Basin and petroleum system modeling in conjunction zone of the Alexander and Srednevasyugan anticlines and Ust-Tym depression, southeastern part of the West Siberian hydrocarbon province (Russia)

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Abstract

The paper is aimed at the basin and petroleum system modeling in the conjunction zone of the Alexander and Srednevasyugan anticlines and Ust-Tym depression during the Mesozoic-Cenozoic time. The exploration area is located in the southeastern part of the West Siberian hydrocarbon province. The present research primarily identifies the oil-window-entry time, maturity, generation points, generation power, and remaining potential of the Togur and Bazhenov source rocks. The Togur oil-window-entry time is 139.5 Ma. The Bazhenov oil-window-entry time is 99 Ma. Liquid hydrocarbons are extensively generated by the source rocks at the present time, since the Togur and Bazhenov Formations are found to be in the oil window. The significant amount of generated hydrocarbons is lost in migration processes. The source rock generation power and remaining potential are 1.1 and 1.5 billion tons of hydrocarbons, respectively.

Keywords: Basin and petroleum system modeling · Source rock · Bazhenov formation · West Siberian hydrocarbon province

Introduction

To solve the problems associated with the evolution of a sedimentary basin and the prediction of oil and gas occurrence, modern technologies such as basin and petroleum system modeling are widely used (Baur et al. 2011; Hakimi et al. 2010; Kerimov et al. 2011; Makeen et al. 2016a; Makeen et al. 2016b). Comprehensive interpretation of geophysical, geological, and geochemical information can be essential theoretical background for the further identifying of burial and thermal histories of a basin (Al-Hajeri et al. 2009).

The West Siberian hydrocarbon province is the largest oil and gas basin in the world. Geographically, it is confined to the West Siberian Plane (Kontorovich 2002). The petroleum industry and the geological exploration of the southeastern part of the province have lasted for more than 40 years (Kontorovich 2002). Most of the fields discovered therein have already reached the stage of declining production. It is obvious that the research of hard-to-recover reserves from complex and deep-seated deposits is a priority direction of the worldwide energy sector. It is the Chkalov oil and gas field that may be classified as an appropriate one. According to the oil and gas zoning, it is situated in the southeastern part of the West Siberian hydrocarbon province (Fig. 1).

Tectonically, the Chkalov field is located in the conjunction zone of the Alexander and Srednevasyugan anticlines and Ust-Tym depression (Fig. 2). There are the following reflection horizons in the exploration area: F₂, IIₐ, III, IV, and V (Fig. 3). The reference surfaces divide the section of the sedimentary cover into four geoseismic complexes, namely Jurassic, Berriasian-Aptian, Aptian-Turonian, and Post-Turonian (Kontorovich 2002; Kosmacheva 2016). According to the structural geometry of the Bazhenov Formation top (reflection horizon IIₐ), the Chkalov anticline can be traced along the contour line of −2510 m (Fig. 2).

There are three stages of tectonic activity in the exploration area, namely Early Jurassic, Early Cretaceous, and Late...
Cretaceous. All faults disappear in the Cenomanian rocks (Kosmacheva 2016).

The lithostratigraphic section of the Chkalov field is mainly represented by the interlayering of sandstones, siltstones, and claystones (Fig. 3). The Togur and Bazhenov Formations are source rocks (Kontorovich 2002). It is worth pointing out that the Bazhenov Formation is a unique group of rocks, where most of the Russian oil shale is concentrated. The M bed of weathering crust located in the contact zone between Paleozoic and Mesozoic rocks and the Yu1 sandstone member are known to be reservoirs (Danenberg et al. 2006; Gurari et al. 2005; Kontorovich 2002). The former is an oil and gas reservoir, while the latter contains only liquid hydrocarbons. The Togur Formation is a cap rock for hydrocarbon accumulations in the M bed of weathering crust. The Bazhenov Formation is considered to be a seal for hydrocarbon accumulations in the Yu1 sandstone member.

The Chkalov field was put into development in 1986. The complex structure of the deposits and the significant remaining potential of the source rocks currently enable the further exploration and production drilling to be carried out (Oilgasinform 2020; Parovinchak and Ezhova 2012). The actual framework of the field involves 24 exploration wells (Fig. 2). According to the Russian classification of deposits in terms of recoverable reserves, the Chkalov field can be treated as the medium size.

The basin and petroleum system modeling in the conjunction zone of the Alexander and Srednevasyugan anticlines and Ust-Tym depression is primarily aimed at the identification of the oil-window-entry time, maturity, generation points, generation power, and remaining potential of the source rocks.
### Methodology and input parameters

Basin and petroleum system modeling applies mathematical algorithms to geoseismic, stratigraphic, lithological, geochemical, and other data to provide a valuable insight into the dynamics of a sedimentary basin and its fluids through time (Baur et al. 2011; Hakimi et al. 2010; Makeen et al. 2016a, b). The basin and petroleum system modeling in the conjunction zone of the Alexander and Srednevasyugan anticlines and Ust-Tym depression during the Mesozoic-Cenozoic time was carried out by using the PetroMod software (Schlumberger 2011). The platform allows the reconstruction of geological history and all processes in a basin to be implemented. The processes are integral to the deposition, subsidence, and transformation of sedimentary rocks and organic matter (Hantschel and Kauerauf 2009; Higley et al. 2006).

The research was based on the following input parameters:

(a) structure maps of principal reflection horizons;
(b) geological age and composition of the lithostratigraphic units;
(c) vitrinite reflectance ($R_0$) with appropriate depth points;

![Regional stratigraphy of the Chkalov field (after Arkhipov et al. 2002; Bakharev et al. 2001; Danenberg et al. 2006; Gaideburova et al. 2000)](image-url)

| Geological age | Lithostratigraphic units | Lithology | Reflection horizons |
|----------------|--------------------------|-----------|---------------------|
| Eocene - Recent | Cenozoic Group | | V |
| Paleocene | Danian - Thanetian | Talit Formation | |
| | Maastrichtian | Gankin Formation | |
| | Campanian | Slavgorod Formation | |
| | Santonian | Ipatov Formation | IV |
| | Coniacian | Kuznetsov Formation | |
| Cretaceous | Albian - Cenomanian | Pokur Formation | III |
| | Aptian | Kiyalin Formation | |
| | Hauterivian - Barremian | Tar Formation | |
| | Valanginian | Kulomzin Formation | IIa |
| | Berriasian | Bazhenov Formation | |
| | Tithonian | Georgiev Formation | |
| | Kimmeridgian | Vasyugan Formation | Y1 member |
| Jurassic | Oxfordian | Vasyugan Formation | Y2 member |
| | Callovian | Tyumen Formation | |
| | Bathonian | Salat Formation | |
| | Bajocian | Togur Formation | |
| | Aalenian | Urman Formation | |
| | Toarcian | | |
| | Hettangian - Pliensbachian | M bed | |
| | | Basement | |

*Fig. 3 Regional stratigraphy of the Chkalov field (after Arkhipov et al. 2002; Bakharev et al. 2001; Danenberg et al. 2006; Gaideburova et al. 2000)*
The source of the Togur organic matter was not only the phytoplankton and bacteria of freshwater lakes (Type I kerogen), but also terrestrial plant matter (Type III kerogen). The Bazhenov organic matter was mainly connected to marine phytoplankton (Type II kerogen) (Bogorodskaya et al. 2005; Burnham 2017; Kontorovich et al. 2013). The Togur and Bazhenov Formations were characterized by HI valued at 500 and 700 mg/g, respectively (Kostyreva 2005).

The source rocks have generated 1.1 billion tons (BT) of hydrocarbons. The contribution of the Togur Formation is essential. 304.3 million tons (MT) of hydrocarbons have remained in the source rocks. 794.4 MT of hydrocarbons have been involved in the expulsion from the source rocks. 22.6 MT of hydrocarbons have accumulated in the reservoir rocks. 771.8 MT of generated hydrocarbons have been lost in migration processes. The source rock remaining potential is 1.5 BT.

### Modeling results

The section presents the modeling results of tectonic development history, heat flow calibration, source rock maturity, quantitative assessment of hydrocarbon resources of the Chkalov field. Distribution of generation and migration densities of source rock hydrocarbons, oil-window-entry time of the source rocks, geological processes through time in the Chkalov field will be discussed in the following section.

The isopach maps of principal geoseismic complexes were obtained to determine the formation time of the potential trap structures (Fig. 4). The maps describe the changes in geoseismic complex thickness in the exploration area. The zones of increasing thickness correspond to the immersed sections and the least thickness coincided with the uplifted ones. There was an apparent tendency for paleo-structures to be on the rise. All the potential hydrocarbon traps of the Chkalov field formed during the Jurassic stage of development, they not undergoing significant changes up to the present.

To represent the natural conditions in the basin, thermal modeling was carried out by reference to the vitrinite reflectance, present-day surface heat flow (Duchkov et al. 2013), and present-day reservoir temperatures (Alipour et al. 2019; Hantschel and Kauerauf 2009; Higley et al. 2006; Makeen et al. 2016b; Osli et al. 2019). The heat flow calibration illustrated in Fig. 5 was based on the adequate agreement between the measured and modeled values of vitrinite reflectance and temperatures.

The modeling results after heat flow calibration involve the present-day temperature maps of the reservoirs (Fig. 6) and the organic matter maturity data of the source rocks.

The present-day temperature range in the M bed and Yu1 member varies from 102 to 110 °C and from 87 to 91 °C, respectively. The highest values naturally conform to the depressions. The lowest values do to the positive structures (Fig. 2).

According to the common features of organic matter maturity in the West Siberian basin (Fomin 2011; Kontorovich 2004), the lacustrine and terrestrial deposits of the Togur Formation are in the oil window (0.69–0.81%R0). The maturity of the Togur source rock is connected to the most intense generation and the initial migration of hydrocarbons. The marine deposits of the Bazhenov Formation are involved in the oil window (0.61–0.64%R0). Early oil generation processes are expected to be in the Bazhenov source rock. The Kiyalin Formation, by comparison, is assumed to be immature (0.33–0.37%R0).

The quantitative assessment results of the Chkalov field hydrocarbon resources are provided below (Table 1).

The source rocks have generated 1.1 billion tons (BT) of hydrocarbons. The contribution of the Togur Formation is essential. 304.3 million tons (MT) of hydrocarbons have remained in the source rocks. 794.4 MT of hydrocarbons have been involved in the expulsion from the source rocks. 22.6 MT of hydrocarbons have accumulated in the reservoir rocks. 771.8 MT of generated hydrocarbons have been lost in migration processes. The source rock remaining potential is 1.5 BT.

### Discussion

Liquid hydrocarbons are considered to be extensively generated by the source rocks at the present time, since the Togur and Bazhenov Formations are found to be in the central part and at the top of the oil window, respectively (Fig. 7). The Togur organic matter is estimated to generate from 70 to 260 (Type III kerogen) and from 4800 to 15,000 kilotons/km² (Type I kerogen) of hydrocarbons to date. The Bazhenov organic matter generates from 200 to 2100 kilotons/km². The deepest eastern and southeastern parts of the territory correspond to the major kitchen areas, where the organic matter of the source rocks has reached a high level of thermal maturity. The minimum values of generation densities are confined to the elevated central part of the territory (Fig. 2).

The distribution of hydrocarbon migration densities is due to the configuration of generation density isolines. The migration densities of the Togur hydrocarbons vary from 70 to 260 (Type III kerogen) and from 3000 to 14,000 kilotons/km² (Type I kerogen). The migration densities of the Bazhenov hydrocarbons vary from 100 to 2100 kilotons/km².

The events chart illustrated in Fig. 8 incorporates the chronological interrelation between the elements and processes of the petroleum systems in the Chkalov field. The
The first petroleum system is related to the Togur source and seal rock. Hydrocarbons originated from the Togur Formation migrated into the M bed of weathering crust. The reservoir rock is formed during the late Paleozoic and early Mesozoic hiatus. The second petroleum system is related to the Bazhenov source and seal rock. Hydrocarbons originated from the Bazhenov Formation migrated into the Yu1 sandstone member. The overburden rocks overlying the Bazhenov Formation include Cretaceous and Cenozoic Groups.

Determining the timing of trap formation and generation, migration, and accumulation processes is one of the main goals of basin and petroleum system modeling (Al-Hajeri et al. 2009). The Togur Formation had not entered the oil window by beginning the sedimentation of the Bazhenov Formation (152.6 Ma); however, the main anticlinal structures, potential hydrocarbon traps, had already existed (Fig. 4). The Togur Formation had reached up to the oil window by ending the sedimentation of the Kulomzin Formation (139.5 Ma). Furthermore, there were initial gas generation processes with the contribution of terrestrial organic matter. The generated gas immediately migrated mainly through the fault zones. The Togur Formation subsiding to a depth of more than 1000 m had completely entered the oil window by ending the sedimentation of the Kiyalin Formation (119 Ma). There was an appropriate environment for the intense generation and migration of gas to be in progress.

**Fig. 4** Isopach maps of the geoseismic complexes in the Chkalov field: Jurassic complex (a); Berriasian-Aptian complex (b); Aptian-Turonian complex (c); Post-Turonian complex (d)
The deepest areas of the Bazhenov Formation had reached up to the oil window by ending the sedimentation of the Pokur Formation (99 Ma). There were initial oil generation and migration processes. The Bazhenov Formation subsiding to a depth of more than 2000 m had completely entered the oil window by ending the sedimentation of the Kuznetsov Formation (88.6 Ma). Hydrocarbon generation and migration processes entirely covered the exploration area.

An important concept in process timing in a petroleum system is the “critical moment.” Generating source rock is estimated to be at a transformation ratio of 50%. The four elements—source rock, reservoir rock, seal rock, and a sufficient amount of overburden must be in place before the critical moment (Al-Hajeri et al. 2009; Makeen et al. 2016b; Schlumberger 2011). The critical moment of the Togur petroleum system is supposed to be at the early Oligocene (31 Ma). The critical moment of the Bazhenov petroleum system has not yet occurred.

**Conclusions**

Basin and petroleum system modeling is a powerful tool providing an ample opportunity to build and evaluate the hydrocarbon history for potential source and reservoir rocks. The approach contributes a much more detailed and realistic representation of petroleum systems and the interconnection of its processes such as hydrocarbon generation, migration or trap formation.

The basin and petroleum system modeling in the conjunction zone of the Alexander and Srednevasyugan anticlines and Ust-Tym depression is primarily aimed at the identification of the oil-window-entry time, maturity, generation points, generation power, and remaining potential of the source rocks.

All the potential hydrocarbon traps are formed during the Jurassic stage of development. The Togur oil-window-entry time is 139.5 Ma. The Bazhenov oil-window-entry time is 99 Ma. The critical moment of the Togur petroleum system is at the early Oligocene (31 Ma). The critical moment of the Bazhenov petroleum system has not yet occurred.

**Fig. 5** Vitrinite reflectance (a) and temperature (b) calibration in a well of the Chkalov field
Liquid hydrocarbons are extensively generated by the source rocks at the present time. The Togur and Bazhenov Formations are found to be in the oil window. The eastern and southeastern parts of the territory correspond to the major kitchen areas. There is an appropriate environment for the hydrocarbon trapping to be in progress.

The generation power of the source rocks is 1.1 BT of hydrocarbons, the Togur Formation contribution being essential. The remaining source rock potential is 1.5 BT. It is important to emphasize that the significant amount of generated hydrocarbons has been lost in migration processes.

### Table 1 Quantitative assessment results of the hydrocarbon resources of the Chkalov field

|                           |               |
|---------------------------|---------------|
| Generation balance, BT    | 1.1           |
| Source rock balance, MT   | 304.3         |
| Expulsion balance, MT     | 794.4         |
| Reservoir balance, MT     | 22.6          |
| Losses balance, MT        | 771.8         |
| Remaining potential, BT   | 1.5           |

The values correspond to hydrocarbon equivalent
Fig. 7 Hydrocarbon generation density maps of the source rocks in the Chkalov field: Togur Formation (Type III kerogen) (a); Togur Formation (Type I kerogen) (b); Bazhenov Formation (c)
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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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Fig. 8 Events chart depicting timing of the petroleum systems in the Chkalov field. Each of the colored horizontal bars represents the time span of an event.
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