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Prospects for the oil and gas content of the Upper Permian deposits of the southwestern part of the Vilyui syneclise based on the analysis of sedimentary environments and geochemical conditions of oil and gas content

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Abstract The article discusses the prospects for the oil and gas content of the Upper Permian deposits in the southwestern marginal part of the Vilyui syneclise. In this margin, the Permian terrigenous complex with proven oil and gas productivity in the central part of the syneclise, pinches out. The study area, represented by the monoclinal slopes of the Vilyui syneclise, is considered a promising area for the exploration of non-structural hydrocarbon traps in the Upper Paleozoic sediments. The objectives of the study include identifying general patterns of sediment formation, associated mainly with the development of the alluvial complex, and substantiating the potential opportunities of migration and accumulation of hydrocarbons in the predicted traps. The research is based on the interpretation of the latest seismic surveys and prior-years geological and geophysical data. Authors carried out structural and paleo-structural analysis, identified lithofacies in the well log, generalized and analyzed the geochemical conditions of the oil and gas content of the Upper Permian deposits, traced the pinching out of the Upper Permian deposits on the southwestern margin of the syneclise, and also outlined areas of river valleys development that form zones of advanced reservoirs. The results of the studies have validated promising oil and gas accumulation zones on the southwestern slopes of the syneclise associated with non-anticlinal hydrocarbon traps. Authors also drew up a diagram of the oil and gas potential of the Upper Permian deposits. The obtained results are of interest for prospecting for oil and gas in the area under study.

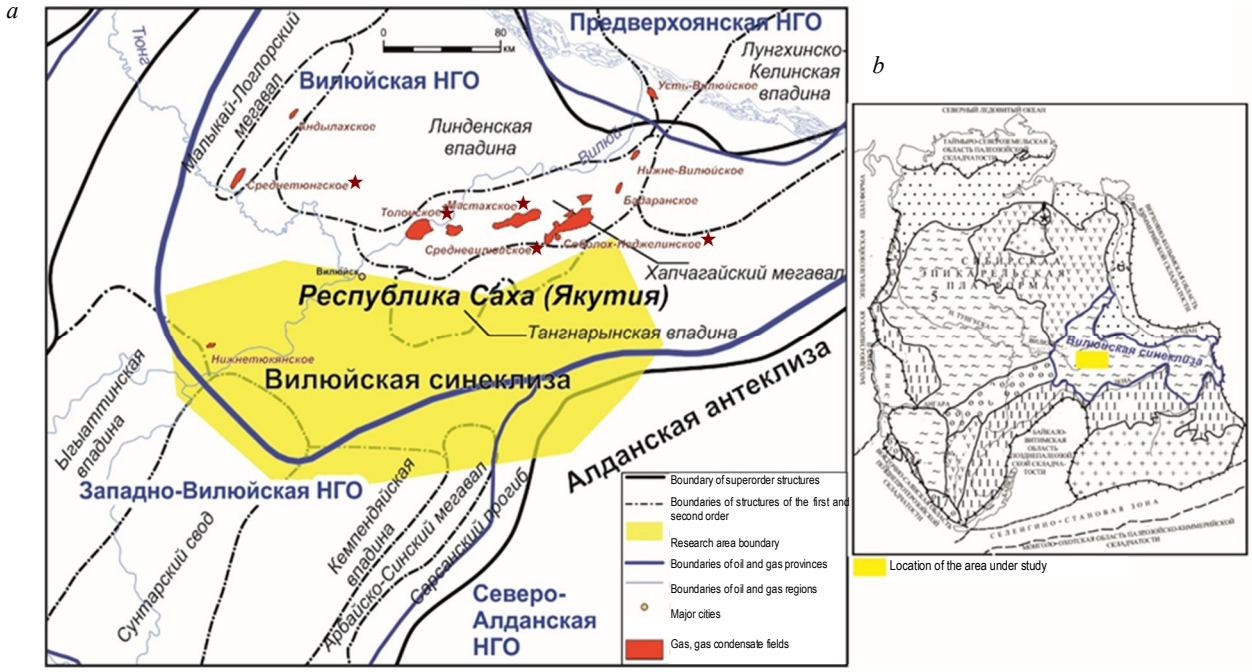
***Key words*:** Vilyui syneclise; oil and gas content; Upper Paleozoic; Permian system; oil; gas; continental deposits

Introduction. One of the current ways to search for new accumulations of hydrocarbons in Eastern Siberia is forecasting oil and gas accumulation zones in the Vilyui syneclise, in particular in the Upper Permian oil and gas complex.

In the second half of the XX century in the central part of the syneclise, gas and gas condensate deposits were discovered in the Upper Paleozoic and Mesozoic sediments. At the same time, in the course of a long history of geological prospecting and exploration, the marginal parts of the syneclise remained understudied, also within the search for non-anticlinal traps. According to the new data of complex geophysical work on the southwestern slope of the syneclise, it is necessary to clarify the prospects for the oil and gas potential of this territory. This is an urgent task for prospecting for oil and gas to increase the raw material base of hydrocarbons in the regions of Russia [1, 25]. Also, no large inherited developed anticlinal structures have been identified. Therefore, it will be very relevant to consider the conditions for the formation of oil and gas accumulation zones, due to the development of advanced reservoirs in areas of regional pinching out of sedimentary complexes. These are the conditions that are outlined on the southwestern edge of the Vilyui sedimentary basin.

The study area is located between the Tangnarynskaya depression in the north, the Ygyattinskaya and Kempendyaiskaya depressions, separated by the Suntarskoe uplift in the southwest and the northwestern edge of the Aldan anteclise (Fig.1).

The geological structure of the sedimentary cover of the area under study includes rocks from the Upper Proterozoic to the Cenozoic. Permian sediments are of the greatest interest in terms of oil



★ deposits where commercial reservoirs have been identified in the Upper Permian sediments

Fig.1. Overview scheme of the study area (*a*) and the scheme of tectonic zoning of Eastern Siberia and the main structural elements of the Siberian platform (*b*)

and gas content. They are widespread within the study area; their thickness decreases from 3.6 km in the central part of the syneclise to complete pitching out on the slopes. The stratum under consideration unconformably overlaps Middle and Lower Paleozoic rocks and is overlaid by Lower Triassic deposits, and in the fringe zone – by Lower Jurassic ones.

The Permian deposits of the Vilyui syneclise were formed in continental, marginal marine and, less often, in marine settings. The considered terrigenous complex is characterized by high carbon saturation and is one of the main oil and gas producing strata of the Upper Paleozoic and Mesozoic section of the basin [9, 20].

In all wells within the study area, which exposed the Permian rocks, reservoir intervals were identified according to GIS data. The open porosity of the Permian sandstones according to laboratory studies of the core samples reaches 12 %, and in some cases even 20 %.

The Upper Permian sediments, according to the decisions of the Interdepartmental Stratigraphic Committee of the USSR in 1979 [11] (with a two-term division of the Permian system), within the study area are subdivided into the Khomustakhskaya, Kharyasskaya, Kyundeiskaya, and Taragaiskaya suites (Fig.2). In the central part of the syneclise, the deposits of the Khomustakhskaya suite overlap the Lower Permian rocks of the Mokhsogolokhskaya stratum. In the area of the Kempendyaiskaya depression, the Permian deposits outcropping was revealed [11].

In addition to the known Upper Permian deposits (Sredne-Vilyuyskoe, Sobolokh-Nedzhelinskoe, Srednetyungskoe, etc.), within the southwestern side of syneclise, gas and gas condensate deposits were identified in small near-fault anticlinal structures (Byrakanskaya and Khailakhskaya), where the gas influx rate reached up to 90.9 thousand m^3/day. Oil and gas showings were also noted in some wells (Bayskaya 1, Yuzhno-Nedzhelinskaya 251).

The revealed oil and gas occurrence in the central parts of the syneclise makes it possible to highly evaluate its side parts [13, 15, 17, 19], where the hydrocarbons migrated. Possible hydrocarbon accumulations, associated primarily with traps of non-structural type, are expected here, in the fringe zone of Permian deposits. This is partly confirmed by the aforementioned gas deposits confined to shallow structural traps.

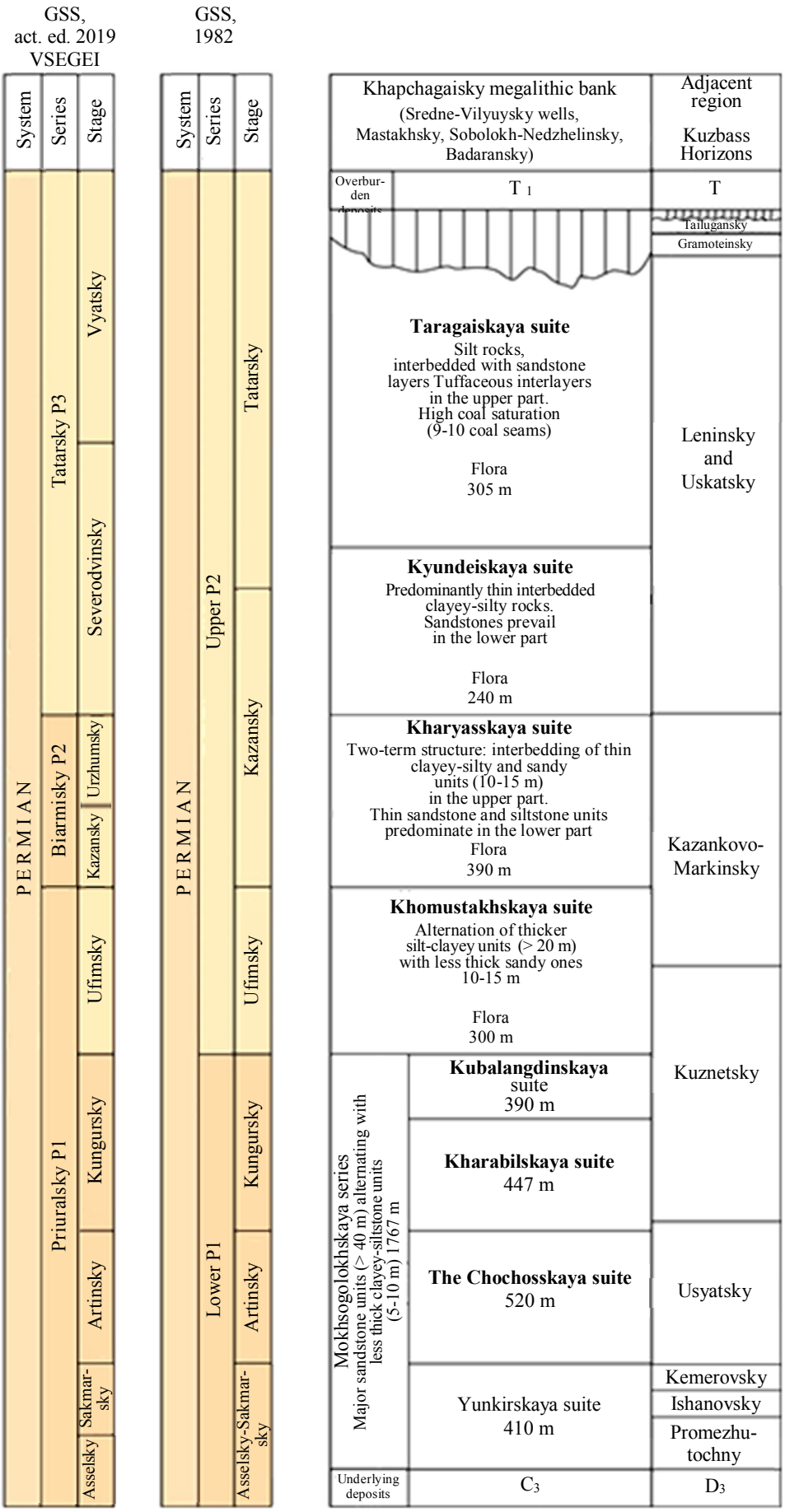


Fig.2. Stratigraphic correlation pattern of the Permian deposits of the Vilyui syneclise (according to [11, 16])

All identified thus far deposits in the Upper Permian, Lower Triassic and Lower Jurassic sediments are controlled by three clayey regional seal rocks – the Nedzhelinskaya and Monomovskaya suites of the Lower Triassic and the Suntarskaya suite of the Lower Jurassic. According to GIS data, clay intervals are noted in the near-bottom part of the Kyzylsyrskaya suite, overlying the Permian rocks in the fringe zone on the southwestern syneclise edge. It may indicate the presence of zonal seals for the promising oil and gas bearing Upper Permian complex.

Methodology. The thickness maps of the suite sediments between the reflecting horizons corresponding to the top and bottom of the Upper Permian deposits are used for the analysis of sedimentation and reconstruction of the paleogeographic conditions of the Upper Permian deposits formation. The construction was based on the seismic data interpretation. Seismic surveys were carried out by specialists from JSC Rosgeologia. To tie the reflecting horizons (RG), the stratigraphic breakdown of the well sections, carried out in the course of long-term study of VNIGRI, SNIIGGIMS, PGO Lenaneftegazgeologiya, etc. research teams was applied.

The electric facial analysis of GIS data using the approach of V.S.Muromtsev [5] to clarify the sedimentation conditions was carried out. This technique is widely used in lithofacies analysis of sediments [7] within oil and gas prospecting.

For paleostructural analysis of the territory, the authors used the isopach triangle method, constructed on the basis of structural plans of the major reflecting horizons (RH) from the base of the Upper Permian to the base of the Lower Cretaceous. For constructions the ROXAR RMS software with subsequent editing in the Surfer package was used.

Results and discussion. *Sedimentation conditions*. In many works [4, 12, 19] it is indicated that during the Upper Permian sedimentation of the Vilyui syneclise, alluvial sediments accumulated in its near-edge parts, which were replaced by deltaic, marginal marine and marine sediments towards the modern Predverkhoyansky trough of [6, 12, 16].

In the paleostructural plan (Fig.3, *a*) of the Upper Permian deposits base, there are large uplifts on the continuation of the Suntarsky arch (southwest), the territory of the modern Arbaisko-Sinskaya zone of uplifts and the northern slope of the Aldan anteclise (southeast). The lowered area, which becomes the Kempendyaiskaya depression to the southwest, stands out in the central axial part. Taking into account the inherited accumulation of the Upper Permian sediments, paleostructural reconstructions were carried out along the base of the Khomustakhskaya, Kharyasskaya Кюндейская, Kyundeiskaya, and Taragaiskaya suites deposits.

The main source area in the Permian period were the Suntarsky arch, where there are no more ancient Middle Paleozoic formations, as well as the northern slope of the Aldan anteclise, where there are no Ordovician to Permian deposits. The proposed river channels are plotted on the diagrams according to the geomorphological features. There are elevated and transition areas in the paleorelief – denudation-accumulative plains and alluvial-lacustrine lowland plains (Fig.3). Over time, the area of sedimentation increased and flattened out.

During the deposit accumulation of the Khomustakhskaya and Kharyasskaya suite (Ufimsko-Kazansky age), thick sediments accumulated in the area surrounding the central part of the syneclise (Fig.3, *b*). In the early Tatarian time, the sedimentation area expanded, and sediments probably accumulated within the Kempendyaiskaya depression (Fig.3, *c*). In the sections of the wells, an increased net-to-gross content of the suite interval is noted. In the late Tatarian time (Fig.3, *d*), the sedimentation area reached its maximum limits. According to the core descriptions, the composition of the suites deposits is represented by sandstones from medium and coarse-grained to fine-grained. The base contains conglomerates and pebbles with interlayers of coals and charcoal remains, siltstones and mudstones.

In a low-lying river valley with low surface slopes (mainly up to 10 m/km), lakes dominate. When moving to higher areas, the rivers are more straightened with increased dynamics of the aqueous medium. At higher elevations, river sediments can be expected to have a limited distribution.

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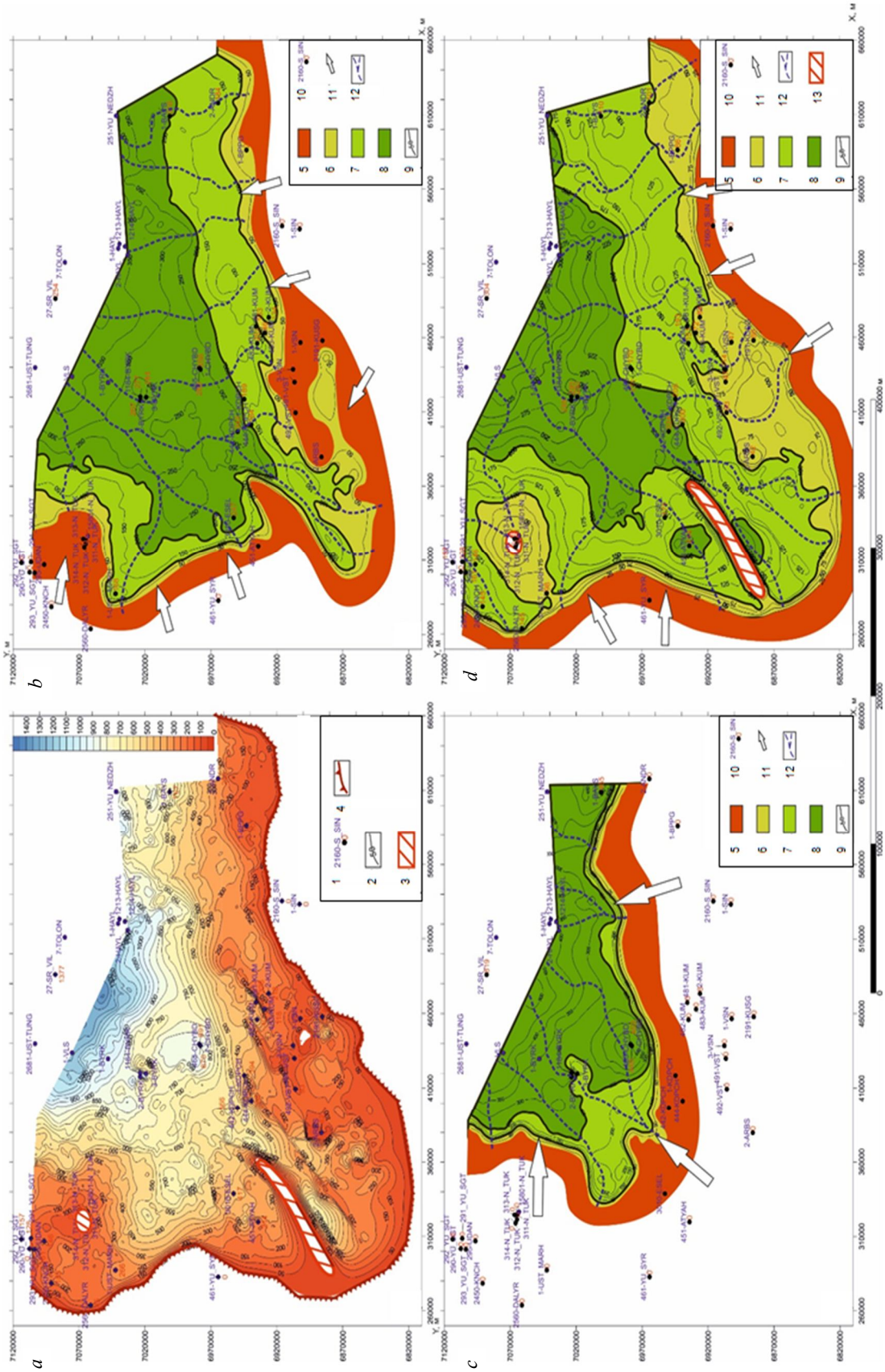


Fig.3. Thickness map of the Upper Permian deposits (*a*), Ufimsko-Kazansky (*b*), Early Tatarian (*c*), Late Tatarian (*d*) ages
1 – wells, sediment thickness, m; 2 – paleo structural contour; 3 – areas of absence of Permian deposits; 4 – line of pitching out; paleogeographic schemes; 5 – source areas; 6 – high plains; 7 – transition areas; 8 – low plains; 9 – paleo structural contour, depth, m; 10 – wells; 11 – directions of denudation; 12 – prospective channels (on a geomorphological basis); 13 – areas of absence of Permian sediments

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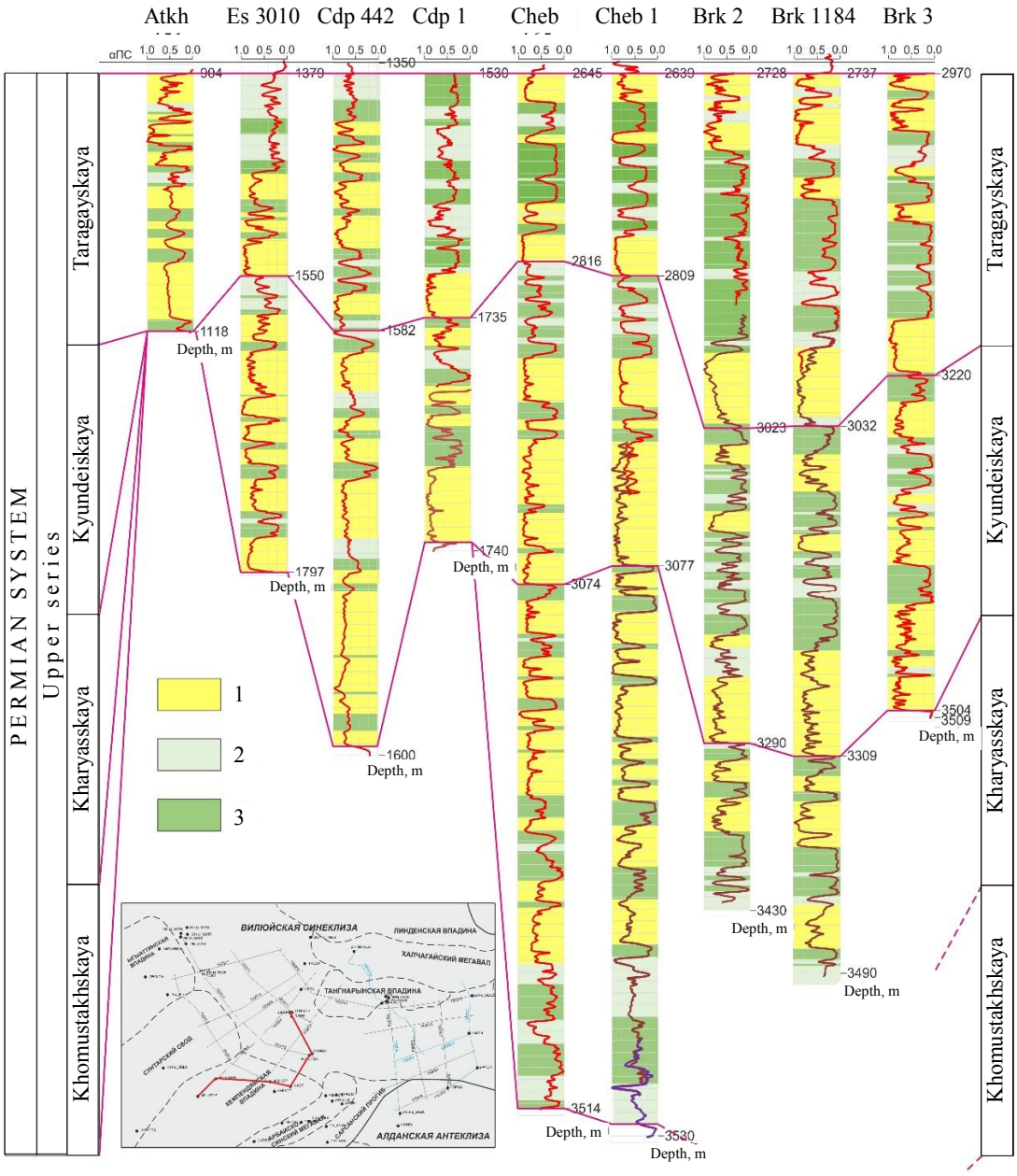


Fig.4. The correlation scheme of the spontaneous potential curve αof the Upper Permian intervals along the line of the wells Atyakhskaya 451 – Byrakanskaya 3

Facies groups: 1 – I (channel); 2 – II (sandy floodland); 3 – III (clayey floodland)

To clarify the sedimentation conditions in the wells sections, αspontaneous potential values were calculated during the research. The spontaneous potential anomalies, based on their thickness, characteristics of the top, bottom and lateral lines, made it possible to assign the intervals of the section to 3 types of facies groups: channel (I), outer (sandy) (II), and inner (clayey) (III) floodlands (according to Muromtsev).

The distribution of type intervals shows the highest content of type I channel sediments in the sediments of the Kyundeiskaya suite, the lowest – in the Taragaiskaya one. As an example, Fig.4 shows the correlation scheme of the wells Atyakhskaya 451 – Byrakanskaya 3.

For the sediments of the Khomustakhskaya and Kharyasskaya formations, which were drilled at full thickness in only three wells within the study area, the share of channel sediments in the total thickness of the sediments is 0.44-0.48. For the Kyundeiskaya suite, the proportion of type I intervals in the section is 0.4-0.7 in all wells within the study area. In the Taragaiskaya suite, it varies within 0.1-0.6 (average 0.3).

Permian sediments are characterized by the formation of these deposits in the process of sedimentation cycles, which consists in the replacement of channel facies by floodlands and lacustrine-boggy facies, and vice versa. In general, for the Taragaiskaya suite, along the wells, there is a general decrease in the share of channel sediments in relation to the underlying formations. In case of the Kyundeiskaya suite sediments, the high net-to-gross sandy content indicates that rivers flowed inheritedly in the drilling sites during the sediments accumulation. This contributed to the erosion and transfer of fine fractions into the interior of the sedimentary basin. Local interruptions in sedimentation and erosion of fine fractions could also be the reason for this. Due to the small number of wells that encountered Kharyasskaya and Khomustakhskaya suites within the study area, it is impossible to identify patterns of the channel sediments and, accordingly, sandy packs content. According to the available materials on syneclise, the deposits of the Kharyasskaya suite also have an increased degree of net-to-gross sandy content. In the Khomustakhskaya and Taragaiskaya suites, the composition changes towards an increase in the proportion of floodland and lacustrine-bog facies.

Analysis of the formation of the Upper Permian sediments in the study area shows the stable development of the alluvial complex, which comes against the backdrop of a general regression of the sea basin located on the territory of present-day Verkhoyansk area. At the same time, according to researchers, the transgressive cycle occurred in the Kazansky-Early Tatarian time, and then it was replaced by the regression of the sea before the Early Triassic transgression [16].

The considered conditions of sedimentation determine the wide development of reservoirs associated with channel sediments on the paleoslopes of the sedimentary basin. The deposits of the Taragaiskaya suite are characterized by a relatively low thickness of channel sandstones and widespread development of silt-clayey rocks. Their facies replacements along the section and area contribute to the emergence of sedimentation lithological traps in the near-tops part of the section, including in the fringe zone on uplands. For the rest of the section, such traps are likely to be less widespread due to the greater sandy content of the sections of the Kyundeiskaya and Kharyasskaya formations.

Geochemical conditions of oil and gas content of the Upper Permian deposits. The conditions of the oil and gas generation and accumulation, hydrocarbon composition features, the nature and direction of hydrocarbon fluids migration within the Upper Paleozoic-Mesozoic structural level of sedimentary basins in the east of the Siberian platform are considered in the works of T.K.Bazhenova [2, 3, 24], V.A.Kashirtsev, S.S.Filatova, R.V.Koroleva, O.N.Chalaya, I.N.Zueva [8, 9, 14] and others [20, 22]. It allows authors to analyze these conditions in detail within the study area.

Dispersed organic matter (DOM) of the Permian complex is represented by mainly humus as well as humite-sapropelites [8]. In clayey sediments, average Corg concentrations vary from 1.2 to 4 %. In the Vilyui syneclise, the maximum Corg values (up to 3-4 %) tend to the sections of the southern flank [14].

DOM catagenesis in the Permian sediments of the Vilyui syneclise varies within the PK-MK5 grading [2]. The zone of protocatagenesis (PC1-PC3) is distributed up to 1.5 km on average (paleotemperature reaches up to 50 °C). The mesocatagenesis zone (grades MC1-MC5) corresponds to the depth range from 1.5-2 to 5-5.5 km. Subzone MC1-MC2 corresponds to depths from 1.5-2.0 to 3.0-3.5 km (temperature varies from 50 to 100 °C). The middle subzone corresponds to the grades MC2-MC3 at depths of 3-4.5 km at temperatures of 100-140 °C. The lower subzone (MC3-MC5) corresponds to depths from 4.5-5.0 to 6 km and more.

The research area is partially located within the source of oil and gas formation. The scope of generation and migration of oil and gas from hydrocarbons source horizons in the Permian period varies dramatically: 0.5-5 mln t/km^3 for oil and more; 0.5-5 bln m^3/km^3 and more for gas [2].

The depression of the Permian sediments in the southwestern part of the syneclise in time is shown in the isopach triangle (Fig. 5). The paleo profile along the composite depth seismic section from the central part of the syneclise to its southern flank (Fig. 6) illustrates the direction of the main path of hydrocarbon migration, taking into account the time of their generation from the Permian oil and gas source deposits.

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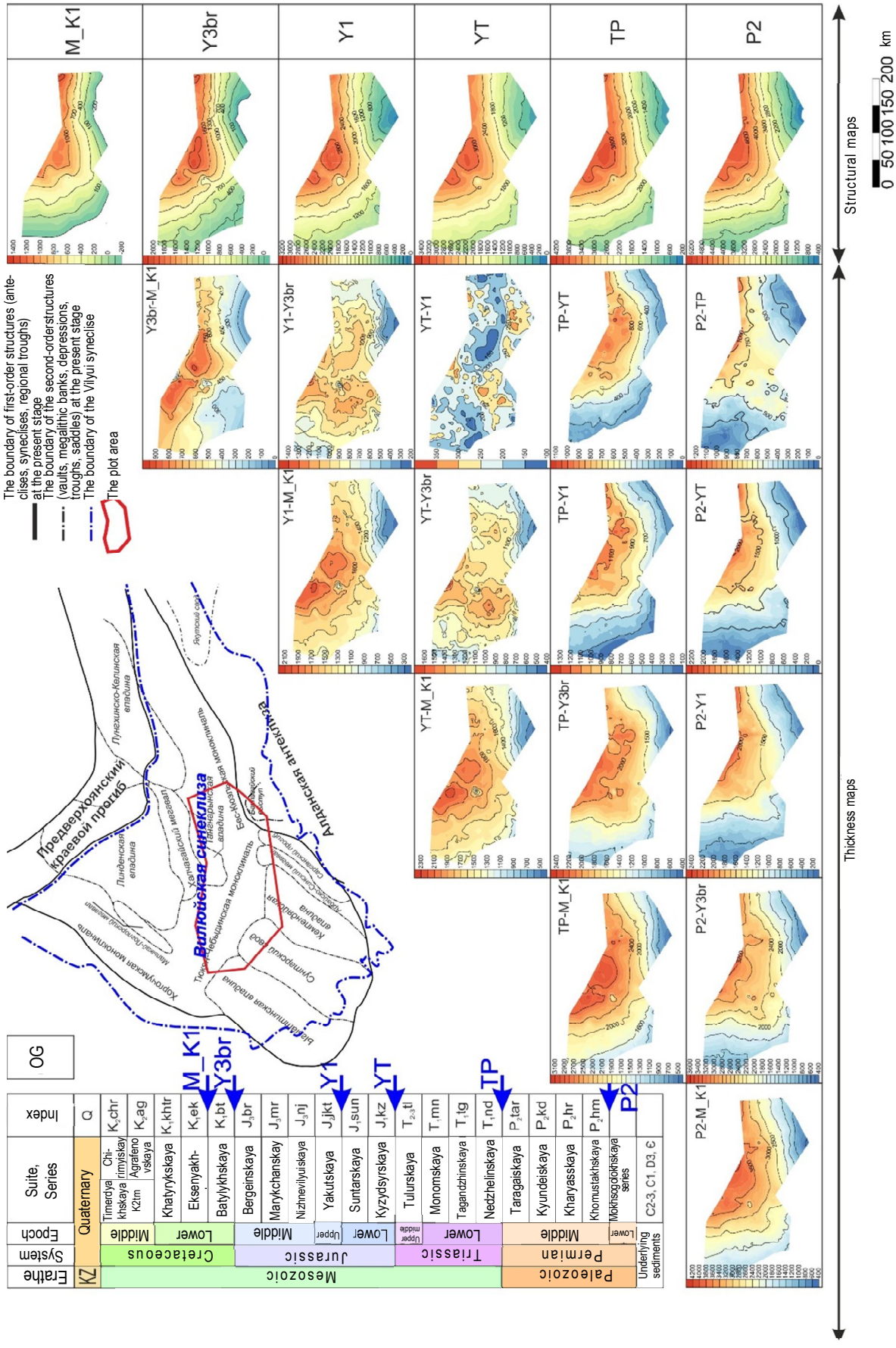


Fig. 5. Isopach triangle

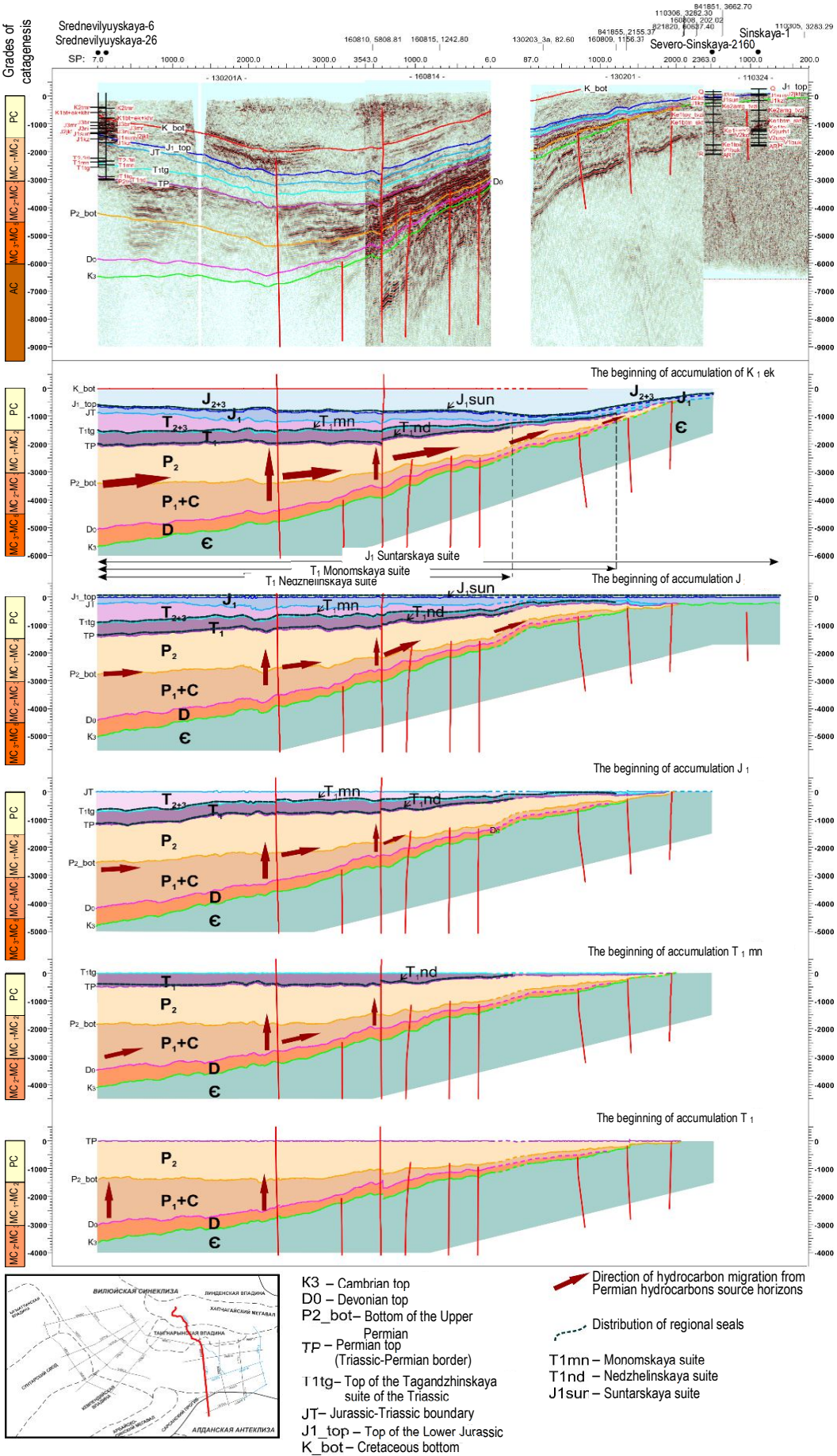


Fig.6. The paleo profile along the composite depth seismic section 130201a-130201

By the beginning of the Triassic epoch, Permian deposits were at the initial stage of the principal phase of oil formation (PFOF) within the Tangnarynskaya depression. Within the territory of the Lindenskaya depression and the modern Khapchagaisky megalithic bank, they approached the main stage of the PFOF [23]. In the southwest of the syneclise, the Permian section could produce only methane dry gases (at depths of up to 1.5 km; in Fig.5 it corresponds to the P_2-TP isopach maps). In the absence of Triassic and Jurassic regional seals, a significant part of hydrocarbons was lost during migration (Fig.6). Therefore, only intraformational reservoir traps provided conditions for gas preservation.

At the end of the Triassic epoch, within the confines of the present-day Khapchagaisky megalithic bank, these deposits passed through the stages of maximum generation, as well as and emigration of hydrocarbons. Within the territory of the Lindenskaya depression, they met the final PFOF stage, manifested in the termination of oil formation. By the end of the Triassic, the southwestern part of the syneclise only entered the upper subzone of mesocatagenesis MK1-MK2 (in Fig.5, it corresponds to the P2-YT and TP-YT isopach maps). Lateral migration from the central part of the syneclise prevailed (Fig.6). In this case, the conditions for the deposit conservation could be controlled by the distribution of the Lower Triassic Nedzhelinskaya and Monomskaya seals, which, in turn, are absent in the southwestern near-flank part of the syneclise.

By the end of the Jurassic, the Permian deposits of the modern Lindenskaya depression moved to the principal phase of gas formation (PFGF), when the formation of gaseous hydrocarbons reaches a maximum. Within the territory of the Khapchagaisky megalithic bank, Permian sediments entered the initial stage of the PFGF. In the southwestern part, the top and bottom of the Upper Permian deposits (in Fig.5 correspond to the P2-Y3br, TP-Y3br isopach maps) were located at depths corresponding to the MC1-MC3 mesocatagenesis. After the formation of the Lower Jurassic deposits, the conditions for vertical migration of hydrocarbons arose, as well as for lateral migration of liquid and gaseous hydrocarbons into the fringe zones of Permian deposits in the marginal part of the syneclise (Fig.6), including their accumulation in lithological intraformational traps and traps confined to pinched out Permian sediments. The post-Jurassic stage during the Verkhoyansk fold area development accounted for the main growth of local uplifts of the Khapchagaisky megalithic bank, the reformation and loss of deposits, and the main phase of the deposit formation and hydrocarbons accumulation.

By the end of the Lower Cretaceous in most of the syneclise, Permian deposits were at the PFGF levels, within the Lindenskaya depression – at the final stage of gas generation processes. In the southwestern part of the syneclise during the Lower Cretaceous (in Fig.5 corresponds to the isopach maps P2-M_K1, TP-M_K1), plunging Permian sediments entered the sub-stage of maximum hydrocarbons generation (3.0-4.0 km around the central part of the syneclise). With the involvement of more and more southern areas of the accumulation of Permian sediments, the conditions for vertical migration also expanded (Fig.6).

At the present stage, corresponding to the depths of maximum sediments downwarping, the Permian strata in the area surrounding the central part of the syneclise is located within the PFGF. Permian deposits in the deepest parts of such depressions (Lindenskaya and others), apparently, have exhausted their gas-producing potential. Conclusions about the time of hydrocarbons generation and migration within the southwestern part of the syneclise are confirmed by computer modeling of hydrocarbon generation within the territory of the Tolonskoye gas-condensate field [22].

In the junction zone of the Vilyui syneclise with the Aldan anteclise, an additional source of hydrocarbons could be the Kuonamskaya (Inikanskaya in the Yudomo-Maya trough) oil and gas source suite of the Lower-Middle Cambrian. Hydrocarbon gases $Є_{1-2}$kn of high gradations of organic matter catagenesis could replenish the reservoirs of deposits in the Upper Paleozoic and younger sediments of the Vilyui syneclise and migrate laterally to the southwest within the Upper Permian complex [24].

In accordance with the identification guidelines of hydrocarbon systems based on the basic elements characteristics, developed by V.S.Sobolev [21], the Permian strata belongs to the oil and gas condensate system of the III class. Based on this type of hydrocarbon systems, it is assumed that up to 20 % of the accumulated hydrocarbons can be presented by the liquid phase. This is confirmed by the results of deep drilling in the central part of the syneclise [9]. The Kuonamskaya suite may additionally contribute to the content of liquid hydrocarbons in the predicted deposits.

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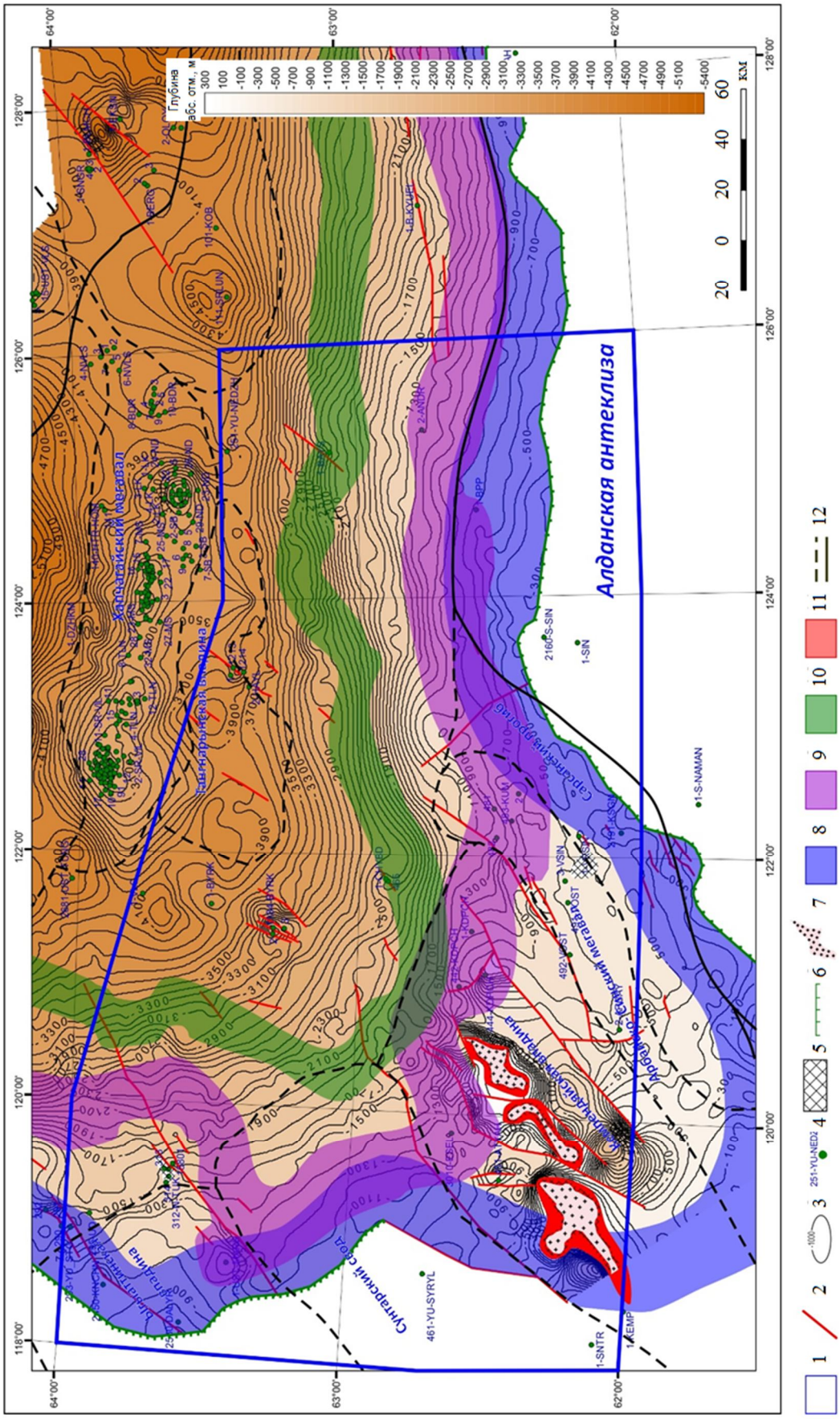


Fig. 7. Layout of promising oil and gas accumulation zones associated with fringe zones in the Upper Permian deposits of the southwestern part of the Vilyui syneclise

1 – research area; 2 – faults; 3 – Contour lines of the Permian deposits top (OG TR), abs. mark., m; 4 – wells; 5 – zones of no deposits; 6 – boundary of the Permian deposits distribution; 7 – areas of the Upper Permian sediments outcrops

Zones of development of traps of predominantly stratigraphic and lithological types: 8 – fringe zone of the Taragaiskaya suite deposits; 9 – fringe zone of the Kyundeiskaya suite deposits; 10 – fringe zone of the Khomustakhskaya and Kharyasskaya suites deposits; 11 – unpromising areas; 12 – boundaries of tectonic structures

Prospects of oil and gas potential. The considered features of sedimentation of the identified suites led to the formation of fringe zones of sedimentary complexes, which the authors compare with the oil and gas accumulation zones. The most promising areas along the lateral of the identified zones will correspond to the development of well-washed river sandstones. The replacement of sandy deposits by floodlands and lacustrine-boggy sediments is a favorable condition for the emergence of lithological sedimentation traps. Stratigraphic traps can also form in the fringe zones both within the Upper Permian complex itself and under the pre-Triassic erosional surface.

Clayey lacustrine-boggy and floodland Upper Permian sediments, as well as the near-bottom part of the Kyzylsyrskaya suite, which is marked by increased clay content according to GIS data, will act as screens as zonal seals for permeable sediments.

The considered geochemical conditions of oil and gas content suggest that the conditions for the deposit formation in the fringe zones of Permian sediments developed by the end of the Mesozoic in the southwest part of the syneclise. The hydrocarbon phase composition of possible deposits may contain an oil component, which is the result of migration from both the Permian hydrocarbons source horizons and from the Kuonamskaya oil and gas source formation.

Thus, within the study area, the development of hydrocarbon deposits associated with lithological and stratigraphic traps is expected directly in the fringe zone of sedimentary complexes (suites) (Fig.7) on the southwestern slope of the syneclise. The compiled scheme also takes into account the possible discovery of deposits associated with the lower horizons of the Upper Permian section in the sediments fringe zones of the Kyundeiskaya, Kharyasskaya, and Khomustakhskaya suites. Areas close to the central part of the syneclise with deposits identified in the Byrakanskaya and Khailakhskaya structures, were transitional along the path of hydrocarbon fluids from the source of oil and gas generation associated with the deep depressions of the Vilyui syneclise, as well as from the deposits disturbed in the late stage of the syneclise development [18] up the slope. Deposits associated with small anticlinal structures, as well as deposits of the lithological type, confined to structural elements such as structural noses, terraces, etc. can exist in such areas.

Elements of tectonic screening, which plays a significant role in the control of previously identified deposits within the syneclise could not be ruled out. The territory of the Kempendyaiskaya depression, which is characterized by active tectonic genesis, including salt-dome one, is not assessed in this work. Nevertheless, it can be expected that here the traps in the Upper Permian sediments will be associated with small structures complicated by tectonic screens. Areas of the Permian deposits outcrops (which arouse as a result of the salt-dome tectonics) in the south-west of the Kempendyaiskayai depression can be considered one of the unpromising.

Conclusion. In the southwest of the Vilyui syneclise, the distribution and characteristics of natural reservoirs in the Upper Permian deposits are determined by the lithofacies conditions of their formation and are associated with the widespread development of alluvial sediments. The sediments are characterized by facies variation and replacement of sandy channel sediments by silty-clayey rocks. This is especially typical for the upper part of the Upper Permian section towards the pinching out of sediments on the southern flank of the syneclise.

The analysis of the geochemical conditions of oil and gas content showed the possibility of hydrocarbons accumulation in the supposed deposits of the southwestern part of the syneclise due to lateral and vertical migration from, mainly, Permian oil and gas source deposits. The Kuonamskaya suite of the Cambrian is considered as an additional source of hydrocarbons.

The considered conditions of sedimentation, generation and migration of hydrocarbons were favorable for the hydrocarbon accumulation in the fringe zones of sediments of the Permian complex, where lithological and stratigraphic hydrocarbon traps are developed, both intraformational and under zonal seals.

When assessing the prospects for oil and gas potential, the authors identified three regional oil and gas accumulation zones, caused by the stepwise pinching out of the Upper Permian sedimentary complexes (suites). Such oil and gas accumulation zones concentrated a significant amount of generated hydrocarbons within the Vilyui sedimentary basin. The greatest prospects for oil and gas content should be associated with deposits confined to the top parts of the Upper Permian strata, since a partial

flow of hydrocarbon fluids from the underlying Upper Permian deposits is not excluded. The main types of hydrocarbon traps in the predicted oil and gas accumulation zones are structural-lithological, lithological and stratigraphic.

The southwestern slopes of the Vilyui syneclise are recommended for further geological and geophysical surveys. Detailed studies would reveal the areal distribution of zones of advanced reservoirs associated with river channel sand bodies, and thoroughly predict local objects for prospecting work.

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