shenfil 1991; Khudoley *et al.* 2015 and references therein) and needs verification.

*Ediacaran*. An Ediacaran sedimentary succession (corresponding approximately to the Vendian in Russian stratigraphic nomenclature) rests unconformably on both Meso- and lower Neoproterozoic sedimentary rocks as well as on the Archean and Paleoproterozoic crystalline basement of the Siberian Craton (Prokopiev *et al.* 2001). In the AKhS, Ediacaran rocks are represented by a 100 m-thick unit of stromatolitic dolomites with shale interbeds and a basal layer of cherty dolomitic breccia (Fig. 6). In the SE part of the Anabar–Lena Basin, a 440 m-thick Ediacaran succession of grey algal dolomites with shaly dolomites was penetrated by the Bur 3410 well. In the Khastakhsk 930 and Ust-Olenek 2370 wells, the Ediacaran succession is represented by a 300–400 m-thick unit of intercalated sandstone, siltstone and shale, containing thin interbeds of dolomite and shaly dolomite (Grausman *et al.* 1996; Kontorovich *et al.* 2013). Deposition occurred in a shallow-water to tidal environment. The Ediacaran age of these units is supported by fauna fossils, as well as detrital zircons and isotope chemostratigraphic studies (Vishnevskaya *et al.* 2017).

*Cambrian*. The Cambrian carbonate succession is documented by wells throughout the AL CTSE except for the Ust-Olenek 2370 well where it, most probably, was eroded during Early Ordovician uplift. Cambrian rocks occur in the same area as Ediacaran rocks and often overlie the latter locally with erosional contact at the base (Prokopiev *et al.* 2001).

A Cambrian shallow-water carbonate platform deposition environment dominated most of the AL CTSE, whereas basinal black shale succession is widely distributed to the south of it (Sukhov *et al.* 2016). Throughout the Siberian Craton, the Cambrian carbonate platform and basinal shale facies are separated by a zone of reefal builds-ups (Sukhov *et al.* 2016).

In the Anabar–Lena Basin, Cambrian rocks are documented in wells Bur 3410, Khastakh 930 and Charchyk 1, where they form a 880–960 m-thick complete section of the Cambrian system (Fig. 6). The lower part of it (Terreneuvian and Series 2) consists of a basal unit of intercalated shale, siltstone and oligomictic sandstones and an overlying unit of shaly limestones with layers of shale and dolomitic marlstone, as well as algal cavernous dolomites and layers of oolithic dolomites (Frolov *et al.* 2017).

The upper part of the Cambrian succession (Miaolingian and Furongian) consists of biohermal build-ups. The thickest (526 m) unit of light grey, massive reefal algal dolomite is documented in well Bur 3410 (Fig. 6) (Shishkin and Isaev 1999). In the Khastakh 930 and Charchyk 1 wells, biohermal dolomite build-ups interbed with dolomitic marlstone and shale units.

In the AKhS, Cambrian rocks are represented by dolomites with shale and rare limestone interbeds (Fig. 6). The lower part of the succession contains variegated dolomites. Stromatolithic dolomites are typical in the upper part for the succession. The total thickness of the Cambrian rocks in the AKhS is 500–650 m, but the upper part of the section was likely eroded during pre-Late Carboniferous uplift.

*Ordovician and Silurian*. The Ordovician and Silurian carbonate succession was encountered by a single well (Ust-Olenek 2370) at the outermost northeastern part of the CTSE (Prokopiev *et al.* 2001; Kontorovich *et al.* 2013). Middle and Upper Ordovician rocks unconformably overlie Ediacaran rocks. The rocks are represented by limestones and dolomites with marlstone and shale interbeds with a total thickness of 316 m. Ordovician rocks are overlain by 151 - m-thick Lower Silurian grey dolomites and dolomitized limestones. The wide distribution of bioclastic beds with well-preserved fauna fragments points to shallow-water depositional environments. Undivided Ordovician and Silurian rocks are inferred in the northern slope of the AKhS based on seismic data (Fig. 5) (Pronkin *et al.* 2012), but this interpretation needs verification.

*Devonian and Lower Carboniferous*. Devonian and Lower Carboniferous rocks are known to occur only in the western part of the AL CTSE at the northern AKhS. The Devonian rocks are exposed in a few salt diapirs and consist mainly of evaporite with carbonate interbeds. They are best known in the Nordvik Field area, where the rocks were studied in natural outcrops and penetrated by wells (Fig. 4) (Matukhin 1991; Proskurnin 2013; Ershova *et al.* 2016*b*; Sennikov *et al.* 2018). The base of the Devonian is not exposed. The lowermost *c.* 300–310 m-thick unit consists of halite with gypsum and anhydrite in the upper part. The overlying *c.* 320–350 - m-thick unit consists of interbedded limestones, dolomite and gypsum in the lower part and limestones in its upper part. Fauna remnants support the presence of Middle and Upper Devonian rocks in the upper part of the unit. Interpretation of seismic data infers a much greater thickness of the Lower–Middle Devonian evaporite-bearing succession, likely reaching *c.* 3 km (Fig. 5) (Pronkin *et al.* 2012).

Salt and evaporite units are likely restricted to the central part of the AKhS. They pinch out northward and, in the southern part of the South Taimyr FTB, Devonian rocks consists of carbonates and shales with no evidence for salt or evaporite occurrence (Proskurnin 2013).

According to well data, Devonian rocks in the northern part of the AKhS are conformably overlain by Lower Carboniferous limestones. However, southward of the AKhS, Lower Carboniferous rocks rest unconformably on Cambrian rocks as a result of pre-Carboniferous erosion. The most complete Lower Carboniferous succession was penetrated by the Nordvik wells (Fig. 4), where it consists of a 640 m-thick unit of Tournaisian micritic limestone overlain by a 210 m-thick unit of Visean bioclastic limestone with anhydrite beds (Pogrebitsky and Shanurenko 1998).

*Upper Carboniferous–Permian*. An Upper Carboniferous–Permian siliciclastic succession unconformably overlies older rocks (Fig. 6) (Egorov *et al.* 2001; Proskurnin 2013; Proskurnin and Shkarubo 2017). In outcrops of the southern margin of the AKhS, it consists mainly of sandstones, often cross-bedded, and subordinate beds of conglomerates, siltstones and shales. Coalified plants, coal pods and interbeds are documented throughout the succession. The total thickness varies from 480 to 730 m. Eastwards on the Olenek Uplift, more fine-grained sediments dominate, consisting of alternating units of sandstones, siltstones and black shales. Sandstones are often enriched with bitumen (tar sands), coalified plants and coal pods. Cross-bedding, desiccation cracks and mud chips are widespread. The total thickness increases northward from 200 to 340 m.

In the central AL CTSE, the Upper Carboniferous–Permian succession is represented by alternating beds and units of sandstone, siltstone and shale (Fig. 6). The rocks contain abundant pollen and coalified plants, although foraminifera shells were found in some sandstone beds as well.

The documented total thickness of the Upper Carboniferous–Permian siliciclastic succession reaches *c.* 2.3–2.4 km (Kontorovich *et al.* 2013). Based on seismic data, the total thickness in the westernmost part of the AL CTSE may reach *c.* 4 km (Fig. 5a) (Pronkin *et al.* 2012). Most of the succession is Permian and only the lower part of the Tustakh Fm is Carboniferous (Fig. 6).

Deposition of the Upper Carboniferous–Permian succession occurred in predominantly deltaic environments. Palaeogeographic restorations show that during the Permian, a continent-scale trans-Siberian river (‘Palaeo-Khatanga’) existed in northern Siberia. It transported clastic material via the AL CTSE from eroded highlands of the Taimyr Orogen, Central Asian Orogenic Belt and Uralian Orogen towards the northern part of the Verkhoyansk passive margin (Ershova *et al.* 2016*a*).

*Triassic*. The Triassic siliciclastic succession unconformably overlies Permian rocks often with a conglomerate unit at the base. Several unconformities are recognized within the succession at the base of the Middle Triassic, Upper Triassic (base of the Osipa Fm), and within the Upper Triassic (Kazakov *et al.* 2002; Konstantinov *et al.* 2013). The latter is the most significant in the AL CTSE, and the associated hiatus corresponds to the Middle Norian–earliest Rhaetian (Polubotko 2010; Konstantinov *et al.* 2013). A local angular unconformity was reported within the Middle Triassic succession between units of Anisian and Ladinian stages (Vasiliev and Prokopiev 2012).

Siliciclastic rocks dominate the Triassic succession, and their total thickness exceeds 850 m in the northeastern AL CTSE, decreasing to the south to 100 m and to 250–300 m in the AKhS (Fig. 7). In the central AKhS, the basal 45–225 m-thick Triassic unit consists of mafic lava flows and sills interbedded with tuffs and volcaniclastic sediments (Proskurnin 2013). Towards the east, volcanic rocks disappear, being replaced by volcaniclastic sandstones with some tuff interbeds. Variegated shale and siltstone units predominate in the Lower Triassic; in the eastern part of the Anabar–Lena Basin a dark bituminous limestone marker up to 65 m thick is reported (Fig. 7) (Kazakov *et al.* 2002). On the northern margin of the Olenek Uplift, the Middle Triassic and a significant part of the Upper Triassic rocks were eroded and only the uppermost Triassic unit of sandstone and conglomerate up to 20 m thick is present. Within the AKhS and central and northern parts of the Anabar–Lena Basin, the Middle and Upper Triassic succession consists of shale, siltstone and sandstone with conglomerate interbeds with a total thickness of up to 280–300 m. Fauna and flora remnants were reported throughout the succession. Deposition of Triassic rocks occurred in variable environments from deltaic to shallow water, interrupted by erosional events, which resulted in migration of the shoreline (Devyatov 1983; Devyatov *et al.* 1989; Frolov *et al.* 2017).

*Jurassic*. The Jurassic siliciclastic succession unconformably overlies Triassic rocks, although the exact age of the unconformity is debatable (see Lutikov *et al.* 2009; Nikitenko *et al.* 2013). The lowermost part of the succession (Hettangian to Lower Pliensbachian) is relatively poor in fossils and its stratigraphic completeness is unclear. Two hiatuses are traced throughout the AL CTSE at the base of Toarcian black shales (Kiterbyut Fm) and within the Aalenian (Nikitenko *et al.* 2013). Similarly to Triassic rocks, the thickness of Jurassic rocks in the Anabar–Lena Basin increases northwards and westwards from approximately 300 to 1200 m. In the central AKhS the thickness decreases to 650–700 m but on its northern margin the Anabar–Khatanga 3 well (Fig. 4) penetrated approximately 1300 m of Upper and Middle Jurassic rocks (Proskurnin 2013; Devyatov *et al.* 2017).

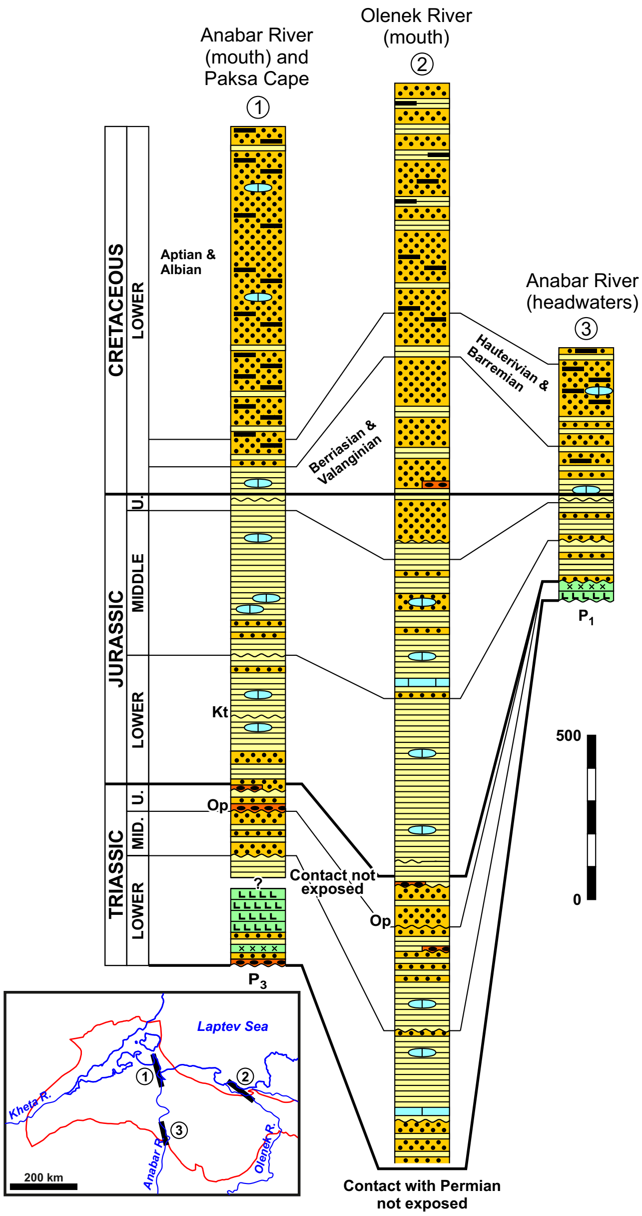


**Fig. 7.** Correlation charts for Mesozoic rocks of the AL CTSE. Data source for the compiled sections are unpublished observations of authors with additional data from Egorov *et al.* (2001), Kazakov *et al.* (2002), Konstantinov *et al.* (2013), Kontorovich *et al.* (2013), Nikitenko *et al.* (2013), Pogrebitsky and Shanurenko (1998), Prokopiev *et al.* (2001), Proskurnin (2013) and Proskurnin and Shkarubo (2014, 2017). Op, Osipa Formation (5–20 m), Kt, Kiterbyut Formation (25–40 m). The red line shows the boundaries of the AL CTSE.

The Jurassic succession is mainly composed of shale and siltstone with calcareous concretions and interbeds. Conglomerate units are widespread in the lowermost Jurassic. Generally, sandstone content increases southwards, although its distribution in the section varies, reflecting transgression and regression events. The Lower Jurassic and the lower part of the Middle Jurassic consist of grey to black shales with calcareous concretions with a total thickness of up to 400–500 m (Fig. 7). Deposition occurred in shelf environments. In the westernmost AL CTSE, sandstone content increases and deltaic environments also occasionally prevail. In the upper Middle Jurassic (Bathonian), a sandstone unit up to 150 m thick is documented, reflecting progradation of a large submarine delta fan system from the east. In the Upper Jurassic section, shale and siltstone predominate, although sandstone units are also documented. Sandstone content significantly increases in the northernmost part of the Khatanga Saddle, where the thickness of the Upper Jurassic rocks reaches 800–850 m (Devyatov *et al.* 2017). Deposition occurred in shelf environments, and the Tithonian age was marked by the most extensive Late Jurassic transgression.

*Cretaceous*. A Cretaceous siliciclastic succession is documented in the central AL CTSE and mainly includes Lower Cretaceous sediments. The lowermost Upper Cretaceous (Cenomanian) sediments are known only in the central AKhS. Thickness of the Cretaceous succession increases northwards from 350–400 m to more than 1200 m (Egorov *et al.* 2001; Proskurnin and Shkarubo 2017). However, available AFT data infer that at least 2 km of sediments were removed (Vasiliev *et al.* 2018) suggesting much wider distribution of the Upper Cretaceous rocks before Cenozoic erosion.

Deposition of Cretaceous rocks marks the transition from marine to fluvial, lacustrine and other continental environments. The lowermost part of the succession consists of shale and siltstone deposited during the latest Jurassic transgression. Starting from the mid-Valanginian, siltstone and sandstone content significantly increases and, in the Hauterivian, deltaic to fluvial sediments with coalified plant debris and coal beds dominate most of the AL CTSE (Ershova *et al.* 2010). A significant amount of siliciclastic material and the predominance of fluvial facies are evidence of a large river system that followed the modern Lena River valley in its northern part up to the present-day delta, and then diverted westwards along the Olenek Fold Zone uplifts.

## Magmatism

Several Mesoproterozoic and Paleozoic mafic magmatic events are documented in the AL CTSE.

The oldest, *c.* 1500 and 1470 Ma, mafic sills cut the Mesoproterozoic rocks along the Anabar Shield and Olenek Uplift margins (Ernst *et al.* 2000, 2016; Gladkochub *et al.* 2010, 2016). A *c.* 1384 Ma event is represented by mafic dykes and, probably, tuffs and volcanic rocks (Ernst *et al.* 2000; Malyshev *et al.* 2018).

Early Cambrian, *c.* 540–530 Ma, alkaline tuffs and volcanic rocks were reported from the margins of the Olenek Uplift and adjacent areas (Prokopiev *et al.* 2016; Vishnevskaya *et al.* 2017).

The most widespread magmatic event is known as the Norilsk, Siberian or Tunguska traps at the Permian/Triassic boundary (Reichow *et al.* 2009; Svensen *et al.* 2018). Although two magmatic pulses have been established in the main Tunguska Province – (1) at the Permian/Triassic boundary and (2) in the Middle Triassic (Ivanov *et al.* 2013) – no mafic rocks were found within the AL CTSE above the volcanic and volcaniclastic unit that correlated with the Permian/Triassic boundary. The age of numerous mafic sills and dykes that intrude Permian and older Paleozoic rocks is estimated at 250 Ma, based on the U–Pb zircon age of mafic sills in the adjacent South Taimyr FTB (Augland *et al.* 2019). The number and thickness of magmatic bodies decrease eastwards. In the AKhS area, the highest density of intrusions of dolerites is within the Lower and Middle Permian sedimentary succession, comprising 3–40% of the total thickness of the section. Some individual intrusions are up to 90–100 m thick (Frolov 1990).

The youngest magmatic event is recorded in the eastern and northern parts of the AL CTSE and is represented by tuffs and volcaniclastic rocks of alkaline composition in the Osipa Fm (Fig. 7). U–Pb dating of zircons yields a *c.* 236–234 Ma age for the magmatic event that is close to the Middle/Late Triassic boundary (Letnikova *et al.* 2014).

## Heat flow

The AL CTSE modern heat flow is very low: measured temperatures in wells are 32–38 °C at 2 km depth and 51–56 °C at 3 km depth in the northern part of the CTSE. The current geothermal gradient at 2.5–3.0 km in the AKhS is 1.3–1.7° C/100 m (Botneva and Frolov 1995).

At the same time, vitrinite reflectance study of the Permian rocks suggests that palaeo-gradients were significantly higher, 3–4°C/100 m (Grebenyuk *et al.* 1982). This may reflect a heat flux increase during the Norilsk trap magmatic event at the Permian/Triassic boundary.

## Petroleum geology

Liquid oil occurrences at the surface have been known since the beginning of the nineteenth century in the AKhS area east of the Khatanga River. The first wells in this area were drilled in the mid-1930s and exploration continued until the beginning of the 1990s (except for the period between 1954 and 1979). In total, approximately 50 deep wells have been drilled on 12 prospects. Despite many oil and gas occurrences and shows (Fig. 8), no significant discoveries were made, except for four small oil fields: the Nordvik, Il'insk, Kozhevnikov and Yuzhno-Tigyan, which represent the most eastern liquid heavily biodegraded oil occurrences in the entire Siberian Arctic region. In 2017, Rosneft announced the discovery of an oil accumulation encountered by the Tsentralno-Olginskaya 1 well (Fig. 8), which is still awaiting appraisal.

### *Discovered and potential petroleum resources*

Despite numerous oil and gas shows documented both on the surface and in wells in the entire sedimentary section of the AL CTSE from the Mesoproterozoic to the Jurassic inclusively, only four small oil and gas accumulations have been discovered, all located in the central part of the AKhS (Fig. 8). These accumulations have no commercial value due to limited reserves and the lack of infrastructure in these remote parts of East Siberia.

*The Yuzhno-Tigyan oil and gas accumulation* is located in the central part of the Tigyan–Anabar Swell (Figs 2 and 8), where it is confined to an east–west-trending fold, 19 × 7 km in map view and 700 m high relative to the top of the Permian horizon, with limb dip angles varying from 4° to 12° (Kashirtsev *et al.* 2013; Proskurnin 2013; Sivtzev *et al.* 2017). The fold is intensively faulted. The trap is filled only for a small portion of its volume, which is mainly controlled by the limited distribution of Permian sandstones with increased permeability (Kalinko 1959). The fold hinge undulates, forming two domes: the Western and Eastern; the latter is 150 m (top Permian) higher than the former (Fig. 9). Eight wells were drilled in the Western Dome, and three in the Eastern Dome. Oil occurrences were documented throughout the entire drilled section of the Lower Cretaceous to Lower Permian siliciclastic rocks (70–1995 m depth interval). The oil is heavily biodegraded (0.93 g $cm^{-3}$) and sulfurous (3.20%), with a high tar (12.56%) and asphaltene (9.62%) content.

Oil flow rates from Mid-Permian sandstones were *c.* 0.1–12.3 $m^3$/day, and gas flows were up to 49 440–88 280 cf/

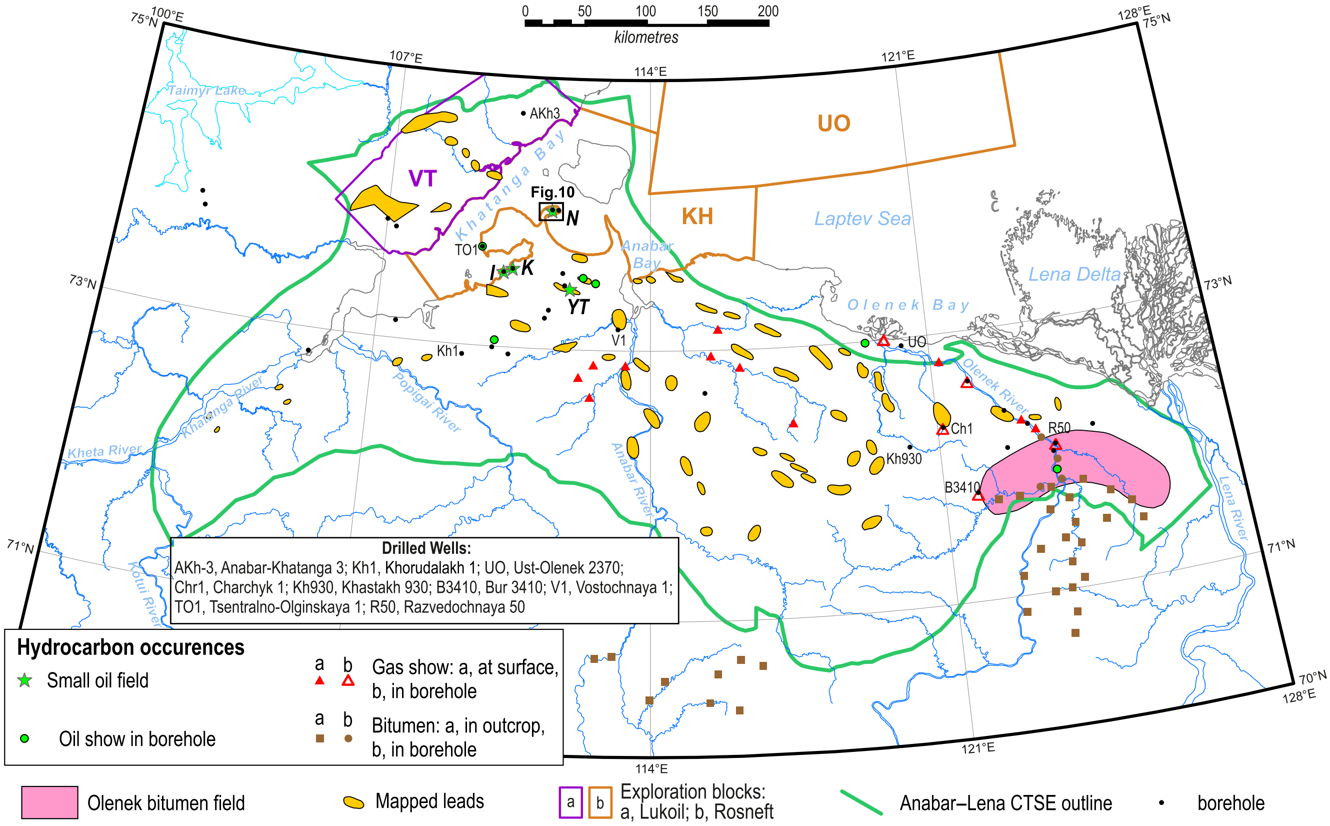


**Fig. 8.** Known hydrocarbon occurrences and mapped leads within the Anabar–Lena CTSE. Black bold italic capitals denote small oil fields: I, Il'insk; K, Kozhevnikov; N, Nordvik; YT, Yuzhno-Tigyan. Exploration blocks: VT, Vostochno-Taimyrskiy; KH, Khatangskiy; UO, Ust' Olenekskiy.

day. Up to 15 $m^3$/day oil flow was reported in the Western Dome from Permian sandstones of the upper Niznekozhevnik Fm (1583–1670 m interval). In the Eastern Dome, the oil flow was significantly lower, up to 0.1 $m^3$/day, while gas flow remained nearly the same, *c.* 70 630 cf/day (all production from the upper Nizhnekozhevnik Fm. According to Safronov *et al.* (2002), the potential oil reserves are *c.* 50 MMbbl.

*The Nordvik (Yuryung–Tumus) oil and gas accumulation* is confined to a 30 × 8 km anticlinal structure in Triassic succession formed by a salt diapir of inferred Devonian age, which is partially located on the peninsula, and partially inferred offshore (Fig. 10). Twenty shallow wells were drilled within this structure, from which 8 penetrated the hydrocarbon accumulation at depths of 100 to 120 m (Fig. 10). In the southern part of the structure in the permafrost zone at 120 m depth, the Lower Triassic sandstones host a small accumulation screened by a normal fault. Test production from this compartment provided low oil and gas flows up to 1 $m^3$/day and 45 910 cf/day, respectively. The oil is heavily biodegraded (0.93 g $cm^{-3}$), sulfurous (1.71%), with a high asphaltene (8.27%) content (Kashirtsev *et al.* 2013). In addition, oil and gas shows were recorded throughout the entire Devonian (?) to Jurassic section.

*The Kozhevnikov small oil accumulation* is also related to a salt dome. There were numerous oil shows throughout the drilled section of Lower Carboniferous to Permian rocks, from the surface down to a depth of 1198.5 m. Low-rate heavy oil flows of *c.* 0.45 $m^3$/day and *c.* 2 $m^3$/day of a water–oil mixture were reported during testing of Permian sandstones.

*The Il'in small oil and gas accumulation* was explored by seven wells. Oil shows were encountered throughout the Mesozoic to Permian section in the depth interval of 30 m to 2088 m. Low-rate heavy oil flow of 0.55 $m^3$/day and gas flow up to 70 630 cf/day were reported from Permian sandstones.

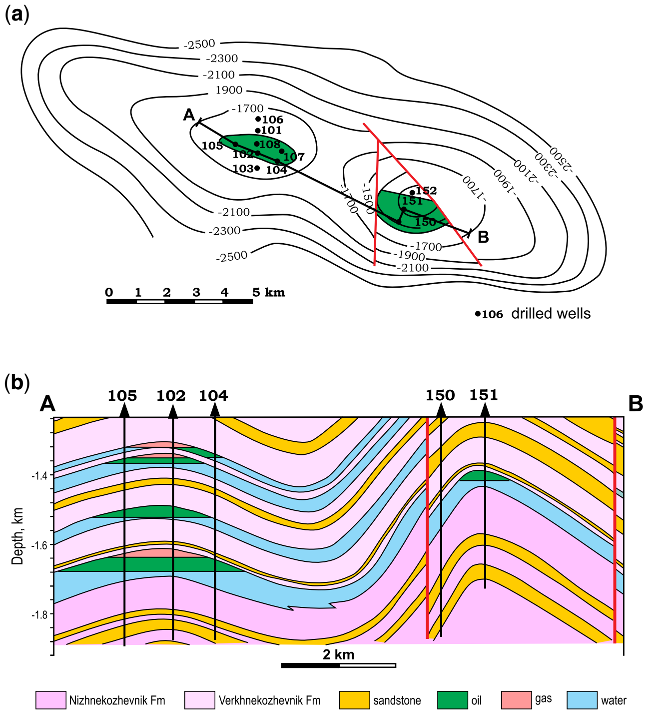


**Fig. 9.** Yuzhno-Tigyan oil and gas accumulation: (**a**) structural map on the top of the Middle Permian (Nizhnekozhevnik Formation, Fig. 6); (**b**) cross-section across the field (location shown in (a)). Based on Kalinko (1959).

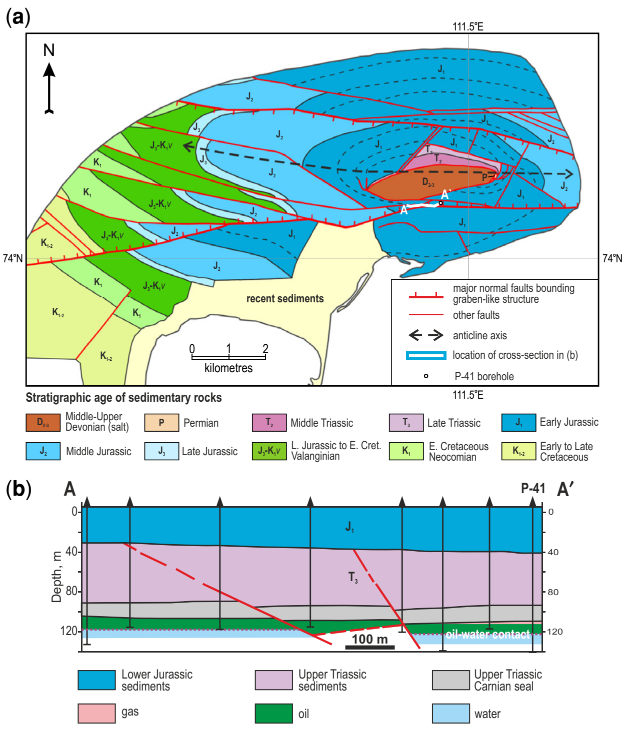


**Fig. 10.** Schematic map of the Nordvik oil and gas accumulation: (**a**) geological map on the Nordvik Peninsula, location shown in Fig. 8 (**b**) cross-section across the field, location shown in (**a**). Based on Kalinko (1959).

Oil density varies in a wide range from very light (0.76 g cm$^{-3}$) in the Nordvik Field to very heavy (0.98 g cm$^{-3}$). Heavy oils with densities of 0.88 to 0.98 g cm$^{-3}$ prevail. They have a high tar content (20–60%), and high asphalt content (2.5 to 10%). The light Nordvik oil is naphthenic. The oils are sulfurous and of low paraffin content. The paraffin content increases with depth, while density and tar contents decrease.

*The giant Olenek Bitumen Field* is located at the southeastern periphery of the Anabar–Lena Basin (Fig. 8). It represents an exhumed and oxidized oil field, which is probably the largest in Russia, with bitumen-bearing rocks covering a total area of 6000 km$^2$ at the present-day surface (Kashirtsev *et al.* 2010; Kashirtsev and Frances 2012). Although the entire section of Proterozoic, Cambrian and Permian sedimentary successions consists of various bitumen occurrences and accumulations, the field itself is limited to the Permian section. The reservoirs are confined to a series of stratigraphic and lithological traps and are represented by Permian fluvial-deltaic and near-shore sandstones. Large individual lenticular accumulations are elongated from west to east for several of tens of kilometres and are up to 8 to 12 km wide. Thickness varies from several metres to several tens of metres; average bitumen content is *c.* 3 wt %, with a maximum up to 10–15 wt%. The bitumen is represented by malthites (55%) and asphalts. The beds dip northward. Well R50, located *c.* 50 km north of the exposed bitumen accumulation, revealed nine bitumen horizons in the depth interval 568–888 m. In the drilled core, there were sandstones with liquid heavy oil. Estimated recoverable reserves are more than 3.5 billion metric tonnes (Kashirtsev *et al.* 2010).

Assessment of further exploration perspectives for the AL CTSE vary significantly. An optimistic view is supported by numerous oil and bitumen shows. Scepticism is related to the failure to discover significant commercial reserves of liquid hydrocarbons to date.

### *Current exploration status*

Recent oil prospecting has been mainly focused on the western part of the AL CTSE, where two large exploration blocks are owned by Rosneft and Lukoil petroleum companies (offshore Khatangskiy block of *c.* 17 200 km$^2$ and onshore Vostochno-Taimyrskiy block of *c.* 13 800 km$^2$, correspondingly) (Fig. 8). In 2017, both companies drilled two prospecting wells, the Anabar–Khatanga 3 well (Lukoil) approximately 5.5 km deep onshore and the directional Tsentralno-Olginskaya 1 well at the coast of Khatanga Bay (Rosneft). According to Oil Capital (https://oilcapital.ru), the Anabar–Khatanga 3 well was dry and the Tsentralno-Olginskaya 1 well encountered an oil-saturated interval at 2305–2363 m depth. Apart from the drilling, several new 2D seismic surveys have been acquired by Russian seismic contractors YuzhMorGeologia (Pronkin *et al.* 2012), and MAGE (Marine Arctic Geological Expedition; Zavarzina *et al.* 2014) during the past decade, the most recent ones as part of the Rosneft and Lukoil exploration programmes.

### *Hydrocarbon systems and plays*

*Source rocks.* The AL CTSE includes numerous intervals of proven and potential hydrocarbon source rocks from the Mesoproterozoic to Neocomian with good to excellent generation potential (Fig. 11). The chemical composition of oils and bitumen from different areas of the AKhS (e.g. Nordvik and Yuzhno-Tigyan fields, Il'insk and Kozhevnikov areas) and the Anabar–Lena Basin implies the same source for the majority of them. In particular, oils from Permian, Triassic and

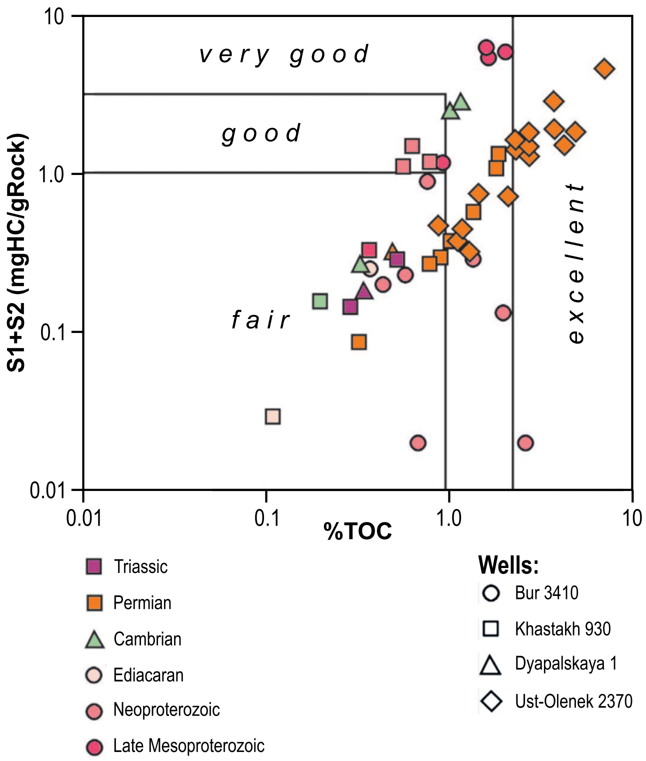


**Fig. 11.** Total organic carbon (%TOC) v. generation potential (S1 + S2) for source rocks of the Anabar–Lena CTSE (our original results). Note that Dyapalskaya 1 well is located in the Priverkhoyansk Foredeep Basin just SE of the study area and is not included in any of the maps.

Jurassic reservoirs have very similar high adiantane/hopane ratio (Kashirtsev *et al.* 2010).

*Anabar–Khatanga Saddle*. In the AKhS, source rocks were found in the Mesoproterozoic and Lower Permian sequences. Some researchers point to the importance of Devonian source rocks in this area (Kashirtsev *et al.* 2013), although none of the drilled wells penetrated Devonian beds.

The Lower Permian (may also include Upper Carboniferous) shallow-marine shaly rocks are considered to represent the main source of hydrocarbons in the AKhS area. The TOC in the rocks of the lower Tustakh Fm varies from 0.1 to 3.3% (average 1.1–1.7%). The organic matter (OM) is of a mixed kerogen II–III type. The quality of source rocks increases to the north, while up-section quality decreases due to a higher content of terrestrial OM (type III kerogen). OM maturity varies from the early oil window in the south, to the late oil/wet gas window in the north of the saddle.

From basin modelling results (Botneva and Frolov 1995), the Lower Permian source rocks might have reached the oil window at the end the Permian or beginning of the Triassic. The following two main factors can be critical for this early generation model: (1) relatively high subsidence rates in the northern part of the saddle; and (2) increased heat flow based on geothermal gradients of 3–4°C per 100 m (Grebenyuk *et al.* 1982), which can be related to the Permo-Triassic magmatism. In the Mesozoic, hydrocarbon generation became considerably less intense due to a reduced heat flow (Botneva and Frolov 1995). The generation potential of the Lower Permian source rocks was probably relatively high. It is highly likely that they were the main source for all the discovered hydrocarbon accumulations in the AKhS and bitumen fields in the northern periphery of the Olenek High, including the Olenek Field. Therefore, the generation peak could have occurred prior to the formation of major anticlinal structures in the late Mesozoic or early Cenozoic time.

Shales at the boundary between the Jurassic and Lower Cretaceous sequences locally have up to 5.5% TOC and are potential oil source rocks. The OM varies from predominantly type III to type II (Ostertag-Henning *et al.* 2009). However, these source rocks are immature.

*Anabar–Lena Basin*. There are very limited published data on potential hydrocarbon source rocks of the Anabar–Lena Basin, especially for the Proterozoic and Cambrian successions. The main source-prone interval is represented by the Permian, mainly Lower Permian, succession (Kalabin *et al.* 2013; Frolov *et al.* 2017 and references therein). Less important sources are identified in the Lower and Middle Jurassic successions.

Mesoproterozoic and Neoproterozoic shallow-marine dolomites and siliciclastic rocks are poorly understood in terms of their hydrocarbon potential. Along the eastern slope of the Anabar Shield, the Mesoproterozoic shallow-marine carbonate rocks (dolomites of Bilyakh Group) reveal *c.* 0.3% type II OM. At the east of the AL CTSE, TOC content in Mesoproterozoic rocks reaches 0.8% in the Khastakh 930 well and more than 1% in the Bur 3410 well. At the southwestern margin of the CTSE (northern margin of the Anabar Shield), Mesoproterozoic black shales at the base of the Bilyakh Group (Ust-Iliya Formation) are characterized by up to 1.8–4.9% TOC content (Botneva and Frolov 1995; Kalabin *et al.* 2013). Bitumen from Permian rocks sampled in the Charchyk 1 well (western Anabar–Lena Basin) contains 12- and 13-methyl alkane biomarkers, which are typical for older oils of the Siberian Craton (Safronov *et al.* 2002). The most probable source of this bitumen is Mesoproterozoic deposits.

The Lower to Middle Cambrian Kuonamka Formation is the most prolific source rock in the NE part of East Siberia south of the AL CTSE. However, it is unknown within the CTSE limits and, therefore, its role as a potential hydrocarbon source in the Anabar–Lena Province may be limited (for more details on Cambrian source rocks see Kalabin *et al.* (2013) and Frolov *et al.* (2017)).

Permian source rocks, in terms of their volume and quality, are considered to be the main source of hydrocarbons (Kalabin *et al.* 2013). They were deposited in fluvial and associated continental (swamp, lacustrine, etc.), deltaic to lagoonal, and shallow-marine environments. OM is predominantly of sapropelic–humic and humic origin (mixed type II–III kerogen). Continental facies occurring along the North Siberian Monocline are dominated by humic OM (type III kerogen). Total OM in Permian mudstone and shale beds is in the range of 1 to 3% (average 2.2%), whereas in siltstone and sandstone it decreases to 0.2–2%. High contents of OM and syngenetic bitumen indicate a high generation potential for these rocks (Fig. 11). The maturity of the Permian source rocks generally increases north- and eastward from immature ($R_o$ less than 0.5%) to the main gas window (>2.5%) in the proximity of the fold-and-thrust deformation fronts, with average values corresponding to the main oil window to early gas window (Botneva and Frolov 1995). The main kitchen is inferred to be related to the Nizhne-Lena and Buolkolakh-Taimylyr troughs (Fig. 2), as well as to the northern part of the Priverkhoyansk Foreland Basin.

The Lower Triassic succession is composed of continental and fluvial clastic rocks of the Induan Stage and of shallow-marine predominantly muddy rocks of the Olenek Stage. Rocks are characterized by a low OM content, from less than 0.2–0.3% in the Induan rocks to 0.42–0.63% in the Olenekian rocks. OM is of mixed type II–III with type II dominating the northern sections of the Anabar–Lena Basin. OM maturity of the Lower Triassic rocks varies from $R_o$ less than 0.5% up to 1.5% in the frontal deformation zone of the Verkhoyansk and Olenek fold belts.

The Upper Triassic rocks contain a rather small amount of OM, with TOC varying from 0.18 to 0.47% in pilitic rocks, and up to 1.0% in mudstones. The exception is represented by the shale rocks from the Khatanga Bay area (the Nordvik Peninsula and the southeastern coast of Taimyr Peninsula), in which the TOC content reaches 1.8%. OM composition is dominated by type III kerogen. Some beds are abundant with allochthonous coalified organic matter. The OM maturity varies with depth from the early oil window to late oil window (depth interval 2.5–3.8 km). The gas window is estimated at a depth of 4.5–5 km (Botneva and Frolov 1995). The main generation kitchen of the Lower Triassic rocks can be located in the Nizhne-Lena and Buolkalakh-Taimylyr troughs.

The highest hydrocarbon generation potential in the Jurassic and Lower Cretaceous sequences of the Anabar–Lena Basin is found in the uppermost Jurassic (Tithonian)–lowermost Cretaceous (Berriassian) organic-rich shale and mudstone units, which contain up to 8.8% TOC and have high hydrogen index (HI) values up to 250 mg HC $g^{-1}$ $C_{org}$ (Kashirtsev *et al.* 2020). However, these source rocks are immature.

*Reservoirs*. The main reservoir siliciclastic rocks that contain oil and gas inflows are associated within Permian succession. More than 20 potentially productive sandstone intervals are distinguished (Frolov *et al.* 2013, 2017, and references therein). Fine-grained arkosic, often clayey and silty sandstones are the most typical reservoir rocks, with porosity up to 7–8% and permeability of a few mD (Ronkina *et al.* 1977). The thickest sandstone interval (20–30 m) occurred in the middle part of the Permian sequence.

Reservoirs of relatively better quality are associated with coastal or deltaic facies, which are located at the basin periphery and are not well preserved. The open porosity of these rocks amounts to 8–16% and permeability reaches 100–400 mD (Frolov 1990).

Fractured and cavernous Mesoproterozoic stromatolithic carbonate rocks, Ediacaran sandstones and Cambrian biohermal build-ups are also considered to represent prospective reservoirs (Frolov *et al.* 2013, 2017; Kalabin *et al.* 2013). The Mesozoic rocks of the Anabar–Lena Basin at the uppermost parts of the sedimentary cover are usually located at shallow depths with insufficient conditions for hydrocarbon preservation. Therefore, although they contain intervals with good reservoir characteristics, their oil-bearing potential seems to be poor.

*Seals*. The seals for the Upper Carboniferous–Permian and also for the Mesozoic reservoirs are the 20–40 m-thick intraformational shale beds. The regional seal for Paleozoic carbonate reservoirs is probably provided by thick Devonian evaporates, which are inferred to be present in the AKhS.

*Traps*. Most of the potential traps are represented by swells (Figs 2 and 8). A set of NW- and NE-trending linear to isometric structural terraces, noses and highs are identified at the North Siberian Monocline. The size of these structural forms varies from 5–10 km to 20–25 km, and the structural relief (amplitude) is from 40 to 150 m (average 60–80 m). Towards the Verkhoyansk FTB and Olenek Fold Zone, the linear swells become more numerous and are likely related to blind thrusts parallel to the strike of the frontal thrusts (Fig. 2). These anticlines vary in size from 3–10 to 10–20 km with the amplitude averaging 100–200 m.

Formation of the swells and many other positive structures of the AL CTSE is clearly related to the Early Cretaceous compressional event, which formed the Verkhoyansk FTB and the Olenek Fold Zone. Two other events may also have contributed to the trap formation: (1) Mesozoic compression, which had the greatest impact on the southern zone of the South Taimyr FTB and adjacent parts of the AKhS; and (2) an early Cenozoic (Eocene–Oligocene and Middle Miocene?) event, or series of events, related to opening of the Eurasia Basin and formation of the Laptev sea rifts. These events resulted in uplift and erosion across the whole of North Siberia, but their structural expression remains unrevealed.

Anticlinal structural traps were considered as the most promising for prospecting in the AL CTSE. The largest are associated with the Tigyan–Anabar and Olenek swells (Fig. 2). Although many wells were drilled to test these structures, only one small oil field (Yuzhno-Tigyan) has been discovered so far.

Traps of another type are related to salt diapiric domes. The Nordvik Field is the only hydrocarbon accumulation discovered related to such traps (Fig. 10). It is represented by a 30 × 18 km faulted anticline screened by a Carnian mudstone unit. However, most of the Norvik exploration results are from the 1950s, and have not been verified by more recent data.

Analysis of facies and thicknesses of the Mesozoic sediments suggests that the growth of the Olenek and Tigyan–Anabar swells took place during the second half of the Cretaceous. If this is correct, then the trap formation postponed the time of hydrocarbon generation and migration that ceased during the Early Cretaceous tectonic compressional deformation and related uplift (Botneva and Frolov 1995). Therefore, earlier formed stratigraphic and non-anticlinal traps could be more promising for hydrocarbon prospecting. The best analogue for these is the giant Olenek Bitumen Field, which is confined to a set of stratigraphic traps along the northern rim of the Olenek High. Considering the lithological heterogeneity of reservoir-prone successions, non-anticlinal traps are assumed to be quite common in the AL CTSE.

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