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Abstract

Russian Arctic shelf opens broad opportunities for oil and gas fields' development and hydrocarbon potential for the years to come. Among a number of other fields, the Prirazlomnoye oilfield is a unique one, as it is the only one currently being under development.

A 36-years field development project has been applied since 2014; and already this day numerous studies on revealing of new potentials within the Pechora Sea water area are getting more relevant. In this connection, specialists consider more ancient reservoirs lying beneath the Permian and Carboniferous deposits which, in turn, are put into development.

It is Silurian deposits which represent one of the keys for effective hydrocarbon extraction. The ways on how to produce petroleum they entrapped within millions of years were offered in this work. Conceptual solutions were undergone qualitative and qualitative analyses made by the author based on a number of articles, technological schemes, open sources and supplementary information gained from Gazprom Neft Shelf specialists.

In the paper it was presented a description of the geological structure of the Prirazlomnoye field, qualitatively assessed of the filtration and reservoir characteristics of productive Silurian reservoirs and the properties of oils; considered lithology, stratigraphy, tectonics, hydrogeology, geocryology. In addition, the current field development scheme was considered, and an analysis was made of winterization issues. Finally, development options were proposed, final solutions were selected and justified with recommendations.

The results achieved would in absolute terms acquire professional significance for field engineers, geophysicists, project managers and other specialists involved in the oil and gas industry.

Acknowledgements

In 2017, when I was a student of Gubkin University 5-year Bachelor in Petroleum Geology and Geophysics, I got acquainted with the educational cooperation of my university and University of Stavanger. I set a goal to join the program by significant self-preparation, in particular, by getting a 2-year English degree of “Interpreter in the field of professional communication”.

Without any doubt I’m grateful to the universities which have provided me the chance to enhance my knowledge in offshore field development, subsea technologies, offshore engineering in the Arctic, marine operations and other professional disciplines.

Master degree proceeding at two major technical universities involves not only professional development, widening range of interest, but also soft skills improvement, setting of new contacts, professional network growth.

In this connection, I would like to thank Ove Tobias Gudmestad for the best supervision of my thesis work and for establishing a positive cooperation. Professor Gudmestad provided a lot of his time for professional advice, quality review via physical and online meetings. There is no way of mentioning his sincere intention to support students in their academic extension, educational maturity.

In equal measure I’m excited to emphasize the contribution of Aleksander Dmitrievich Dzyublo for his expert knowledge of the Prirazlomnoye and adjacent offshore oil and gas fields. Aleksander Dmitrievich has provided me much information and data needed for the thesis writing, as well as the clear vision in regards with the fields’ historical background, process and production features.

I hope the contacts established during these two years will keep themselves in the future, because united we stand, divided we fall.

Table of contents

Introduction

The implementation of projects for the development of the Arctic shelf of the Russian Federation is one of the main challenges and one of the considerable prospects that are increasingly facing the domestic oil and gas industry. The development of offshore oil and gas fields, of technical and technological solutions, of coastal infrastructure will make it possible to determine the hydrocarbon potential for many years to come.

One of the modern, technological and discussed development projects is the Prirazlomnoye oilfield, which is currently being developed by one offshore platform.

In general, in order to achieve maximum productivity in the long prospective, the oil and gas industry must create the appropriate conditions; and every error or omission must be corrected at every stage of the transition from crude oil to petroleum product. Taking into account the long history of the oil and gas industry, risk analysis and rational implementation of a computed field development project have not lost their relevance to this day. Arctic hydrocarbon reserves appear to be a strong competitor in the oil and gas market; a number of countries claims to develop these fields, and the Russian Federation which owns one third of the territory located in the Arctic shelf plays a key role in the development of the productive zones of the North.

The purpose of the thesis is to compose conceptual solutions for the development of the Silurian deposits of the Prirazlomnoye oilfield in the Pechora Sea. This goal implies that the complex of geological, geophysical, technical, technological, economic and design studies of the Prirazlomnoye deposits considered in the framework of this thesis will be subject to description and analysis.

The main idea for achieving the set goal is to forecast production characteristics and the nature of the development of Silur, which is necessary as the next step in the development of the field after the depletion of the Permian deposits.

The objectives of this work include the following points:

- to study the geology, hydrogeology, lithology, stratigraphy, tectonics, seismics of the considered section and the deposit as a whole;
- to describe climate, weather and geocryology conditions;
- to consider the position of the Arctic reserves at the global level with a description of the history, numbers, significance and prospects;
- analyze the stages and methods of implementing the field development in accordance with the current project, the current development scheme;
- to justify geophysically and statistically the reasons for studying the Silurian deposits and describe the place occupied by these rocks for the field and the oil and gas sector as a whole;
- to offer basically a possible scheme for the development of the field, taking into account geophysics, economics, risks and prospects, and to justify the choice;

- assess the possibility of adverse effects of natural and climatic forces on the development of the deposits;
- to carry out a forecast of production characteristics in terms of the development of the Silurian deposits;
- to draw up the main conclusions on the above points of the studied territories and deposits.

The object of the study is the rocks of Prirazlomnoye. The subject of the study is the deposits of Silur.

The considered productive zone has a high professional interest due to rather high productivity of the deposits. The Silurian deposits are one of the keys to efficient field development.

The theoretical basis for writing the thesis is the works of both foreign and domestic authors.

To achieve these goals, as well as for the efficiency of the work, the following software necessary for qualitative and quantitative analyses will be used: MS Office package.

Part 1. Geological framework

In this chapter, attention will be paid to a detailed description of Prirazlomnoye deposits starting from the general picture (regional tectonics, geology, structural geology, lithology, stratigraphy and other aspects) and ending with a more specific description of the rocks being under consideration (local geology, parameters, characteristics and properties of reservoirs, etc.).

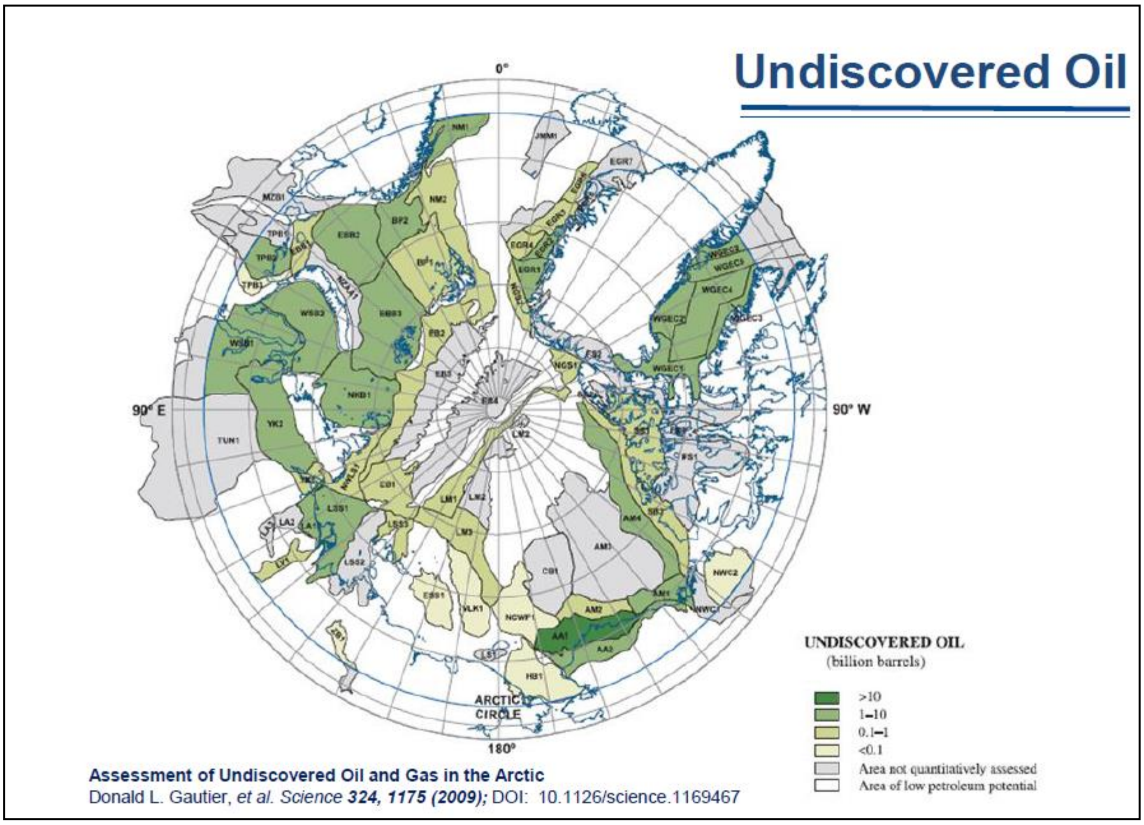
The chapter will consist of a number of subsections the purpose of which is to obtain a broad understanding of the study area in order to justify the choice of one or another development scheme. In such a way attention will be paid to general information about the field, geological and tectonic description, oil and gas potential, climatic, weather and geocryological conditions.

In addition, the prospects for the development of specific Silurian deposits which are necessary for composing of a new development scheme for Prirazlomnoye will also be subject to description.

1.1. Major facts and perspectives of Arctic

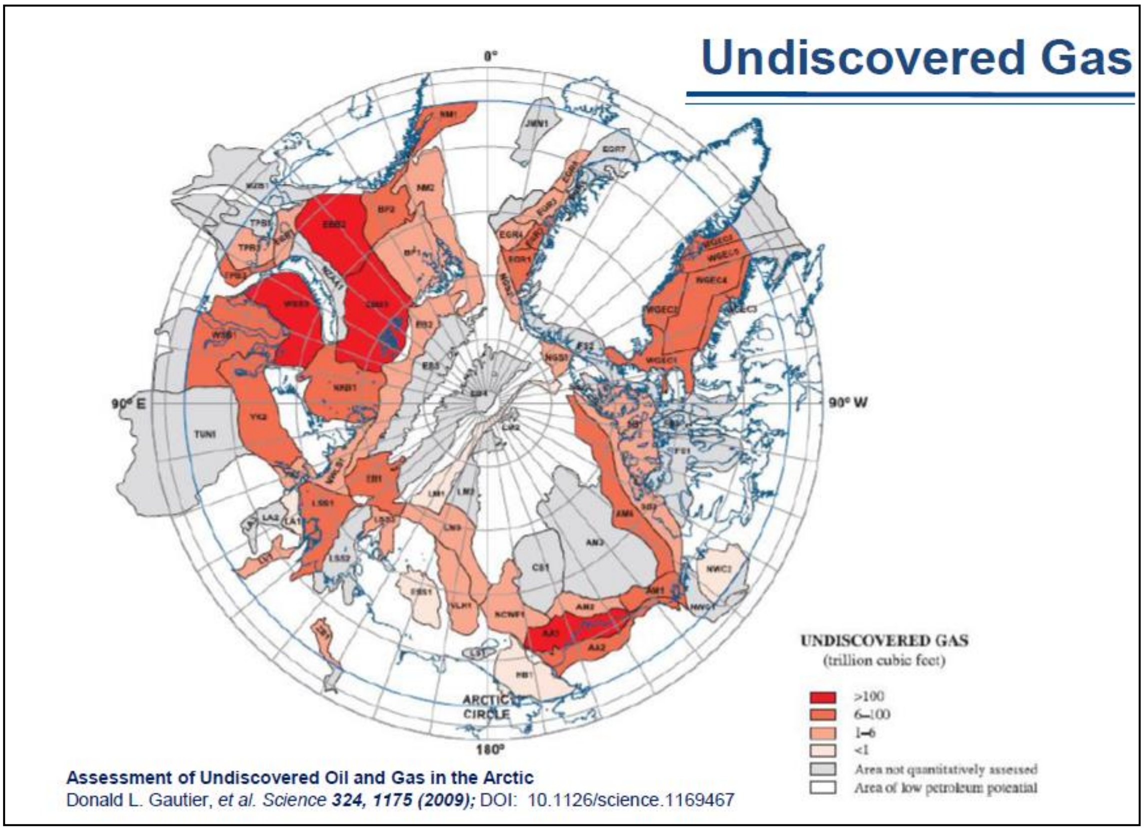
Many experts believe that by 2035 the demand for oil and gas will grow at the global level to 18% and 44%, respectively. About 60% of the planned oil and gas production by the same year will be produced from fields that have not been discovered and undeveloped this day.

As can be seen from Fig. 1.1 and Fig. 1.2, the distribution of undeveloped hotspots is large enough to open up the possibility of long-term development. In terms of oil resources, more than 10 billion barrels reach approximately 10% of the Arctic area, with the bulk (about 50%) falling within a range of 1 to 10 million barrels. A considerable percentage – about 20% – is occupied by reserves which values range from 0.1 to 1 million.



Assessment of Undiscovered Oil and Gas in the Arctic
Donald L. Gautier, *et al. Science* **324, 1175 (2009);** DOI: 10.1126/science.1169467

Figure 1.1 – Map of North territories with an indication of non-discovered and undeveloped oil deposition areas [ll]



Assessment of Undiscovered Oil and Gas in the Arctic
Donald L. Gautier, *et al. Science* **324, 1175 (2009);** DOI: 10.1126/science.1169467

Figure 1.2 – Map of North territories with an indication of non-discovered and undeveloped gas deposition areas [ll]

Gas resources have a somewhat different picture. Reserves of more than 100 trillion cubic feet occupy approximately 20% of the Arctic, and from 6 to 100 trillion – about 30%.

According to the Oxford Institute for Energy Studies and estimates by Russian energy authorities, the world's undiscovered oil and gas reserves in the Arctic region amount up to 22%. At the same time, the share of the Arctic in Russian development and study is 58%. In total, the Arctic region accounts for 61 large hydrocarbon fields where 43 are located on the territory of the Russian Federation.

Moreover, the development of the Arctic represents a strong international cooperation, since about six countries (USA, Canada, Greenland (Denmark), Iceland, Norway, Russia) claim their role.

Thus, the predicted oil and gas resources make up the majority of hydrocarbons when compared with those developed today. The potential is huge, but due to the complexity of development (harsh climatic conditions, permafrost, lack of developed infrastructure, expensive cost of equipment and staffing and development, and other factors), the question of expediency and profitability arises, because under such framework conditions, probably, development and obtaining of energy from alternative energy sources may become more effective.

1.2. General insight into Prirazlomnoye oil field

The history of Russia in the Arctic dates back to the 11th century, when Russian navigators began to explore the seas of the Arctic Ocean. In 1733-1742 the Great Northern Expedition described and mapped the Arctic coast. Further, in 1898, the world's first Arctic icebreaker "Ermak" was built, and in 1937, the world's first drifting polar station "North Pole-1" was launched. The year 1972 was unique for the USSR marine Arctic exploration expedition which began oil and gas exploration on the shelf.

The Prirazlomnoye field is unique today, as it is the only one being developed within the Arctic shelf in the Russian Federation. Prirazlomnoye is an oil field that was discovered in 1989 and has balance oil reserves of approximately 83 million cubic tons. Oil was first shipped here in 2014, and exploration work was carried out in the late 1970s.

Drilling, production, storage, loading onto tankers and other operations are carried out by means of the offshore ice-resistant stationary oil production platform Prirazlomnaya (Fig. 1.3). This platform is ready for the harsh climatic conditions of the Arctic – a seven-month drifting ice cover, two-meter hummocks, increased wind and precipitation activity. Prirazlomnaya has a width and a length of 126 meters, and a height of 122 meters.

Figure 1.3 – Prirazlomnaya platform [s]

Prirazlomnoye is located on the shelf of the Pechora Sea (Fig. 1.4), about 60 kilometers to the North from the village of Varandey, has a sea depth of about 19-20 meters and geologically belongs to the Timan-Pechora oil and gas province. Productive horizons being under development, on average basis, are located at a depth of about two and a half kilometers.

Figure 1.4 – Map of Prirazlomnoye location [r, corrected by the author]

The license for the exploration and production of hydrocarbons at the Prirazlomnoye field is held by Gazprom Neft Shelf LLC (before the renaming – Sevmorneftegaz CJSC), a 100% subsidiary of Gazprom Neft PJSC [r].

After the discovery of the field in the mentioned above year, drilling of exploration wells began in 1993-1994. The construction and transportation of Prirazlomnaya was carried out in the period of 2003-2011. Oil production at the Prirazlomnoye field began in December 2013, and already in April 2014 the first batch of oil was shipped.

The platform is fully equipped with horizontal wells, where 19 out of 32 planned wells are productive (put into operation), 12 are injection wells.

The field being under consideration has a rather complex geological structure (Fig. 1.5), natural conditions, geographical position, which creates obvious difficulties for rapid and safe development of the territories.

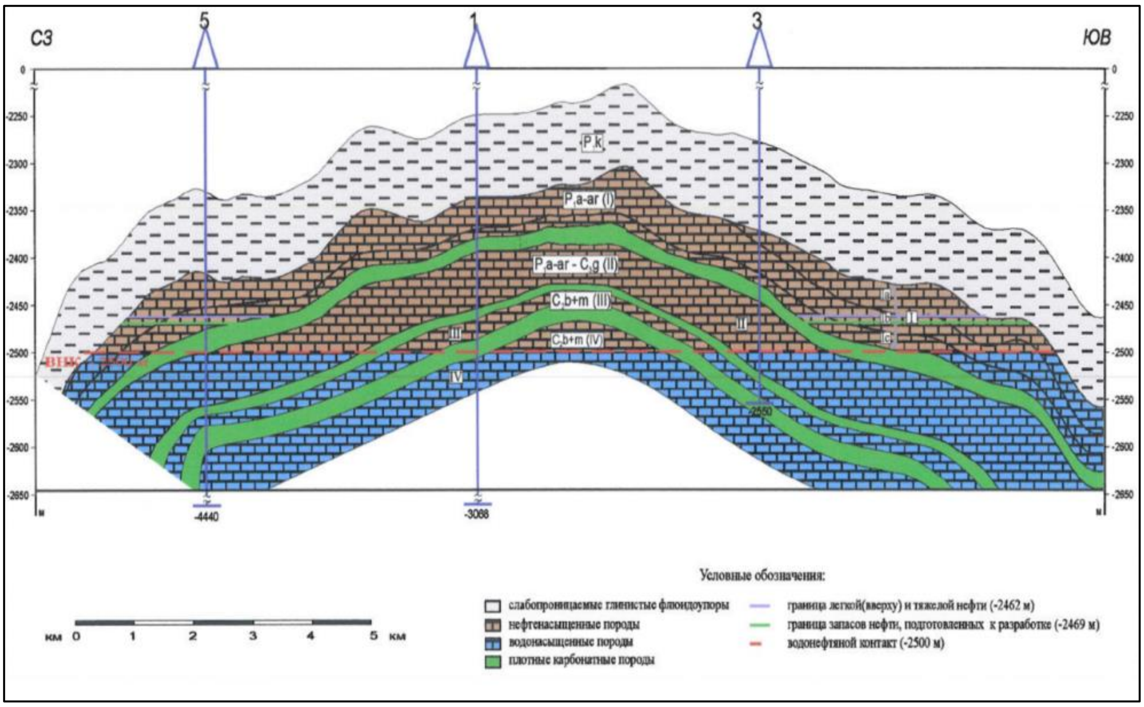


Figure 1.5 – Geological cross-section of Prirazlomnoye [uu]

The shelf of the southeastern part of the Pechora Sea in the zone of the Varandey-Adzvinsk structural zone is about 980 kilometers from the seaport of Murmansk – the location of Prirazlomnoye. The area is characterized by rather difficult natural and climatic conditions.

ARCO oil is characterized by high density (about 910 kg per cubic meter), high sulfur content and low paraffin content. Relatively heavy compared to conventional Russian export oil ARCO is well suited for deep treatment at northwest European refineries. It produces unique chemical products that can be used in road construction, tire production, space and pharmaceutical industries [vv].

Four large oil fields were discovered in the waters of the Pechora shelf (Fig. 1.6): Prirazlomnoye (1989), Varandey-More (1995), Medynskoye-More (1997) and Dolginskoye (1999). All deposits are underexplored.

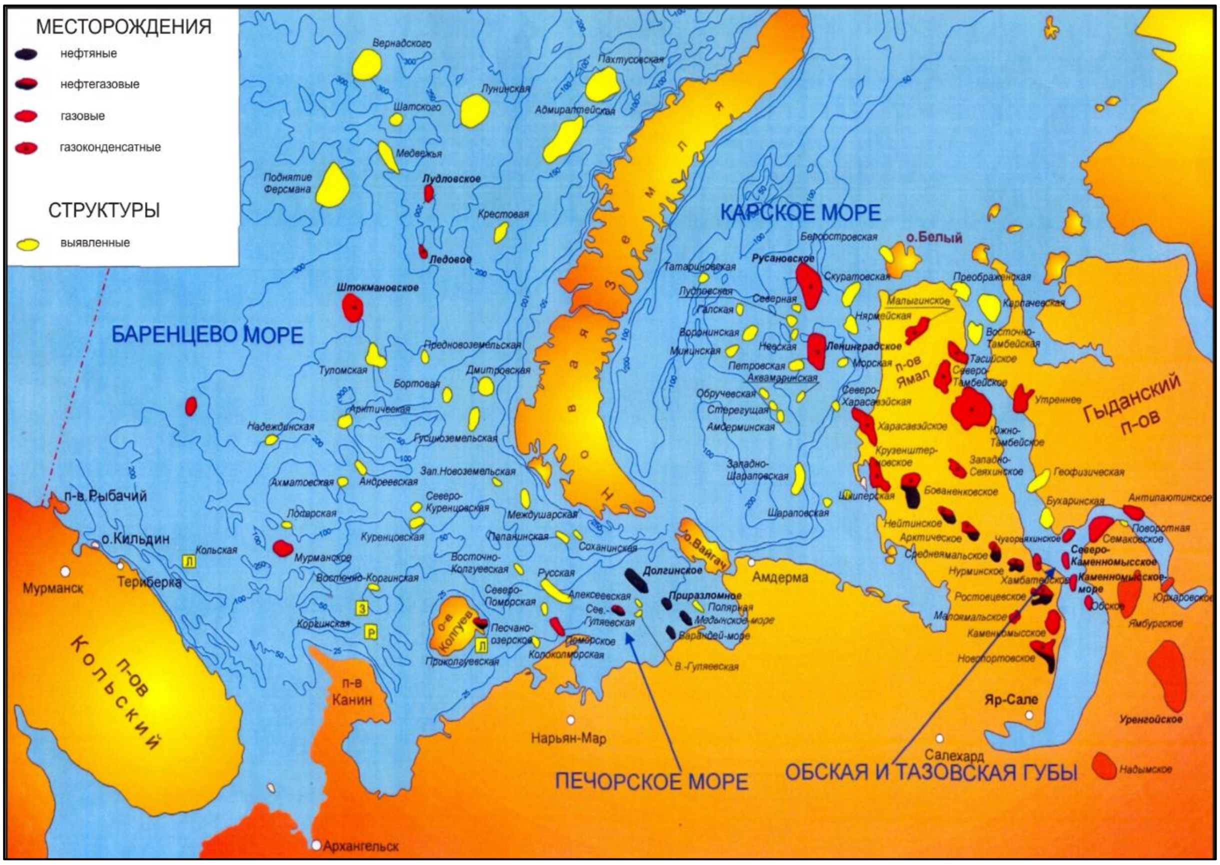


Figure 1.6 – Barents and Kara Seas map [h]

As for figures' description of the field, almost 3.2 million tons of oil were produced in 2019, recoverable reserves reach up to 70 million tons, and the exploitation life is 36 years.

1.3. Geological description of the area

1.3.1. Basic information on Timan-Pechora oil and gas province

The Timan-Pechora oil and gas province is located (Fig. 1.7) in the region of the Nenets Autonomous District, the Komi Republic and the Pechora Sea.

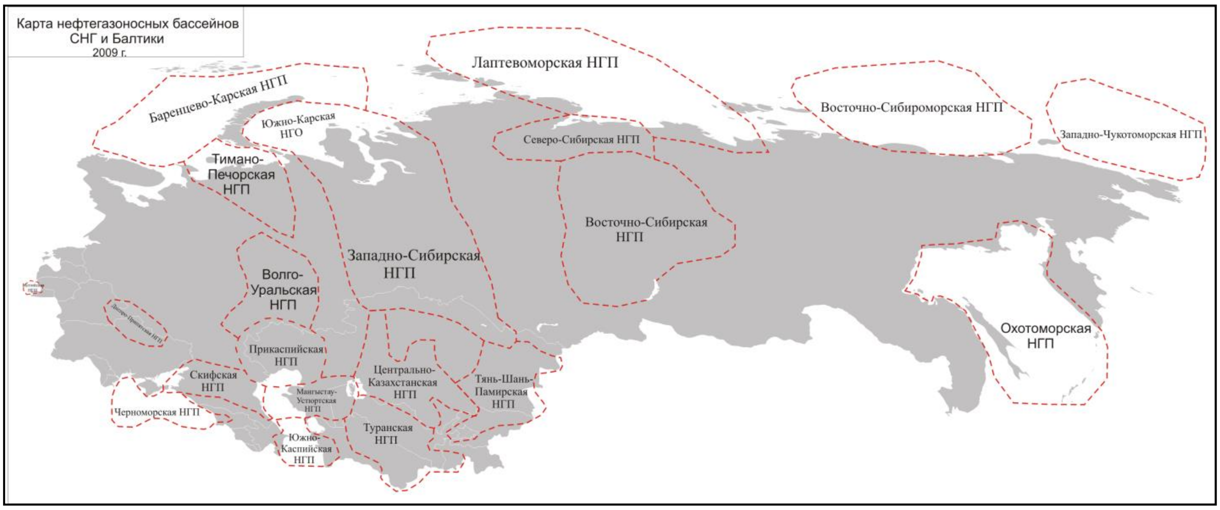


Figure 1.7 – Oil and gas bearing basins location map of CIS and Baltic [ww]

With an area of about 600 000 square kilometers the province has a rather complex structure from a geological point of view.

Resources are about 2.4 billion tons, 60% of which are oil. One third of the resources are located on the territory of the Komi Republic, two thirds are on the territory of the Nenets Autonomous District. The depth of the deposits ranges from 800 meters to 3 kilometers. Currently, more than 200 deposits have been discovered. The richest oil and gas regions are Pechoro-Kolvinskaya (44%), Khoreyverskaya (20%) and Izhma-Pechora (11%). Currently, there are more than 180 fields on the territory of the Timan-Pechora oil and gas province, of which 136 are oil, 4 are gas condensate, 2 are oil and gas, 13 are oil and gas condensate, 12 are gas condensate and 16 are gas fields. Oil has a density of 0.826-0.885 g/cm^3; it can be characterized as low-sulfurous and medium-sulfurous, paraffinic (from 0.4 to 6.6%), low-resinous. Methane gas (more than 80%) is enriched with heavy hydrocarbons (10-17%) and has increased condensate content. In gas condensate fields the output of stable condensate is from 50 to 500 cubic cm. per 1 cubic meter [ww].

This province as well as Prirazlomnoye is a unique composition of rocks in terms of their evolution and geological structure. From a tectonic point of view the basin represents a transition from active subsidence with massive marine transgressions to inversions and orogenesis. The sedimentary cover embraces most types of deposits, has a variety of reservoirs and traps, and fluid characteristics. This suggests that this province has a great potential for the study and discovery of new deposits and fields.

1.3.2. Climate of Timan-Pechora oil and gas province and Pechora Sea

Since most of the researches and statistics have been carried out in the Barents Sea which includes the Pechora Sea it is the former that will be the subject of consideration.

Frequent Arctic and Atlantic winds, critical changes in precipitation and wind direction are typical for this province, since it is located at the territory of the plain and exposed to the Arctic and Atlantic oceans.

The location in the subarctic (in the far North and North-East) and moderate (in most of the territory) climatic zones causes a rather severe, harsh continental climate with long, rather severe winters and short, relatively cool summers. The average annual air temperature has negative values, decreasing from the South to the North-East from +1°C to -6°C; the annual amount of precipitation in the same direction varies from 625 to 450 mm.

Flat, in some places gently hilly, the Pechora lowland is easily accessible for invasions of air masses from any direction. Therefore, the weather is characterized by great instability associated with the frequent passage of cyclones. The influx of cold air from the Arctic causes sharp drops in air temperature almost throughout the entire territory. In winter, cold snaps can reach up to -50°C, and in the warm period cause frosts.

A large amount of precipitation with relatively low evaporation leads to excessive humidity of the territory. During the winter, which lasts from 130 to 200 days, a large amount of snow (70-80 cm) accumulates for the melting of which a significant amount of heat is consumed in Spring. No less of it is spent on heating frozen soils and melt waters [m].

As for figures, the temperature minimum is minus 50°C. During storms that occur about 22 times a year and create a wind force of up to 8-9 points the height of the waves can reach 7-9 meters. The speed of the currents around the platform increases to a range of 7 to 12 km/h.

The area of the Barents Sea (Pechora Sea) is 1 405 000 km^2 (81 300 km^2), the average water volume is 282 000 km^3 (4 400 km^3), and the average depth is 200 m (6 m).

The climate of the sea is polar and marine, and the warmest among the shelf seas of the Arctic Ocean. Although the Barents Sea is one of those covered with ice, and almost 3/4 of its surface is covered with ice every year, unlike other seas in the Arctic, it never freezes completely. Even in winter, about 1/4 of its area remains ice-free, which is explained by the influx of warm Atlantic waters that prevent the surface layer from cooling to the freezing point [n].

The Barents Sea is typically continental, entirely located on the shelf of the Arctic Ocean, which is deeper within it than in other Arctic seas. Most of the sea has a depth of 300-400 m (Fig. A-1, Appendix A). Coastal shallow waters with depths of less than 50 m occupy a significant area only in the South-East and in its northwestern part (Fig. 1.8). The terrain of the bottom of the Barents Sea is strongly dissected. At distances of tens of kilometers the depth difference is 50-100 m.

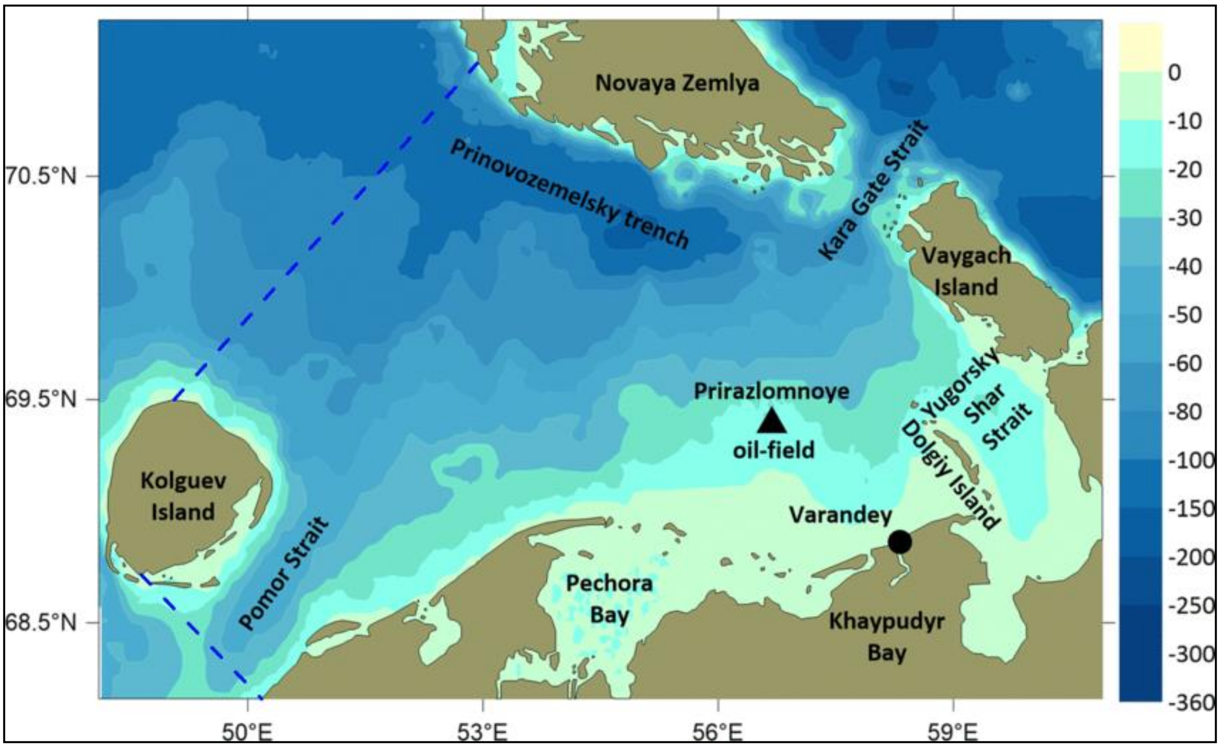


Figure 1.8 – Shallow water map of Barents Sea South-East part [ss]

The Barents Sea has a complex system of surface and deep currents (Fig. A-2, Appendix A), the most common feature of which is the movement of water in a counterclockwise direction. Formed by large-scale processes in the ocean-atmosphere system in the North Atlantic, it actively reacts to the variability of synoptic conditions directly over the Barents Sea, the propagation of a tidal wave from the Atlantic and the Arctic Basin, and the variability of the density structure of sea waters.

However, the actual study of oceanological characteristics and processes cannot be considered as uniform and complete. There are significant gaps in thematic areas and spatial-temporal coverage of research objects. This is largely due to the specifics of marine expeditionary and coastal researches.

1.3.3. Lithologic-and-stratigraphic characteristics

1.3.3.1. Studied cross-section description

The field under consideration is represented by thick (more than 4400 m) strata of sedimentary rocks, where the most ancient deposits are the Lower Devonian rocks.

A generalized lithological-stratigraphic section within Prirazlomnoye is presented below (Fig. 1.9). This section characterizes the stratigraphic structure of the studied interval and also contains information about lithology.

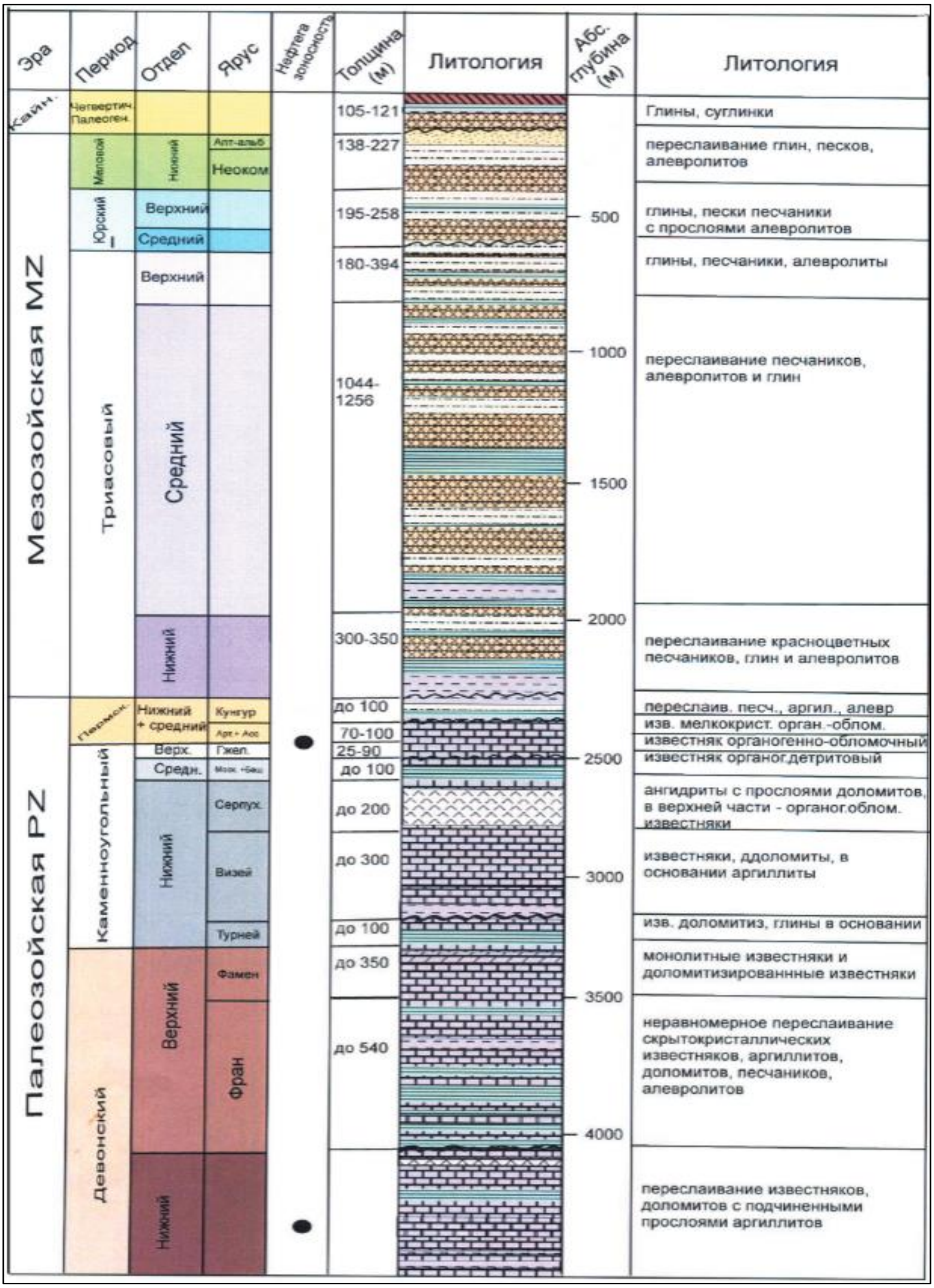


Figure 1.9 – Generalized lithological-stratigraphic cross-section of Prirazlomnoye [uu]

The Paleozoic erathem

At Prirazlomnoye, the studied part of the section of the Paleozoic erathem is represented by deposits of the Devonian, Carboniferous, and Permian systems. In this regard, the description of the deposits which are planned for invasion by exploratory drilling with respect to oil and gas potential of the Silurian system is given for the Varandey field on adjacent land.

The Silurian system

The Upper Silurian deposits were discovered in the Varandeyskaya area in one of the wells at a depth of 77 meters. The deposits are represented by uneven clayey fine-crystalline, lumpy, unevenly layered limestones. In the top part of the section there is a member of clays with interlayers of dolomites. In the southern part of the Sorokin swell at the Osoveiskoye and Khosoltinskoye deposits the development of carbonate reef structures was established in the section of the Silurian deposits. Potential reservoir strata in this interval of the section can be organogenic limestones and interlayers of dolomitic limestones. The estimated thickness of the Silurian deposits at the Prirazlomnoye field is over 500 m.

The Devonian system

According to drilling data in the Varandey area, the Devonian deposits conformably overlie the Upper Silurian. In the section of the Prirazlomnoye deposit the Devonian deposits are represented by formations of the lower and upper series. The penetrated thickness of the Devonian deposits in one of the wells is 1268 m.

The sedimentation conditions of the Lower Devonian were generally favorable for the development of reef-building organisms.

The Carboniferous system

The system is represented by all series. Deposits of the Carboniferous system conformably overlie the underlying Upper Devonian. The total thickness of the deposits of the system reaches 690 m.

The Permian system

It is represented only by deposits of the lower series which occurs with erosion on the Upper Gzhel limestones. The Asselian and Sakmarian, Artinskian, and Kungurian stages are distinguished in the composition of the lower series. The total thickness of the deposits of the system reaches 210 m.

The Mesozoic erathem

At the Prirazlomnoye field the section of the Mesozoic erathem is represented by terrigenous deposits of the Triassic, Jurassic, and Cretaceous systems. The total thickness of the sediments of this erathem is 1855-2490 m. The sedimentation conditions of the Mesozoic sediments change from continental in the Triassic to typically marine ones in the Upper Jurassic and Lower Cretaceous.

The Triassic system

The system is represented by the lower, middle and upper series. The Triassic deposits with significant stratigraphic unconformity overlie the Kungurian deposits of Lower Perm and are represented by continental facies.

The Jurassic system

The system is represented by the middle and upper series. The Jura deposits intermittently rest on the eroded surface of the Triassic.

The Cretaceous system

The system is presented only in the lower series. Cretaceous deposits conformably overlie the Upper Jurassic. The lower part of the section is dominated by gray, brownish-gray, fine-grained siltstones. In the middle part of the section gray, quartz, fine-grained sands occur. The upper part of the section is dominated by dark gray and gray clays. The thickness of the deposits is 136-227 m.

The Cenozoic erathem

Deposits with deep stratigraphic unconformity conformably overlap the Lower Cretaceous formations. They are represented by a thin (101-130 m) sequence of Neogene (Pliocene) and anthropogenic sediments composed of sands, clays, sandy loams and loams with inclusions of pebbles and gravel. The sands are gray, quartz, fine-grained. In the upper part of the section, they are fine and silty. The clay loams are dark gray and often contain coarse clastic material. Clays are gray and soft.

1.3.3.2. Silurian deposits description and perspectives

Silurian deposits were discovered at the territories of such onshore fields as Varandeyskoye, Toboyskoye, Myadseyskoye and others. As for the offshore penetration, Pakhanchenskaya, Medynskoye-More, Prirazlomnaya and other structures are characterized by drilling of the upper part of the Ordovician-Lower Devonian oil and gas complex, in particular, the Lower Silurian [l]. Major unconformities or stratigraphic breaks within the Silurian system have not been identified.

As for the drilling characteristics, the lower stratum (about 160 meters) was penetrated and characterized by a core. It is composed of gray layered microcrystalline limestones which are microclotty and microlumpy, occasionally spotted by dolomites. Beds containing remains of stromatoporates, brachiopods, ostracods, and crinoids are frequent; stromatolites are found. The lower part of the sequence is characterized by layers of detrital limestones (grainstones), which may indicate the presence of stromatoporous and algal biostromes in the series [a].

The middle stratum (about 186 m) was characterized by a core from the lower part. It differs from the lower one in higher background values of gamma-ray logging, hence, increased clay content. In the section of the stratum members and layers of weakly and more strongly argillaceous limestones alternate rhythmically. In the latter, layers of marls up to 2-3 m thick are noted. Limestones are predominantly dark gray, microcrystalline, microclotty with remains of brachiopods, many ostracods, crinoids, sometimes with stromatoporates and tabulates. There are also stromatolites. Layers of sedimentary breccias, layers with burrows (patterned limestones) are noted. Dolomitization is weak. Near the top of the sequence, thin sections show a silty admixture of quartz grains.

The upper stratum (about 83 m) was characterized by cores from the upper part of the gouging. It differs from the underlying strata by a sharp increase in the total clay content fixed by the gamma-ray logging curve. At the base of the stratum carbonate conglomerates and breccias are raised in the core interbedded with carbonate-argillaceous rocks. Above, gray and dark gray limestones, thinly layered, often with a characteristic nodular or lumpy structure, predominate.

Based on the structural geology of the Pechora Sea, hydrocarbon traps are predicted to be in the vicinity of Devonian and Silurian sandstone pinch-outs (Figure 1.10) with a thickness of about 100 meters [b].

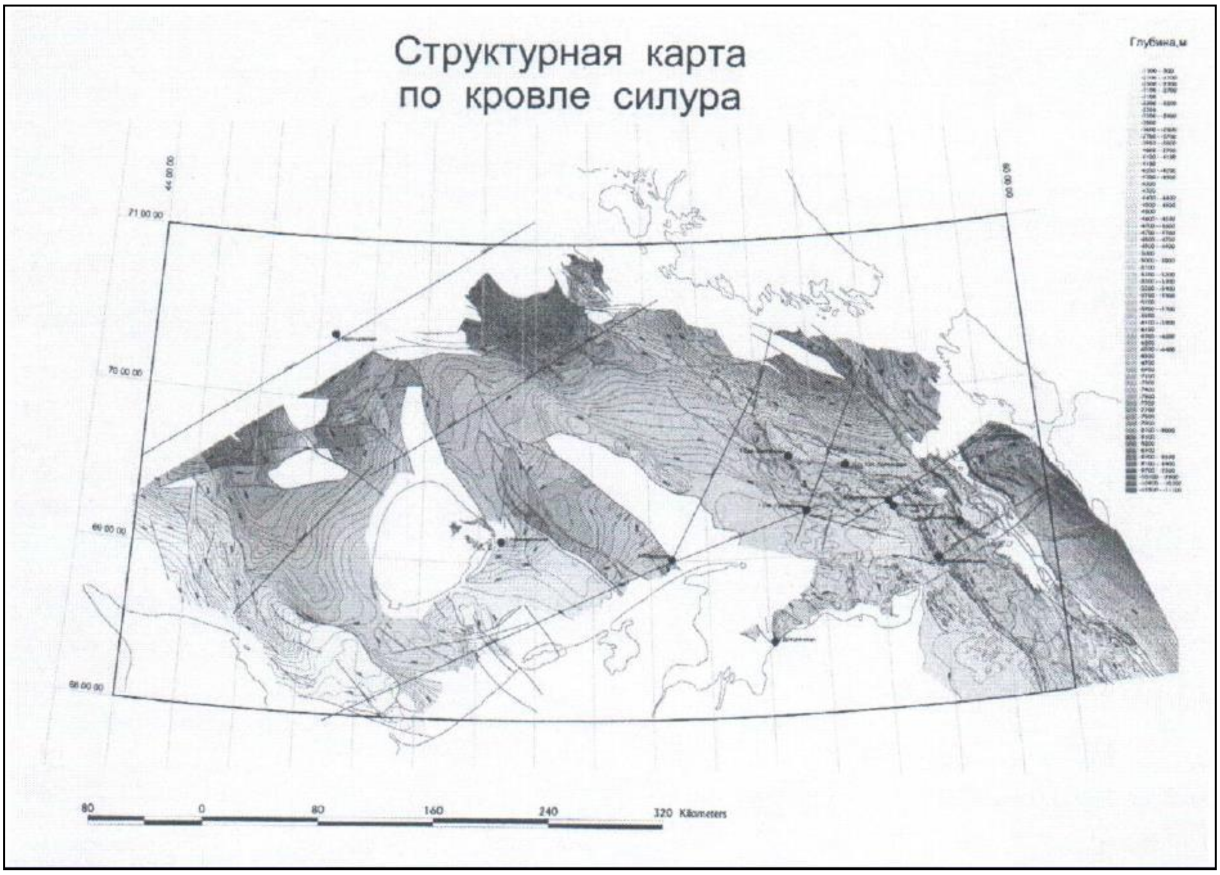


Figure 1.10 – Silurian deposits map (by top) [b]

In addition, the existence of organogenic structures in the Lower Perm is assumed.

1.4. Tectonic characteristics

Structurally (Fig. 1.11), Prirazlomnoye is located on the territory of the Pechora Platform bordering the East European Platform from the West, the West Siberian Platform from the East, and the Baltic Shield from the North-West.

Figure 1.11 – Russian Federation lithosphere plates map [xx]

The Pechora platform, in turn, characterizes (Fig. 1.12) the field under consideration as a section of the Pechora synclise bordering the Timan uplift zone from the West and the downlift from the East.

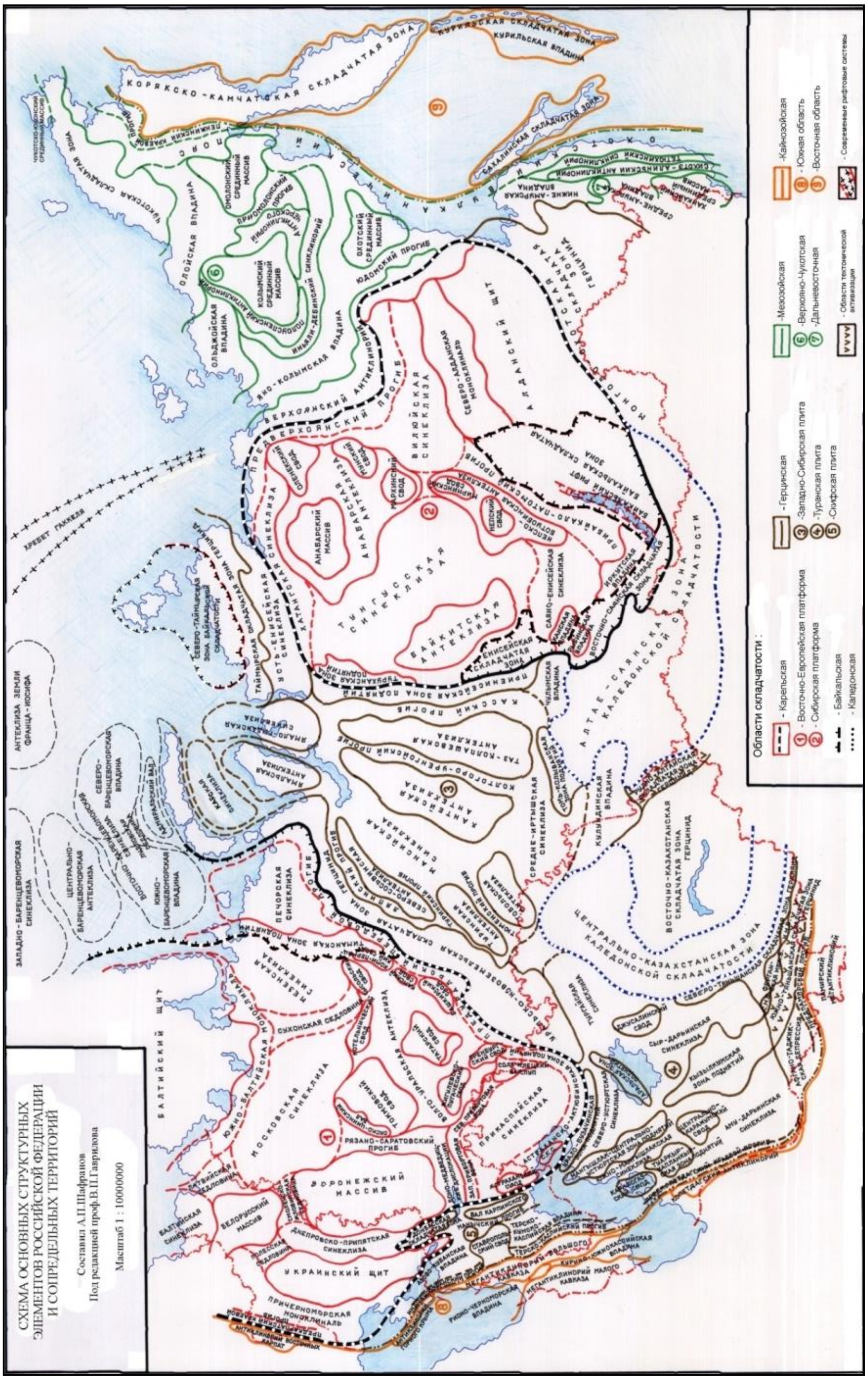


Figure 1.12 – Structural map of Russian Federation [pp]

In addition, tectonically, the Prirazlomnoye field (Fig. 1.13) is associated with the anticline fold of the same name, which complicates the northern part of the large Sorokin swell extending from land to the offshore continuation of the Pechora syncline.

Thus, the structures of the Barents Sea are located at the junction of several large tectonic regions – the East European Platform (the Baltic Shield, the Mezen and Timan-Pechora synclines), the Paikhoi-Novaya Zemlya structure, the Paikhoi and Prevaigach troughs, as well as the Baikalid of the Timan Range. In the West the region borders on the structures of the Atlantic

Ocean, and in the North – the Arctic Ocean. To the East is the Kara-Yamal sector of the West Siberian plate.

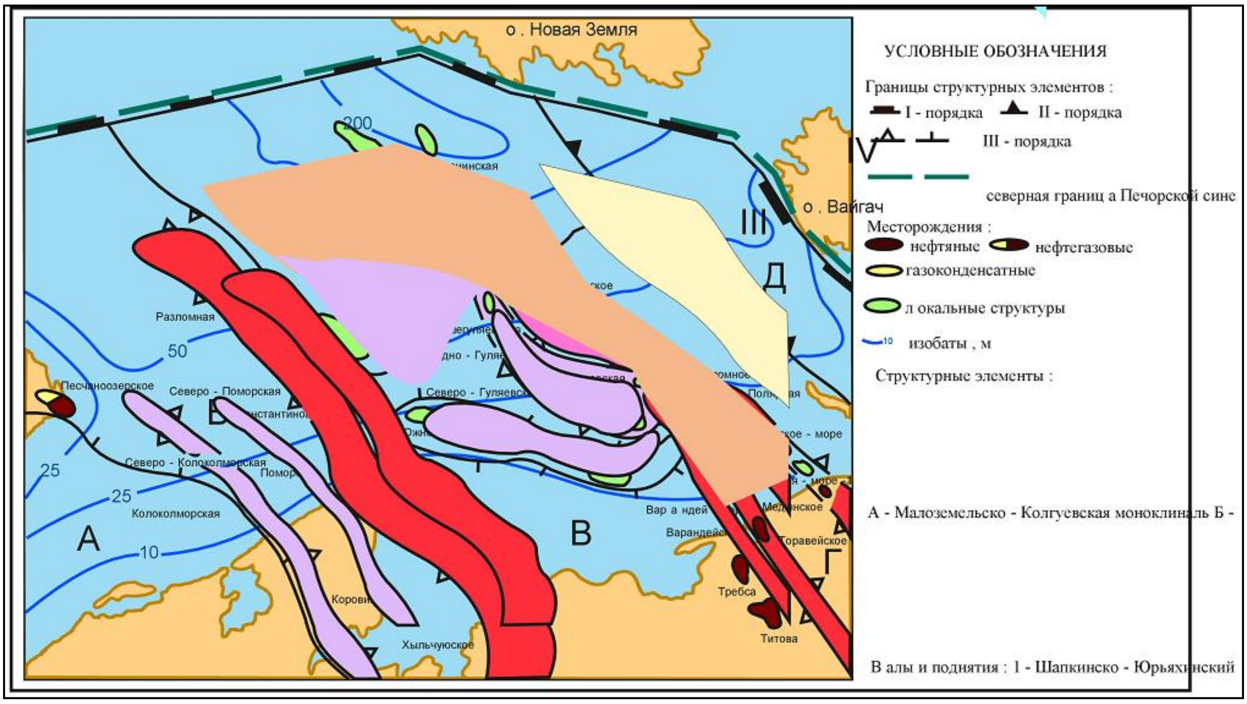


Figure 1.13 – Tectonic map of South-East Pechora Sea shelf [uu]

The Prirazlomnaya structure is a two-domed anticlinal fold of the northwestern strike. The fold is clearly expressed from the bottom of the sedimentary cover to the Jurassic deposits. The southwestern flank of the structure is complicated by a series of echelon-shaped conjugated tectonic faults of the northwestern strike type. The disturbance is characterized by displacement amplitude of 50-150 m and can be traced in the Devonian, Carboniferous and Permian deposits.

The Barents-Kara region can be characterized as seismically active in the continent-ocean transition zone. Concentrated seismic activity indicates the recent geodynamic activity of tectonic faults traced along the ledge of the shelf and framing large grabens of submeridional strike. The seismotectonic deformations of the Gakkel, Knipovich and other ridges influence the current geodynamic situation in the Barents Sea region. Against the background of shear deformations, alternation of sections with compressive deformations and tensile sections are manifested. These shifts in the areas of oceanic ridges and grabens lead to a compression setting, which is confirmed by the concentration of earthquakes here and the nature of their mechanism.

Thus, the water area of the Barents Sea and its framing as a whole is an area with relatively weak seismic activity, within which, however, there are rather highly active areas. The earthquake epicenters here are very unevenly distributed and clearly gravitate towards the marginal parts of the depression. Within the region under consideration these include the Svalbard archipelago and the adjacent part of the water area, as well as areas of increased seismicity in the trenches of the marginal shelf, especially in the Franz Victoria Trench.

1.5. Seismic characteristics

The structure of the fold along the Lower Permian-Carboniferous productive deposits has been studied in sufficient details. The field was studied by 2D, 3D seismic surveys, drilling of exploration wells.

Deposits of the Ordovician-Lower Frasnian mega-complex are widespread (Fig. 1.14) within the continental part of the Timan-Pechora province and the waters of the Pechora Sea and occur at depths from 2 to 8 km. The thickness of sediments in the offshore part of the mega-complex exceeds 1.5-3 km. The lower boundary of the carbonate mega-complex is transgressive, delimiting the terrigenous Cambrian-Lower Ordovician and carbonate Lower Ordovician deposits. The upper boundary of the complex is represented by regional Pre-Middle-Late Devonian erosions.

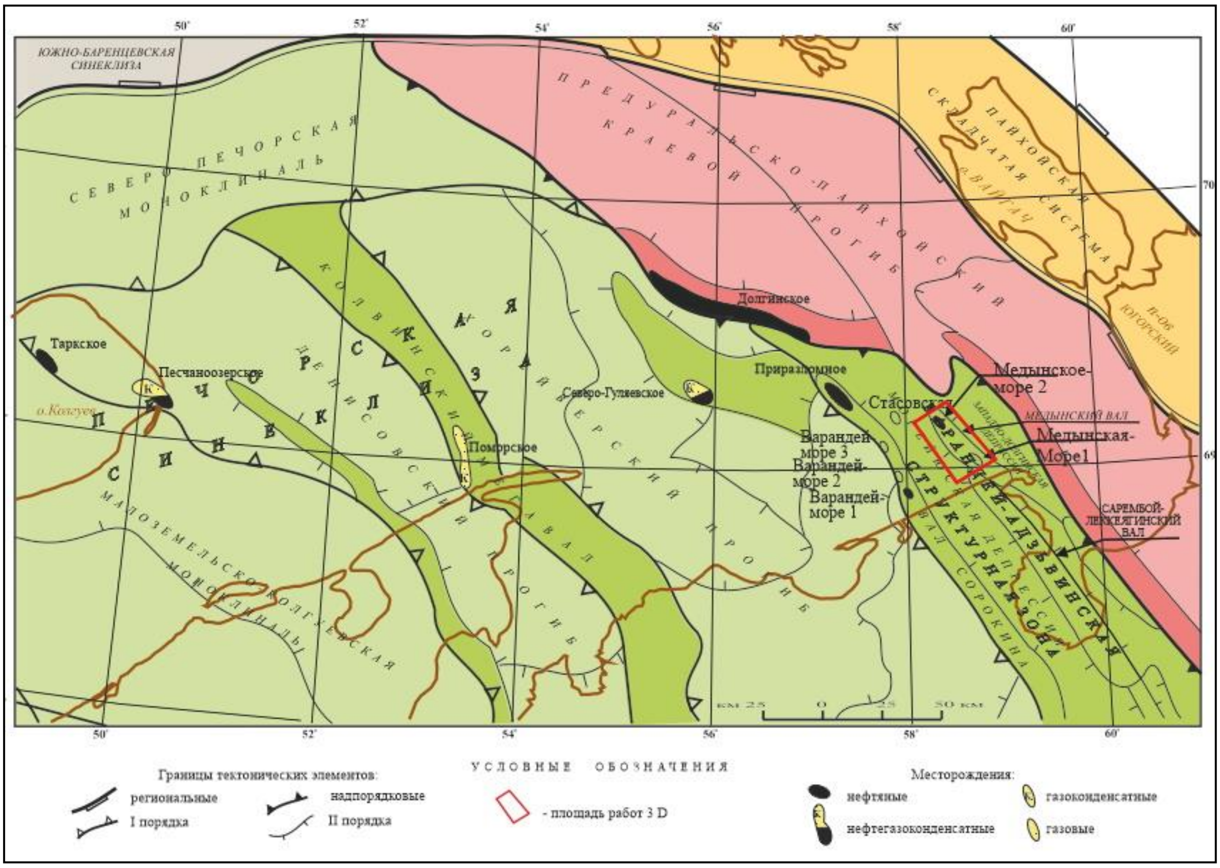


Figure 1.14 – Tectonic terrain analysis scheme of northern part of Timan-Pechora province [uu]

Based on 2D seismic survey data and taking into account drilling data from four wells the Prirazlomnaya structure along the top of the Lower Permian-Carboniferous stratum (along the top of productive horizon I) is a small, large-amplitude two-dome near-fault anticline fold of the North-West strike. The main dome is located in the central part of the fold; the second small dome is located in its northwestern pericline.

According to late 3D seismic data (1997) and the results of reinterpretation of 3D data for the Lower Permian-Carboniferous deposits (2000), taking into account drilling data from four wells the main elements of the fold structure are preserved, but the fault framework is detailed.

According to the reflecting horizon IIv confined to the bottom part of the deposits of the Visean stage, the structure of the near-fault anticline changes insignificantly. The maximum amplitude of vertical displacement along the faulter is observed in the northwestern part of the fold and is 175 m. The number of faults in the periclinal sections of the structure increases.

For the underlying Devonian deposits, the fold is mapped along two reflectors. According to the reflecting horizon III3d in the top of the Semiluksky horizon of the Lower Frasnian stage of the Upper Devonian, the near-fault anticline fold has a three-dome structure. The domes are low-amplitude, two of them are located in the central part of the structure and one is located on its northwestern pericline.

According to the reflecting horizon III1l/ in the top of the Lochkian carbonate sequence of the Lower Devonian, the near-fault anticline fold has a complex block structure.

Along the reflecting horizon III-IV confined to the top by the terrigenous member underlying the Lower Devonian carbonates, the near-fault anticline fold is divided into separate blocks by a series of faults.

1.6. Oil-and-gas content of the area

The Prirazlomnoye oilfield is located in the Varandey-Adzva oil and gas region (OGR) of the Timano-Pechora oil and gas province (OGP). Within the limits of the Varandey-Adzva OGR on land in the section of the sedimentary cover the following oil and gas bearing complexes (OGC) are distinguished.

The Ordovician-Lower Devonian oil and gas complex in the area being under consideration in the water area has been studied extremely poorly. The commercial oil-bearing capacity of this complex in the Varandey-Adzvinskaya OGR has been established on the adjacent land. Oil-bearing layers have been identified in carbonate deposits of the Silurian age, in the Lower Devonian carbonate deposits of the Lochkovian stage, and in terrigenous deposits of the Pragian stage.

In the Upper Silurian deposits, oil-bearing layers were discovered at the Osoveiskoye and Khosoltinskoye fields in the southern part of the Sorokin swell. Oil deposits here are confined to reef structures. Oil deposits are strata with lithological restrictions. The reservoirs are represented by organogenic and organogenic-detrital limestones. Average values of open porosity are 11%. Oil density is 0.887 t/m^3. Oils are resinous, and sulfur content in oil is 0.9-1.1%.

The Carboniferous-Lower Permian oil and gas complex in the Timan-Pechora province is characterized by the highest concentration of proven oil and gas reserves.

The Lower-Upper Permian terrigenous oil and gas complex within the Varandey-Adzvinskaya oil and gas region is productive on land at the Toraveysky, South Toraveysky, Naulsky and Labagansky fields of the Sorokin swell. Oils are mainly heavy, sulphurous. The reservoirs are fine-grained porous sandstones of the Upper Permian and Triassic. The complex is covered by a Lower Triassic silty-argillaceous stratum. There are no Upper Permian deposits at the Varandey-More, Prirazlomnoye, and Medynskoye-More deposits, and the section of the complex is represented only by Lower Permian deposits.

The Triassic terrigenous oil and gas complex on land is productive at all structures of the Sorokin swell.

Higher in the cross-section commercial oil-bearing capacity has not been established.

Prospecting and exploratory drilling at the Prirazlomnaya structure proved the commercial oil potential of Permian-Carboniferous carbonate deposits. According to GIS data and lithological and petrographic studies, in the section of the Permian-Carboniferous carbonate strata three productive horizons were identified (from top to bottom - I, II, III) separated by interlayers of dense carbonate rocks and containing a single oil deposit.

The structural map along the top of horizon I is shown in Figure 1.15.

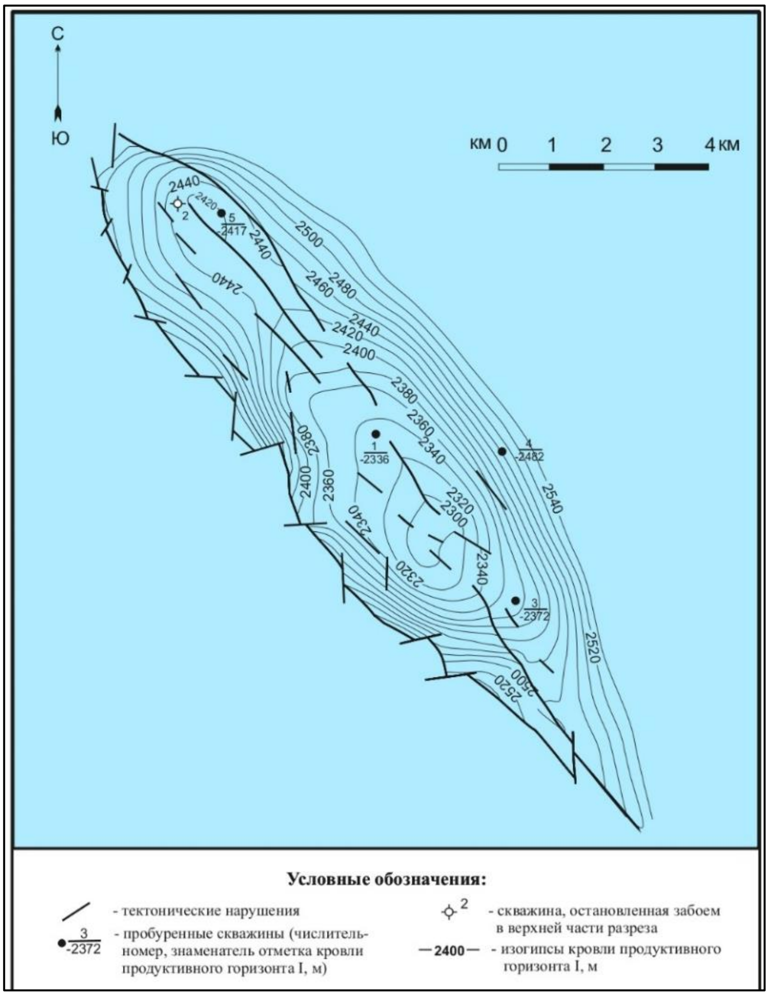


Figure 1.15 – The structural map along the top of horizon I [uu]

The total and effective oil-saturated thicknesses of the productive horizons were determined from the data of field geophysical studies of prospecting and exploration wells.

The sediment correlation scheme and the structural map of the same productive horizon are shown in Figure 1.16.

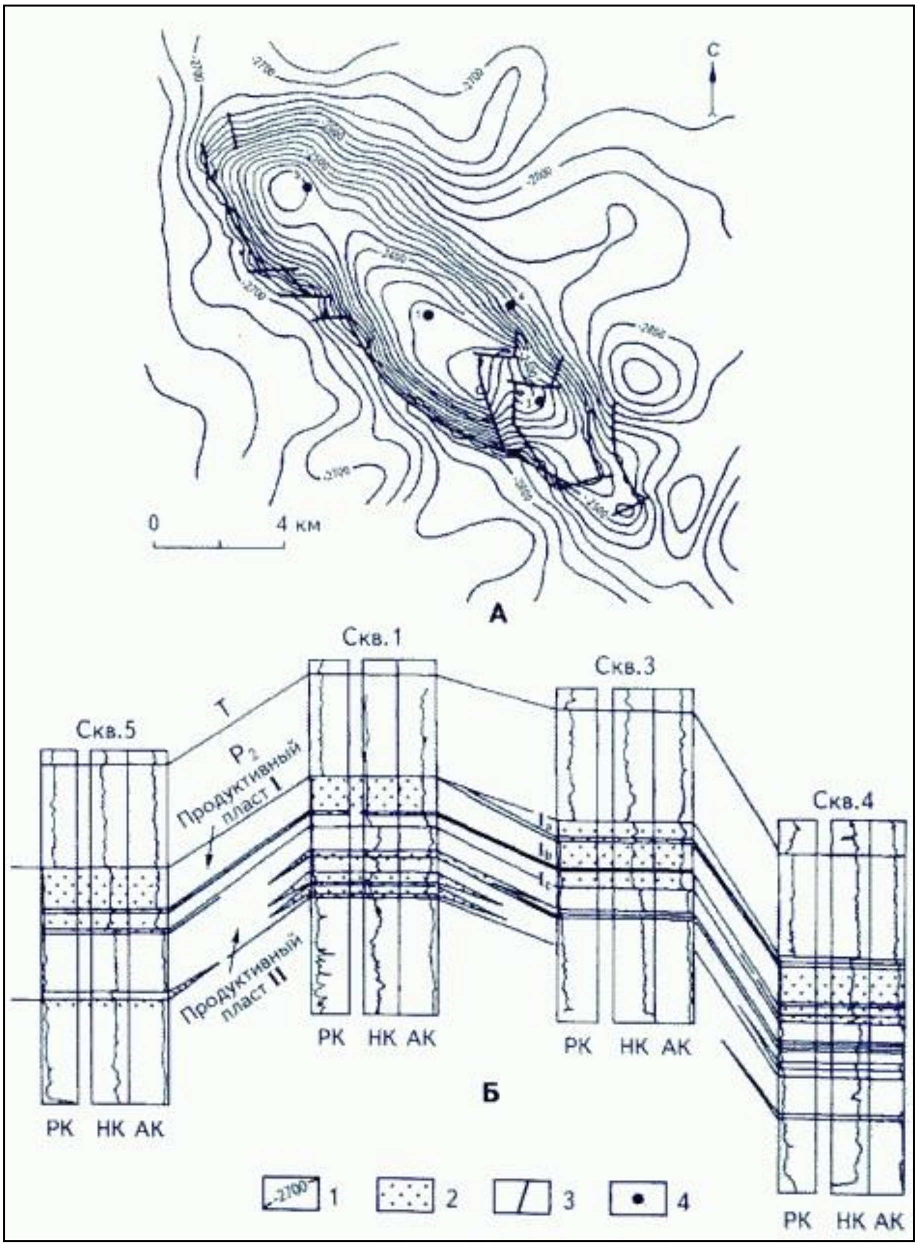


Figure 1.16 – The structural map along the top of horizon I and The sediment correlation scheme [q]

A brief description of Permian-Carboniferous oil is presented in Table 1.1.

Table 1.1. Key indicators of Permian-Carboniferous oils

Parameter	Unit	Value
sulfur content	weight %	2.16
paraffins content	%	0.95
resins content	weight %	10.25
density	kg/m^3	955
dynamic viscosity	sP	3.87

Characteristics of the physicochemical properties of oils in the carbonate deposits of the Lochkian stage of the Lower Devonian and in the carbonate deposits of the Upper Silurian which are considered as promising objects for prospecting at the Prirazlomnoye field is given for the deposits of adjacent land.

1.7. Hydrogeological conditions

According to the hydrogeological zoning of the Arctic shelf, Prirazlomnoye is confined to the Pechora artesian basin. Hydrogeologically, the Prirazlomnoye field has not been studied. Aquifers are practically not characterized by sampling (the available single tests and the selected samples are of poor quality). In this regard, a description of the hydrogeological conditions of the field is given for neighboring well-studied areas.

In accordance with the geological structure of the field and the hydrogeological features of the section studied in neighboring areas, it seems possible to distinguish the following aquifers (from top to bottom):

- Lower Cretaceous and Quaternary deposits,
- Jurassic deposits,
- Triassic deposits,
- Permian deposits,
- Lower Carboniferous-Lower Permian deposits,
- Upper Devonian-Lower Carboniferous deposits,
- Silurian-Lower Devonian deposits.

The Silurian-Lower Devonian aquifer complex is represented by carbonate and carbonate-terrigenous rocks. The total thickness of the complex is more than 1000 m. The penetrated thickness of the complex within the Prirazlomnoye field is 615 m in one of the representative wells. The clayey stratum at the base of the Lower Frasnian deposits (Kynovsky + Sargaevsky horizons), considered as a regional seal, serves as a water seal. The underlying deposits in the penetrated part of the section are represented by carbonate-anhydrite-terrigenous deposits of the Lochkovian stage of the Lower Devonian. The reservoirs in the deposits of the complex are layers of fractured carbonate rocks (in the lower part of the section of the complex, according to seismic data, the development of organogenic structures is assumed). Clay and anhydrite layers are considered as local and zonal fluid seals in the volume of the complex.

The water content of the complex was studied based on the results of testing individual wells on land in the areas of the Sorokin Shaft (Varandey, Toravey). Formation waters are of the calcium chloride type complex with mineralization up to 200 g/l. Reservoir pressure in the deposits of the complex on the areas of the Sorokin Shaft exceeds hydrostatic pressure. The depth gradient of reservoir pressure in the Varandey and Toravey areas is 1.4 MPa/100 m, in other areas in the onshore part of the Varandey-Adzvin structural zone it reaches 1.80 MPa/100 m. At the

Prirazlomnoye field, according to the results of formation pressure measurements during drilling with the FMT-3E tool, the coefficient of formation pressure anomaly in the Lower Devonian deposits is 1.80-1.81 MPa/100 m.

The regime of the Lower Permian-Carboniferous oil deposits of the Prirazlomnoye field is elastic-water-driven.

Information on the temperature regime of the subsoil in the water area at the territory under consideration is extremely limited. According to the data of the State Unitary Enterprise Arktikmorneftegazrazvedka and basing on the offshore fields and areas studied by drilling, the geothermal gradient in the area under consideration is 2.5°C/100 m.

1.8. Geocryological conditions

At Prirazlomnoye, according to the results of engineering and geological surveys at the drilling sites for exploration wells and at the construction site of a stationary production platform (the section was studied to a depth of 130 m from sea level) and during the drilling of exploration wells, permafrost soils were not identified.

However, taking into account their presence in neighboring areas (Medynskaya-More, Varandey-More, Pomorskaya) and taking into account the results of temperature measurements in the soils of the Prirazlomnoye field, in the northern part of the Prirazlomnoye field area (in the zone of lower average annual temperatures of the bottom surface), there is a possibility of the existence of cryolithozone in the form of frozen island relics at depths of 80-100 m from the sea bottom, according to OOO VNIIGAZ, 2003.

1.9. Key conclusions

The Prirazlomnoye oilfield is located in the Varandey-Adzvin oil and gas region of the Timan-Pechora oil and gas province. Clay content increases in the North-West direction.

No major unconformities and stratigraphic breaks have been identified within the Silurian deposits. Stacked reservoir with lithological limitations oil deposits here are confined to reef structures the rocks of which have average values of open porosity of about 11%.

From the hydrogeological zoning of the Arctic shelf point of view Prirazlomnoye is confined to the Pechora artesian basin. Formation waters are chloride-calcium. Permafrost soils have not been established.

In general, within the framework of the Western Arctic region a fairly clear relationship between oil and gas content and reef systems is recorded. However, there are also specific features, for example, the influence of basic magmatism on the formation of sedimentary cover structures and on the phase state of hydrocarbons. The formation of the hydrocarbon potential is determined by the formation of the geodynamic system of the basin itself.

Part 2. Current field development scheme of Prirazlomnoye oilfield

This chapter is devoted to the study and description of the current scheme for the development of Prirazlomnoye. In particular, such topics as the development project, production and transport infrastructure, industrial and environmental safety will be touched upon.

The weaknesses of the applied development scheme, as well as extensive planning for the integrated development of the Russian shelf have an impact on the consideration of other projects that have their own advantages and disadvantages, which still do not lose their relevance due to the early history of the development of the Arctic.

In total, the Prirazlomnoye project provides for the commissioning of 36 wells, including 19 production, 16 injection and one water disposal wells. All wells at the Prirazlomnaya platform are drilled using the directional drilling approach; their length is from 4 to 8 thousand meters.

As it was mentioned above, Prirazlomnoye is the first and so far the only field on the Russian Arctic shelf where oil is being produced. This is the only project in the world where production in the Arctic is carried out from a fixed platform.

The drilling of wells was carried out using the method of multilateral and conventional wells, that is, several wellbores proceeded from the platform in a deviated direction, taking a subhorizontal direction at depth. The length of subhorizontal wells (diametrically relative to the wellhead) is 1.5 kilometers with a total drilling length of 200 kilometers [u].

Since the wells have a horizontal direction, hydraulic fracturing was carried out. Successful fractures led to the evaluation of the efficiency of the horizontal wells, the determination of the optimal well spacing. Thus, a condition was adopted on not to use horizontal wells parallel to both the prevailing permeability distribution flow and the line characterizing the maximum stress. The upper limit of hydraulic fracturing was also indicated, equal to four per well. For the stage of planning of fracturing at the oilfield the wellbore length was assumed to be 0.5 km, and the distance between wells was 0.4 km. The intervals of 0.5 km [v] were marked between the well rows.

However, the use of horizontal wells is limited due to the geology of the field and the lack of data on its features. The principle of combining multiple point stimulation of horizontal wells and traditional hydraulic fracturing in vertical wells was identified as the most effective.

2.1. Prirazlomnaya platform design

The development of the field is currently carried out by the only one platform. The length and width of the offshore ice-resistant stationary platform "Prirazlomnaya" is 126 meters, the height is 141 meters (Fig. 2.1). The scheme illustrates split parts of the structure. In this connection, ice deflector is actually in the waterline.

The platform is securely held at the bottom of the sea due to its gravitational weight, which, including the ballast, exceeds 500 000 tons, and after installation it actually became an artificial island. Its gravitational stability and protection against soil erosion are also provided by a crushed stone berm (its volume is over 45 thousand cubic meters) backfilled around the perimeter of the platform bottom.

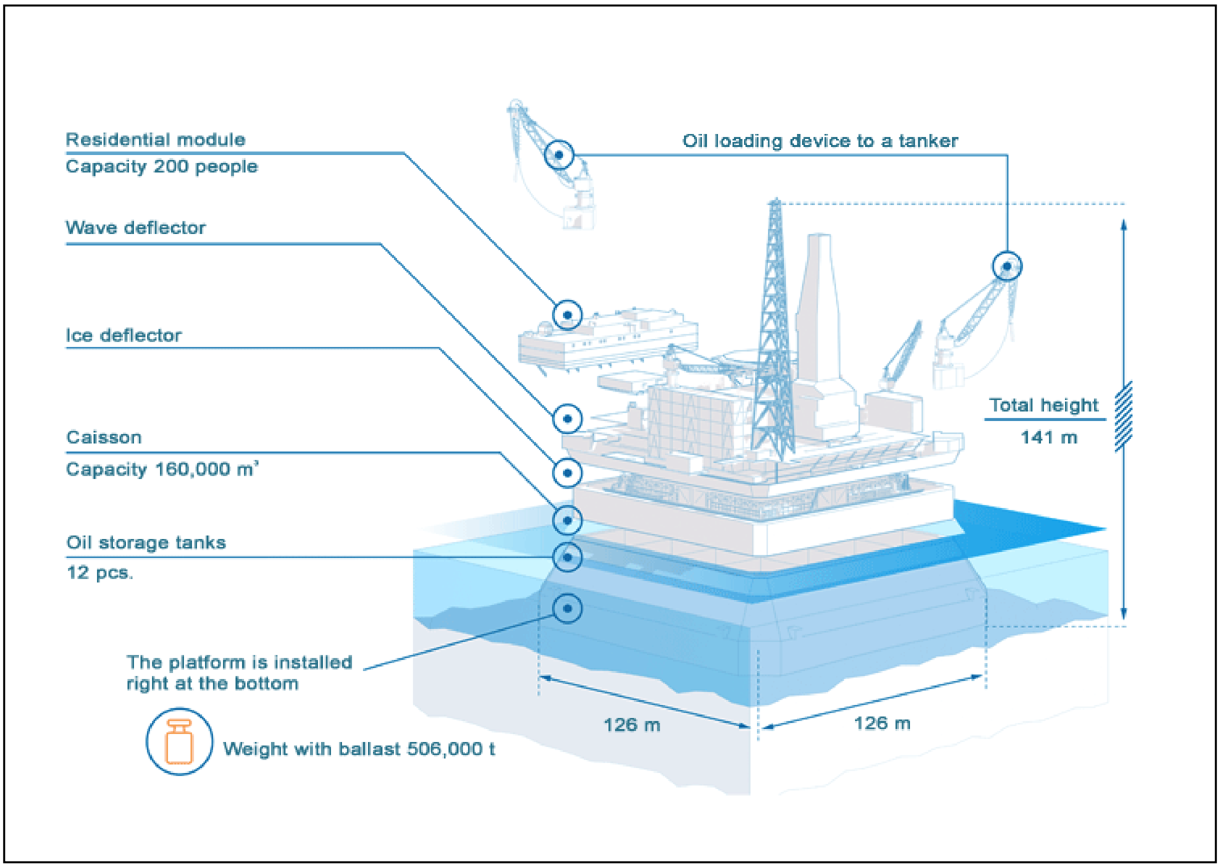


Figure 2.1 – Prirazlomnaya design scheme [w]

The upper part weighs 39 000 tons. Prirazlomnaya has one drilling rig and 40 slots, two offloading systems with a capacity of up to 10 000 m^3/h. The caisson itself weighs 97 000 tons and covers an area of 126 m^2. It includes 14 oil storage facilities with a capacity of 113 000 m^3 as well as two water storage compartments with a capacity of 28 000 m^3 [x].

Structurally (Fig. 2.2), the platform consists of several parts: a caisson where the oil storage is located, an intermediate deck, an auxiliary module, a topside structure, an accommodation module, and two complexes of direct oil export devices (KUPON). More than 200 personnel work on the platform on a rotational basis every day with a shift change every 14-15 days [rr].

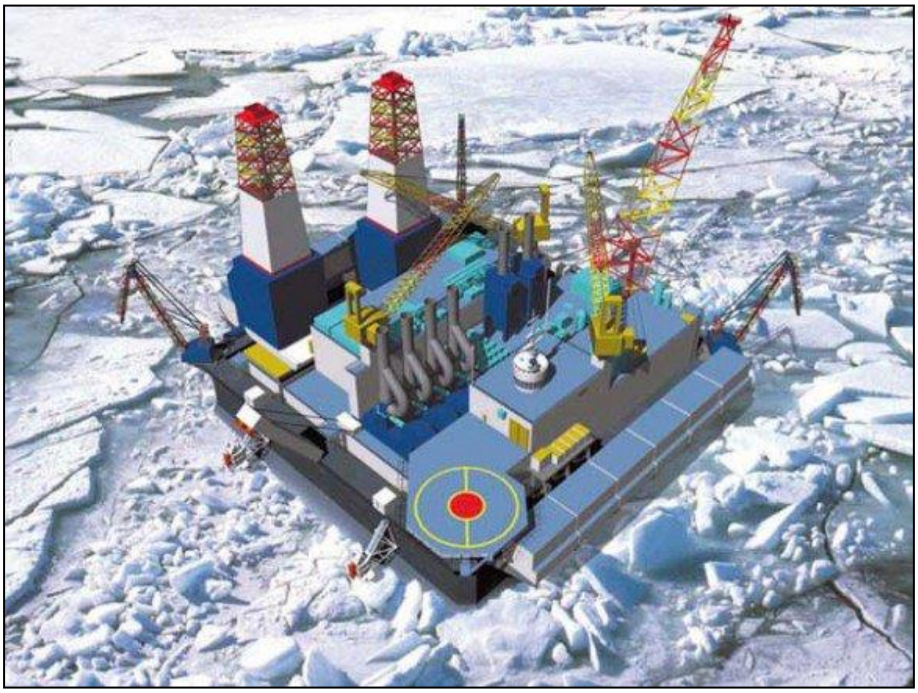


Figure 2.2 – Prirazlomnaya design principle scheme [p]

Prirazlomnaya can be subdivided into:

- the drilling complex which provides a full volume of drilling works, as well as the functioning of all auxiliary systems related to providing of drilling processes for the platform;

- the technological complex which provides the process of production, separation of formation fluid, refining of commercial oil, storage and shipping of oil, treatment of associated petroleum gas for use for the needs of technological complex (electricity production) and own needs of the platform. The excess gas is burnt in the flare, although gas injection would represent a better solution to protect the environment. The technological complex also provides refining of formation and oily water and also water injection into the reservoir to maintain reservoir pressure;

- systems and equipment of the electric power complex which were designed for autonomous supply of electricity for platform consumers in all modes of operation. Excessive gas is used for energy conversion;

- automated control and safety system which provides control and management of both systems of the technological complex, the auxiliary complex and other complexes of the platform;

- systems and equipment of the auxiliary complex which provides: collection of safe and household waste water, heating, ventilation and air conditioning of accommodation, supplying of consumers with fresh, flushing and seawater, heat and steam, compressed air, lubricating oil and diesel fuel, as well as waste oil collection, water drainage overboard through the scupper system [y].

The structures and technological complex of the platform are designed taking into account environmental conditions, production infrastructure capabilities, technological indicators of development and the adopted field development scheme.

24/7 monitoring of Prirazlomnaya’s state is provided by a special system of more than 60 sensors that instantly respond to changes in their operation. Main sensors used are the following:

- Inclinometer (measuring the inclinations of the caisson);
- Strain gauge (measuring ice loads);
- Soil Dynamometer (measuring the load on the ground);
- Accelerometer (monitoring seismic activity around the platform);
- Piezometer (measuring soil pressure from dynamic horizontal loads).

2.2. Winterization issues of Prirazlomnaya platform

The purpose of this subchapter is to consider the Prirazlomnaya platform and the effects of waves influencing it, wind and temperature in winter conditions. The result of the study will be an understanding of how to optimize the operation of the platform and whether any improvements should be considered or not.

Severe arctic conditions may cause difficulties, interruptions, weather window restrictions and other exploitative, technical and operational limitations on Prirazlomnaya. Fortunately, according to data from open sources, to date there are no officially recorded accidents due to unacceptable weather. This is due to the appropriate preparation for winter conditions, the appropriate training of the facility personnel and other involved specialists, and, in addition, the relatively short period of the structure's operation. However, the probability of an event or accident should still be taken into account.

In order to avoid any possible operational and/or technical troubles safe and productive platform operation should be considered and maintained.

Sustainability could be defined as the requirement to manage the resources such that the average quality of life that we ensure ourselves can be shared by future generations. The qualities of life are as follows:

- the safety of personnel involved in an activity and the safety of third persons;
- the clean, non-polluted environment;
- safe use of asset for owners and investors [tt].

Sustainability and safety are interconnected, as they require technologies application to be reliable, secure and ecologically friendly. Those technologies must be reflected in all activities deploying in the structure’s and supportive subjects’ functionality. Furthermore, they should be prioritized. Activities that are safe mean they are, particularly, capable of physical environment issues (winds, waves, low temperatures, ices, precipitations).

At the platform located in the Arctic it is significant to place safety of personnel and operations at the first level. Whereas winterization processes stay secondary.

In order to provide safe operations a risk analysis must be applied. The risk analysis hazard identification phase will be most important where the following aspects which are of main concern:

- experience from operations in the area;
- experience with the technology being applied;
- weather forecast’s reliability during the operation;
- human factors relevant for the participants;
- the crew’s experience;
- the company’s experience with activities in the area;
- the company management’s ability to handle activities in the high north [tt].

As it was mentioned above, winterization issues have to be highly considered in order to protect staff and safety critical equipment to be and would be exploited. Winterization must find itself in drilling, production, shipping, transportation as well as in onshore activities.

Concerning ice accretion, platform stability, availability of rescue equipment, personnel safety are the key points of awareness. Extreme temperatures may affect materials, ballast and fire water, staff working climate. As for personnel convenience, ventilation and appropriate energy supply have to be cared of. Moreover, ergonomics and available and enclosed space play a great deal. Deicing activities, instrumentation and apparatus, electric and mechanical equipment have to fulfill the winterization requirements.

The following aspects must be considered to get a platform or another offshore unit winterized:

- historical background and mistakes study;
- rescue experience;
- verified technology, equipment and apparatus;
- risk and uncertainties management;
- maintenance and checks at a systematic basis.

According to Gazprom [aa], the platform is designed to operate under extreme climate conditions. It meets the most stringent safety requirements and is able to withstand maximum ice loads.

The platform is protected from ice and wave effects by a special element – a deflector (Fig. 2.3) made of clad steel with a stainless layer and installed around the entire perimeter. The deflector is a vertical 16-meter wall with a slope at the top to prevent ice and waves from penetrating the platform.

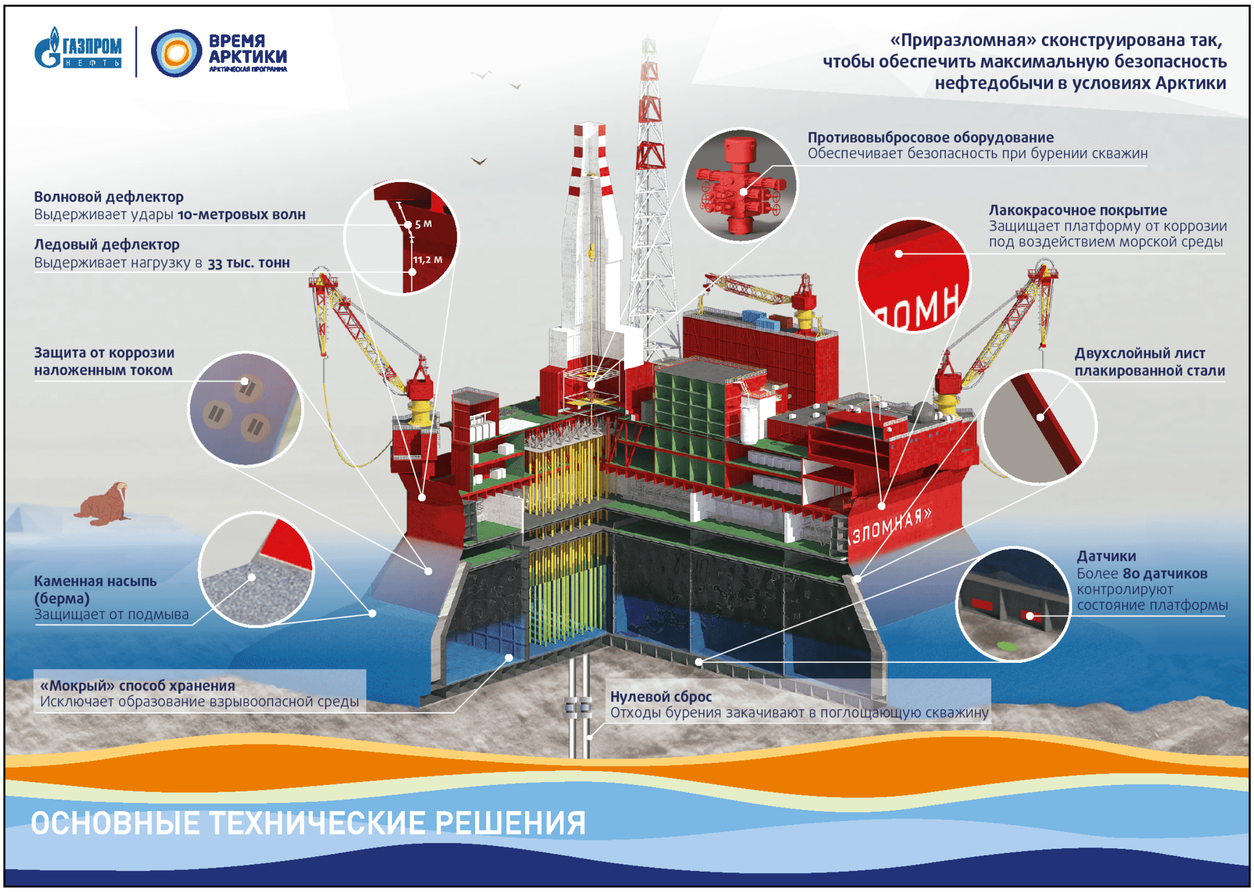


Figure 2.3 – Basic technological solutions scheme at Prirazlomnaya [bb]

Special equipment is installed on the seabed and on ice floes drifting close to the platform, which during the entire ice period measures drift parameters and size of ice fields, assesses the ice cover, sea level fluctuations and currents, and also records local meteorological parameters in the area of Prirazlomnaya [cc].

For offloading of produced oil specifically for operation at Prirazlomnoye enhanced ice-class oil tankers (Fig. 2.4) with double-hull and deadweight (permissible cargo weight) of 70 thousand tons (Mikhail Ulyanov and Kirill Lavrov) were built. These vessels are a part of the offshore transport and technological system (MTTS) which, in turn, is a part of the Prirazlomnoye oil field development complex.

Figure 2.4 – Offloading by ice-class oil tanker [hh]

In addition to Ulyanov and Lavrov, MTTS is made up of multifunctional icebreaking vessels (MFLS) Vladislav Strizhov and Yuri Topchev specially created for the project and pictured in Fig. 2.5. The icebreakers were specially built by order of Gazprom Neft Shelf which is developing the Prirazlomnoye field. All icebreakers are designed to provide year-round platform maintenance, cargo delivery, and rescue duty. In addition, as auxiliary tugs, they assist the offloading of oil into tankers. The vessels are designed to operate in conditions of increased ice loads and are equipped with state-of-the-art complexes of emergency oil-gathering equipment designed to eliminate oil spills both in open water and in ice conditions [o].

Figure 2.5 – Vladislav Strizhov multifunctional icebreaking vessel [ii]

One of the hazards for the Prirazlomnaya platform is associated with the drift of ice fields. In the spring the ice sets in motion. Sometimes fields with an ice thickness of ten meters go to Prirazlomnaya. These are ice floes frozen into a monolith. The surface is smooth, and from below there are pieces of ice up to 12 meters deep.

To combat ice floes, an icebreaker rescue ship is on duty at the platform. However, it is impossible to continually chop the ice – costs grow, the equipment is worn out.

At the platform a forced ventilation system is provided, combined with an air heating system using air heater, where the air is heated during the cold season. The heating medium (heat transfer fluid) for the air heater is a 60% solution of triethylene glycol dissolved in water. Heat transfer fluid is supplied from the circuit heat supply systems.

The main task is to reduce the risks of oil pollution in the Russian Arctic. A mistake will be very expensive – therefore, security monitoring, analytical work is carried out day and night, and at the end are testing of new equipment, non-standard management solutions.

2.2.1. Possible improvements and recommendations

During the winterization process the main factor influencing the prioritization of winterized platform parts is safety. Based on the safety criterion, all subdivisions of the structure can be divided into several groups. The most important one is drilling equipment. Further, the technological equipment, then auxiliary and power equipment, and the least important (in terms of safety criterion) group is the residential module.

In general, the reliability of platform onloading and offloading should be increased through the following measures:

- organization of ice management to prevent the formation of ice piles;
- duplication of the necessary equipment by placing it on the two opposite sides of the platform;
- use of cargo cranes with a large arm for the possibility of working outside the ice pile;
- paying special attention to the issues of fatigue strength of structures during low temperatures [jj].

In order to get rid of ice piles accumulation the following possible improvements have to be considered:

- electrically driven mechanical ice piles preventers located along the structure’s perimeter and which can provide necessary force aimed to destroy ice formations coming onto the platform;
- constantly heated the mechanical ice piles preventers or the currently applied deflectors;
- powerful vibrators around the platform with strong inhibitors of vibration close to platform’s operation, accommodation, offloading and safety areas;
- enhancing qualitatively and/or quantitatively ice breaking vessels constantly available and ready to work.

As for technological and drilling equipment, protective sheathing and heating have to be applied. Technological equipment can be closed completely or partly with the location of some units and process tanks outside the closed module. Rotating equipment should be housed in heated enclosed modules.

The drilling equipment has to be completely enclosed with the possible exception of the rig derrick which can only be covered at the floor level of the drilling rig, or pipe storage module, or at the crown block level. Storage tanks for dry components of drilling mud and cement as well as pipe storage modules might be located outside the modules. It is worth providing heated pipe storage equipped with an inclined platform for lowering pipes. Dimensions of pipe storage module should provide storage of a set of pipes for the longest casing and extra supply of drill pipe.

Instrumentation located outside the containers (including level gauges and transmitters) must be located inside the heated module or be isolated and equipped with a heating system.

External modules and decks should be insulated to avoid formation of condensation or icing. This is particularly important for deck areas where slippery surface can pose a hazard to personnel.

Equipment installed in open areas that requires periodic maintenance should be equipped with temporary or permanent shelters from the wind. Storage areas, external temporary shelters and locations needed for offloading into evacuation vehicles will also be equipped with wind protection. Measures should be taken to reduce the accumulation of ice or snow in walkways and stairs, for example, through the use of lattices.

Winterization issues were covered by the owners of the platform and there were established calculated, proven and optimized ways, concerns and techniques aimed for providing a sustainable, safe and productive operation during winter seasons for a number of years. As practice shows, there are, fortunately, no any officially registered accidents of various interruptions, breakages, failures and/or crashes.

However, climate historical background has not to be avoided for taking into account. Low or extremely low probability environmental events may occur in the nearest future; and for the Arctic region that means not only severe temperatures, strong winds and harsh precipitations, but also long-period ice accumulation and drifting.

A number of improvements were suggested for additional enhancing of currently applied winterization issues. Mainly, extra support was directed to heating system covering drilling equipment, technological, accommodation and safety areas. Moreover, wind-stopping lattices would decrease air masses effects to openly located areas. Finally, innovative solutions concerning ice piles formation struggling were discussed.

All mentioned improvements have to be studied in terms of economics, feasibility and risks. Nevertheless, the higher the protection, the more optimized is the operation of a platform.

2.3. On- and offloading realization and HSE issues

When developing productive intervals, the average depth of which is 2.5-2.7 kilometers, the following technological solutions are used:

- drilling wells on the platform with one rig;
- simultaneous drilling and operation of wells;
- all wells are equipped with high-performance Russian-made electric centrifugal pumps [mm];
- the length of horizontal sections within the reservoir is 0.8-1.0 kilometers;
- well construction is carried out around the clock;
- rotary type drilling with the possibility of logging while drilling;
- treatment of carbonate reservoirs with hydrochloric acid compounds.

Control over possible unscheduled releases is carried out with the help of remotely operated blowout control equipment and appropriate specialists. BOP equipped with cut-off valves is located at the depth of 150 m. In addition, the wellheads are equipped with horizontal X-mas trees. BOPs and X-mas trees hydraulics is controlled by an automated control and safety system (ASUB). The tasks of the automated control system also include the processes of production, preparation, storage and offloading of hydrocarbons, control over life support systems, heat and power complex, fire and gas systems [z].

The Prirazlomnaya platform is equipped with two sets of direct oil offloading devices (KUPON) which operate on the basis of a crane system and allow loading of tankers (Fig. 2.6) from the platform's oil storage. KUPONs are located at the opposite edges of the platform, which makes it possible for tankers to approach the platform directly in all weather and navigational conditions.

Figure 2.6 – Hydrocarbon offloading from Prirazlomnaya into a tanker [t]

KUPON devices are equipped with a special bow receiver. Oil is offloaded through one of the devices depending on the direction of external loads (waves, ice drift, current, wind). KUPON tracks tanker movements in a 180° sector. If it deviates from the sector served by one device, the tanker is unmoored and transferred to another KUPON.

A developed coastal infrastructure has been created for the operational management of production and delivery of shift personnel and cargo to Prirazlomnaya. It includes a supply base and a production service base in Murmansk, as well as a transshipment base at Varandey with a shift camp under construction for 180 people to temporarily accommodate the personnel of Prirazlomnaya. In the near future, it is planned to design and build a heliport [rr] at Varandey.

The Prirazlomnaya platform is designed to ensure maximum oil production safety. The platform is designed for maximum ice loads and is able to withstand a direct impact of a ten-meter wave.

A special design protects Prirazlomnaya from wave and ice impacts – a deflector which is made of high-strength steel. It is a 16.4 m high wall the inclined upper part of which prevents the incoming waves from overflowing the protector. The drilling rig at Prirazlomnaya is reliably protected from external influences, which allows drilling in any weather. The lifting capacity of the drilling rig is 547 tons; it can withstand a wind load of 51 m/s.

The operating technology of the Prirazlomnaya structure completely excludes the discharge of industrial and domestic waste, oils, formation water, polluted industrial effluents and other harmful substances into the sea. The platform uses the “zero discharge” principle: used drilling fluid, cuttings and other wastes including those collected by the drainage system and treated oily and oily water, polluted rainwater and snow are transported to the mainland and disposed.

At Prirazlomnaya, a bioacoustic bird protection device with a range of 3000 m is installed. A powerful acoustic system with a power of up to 125 dB broadcasts disturbing and annoying sounds, as well as authentic voices of predators and technogenic noises. This prevents birds from nesting and forming permanent flocks in the protected area.

2.4. Key conclusions

The Prirazlomnoye field is being developed by the Prirazlomnaya offshore ice-resistant fixed platform which has a number of sensors to stabilize operations, at a water depth of about 20 meters.

The wells exit vertically from the platform passing into horizontal ones which, in turn, have been subjected to hydraulic fracturing. The target of the wells is productive intervals at a depth of about 2.5 kilometers. The produced oil enters platform storages from which it is subsequently offloaded to tankers after being processed to a stable condition.

The platform ensures reliable oil production under severe weather and climatic conditions.

Part 3. Conceptual solutions for the development of Silur hydrocarbon structure

This chapter represents the main part of the work revealing perspective options for the development of the Prirazlomnoye field in the Pechora Sea, creating forecasts and analyzing different scenarios.

As it was mentioned above, in the case of depletion of the upper horizons that are currently in development new approaches are required to develop the lower ones, in particular, the Silurian deposits. In other words, the ongoing study is directed to create a potential reserve required in the event of a period of declining production.

The development of offshore fields is associated with very high operating and capital expenditures, so any financial risks should be considered before accepting any development scenario. Offshore projects tend to have longer forecast periods than onshore development options.

Before considering possible development scenarios, first of all, it is worth paying attention to the degree of knowledge of the Silurian deposits, the opening scheme. In addition, after a detailed analysis of the proposed projects (achievements and weaknesses, feasibility, predicted production characteristics) it is important to compare them according to various criteria on an equal footing to form the final choice. The above points will be discussed below.

Moreover, to this or that extent, the following questions will be answered: are technical and/or technological improvements in the development (production) process necessary? How can the oil of the Silurian deposits be characterized and does this require the commissioning of new relevant equipment? To what extent can the potential reserve be realized? Is there a need to use secondary and/or tertiary methods of enhanced oil recovery? What are the predictive characteristics of the development?

3.1. Silur extraction background and reservoir details

The outcropping of Silurian deposits is observed on Novaya Zemlya, as well as on Northern Timan, however, within the Timan-Pechora province their sections are the most complete. The North of the Pechora Sea (East of the Barents Sea) is characterized by various carbonates with silty and pelitic inserts, an increasing proportion of which is observed upwards the section. The thickest deposits reach 2.5 km in the South of the Barents Sea, and the least (0.6-1 km) in the North [qq]. The thickness of Silur in the Pechora Sea is about 0.5 km (due to erosion and consedimentary reduction).

The reservoir rocks consist from specific primary features, recrystallization, together with compaction and the presence of clay impurities. Separate thin interlayers contain a porous-fractured low-capacity reservoir [a].

The production scheme is shown in Fig. B-1, Appendix B. Based on the data of geophysical research and paleontology, the correlation of Silurian cross-section was made, as well as their division into stages and regional horizons. Exploration well № 5 was drilled in the range of 3989-4417 meters at Prirazlomnoye. The lithological-stratigraphic characterization of the lower, middle, and upper strata was described in section 1.3.3.

According to the additional exploration project of the Prirazlomnoye made by LLC VNIIGAZ (2006), the oil potential of the Lower Devonian and Silurian deposits is predicted. In order to identify deposits it was proposed to drill two exploratory wells in the Devonian and Silurian to a depth of 4700 meters. The planned increase in oil reserves in the Lower Devonian-Silurian deposits in categories C1+C2 is 41 mln tons (geological) and 15 mln tons (recoverable) [a].

According to recent 3D seismic results (2020), oil has been proven in the Upper Silurian and Lower Devonian series. The Upper Silurian deposits considered in the framework of this work represent a reef trap with an area of 2.6 km^2 and C3 resources in the amount of 17.4 mln tons (geological) and 5.2 mln tons (recoverable). Effective oil-saturated strata have a thickness of about 110 m. The deposit is located at some (5-7 km) distance from Prirazlomnaya. In depth, the trap of a reef kind underlies at the absolute mark of minus 4700-4800 m. The thickness of the Upper Silurian series is about 120-150 m. The Lower Devonian deposits are characterized by great potential – 75 mln tons (geological) and 22.4 mln tons (recoverable).

Thus, the development of the Silurian deposits is promising due to the exploitation of the underlying strata and the extraction of additional products. In the future, it is worth considering the development of the Lower Devon.

A brief description of the oil can be found in Table 3.1. Present production is conducted in Perm and Carbon reservoirs. The theme if the thesis is on the development if the Silurian deposits only. Compared to Permian-Carboniferous Silurian (as well as Devonian) oil it has a lower viscosity due to a decrease in the content of sulfur, resins and other impurities. However, this hydrocarbon has a high content of paraffins. Also, its density is lower than that of Permian and Carboniferous oil.

Table 3.1. Key indicators of different oils

Parameter	**Unit**	**Value**	
		Silur	**Perm, Carbon**
sulfur content	weight %	0.28	2.16
paraffins content	%	11.25	0.95
resins content	weight %	4.2	10.25
density	kg/м^3	830	955
dynamic viscosity	sP	1.14	3.87

In general, Silurian oil is lighter than currently produced, which makes it easier to extract.

Oil properties were taken from the results of sampling at Prirazlomnoye, from the development of the Silurian deposits of neighboring offshore fields, as well as from open sources [d], [nn].

3.2. Field development possibilities

Currently, Carboniferous and Permian deposits are involved in the development of Prirazlomnoye using the Prirazlomnaya platform. Based on numerous studies (official sources, published articles, technological schemes, etc.) at Prirazlomnoye and neighboring deposits (Dolginskoye, Medynskoye-More, etc.) of the Pechora water area, the Silurian and Devonian potential is considered. However, within the framework of the topic of the work, Silurian rocks only will be considered.

It is proposed to consider two scenarios for the development of Silur at Prirazlomnoye in case of depletion of current deposits:

- development by means of the Prirazlomnaya platform (Platform concept);
- development by means of an ice-resistant satellite platform (IRSP) connected to the Prirazlomnaya with a pipeline (IRSP concept).

Each of the scenarios is subdivided into several variants, or solutions (Table 3.2.). So, two cases will be considered in the scenario with a platform and five cases in the scenario with the use of IRSP.

Table 3.2. Structure of conceptual solutions

Scenario	Solution	Description
Platform	Solution 1.1	3 onehole prod wells without RPM
	Solution 1.2	2 onehole prod wells with RPM (2 onehole inj wells)
Platform with IRSP	Solution 2.1	2 twohole prod wells without RPM
	Solution 2.2	3 twohole prod wells without RPM
	Solution 2.3	2 twohole prod wells, 1 onehole prod well without RPM
	Solution 2.4	1 twohole prod well, 2 onehole prod wells without RPM
	Solution 2.5	3 onehole prod wells without RPM

(RPM – reservoir pressure maintenance system; prod – production wells; inj – injection wells)

These solutions will be considered as a potential further development of Prirazlomnoye after the depletion of the Permian-Carboniferous deposits. Consideration of the concepts of simultaneous development of the Permian-Carboniferous and Silurian deposits was canceled due to possible documentary, technical, technological, economic and other overlaps of the current and reserve projects, due to technical features of the platform and physical feasibility and limitations. Therefore, the development of the Silurian deposit has to be done after the production of the Permian-Carboniferous deposits. It should be noted that simultaneous production would benefit the extraction of the oil in the field and further work can be subjected to see if simultaneous production can be achieved.

Well drilling will be directed towards the drilled exploration well № 5 (approximately 100-200 m below the well bottom) through the Silurian reef structure. That is because the 5th well was drilled closely to the productive structure.

All figures, tables and diagrams were made by the author; therefore, sources for them will not be indicated.

A number of conceptual solutions for the development of Silur can be proposed, however, the most feasible and cost-effective scenarios will be chosen, according to the author's opinion. The development of individual solutions requires the collaboration of highly qualified geologists, technologists, geosteering experts, reservoir engineers and other specialists. The solutions under consideration are feasible under a stable economical situation, proper maintenance of all used equipment on the platform, maintaining contracts with current contractors, and after a period of declining production.

Drilling and development of offshore wells are characterized by high capital and operating costs, especially at great depths. In this regard, it is proposed to reduce the number of wells and improve their quality and quality of service; it is required that an individual, balanced approach is to be taken.

3.3. Platform concept

Based on the policy of the current development scheme (multiple well drilling, edge and contour waterflooding), as well as on the features of the geological structure of the deposit, it is proposed to carry out drilling in the following way: injection and production wells are characterized by a long vertical section, turning into a short directional section, and then into a long horizontal section.

For solution 1.1, it is proposed to drill three single-lateral horizontal wells (Fig. C1-C3, Appendix C). Predictive drilling data is presented in Table 3.3.

Table 3.3. Predictive drilling data for solution 1.1

Measured depth, km			
Well type	**Prod**		
Well №	**№ 1**	**№ 2**	**№ 3**
Vertical section	4.3	4.3	4.3
Deviated section	1.5	1.5	1.5
Horizontal section	5.3	3.7	4.0
Sum	11.1	9.5	9.8
Total	30.4		

(prod – production well)

Data on well stock and commissioning of wells are presented in Table 3.4. It is proposed to commit one production well every two years.

Table 3.4. Well stock and well commission data for solution 1.1

Year	**Wells commissioned**			**Wells fund at start of year**		
	Total	**Prod**	**Inj**	**Total**	**Prod**	**Inj**
1	1	1	0	1	1	0
2	0	0	0	1	1	0
3	1	1	0	2	2	0
4	0	0	0	2	2	0
5	1	1	0	3	3	0
6	0	0	0	3	3	0
7	0	0	0	3	3	0
8	0	0	0	3	3	0
9	0	0	0	3	3	0
10	0	0	0	3	3	0

Well commissioning is shown graphically in Fig. 3.1.

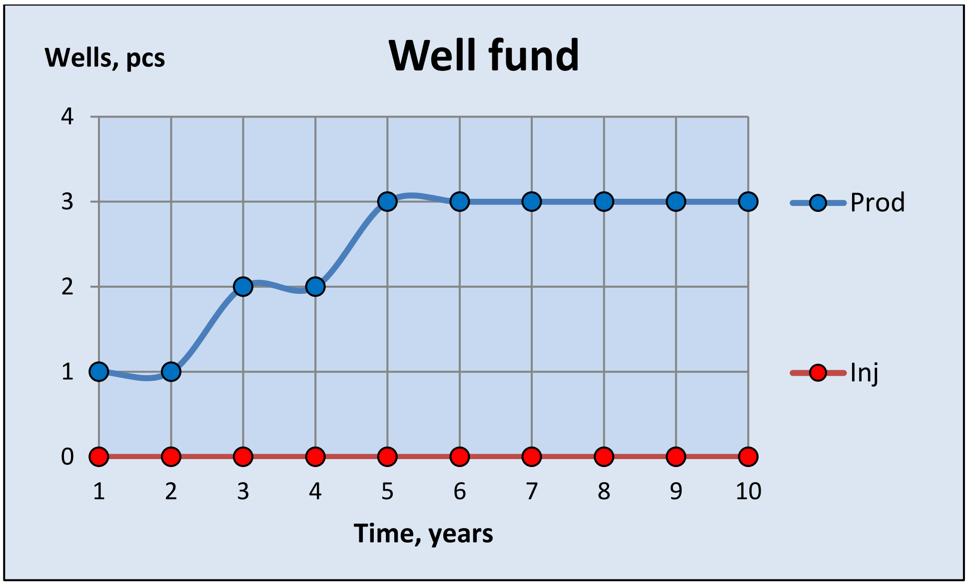


Figure 3.1 – Well commissioning schedule for solution 1.1
(prod – production wells; inj – injection wells)

For solution 1.2, it is proposed to drill two single-lateral horizontal wells (Fig. D1-D3, Appendix D). Predictive drilling data is presented in Table 3.5.

Table 3.5. Predictive drilling data for solution 1.2

Measured depth, km				
Well type	**Prod**		**Inj**	
Well №	**№ 1**	**№ 2**	**№ 1**	**№ 2**
Vertical section	4.3	4.3	4.3	4.3
Deviated section	1.5	1.5	1.5	1.5
Horizontal section	5.3	3.7	6.2	3.9
Sum	11.1	9.5	12.0	9.7
Total	42.3			

(prod – production well; inj – injection well)

Data on well stock and commissioning of wells are presented in Table 3.6. It is proposed to commit one production and one injection wells every two years.

Table 3.6. Well stock and well commission data for solution 1.2

Year	**Wells commissioned**			**Wells fund at start of year**		
	Total	**Prod**	**Inj**	**Total**	**Prod**	**Inj**
1	1	1	0	1	1	0
2	1	0	1	2	1	1
3	1	1	0	3	2	1
4	1	0	1	4	2	2
5	0	0	0	4	2	2
6	0	0	0	4	2	2
7	0	0	0	4	2	2
8	0	0	0	4	2	2
9	0	0	0	4	2	2
10	0	0	0	4	2	2

Well commissioning is shown graphically in Fig. 3.2.

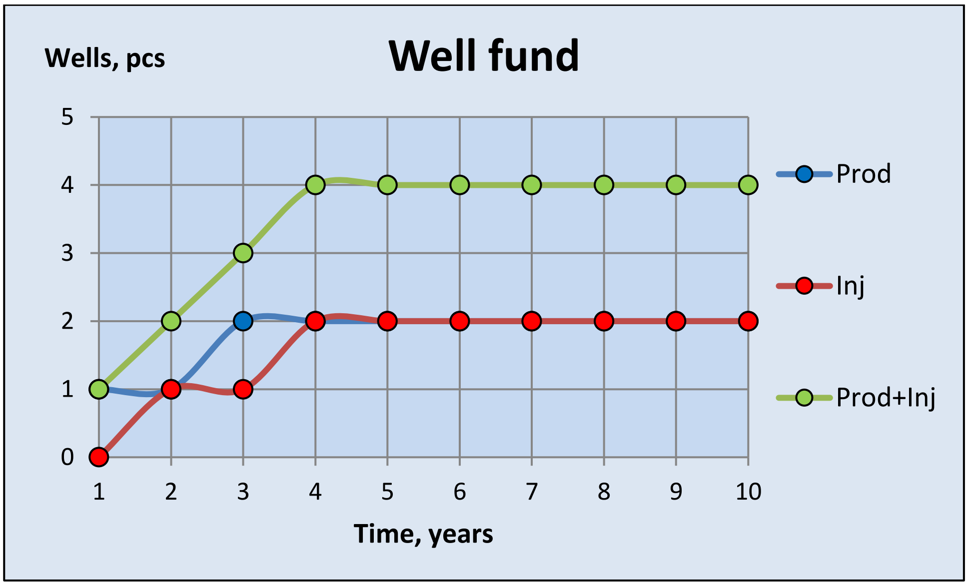


Figure 3.2 – Well commissioning schedule for solution 1.2

The placement of production wells in the dome of the reservoir will increase the sweep efficiency, and injection wells located at the edges of the reservoir (peripheral waterflooding system) will ensure timely compensation of production by injection and reduction of the unaffected part of the reservoirs.

Due to the great depth of the Silurian deposits, as well as the long length of the wellbores, high temperatures, abnormally high reservoir pressures, collapses, compressions and other complications during drilling and development are possible.

The design of the Prirazlomnaya platform allows simultaneous drilling and operation. The ram-type spherical BOP installed in the technical compartment of the platform will not need to be modified. The construction of new wells is allowed in any season for several years.

The system for utilization of wide fractions of light hydrocarbons will require modernization, since “with an increase in the commissioning of production wells, oil and associated gas production, the amount of gas condensate released as a result of oil separation and associated produced gas compression increases. At the same time, an increase in the content of natural gas liquids in associated produced gas leads to an increase in heavy fractions in the component composition of the flared gas, which leads to incomplete gas combustion in the flare and an increase in emissions, to an increase in emissions charges” [y].

Regarding reservoir pressure maintenance systems, as new wells are put into operation, it will be necessary to increase the pumping capacity. With the development of the deep Silurian deposits forecast, the injection equipment will need to be upgraded or replaced. At the moment, the maximum capacity of the injection system is 859 m^3/h.

3.3.1. Main technological parameters

For the Platform concept the following quantitative and qualitative assumptions were made:

- the average annual flow rate of one individual well falls over time due to a drop in reservoir pressure;
- a two-phase mixture (oil with water) is produced in an oil field;
- in the calculations, gas was not included in the analysis. This might be a reasonable first approach as the volume of gas is low and it serves for electricity generation only;
- gradual commissioning of new wells (one well every two years);
- the term of the development project is 10 years;
- tendency to reduce the number of commissioned wells due to the high cost of drilling and offshore development;
- the development project does not take into account long dead time due to technical complications, accidents, the economic situation, global political problems;
- the predictive drilling does not take into account detailed geological, stratigraphic, lithological conditions;
- some initial data were taken from neighboring deposits, as well as from [dd], [mm];
- for certain parameters (e.g. reservoir permeability, dynamic fluid viscosity, skin factor, bottom hole pressure) were assigned constant values;

- the natural logarithm of the ratio of the external reservoir boundary to the borehole radius is 7.9 (according to common practice);

- the reservoir pressure maintenance system provides an almost stable reservoir pressure;

- other.

In this connection, according to Dupuis formula for imperfect wells [e], the predicted average annual production rates were calculated for one individual single-bore production well for solution 1.1 (Fig. 3.3) and solution 1.2 (Fig. 3.4). The curve's behavior is reasonable in view of influence of pressure maintenance.

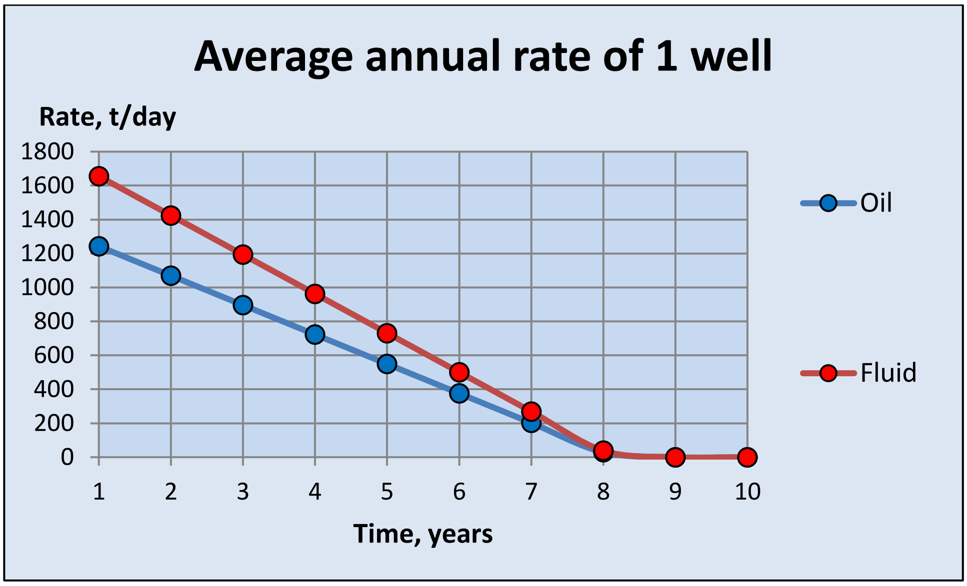


Figure 3.3 – Graph of the decline in oil and fluid production flowrate over time for solution 1.1 (no pressure maintenance)

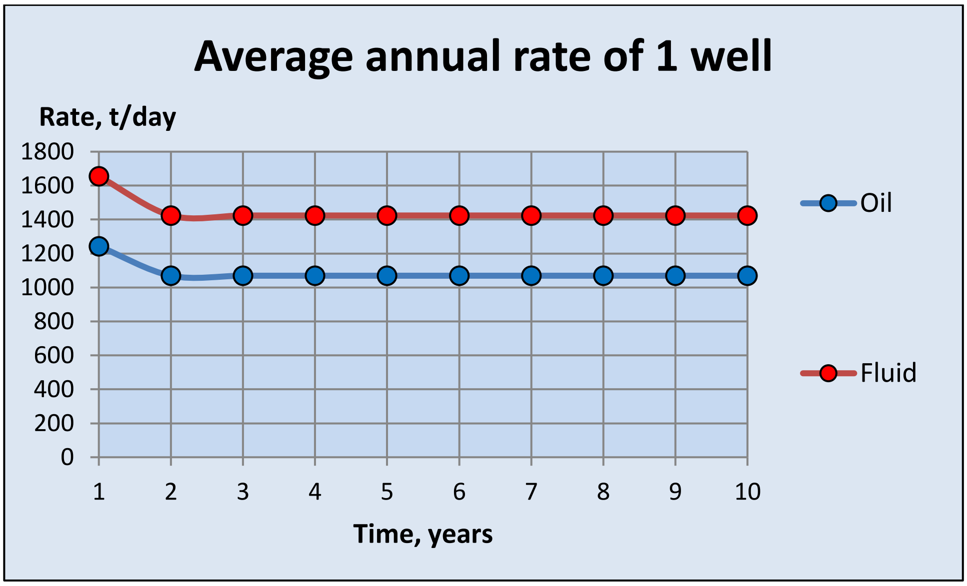


Figure 3.4 – Graph of the distribution in oil and fluid production flowrate over time for solution 1.2 (pressure maintenance is applied)

For solution 1.1, taking into account the decline in production rates and the gradual commissioning of new wells, the forecast production (Fig. 3.5), as well as the forecast net production (Fig. 3.6) for two phases, was calculated. In addition, a forecast was made for the withdrawal of recoverable Silurian reserves (Fig. 3.7).

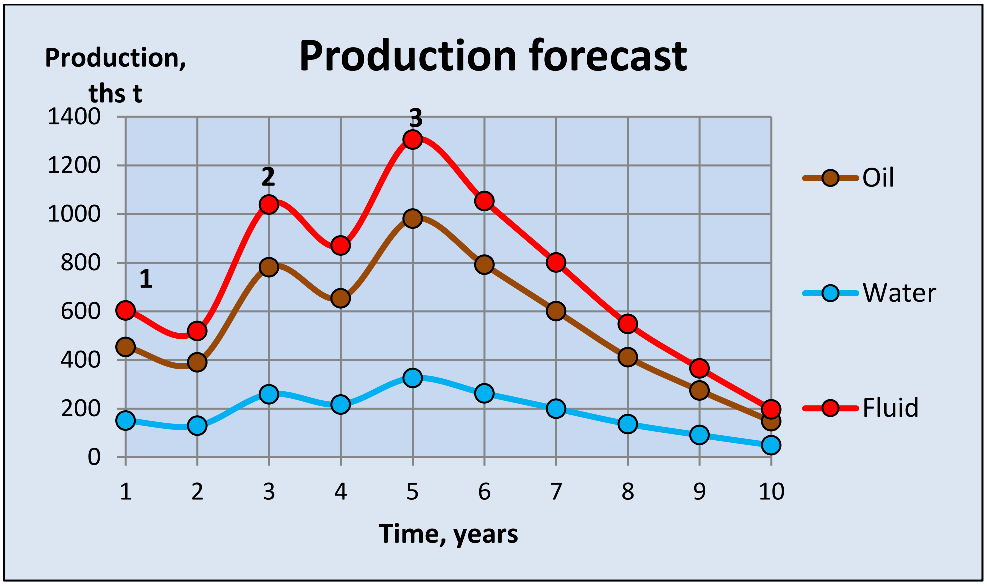


Figure 3.5 – Graph of production forecast for solution 1.1

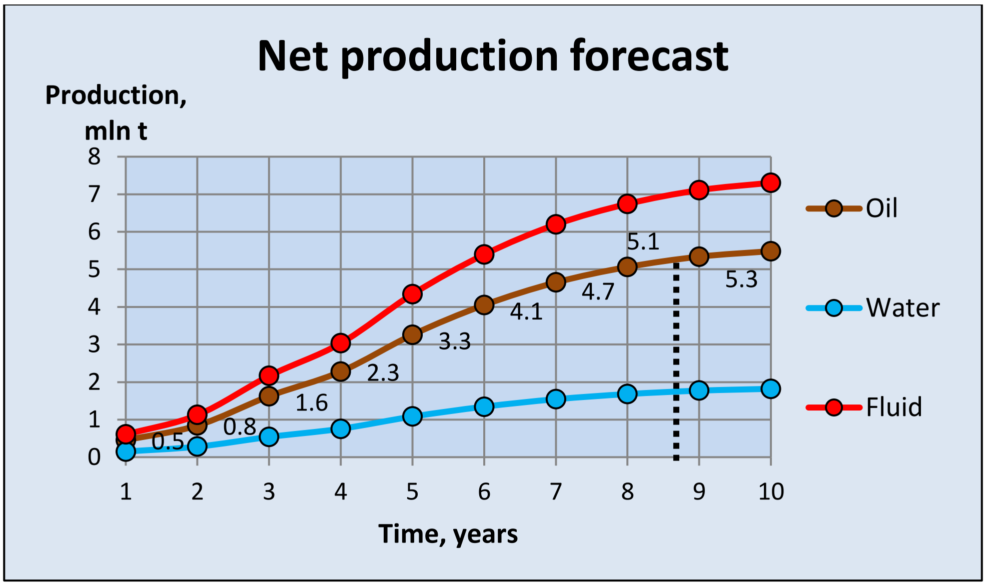


Figure 3.6 – Graph of cumulative production forecast for solution 1.1

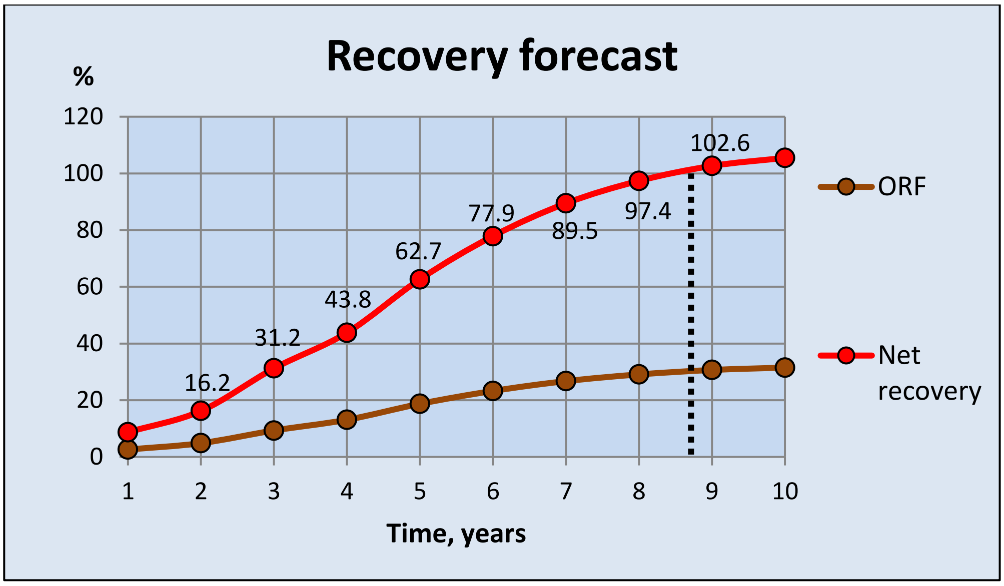


Figure 3.7 – Graph of the forecast for the extraction of recoverable reserves for solution 1.1 (ORF – oil recovery factor)

According to this solution 1.1, by 3 production wells without reservoir pressure maintenance 100% recovery of reserves will be achieved by the end of the 9th year of development.

For solution 1.2, taking into account the maintenance of flow rates and the gradual commissioning of new wells, the forecast production (Fig. 3.8), as well as the forecast net production (Fig. 3.9) for two phases, was also calculated. In addition, a forecast was made for the withdrawal of recoverable Silurian reserves (Fig. 3.10).

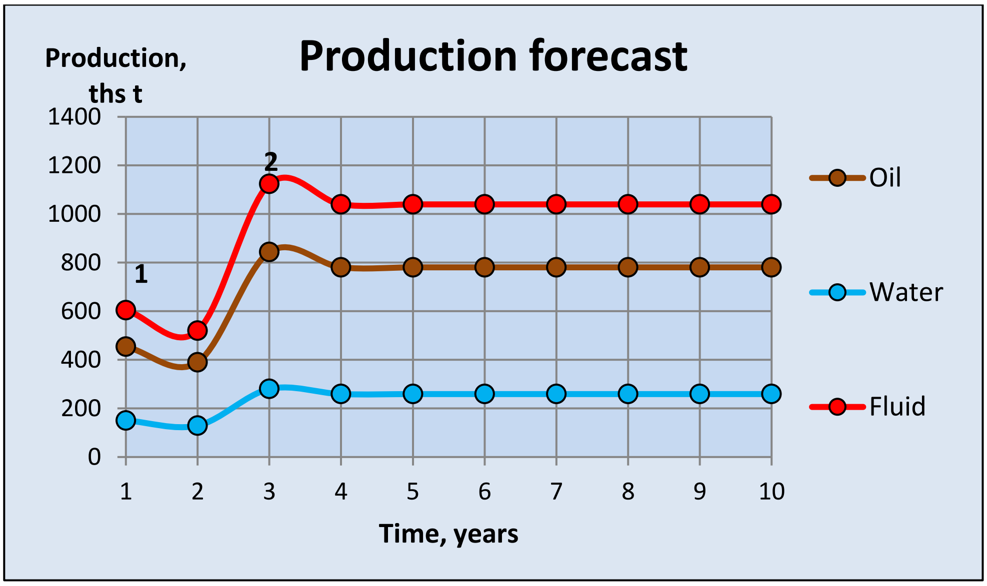


Figure 3.8 – Graph of production forecast for solution 1.2

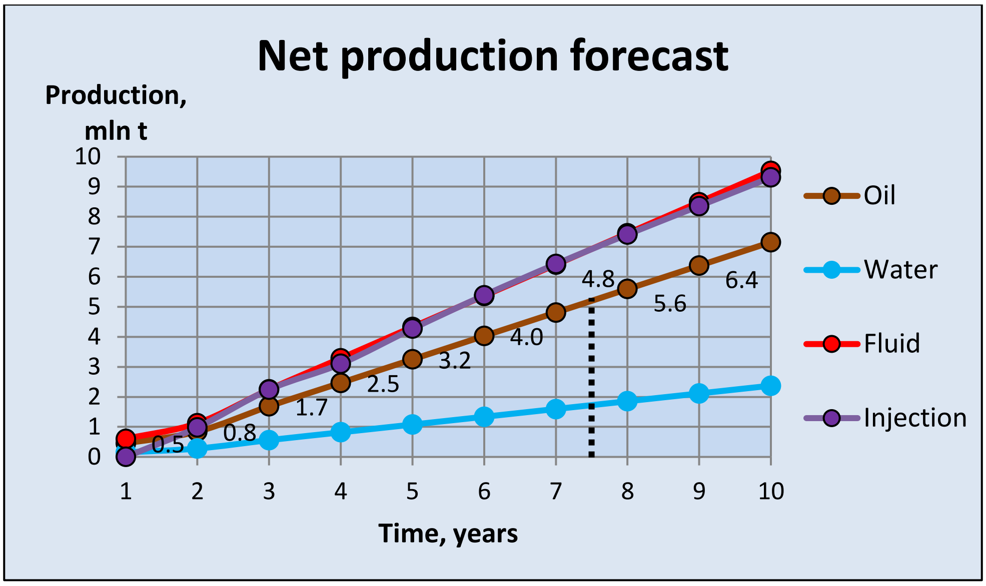


Figure 3.9 – Graph of cumulative production forecast for solution 1.2

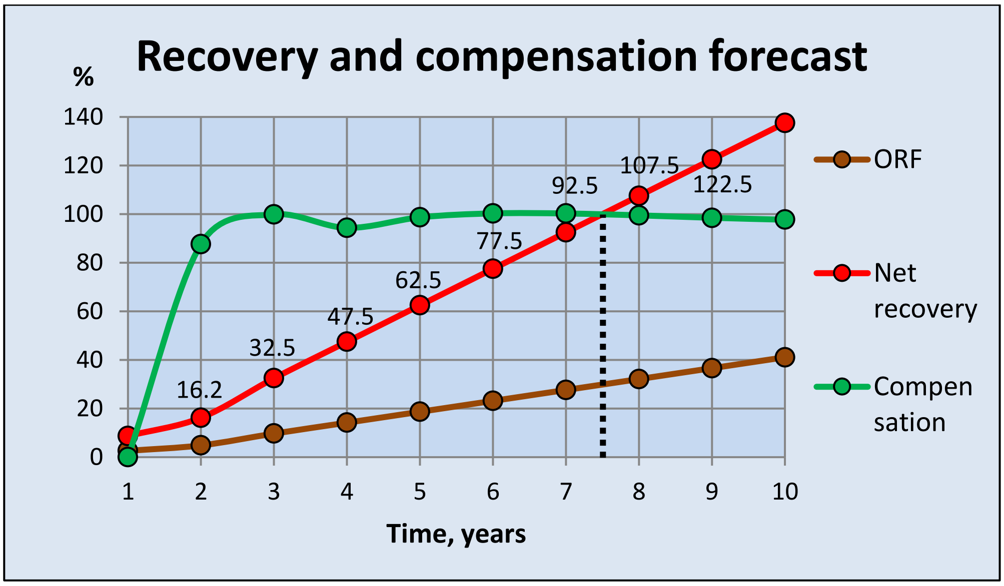


Figure 3.10 – Graph of the forecast for the extraction of recoverable reserves for solution 1.2
(ORF – oil recovery factor; Compensation – water injected for pushing the oil to the surface, pressure maintenance system)

According to this solution 1.2, by 2 producers and 2 injection wells with reservoir pressure maintenance 100% recovery of reserves will be achieved by the middle of the 8th year of development.

Obviously, the part of the graphs located to the right of the vertical dotted line is out of consideration.

Since the distribution of the Silurian horizons is much wider within the area compared to the Permian and Carboniferous ones, the horizontal section of production wells will be longer (appr. 4-5 km). This opens up the possibility of implementation of multi-stage hydraulic fracturing at the stage of declining production.

In general, against the background of the existing development practice with Prirazlomnaya, the implementation of the proposed schemes is optimistic; however, the complex of equipment and equipment used needs to be analyzed for deep directional drilling. With timely maintenance, gentle attitude (operation not within the limits of capabilities), constant monitoring of damage and complications, modernization of pumping equipment, drilling and development are allowed.

It should be noted that in the water areas of other fields in the Russian Arctic, classical directional drilling of horizontal wells of similar measured depths was not practiced.

3.4. Ice Resistant Satellite Platform (IRSP) concept

The description of a satellite platform is presented at the end of the current subchapter. The technological features of the proposed solutions are presented in Table 3.2 of chapter 3.2.

The relatively high thicknesses of the sediments, as well as issues of economic viability, require the use of multibranch wells. Multilateral operation will provide independent regulation of production and flow rates, implementation of measures to stimulate inflows, disconnection / connection of holes. The applied "fish bone" technology [j] is not entirely appropriate here due to the depth and cylindricity of the deposit (area is 2.6 km^2, oil net thickness is 110 m). The most optimal solution here is the use of two- and single-hole production wells. Placement of injection wells with subsequent reservoir pressure maintenance is similarly unprofitable and is physically limited by the geology.

For solution 2.1, it is proposed to drill two double-hole horizontal wells (Fig. E1-E3, Appendix E) with no pressure maintenance system. The predictive drilling is presented in Table 3.7.

Table 3.7. Predictive drilling data for solution 2.1

Measured depth, km				
Well type	**Prod**			
Well №	**№ 1**		**№ 2**	
Borehole	**Top**	**Btm**	**Top**	**Btm**
Vertical section	4.5	4.5	4.5	4.5
Deviated section	0.3	0.4	0.9	1.2
Horizontal section	0.4	0.5	1.0	1.2
Sum	5.2	5.4	6.4	6.9
Total	23.9			

Data on number and type of wells and commissioning of wells are presented in Table 3.8. It is proposed to commit one production well every two years.

Table 3.8. Quantity and type of wells and well commission data for solution 2.1

Year	**Wells commissioned**			**Well fund at start of year**		
	Total	**Prod**	**Inj**	**Total**	**Prod**	**Inj**
1	1	1	0	1	1	0
2	0	0	0	1	1	0
3	1	1	0	2	2	0
4	0	0	0	2	2	0
5	0	0	0	2	2	0
6	0	0	0	2	2	0
7	0	0	0	2	2	0
8	0	0	0	2	2	0
9	0	0	0	2	2	0
10	0	0	0	2	2	0

Well commissioning is shown graphically in Fig. 3.11.

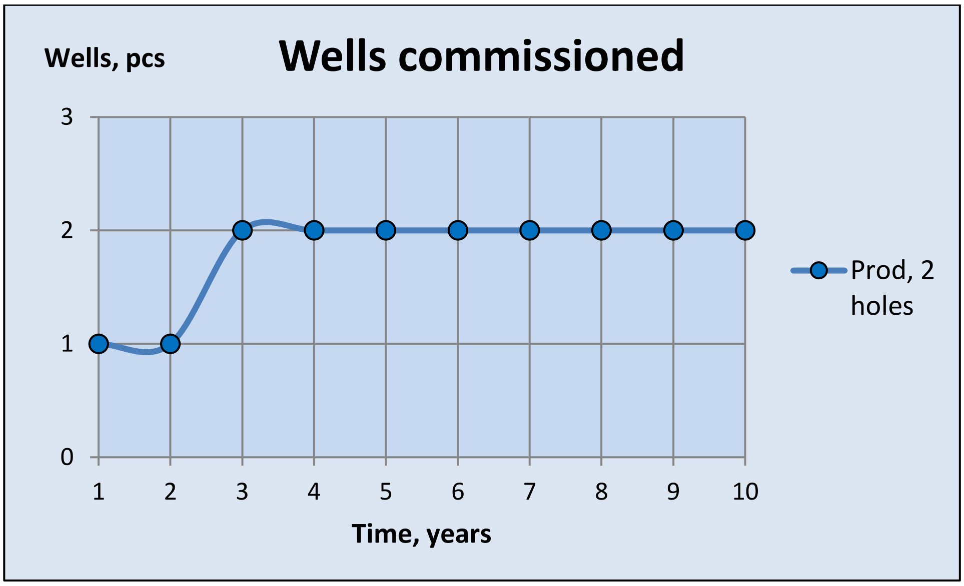


Figure 3.11 – Well commissioning schedule for solution 2.1

For solution 2.2, it is proposed to drill three double-hole horizontal wells (Fig. F1-F3, Appendix F). The predictive drilling is presented in Table 3.9.

Table 3.9. Predictive drilling data for solution 2.2

Measured depth, km						
Well type	**Prod**					
Well №	**№ 1**		**№ 2**		**№ 3**	
Borehole	**Top**	**Btm**	**Top**	**Btm**	**Top**	**Btm**
Vertical section	4.5	4.5	4.5	4.5	4.6	4.6
Deviated section	0.3	0.4	0.9	1.2	0.8	0.4
Horizontal section	0.4	0.5	1.0	1.2	0.4	0.5
Sum	5.2	5.4	6.4	6.9	5.8	5.5
Total	35.2					

Data on number and type of wells and commissioning of wells are presented in Table 3.10. It is proposed to commit one production well every two years.

Table 3.10. Quantity and type of wells and well commission data for solution 2.2

Year	**Wells commissioned**			**Well fund at start of year**		
	Total	**Prod**	**Inj**	**Total**	**Prod**	**Inj**
1	1	1	0	1	1	0
2	0	0	0	1	1	0
3	1	1	0	2	2	0
4	0	0	0	2	2	0
5	1	1	0	3	3	0
6	0	0	0	3	3	0
7	0	0	0	3	3	0
8	0	0	0	3	3	0
9	0	0	0	3	3	0
10	0	0	0	3	3	0

Well commissioning is shown graphically in Fig. 3.12.

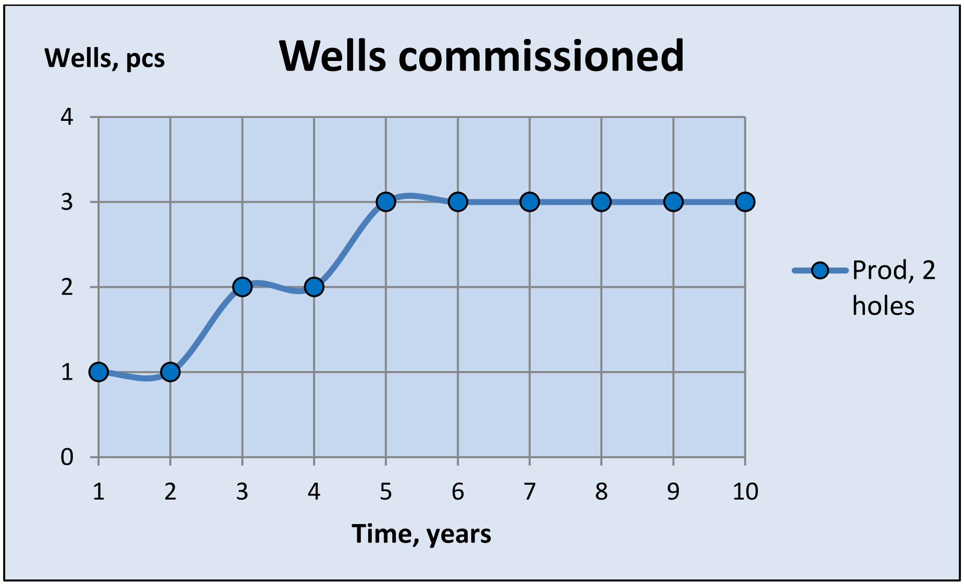


Figure 3.12 – Well commissioning schedule for solution 2.2

For solution 2.3, it is proposed to drill two double-hole and one single-hole horizontal wells (Fig. G1-G3, Appendix G). The predictive drilling is presented in Table 3.11.

Table 3.11. Predictive drilling data for solution 2.3

Measured depth, km					
Well type	**Prod**				
Well №	**№ 1**		**№ 2**		**№ 3**
Borehole	**Top**	**Btm**	**Top**	**Btm**	**Btm**
Vertical section	4.5	4.5	4.5	4.5	4.6
Deviated section	0.3	0.4	0.9	1.2	0.4
Horizontal section	0.4	0.5	1.0	1.2	0.5
Sum	5.2	5.4	6.4	6.9	5.5
Total	29.4				

Data on number and type of wells and commissioning of wells are presented in Table 3.12. It is proposed to commit one production well every two years.

Table 3.12. Quantity and type of wells and well commission data for solution 2.3

Year	**Wells commissioned**			**Wells fund at start of year**		
	Total	**Prod**	**Inj**	**Total**	**Prod**	**Inj**
1	1	1	0	1	1	0
2	0	0	0	1	1	0
3	1	1	0	2	2	0
4	0	0	0	2	2	0
5	1	1	0	3	3	0
6	0	0	0	3	3	0
7	0	0	0	3	3	0
8	0	0	0	3	3	0
9	0	0	0	3	3	0
10	0	0	0	3	3	0

Well commissioning is shown graphically in Fig. 3.13.

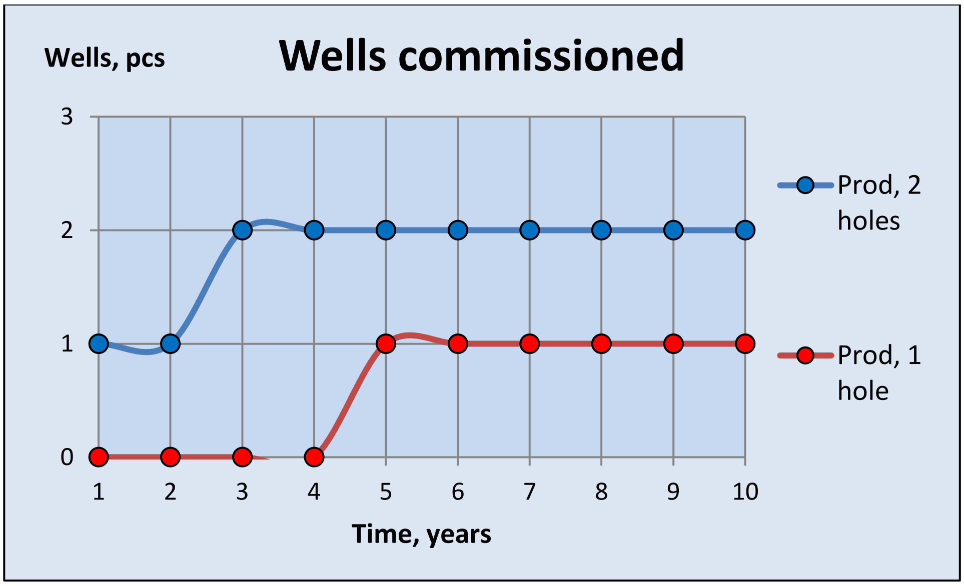


Figure 3.13 – Well commissioning schedule for solution 2.3

For solution 2.4, it is proposed to drill one double-hole and two single-hole horizontal wells (Fig. H1-H3, Appendix H). The predictive drilling is presented in Table 3.13.

Table 3.13. Predictive drilling data for solution 2.4

Measured depth, km				
Well type	**Prod**			
Well №	**№ 1**		**№ 2**	**№ 3**
Borehole	**Top**	**Btm**	**Btm**	**Btm**
Vertical section	4.5	4.5	4.5	4.6
Deviated section	0.3	0.4	1.2	0.4
Horizontal section	0.4	0.5	1.2	0.5
Sum	5.2	5.4	6.9	5.5
Total	23.0			

Data on number and type of wells and commissioning of wells are presented in Table 3.14. It is proposed to commit one production well every two years.

Table 3.14. Quantity and type of wells and well commission data for solution 2.4

Year	**Wells commissioned**			**Wells fund at start of year**		
	Total	**Prod**	**Inj**	**Total**	**Prod**	**Inj**
1	1	1	0	1	1	0
2	0	0	0	1	1	0
3	1	1	0	2	2	0
4	0	0	0	2	2	0
5	1	1	0	3	3	0
6	0	0	0	3	3	0
7	0	0	0	3	3	0
8	0	0	0	3	3	0
9	0	0	0	3	3	0
10	0	0	0	3	3	0

Well commissioning is shown graphically in Fig. 3.14.

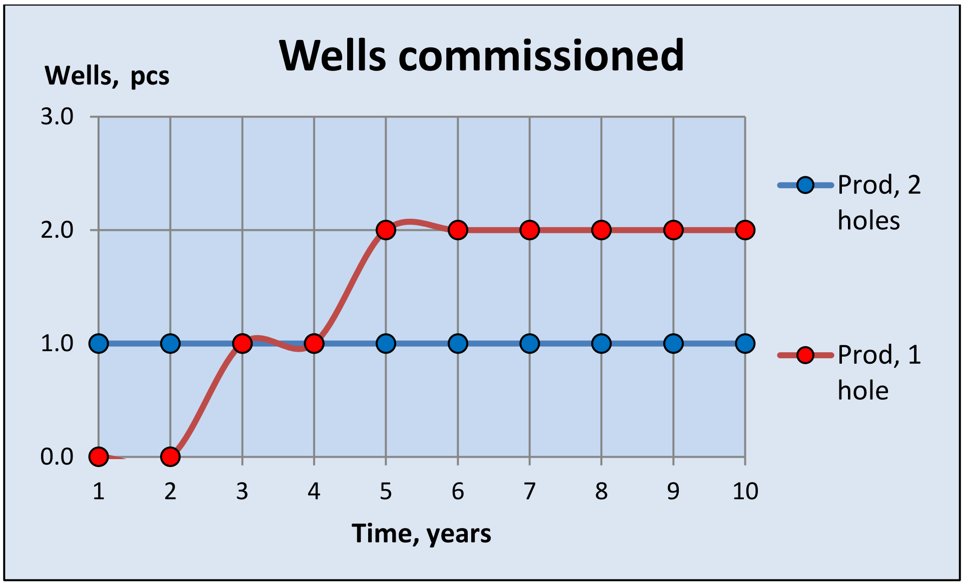


Figure 3.14 – Well commissioning schedule for solution 2.4

For solution 2.5, it is proposed to drill three single-hole horizontal wells (Fig. I1-I3, Appendix I). The predictive drilling is presented in Table 3.15.

Table 3.15. Predictive drilling data for solution 2.5

Measured depth, km			
Well type	**Prod**		
Well №	**№ 1**	**№ 2**	**№ 3**
Borehole	**Btm**	**Btm**	**Btm**
Vertical section	4.5	4.5	4.6
Deviated section	0.4	1.2	0.4
Horizontal section	0.5	1.2	0.5
Sum	5.4	6.9	5.5
Total	17.8		

Data on number and type of wells and commissioning of wells are presented in Table 3.16. It is proposed to commit one production well every two years.

Table 3.16. Quantity and type of wells and well commission data for solution 2.5

Year	**Wells commissioned**			**Wells fund at start of year**		
	Total	**Prod**	**Inj**	**Total**	**Prod**	**Inj**
1	1	1	0	1	1	0
2	0	0	0	1	1	0
3	1	1	0	2	2	0
4	0	0	0	2	2	0
5	1	1	0	3	3	0
6	0	0	0	3	3	0
7	0	0	0	3	3	0
8	0	0	0	3	3	0
9	0	0	0	3	3	0
10	0	0	0	3	3	0

Well commissioning is shown graphically in Fig. 3.15.

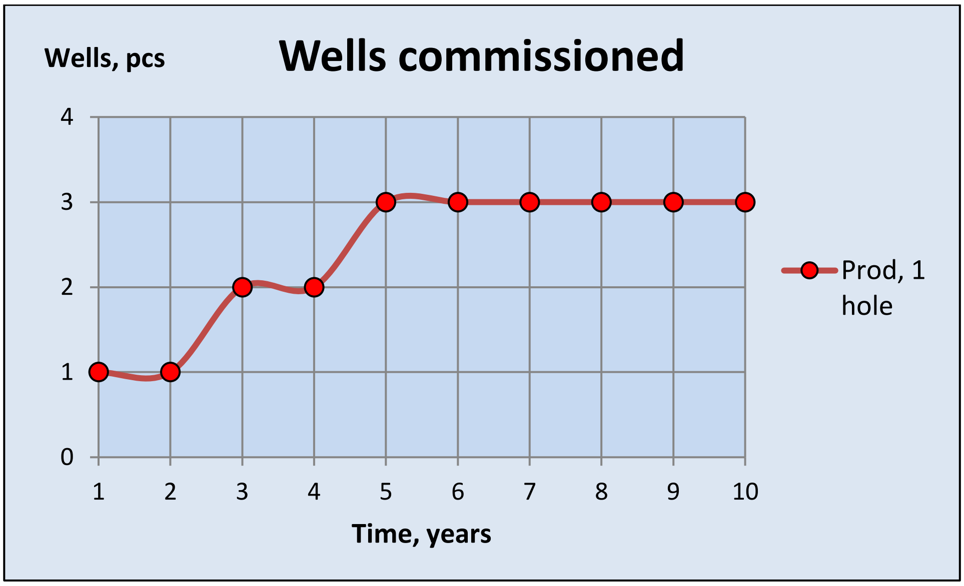


Figure 3.15 – Well commissioning schedule for solution 2.5

So, various combinations of single- and double-lateral wells were considered in order to choose the least expensive solution, but at the same time a solution capable of ensuring the full extraction of the Silurian reserves.

The installation of IRSP will require huge capital expenditures which, within the framework of the given economic situation, may lead to non-profitability of the project, but the justification for this approach has been described above. In addition to the SP itself, it is required to set up an oil pipeline to the main structure. Due to the shallow depth of the waters, the uniformity of the bottom, this is quite feasible by installing pipes at the bottom of the sea. It is recommended to trench the oil pipeline to a depth of 1-2 meters, since the muddy bottom is unstable and the presence of stamukhas is possible.

An illustrative example of ice resistance in the climatic conditions of the Pechora Sea is the Varandey terminal (Fig. 3.16) which, in fact, is a complex of pipelines, storage facilities and loading and unloading equipment for liquids. The terminal supervised by icebreakers with an octagonal rigid base is operated annually.

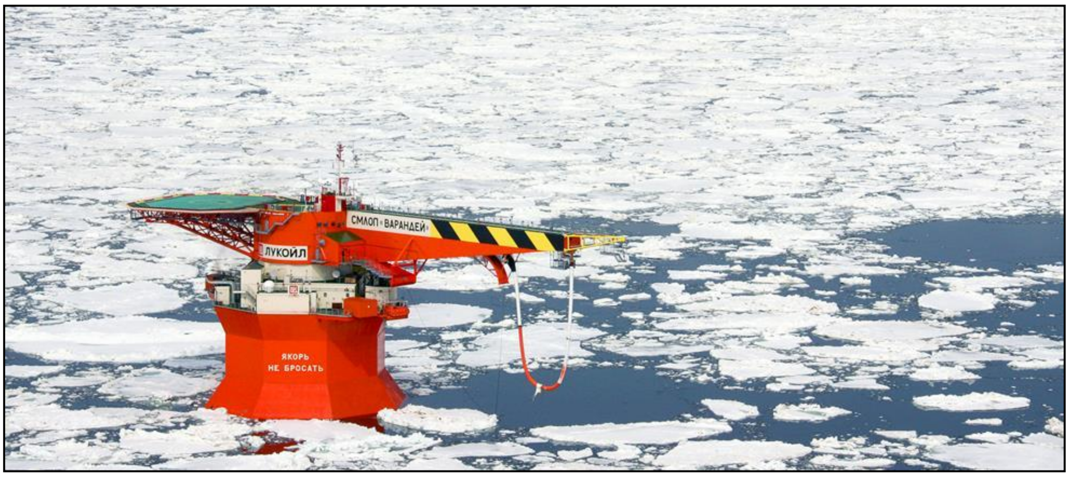


Figure 3.16 – Varandey terminal [ee]

3.4.1. Main technological parameters

For the IRSP concept the following quantitative and qualitative assumptions were made:

- the average annual flow rate of one individual well falls over time due to a drop in reservoir pressure;
- a two-phase mixture (oil with water) is produced in an oil field;
- in the calculations, gas was not included in the analysis. This might be a reasonable first approach as the volume of gas is low and it serves for electricity generation only;
- gradual commissioning of new wells (one well every two years);
- the term of the development project is 10 years;
- tendency to reduce the number of commissioned wells due to the high cost of drilling and offshore development;
- the development project does not take into account long dead time (no production, no process) due to technical complications, accidents, the economic situation, global political problems;
- predictive drilling does not take into account detailed geological, stratigraphic, lithological conditions;

- some initial data were taken from neighboring deposits, as well as from [dd], [mm];

- certain parameters (e.g. reservoir permeability, dynamic fluid viscosity, skin factor, bottom hole pressure) were assigned constant values;

- the natural logarithm of the ratio of the external reservoir boundary to the borehole radius is 10;

- due to possible technological, technical, geological, hydrodynamic features and complications, the predicted production rate of one two-hole well was calculated as the predicted production rate of one single-hole well with a coefficient of 1.5;

- predicted production rates of double-hole wells do not take into account plugging, collapse and other development complications, therefore, continuous equivalent operation of all wells is assumed;

- the RPM system is not financially appropriate here due to the large capital costs for the construction of IRSP;

- other.

So, according to the Dupuis formula for imperfect wells [e], the predicted average annual production rates were calculated for one individual production well for solutions 2.1-2.5 (Fig. 3.17).

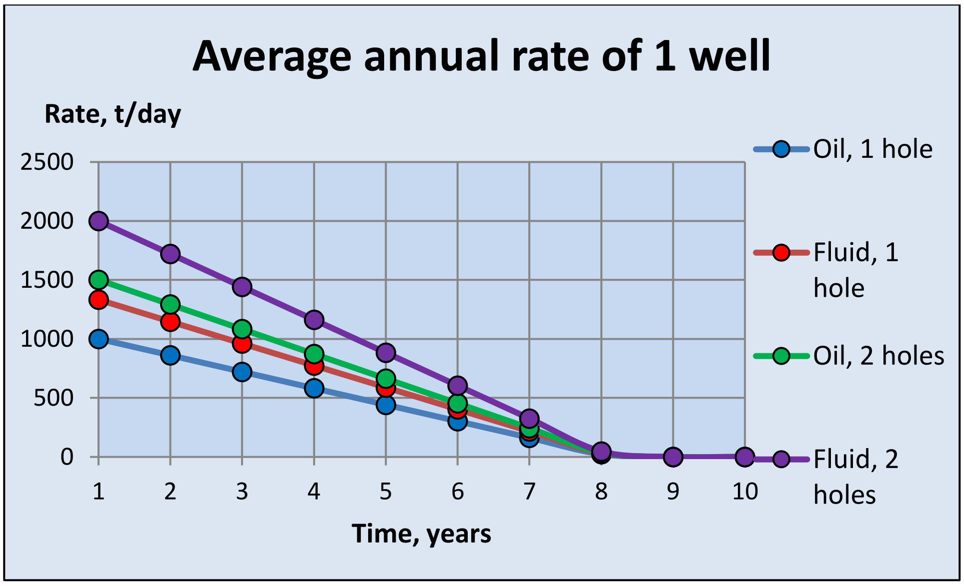


Figure 3.17 – Graph of the decline in oil and liquid production over time for solutions 2.1-2.5 (no pressure maintenance)

Similarly to Fig. 5.3, the predicted flow rate drops rapidly over time and reaches a near-zero number in the 8th year of operation.

For solution 2.1 (see Table 3.2, chapter 3.2), taking into account the decline in flow rates and the gradual commissioning of new wells, the forecast production (Fig. 3.18), as well as the forecast net production (Fig. 3.19) for the two phases, was calculated. In addition, a forecast was made for the withdrawal of the recoverable Silurian reserves (Fig. 3.20).

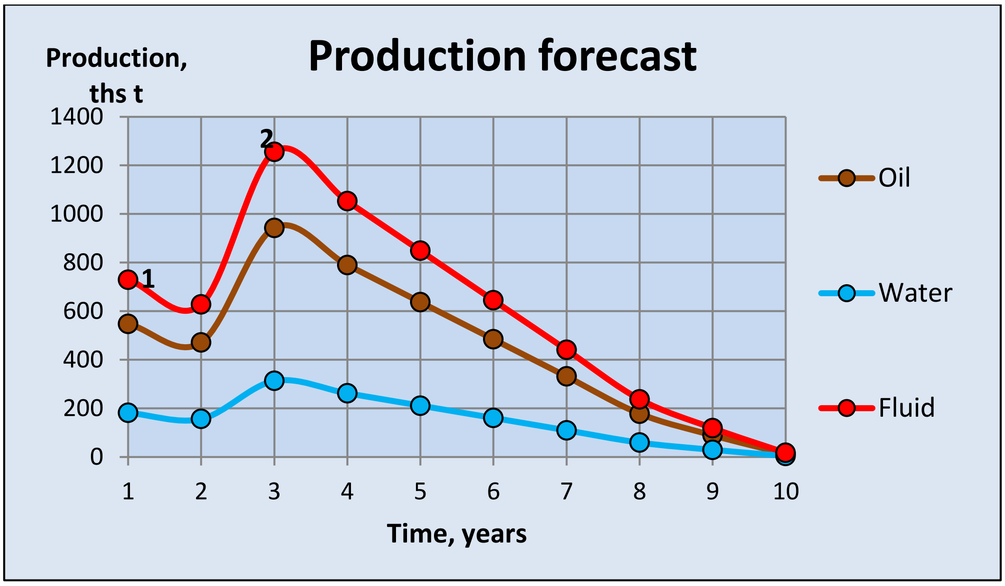


Figure 3.18 – Graph of the decline in oil and fluid production flowrate over time for solution 2.1

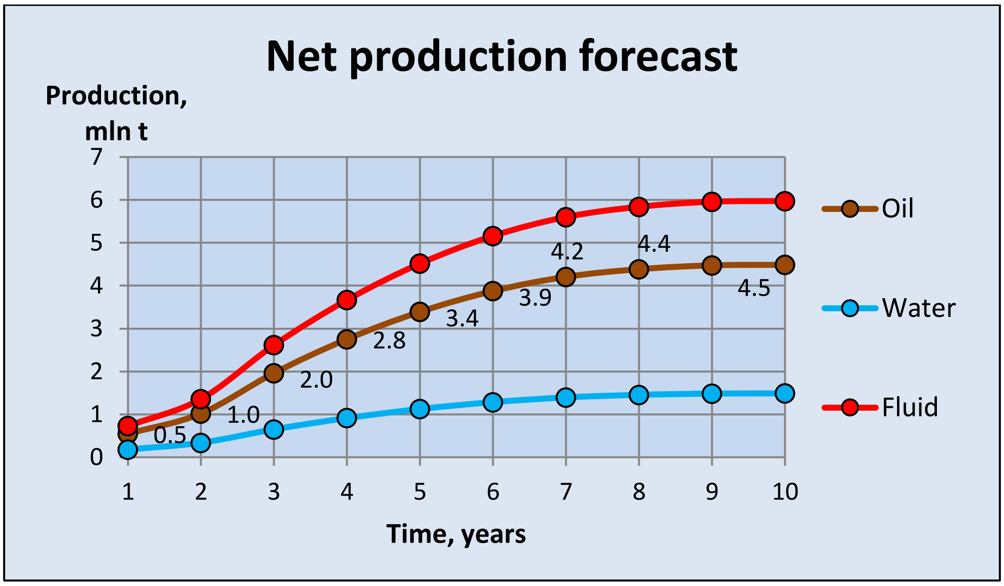


Figure 3.19 – Graph of cumulative production forecast for solution 2.1

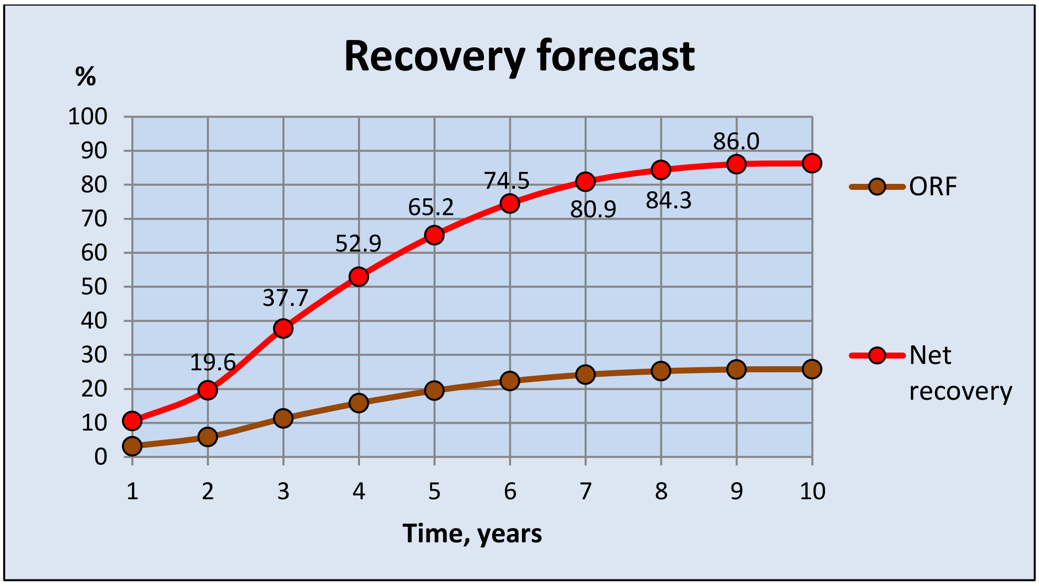


Figure 3.20 – Graph of the forecast for the extraction of recoverable reserves for solution 2.1

According to this solution 2.1, by 2 double-lateral wells 100% recovery of reserves will not be achieved for 10 years or more, since the productive capacities of these wells do not correspond to the reserves. An increase in the number and capacity of wells or the use of EORM or IORM is required.

For solution 2.2 (see Table 3.2, chapter 3.2), taking into account the decline in flow rates and the gradual commissioning of new wells, the forecasted production (Fig. 3.21), as well as the forecasted cumulative production (Fig. 3.22) for the two phases, was calculated. In addition, a forecast was made for the withdrawal of the recoverable Silurian reserves (Fig. 3.23).

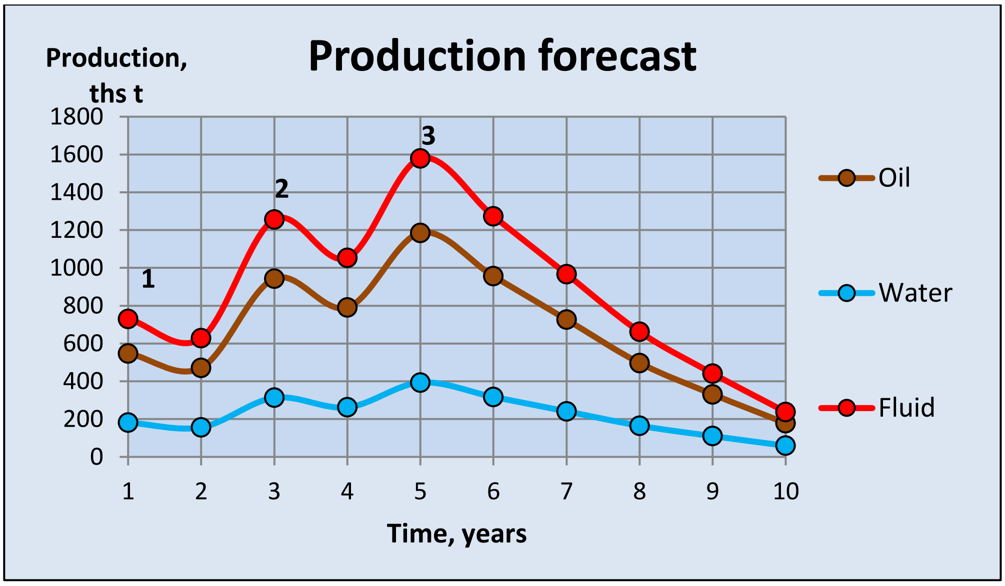


Figure 3.21 – Graph of the decline in oil and fluid production flowrate over time for solution 2.2

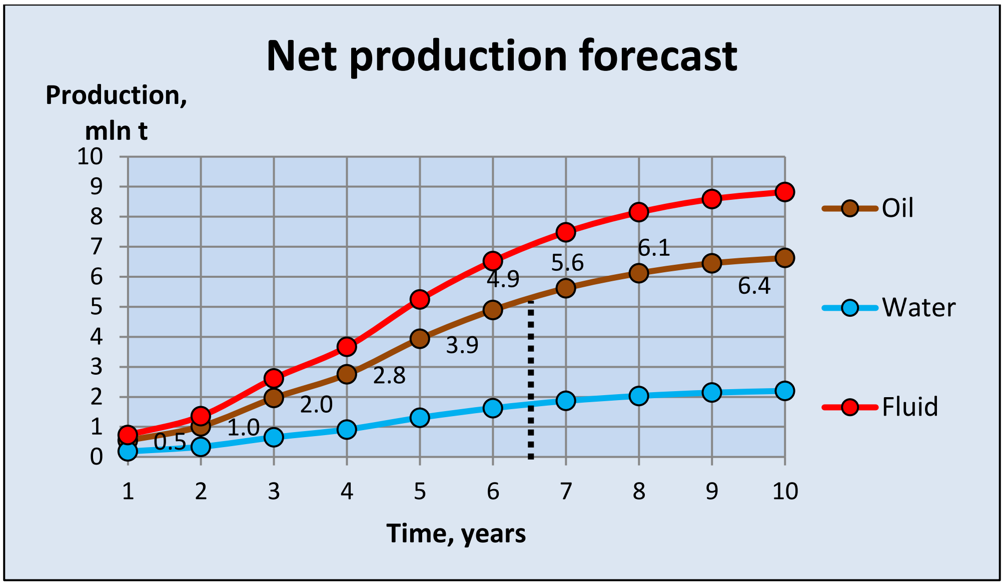


Figure 3.22 – Graph of cumulative production forecast for solution 2.2

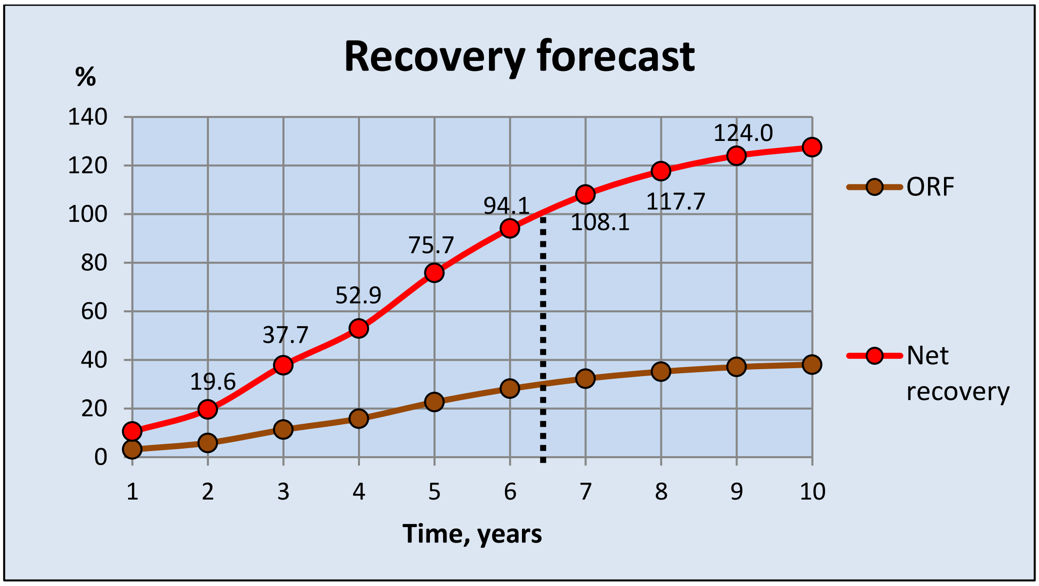


Figure 3.23 – Graph of the forecast for the extraction of recoverable reserves for solution 2.2

According to this solution 2.2, by means of 3 double-lateral wells 100% recovery of reserves will be achieved by the middle of the 7th year. This solution is efficient and productive in terms of development, however, drilling such wells is characterized by high costs.

For solution 2.3 (see Table 3.2, chapter 3.2), taking into account the decline in flow rates and the gradual commissioning of new wells, the forecasted production (Fig. 3.24), as well as the forecasted cumulative production (Fig. 3.25) for the two phases, was calculated. In addition, a forecast was made for the withdrawal of the recoverable Silurian reserves (Fig. 3.26).

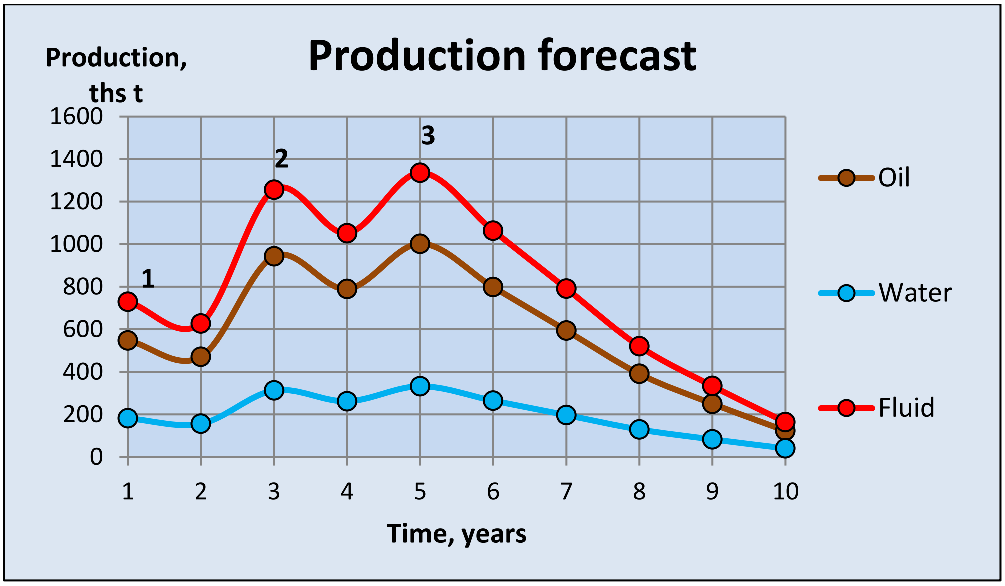


Figure 3.24 – Graph of the decline in oil and fluid production flowrate over time for solution 2.3

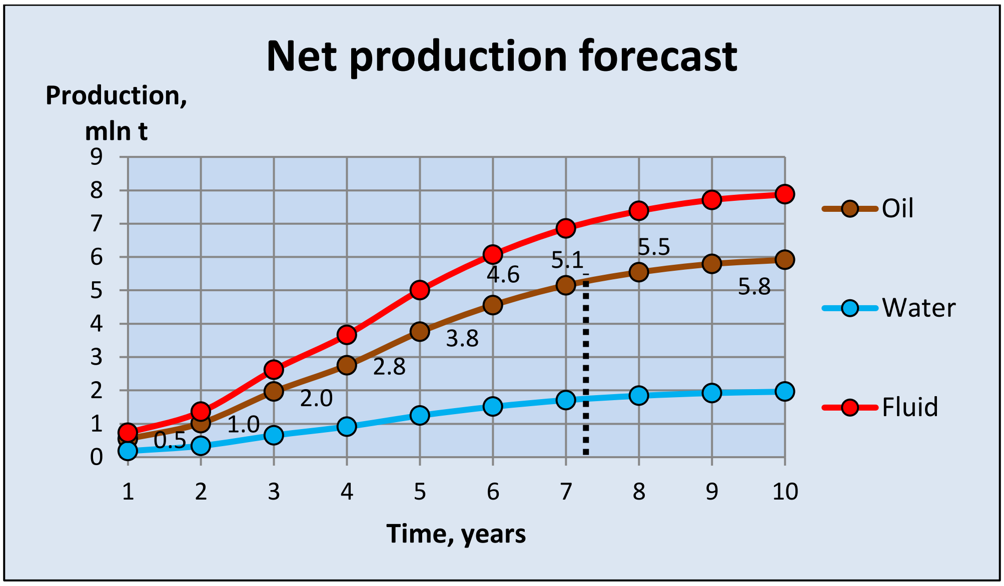


Figure 3.25 – Graph of cumulative production forecast for solution 2.3

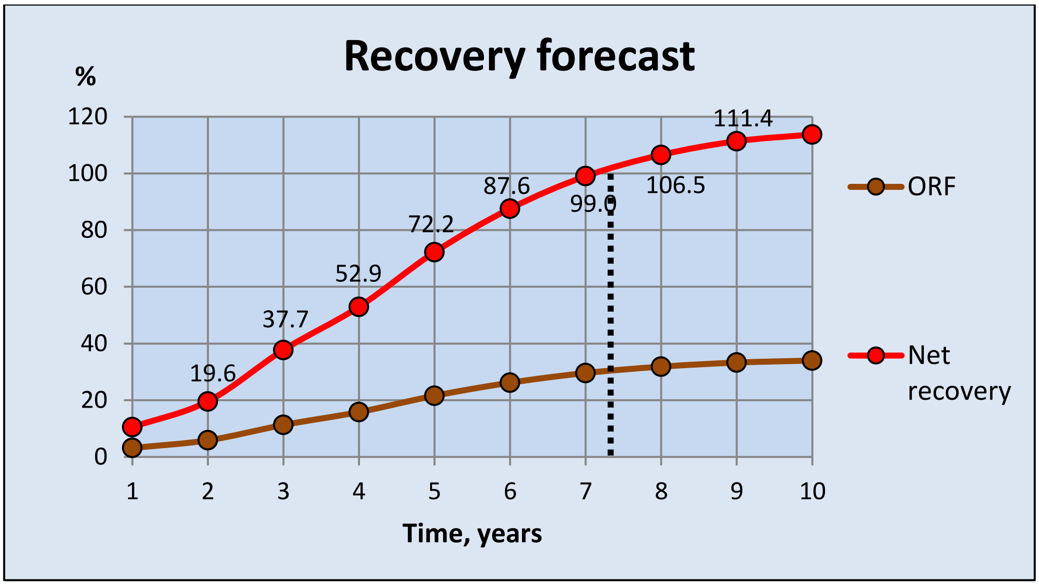


Figure 3.26 – Graph of the forecast for the extraction of recoverable reserves for solution 2.3

According to this solution 2.3, with 2 double-lateral and 1 single-lateral wells 100% recovery of reserves will be achieved by the middle of the 8th year. This solution is operational and productive in terms of development and is cheaper than solution 2.2, however, drilling is still characterized by high costs.

For solution 2.4 (see Table 3.2, chapter 3.2), taking into account the decline in flow rates and the gradual commissioning of new wells, the forecast production (Fig. 3.27), as well as the forecast cumulative production (Fig. 3.28) for the two phases, was calculated. In addition, a forecast was made for the extraction of the recoverable Silurian reserves (Fig. 3.29).

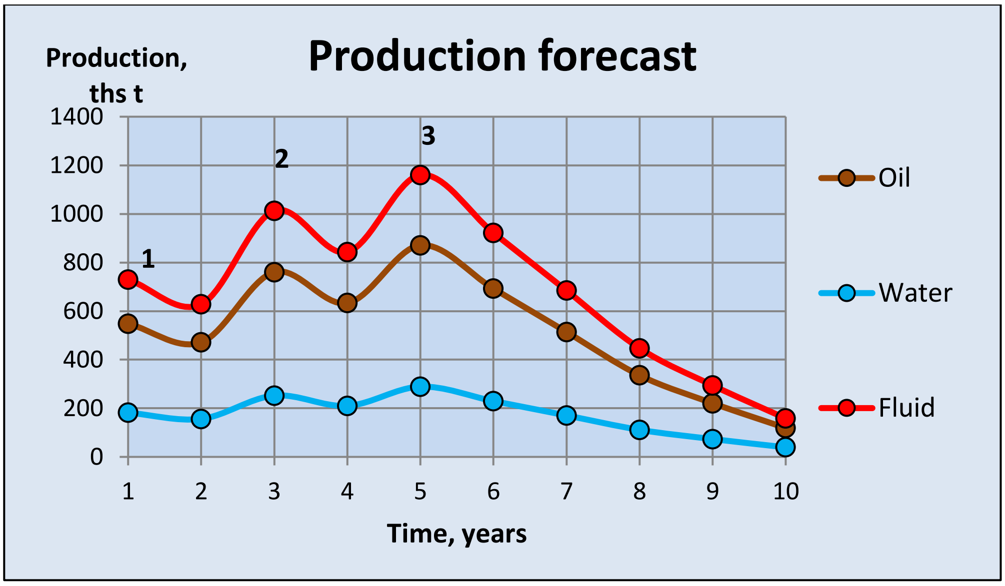


Figure 3.27 – Graph of the decline in oil and fluid production flowrate over time for solution 2.4

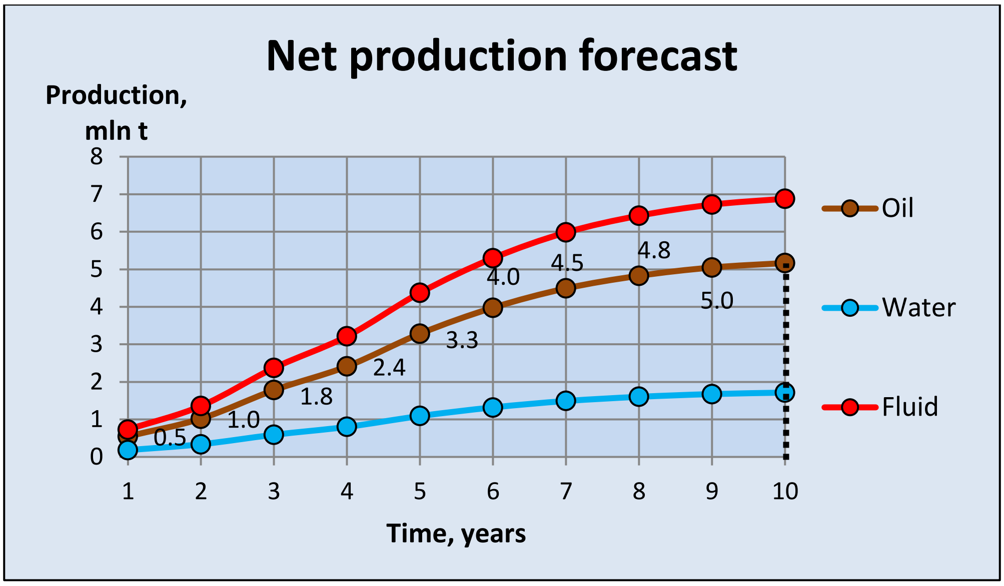


Figure 3.28 – Graph of cumulative production forecast for solution 2.4

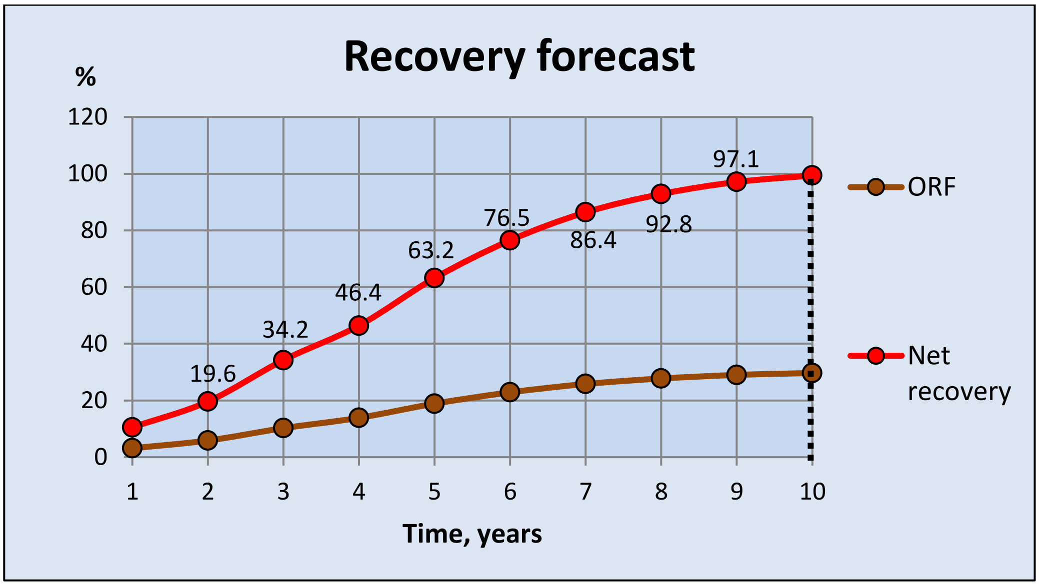


Figure 3.29 – Graph of the forecast for the extraction of recoverable reserves for solution 2.4

According to this decision regarding solution 2.4, by 1 double-lateral and 2 single-lateral wells 100% recovery of reserves will be achieved during a 10-year period. This solution is moderate in terms of development and cheaper than solutions 2.1-2.3.

For solution 2.5 (see Table 3.2, chapter 3.2), taking into account the decline in flow rates and the gradual commissioning of new wells, the forecast production (Fig. 3.30), as well as the forecast net production (Fig. 3.31) for the two phases, was calculated. In addition, a forecast was made for the extraction of the recoverable Silurian reserves (Fig. 3.32).

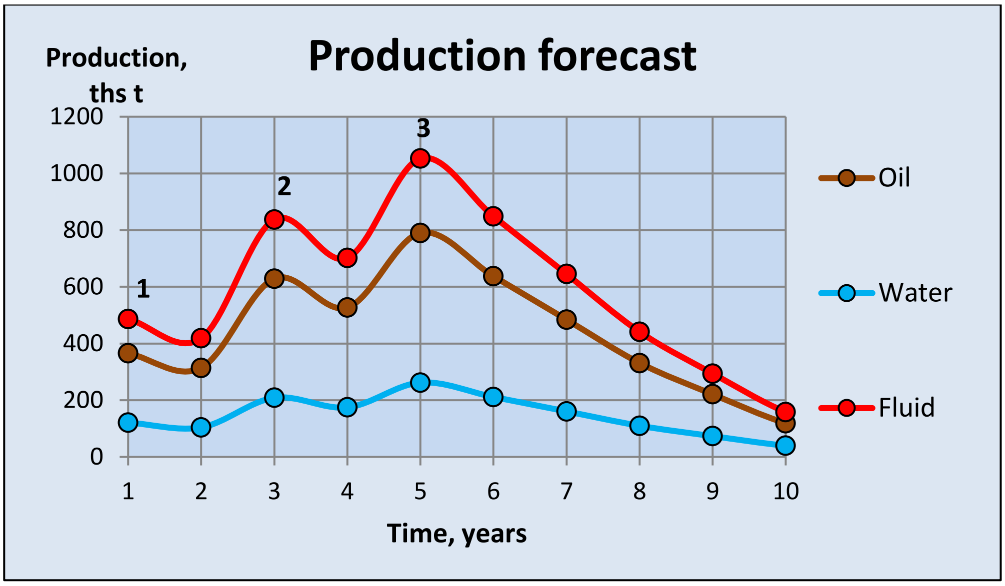


Figure 3.30 – Graph of the decline in oil and fluid production flowrate over time for solution 2.5

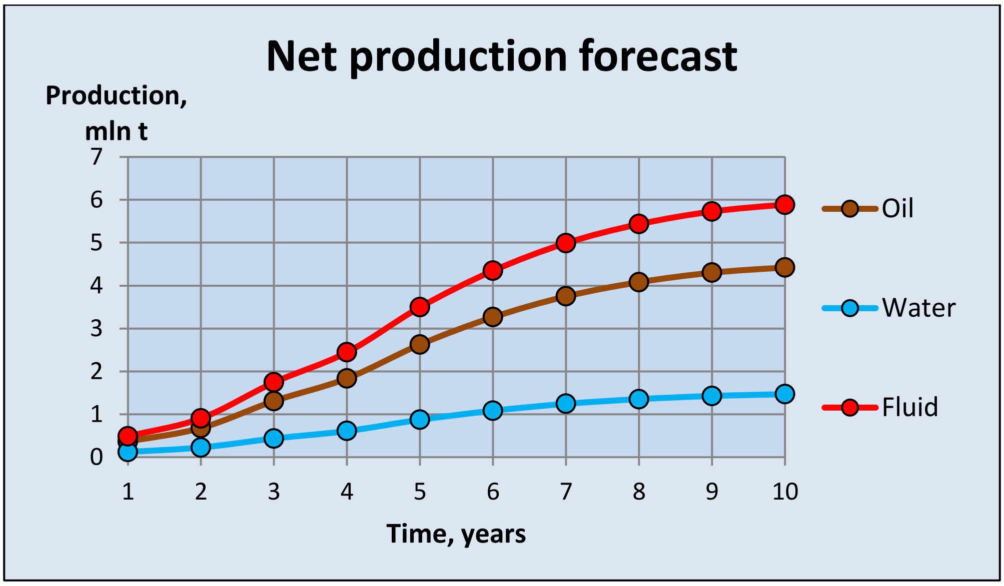


Figure 3.31 – Graph of cumulative production forecast for solution 2.5

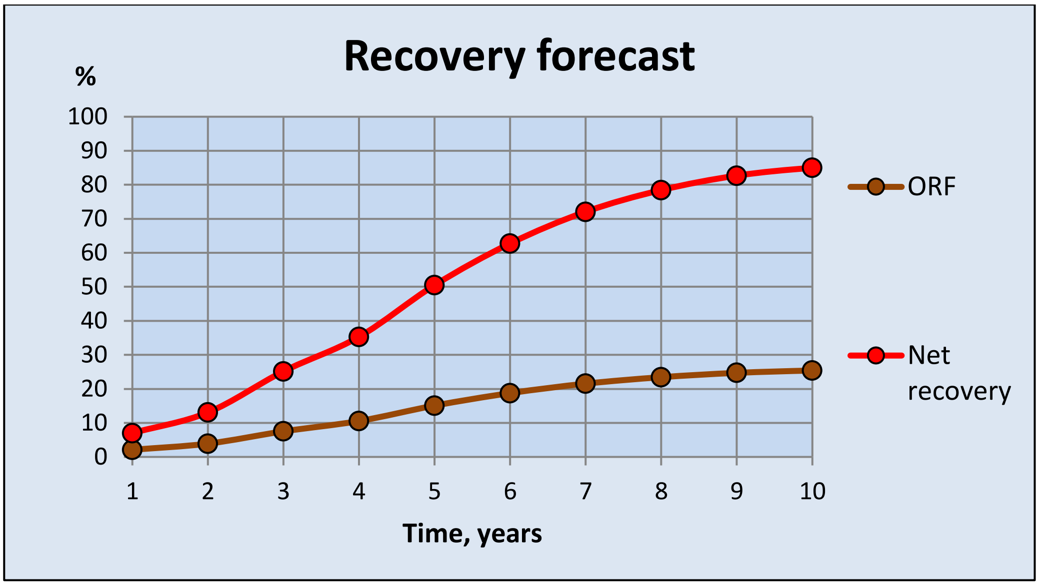


Figure 3.32 – Graph of the forecast for the extraction of recoverable reserves for solution 2.5

According to this solution 2.5, by 3 single-bore wells 100% of recoverable reserves will not be achieved for 10 years or more. Since the productive capacities of these wells do not correspond to the reserves, a change in the type and diameter of wells or the use of EORM or IORM is required.

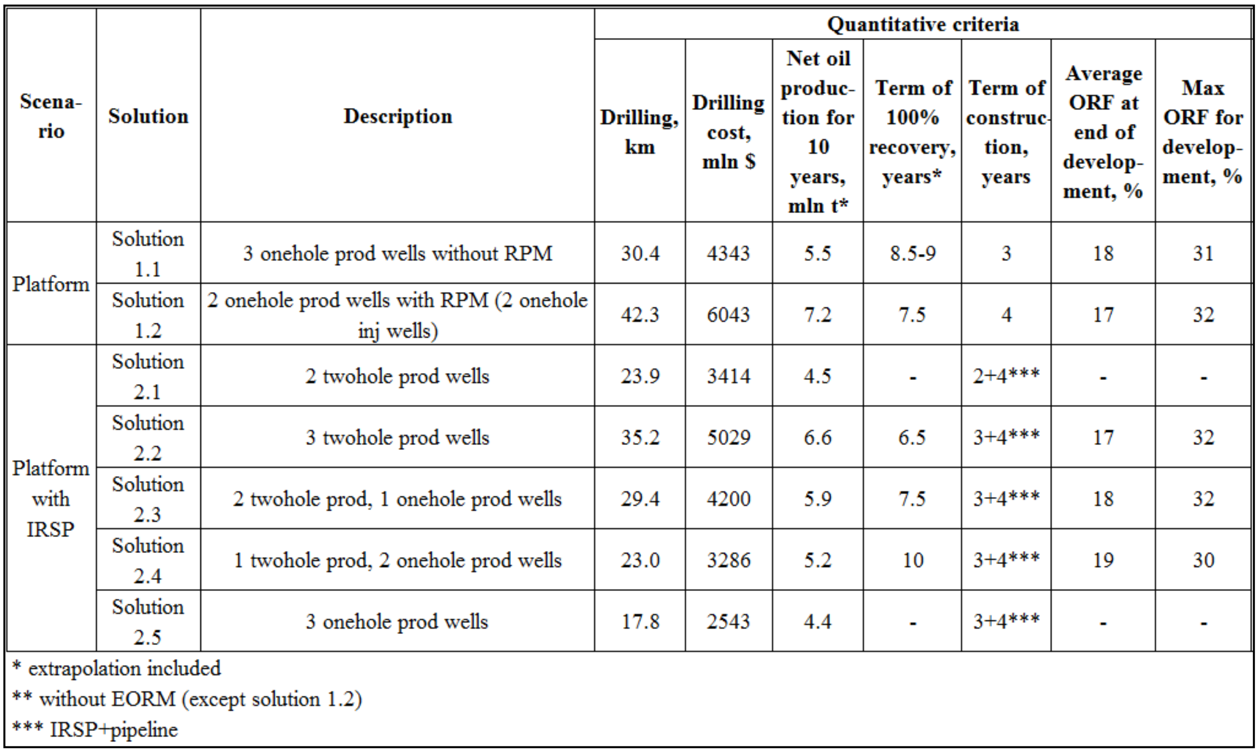
A significant reduction in the measured length of the wells will be achieved by installing IRSP (reduction up to 5 km). SP opens up the possibility of connecting the overlying strata to exploitation later, so its installation will not be focused only on the Upper Silurian. Other offshore fields (e.g. the Sea of Okhotsk, the Bay of Ob) are successfully designing their development in a similar manner.

The satellite will allow, similar to the platform, simultaneous drilling and production. With the current level of development of equipment and technologies in the Russian Federation, it is possible to implement the installation and operation of the SP, which ensures the full safety of personnel due to its absence. The use of satellite platforms is also being considered in other offshore fields, for example, at the Ob and Taz Bays.

3.5. Solutions comparison and decision making

First of all, it is worth noting the predictive nature of the scenarios under consideration which implies a number of assumptions and simplifications. The concepts which included seven different, somewhat similar, solutions were subject to comparison from quantitative and qualitative points of view.

Comparison of solutions by quantitative criteria is shown in Fig. 3.33.



Scenario	Solution	Description	Quantitative criteria						
			Drilling, km	**Drilling cost, mln $**	**Net oil production for 10 years, mln t***	**Term of 100% recovery, years***	**Term of construction, years**	**Average ORF at end of development, %**	**Max ORF for development, %**
Platform	Solution 1.1	3 onehole prod wells without RPM	30.4	4343	5.5	8.5-9	3	18	31
	Solution 1.2	2 onehole prod wells with RPM (2 onehole inj wells)	42.3	6043	7.2	7.5	4	17	32
Platform with IRSP	Solution 2.1	2 twohole prod wells	23.9	3414	4.5	-	2+4***	-	-
	Solution 2.2	3 twohole prod wells	35.2	5029	6.6	6.5	3+4***	17	32
	Solution 2.3	2 twohole prod, 1 onehole prod wells	29.4	4200	5.9	7.5	3+4***	18	32
	Solution 2.4	1 twohole prod, 2 onehole prod wells	23.0	3286	5.2	10	3+4***	19	30
	Solution 2.5	3 onehole prod wells	17.8	2543	4.4	-	3+4***	-	-

* extrapolation included
** without EORM (except solution 1.2)
*** IRSP+pipeline

Figure 3.33 – Table of comparing decisions by quantitative criteria

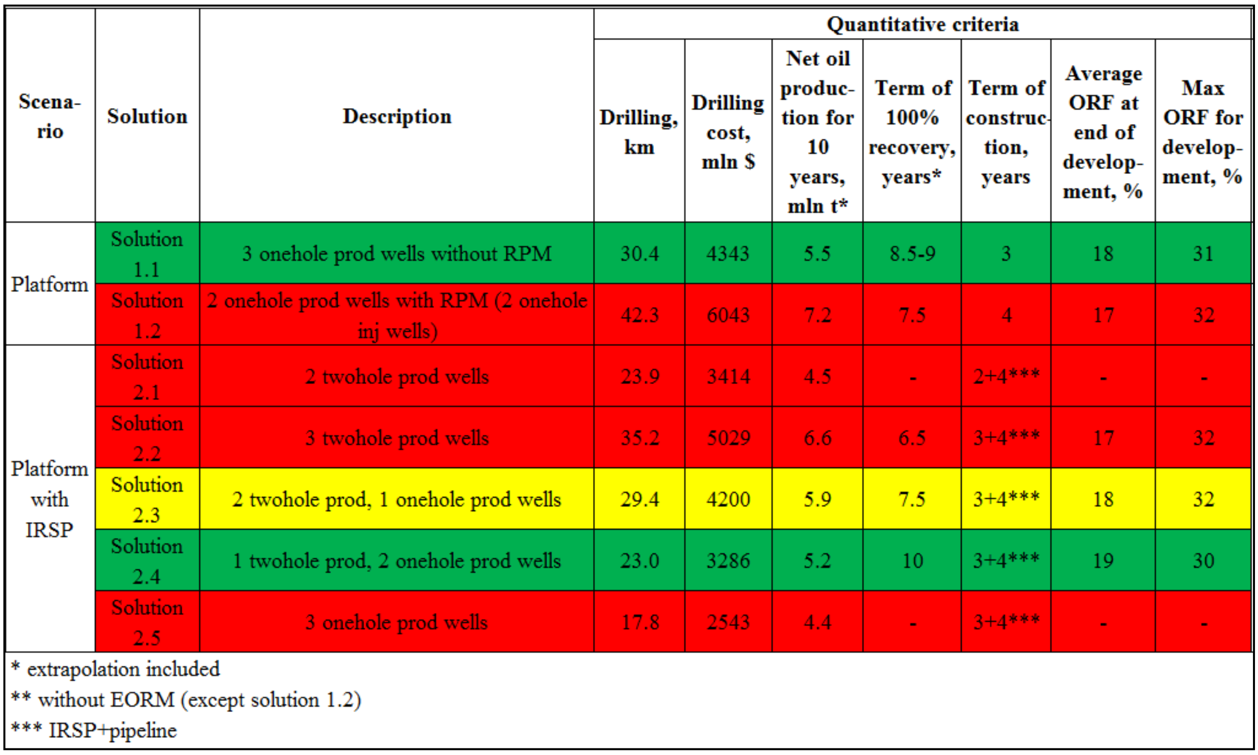
The predictive drilling has been discussed in detail in sections 3.3 and 3.4.

Regarding the cost of drilling, data from various sources were studied, in particular, [ff], [gg], [f], [c], [k]. The cost of an average well in arctic conditions is currently difficult to estimate, but a figure of $1 billion for a seven-kilometer borehole has been used.

The cumulative production and the terms of the extraction of the recoverable reserves, as well as the values of the oil recovery factors were studied in detail in sections 3.3.1 and 3.4.1.

The terms of construction are determined conditionally taking into account general information. Thus, the construction of one well takes a year and the construction of a satellite with a pipeline to the platform takes four years.

The choice of solutions according to quantitative criteria is shown in Fig. 3.34.



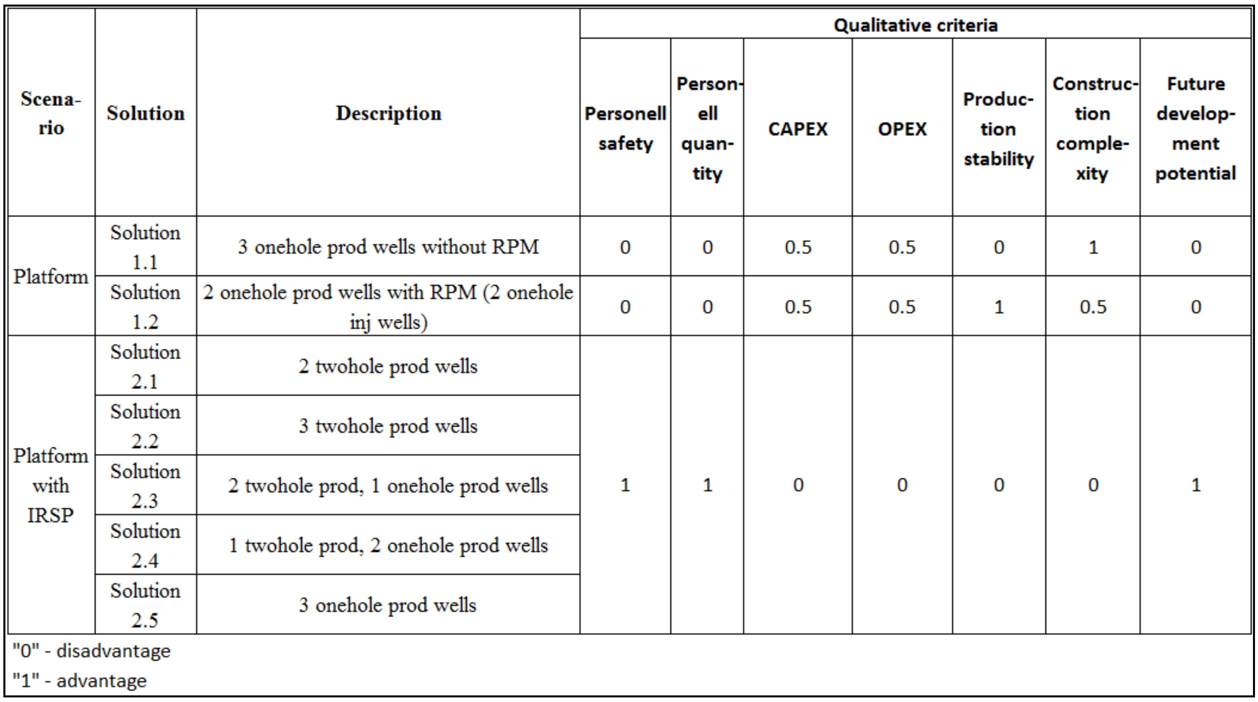
Scenario	Solution	Description	Quantitative criteria						
			Drilling, km	Drilling cost, mln $	Net oil production for 10 years, mln t*	Term of 100% recovery, years*	Term of construction, years	Average ORF at end of development, %	Max ORF for development, %
Platform	Solution 1.1	3 onehole prod wells without RPM	30.4	4343	5.5	8.5-9	3	18	31
	Solution 1.2	2 onehole prod wells with RPM (2 onehole inj wells)	42.3	6043	7.2	7.5	4	17	32
Platform with IRSP	Solution 2.1	2 twohole prod wells	23.9	3414	4.5	-	2+4***	-	-
	Solution 2.2	3 twohole prod wells	35.2	5029	6.6	6.5	3+4***	17	32
	Solution 2.3	2 twohole prod, 1 onehole prod wells	29.4	4200	5.9	7.5	3+4***	18	32
	Solution 2.4	1 twohole prod, 2 onehole prod wells	23.0	3286	5.2	10	3+4***	19	30
	Solution 2.5	3 onehole prod wells	17.8	2543	4.4	-	3+4***	-	-

* extrapolation included
** without EORM (except solution 1.2)
*** IRSP+pipeline

Figure 3.34 – Marked table for comparing decisions by quantitative criteria
(ORF – oil recovery factor, EORM – enhanced oil recovery methods, IRSP – ice resistant satellite platform)

So, first of all, it is possible to cut off (red color) development options that are not able to provide 100% recovery of recoverable reserves (solutions 2.1 and 2.5). Then the options with the highest drilling (and, consequently, maintenance) costs are removed (red color) – solutions 1.2 and 2.2. Further highlighted (green color) are the least expensive options for drilling – solutions 1.1 and 2.4. Finally, there remains (yellow) one option in doubt (solution 2.3).

Comparison of solutions by qualitative criteria is shown in Fig. 3.35.



Scenario	Solution	Description	Qualitative criteria						
			Personell safety	Personell quantity	CAPEX	OPEX	Production stability	Construction complexity	Future development potential
Platform	Solution 1.1	3 onehole prod wells without RPM	0	0	0.5	0.5	0	1	0
	Solution 1.2	2 onehole prod wells with RPM (2 onehole inj wells)	0	0	0.5	0.5	1	0.5	0
Platform with IRSP	Solution 2.1	2 twohole prod wells	1	1	0	0	0	0	1
	Solution 2.2	3 twohole prod wells							
	Solution 2.3	2 twohole prod, 1 onehole prod wells							
	Solution 2.4	1 twohole prod, 2 onehole prod wells							
	Solution 2.5	3 onehole prod wells							

"0" - disadvantage
"1" - advantage

Figure 3.35 – Table of comparison of solutions by qualitative criteria

Personnel safety refers to the risks of causing harm to health at the offshore facility.

Capital expenditures cover construction, transportation, installation, testing and other stages connected with the platform, IRSP and pipeline. Operating expenditures include pipeline, wells and SP maintenance costs.

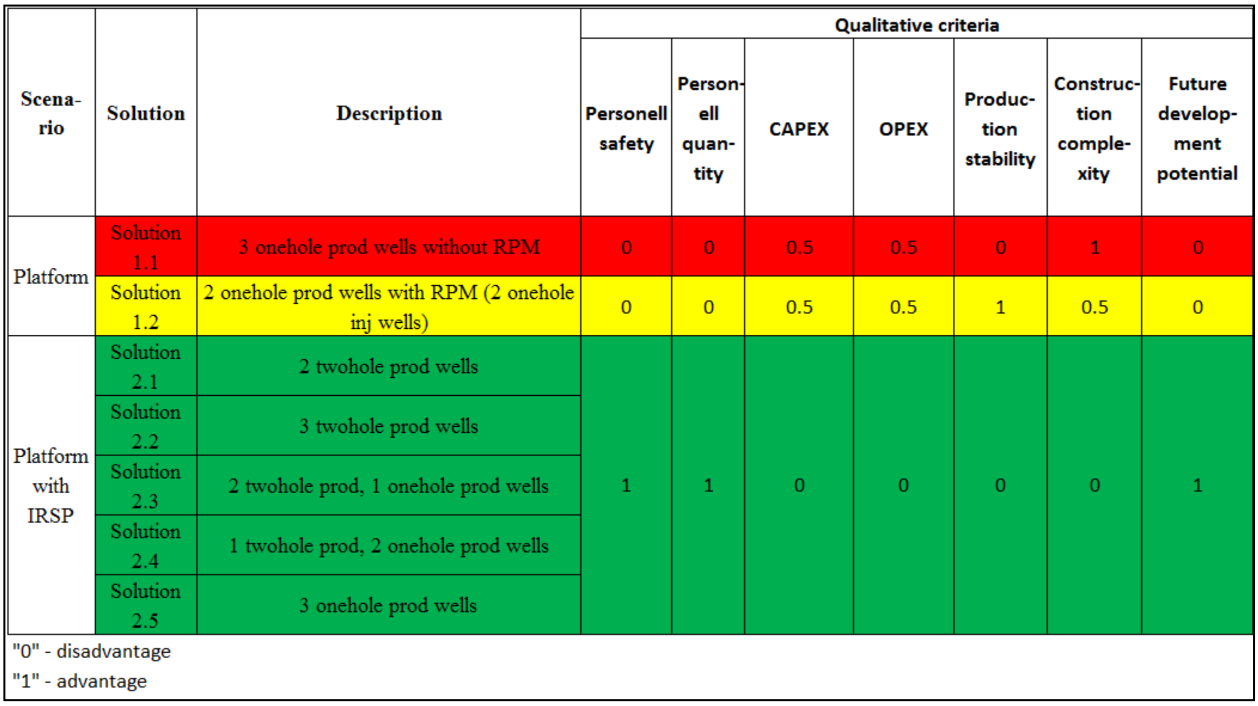
Production stability refers to a long-standing (appr. 5 years) relatively constant period of forecasted production rates.

Complexity of construction means financial, material, time costs for the construction of facilities necessary for the development of the field within the framework of the proposed solutions.

The potential for future development is the possibility of involving over- and underlying objects into development after depletion of the Silurian deposits.

Values were chosen based on general information and opinion of the author.

The choice of solutions according to qualitative criteria is shown in Fig. 3.36.



Scena-rio	Solution	Description	Qualitative criteria						
			Personell safety	Person-ell quan-tity	CAPEX	OPEX	Produc-tion stability	Construc-tion comple-xity	Future develop-ment potential
Platform	Solution 1.1	3 onehole prod wells without RPM	0	0	0.5	0.5	0	1	0
	Solution 1.2	2 onehole prod wells with RPM (2 onehole inj wells)	0	0	0.5	0.5	1	0.5	0
Platform with IRSP	Solution 2.1	2 twohole prod wells	1	1	0	0	0	0	1
	Solution 2.2	3 twohole prod wells							
	Solution 2.3	2 twohole prod, 1 onehole prod wells							
	Solution 2.4	1 twohole prod, 2 onehole prod wells							
	Solution 2.5	3 onehole prod wells							

"0" - disadvantage
"1" - advantage

Figure 3.36 – Marked table of comparing decisions by quality criteria

So, by the sum of the values, it can be determined the best scenario of proposed. Solution 1.1 has the smallest number (red), solutions 2.1-2.5 have the largest (green). Solution 1.2 (yellow) is in doubt.

Combining all the above information, it is obvious to single out solution 2.4 as the most optimal of the proposed development options.

For the Silurian carbonate reservoir, the use of horizontal wells will be reflected in an increase in the drainage area and sweep efficiency. Access to potentially unaffected reservoirs will be provided by two multilateral wells.

Despite the long development period compared to other options (10 years), this approach will significantly reduce drilling costs while at the same time ensuring the full extraction of Silurian hydrocarbons. A ten-year period is rather short for development of offshore deposits, however, the reserves themselves in the Upper Silurian are similarly small. The connection of the overlying Devonian deposits was not considered in this work; however, their potential justifies the expensive and lengthy construction of the SP.

The platform scenario is much more profitable, however, as mentioned, serious technical difficulties can arise when drilling 12 km wells. In addition, wells drilled in this way do not open up the possibility of reconstruction them to injection wells, since the deposit is located at a distance from the platform and at a great depth. As for the scenario with platform satellite, it is quite possible.

3.6. Environmental matters

After the catastrophic oil spill in the summer of 2010 in the Gulf of Mexico, the whole world began to re-evaluate the safety system for offshore oil and gas production. In a number of cases, decisions were made to temporarily freeze them. The need for increased precautions is especially evident in the Arctic with its rich, but extremely vulnerable nature.

Offshore hydrocarbon production is a potentially dangerous and technically complex job associated with risks of various kinds. The most expensive, laborious and responsible is the development of offshore fields, especially in the northern seas. In addition to solving complex problems typical for the continental fishery, a whole range of issues arise in the waters of the northern seas due to marine specifics, while the threats to environmental safety in oil and gas production areas increase by many times. The success of their solution largely depends on industrial safety and environmental well-being of the area of development.

Nevertheless, the operation technology of the Prirazlomnaya platform completely eliminates the discharge of industrial and domestic waste, oils, formation water, polluted industrial, storm drains and other harmful substances into the sea. Formation water and oily ballast are pretreated and pumped into the formation.

As a part of the platform for the generation of heat and electricity an energy complex is provided, in which hydrocarbon raw materials produced directly at the field are used as fuel. However, associated petroleum gas is recommended to be used for own needs – as fuel for turbines of electric generators, for generating thermal energy and for oil treatment.

The environmental safety of the Prirazlomnaya platform would be significantly higher if oil is transported to the shore by a pipeline rather than by tankers.

3.7. Recommendations and proposals

Economics

Obviously, the most important part of any project, especially those designed for offshore activities, is economic viability. In this paper it was not calculated the cost of construction, maintenance, abandonment, etc., and the figures for drilling are rough and based on general information. A detailed study of the economics is recommended taking into account the prospects for years to come, which at the time of writing is dramatically relevant and uncertain. The involvement of financial specialists is necessary for a comprehensive economical and informational multi-criteria assessment of the development project at all stages of development.

Politics

No matter how effective the potential of the project is, it is political support, international cooperation, business contacts of contractors and customers that are the navigators of oil and gas activities. Sanctions, freezing of activity, import substitution policy have an extremely negative impact on the prospects for field development, especially on construction of new wells. It is recommended to take into account the political side to some extent when planning development scenarios.

Engineering

As mentioned above, to ensure the necessary productivity modernization of a number of equipment and mechanisms is required. In particular, this applies to injection and production pumps. Experience in the construction of platform satellite must be obtained from specialists from neighboring fields. To ensure safe and timely response, as well as operation in winter conditions, the use of ice-resistant icebreakers around the IRSP is recommended. The depth of the water allows their presence and work.

In addition, in the prospect of developing the Devonian deposits, it is worthwhile to install a sufficient number of slots at the SP in advance for the operation of additional wells, as well as to build the appropriate apparatus and equipment. The operating capacity of all equipment is recommended to be used at a level of up to 50% in order to extend their service life. For the same purpose, it is necessary to carry out scheduled and unscheduled maintenance, calibration, verification and check-up activities.

Technology

Upon reaching the period of declining production it is recommended to use enhanced oil recovery methods, in particular, multi-stage hydraulic fracturing. As practice at Prirazlomnaya shows, spotty multi-stage hydraulic fracturing strictly increases development performance.

Furthermore, it is important the above-mentioned proposal to change the type of well from production to injection. After the depletion of the Silurian raw material, hydrocarbons will inevitably be replaced by water, which can be used for productive purposes of pushing oil upwards the section. Additional drilling inside the production wells may be required.

Conclusions

The Prirazlomnoye oil field is located in the Varandey-Adzva oil and gas region of the Timan-Pechora oil and gas province. Here, structural anticlinal oil deposits with lithological limitations are confined to reef structures.

The Prirazlomnoye is an oil field and is the only one being developed within the Arctic shelf in the Russian Federation.

The water area of the Pechora Sea is characterized by frequent Arctic and Atlantic winds, critical changes in precipitation and wind direction, as it is exposed to the influence of the Arctic and Atlantic oceans.

The field is being developed by the Prirazlomnaya offshore ice-resistant fixed platform at a water depth of about 20 meters. The platform ensures reliable oil production under severe weather and climatic conditions. Permian-Carboniferous deposits at a depth of about 2.5 km are subject to current development. The studied carbonate section with a thickness of about half a kilometer is represented by interlayers of limestones and dolomites with clay content.

In the paper it is proposed two scenarios for the development of the Silurian structure as follows:

- by the use of the Prirazlomnaya platform;
- by means of satellite platform connected to the platform.

Based on a number of criteria, a decision was made to develop the structure through one double- and two single-lateral wells using satellite platform. For the Silurian carbonate reservoir, the use of horizontal wells will be reflected in an increase in the drainage area and sweep efficiency. Access to potentially unaffected reservoirs will be provided by a multilateral well.

The putting into production of the overlying Devonian deposits was not considered in this work. Nevertheless, their potential justifies the expensive and time-consuming construction of the SP.

It is recommended to involve financial specialists for the purpose of a comprehensive economic and informational multi-criteria assessment of the development project at all stages of the development. In addition, it is recommended to apply enhanced oil recovery methods, in particular multistage hydraulic fracturing, as well as secondary methods upon reaching the period of declining production.

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NOTE: all internet links were accessed during the period from late 2020 to late 2021. During recent months, Gazprom has decided to close access to many of the links.

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Appendix A

Hydrogeology and climate of Barents Sea

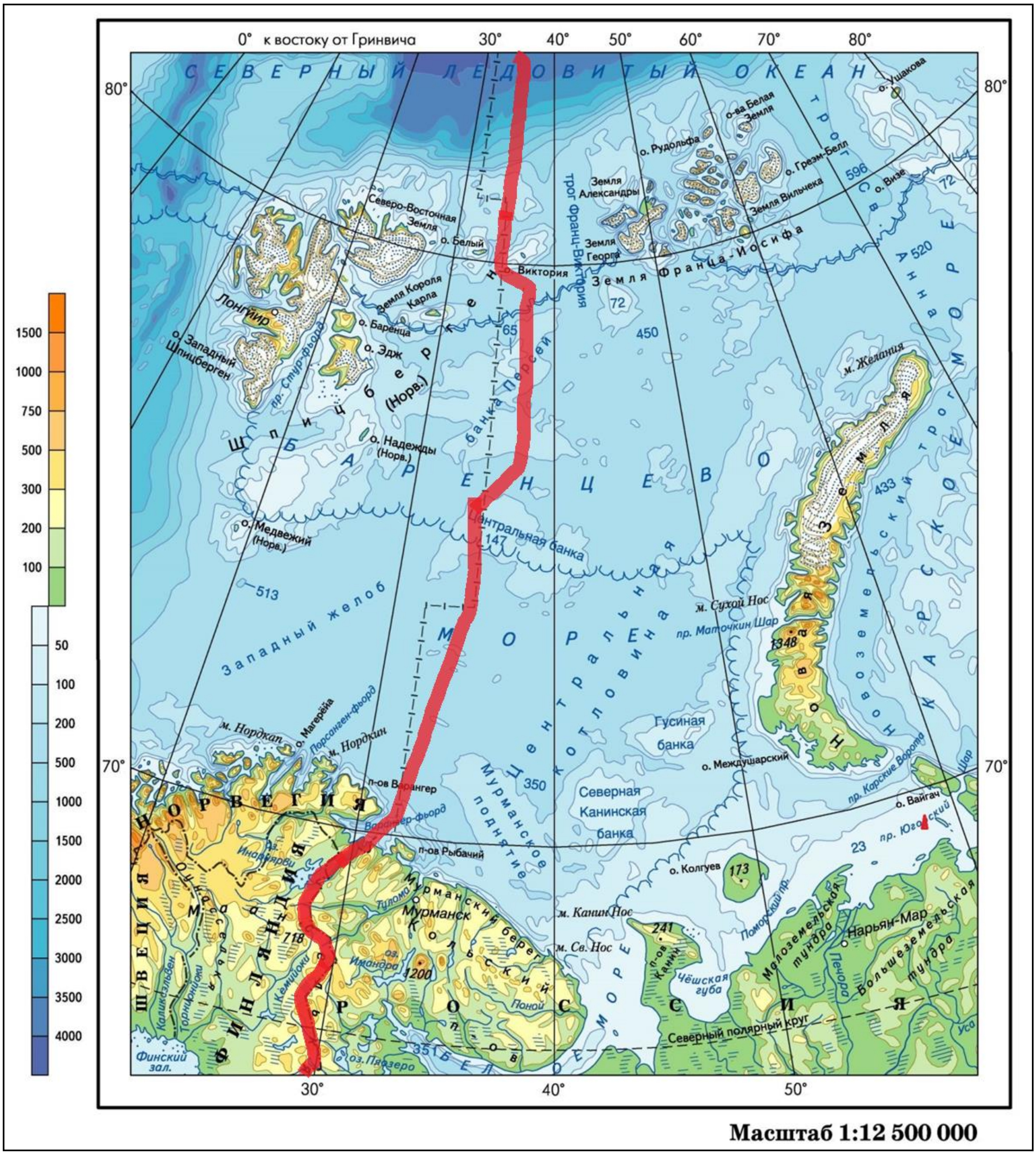

Figure A-1. Water depth map of Barents Sea

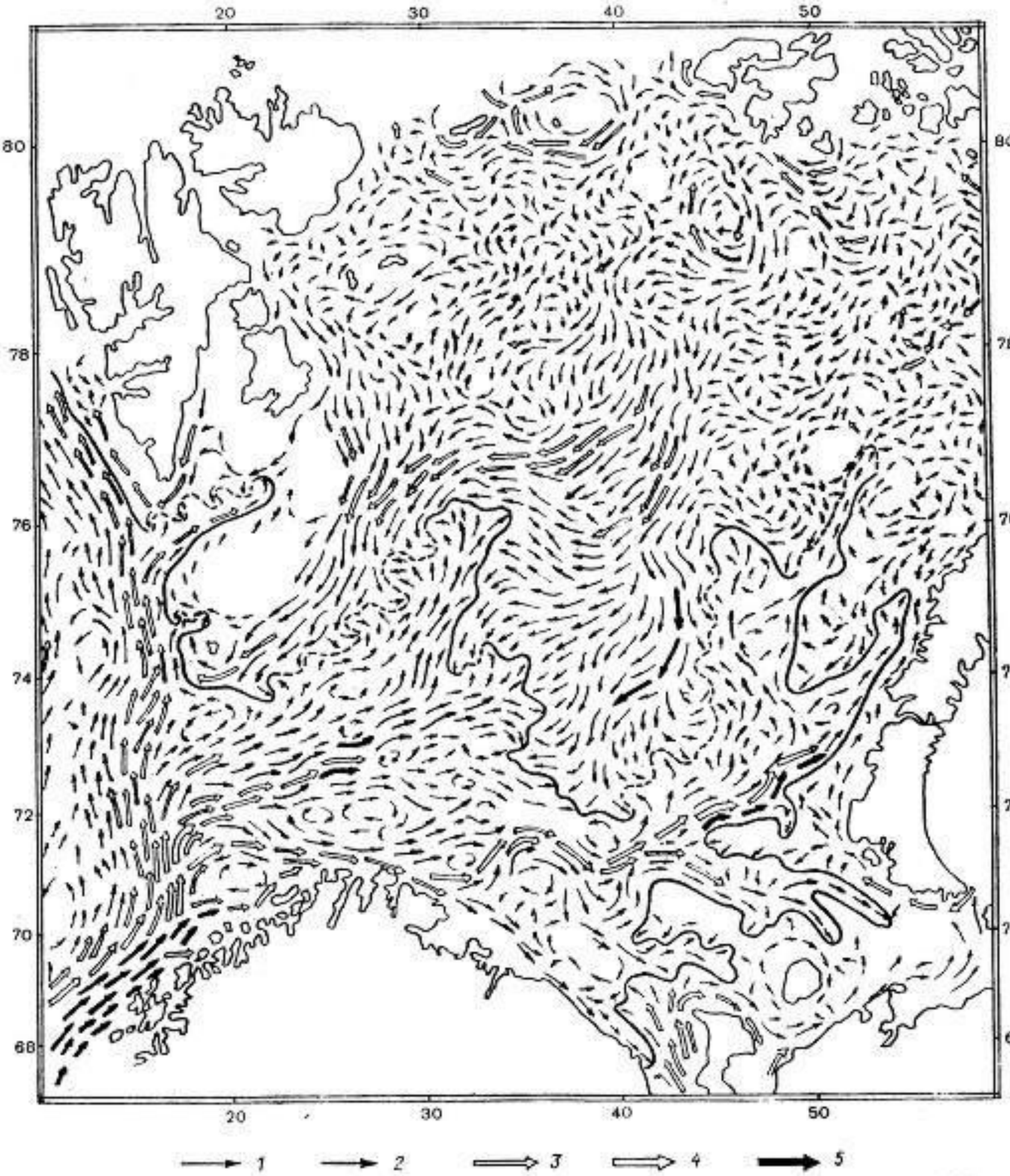

Рис. 8 Карта преобладающих поверхностных течений Баренцева моря (ПИНРО, 1961). /1/

Толщиной стрелок показана скорость течения, уз: 1 — до 0,1; 2 — 0,1—0,2; 3 — 0,3—0,5; 4 — 0,6—1,0; 5 — свыше 1,0. Длина стрелок соответствует устойчивости течений. Сплошной линией показано положение фронтальной зоны.

Figure A-2. Water surface currents map of Barents Sea

Appendix B

Silur extraction background

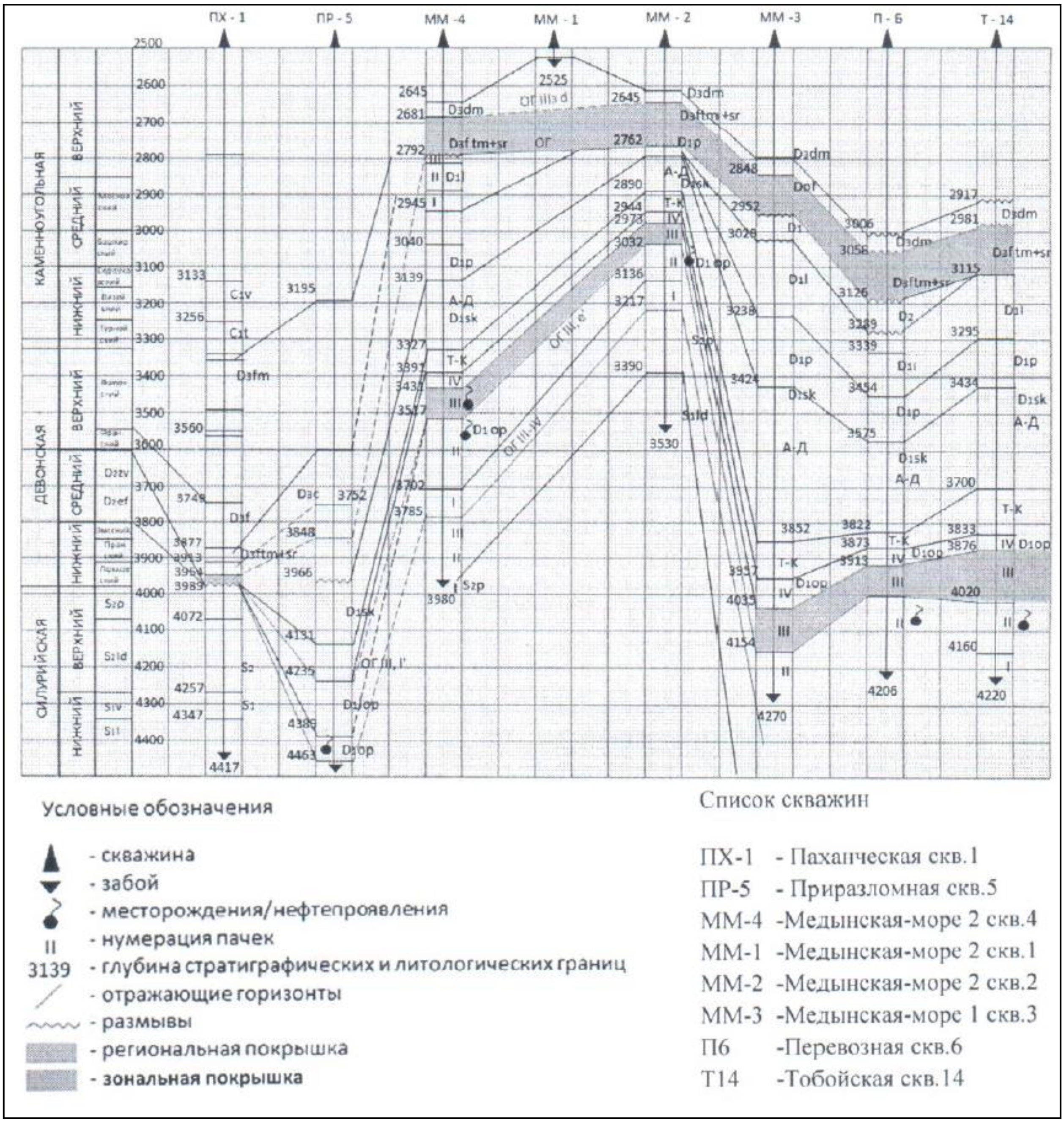

Figure B-1. Opening scheme of Silurian-Lower Frasnian mega complex

Appendix C

Proposal development scheme of Platform concept for solution 1.1

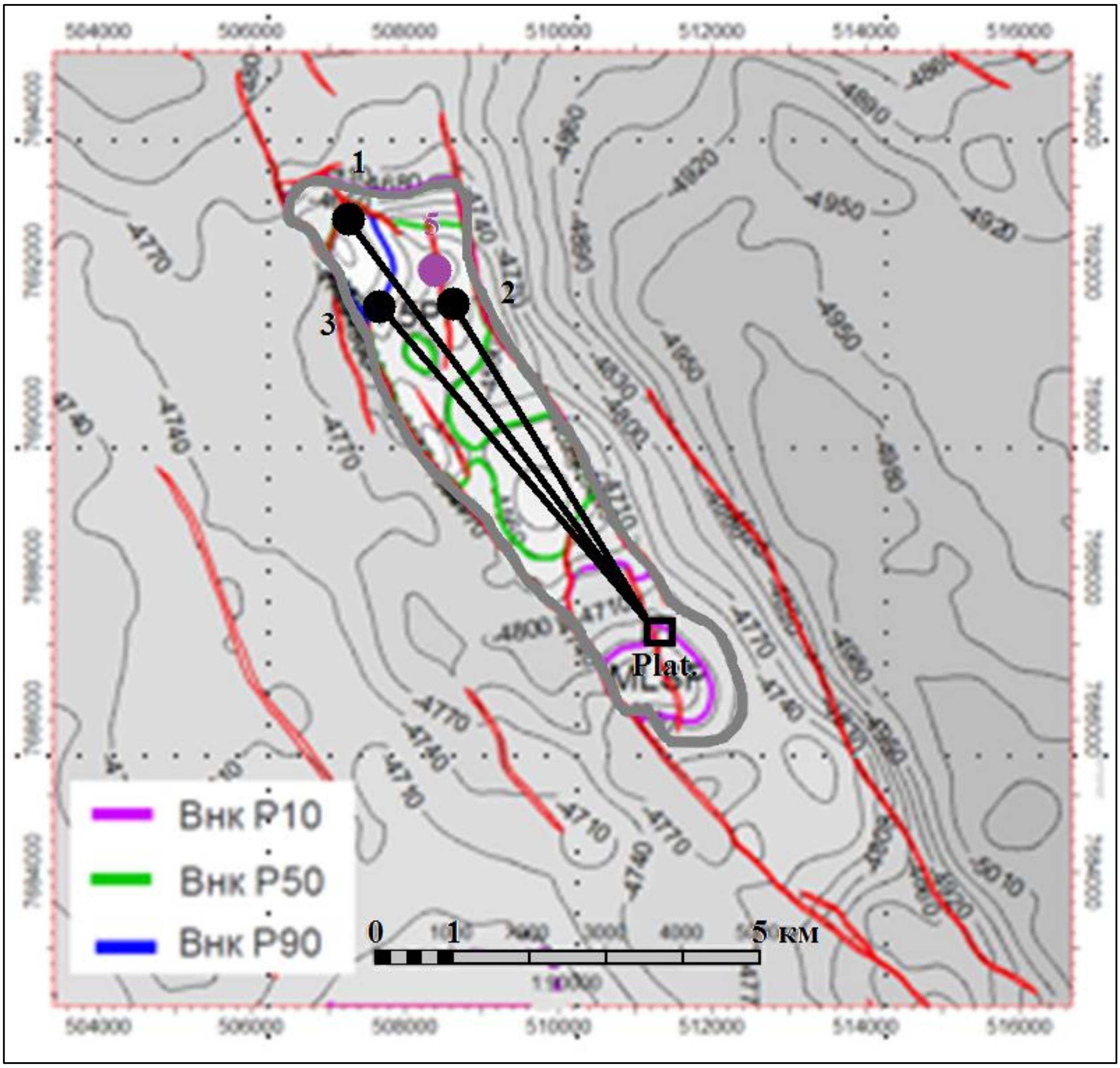

Figure C-1. Structural map with schematic development

(black dots 1,2,3 – corresponding production wells bottoms; purple dot 5 – drilled exploration well № 5 bottom)

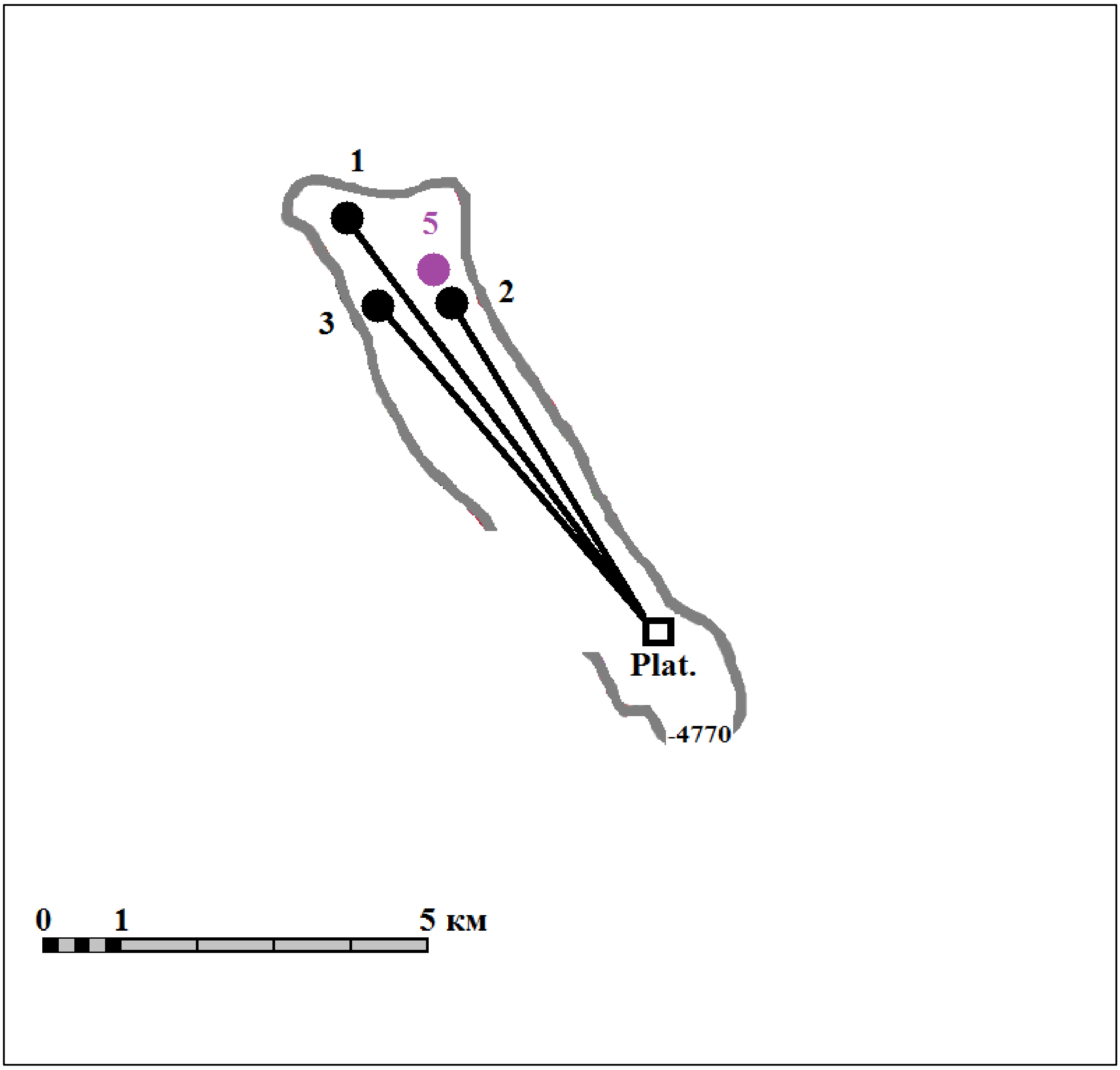

Figure C-2. Basic development scheme within «-4770» isohyps

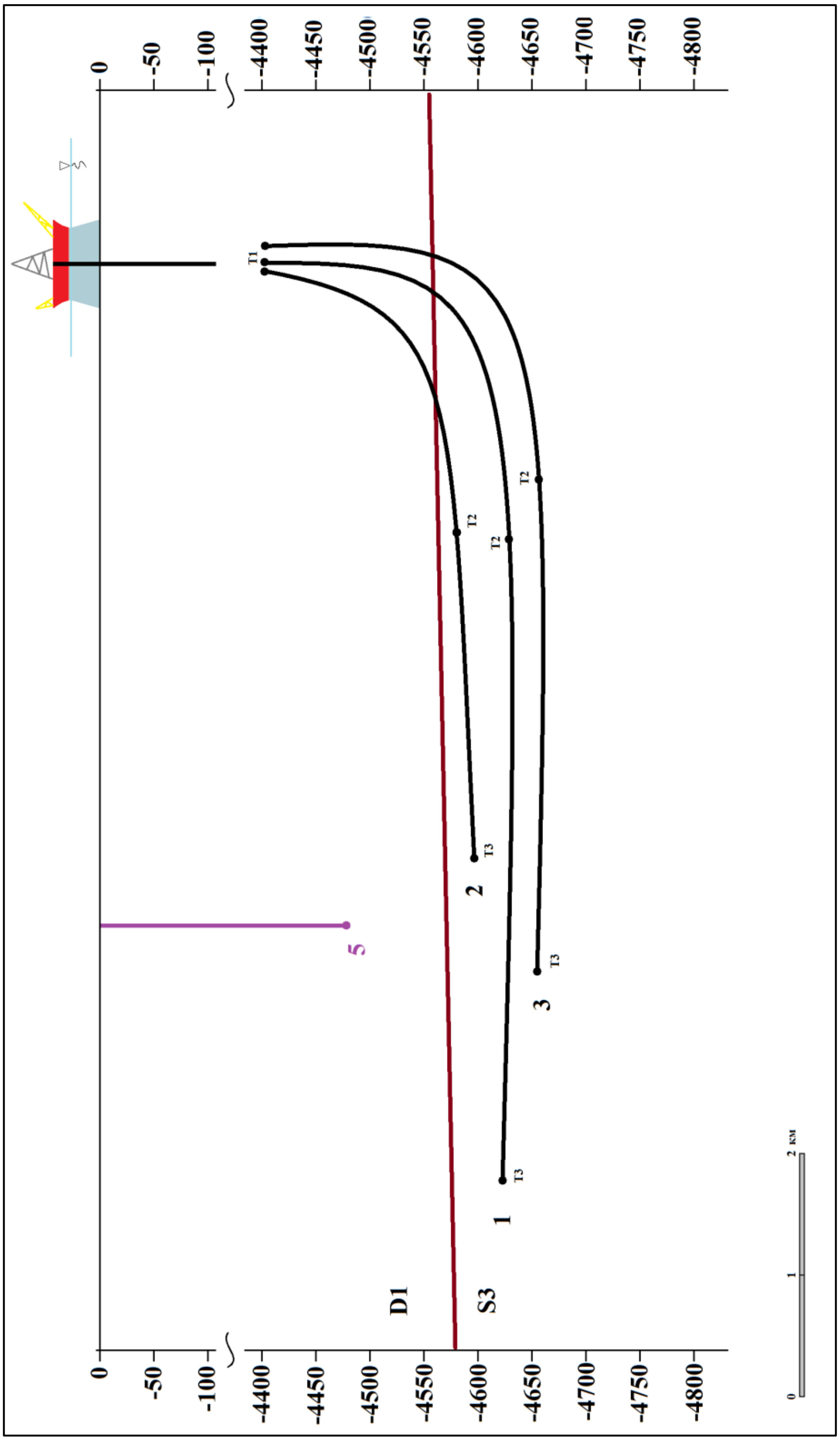

Figure C-3. Schematic cross-section of development

(black digits – assigned numbers of production wells; T1, T2, T3 – geosteering markers; purple digit – drilled exploration well)

Appendix D

Proposal development scheme of Platform concept for solution 1.2

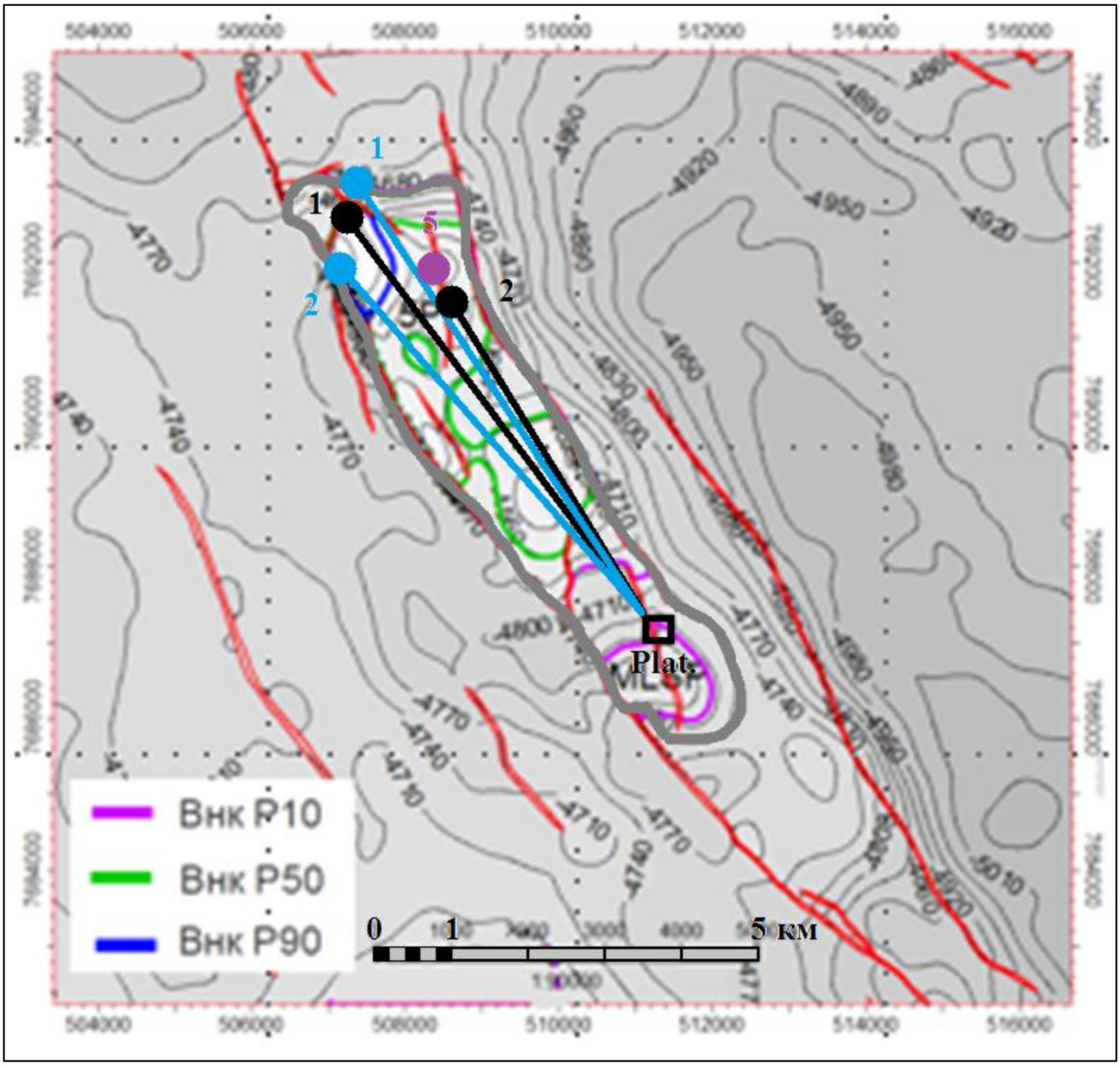

Figure D-1. Structural map with schematic development

(black dots 1,2 – corresponding production wells bottoms; purple dot 5 – drilled exploration well № 5 bottom; blue dots 1,2 – corresponding injection wells bottoms)

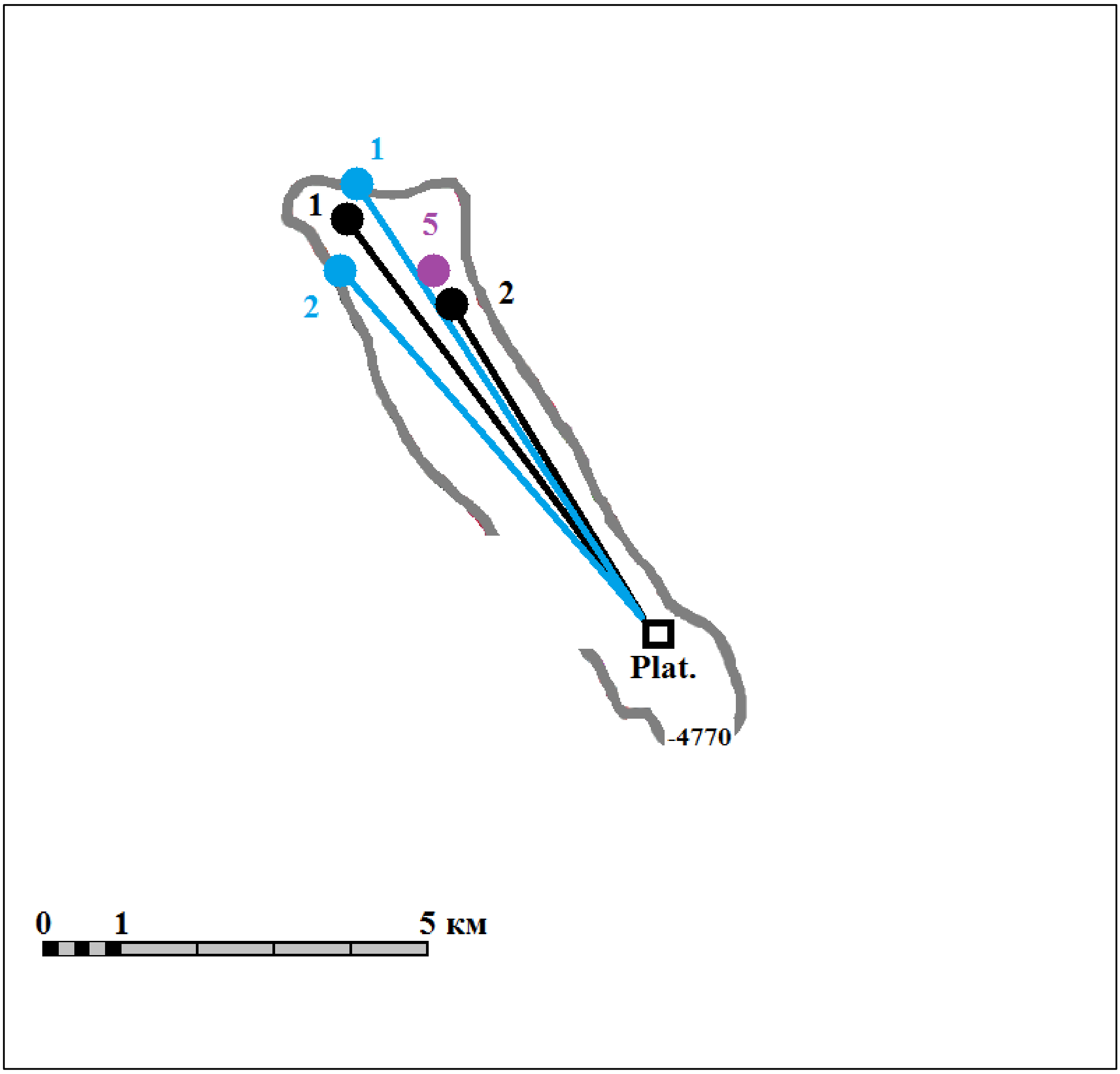

Figure D-2. Basic development scheme within «-4770» isohyps

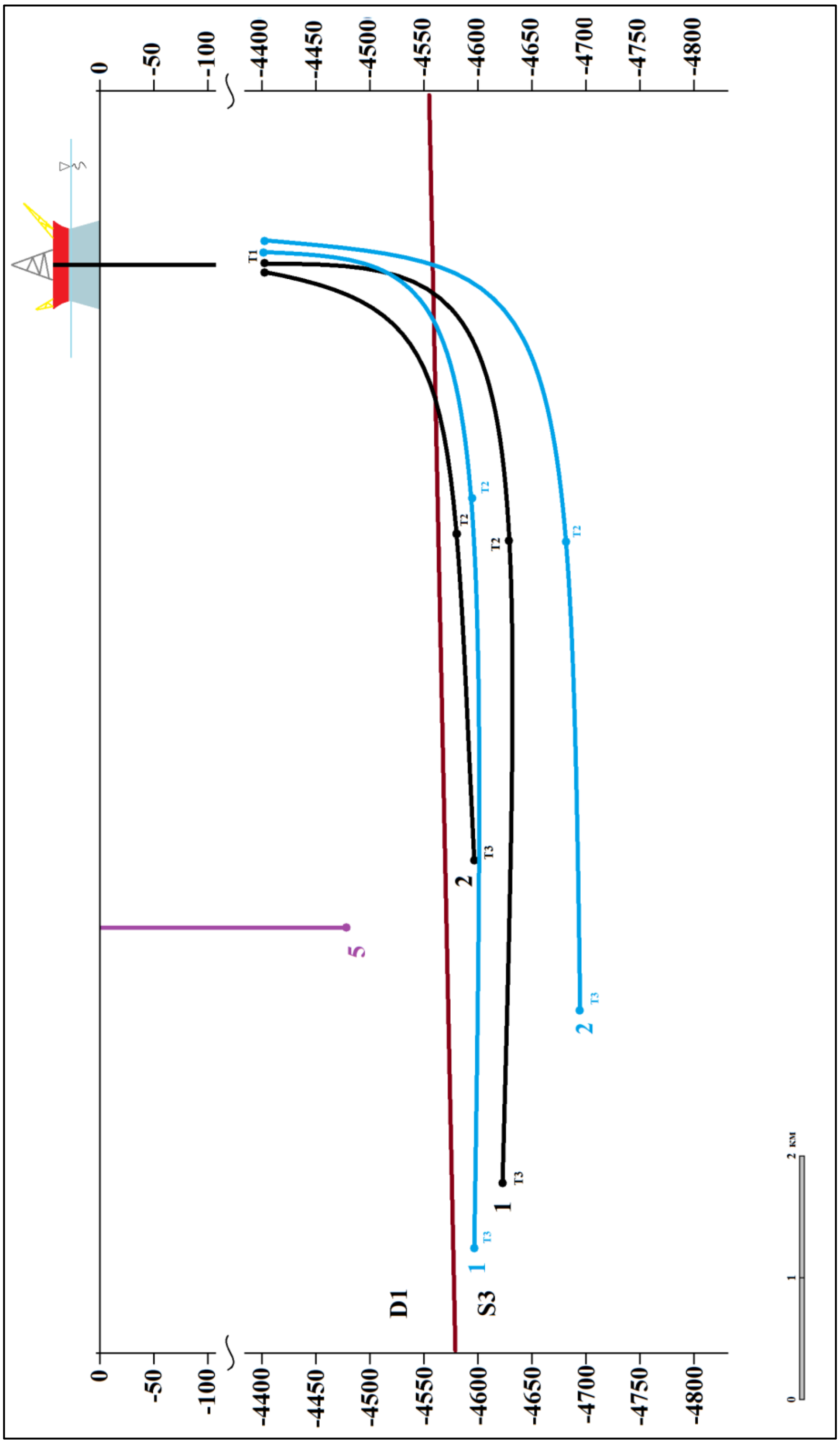

Figure D-3. Schematic cross-section of development

(black digits – assigned numbers of production wells; T1, T2, T3 – geosteering markers; purple digit – drilled exploration well; blue digits – assigned numbers of injection wells)

Appendix E

Proposal development scheme of IRSP concept for solution 2.1

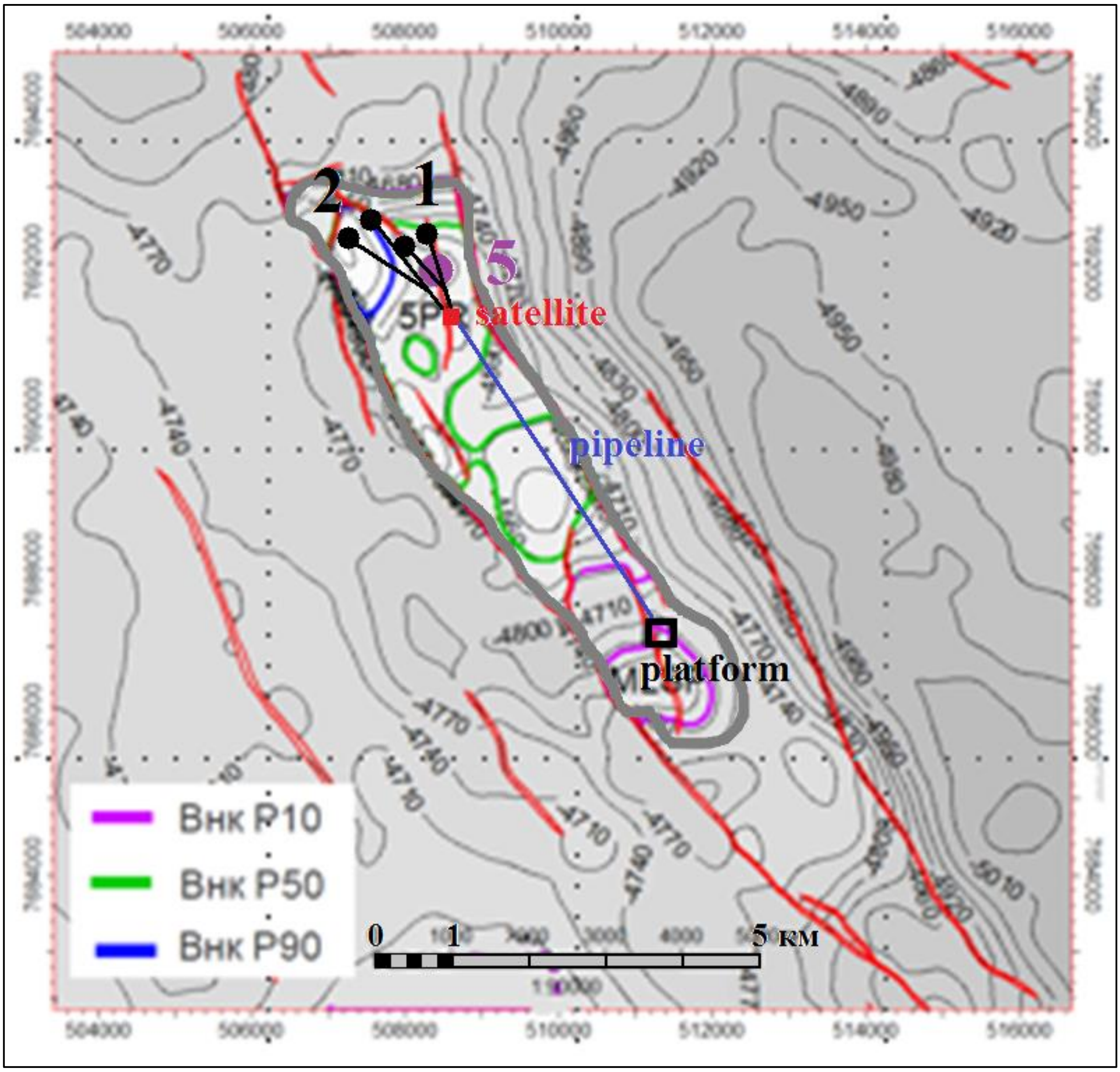

Figure E-1. Structural map with schematic development

(black dots 1,2 – corresponding production wells bottoms; purple dot 5 – drilled exploration well № 5 bottom)

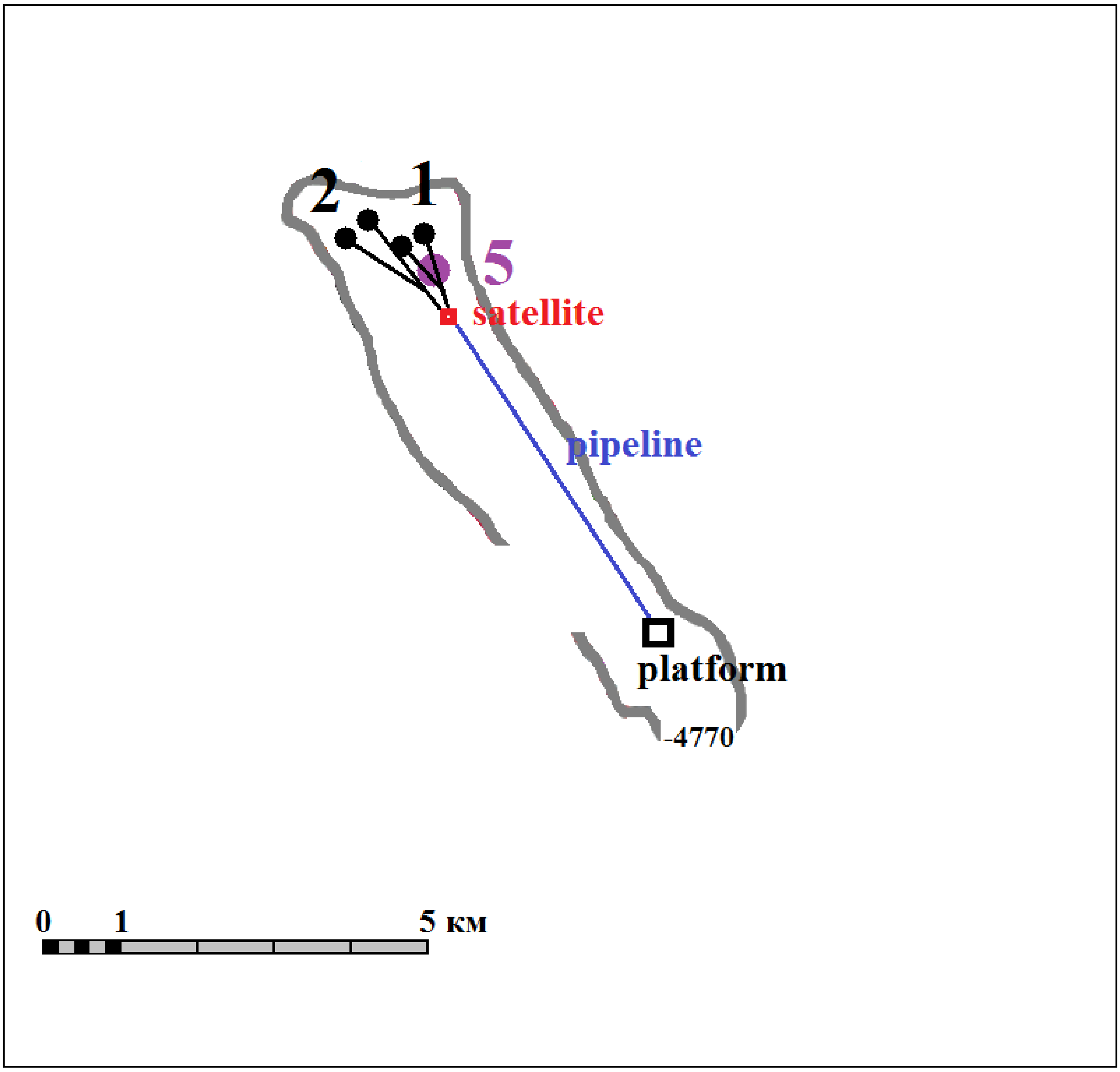

Figure E-2. Basic development scheme within «-4770» isohyps

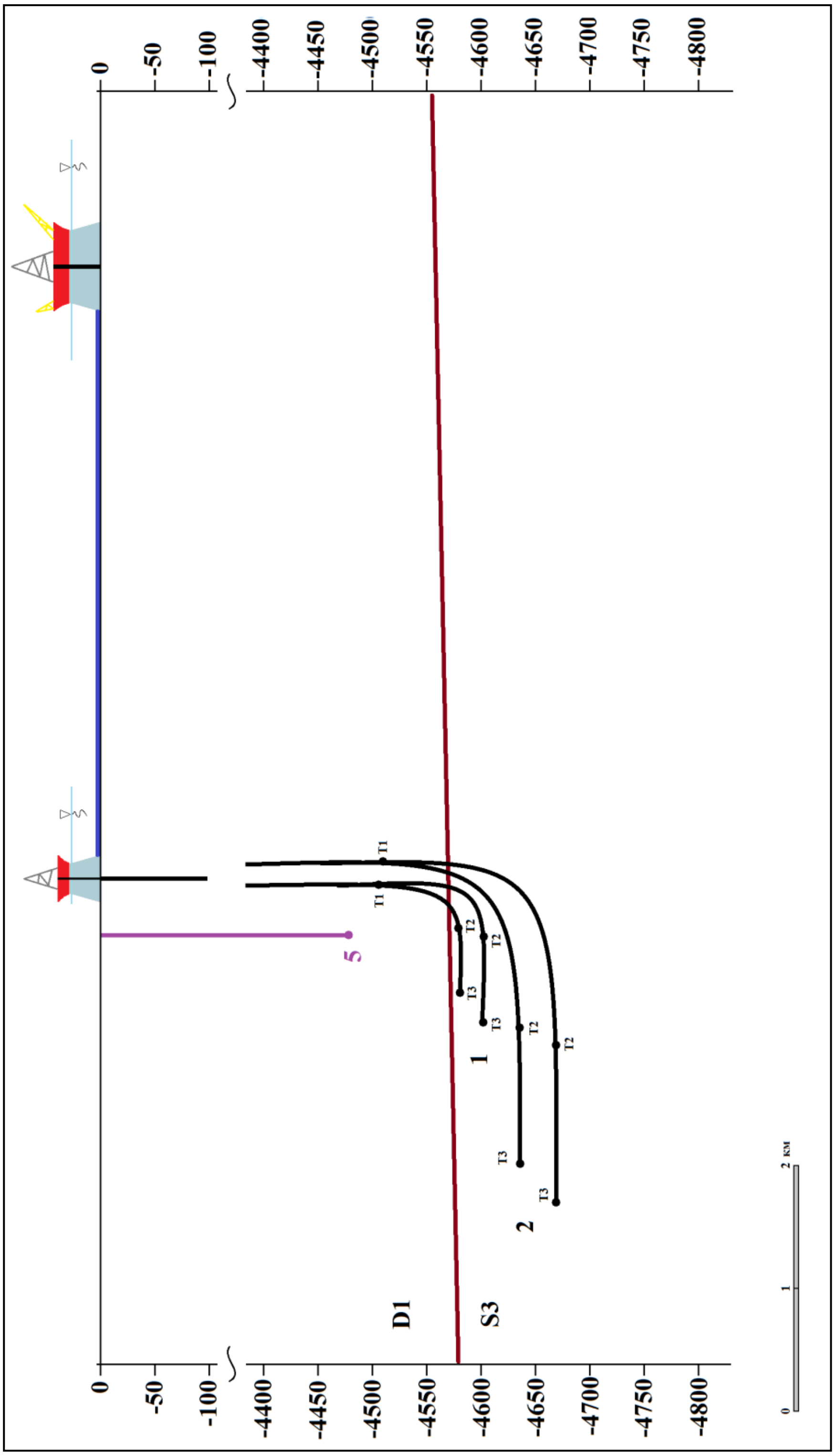

Figure E-3. Schematic cross-section of development

(black digits – assigned numbers of production wells; T1, T2, T3 – geosteering markers; purple digit – drilled exploration well)

Appendix F

Proposal development scheme of IRSP concept for solution 2.2

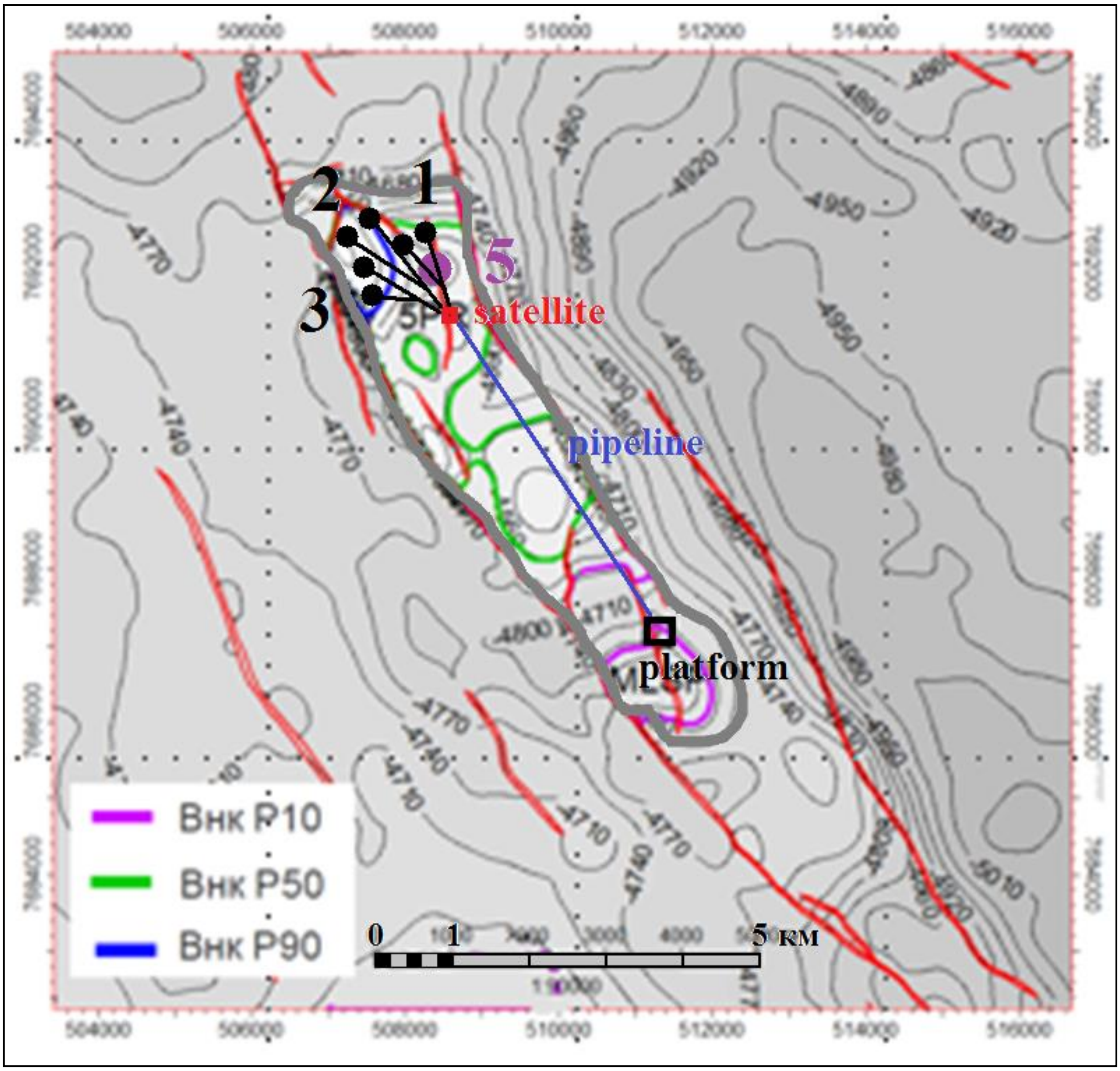

Figure F-1. Structural map with schematic development

(black dots 1,2,3 – corresponding production wells bottoms; purple dot 5 – drilled exploration well № 5 bottom)

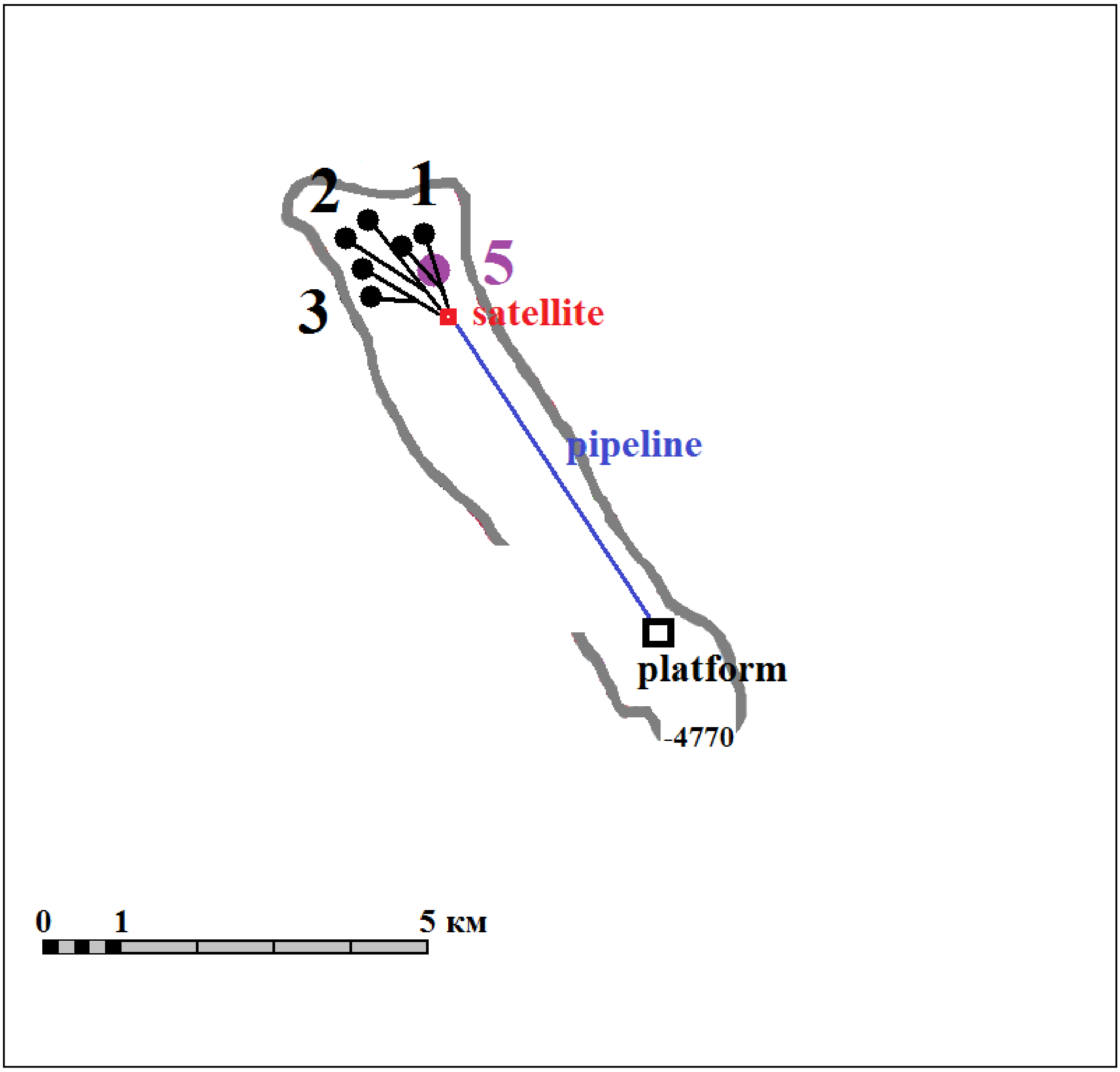

Figure F-2. Basic development scheme within «-4770» isohyps

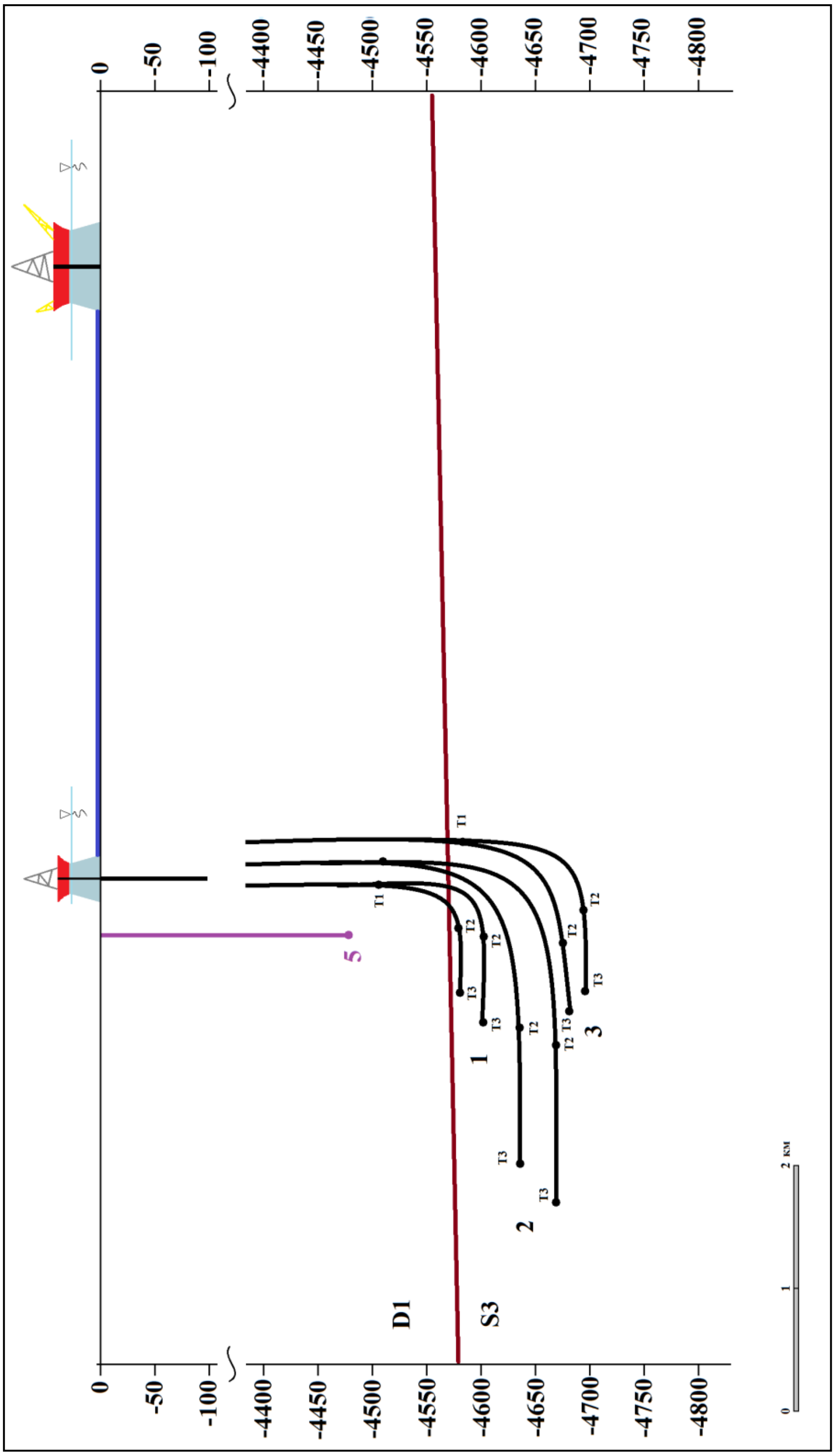

Figure F-3. Schematic cross-section of development

(black digits – assigned numbers of production wells; T1, T2, T3 – geosteering markers; purple digit – drilled exploration well)

Appendix G

Proposal development scheme of IRSP concept for solution 2.3

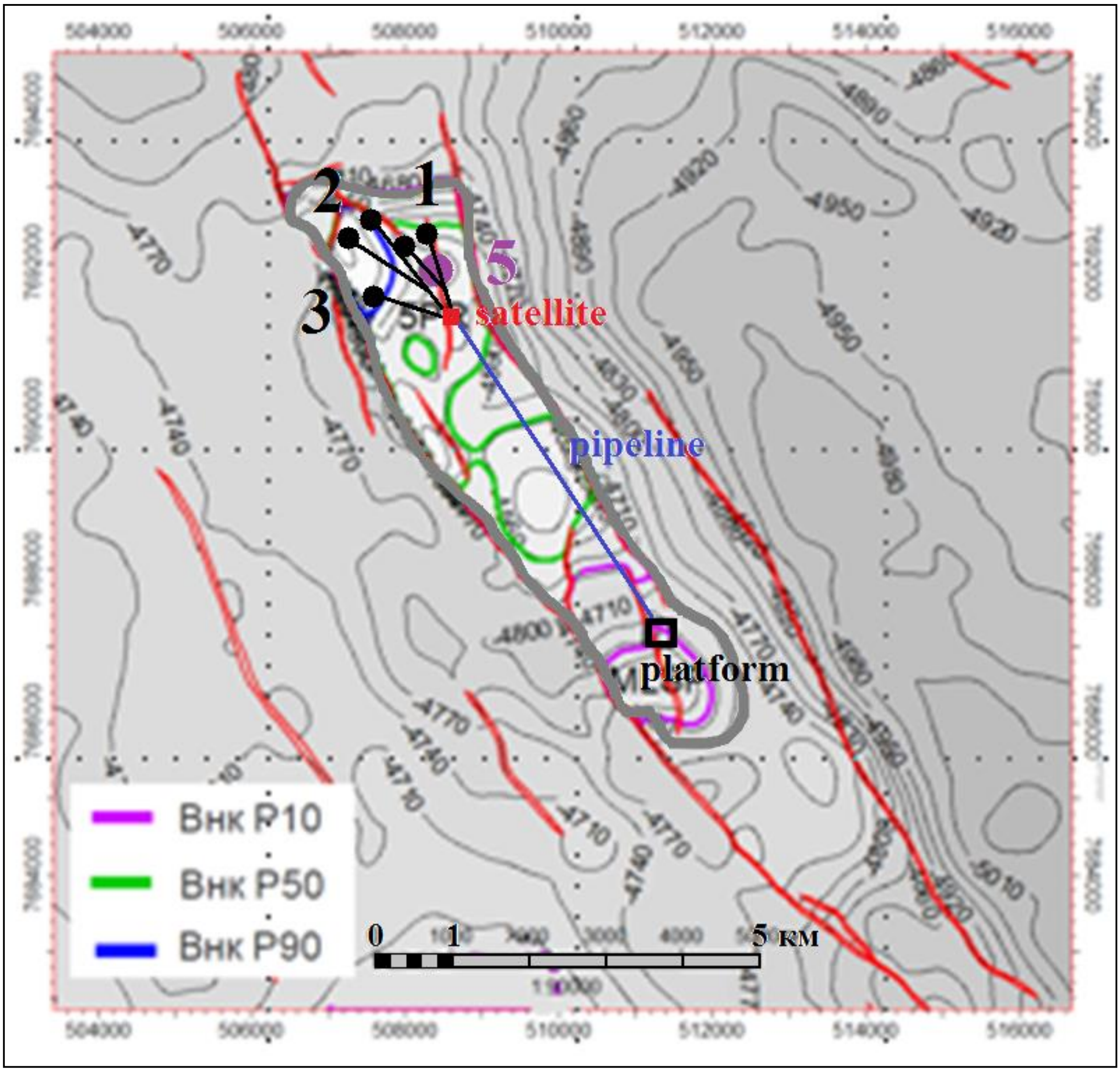

Figure G-1. Structural map with schematic development

(black dots 1,2,3 – corresponding production wells bottoms; purple dot 5 – drilled exploration well № 5 bottom)

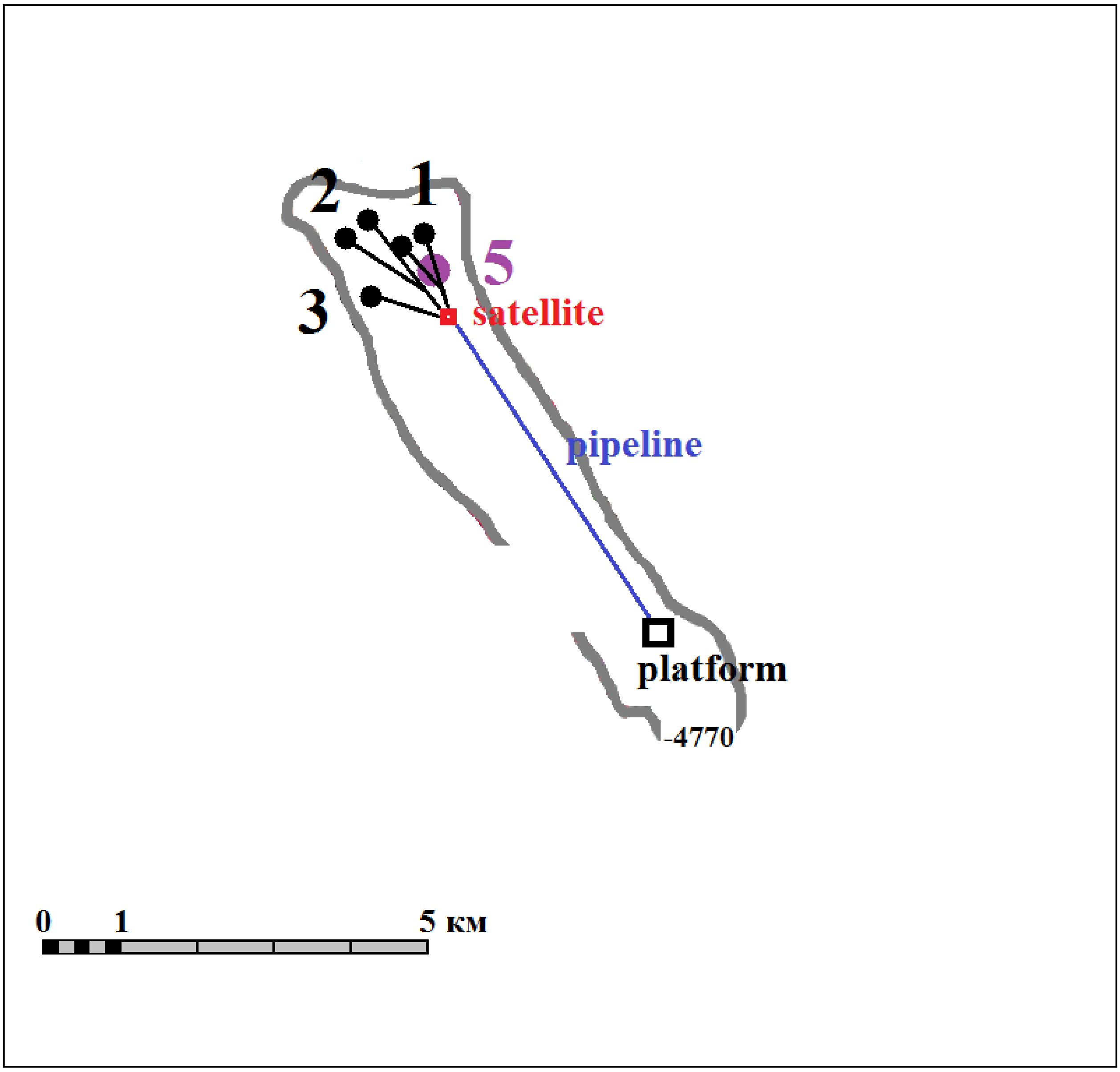

Figure G-2. Basic development scheme within «-4770» isohyps

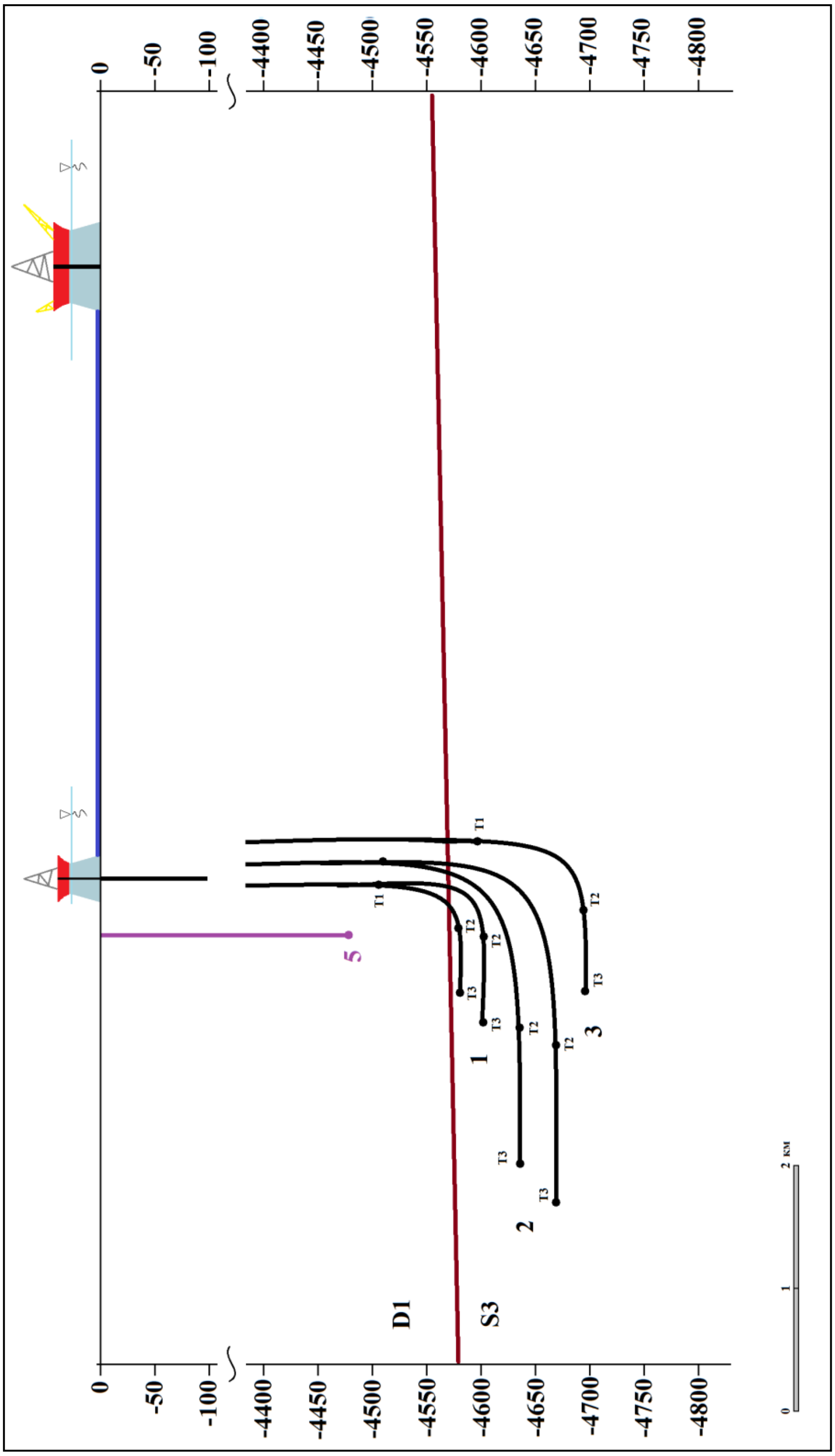

Figure G-3. Schematic cross-section of development

(black digits – assigned numbers of production wells; T1, T2, T3 – geosteering markers; purple digit – drilled exploration well)

Appendix H

Proposal development scheme of IRSP concept for solution 2.4

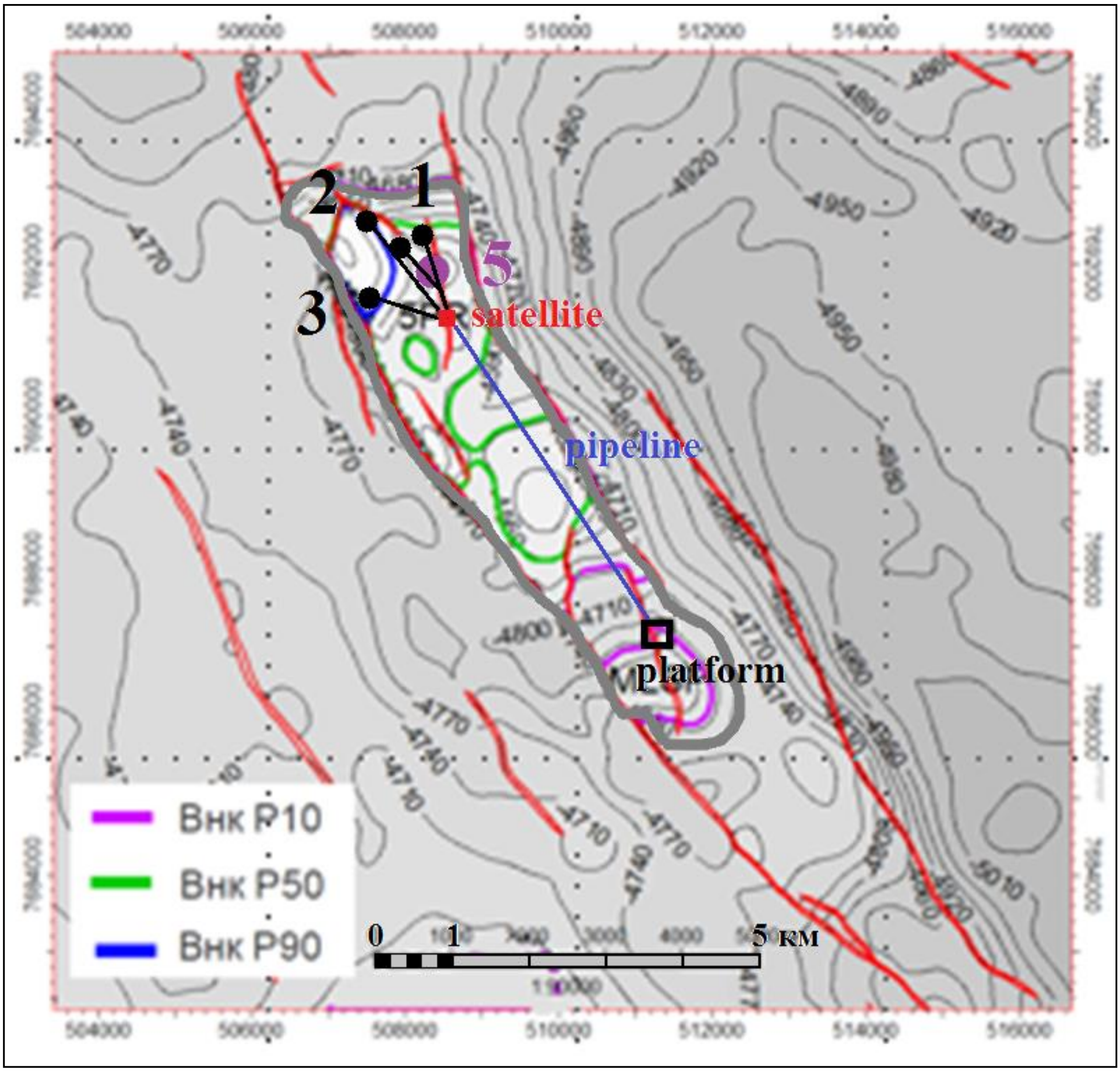

Figure H-1. Structural map with schematic development

(black dots 1,2,3 – corresponding production wells bottoms; purple dot 5 – drilled exploration well № 5 bottom)

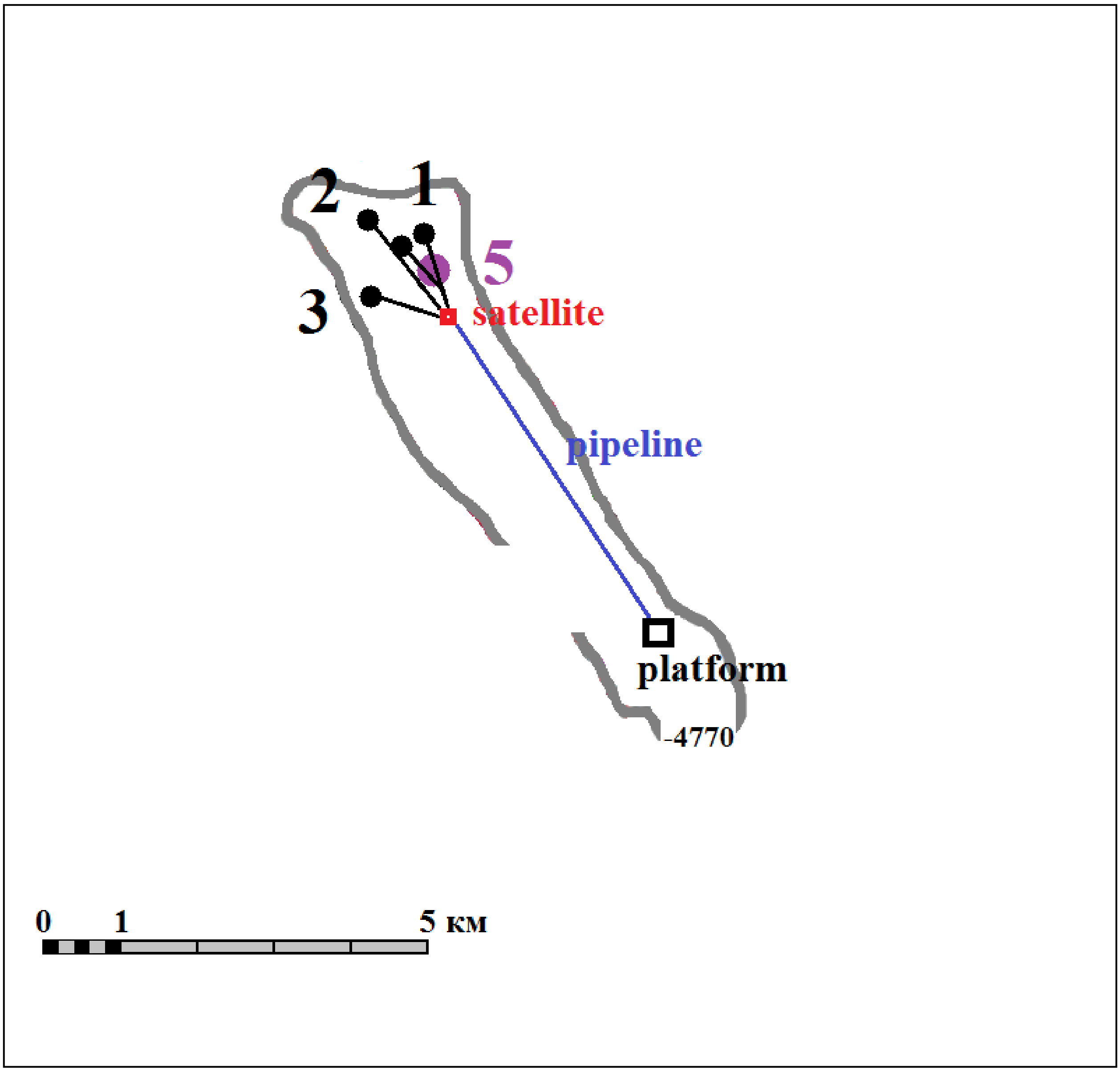

Figure H-2. Basic development scheme within «-4770» isohyps

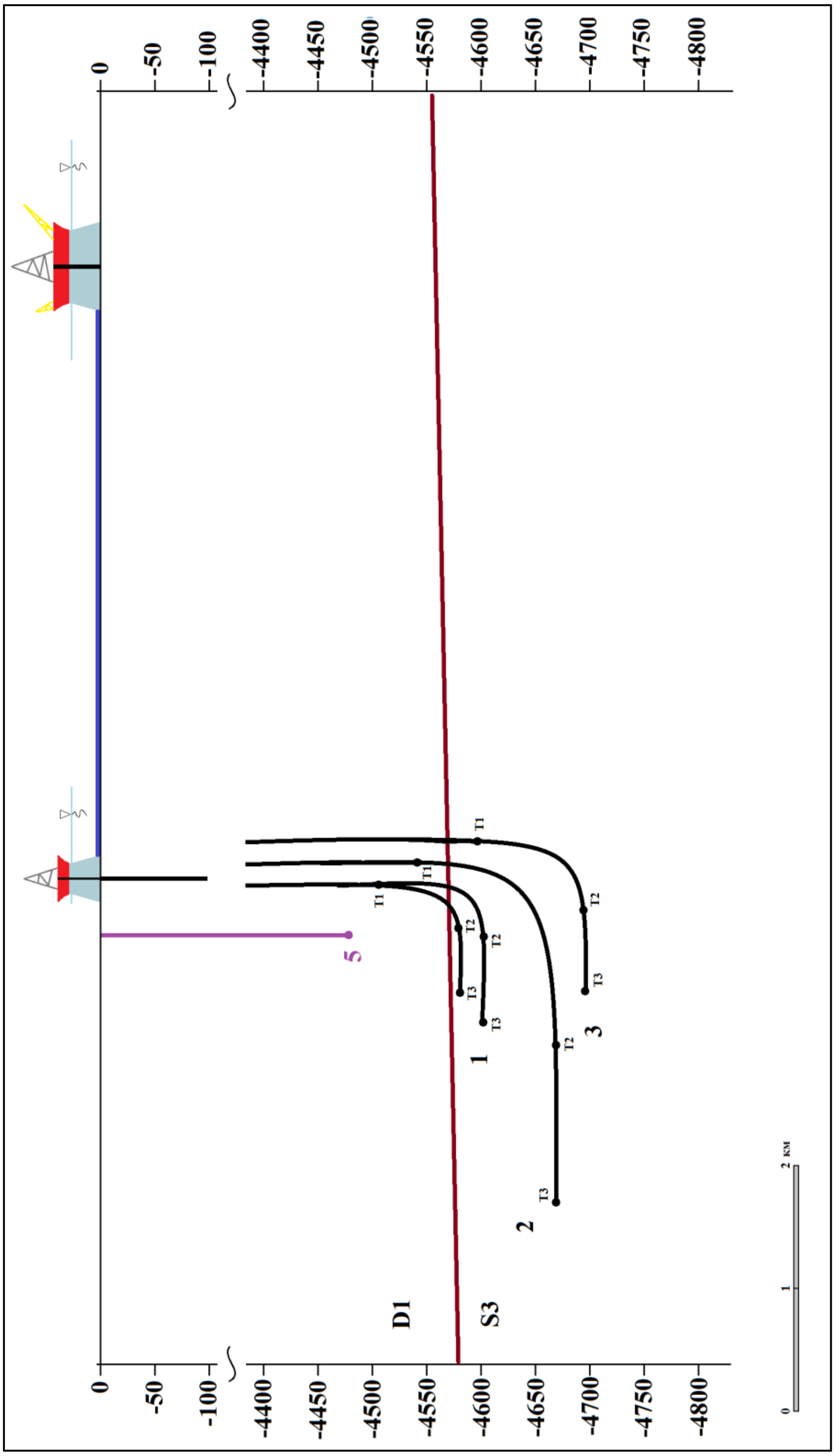

Figure H-3. Schematic cross-section of development

(black digits – assigned numbers of production wells; T1, T2, T3 – geosteering markers; purple digit – drilled exploration well)

Appendix I

Proposal development scheme of IRSP concept for solution 2.5

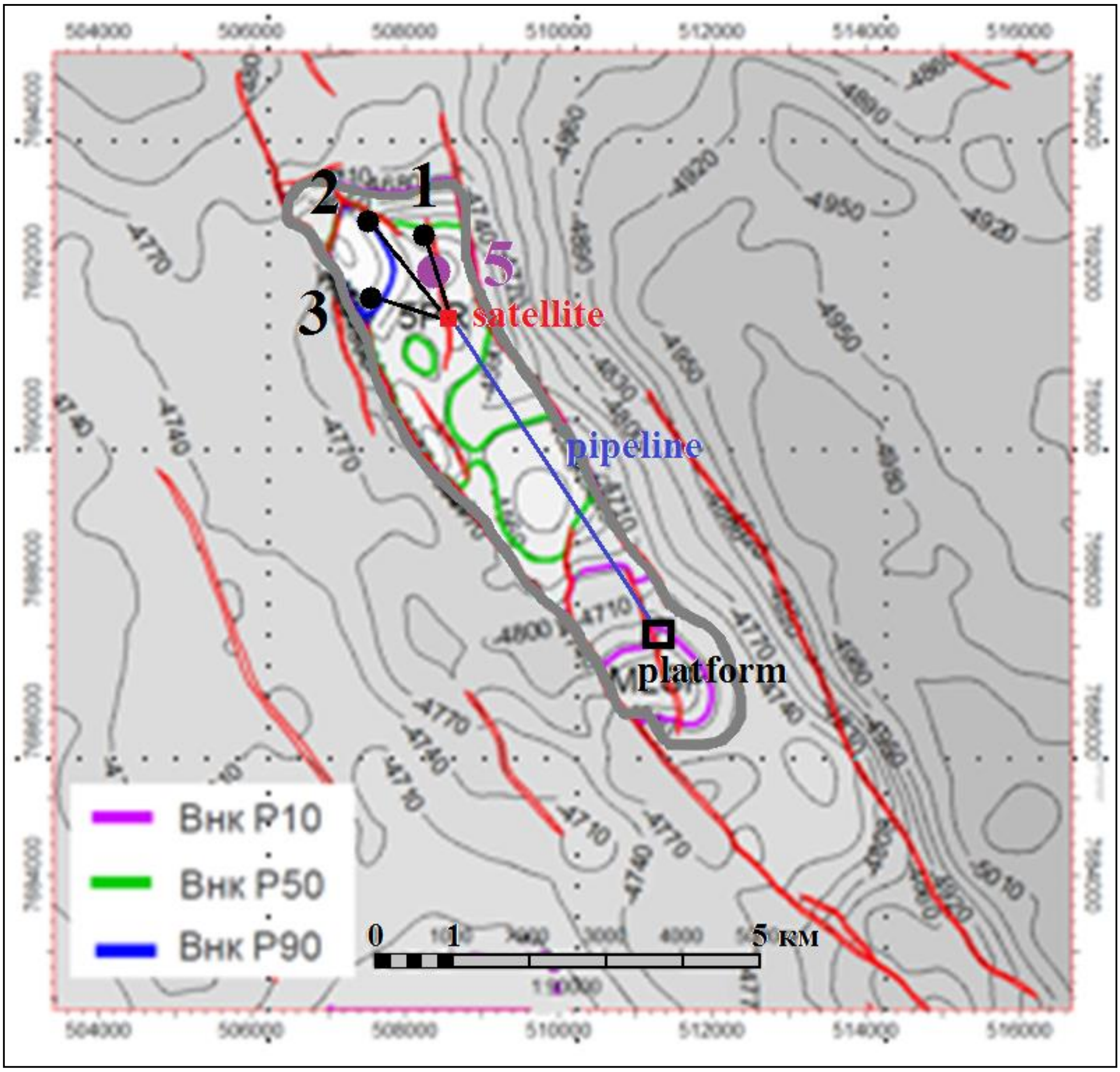

Figure I-1. Structural map with schematic development

(black dots 1,2,3 – corresponding production wells bottoms; purple dot 5 – drilled exploration well № 5 bottom)

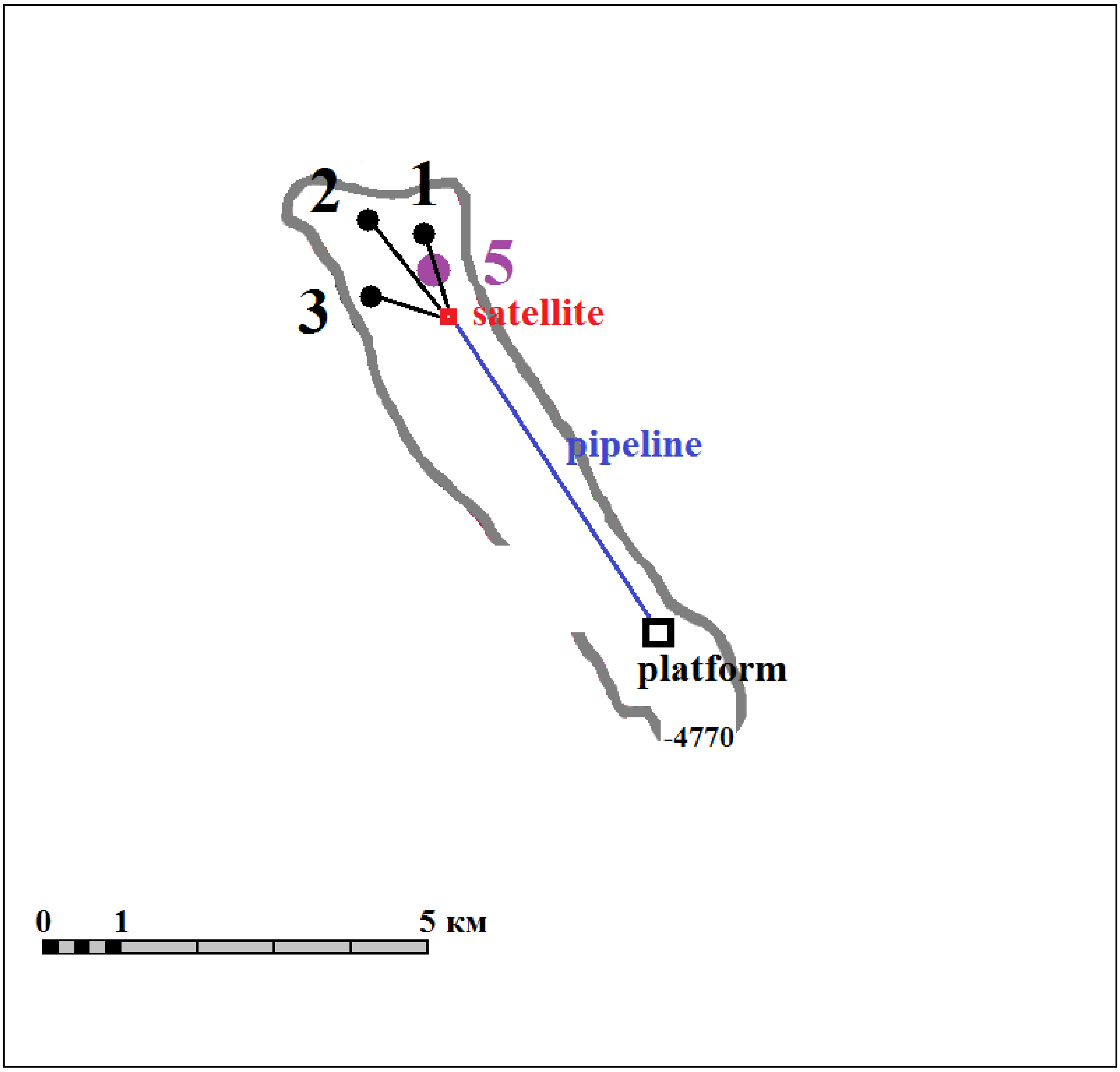

Figure I-2. Basic development scheme within «-4770» isohyps

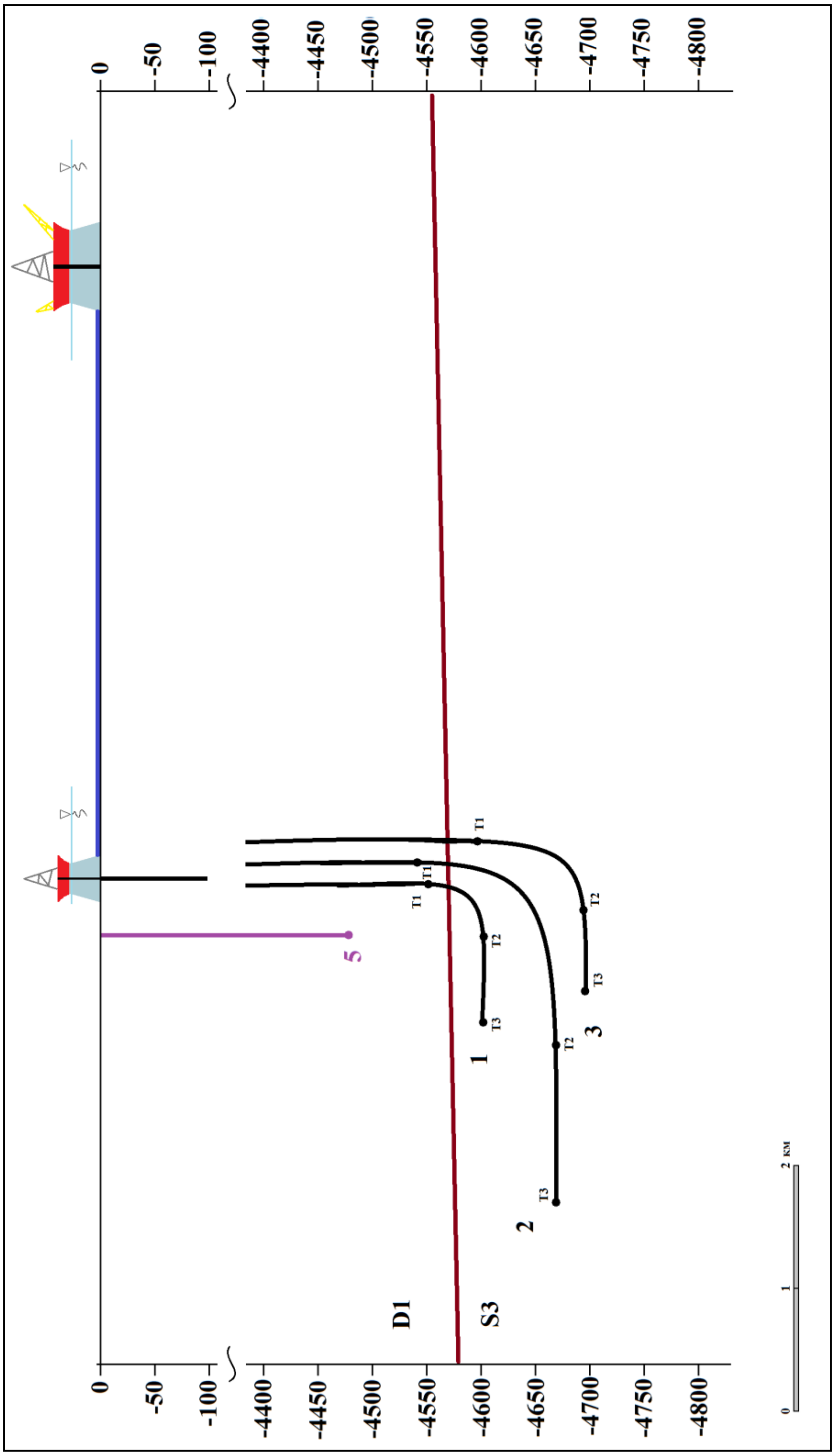

Figure I-3. Schematic cross-section of development

(black digits – assigned numbers of production wells; T1, T2, T3 – geosteering markers; purple digit – drilled exploration well)