Technologies for efficient development of hydrocarbon resources on the Arctic and sub-Arctic shelf of Russia

Alexander Dziublo1 and Anna Storozheva
Gubkin University, Department of Offshore Oil and Gas Field Development, 119991 Moscow, Russia
E-mail: 1anne.storozheva@gmail.com

Abstract. This article discusses the technical capabilities and results of the application of modern technologies for geological exploration, well drilling, development and operation of offshore oil and gas fields on the Arctic and sub-Arctic shelf of Russia. Based on the scientific and production experience of the authors, analysis of the results of search and exploration in the seas of the Arctic and the Far East, a consistent system of technologies for geological exploration is proposed. The use of such an integrated set made it possible to discover large and unique oil and gas fields in the Barents-Kara region (Medynskoe-more, Dolginskoe, Varandey-more, Kamennomysskoe and others). The features of geophysical work and technologies for achieving high-quality seismic material the transition zone (land-sea) in the Ob bay, where due to the presence of permafrost in the upper part of the geological section, there is a significant change in the velocities and absorbing properties of rocks, are shown. Using the example of the Varandey-more field, a technology for integrating 3D deep-sea seismic data and seismic surveys in the land-sea transition zone is described, which made it possible to update the geological model of the field, detail the structural plans of oil-bearing horizons. As a result, after the completion of the interpretation of the survey data in the transit zone, it was recommended to drill an exploration well in the southern part of the field. It has been substantiated that the efficient shelf field exploitation is ensured through the use of new technologies (drilling of long horizontal wells; 4D seismic surveys at the Piltun-Astokhskoye and Lunskoye fields; well designs providing high gas production rates; subsea production at the Kirinskoye field).

1. Introduction
The development of Arctic offshore fields requires solving many complex problems. The development of the Arctic shelf has a long history. Since the middle of the last century, geological exploration has been carried out in the south-western part of the Barents Sea and in the North Sea (Norway, England). During this period, a large number of oil and gas fields were discovered in this area, among which are Statfjord, Brent, Ninian, Sleipner and others. To a large extent, the results of these works were continued in the studies of the Russian Arctic shelf. As a result of active complex geological exploration, starting in the 1970s on the Arctic shelf of the Russian Federation, large and giant oil and gas fields were discovered: Prirazlomnoye, Shtokmanovskoye, Murmanskoye, Leningradskoye and others.

The complex and varied geological structure, location at various depths of the sea, extreme climatic conditions require highly efficient geological exploration, the use of the latest technologies and technical equipment confirmed.
2. Geological exploration

Geological exploration on the Arctic and sub-Arctic shelf is due to the following specific factors:
- the need to complete all work in the shortest possible time (4-6 months a year), when the water area of the seas is free of ice cover;
- the need to carry out work at various depths of the sea, including in the transition zone (land-sea);
- technological difficulties of drilling in extreme climatic conditions, the high cost of drilling exploration wells and seismic surveys. [1-3]

Taking into account the above factors, one of the authors of this article has developed a set of modern technologies for marine exploration (figure 1). The use of this set has led to the discovery of large oil fields on the shelf of the Barents-Kara region (Medynskoe-more, Dolginskoe, Varandey-more) and large gas fields in the Ob and Tazov bays: Kamennomysskoe-more, Semakovskoe, Severo-Obskoe.

![Figure 1. Set of modern technologies of marine exploration.](image)

Currently, seismic monitoring of deposits during their operation (4D seismic survey) is increasingly used in the world [4]. For the first time in Russia, a 4D seismic was carried out at the Piltun-Astokhskoye and Lunskoye fields of the Sakhalin-2 project.

The obtained results of data interpretation of the Astokh area made it possible to clarify the position of flooding fronts, identify areas not covered by development, and, thereby, determine targets for subsequent infill drilling, as well as optimize waterflooding. For the Piltun area, a first overview of the impacts of injection and production across the area was provided, which helped to justify the current hydrodynamic model, identify barriers (structural or lithologic) and areas with potentially reduced reservoir properties.

As a result of the 4D seismic survey carried out at the Lunskoye field, changes related to gas production were recorded, affecting the planning of extended reach wells; the rise of the gas-water contact was estimated, the hydrodynamic connection between the individual blocks of the field was confirmed.
2.1. Technologies for marine seismic surveys in transition zone

From a geographical point of view, transitional zones include coastal marshes, flooded parts of the land, shoals, river deltas, open shallow reefs, wide tidal zones, littoral zones and shallow areas close to the coast, the water depth in which is usually less than 10-20 m.

From the point of view of seismic exploration, seismic studies in in zones of transition from land to sea (transit zones), which include elements of both offshore and onshore operations, are one of the most high-tech types of geophysical services that require the use of the most modern equipment, technology and logistics.

In the water area of the transition zone, the use of a towed streamer is impossible due to shallow depths, the coordination of geophones with the environment is difficult, the use of explosives is prohibited, use of a pneumatic source is ineffective.

The land-sea transit zone includes transit shallow water area with sea depths of 0-20 m and a strip of adjacent coast. The least accessible for observation, requiring special technologies and vehicles, is the central part of the transit zone with sea depths of 0-10 meters. The width of the zone of transit shallow water of the seas of Russia, including the Arctic, varies from the first kilometers to 100-200 km.

The main problems of seismic studies in transit zones are as follows:

- in the «land – sea» transition zone in the upper part of the geological section, there is a significant change in the velocities and absorbing properties of rocks therefore the construction of an adequate seismic model is a serious scientific and methodological problem [5], and the use of modern techniques ensures the production of high quality seismic material (figure 2);
- the need to use multivariate systems of excitation, reception and registration, i.e. combined use of explosions, surface sources, pneumatic sources - in combination with bottom, surface and submerged geophones and hydrophones;
- the need to use a special technology for linking data obtained by different systems, including different (summer, winter) seasons [6].

![Figure 2](image_url)

**Figure 2.** a) time section before taking into account the influence of the upper part of the section; b) after taking into account the influence of the upper part of the section along the compositional line (V.I. Kuznetsov, NOVATEK STC, 2016).

The solution of the problems of seismic studies in transit zones is partly possible by using the radio telemetry method - an innovative technology for the production of 3D seismic survey. In this case, the registration system is transferred from the sea surface to the bottom [7].
2.2. Integration of 3D deep-sea seismic data and seismic survey in the land-sea transition zone at the Varandey-more field

At the prospecting and exploration stages, in order to select and substantiate the locations of deep wells, it is necessary to carry out comprehensive studies, in-depth interpretation of heterogeneous geological and geophysical information to select zones characterized by the highest effective oil and gas-saturated thicknesses and the best reservoir properties.

The Varandey-more field was discovered in 1995 in the Pechora Sea as a result of drilling a well, which established the oil-bearing capacity of carbonate deposits of the Lower Permian-Carboniferous age.

The location of the first well was determined based on the results of detailed seismic surveys in 1989-1994, the quality of which, however, ensured the solution of only a limited range of geological problems, mainly of a structural nature. The tasks of studying the structural features of a complex carbonate reservoir and assessing the properties of productive reservoirs required a higher level of seismic information.

The Varandey-more structure was studied by seismic surveys of the CDP seismic reflection method with a network of 1.0 x 2.0 km. A narrow area about 3 km wide along the coastline, characterized by a depth of less than 10 m, remained unexplored.

As a result of drilling two wells, the Lower Permian and Middle Carboniferous horizons were discovered and tested. During the testing of the Varandey-more-1 well, a gushing oil flow was obtained from the carbonate strata of the Lower Permian-Middle Carboniferous deposits. Oil-saturated sandstone strata of the Visean stage and in the underlying sediments of the Tournaisian stage were identified using logging and core data. The Lower Devonian, productive in onshore fields, has not been penetrated in any of the wells.

In order to update the geological model of the Varandey-more field - to determine the spatial boundaries of hydrocarbon reservoirs, to clarify the location and amplitude of faults, 3D seismic survey of the deep-water part of the field was carried out over an area of 300 km².

The main geological tasks for 3D work included: detailing structural plans for oil-bearing and oil-promising carbonate horizons, forecasting reservoir properties, creating a geological model of the field.

Based on the results of drilling and geophysical studies, it was found that the oil reservoir is confined to a layered massive reservoir, the structure of which is significantly different in the wells of the adjacent land. The latter is subdivided into three layers of different properties (figure 3.)

In connection with the fundamental importance of resolving the issue of clarifying the deep structure and southern closure of the Varandey structure, the continuation of which was supposed to be continued from the work area towards the coast, seismic works were carried out in the transit zone using 3D and 2D seismic methods.

To study the geological structure of the structure in the land-sea transition zone, work was performed using 3D method on an area of 48 km². In addition, onshore profiles were worked out through deep wells of the Varandey - onshore field.

Thus, for the first time in the conditions of the Arctic shelf of Russia, complex seismic studies of 3D were carried out, which made it possible to solve the set geological problems, to work out the method of work in the shallow water zone.

2D profiles were worked out to link the offshore sections with the studied drilling onshore section (Figure 4).
As a result, a unified (consolidated) data cube was created, including partially seismic information on the relatively deep-water part of the Varandey-more field (including the Varandey-more-1 well), the shallow-water land-sea transition zone, and well tie profiles passing through land wells. The interpretation of the data obtained made it possible to trace the continuation of the Varandey structure towards the land, as well as to indicate a clear tendency to expand the oil-bearing contour to the south with an increase in the thickness of the reservoirs and an improvement in their filtration-capacity properties.

After completion of the interpretation of the survey data in the transit zone, it was recommended to drill another exploration well (depth 2500 m) of the Varandey structure to clarify the southern boundary of the oil-bearing contour and the size of the field as a whole.

3. Offshore field development

At present, oil is being produced in the Arctic on the Pechora Sea shelf (the Prirazlomnoye field). In 2019, oil production at the field amounted to 3.1 million tons. In the Sea of Okhotsk, oil and gas condensate fields are being successfully developed under the Sakhalin-1, -2, -3 projects: Odoptu, Chayvo, Arkutun Dagi, Piltun-Astokhskoye, Lunskoye, Kirinskoye (figure 5) [8].

The Chayvo field was initially developed using both onshore (Yastreb) and offshore (Orlan) drilling facilities. While the Orlan platform has been in continuous operation there, the Yastreb drilling rig was dismantled and moved to the Odoptu field.

The Yastreb rig was engineered exclusively for Sakhalin-1. It is designed to drill extended reach wells to offshore targets from land-based locations. Extended reach drilling (ERD) technology reduces
the high capital and operating costs of large offshore structures while minimizing environmental impact to sensitive near shore areas [9].

In 2017 successfully completed drilling of the world's longest well from Orlan platform at the Chayvo field. The length of the well with horizontal completion is 15000 m. This is a supercomplex well with DDI (Directional difficulty index) of 8.0 and 14129 m stepout.

Gas production at the Lunskoye field (Sakhalin-2 project) is carried out by high-rate wells (from 1.5 to 8 million m$^3$ per day). Wells have a typical four-string design with a mono-diameter and completion with a production liner with a diameter of 9 5/8” in the productive interval [10, 11].

Under the Sakhalin-2 project, 300 km long subsea pipelines were built and put into operation, connecting three production platforms with the shore, onshore oil and gas pipelines 800 km long, an onshore processing facility, an oil export terminal and Russia's first LNG plant with a capacity of 9.6 million tons of LNG per year.

Design solutions for the development and facility construction of the Kirinskoye fields (Sakhalin-3 project) are due to three main factors: ice conditions, water depth and distance to the coastal infrastructure. Given the small number of wells and the proximity of onshore facilities, the Kirinskoye gas condensate field is being developed using subsea production technologies [12, 13]. Gas production at the field started in 2013. Currently, 2 wells with a cumulative gas production of 4.5 million m$^3$ per day have been put into operation at the field [14]. The calculations performed by the authors have shown the possibility of operating the field at well production rates higher than the design ones [15]. The results of the research to substantiate well production rates can be used in the design development of the Yuzhno-Kirinskoye, Mynginskoye and Yuzhno-Lunskoye fields.

High well production rates allow for accelerated development of the field with a small number of wells, while reducing the time of hydrocarbon production. Domestic and foreign experience in the operation of offshore gas fields shows that production rate of wells can be significantly increased due to the reservoir pressure reserve or well design.

For offshore fields, there is a limitation on the period of operation of field facilities. Offshore hydrocarbon production is more costly than onshore fields, therefore, the reconstruction of offshore structures is usually not performed. The design life of offshore structures and equipment determines the period of field development, which often does not exceed 30 years. It is during this time that it is necessary to ensure the maximum possible oil and gas production.

4. Conclusions
As a result of the research carried out in the field of prospecting, exploration and development of offshore Arctic and subarctic oil and gas fields, it is proposed to apply a set of geological exploration technologies, which has shown high efficiency on the shelf of the Arctic and Far East seas. The set, combining high-tech methods of areal and borehole geophysics, geochemical research, efficient drilling and high-quality well testing, makes it possible to provide an increment in hydrocarbon reserves in the short term of the Arctic seasons.

Design solutions for the development and facility construction of northern offshore oil and gas fields are due to the presence of a seasonal ice conditions, water depth, distance to coastal infrastructure facilities and the service life of structures. Due to these factors, it is necessary to use the possibilities of new technologies capable of ensuring the efficient production of oil and gas in offshore fields.

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