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Arctic Ocean Mega Project: Paper 1 - Data collection

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A R T I C L E I N F O

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A B S T R A C T

Over a period of the past 15–20 years, the Russian Government implemented the Arctic Mega Project for geological and comprehensive study of the Arctic Ocean. In this paper we discuss the methods that were used in the implementation of this project. In the course of several expeditions, multiple types of data were acquired, which included: (1) seismic data of different types, (2) subbottom profiler data, (3) geological sampling on slopes of the Mendeleev Rise with the use of special equipment, (4) borehole drilling, (5) gravity and magnetic anomalies, (6) offshore geodetic data, (7) multi-beam bathymetry surveys, and (8) field surveys on multiple Arctic islands. Several nuclear icebreakers and a scientific research submarine were deployed in these operations. Specifically, more than 23,000 km of 2D multi-channel seismic lines and more than 4000 km of wide-angle refraction/reflection seismic lines were acquired, in addition to subbottom profiles for the Eurasia Basin and new bathymetric data of the Arctic Ocean. The new database is intended to facilitate the development of new insights into Arctic geology and geodynamics and contribute to a better understanding of the structure and tectonic evolution of the Arctic Ocean as a whole.

1. Introduction

The Arctic Ocean remains one of the most poorly explored regions on Earth. The Arctic is surrounded by multiple countries: USA, Canada, Denmark (Greenland), Norway and Russia. This naturally implies the necessity of cooperation between different countries to investigate and explore the Arctic. A milestone in international scientific cooperation in the Arctic was the First International Polar Year (IPY) (1882–1883), initiated by the Austrian explorer and naval officer Lt. Karl Weyprecht (Weber and Roots, 1990; Stein, 2008). Over the years, Russia has taken active part in national and the international investigation of the Arctic Ocean. The current project takes Arctic investigation to a new level.

The Arctic Ocean comprises the deep-water Arctic Basin and the continental shelves adjacent to it (Fig. 1). On the Russian side the continental shelf is widest and is represented by the Barents, Kara, Laptev, East Siberian, and Chukchi seas. On the margins of the USA (Alaska), Canada and Greenland, the continental shelves are significantly narrower. The deep-water Arctic Basin is traditionally divided into the Eurasia and Amerasia basins. The boundary between the basins is marked by the Lomonosov Ridge. It has been suggested (Nikishin et al., 2014) that the Amerasia Basin be divided into two subbasins: the South Amerasia and the North Amerasia basins. Key bathymetric features subsequently can be associated with each of these domains; the Canada Basin lies within the South Amerasia domain. The Alpha-Mendeleev Rise is located within the central part of the North Amerasia domain. The Podvodnikov Basin and deep-water Makarov Basin are situated between

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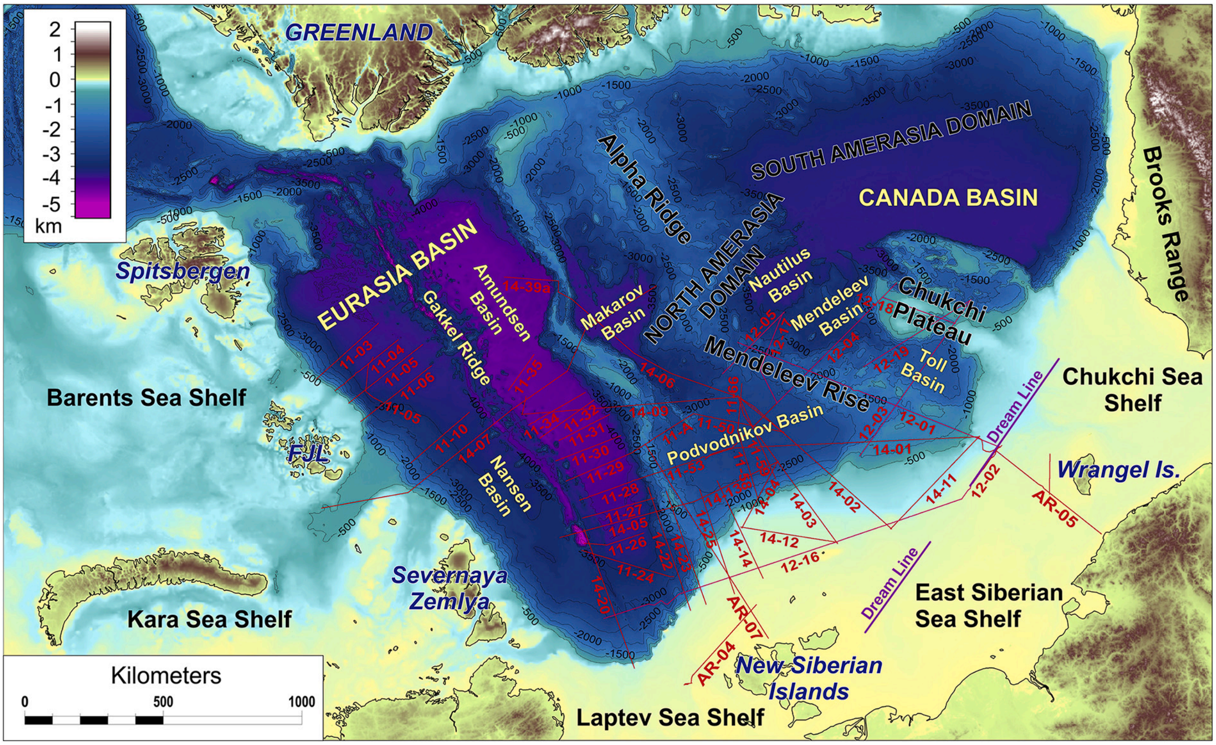

Fig. 1. Topography and bathymetry of the Arctic region (Jakobsson et al., 2012, 2020). Red lines indicate seismic data acquired during the Russian expeditions *Arktika-2011, Arktika-2012*, and *Arktika-2014*. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the Alpha-Mendeleev Rise and the Lomonosov Ridge. The deep-water Nautilus and Mendeleev basins are located between the Alpha-Mendeleev Rise and the Canada Basin and the Toll Basins is identified between the Mendeleev Rise and the Chukchi Plateau. The Eurasia Basin is divided by the Gakkel Mid-Oceanic Ridge into the Nansen and Amundsen basins. The Eurasia Basin is asymmetric because the Amundsen Basin has a greater water depth than the Nansen Basin (Fig. 1). This asymmetry is also associated with its geological structure (e.g., Nikishin et al., 2018).

The Arctic comprises a considerable part of the Earth's surface. In the past, global plate reconstructions of the evolution of the Earth tended to largely disregard the Arctic simply because of lack of reliable data from that region. The kinematic history of lithospheric plates in the Arctic was developed with data from extra-Arctic regions (for instance, the North Atlantic and the Pacific Ocean) (e.g. Shephard et al., 2013). In order to construct an adequate model of the Mesozoic and Cenozoic global geodynamic history of the Earth, understanding the history of opening of the Arctic Ocean is clearly a prerequisite. The presence of the High Arctic Large Igneous Province (HALIP) complicates Arctic tectonic history. Until this project, limited data on its tectonic structure in the area of the Alpha-Mendeleev Rise had been available (e.g., Van Wagoner et al., 1986; Døssing et al., 2013; Coakley et al., 2016; Oakey and Saltus, 2016). Consequently, there were widely different interpretations of this territory, ranging from a continental volcanic area to an oceanic basaltic plateau to a mid-oceanic ridge (e.g., Van Wagoner et al., 1986; Weber, 1990; Dove et al., 2010; Bruvoll et al., 2012; Døssing et al., 2013; Laverov et al., 2013; Pease et al., 2014; Jokat and Ickrath, 2015; Coakley et al., 2016; Oakey and Saltus, 2016; Petrov and Smelror, 2019; Mukasa et al., 2020).

The ultra-slow spreading Gakkel Mid-Oceanic Ridge is situated in the Eurasia Basin (e.g., Dick et al., 2003; Nikishin et al., 2018). This is a unique geological feature. Its mechanism of formation to account for its ultra-slow spreading nature is poorly known, as is its mineralogical composition (e.g., Dick et al., 2003; Lutz et al., 2018; Jokat et al., 2019). Also unknown in detail is the exact timing of the initiation of Eurasia Basin opening and whether it was accompanied by magmatism or mantle exhumation during its formation, especially in the area close to the Laptev Sea. Although more than 20 km of sedimentary section has been documented on the Arctic shelves (e.g., the North Chukchi Basin, Nikishin et al., 2014, 2019; Piskarev et al., 2019, Petrov and Smelror, 2019), its origin and the nature of the underlying crustal structure remain unclear.

As recently as 2000, the Arctic Ocean, and especially its Russian part, had been poorly studied and consequently poorly understood. The history of exploration of this ocean has already been reviewed, e.g., in Weber and Roots (1990) Stein (2008), Coakley et al. (2016), Piskarev et al. (2019). Several models for the structure and evolutionary history of the Arctic have been proposed based on available data (e.g., Grantz et al., 1998; Lawver and Scotese, 1990; Embry, 1990; Jokat et al., 1992; Lane, 1997; Vogt et al., 1998; Weber, 1990; Zonenshain et al., 1990; Ziegler, 1988). Based on these studies using limited data control one could incorrectly surmise that the principal models of the Arctic Ocean's evolution had already been formulated. The current study, which incorporates a vast new dataset, has afforded a whole new view of this basin.

Between 1990 and 2000, the Arctic states (Canada, Denmark, Norway, Russia and the USA) faced the challenge of establishing the outer limits of their continental shelves in the Arctic Ocean. The solution to this issue was to be based upon the United Nations Convention on the Law of the Sea (UNCLOS). Many of the requirements for establishing the outer limits of continental shelves involved the mapping of key morphological and geological structures of such offshore territories that are contiguous with the coastal State.

UNCLOS assigns sovereign rights of resources of the seabed and underneath the seabed to the coastal state that lies adjacent. In this context, some of the same information used in establishing extended continental shelf areas can also be indicative of high hydrocarbon potential under the shelves of the Arctic Basin. As a result, several

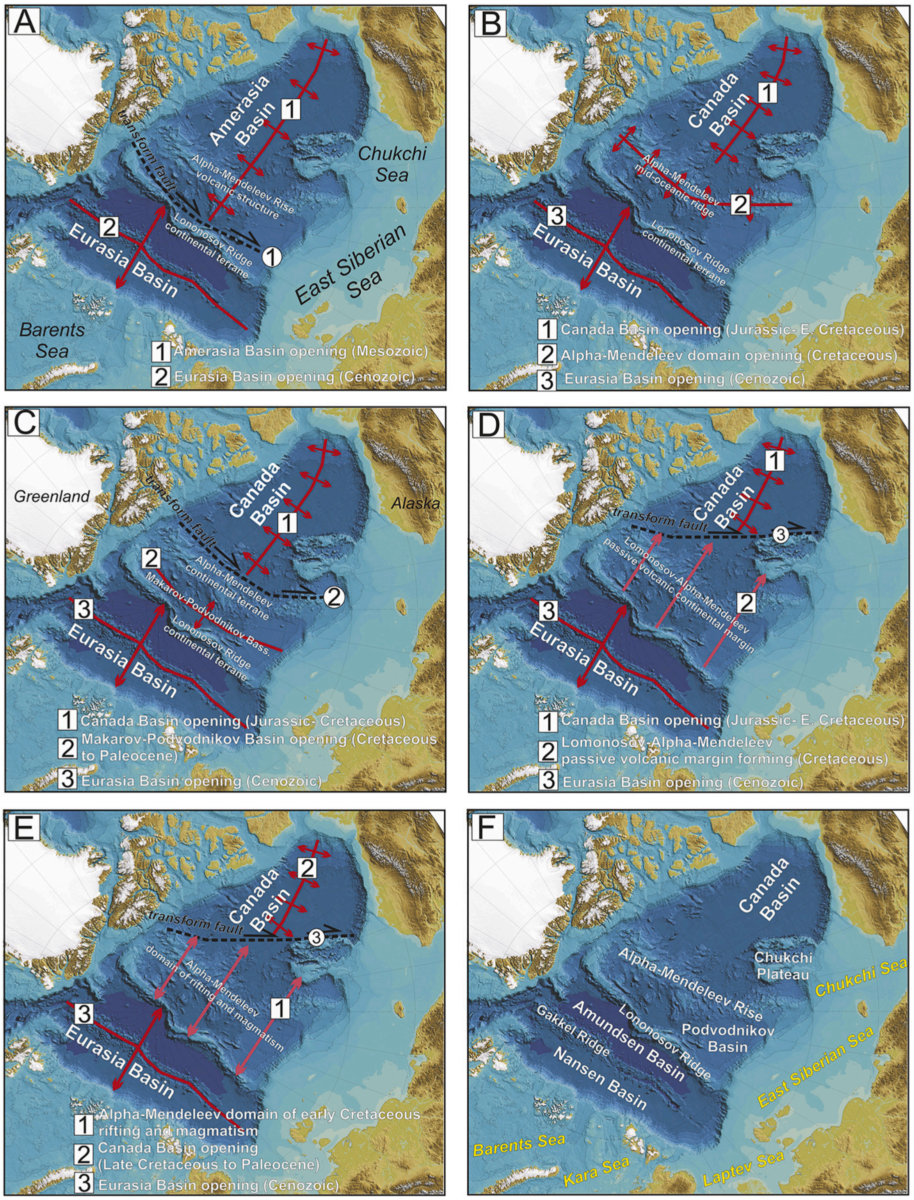

Fig. 2. The five most frequently discussed models of the geological history of the Arctic Ocean. (A) Classical rotation model; (1) (in the square) the opening of the Amerasia Basin in the Jurassic–Cretaceous (the position of the spreading axis is shown), (2) (in the square) the opening of the Eurasia Basin in the Eocene–Quaternary; (1) (in the circle) the main transform fault along Lomonosov Ridge. (B) Model with the Alpha–Mendeleev Rise as the mid-oceanic ridge; (1) the opening of the Canada Basin in the Jurassic–Cretaceous, (2) the formation of a mid-oceanic ridge over the mantle plume in the Cretaceous, (3) the opening of the Eurasia Basin in the Eocene–Quaternary. (C) Rotation model with the main transform fault along the Alpha–Mendeleev Rise; (1) the opening of the Canada Basin in the Jurassic–Cretaceous, (2) the opening of the Podvodnikov–Makarov basin in the Late Cretaceous–Paleocene, (3) the opening of the Eurasia Basin in the Eocene–Quaternary; (2) (in the circle) the main transform fault. (D) Model with the Alpha–Mendeleev Rise as a volcanic continental margin; (1) the opening of the Canada Basin with the main transform fault along the edge of the Chukchi Plateau (Northwind Ridge, shown as 3 in the circle), (2) the formation of the Alpha–Mendeleev–Lomonosov area as a volcanic continental margin with large-scale rifting and mantle magmatism in the Cretaceous, (3) the opening of the Eurasia Basin in the Eocene–Quaternary. (E) Model with the Canada Basin as Late Cretaceous to Paleocene structure; (1) rifting and magmatism in the Alpha-Mendeleev domain in the Early Cretaceous, (2) opening of the Canada Basin in Late Cretaceous to Paleocene with the main transform fault along the edge of the Chukchi Plateau (Northwind Ridge, shown as 3 in the circle), (3) the opening of the Eurasia Basin in the Eocene–Quaternary. (F) General geography. Based mainly on Dove et al. (2010 and references therein), with additional information from Doré et al. (2015) (model "C"), Miller et al., 2018 (model "E"), Nikishin et al. (2020) (model "D").

countries started evaluating the economic potential of the Arctic. Concern over issues of global ecology and climatic change became widely relevant in the process.

To further knowledge of the Arctic Ocean, the new Arctic Mega Project was initiated in Russia in 2005. Prior to that time, most geophysical expeditions in the Arctic Ocean were carried out using drifting ice stations. Subsequently, from 2005 to 2020, using additional data collection methods, Russian scientists conducted integrated geological and geophysical surveys designed to produce a regional grid of lines, which would lead to a better understanding of the major Arctic Ocean's structures (Fig. 1).

For surveying purposes several research vessels (RV) were used, however, most surveys were performed by the special ice-class research vessel *Akademik Fedorov*. In areas with heavy ice conditions, research vessels were accompanied by the nuclear icebreakers *Rossiya*, *Yamal* and *Arktika*. Seismic surveys were conducted in 2011, 2012 and 2014. A substantial number of new 2D seismic lines were collected, including for the first time regional seismic profiles for the Laptev, East Siberian, and Chukchi seas. As of 2020, the database volume accumulated includes 35,000 km of bathymetry profiles, more than 23,000 km of multi-channel seismic (MCS) lines, more than 4000 km of wide-angle refraction/reflection (WARR) (or deep seismic sounding) lines, and 150 sonobuoy seismic soundings.

Throughout the program, geological sampling was undertaken on different structures of the Amerasia Basin using dredge, ROV and drilling techniques. In 2012, 2014, and 2016, rock samples were collected from the Mendeleev Rise with the support of a nuclear scientific research submarine. In 2019, a subbottom profiler survey was conducted in the Eurasia Basin with in the areas of Gakkel Ridge and Nansen Basin. Given the perennial sea ice conditions and water depths, these wide-scale geological and geophysical surveys in the Arctic Ocean could have been conducted only with the support of a nuclear icebreaker and a nuclear submarine. To date, the Russian Arctic Ocean Mega Project has probably been the most cost-intensive geoscience project in Russia.

We have prepared three papers based on the findings of the Russian Arctic Ocean Mega Project: (1) Data collection; (2) Arctic stratigraphy and regional tectonic structure (Nikishin et al., 2021a); and (3) Mesozoic to Cenozoic geological evolution (Nikishin et al., 2021b).

We will discuss many aspects of the geology of the Arctic in these three papers focusing on two key issues: (1) the structure and formation

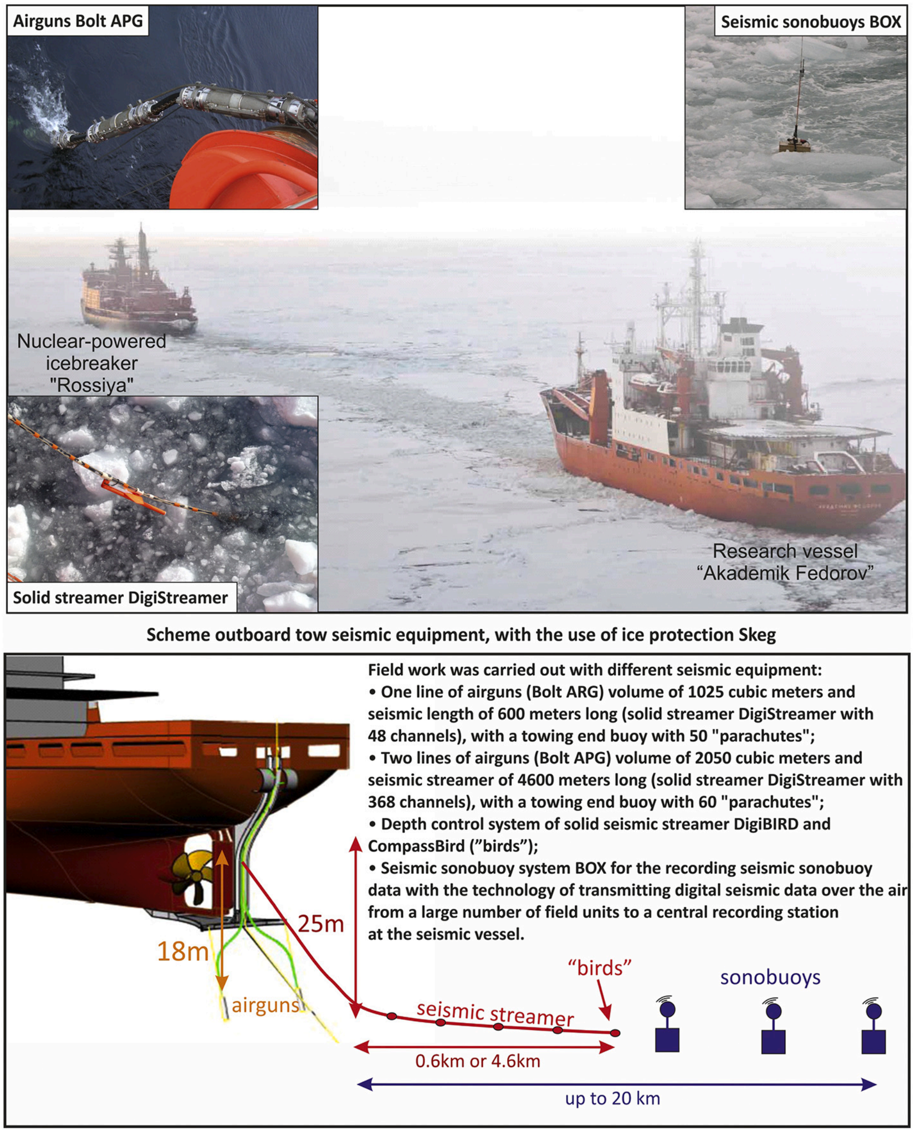

Fig. 3. Example of marine technologies for seismic data acquisition adopted for Russian *Arktika* expeditions, using a combination of a nuclear-powered icebreaker and a research vessel. Information from *Ministry of Natural Resources and Environment of the Russian Federation.*

history of the Alpha-Mendeleev Rise and adjacent deep-water basins and (2) the general chronology of geologic events in the Arctic Ocean's history (Fig. 2). Further insight into these issues will clearly contribute to a better understanding of global geodynamics and of global Earth history for the Meso-Cenozoic.

2. Data types

As briefly mentioned above, a variety of different data types were acquired as part of the Arctic Ocean Mega Project: (1) multiple types of seismic data, (2) subbottom profiler data, (3) geological sampling on the slopes of the Mendeleev Rise with the use of special equipment, (4) borehole data, (5) gravity and magnetic anomaly data, (6) offshore geodetic data, (7) multi-beam bathymetry data, and (8) data from geological surveys on adjacent Arctic islands.

2.1. Seismic data

The Arctic Ocean is characterized by the presence of a solid ice cover with ever-changing properties, both from year to year as well as within the year (the area of ice cover is smaller in summertime and much larger in wintertime). This characteristic introduces the necessity of corrections both in the timing (season) as well as in the techniques of conducting classical seismic surveys - e.g., in the use of a towed seismic streamer and in the use of seismic stations of different types.

The season for conducting seismic surveys northward of 82°N commonly is limited to a period of a few months, ranging from July to October. During this time, due to the polar day and solar activity, the southern edge of the first-year ice cover retreats farthest northwards, while the multi-year ice cover thaws out to its thinnest within that calendar year.

In solid ice conditions, two vessels sailing one after the other, are used for operations (Figs. 3, 4) along pre-planned seismic acquisition lines. This is a commonly used scheme for geophysical works in the Arctic Ocean (e.g., Hutchinson et al., 2009; Mosher et al., 2013; Piskarev et al., 2019; Petrov and Smelror, 2019). The main task for the lead vessel (the icebreaker) is to create an ice-free channel (a passage without solid ice or with ice crushed into smaller bits). The geophysical data-acquisition vessel follows the icebreaker. In the case of these Russian surveys, a nuclear icebreaker was used as the lead vessel, and the acquisition vessel, equipped with all the geophysical instrumentation, usually armored with some ice protection (e.g., strengthened hull), follows.

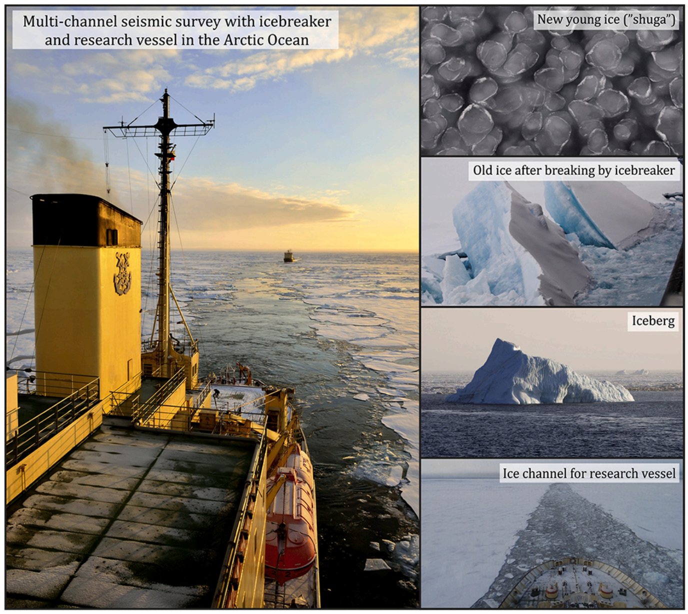

Fig. 4. Photos of seismic data acquisition in the Arctic. An icebreaker is in the front, creating a channel within the ice for the research vessel. The research vessel has all the scientific equipment. Ice conditions are illustrated on the right.

The main task of the data-acquisition vessel (a research vessel (RV), e.g. *Akademik Fedorov*) was to conduct the seismic survey, deploying a towed seismic streamer and seismic stations. Solid ice and pressure ice ridges handicap the constant-speed sailing of the RV, whereas crushed ice does not prevent maintaining a constant speed but can introduce noise on seismic recordings. For conducting surveys with a towed seismic streamer, all equipment trailed from the stern of the research vessel. These include airguns, seismic streamers, and "birds". RV *Akademik Fedorov* was equipped with a special ice protection system for safe deployment and recovery of the airgun and associated high-pressure lines as well as the seismic streamer. Stable speed of the acquisition vessel was critical to maintaining geometry for acquisition of quality data and to facilitate processing of the data. "Birds" on the seismic streamer helped ensure a constant tow depth.

For conducting multi-channel seismic surveys, the containerized geophysical Arctic-service hardware system with solid-filled and gel-filled seismic streamers of various lengths were used. In different years, seismic equipment included:

- Integrated offshore seismic data acquisition system *ION DigiSTREAMER* or *Sercel SEAL System*;
- Solid-filled seismic streamer *ION DigiSTREAMER* or solid-filled and gel-filled seismic streamers *Sercel SEAL Streamer*;
- *Bolt APG* airguns;
- Control and monitor navigation system *ORCA* or *QINSy*;
- Streamer depth control and positioning system *DigiBIRD* and *DigiCourse*, with the use of special devices ('birds') on a seismic streamer;
- Digital airgun controller *DigiSHOT* or *RTS Big Shot*.

In the Arctic Ocean, two versions of seismic streamer lengths were used. A 600 m long solid streamer was used when solid ice cover conditions existed or when an ice channel would close relatively quickly. A streamer 4500 m long and longer (solid or gel-filled) was used in the absence of sold ice cover and when the ice channel remained open for sufficient time for the survey. The streamer towage depth for most of the seismic acquisition was 15 m in order to keep it below any ice keels. The shotpoint spacing on most of the seismic lines was 50 m, with a record length of 12 s.

Additionally, while conducting multi-channel reflection seismic acquisition, sonobuoy seismic soundings were carried out for refraction data acquisition. These soundings were performed for some seismic lines with the use of floating seismic stations (sonobuoys). In the course of movement of the RV along a seismic line, these sonobuoys were released overboard at certain points, though only during the acquisition of multi-channel seismic data. These sonobuoys were not tied to the vessel in any manner. Thereafter, during the continuation of seismic signal shooting, these sonobuoys recorded seismic signals. These data were immediately transmitted to the research vessel via a wireless communication system. This communication channel continues to operate up to distances of 15–20 km (from RV to sonobuoy). As a consequence, the obtained data contain reflected seismic events; nonetheless, their core value lies in the fact that they also contain refracted seismic events. Refracted seismic events are recorded especially well at offset distances over 10 km. These techniques commonly are used for Arctic Ocean geophysical procedures (e.g., Mosher et al., 2013).

The main objective of refracted sonobuoy seismic soundings is to obtain a velocity model for seismic profiles that are acquired with the use of a short (600 m) seismic streamer. On these seismic lines, a reflection time-distance graph is too short to place reliance on stack velocities if the Dix formula is used for obtaining a velocity model for the line. That is why on such lines refracted sonobuoy seismic soundings were obtained. Consequently, this enabled velocity models to be computed for lines shot with a long seismic streamer (4500 m and more) where interval velocities could be obtained using the Dix formula. The hardware-software system used for conducting refracted sonobuoy seismic soundings was the radio telemetry seismic data acquisition system *BOX* (*Fairfield Industries*, USA).

Wide-angle reflection and refraction (WARR) surveys were carried out during both dedicated expeditions (*TransArctic-89-91*, *Arktika-2000*, etc.) as well as in conjunction with integrated geophysical expeditions (*Arktika-2012*, *Arktika-2014*). In the early expeditions, seismic receivers were arranged on the water surface (or on ice surface) with the use of airborne landing operations from ice-based RVs. However, subsequently the method of self-emerging 4-component ocean-bottom stations was employed. In most operations, *ADGS-2 M* and *ADSS-5000* stations with *M-K-4-SM26m* recorders (provided by the company *EDB OE RAS*) were used.

The ocean-bottom station is a sphere of 450 mm diameter with a special housing at the top pole. This special housing combines, in terms

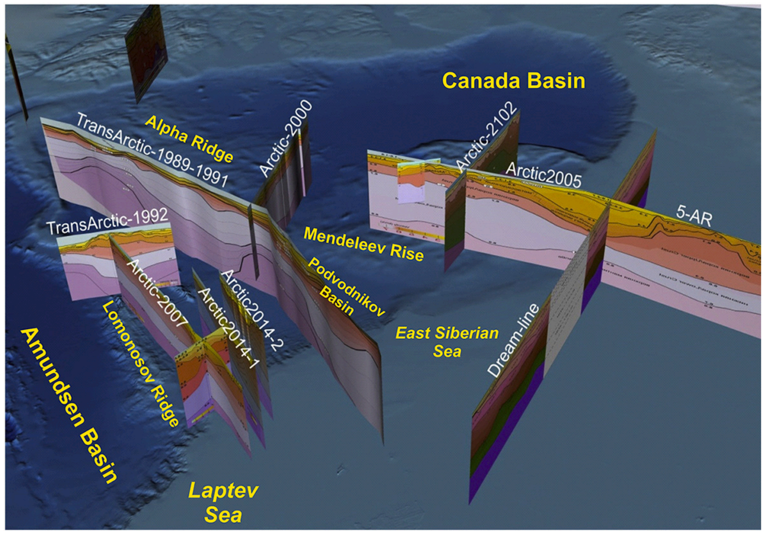

Fig. 5. Location of wide-angle refraction/reflection seismic lines. Presented by *VNIIOkeangeologia*. For details see Piskarev et al. (2019).

of design, an electrochemical release, a hydroacoustic antenna, and a hydrophone (H component). Components such as a geophone module (X, Y, Z components) and power supply are placed inside the sphere. The encasing sphere of the ocean-bottom station is made of a high-strength aluminum alloy. Single-beam and multi-beam hydrographic echosounders installed on the RV were used for determining coordinates and depth at installation points of ocean-bottom stations.

The seismic signal was produced through blasting TNT charges in early expeditions (*TransArctic-1989–91*, *Arktika-2000* and onwards). Later, starting with the *5-AR* expedition (2008), a special big-volume low-frequency airgun *SIN-6 M* was used, whose specifications are as follows:

- Working pressure – 120-130 atm;
- Volume of pneumatic chamber – 120 l;
- Energy of signal produced – 310 kJ;
- Frequency range – 8-12 Hz;
- Submergence depth – 34-37 m;
- Minimum interval between shots – 150 s;
- Airgun offset distance from vessel hull – 70 m.

Key details of each of the multi-channel seismic acquisition and deep wide-angle refraction/reflection data expeditions are described below.

2.1.1. Multi-channel seismic surveys (MCS)

Under the government-funded *Arktika* program a total of more than 23,000 running km of state-of-the-art seismic lines in the deep-water part of the Arctic Ocean were acquired (Fig. 1). Below is a list of expeditions with associated data volumes produced, equipment used, and specific features of seismic data acquisition.

2.1.1.1. Traverse A-7 expedition. In 2007, the company *MAGE* conducted an MCS of 820 km along a line (parallel to line *A-7*) from the New Siberian Islands to 83.5° N latitude, along the axial part of the Lomonosov Ridge. *SEAL System* (*Sercel,* France) recording station, *BoltAPG* (1500 in^3, 2000 PSI) guns as seismic source and *SEAL Sentinel Solid* (8100 m length, 648 channels) seismic streamer were used. The record length was 12 s and reached a CDP stacking fold of 108. Positioning was carried out using *GPS Spectra* system with an accuracy of at least 2 m. The main exploration target was the junction of the Lomonosov Ridge and the East Siberian shelf.

2.1.1.2. Traverse 5-AR expedition. Also in 2009, *MAGE* completed a 540 km MCS line from the Chukchi coastline to the edge of the Chukchi shelf using RV *Geolog Dmitry Nalivkin*. *Sercel SEAL System* recording station and *I/O Sleeve* guns (4010 in^3, 2000 PSI) as seismic source. The *SEAL Sentinel Solid* (8100 m with 648 channels) seismic streamer was used, with a record length of 15 s, reaching a CDP stacking fold of 81. The seismic navigation system *Spectra* also was used for positioning.

2.1.1.3. Arktika-2011 expedition. In 2011, a MCS survey was undertaken by the company *GNINGI*, using the RV *Akademik Fedorov* and the icebreaker *Rossiya*. The total length of MCS lines was 6300 km. *Sercel SEAL* was utilized with a solid-filled 48-channel streamer of 600 or 4600 m length, one or two air guns *BoltAPG* of 1025 or 2050 in^3 volume, and 2050 PSI working pressure. Navigation and positioning was provided by the integrated navigation system *ORCA* and software package *SPRINT*. The data were recorded and pre-processed by telemetric system *BOX*. Record length was 14–15 s and CDP stacking fold for the short streamer was 6 with 46 for the long streamer. The expedition's main objective was to determine the thickness of sedimentary sequences within the Amundsen, Nansen and Podvodnikov basins.

2.1.1.4. Arktika-2012 expedition. In 2012, the geological and geophysical surveys shifted to the Podvodnikov Basin, the Mendeleev Rise, the Chukchi Plateau, and the De Long High, with the company *Sevmorgeo* performing the surveys. The icebreaker *Kapitan Dranitsyn* and RV *Dikson* (a former icebreaker converted to RV, equipped to perform any kind of offshore seismic surveys) were used. The air gun used was a *BoltAPG* of 1600–2000 in^3 with 2050 PSI working pressure, and for navigation and positioning a *Trigger Fish* system was used.

Nine lines comprising 5300 linear km were acquired using a long seismic streamer (4500 m – 360 channels) – 1930 km – and a short seismic streamer (600 m – 48 channels) – 3370 km. This expedition's main goal was to study and refine the structure of the sedimentary cover of the Mendeleev Rise.

2.1.1.5. Arktika-2014 expedition. In 2014, MCS surveys were carried out by *MAGE* in the Nansen, Amundsen, Makarov and Podvodnikov basins, across the Lomonosov Ridge and along the margins of the Laptev and East Siberian seas using the RV *Akademik Fedorov* and the icebreaker *Yamal*. The total length of MCS lines acquired was 9900 km.

The MCS complex employed the *DigiStreamer* data acquisition system and solid-fill seismic streamers 600 or 4500 m length. *BoltAPG* air guns with total volumes of 1025/1300/2050 in^3 and 2050 PSI working pressure were used as seismic sources. Positioning was performed with navigation system *QINSy*. The record length was 12 s. and CDP sections were obtained with 6 stacking fold or 45 stacking fold for short and long streamers, respectively.

The main objective of these MCS surveys was to study and refine the structure of the sedimentary cover of the Eurasia and Amerasia basins and the adjacent shelf, and to link with the stratigraphy of the major morphological structures of the region.

2.1.2. Russian wide-angle refraction/reflection (WARR) lines

The main purposes of the WARR surveys were to investigate major structures of the Arctic Ocean and to obtain velocity models of the crust. WARR lines were surveyed along regional lines through the Amerasia Basin (Lomonosov and Alpha ridges, the Mendeleev Rise, the Chukchi Plateau, Podvodnikov and Makarov basins), terminating at the adjacent shelf of Northeast Eurasia (Fig. 5). A brief description of key expeditions undertaken by Russia in the Arctic during the last three decades is presented below. As indicated above, WARR surveys were conducted by two main methods:

- Arranging seismic receivers at the sea surface (including on ice) with the use of airborne operations conducted from ice bases or RVs. This method was used in the *TransArctic-89-91, Arktika-2000, Arktika-2005* and *Arktika-2007* expeditions.
- Utilization of ocean-bottom stations with participation of RVs. This method was used in the *5-AR*, *Arktika-2012*, *Dream Line*, *Arktika-2014* expeditions.

2.1.2.1. TransArctic-1989–91, TransArctic-92 expeditions. The total length of WARR lines acquired during the *TransArctic 1989–1991* expedition was 1490 km. These lines extended from the Makarov Basin across the Podvodnikov Basin to the East Siberian Shelf. The *TransArctic-1992* WARR line crossed the Lomonosov Ridge approximately along 84°N latitude, including the adjacent Amundsen and Makarov basins. The length of the *Transarctic-1992* line was 280 km.

Acquisition of these *Transarctic* lines was the first Russian experience involving a regular WARR survey in high latitudes of the Arctic. These early data were characterized by sparse intervals between seismic receivers. Consequently, the sedimentary cover over the crust was only poorly studied, controlled as it was by refraction data and modeled based on reflection data. Only high-velocity waves propagating within the crystalline crust were interpreted with some reliability.

Each of WARR lines had three arrays that were characterized by the following parameters:

- 30 receive points with an average spacing of 5–6 km;
- Shot points spaced at 40 km and 50 km;
- Generation of seismic waves by TNT charges weighing 0.2–1.2 tons, with an amount of explosives per entire line of 18 tons.

Seismic waves were recorded by *Delta-Geon-1* digital recorders with the following specifications:

- Number of channels - 3;
- Frequency range 0.2–15 Hz;
- Dynamic range – 100 dB;
- Sampling interval – 7 ms.

2.1.2.2. Arktika-2000, Arktika-2005 and Arktika-2007 expeditions. The *Arktika-2000* WARR line (500 km long) was routed across the northern part of the Mendeleev Rise and the adjacent Canada and Podvodnikov basins at 82°N. The *Arktika – 2005* WARR line was acquired in 2005 along the axial part of the Mendeleev Rise and its junction with the shelf (500 km). Finally, the *Arktika-2007* regional WARR line (650 km long) was routed from the near-Siberian part of the Lomonosov Ridge to the Laptev Sea Shelf north of the Kotelny Island.

Each of these WARR lines had the same survey parameters as the *TransArctic-89-91* and *TransArctic-92* WARR lines. Seismic waves also were generated by TNT charges. The main airborne operations were supported by helicopters from the research vessel *Akademik Fedorov* accompanied by the nuclear icebreakers *Rossiya* and *Sovetskiy Soyuz*.

2.1.2.3. 5-AR expedition. This expedition utilized bottom stations to acquire WARR data. The *5-AR* Line (550 km long) extended from Cape Billings (Chukotka coast) to the southern end of the *Arktika-2005* line. Data were acquired by 56 4-component ocean-bottom stations, with 10 km spacing between stations in the receiving array. Generation of seismic signals was done using a *SIN-6 M* airgun. It should be noted that only one station was lost during the *5-AR* line survey.

Two main types of ocean-bottom stations were used – 'boomerang' and 'buoy-based' stations. During the survey, it was decided to use boomerang ocean-bottom stations in deep water areas and in water areas with moving ice floes instead of buoy-based stations.

2.1.2.4. Dream Line expedition. The WARR line (925 km long) was completed in 2009 by the company *Sevmorgeo* on the East Siberian Sea shelf, under a contract with British Petroleum. WARR data were acquired using self-emerging 4-component ocean-bottom stations (X,Y,Z geophones and H hydrophone).

2.1.2.5. Arktika-2012 expedition. The 480 km long WARR line ran from the Podvodnikov Basin to the Chukchi Plateau, crossing the southern part of the Mendeleev Rise. WARR data were acquired by *Sevmorgeo* using 4-component ocean-bottom stations of 'boomerang' type. The

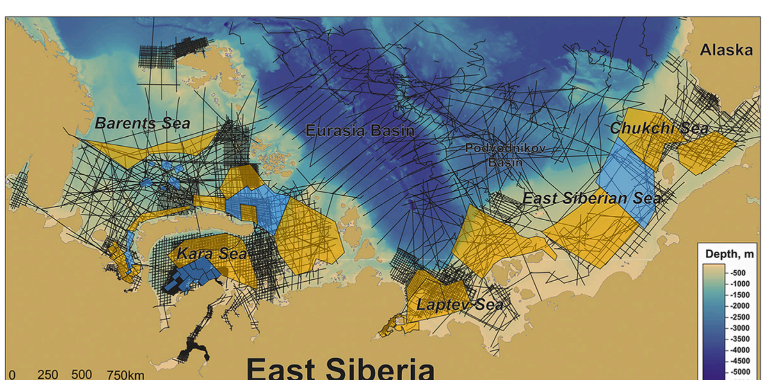

Fig. 6. Location of the main part of the seismic lines in the Arctic Ocean with greater detail over the Russian shelves. Yellow blocks – *Rosneft* licenses. Blue blocks – *Gazprom* licenses. Licensed blocks have many new seismic and other geophysical data. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

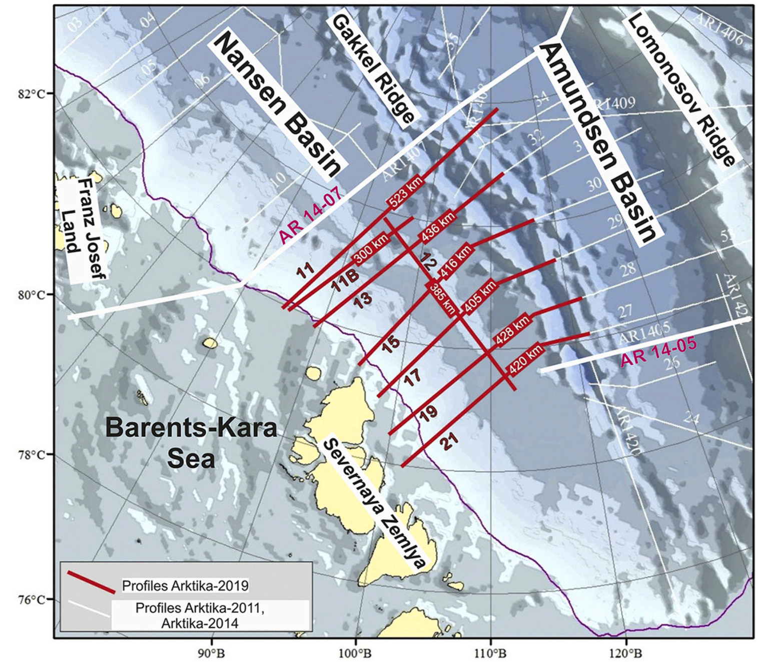

Fig. 7. Location of subbottom profiles of expedition *Arktika-2019* and location of some seismic lines.

survey was carried out by the diesel electric icebreaker *Dikson*.

Generation of seismic signals was carried out using a *SIN-6 M* airgun with working pressure of 120–130 atm and pneumatic chamber volume of 120 l. In the course of the work, one receiver array of seismic stations was set up with 30 seismic stations. Parameters of the acquisition geometry and of seismic signal recording were:

- Shot points spacing – 312 m;
- Receive points spacing in the receiver array – 10-20 km;
- Length of time-distance graph – not less than 150 km;
- Record length – 60 s.

2.1.2.6. Arktika-2014 expedition. This WARR survey was undertaken by *MAGE* using the RV *Nikolay Trubyatchinsky* and consisted of two lines (250 km and 350 km). 4-component ocean-bottom stations of 'boomerang' type and a 7300 in^3 airgun were utilized. These WARR lines were located in the De Long High and the associated linkage area. The survey aimed to investigate the continuity and structure of the crustal complexes. Parameters of the acquisition geometry and seismic signal recording were:

- Interval between excitations - 150 s;
- Receive points spacing in the receiver array – 6-8.5 km;
- Length of time-distance curve – not less than 150 km;
- Record length – 60 s.

2.1.3. Other new 2D and 3D seismic data for the Russian Arctic shelf

As mentioned above, during the past two decades, many 2D seismic lines have been acquired in the Russian deep-water part of the Arctic continental shelf (Fig. 6). Prior to that, the continental shelves of the Laptev, East Siberian, Chukchi and North Kara seas had been poorly studied. All seismic data in the deep-water part of the Arctic Ocean belong to the *Ministry of Natural Resources and Environment of the Russian Federation* and are open to Russian investigators as well as foreign investigators involved in international scientific projects.

On the Russian part of the shelf, the Russian companies *Rosneft* and *Gazprom* have vast licensed blocks (Fig. 6). For these blocks, a new dense grid of 2D seismic lines is now available. However, these data so far remain private. The bulk of the new seismic data was acquired by the Russian geophysical companies *Rosgeo, DMNG, SMNG, Sevmorgeologia, Yuzhmorgeologiya,* and *MAGE*. In addition, many other companies and institutes conducted seismic surveys there as well: *BGR, Halliburton, British Petroleum, ION, CGG, TGS*, and *PGS*. The Russian geophysical companies published key results of their surveys mainly in Russian. Geologists of scientific institutes of the *Federal Subsoil Resources Management Agency* and the *Russian Academy of Science* developed a modern seismo-stratigraphic framework of the shelf areas. Outside of Russia, *BGR* (Germany) has been a pioneer in investigating the Laptev Sea with the studies by Franke (2013).

3D seismic data for the Russian shelf are available for individual licensed blocks of the East Barents and South Kara seas. They were acquired by *Rosneft* and *Gazprom* and afforded the possibility to refine seismic stratigraphic models for these areas. Principal unconformities and major sequences were identified, and the history of the geologic and tectonic evolution was worked out in detail. For the Barents Sea, 3D seismic data demonstrated, for example, evidence of Early Cretaceous intrusions.

The scientific institutes of the *Federal Subsoil Resources Management Agency VSEGEI* and *VNIIOkeangeologia* conducted regional geological and geophysical studies in multiple shelf areas. Results of their studies are available in open-source technical reports and were published openly (e.g., https://vsegei.ru/ru/info/; http://vniio.ru/publications/).

In the Barents and South Kara seas, data from deep boreholes are available and have been tied to seismic lines to provide ground truth calibration (e.g., Smelror et al., 2009). Stratigraphic and seismic stratigraphic frameworks for these seas have been extensively established. However, for the Laptev and East Siberian Seas, as no boreholes are available, seismic stratigraphic interpretations remain uncalibrated.

2.2. Subbottom profiler surveys in the Eurasia Basin in 2019

An expedition to the Eurasia Basin involving the acquisition of subbottom seismo-acoustic data was conducted in 2019. At the present time, this is the most recent high-latitude integrated geophysical expedition carried out by Russia in the Arctic. These offshore subbottom studies were aimed at obtaining high-quality data on bottom relief and structure of the upper part of the geological section in the area of the Gakkel Ridge. The following tasks were planned:

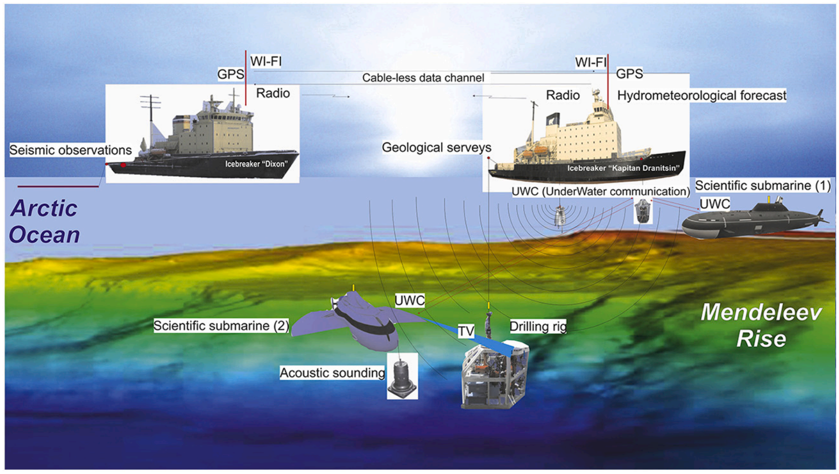

Fig. 8. Comprehensive study of seafloor scarps with bedrock outcrops on the Mendeleev Rise using shallow drilling and the manipulator of the research submarine in 2012 – conceptual scheme (expedition *Arctika-2012*). Data are presented by *Ministry of Natural Resources and Environment of the Russian Federation* and published by Morozov et al. (2014).

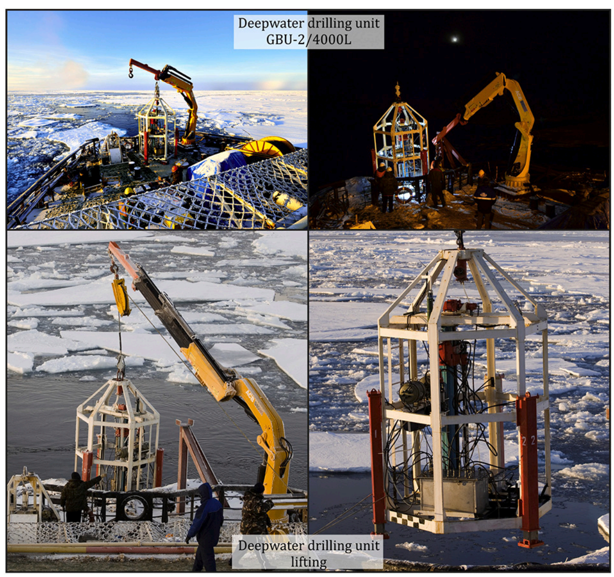

Fig. 9. Photos of deep-water drilling unit during the expedition *Arktika-2012.*

- Acquisition of additional data by multi-beam and single-beam echosounders with the purpose of preparing a digital bathymetry database;
- Acquisition of subbottom profiling accompanying the bathymetry surveying.

Two nuclear icebreakers took part in the expedition initially: *Taimyr* and then *50 Let Pobedy*. For research operations, as with earlier integrated geophysical expeditions, the ice-class RV *Akademik Fedorov* was used. Continuous subbottom profiling was conducted with the purpose of studying the upper part of the geological section to a depth up to 100–200 m. The location of profiles is shown in Fig. 7.

New bathymetric data for the Eurasia Basin and data on modern geological processes on the continental slope and on the basin floor were obtained as a result of this expedition. Currently, these data are being processed.

2.3. Rock sampling on slopes of the Mendeleev Rise

To facilitate the geological study of the sedimentary cover and bedrock on the Mendeleev Rise, within the framework of the expedition *Arktika-2012,* specialized operations were conducted using two icebreakers with additional participation of a scientific research submarine (SRS). Later in 2014 and 2016, deep-water geological expeditions (*Mendeleev-2014* and *Mendeleev-2016*) were conducted with full-scale participation of a nuclear SRS. The full-scale use of the SRS made it possible to replace the use of a RV, and the unique equipment on the SRS allowed rock samples to be taken from the sea floor precisely at the locations intended. The principal research methods utilized in these expeditions are described below.

2.3.1. Arktika-2012 expedition

On the *Arktika-2012* expedition the objective was to sample bedrock on the slopes of the Mendeleev Rise. The expedition was undertaken by *Sevmorgeo*. Seabed sampling and deep-water drilling were conducted from the icebreaker *Kapitan Dranitsyn*. In conventional dredging, rock samples brought from the seabed usually are derived from "exotic" debris transported to the sampling site by ice rafting processes. The principal challenge was to make certain that the rock samples taken were in situ on the seabed, and shallow drilling with the use of an ice-

Fig. 10. Photos of bottom grab during the expedition *Arktika-2012*.

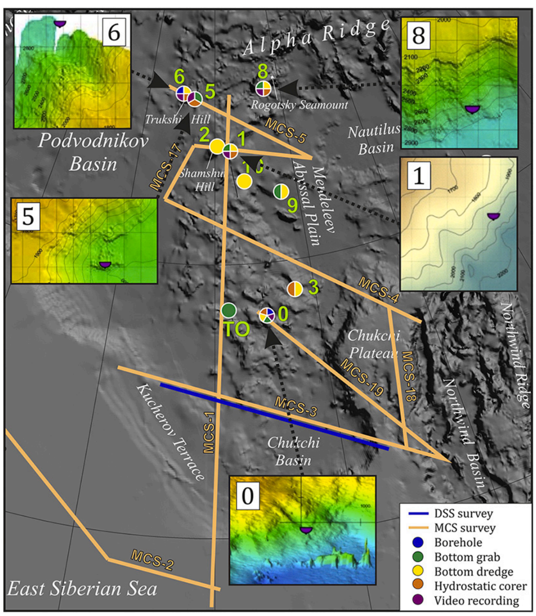

Fig. 11. Locations of polygons of the *Arctic-2012* expedition on the Mendeleev Rise. The various sampling methods are shown with colour. Bathymetry of polygons is illustrated in greater detail. Data are provided by the *Ministry of Natural Resources and Environment of the Russian Federation.*

class deep-water drilling unit ensured this objective. Sampling of bottom rock material was carried out using a hydrostatic corer, a grab sampler and a bottom dredge. For all of these operations the SRS was used.

In accordance with the sampling plan, the following tasks were designated for surveying areas of 10 × 10 km size as envisaged during the pre-project planning:

1. Detecting locations of bedrock exposure projecting through the surficial cover of loose sediments in areas using a grid size of 2 × 2 km;
2. Determining site parameters for positioning the drilling unit within the selected locations: seabed slope angle, current speed vector, dimensions of the revealed sites;
3. Video-photometric and sonar documentation of the selected sites for geological sampling and deep-water drilling.

The suite of studies included the following methods and equipment: in 10 × 10 km areas – multi-beam surveying; in 2 × 2 km areas – sub-bottom profiler and side-scan sonar surveying. In the final stage of the studies, visual and video inspection of the sites where sampling was to be conducted was performed. Results of these inspections were decisive in selecting the appropriate seabed sampling method (Fig. 8).

Within the framework of the *Arktika-2012* expedition, 11 polygons (10 × 10 km) were surveyed. With the use of the SRS, six polygons were surveyed (Nos. 0, 1, 3, 5, 6, 8) and designated as the top priority targets, with the remaining five polygons to be sampled using alternative equipment. Polygons No. 0 and No. 6 were selected for core drilling. Shallow drilling with video tracking was conducted at four sites (*KD12–06-21b* on Polygon 6, *KD12–00-31b*, *KD12–00-32b* and *KD12–00-33b* on Polygon 0). On sites *KD12–01-29b, KD12–06-31b, KD12–00-33b*, bedrock cores were drilled; the lengths of cores recovered at these three stations were 60, 40, and 15 cm respectively.

Drilling was conducted using the ice-class deep-water drilling unit *GBU-2/4000 L* (Fig. 9) developed by *Sevmorgeo*. It was designed in 2012 especially for operations in the Arctic, capable of drilling holes up to 2 m in depth with 76 mm diameter tool and up to a water depth of 4000 m. During this expedition, operations with the deep-water drilling unit were conducted for the first time at negative ambient temperatures and in hazardous ice conditions. The drilling unit was installed at water depths over 2000 m. The icebreaker equipped with additional deployment and hoisting equipment was used for the first time as a RV.

A bottom dredge developed by *VNIIOkeangeologia,* had a rectangular shape with a size of 1 × 0.5 m and a mass of 500 kg. The dredging method is standard for marine geology. The dredging sites were selected following the recommendations based on surveys of the sea floor acquired by the SRS, coupled with analyses of seabed geomorphology within the work polygon. In total, 9 sites were sampled.

For bottom rock sampling, the clamshell-type grab sampler *DG-1-TV* also was used (Fig. 10). It was developed more than twenty-five years ago and is widely utilized for seabed sampling. It consists of two half-scoops mounted on a frame equipped with a remote video system. From the nine locations sampled, bottom sediment samples weighing between 200 and 450 kg were obtained from seven of the locations. Video recordings of lowering and reaching the bottom were made at five sites. Finally, the hydrostatic corer *E414M/01–00.000* was used for bottom sampling at total of 6 locations.

The combined sampling methodology using all available sampling tools resulted in the collection of a large body of material, including more than 20,000 fragments of gravel-to-block size clasts (Fig. 11). The main results of the *Arktika-2012* expedition were published in subsequent years (Morozov et al., 2013; Petrov et al., 2016: Vernikovsky et al., 2014; Kossovaya et al., 2018; Petrov and Smelror, 2019). They showed that dredging of slopes and shallow (up to 2 m) drilling resulted in recovery of primarily loose sediments. Consequently, there was no guarantee that samples thus taken were actually basement bedrock. As a result, many Arctic researchers assumed that the dredged sedimentary rocks were the product of ice rafting.

2.3.2. Deepwater geological expeditions in 2014 and 2016

The deep-water geological expeditions of 2014 and 2016 (*Mendeleev-2014* and *Mendeleev-2016*) were able to reproduce the concept of "a field geologist with a hammer" analogous to the classical approach applicable to onshore surveys. The *Geological Institute of the Russian Academy of Sciences (GIN RAS)* and *Geological and Geophysical Survey of GIN RAS (GEOSURVEY GIN RAS)* have developed novel methodologies for comprehensive bottom surveys using the scientific research submersible (SRS). Bedrock samples from outcrops on the seabed were leveraged to produce stratigraphic columns similar to what could be obtained from deep drilling. This approach ensures that rock samples collected were indeed from bedrock. The most important aspect of this comprehensive methodology is the direct sampling of rocks from recognized bedrock outcrops by means of manipulators, thus excluding ice rafted debris. To accomplish this, a field geologist (Sergey Skolotnev) was submerged to the seafloor in a special manned deep-water vehicle where he could visually confirm outcrops presence and extract rock samples with the use of special manipulators.

To fulfill this mission a special purpose-equipped SRS was used. The

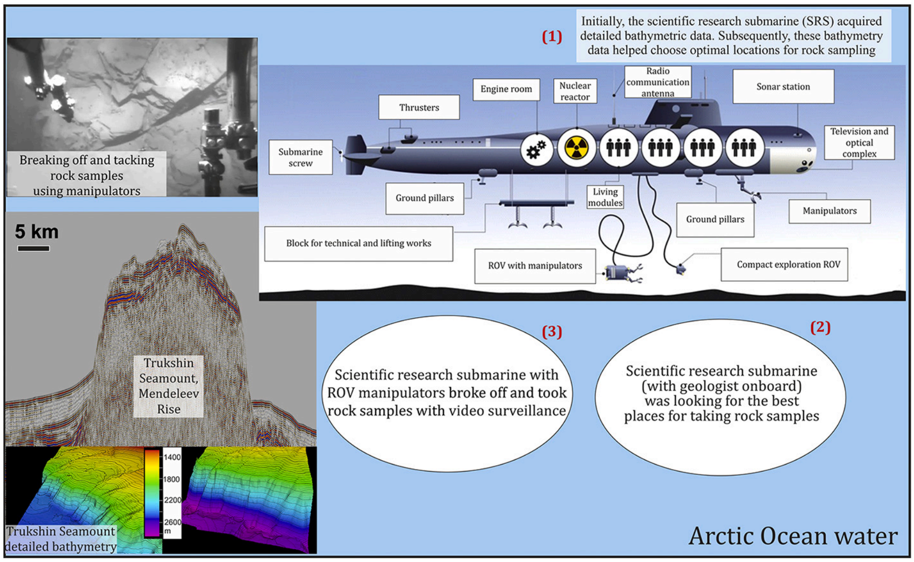

Fig. 12. Conceptual scheme of rock samples taking during *Deepwater Geological Expeditions* to the Mendeleev Rise in 2014 and 2016. Numbers 1, 2, 3 show the sequence of events.

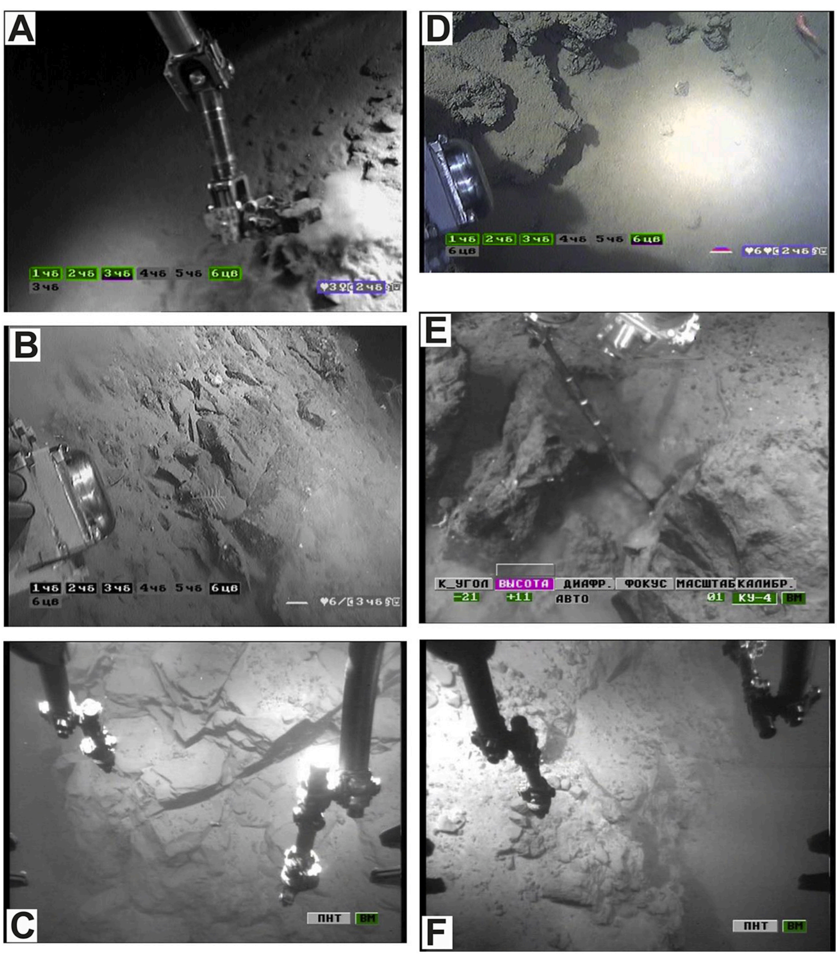

Fig. 13. Submarine bedrock outcrops on the slopes of the Mendeleev Rise. A – sandstone (sample 14–09) (78° 10,8′ N, 179° 07,0′ W, water depth 1229 m). B – andesite (14–02, 78° 10,3′ N, 179° 07,5′ W, water depth 1484 m). C – dolomite (1601/22) (79° 00,8′ N, 174° 43,0′ W, water depth 2343 m). D – limestone (14–10, 78° 10,9′ N, 179° 03,3′ W, water depth 1282 m). E – andesite basalt (1601/14) (79° 01,4′ N, 174° 51,6′ W, water depth 2205 m). F – volcanic tuff (1601/25) (79° 00,5′ N, 174° 43,4′ W, water depth 2111 m). The photos were taken by a manned underwater vehicle. Data are provided by the *Ministry of Natural Resources and Environment of the Russian Federation*, and partly from Skolotnev et al. (2019).

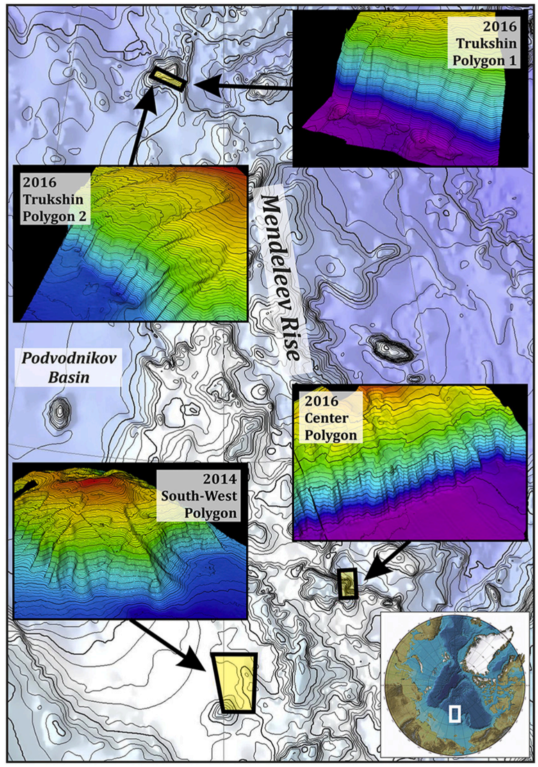

Fig. 14. Locations of polygons of Deepwater Geological Expeditions to the Mendeleev Rise in 2014 and 2016, modified after Skolotnev et al. (2019). Background map is bathymetry data from the International Bathymetric Chart of the Arctic Ocean (Jakobsson et al., 2012). More detailed bathymetry data of polygons are provided by the *Geological and Geophysical Survey of the Geological Institute of the Russian Academy.*

SRS was equipped with a multi-beam echosounder, a subbottom profiler, searchlights, photo and video cameras to detect rock outcrops and document the sampling process. The SRS also was equipped with special manipulators for rock sampling (Fig. 12).

This unique methodology used on the *Mendeleev-2014* and *Mendeleev-2016* expeditions involved six consecutive steps:

- Select polygons for rock sampling based on outcrops detected using seismic sections;
- Undertake a bathymetric survey followed by subbottom profiling of the slope in order to ascertain the precise locations of exposed rocks on the seafloor;
- Have an experienced geoscientist observe the seafloor using video recordings of the nature of rock outcrops, and select sampling locations;
- Recover bedrock samples from seafloor outcrops;
- Identify and record photographically collected rock samples (Fig. 13);
- Process in-lab (e.g., petrographic description and microscopic examination of rocks, X-ray phase analysis, chemo-analytical studies, rock dating) and construct composite geological cross-sections.

The field trial studies conducted in 2014 in the southwestern part of the Mendeleev Rise were aimed at validating a methodology for constructing geological cross-sections across seafloor structures in the Arctic Ocean. For the first time, rock samples were taken at substantial depths (1600 m) directly from bedrock exposures on the Mendeleev Rise (supported with photo- and video-recording and ties to geophysical data). The 2014 field trials helped to work out the best possible suite of methods for reliable characterization of bedrock exposures. An important advantage of this methodology was that a geologist was able to monitor while sampling was being conducted.

The *Mendeleev-2016* expedition successfully employed a SRS to recover rock samples from bedrock exposures within three polygons. The bedrock geology at the Mendeleev Rise was sampled at greater depths (2000–2400 m) and an improved sampling technique was applied. This work considerably expanded knowledge of the temporal and spatial limits of the geological record of the Mendeleev Rise, which is critically important for correlation with adjacent Arctic coastal geology.

Thus, in the course of two expeditions, four separate steep slopes on the Mendeleev Rise were surveyed (Fig. 14). A principal aspect of this methodology is that rocks were sampled at regular depth intervals along such outcrops specifically for the purpose of constructing a geological cross-section. In total, 77 sites were sampled (Skolotnev et al., 2017, 2019).

The prime conclusion was that all four slopes on the Mendeleev Rise have similar Paleozoic sections, which are represented mainly by shelf carbonate and clastic deposits, and the distance from the southernmost point to the northernmost point is more than 500 km. It is highly likely that the entire Mendeleev Rise has a Paleozoic sedimentary cover. The findings of the *Mendeleev-2014* and *Mendeleev-2016* expeditions confirmed that the recovered bottom rock material during expedition *Arktika-2012* was likely not of ice rafting origin, which is consistent with the paleontological data acquired during the previous *Arktika-2012* expedition (Kossovaya et al., 2018).

2.4. Borehole data

The Arctic Ocean is relatively poorly studied by deep drilling. This is especially true for its deep-water part within which only one borehole has been available. The first scientific drilling expedition to the central Arctic Ocean was completed in September 2004. *Integrated Ocean Drilling Program Expedition (IODP) Leg 302, Arctic Coring Expedition (ACEX)*, recovered sediment cores up to 428 m below seafloor in water depths of ~1300 m, 250 km from the North Pole (Backman et al., 2006). Results of studies of these boreholes have previously been published (e.g., Moran et al., 2006; Jakobsson et al., 2007).

Several commercial wells (*Popcorn, Crackerjack, Klondike, Burger, Diamond*) have been drilled in the Chukchi Sea, located in the American part of the Arctic region (Craddock and Houseknecht, 2016; Homza and Bergman, 2019; Houseknecht et al., 2016; Houseknecht and Wartes, 2013; Ilhan and Coakley, 2018; Kumar et al., 2011; Sherwood et al., 2002). Based on data from these wells, a stratigraphic scheme for Late Paleozoic to Cenozoic was developed for the Alaska shelf (Sherwood et al., 2002; Homza and Bergman, 2019). In Alaska, two wells were drilled on the margin of the Hope Basin in the Chukchi Sea (Bird et al., 2017). These wells penetrated Neogene to Eocene deposits. This sedimentary section overlies Paleozoic carbonates. In the Russian part of the Chukchi Sea, one well was drilled on Ayon Island near the Chukchi Peninsula (Aleksandrova, 2016). The well penetrated deposits from the Quaternary to the Paleocene.

In 2014, *Rosneft* and its US partner *ExxonMobil* successfully completed drilling of the world's northernmost Arctic vertical well *Universitetskaya-1* in the Kara Sea (the well TD is 2.1 km). Multiple companies participated in the drilling of this well, including *ExxonMobil, Nord Atlantic Drilling, Schlumberger, Halliburton, Weatherford, Baker, Trendsetter, and FMC*. A new oil field, *Pobeda,* was discovered and the section comprising Jurassic, Cretaceous and Cenozoic deposits was studied in detail.

In 2017, *Rosneft* drilled the 2363 m deep well *Tsentralno-Olginskaya* in the Khatanga Gulf of the Laptev Sea. The well penetrated deposits of the Cretaceous, Jurassic, Triassic and Upper Paleozoic. Results of this drilling have resulted in a refinement of the stratigraphic model for the Laptev Sea. In the Russian part of the Barents Sea, several boreholes from the Soviet era are available and in the Norwegian part of the Barents Sea several new boreholes also are available. For the Barents Sea, a well-worked-out stratigraphy and seismic-stratigraphic framework for Mesozoic and Cenozoic deposits is available (e.g. Smelror et al., 2009). In the Russian part of the Barents Sea, Cenozoic deposits are largely absent, having been glacially eroded.

On the whole, data derived exclusively from drilling on the shelves of the Arctic Ocean are insufficient to assemble an integrated seismic-stratigraphic framework for the entire Arctic Ocean.

2.5. Gravity and magnetic data

Within the framework of the geophysical expeditions in the Arctic Ocean, a shipboard gravity survey was conducted during the *Arktika-2014* expedition in combination with multi-channel seismic surveying. For gravity data acquisition two gravimeters *Chekan-AM* and *Shelf-E,* produced by the company *Elektobribor,* were used. These gravimeters were positioned on two research vessels taking part in the *Arktika-2014* expedition.

Data from the gravimetric sensors and gyro stabilization systems of the gravimeters were recorded using of *SeaGrav* software. For the *Shelf-E* gravimeter, data from the thermo-stabilization system of the gravimetric sensor were also recorded. The sampling rate of the primary gravimeter data, which were processed in-office, was 0.1 s. Recording of navigation data from the *Trimble SPS 461* onboard satellite receiver also was made with the use of *SeaGrav* software for quality control of the gravimetric equipment, with a sampling rate of navigation data of 1 s.

For in-office processing of gravity data we used data from the files in the format of the international exchange of geophysical data P1/90. These files contain navigation (latitude, longitude) and bathymetric (sea depth) information with 50 m (25 m) discretization. Gravimeters were placed in the specialized equipment rack near the vessel's center, with the place of gravimeter installation determined relative to the reference point. The sensitive element of the gravimeter was located at the water level.

Primary processing of gravimeter output data was made in real time mode with the use of the *SeaGrav* software module. The *SeaGrav* module results yield gravity increments with corrections for the gravimeter's zero drift. The delay of resultant data caused by the time constant of the gravimeter and the digital filters was also taken into account in the processing. The quality of gravimetric observations was evaluated in real time in the course of data acquisition. Within the framework of the *Arktika-2014* expedition, gravimetric data along the pre-planned geophysical lines were obtained, with 9900 km total length. Precise gravimetric data in the area near the point of the Geographic North Pole were obtained for the first time ever.

All other key data on gravity and magnetic anomalies have been summarized in the course of various international projects (e.g., Gaina et al., 2011; Saltus et al., 2011). In particular, the most comprehensive map of anomalous magnetic fields of the Arctic and the grid of magnetic anomalies with 2×2 km cell size were produced by the *Geological Survey of Norway* as part of the *CAMP-GM* Project (Gaina et al., 2011). This group also produced a composite digital map of gravity field anomalies and a digital model with 10×10 km cell size (Gaina et al., 2011).

It is worth noting that a vast portion of the Russian shelf has been licensed for exploration by petroleum companies (Fig. 6) and for most of them, new commercial gravity and magnetic surveys have been conducted. All these data will become open source after several years. The new data have confirmed the anomalies known earlier and there are no fundamental changes in the regional character of magnetic and gravity anomalies. With these new data, the structure of the sedimentary basins of the Russian continental shelves can be resolved in more detail. An important discovery is the likely identification of new igneous provinces. Evidence for a large-size igneous province with volcanics at the base of the sedimentary basin and numerous probable intrusions within the stratigraphic section of the Chukchi Sea north of Wrangel Island have been found (its contours approximately correspond to the previously known magnetic anomaly). The igneous province in the area of De Long Islands was studied. Its area turned out to be larger than previously assumed. A new igneous province appears to be present in the area at the junction of the East Siberian Sea and the Lomonosov Ridge, as well as on the shelf along the western edge of the Eurasia Basin. The new magnetic and gravity data showed that magmatism played a key role in the formation history of the North Chukchi Basin and basins of the Laptev Sea. For the East Barents Sea, belts of Cretaceous dykes are readily detectable.

2.6. Offshore geodetic operations

An important aspect of the integrated geophysical surveys is the accurate determination of coordinates (positioning) of the research vessel. For this purpose two independent positioning systems for determining vessel position were used.

The primary system was the *SeaPath 330* satellite integrated navigation system using signals from the GPS/GLONASS satellite positioning systems. Due to the fact that the study area is situated in the Earth's high-latitude zone and hence beyond the zone of reception of any systems improving vessel positioning accuracy, data were collected in an autonomous mode, and no differential corrections were incorporated.

The secondary systems, *C-Nav-2050R* and *C-Nav-3050*, were used in order to corroborate and confirm location readings as well as for backup. During the mobilization period before the start of combined survey operations, calibration and accuracy checks were performed for these systems. These calibration operations also were carried out periodically for the entire period of the expeditions. However, the confidence zone of these operations ends at approximately 78° N, a location farther south than the survey areas. For this reason, in the period between the expeditions and receipt of corrections, an evaluation of accuracy characteristics of the primary positioning system relative to the secondary positioning system was made. Calculations were also performed on the positioning uncertainties by difference in coordinates obtained from these two systems. From the results of control tests in the expeditions *Arktika-2011*, *Arktika-2012* and *Arktika-2014*, the accuracy of operation of the main vessel positioning system was determined as being better than ±5 m with confidence level of 95%.

Instantaneous sea level was used as the elevation datum for geophysical surveys. Water depths in the survey's area varied within the range of 700–4500 m. Tide variations were not accounted for as this is not required by the IHO S-44 standard for depths in excess of 200 m for bathymetry surveys and hence for geophysical surveys as well.

2.7. Multi-beam bathymetric surveying

In the course of the bathymetric expedition *Arktika-2010* and the integrated geophysical expeditions *Arktika-2011 and Arktika-2014*, bottom relief was surveyed from the RV *Akademik Fedorov* with support of the nuclear icebreakers *Yamal* and *Rossiya*. Surveys of bottom relief were performed using an *EM122* (*Kongsberg Maritime AS*) multi-beam echosounder. In addition to the multi-beam echosounder, surveying with the single-beam echosdounder *EA600* (*Kongsberg Maritime AS*) was also conducted. The main objective of single-beam surveying was the control of data obtained from the multi-beam echosounder as well as depth control at the time of data processing.

Bottom relief surveying was performed by the research vessel *Akademik Fedorov* in severe ice conditions in conjunction with a nuclear icebreaker. Because the main objective of the expeditions *Arktika-2011 and Arktika-2014* was to obtain good-quality geophysical data, bathymetric surveying was made along the pre-planned geophysical survey lines. Vessel speed during performance of the survey ranged from 4 to 6 knots depending on ice conditions. This vessel speed ensured optimal quality of acoustic coverage of the seabed within the swath, making it possible to obtain a continuous digital model of the relief without considerable blanks.

Computerized multi-beam echosounder control systems using *Seafloor Information System* software (*Kongsberg Maritime AS*) produced seabed relief surveys. Continuous 24-h monitoring by hydrographers and engineers resulted in uninterrupted round-the-clock operation of positioning/surveying. In addition, data quality monitoring and records of measurements of sound velocity in water were logged. All data were properly marking and annotated, and were maintained in accordance with pre-determined instructions. Hydrographers on watch also maintained scheduled documentation of performance quality with depth reading difference determinations between depths measured by the central beam of the multi-beam echosounder *EM122* and depths measured by the *EA600* single-beam echosounder.

The approach of conducting bathymetric surveying in combination with geodetic operations ensured: (1) implementation of navigation along pre-planned survey lines, (2) quality control of vessel positioning determinations, (3) control of completeness and confidence of obtained bathymetric data, (4) uninterrupted recording of bathymetric data, and (5) obtaining necessary corrections for depth adjustment.

In accordance with the classification of the IHO S-44 Standard, seabed relief surveying was conducted consistent with requirements of the second category of accuracy. The width of the swath covered by regular bathymetry grids was 3–4 km.

2.8. Field surveys on Arctic islands

Since 1937 the *Russian Academy of Sciences* has conducted many field expeditions focused on geological studies of islands and adjacent continental lands of the Arctic region. During the last decade, the geology of almost all islands of the Russian Arctic was re-examined. Most of these operations were organized by the *Federal Subsoil Resources Management Agency* (*VSEGEI* and *VNIIOkeangeologia*, Petrov, Proskurnin, Kos'ko, Korago, Sobolev, Gusev, Rekant et al.). Investigations also were conducted by geologists from the *Russian Academy of Sciences* (Sokolov, Kuzmichev, Tuchkova, Danukalova, Karyakin, Lobkovsky, Rogov et al., Moscow; Vernikovsky, Metelkin, Nikitenko et al., Novosibirsk; Prokopiev, Yakutsk; Akinin, Magadan), *St. Petersburg State University* (Ershova, Khudoley et al.) and *Moscow State University* (Nikishin et al.). During the last 7 years, *Rosneft* has undertaken geological investigations of almost all islands of the Russian Arctic as well as the study of cores from boreholes from the Arctic shelf. As a result, we have had access to: (1) a revised version of the stratigraphy of the Arctic islands, (2) state-of-the-art age dating of almost all igneous complexes on all islands, (3) age dating of detrital zircons from almost all stratigraphic intervals on all islands, (4) new paleomagnetic data, and (5) new models of the geological history of the Arctic islands. All of these new data are vital for better understanding of the geological history of the Arctic Ocean.

3. Collected data summary

All planned surveys within the framework of the Russian Arctic Ocean Mega Project have been completed. As a result of surveys conducted between 2005 and 2020, the database as of today includes 35,000 km of bathymetric profiles, more than 23,000 km of multichannel seismic (MCS) lines, more than 4000 km of wide-angle refraction/reflection (WARR) data, 150 refracted sonobuoy seismic soundings, approximately 10,000 km of gravity surveys, and a large amount of ocean bottom rock samples. All geophysical surveys along the pre-planned survey lines have been made possible only through the support of nuclear icebreakers.

In total, during three years of expeditions *Arktika-2011*, *Arktika-2012* and *Arktika-2014*, the vast majority of planned MSC lines were successfully acquired. Unfortunately, under conditions of solid ice cover, the long seismic streamer (4500 m and more) could be deployed to a lesser extent than planned. This was especially the case for the *Arktika-2011* expedition when ice conditions were extremely severe. In contrast, for the *Arktika-2014* expedition, more than half of the planned MCS lines could be acquired with the long seismic streamer, owing to improved ice conditions that year.

Taking rock samples on slopes of submarine highs turned out to be a challenging task. Utilization of a bottom dredge and a grab sampler gives no guarantee that samples taken are just bedrock. Drilling 2-m deep boreholes showed that rocky formations have moved along the slope and became intermingled with loose sediments. The most effective method for taking samples of bedrock proved to be through the deployment of the scientific research submarine (SRS) equipped with special manipulators using *GEOSURVEY GIN RAS* methodology in the course of the *Mendeleev-2014* and *Mendeleev-2016* expeditions. Utilization of the SRS made it possible to locate the most reliable places for sampling with manned underwater vehicles. The unique methodology available to the *Mendeleev-2014* and *Mendeleev-2016* expeditions enabled the construction of a composite stratigraphic column comparable to the results produced by deep drilling.

Bathymetric and subbottom surveys used jointly with other methods of studying the bottom of the Eurasia Basin demonstrated a high level of effectiveness, but could only be acquired when a nuclear icebreaker was

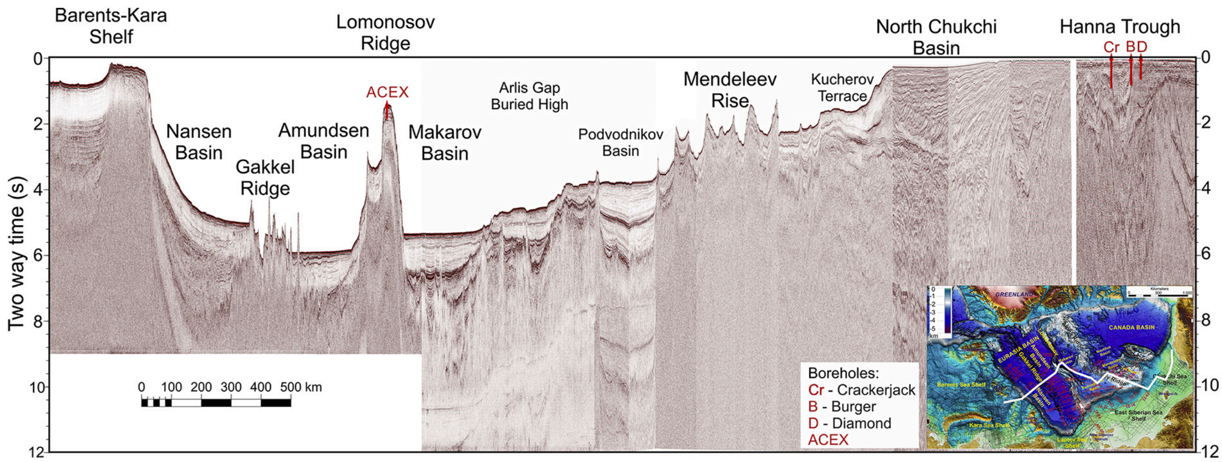

Fig. 15. Composite seismic section running from the Barents-Kara shelf to Alaska shelf. Profile location is shown on the map.

used. The detailed bathymetry and geological structure of the uppermost 100 m were resolvable, facilitating the study of the rift valley area of the Gakkel Ridge as well as present-day geological processes on the continental slope and on the Nansen basin floor.

4. Seismic data processing

Processing of the MSC refracted sonobuoy seismic soundings and WARR seismic data were performed by several Russian and international geophysical companies, in particular *Rosgeo, SMNG, Sevmorgeo, MAGE, Geolab, GNINGI, WGP*. As the processing standard, techniques of the company *ION,* with many years of geophysical experience, were used and many seismic lines were acquired and/or processed with their participation. The participating Russian geophysical companies utilized known and proven software packages (*Paradigm Echos*, *SeisSpace ProMAX, GEOLAB* and others) and processing was undertaken in accordance with international standards for seismic data processing.

4.1. MCS data processing

The generalized processing sequence for MCS data incorporated modern processing procedures. Interference waves and irregular noise suppression and multiple wave attenuation were the main processing procedures for stable tracking of seismic horizons and acoustic basement.

LIFT (Leading Intelligent Filter Technology) procedure was used to suppress low-speed surface interference waves as well as impulse and irregular noise. LIFT provides effective suppression of interference waves of various types with conservation of signal amplitudes and phase characteristics. This technique is based on the extraction of signal and noise in different frequency ranges from seismic data, attenuation of interference waves to a level less than or equal to the signal in each frequency range using velocity filters, and calculation of the sum of the residual signal components that form the signal part of the seismic data.

Multiple wave energy that is generated in offshore seabed seismic surveys and recorded on seismic records were predicted by combining mathematical extrapolation of the wavefield through the water column and calculation of the reflectivity from the seabed. The WEMA (Wave Equation Multiple Attenuation) procedure was used primarily for simulation and adaptive subtraction of multiple waves. Seabed reflectivity in relation to the amplitudes of upward and downward waves was used to successfully suppress multiple waves. In WEMA, instead of estimating the seabed reflectivity, a least-squares calculation of the space-time variable of the matching filter was performed. No additional assumptions about the nature and complexity of the seabed were required to apply WEMA. Also, multiple wave attenuation was performed with the surface-related multiple elimination (SRME) as well as Radon transform procedures with the help of FK-transformation. Predictive deconvolution was applied to increase the seismic resolution, the frequency spectrum, and suppress reverberant waves in the shallow water part of the seismic lines.

After seismic stacking 2D-FX deconvolution, spectral and amplitude balancing and two-way coherency filtration were applied. Increased vertical resolution was achieved by applying spectrum alignment. This has allowed for effectively compensating for the non-uniformity of definitive sections primarily within the section characterized by low acoustic velocities.

Several iterations of velocity analyses were performed for the MCS data. In addition, sonobuoy seismic soundings data were used for obtaining final velocity models for each MCS line and for constructing depth sections. The data of sonobuoy seismic soundings were especially helpful for obtaining velocity models for the MCS lines acquired with short seismic streamers. The short seismic streamer records from MCS demonstrated low sensitivity to variations of stacking velocities. In general, stacking, supported by reliable velocity functions from sonobuoy seismic soundings (150 in total), produced good quality seismic sections, especially in the noiseless environment of abyssal seas.

The final processed seismic data were time or depth sections with 6 CDP fold for short seismic streamer data (600 m), and time or depth sections with minimum 45 CDP fold for long seismic streamer data (4500 m. and longer).

4.2. Seismic data interpretation

In Russia, interpretation of the seismic lines of the *Arktika* expeditions was conducted mainly by three groups: (1) the *VSEGEI* (St. Petersburg) group (e.g., Daragan-Sushchova et al., 2015; Petrov, 2017; Petrov and Smelror, 2019, 2) the *VNIIOkeangeologia*, St. Petersburg group (e.g. Poselov et al., 2012; Piskarev et al., 2019), (3) the so-called Moscow group (*Moscow State University*, *Rosneft* and *GEOSURVEY GIN RAS*) (e.g. Nikishin et al., 2014, 2018, 2019). Our Paper-2 summarizes the principal results of the interpretation of Russian seismic lines for the Arctic (Nikishin et al., 2021a).

Sonobuoy seismic soundings data were obtained for most seismic lines. A part of the processing results has been presented elsewhere (Daragan-Sushchova et al., 2015; Petrov, 2017; Piskarev et al., 2019; Butsenko et al., 2019; Petrov and Smelror, 2019). Results of wide-angle refraction/reflection surveys were processed and published (Lebedeva-Ivanova et al., 2011, 2019; Poselov et al., 2012; Petrov et al., 2016; Petrov, 2017; Kashubin et al., 2018; Piskarev et al., 2019) and included in international reviews (e.g. Pease et al., 2014; Lebedeva-Ivanova et al., 2019).

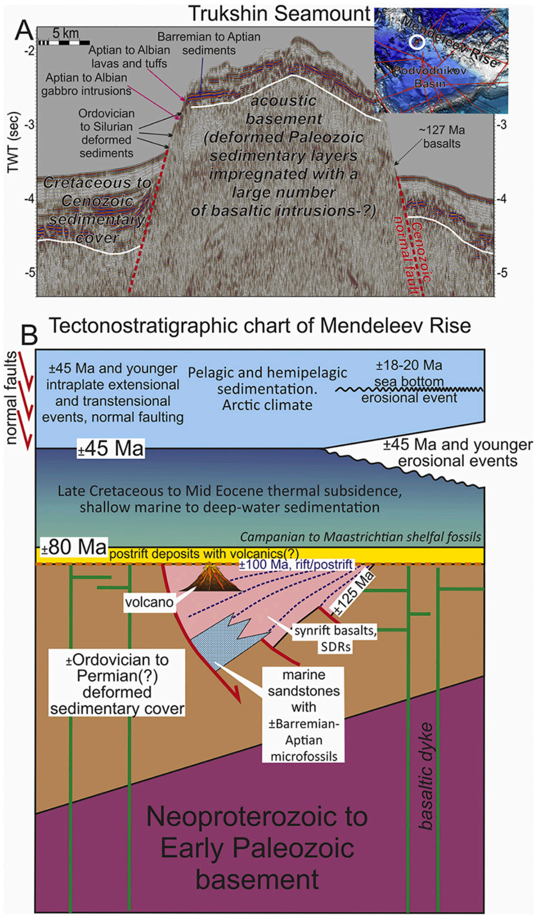

Fig. 16. A. Fragment of seismic section ARC-12-05 for the Trukshin Seamount (Mendeleev Rise). Location of the section is shown on the map. The seamount is denoted by a white circle. The approximate locations of Russian samples for this seamount are presented. Ages of basalts are after Morozov et al. (2013) and Skolotnev et al. (in preparation). Fossils after Skolotnev et al. (2019). B. Tectonostratigraphic chart of the Mendeleev Rise. The ages are based on Morozov et al. (2013), Skolotnev et al. (2019), and Mukasa et al. (2020),

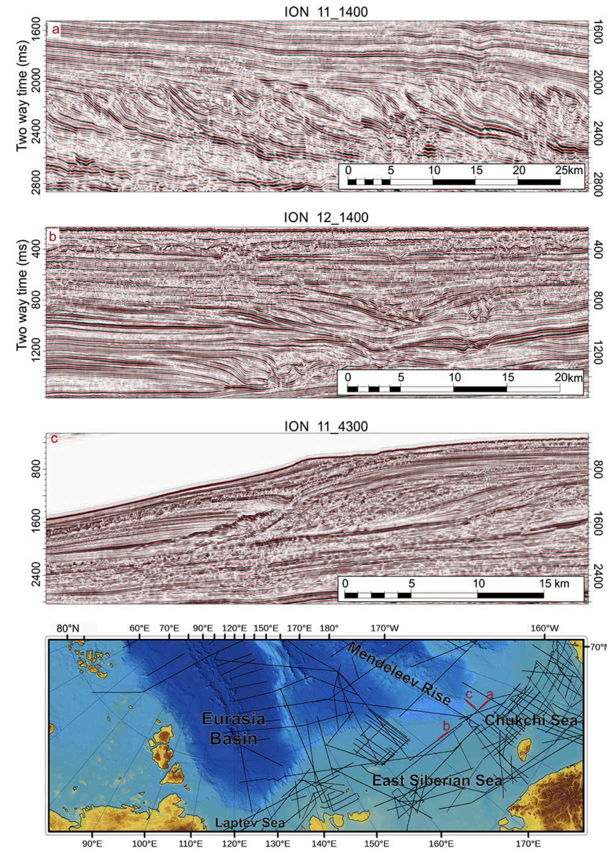

Fig. 17. Examples of seismic sections for shelf and continental slope, North Chukchi Basin.

5. International cooperation in the investigation of the Arctic Ocean

Russia has taken part in many international projects aimed at the investigation of the Arctic, including in particular, the first scientific drilling expedition to the central Arctic Ocean in September 2004. Plans for this first-ever event were carefully crafted over several years and included a fleet of three icebreaker-class ships: a drilling vessel, the *Vidar Viking*, which remained at a fixed location and suspended over 1600 m of drill pipe through the water column and into the underlying sediments, a Russian nuclear icebreaker, *Sovetskiy Soyuz*, and the diesel-electric Swedish icebreaker *Oden*. The *Sovetskiy Soyuz* and *Oden* protected the *Vidar Viking* by breaking heavy flows into smaller bits to allow the *Vidar Viking* to stay positioned in order to drill and recover the sediment cores. The *Sovetskiy Soyuz* conducted the first "attack" on oncoming heavy flows, whereas *Oden* was the last defense in protecting the drilling operation against the oncoming ice (Backman et al., 2006). When conducting seismic surveys in the Arctic Ocean, many international companies participated on a commercial basis.

Field surveys on the Russian Arctic islands were often conducted by international teams of geologists, organized by *VSEGEI* and institutes of the *Russian Academy of Sciences*. In these operations geologists took part from Sweden (D. Gee, V. Pease), USA (E. Miller), Germany (C. Brandes, D. Franke et al.), UK (R. Scott) and other countries. Other successful international projects included, for example, the *Swedish-Russian-US Arctic Ocean Investigation of Climate-Cryosphere-Carbon Interactions (SWERUS-C3)*.

One of the products of international cooperation was the *Tectonic Map of the Circumpolar Arctic (TeMAr)*, which was compiled under the *International Project Atlas of Geological Maps of the Circumpolar Arctic*. The project has been ongoing since 2004 by geological surveys of the Arctic countries supported by the *UNESCO Commission for the Geological Map of the World (CGMW)* and national programs for scientific substantiation for the *United Nations Commission for the Law of the Sea (UNCLOS)*. The *TeMAr* working group coordinated by Russia (*VSEGEI*) includes leading scientists from geological surveys, universities and national academies of science of Denmark, Sweden, Norway, Russia, Canada, the USA, France, Germany and Great Britain (see Petrov et al., 2016).

6. Results and discussion

Results of all these operations were consolidated into GIS-projects (e.g. *Petrel, ArcGIS*). With 2D seismic data we have been able to construct composite regional seismic profiles for all regions (Fig. 15) tied to drilling and magnetic and gravity anomalies data. We have also correlated the seismic-based stratigraphy across multiple deep-water and shelf basins. This has enabled the construction of an integrated seismic-stratigraphic framework for the entire Arctic Ocean and its shelves (see Paper-2).

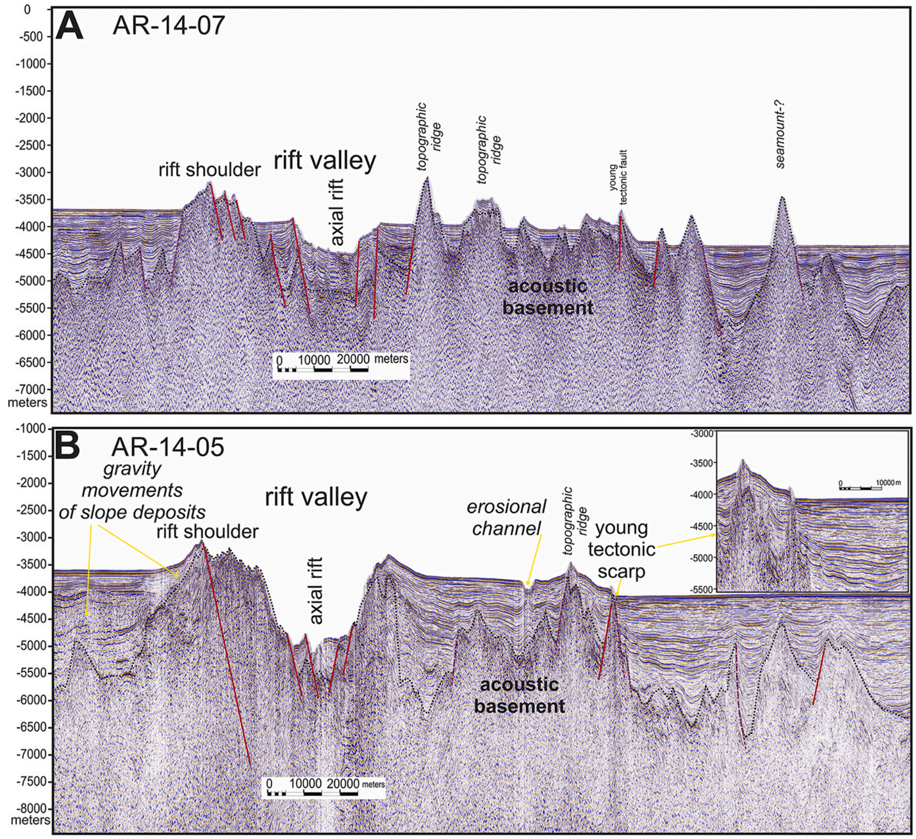

Fig. 18. Seismic sections across the Gakkel Rift valley. For location see Fig. 7. Modified after Nikishin et al. (2018).

Integration of seismic and sampling data from submarine slopes of the Mendeleev Rise acquired by SRS during the *Mendeleev-2014* and *Mendeleev-2016* expeditions has enabled us to construct a model for the structure and stratigraphy of this feature. Skolotnev et al. (2019) suggested that based on subsea observations, Paleozoic deposits appear deformed and are not horizontally oriented (it should be noted that we cannot confirm this one way or the other). It is important to point out that on seismic sections all Paleozoic complexes look like acoustic basement, i.e., opaque, with no apparent coherent internal reflections. This suggests that the Paleozoic deposits are likely to be deformed into folds that image poorly due to their likely steep dip. At one site on the Trukshin Seamount (Skolotnev et al., 2019) samples of sandstones were taken at the base of a section of horizontal architecture that is well imaged on seismic sections. These sandstones were found to have Barremian-Aptian microfossils and detrital zircons with an age of about 120 Ma (Skolotnev et al., in preparation). This might indicate that the development of the sedimentary and volcanic section of the Mendeleev Rise started approximately at the Barremian/Aptian boundary.

It was also found that among exposures of Paleozoic rocks, many instances of basalt, dolerite and basaltic tuff (Skolotnev et al., 2017, 2019) are present with isotopic ages of about 105–124 Ma (Skolotnev et al., in preparation). From the data acquired during the *Arktika-2012* expedition, an isotopic age of approximately 127 Ma was obtained for basalts collected from the Trukshin Seamount (Morozov et al., 2013). The large number of basalt outcrops indicates that the Paleozoic section as well as the entire basement underlying the Mendeleev Rise are impregnated with basaltic intrusions. Arctic Ocean researchers obtained isotopic ages of basalts in the intervals of 118–112, 105–100 and 90–70 Ma at the northern part of the Chukchi Borderland (Mukasa et al., 2020). Our stratigraphic model of the Trukshin Seamount and the entire Mendeleev Rise is shown in Fig. 16. The main conclusion is that deformed Paleozoic sedimentary deposits cover the continental basement there and that the Paleozoic deposits are impregnated with a large number of basaltic intrusions of Aptian-Albian age. The section covering the Mendeleev Rise comprising sandstones, tuffs and basalts, ranges in age from Barremian to Aptian; the presence of Triassic and Jurassic deposits has not yet been substantiated.

In the North Chukchi Basin and on the continental slope of the Amerasia and Eurasia basins, clinoforms within various sedimentary sequences are well resolved (Fig. 17), and provide the basis for developing the seismic stratigraphic framework for the Cretaceous and Cenozoic of the Arctic Ocean.

The Gakkel Ridge is a classic example of an ultra-slow spreading mid-oceanic ridge (Dick et al., 2003; Nikishin et al., 2018). For this area we acquired several multi-channel seismic lines and subbottom profiler lines (Figs. 18, 19). These data will contribute to a better understanding of the geodynamics of ultra-slow spreading. Seismic sections show that the Gakkel Ridge is asymmetrical and that along the strike of the rift valley, seamounts, which may be of volcanic or tectonic origin, are present. We also observe young normal faults along the Gakkel Ridge trend. These new data will be valuable for further special analysis and new expeditions.

The data collected from the Arctic Ocean confirm the likely presence of volcanoes and volcanic complexes of Cretaceous age, which were detected earlier (e.g. Coakley et al., 2016; Mukasa et al., 2020). For example, our data confirmed that Aptian-Albian lavas and intrusions occur on slopes of the Mendeleev Rise. Seismic data demonstrate the presence of many seaward dipping reflectors (SDR) within sections in

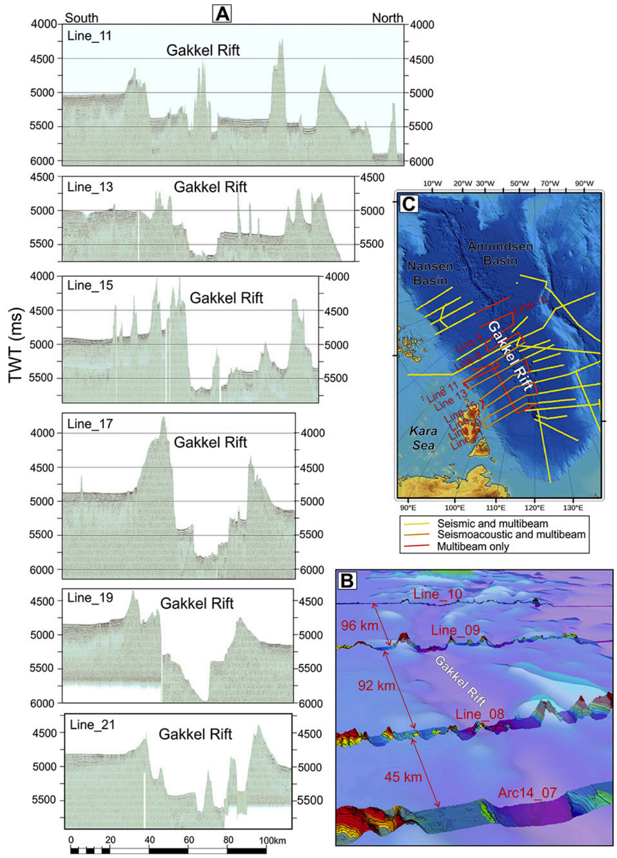

Fig. 19. Subbottom profiler and multibeam data for the Eurasia Basin and Gakkel rift valley. A. Subbottom lines for the Gakkel Rift region (preliminary field processing). B. Multibeam profiles for the Gakkel Rift region. Background colored map is official bathymetry of the Eurasia Basin (IBCAO, Jakobsson et al., 2012). Note the significant difference between the new multibeam data and published bathymetry. C. Location map and data types.

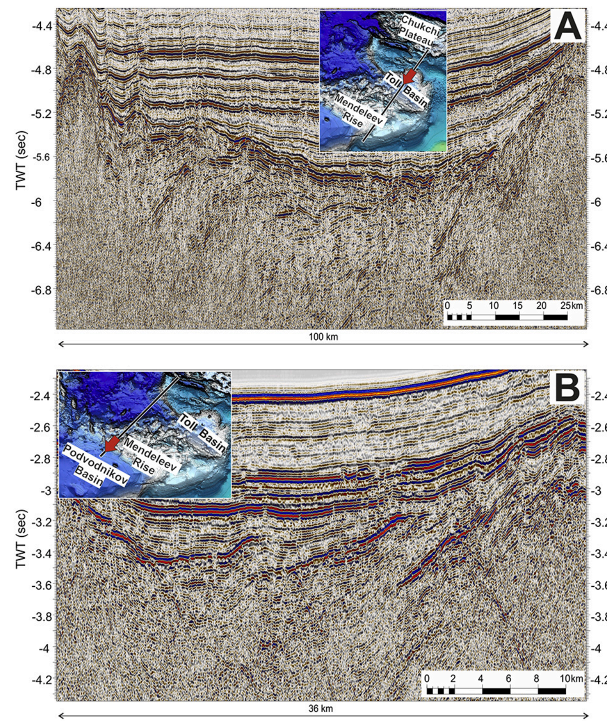

Fig. 20. Examples of seismic sections for regions of the Mendeleev Rise and Toll Basin. SDR-like seismic units are proposed. Possible half-grabens are filled by basalts.

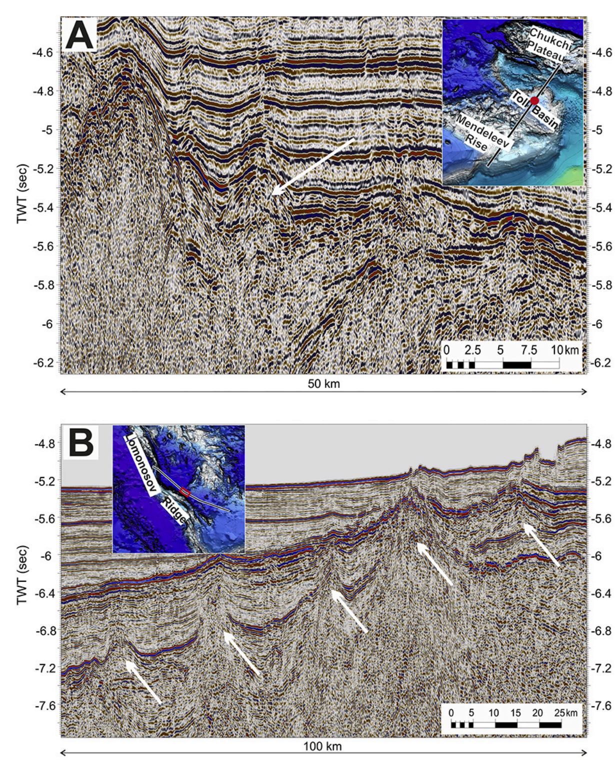

Fig. 21. Examples of seismic sections for regions of the Makarov and Toll basins. Possible volcanic edifices are indicated by arrows.

the Mendeleev Rise area and of the adjacent Podvodnikov and Toll basins (Fig. 20). Many buried seamounts, interpreted as volcanic edifices, have been found in the Mendeleev Rise and in the Podvodnikov, Makarov, and Toll basins, as well as on the Lomonosov Ridge (Fig. 21). Our data show the existence of a vast volcanic edifice in the area of the Alpha-Mendeleev Rise, which was predicted by analyses of magnetic anomalies (e.g., Gaina et al., 2011; Saltus et al., 2011; Det al. et al., 2013; Oakey and Saltus, 2016).

On seismic sections across the deep-water part of the Arctic Ocean, we observe many half-grabens that are characteristic of continental rift systems. At the same time, we found at least two V-shaped structures suggestive of rift valleys not typical of continental rifts (Fig. 22). Alternative interpretations of such structures are presented in Paper-2.

On the shelves of the Russian East Arctic in the Laptev, East Siberian and Chukchi seas, many synrift to postrift sedimentary basins with complex structure are identified. On many regional seismic sections across these basins, the seismic Moho is clear, occurring at depths between 9 and 11 s (Figs. 23, 24). This suggests that for these basins better constrained geometrical models for the structure of rift systems can be constructed for the entire thickness of the crust. The new data therefore make it possible to develop well-constrained models for the origin of these basins.

Thicknesses of sedimentary deposits in excess of 10 s (more than 20 km) have been observed in the North Chukchi Basin (Figs. 15, 24). An obvious and first-order question that will be addressed in Paper-2 is how such super-deep basins originate and what type of underlying crust is associated with them.

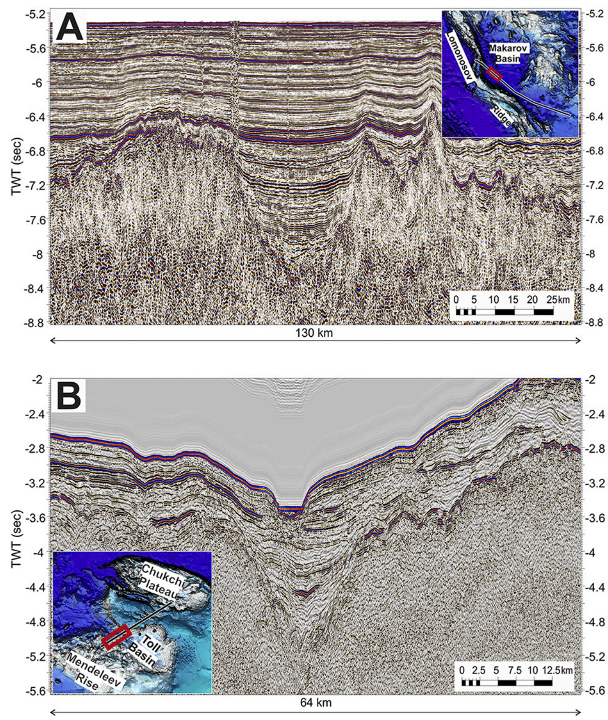

Fig. 22. Example of seismic sections for regions of the Makarov and Toll basins. V-shaped troughs are filled by sediments.

The Arctic Ocean can be called a lake-ocean during some periods of its history (e.g., Stein, 2008). At least from Cretaceous time until the present, it has been situated in the vicinity of the geographic North Pole. Its sediments contain records of paleoclimatic changes for the time period of more than 100 million years. To a large extent, sedimentation and lithology of sediments were controlled by the paleoclimate. On seismic sections we recognize packages of reflections of variable amplitude representing variable lithologies that can be traced regionally. Seismic data allow us to infer different climatic epochs in the history of the Arctic (see Paper-2).

An example of data integration focused on the understanding of the geological structure of the Podvodnikov Basin is shown in Fig. 25. Interpretation of this seismic section shows that synrift and postrift complexes can be identified. The synrift complex contains unidirectional dipping bright reflectors, which can be interpreted as synrift deposits with interbedded basalts (SDR-like units). The velocity model shows that in the synrift complex, rocks with high seismic velocities are present, which can be interpreted as basalt. Data on magnetic and gravity anomalies also exhibit a large anomaly in this basin (the High Arctic Magnetic High Domain of Gaina et al., 2011; Oakey and Saltus, 2016), which is thought to be associated with HALIP basalts (Oakey and Saltus, 2016).

Integration of the entirety of the new data available enables us to develop a comprehensive stratigraphic and regional tectonic structural framework (see Paper-2) and a new model for the Mesozoic-Cenozoic geological evolution of the Arctic Ocean (see Paper-3).

7. Conclusions

The Russian Arctic Ocean Mega Project was undertaken in the past 15–20 years. A very substantial amount of new data was obtained:

(1) More than 23,000 km of multi-channel seismic lines, enabling the construction of a new comprehensive stratigraphic and regional tectonic structural framework and a new model for the Mesozoic-Cenozoic geological evolution of the Arctic Ocean.
(2) More than 4000 km of wide-angle refraction/reflection lines enabling the construction of models for the structure of the Earth's crust for various regional features.
(3) For the Mendeleev Rise, many rock samples were taken on slopes of seamounts in the course of three expeditions. Notably, sampling was undertaken with the use of drilling and a scientific research submarine. These data facilitates creation of a model for the structure of the Mendeleev Rise.
(4) *The Ministry of Natural Resources and Environment of the Russian Federation*, as well as *Rosneft* and *Gazprom* made a major effort in setting the stage for seismic surveying and the study of magnetic and gravity anomalies. Contributing to this effort were several new commercial wells that have recently come available. Integration of all new data for the shelf provides a robust base for improvement of our understanding of the entire Arctic Ocean.
(5) New subbottom profiles for the Eurasia Basin have been acquired. This makes it possible to better understand the structure of the Gakkel Ridge and Quaternary processes in the entire Eurasia Basin.
(6) New data on the bathymetry of the Arctic Ocean have been collected, improving the previously poorly studied bathymetry in major parts of this ocean.
(7) A large body of additional new data including, for example, bottom dredging, gravity and magnetic anomalies, has been obtained.

Our expeditions demonstrated that for an effective investigation of the Arctic Ocean, deployment of modern icebreakers and submarines is vital.

Declaration of Competing Interest

We have no conflict of interest.

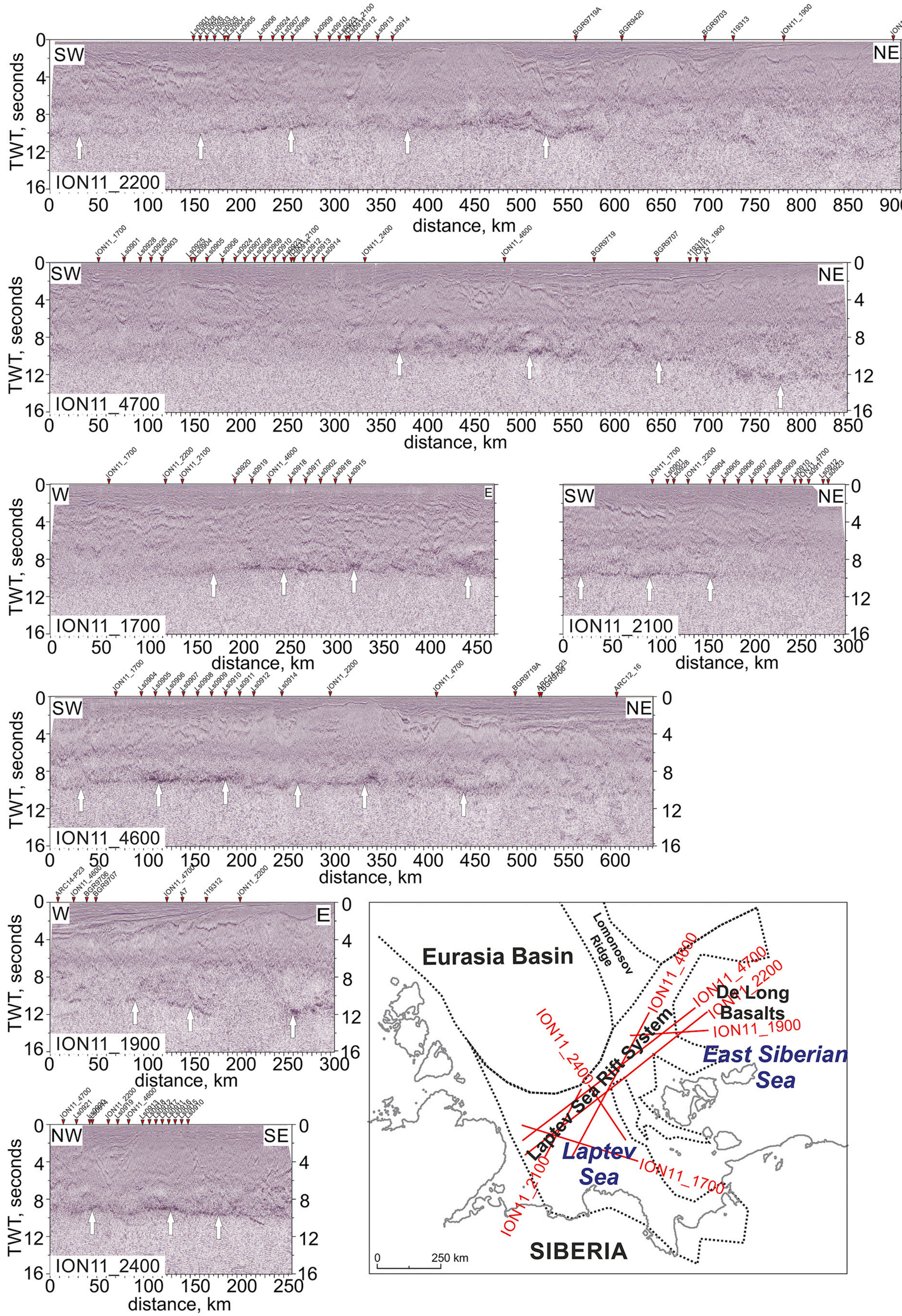

Fig. 23. Examples of seismic sections for the Laptev and East Siberian seas. Seismic Moho (white arrows) is well expressed within the synrift-postrift basins.

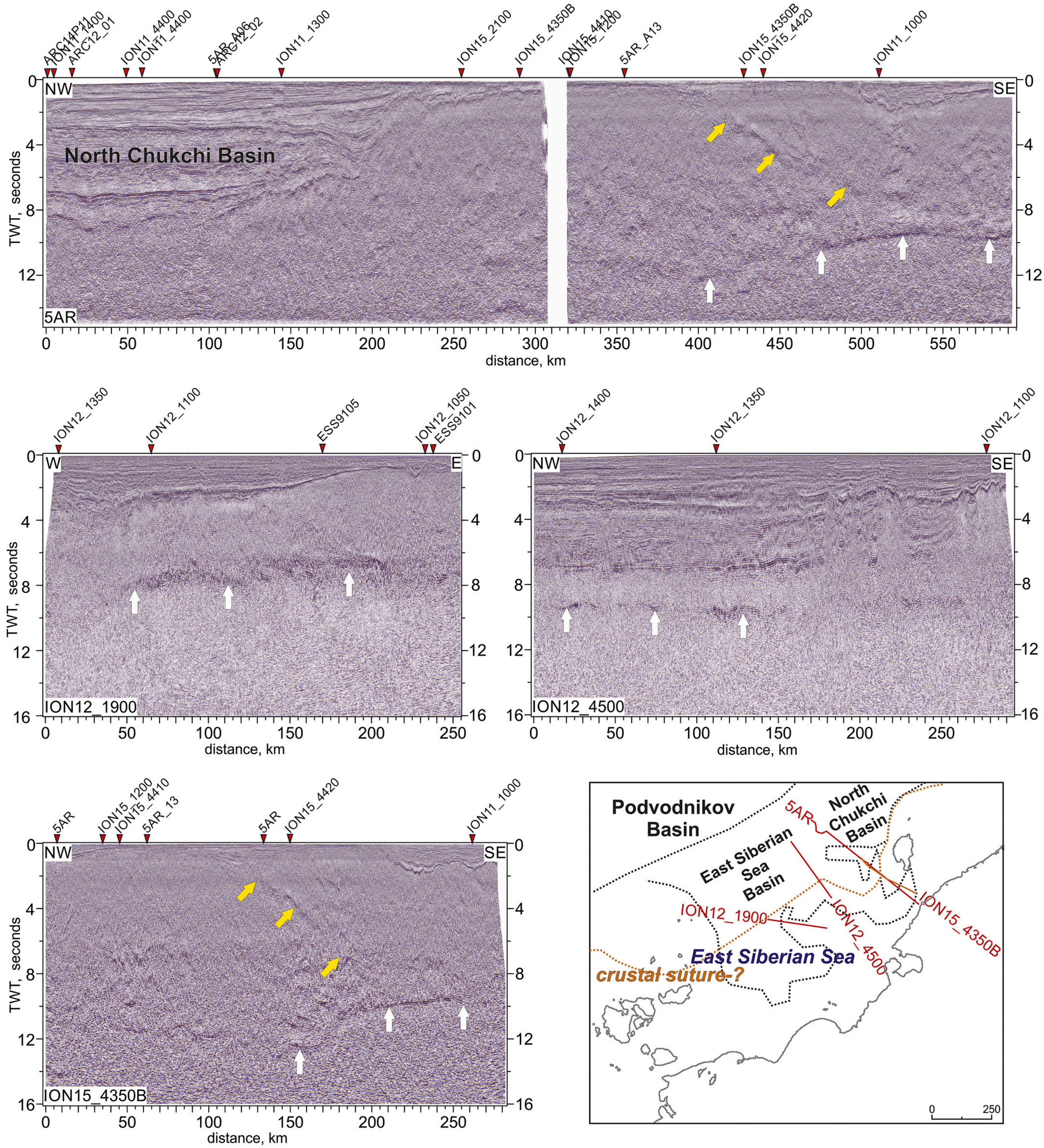

Fig. 24. Examples of seismic sections for the East Siberian and Chukchi seas. Seismic Moho (white arrows) is well recognized for synrift-postrift basins. Yellow arrows show possible crustal suture. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

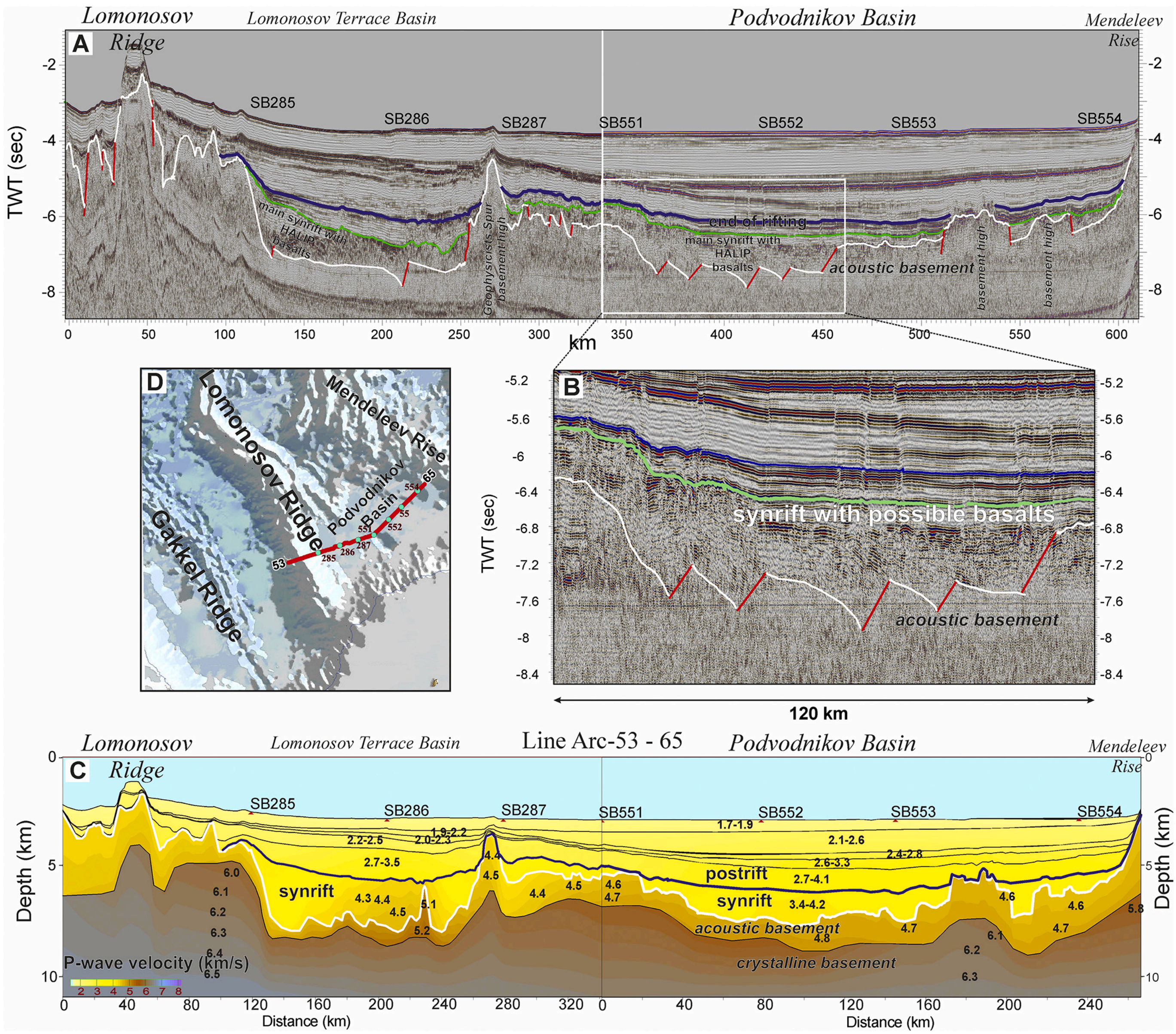

Fig. 25. An example of seismic data interpretation for the Podvodnikov Basin. A. Interpretation of the MCS seismic section (performed at *Moscow State University*). Key elements are synrift and postrift complexes. B. Fragment of this seismic sections with synrift unit and rift/postrift boundary. Synrift complex hasbright reflectors dipping in one direction. C. Seismic velocity model along the same seismic sections based on refracted sonobuoys seismic soundings data (carried out by *VNIIOkeangeologia*). Interpretations by two different teams are very similar. Synrift complex has relatively high seismic velocity. We propose that the synrift complex is partly associated with basalts. D. Location of the section. Blue circles are location of sonobuoys and its numbers. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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References

Aleksandrova, G.N., 2016. Geological evolution of Chauna Depression (North-Eastern Russia) during Paleogene and Neogene. 1. Paleogene. (in Russian). Bull. Moscow Soc. Nat. Geol. Ser. 91, 148–164 (in Russian).

Backman, J., Moran, K., McInroy, D.B., Mayer, L.A., the Expedition 302 Scientists, 2006. Proc. IODP, 302. College Station TX (Integrated Ocean Drilling Program Management International, Inc.). https://doi.org/10.2204/iodp.proc.302.101.2006.

Bird, K.J., Houseknecht, D.W., Pitman, J.K., 2017. Geology and assessment of undiscovered oil and gas resources of the Hope Basin Province, 2008. In: Moore, T. E., Gautier, D.L. (Eds.), The 2008 Circum-Arctic Resource Appraisal. U.S. Geological Survey Professional Paper 1824, Reston, Virginia, pp. 1–9. https://doi.org/10.3133/pp1824D.

Bruvoll, V., Kristoffersen, Y., Coakley, B.J., Hopper, J.R., Planke, S., Kandilarov, A., 2012. The nature of the acoustic basement on Mendeleev and northwestern Alpha ridges, Arctic Ocean. Tectonophysics 514–517, 123–145. https://doi.org/10.1016/j.tecto.2011.10.015.

Butsenko, V.V., Poselov, V.A., Zholondz, S.M., Smirnov, O.E., 2019. Seismic attributes of the Podvodnikov basin basement. Dokl. Earth Sci. 488 (2), 1182–1185. https://doi.org/10.1134/S1028334X19100015.

Coakley, B., Brumley, K., Lebedeva-Ivanova, N., Mosher, D., 2016. Exploring the geology of the Central Arctic Ocean; understanding the basin features in place and time. J. Geol. Soc. Lond. 173, 967–987. https://doi.org/10.1144/jgs2016-082.

Craddock, W.H., Houseknecht, D.W., 2016. Cretaceous–Cenozoic burial and exhumation history of the Chukchi shelf, offshore Arctic Alaska. Am. Assoc. Pet. Geol. Bull. 100, 63–100. https://doi.org/10.1306/09291515010.

Daragan-Sushchova, L.A., Petrov, O.V., Sobolev, N.N., Daragan-Sushchov, Yu.I., Grin'ko, L.R., Petrovskaya, N.A., 2015. Geology and tectonics of the Northeast Russian Arctic region, based on seismic data. Geotectonics 49, 469–484. https://doi.org/10.1134/S0016852115060023.

Dick, H.J.B., Lin, J., Schouten, H., 2003. An ultraslow-spreading class of ocean ridge. Nature 426, 405–412. https://doi.org/10.1038/nature02128.

Doré, A.G., Lundin, E.R., Gibbons, A., Sømme, T.O., Tørudbakken, B.O., 2015. Transform margins of the Arctic: a synthesis and re-evaluation. Geol. Soc. Lond. Spec. Publ. 431, 63–94. https://doi.org/10.1144/SP431.8.

Døssing, A., Jackson, H.R., Matzka, J., Einarsson, I., Rasmussen, T.M., Olesen, A.V., Brozena, J.M., 2013. On the origin of the Amerasia Basin and the High Arctic large Igneous Province—results of new aeromagnetic data. Earth Planet. Sci. Lett. 363, 219–230. https://doi.org/10.1016/j.epsl.2012.12.013.

Dove, D., Coakley, B., Hopper, J., Kristoffersen, Y., Team, H.G., 2010. Bathymetry, controlled source seismic and gravity observations of the Mendeleev ridge; implications for ridge structure, origin, and regional tectonics. Geophys. J. Int. 183, 481–502. https://doi.org/10.1111/j.1365-246X.2010.04746.x.

Embry, A.F., 1990. Geological and geophysical evidence in support of anticlockwise rotation of northern Alaska. Mar. Geol. 93, 317–329.

Franke, D., 2013. Rifting, lithosphere breakup and volcanism: Comparison of magma-poor and volcanic rifted margins. Mar. Pet. Geol. 43, 63–87. https://doi.org/10.1016/j.marpetgeo.2012.11.003.

Gaina, C., Werner, S.C., Saltus, R., Maus, S., 2011. Chapter 3 Circum-Arctic mapping project: new magnetic and gravity anomaly maps of the Arctic. Geol. Soc. Lond. Mem. 35, 39–48. https://doi.org/10.1144/M35.3.

Grantz, A., Clark, D.L., Phillips, R.L., Srivastava, S.P., 1998. Phanerozoic stratigraphy of Northwind Ridge, magnetic anomalies in the Canada Basin, and the geometry and timing of rifting in the Amerasia Basin. Arctic Ocean. Geol. Soc. Am. Bull. 110, 801–820.

Homza, T.X., Bergman, S.C., 2019. A Geologic Interpretation of the Chukchi Sea Petroleum Province. The American Association of Petroleum Geologists, Offshore Alaska, USA. https://doi.org/10.1306/AAPG119.

Houseknecht, D.W., Wartes, M.A., 2013. Clinoform deposition across a boundary between orogenic front and foredeep - an example from the Lower Cretaceous in Arctic Alaska. Terra Nova 25, 206–211. https://doi.org/10.1111/ter.12024.

Houseknecht, D.W., Craddock, W.H., Lease, R.O., 2016. Upper Cretaceous and Lower Jurassic strata in shallow cores on the Chukchi Shelf, Arctic Alaska. In: USGS Prof. Pap, 1814, p. 37. https://doi.org/10.3133/pp1814C.

Hutchinson, D.R., Jackson, H.R., Shimeld, J.W., Chapman, C.B., Childs, J.R., Funck, T., Rowland, R.W., 2009. Acquiring marine data in Canada Basin, Arctic Ocean. EOS Transactions 90, 197–204.

Ilhan, I., Coakley, B.J., 2018. Meso–Cenozoic evolution of the southwestern Chukchi Borderland, Arctic Ocean. Mar. Pet. Geol. 95, 100–109. https://doi.org/10.1016/j.marpetgeo.2018.04.014.

Jakobsson, M., Backman, J., Rudels, B., Nycander, J., Frank, M., Mayer, L., Jokat, W., Sangiorgi, F., O'Regan, M., Brinkhuis, H., King, J., Moran, K., 2007. The early Miocene onset of a ventilated circulation regime in the Arctic Ocean. Nature 447, 986–990. https://doi.org/10.1038/nature05924.

Jakobsson, M., Mayer, L., Coakley, B., Dowdeswell, J.A., Forbes, S., Fridman, B., Hodnesdal, H., Noormets, R., Pedersen, R., Rebesco, M., Schenke, H.W., Zarayskaya, Y., Accettella, D., Armstrong, A., Anderson, R.M., Bienhoff, P., Camerlenghi, A., Church, I., Edwards, M., Gardner, J.V., Hall, J.K., Hell, B., Hestvik, O., Kristoffersen, Y., Marcussen, C., Mohammad, R., Mosher, D., Nghiem, S. V., Pedrosa, M.T., Travaglini, P.G., Weatherall, P., 2012. The International Bathymetric Chart of the Arctic Ocean (IBCAO) Version 3.0. Geophys. Res. Lett. 39 https://doi.org/10.1029/2012GL052219 n/a-n/a.

Jakobsson, M., Mayer, L.A., Bringensparr, C., et al., 2020. The international bathymetric chart of the Arctic Ocean version 4.0. Sci. Data 7, 176. https://doi.org/10.1038/s41597-020-0520-9.

Jokat, W., Ickrath, M., 2015. Structure of ridges and basins off East Siberia along 81°N, Arctic Ocean. Mar. Pet. Geol. 64, 222–232. https://doi.org/10.1016/j.marpetgeo.2015.02.047.

Jokat, W., Uenzelmann-Neben, G., Kristoffersen, Y., Rasmussen, T.M., 1992. Lomonosiv Ridge – a double-sided continental margin. Geology 20, 887–890.

Jokat, W., O'Connor, J., Hauff, F., Koppers, A., Miggins, D., 2019. Ultraslow spreading and volcanism at the eastern end of Gakkel Ridge, Arctic Ocean. Am. Geophys. Union. https://doi.org/10.1029/2019GC008297.

Kashubin, S.N., Petrov, O.V., Artemieva, I.M., Morozov, A.F., Vyatkina, D.V., Golysheva, Y.S., Kashubina, T.V., Milshtein, E.D., Rybalka, A.V., Erinchek, Y.M., Sakulina, T.S., Krupnova, N.A., Shulgin, A.A., 2018. Crustal structure of the Mendeleev Rise and the Chukchi Plateau (Arctic Ocean) along the Russian wide-angle and multichannel seismic reflection experiment "Arctic-2012.". J. Geodyn. 119, 107–122. https://doi.org/10.1016/j.jog.2018.03.006.

Kossovaya, O.L., Tolmacheva, T.Yu., Petrov, O.V., Isakova, T.N., Ivanova, R.M., Mirolyubova, E.S., Rekant, P.V., Gusev, E.A., 2018. Palaeozoic carbonates and fossils of the Mendeleev rise (Eastern Arctic): study of sea bottom dredged material. J. Geodyn. 120, 23–44. https://doi.org/10.1016/j.jog.2018.05.001.

Kumar, N., Granath, J.W., Emmet, P.A., Helwig, J.A., Dinkelman, M.G., 2011. Chapter 33 Stratigraphic and tectonic framework of the US Chukchi Shelf: exploration insights from a new regional deep-seismic reflection survey. Geol. Soc. Lond. Mem. 35, 501–508. https://doi.org/10.1144/M35.33.

Lane, L.S., 1997. Canada Basin, Arctic Ocean: evidence against a rotational origin. Tectonics 16, 363–387.

Laverov, N.P., Lobkovsky, L.I., Kononov, M.V., Dobretsov, N.L., Vernikovsky, V.A., Sokolov, S.D., Shipilov, E.V., 2013. A geodynamic model of the evolution of the Arctic basin and adjacent territories in the Mesozoic and Cenozoic and the outer limit of the Russian Continental Shelf. Geotectonics 47, 1–30. https://doi.org/10.1134/S0016852113010044.

Lawver, L.A., Scotese, C.R., 1990. A review of tectonic models for the evolution of the Canadian Basin. In: Grantz, A., Johnson, L., Sweeney, J.F. (Eds.), The Arctic Ocean region, The Geology of North America, vol. L, pp. 593–618.

Lebedeva-Ivanova, N., Gaina, C., Minakov, A., Kashubin, S., 2019. ArcCRUST: Arctic crustal thickness from 3-D gravity inversion. Geochem. Geophys. Geosyst. https://doi.org/10.1029/2018GC008098, 2018GC008098.

Lebedeva-Ivanova, N.N., Gee, D.G., Sergeyev, M.B., 2011. Chapter 26 Crustal structure of the East Siberian continental margin, Podvodnikov and Makarov basins, based on refraction seismic data (TransArctic 1989–1991). Geol. Soc. Lond. Mem. 35, 395–411. https://doi.org/10.1144/M35.26.

Lutz, R., Franke, D., Berglar, K., Heyde, I., Schreckenberger, B., Klitzke, R., Geissler, W., 2018. Evidence for mantle exhumation since the early evolution of the slowspreading Gakkel Ridge, Arctic Ocean. J. Geodyn. https://doi.org/10.1016/j.jog.2018.01.014.

Miller, E.L., Akinin, V.V., Dumitru, T.A., Gottlieb, E.S., Grove, M., Meisling, K., Seward, G., 2018. Deformational history and thermochronology of Wrangel Island, East Siberian Shelf and coastal Chukotka, Arctic Russia. Geol. Soc. London Spec. Publ. 460, 207–238. https://doi.org/10.1144/SP460.7.

Moran, K., Backman, J., Brinkhuis, H., Clemens, S.C., Cronin, T., Dickens, G.R., Eynaud, F., Gattacceca, J., Jakobsson, M., Jordan, R.W., Kaminski, M., King, J., Koc, N., Krylov, A., Martinez, N., Matthiessen, J., McInroy, D., Moore, T.C., Onodera, J., O'Regan, M., Pälike, H., Rea, B., Rio, D., Sakamoto, T., Smith, D.C., Stein, R., St John, K., Suto, I., Suzuki, N., Takahashi, K., Watanabe, M., Yamamoto, M., Farrell, J., Frank, M., Kubik, P., Jokat, W., Kristoffersen, Y., 2006. The Cenozoic palaeoenvironment of the Arctic Ocean. Nature 441, 601–605. https://doi.org/10.1038/nature04800.

Morozov, A.F., Petrov, O.V., Kashubin, S.N., Kremenetsky, A.A., Shkatov, M.Y., Kaminsky, V.D., Gusev, E.A., Grikurov, G.E., Rekant, P.V., Shevchenko, S.S., Sergeev, S.A., Shatov, V.V., 2013. New geological data substantiating continental nature of region of Central-Arctic rises. Reg. Geol. i Metallog. 55, 34–55.

Morozov, A.F., Shkatov, M.Yu., Korneev, O.Yu., Kashubin, S.N., 2014. Complex geological and geophysical expedition "Arctic-2012" for continental nature definition of the Mendeleev Rise in Arctic Ocean. Prospect Protect. Min. Resour. 3, 22–27 (in Russian).

Mosher, D.C., Chapman, C.B., Shimeld, J., Jackson, H.R., Chian, D., Hutchinson, D., Lebedeva-Ivanova, N., Verhoef, J., Pederson, R., 2013. High Arctic marine geophysical data acquisition. Lead. Edge 524–536. May, 2013.

Mukasa, S.B., Andronikov, A., Brumley, K., Mayer, L.A., Armstrong, A., 2020. Basalts from the Chukchi Borderland: 40Ar/39Ar Ages and Geochemistry of submarine intraplate lavas dredged from the western Arctic Ocean. Am. Geophys. Union. https://doi.org/10.1029/2019JB017604.

Nikishin, A.M., Petrov, E.I., Malyshev, N.A., 2014. Geological Structure and History of the Arctic Ocean. EAGE Publications bv. https://doi.org/10.3997/9789462821880.

Nikishin, A.M., Gaina, C., Petrov, E.I., Malyshev, N.A., Freiman, S.I., 2018. Eurasia Basin and Gakkel Ridge, Arctic Ocean: Crustal asymmetry, ultra-slow spreading and continental rifting revealed by new seismic data. Tectonophysics 746, 64–82. https://doi.org/10.1016/j.tecto.2017.09.006.

Nikishin, A.M., Startseva, K.F., Verzhbitsky, V.E., Cloetingh, S., Malyshev, N.A., Petrov, E.I., Posamentier, H., Freiman, S.I., Lineva, M.D., Zhukov, N.N., 2019. Sedimentary Basins of the East Siberian Sea and the Chukchi Sea and the Adjacent Area of the Amerasia Basin: Seismic Stratigraphy and Stages of Geological history. Geotectonics 53, 635–657. https://doi.org/10.1134/S0016852119060104.

Nikishin, A.M., Malyshev, N.A., Petrov, E.I., 2020. The main problems of the structure and history of the geological development of the Arctic Ocean. Her. Russ. Acad. Sci. 90 (3), 345–356. https://doi.org/10.1134/S101933162003003X, 2020.

Nikishin, A.V., Petrov, E.I., Cloetingh, S., Freiman, S.I., Malyshev, N.A., Morozov, A.F., Posamentier, H.W., Verzhbitsky, V.E., Zhukov, N.N., Startseva, K.F., Rodina, E.A., 2021a. Arctic Ocean Mega-project: paper 2 – Arctic stratigraphy and regional tectonic structure. Earth Sci. Rev. (in press).

Nikishin, A.V., Petrov, E.I., Cloetingh, S., Freiman, S.I., Malyshev, N.A., Morozov, A.F., Posamentier, H.W., Verzhbitsky, V.E., Zhukov, N.N., Startseva, K., 2021b. Arctic Ocean Mega-project: Paper 3 – Mesozoic to Cenozoic geological evolution. Earth-Sci. Rev. (in press).

Oakey, G.N., Saltus, R.W., 2016. Geophysical analysis of the Alpha–Mendeleev ridge complex: Characterization of the High Arctic Large Igneous Province. Tectonophysics 691, 65–84. https://doi.org/10.1016/j.tecto.2016.08.005.

Pease, V., Drachev, S., Stephenson, R., Zhang, X., 2014. Arctic lithosphere — a review. Tectonophysics 628, 1–25. https://doi.org/10.1016/j.tecto.2014.05.033.

Petrov, O., Morozov, A., Shokalsky, S., Kashubin, S., Artemieva, I.M., Sobolev, N., Petrov, E., Ernst, R.E., Sergeev, S., Smelror, M., 2016. Crustal structure and tectonic

model of the Arctic region. Earth-Sci. Rev. 154, 29–71. https://doi.org/10.1016/j.earscirev.2015.11.013.
Petrov, O.V., 2017. Tectonic Map of the Arctic. VSEGEI Publishing House, St. Petersburg.
Petrov, O.V., Smelror, M. (Eds.), 2019. Tectonostratigraphic Atlas of Eastern Arctic (Eastern Russia and Adjacent Areas). VSEGEI Publishing HousePress, St. Petersburg, 152 p. (in Russian).
Piskarev, A., Poselov, V., Kaminsky, V. (Eds.), 2019. Geologic Structures of the Arctic Basin. Springer International Publishing, Cham. https://doi.org/10.1007/978-3-319-77742-9.
Poselov, V.A., Avetisov, G.P., Butsenko, V.V., Zholondz, S.M., Kaminsky, V.D., Pavlov, S. P., 2012. The Lomonosov Ridge as a natural extension of the Eurasian continental margin into the Arctic Basin. Russ. Geol. Geophys. 53, 1276–1290. https://doi.org/10.1016/j.rgg.2012.10.002.
Saltus, R.W., Miller, E.L., Gaina, C., Brown, P.J., 2011. Chapter 4 Regional magnetic domains of the Circum-Arctic: a framework for geodynamic interpretation. Geol. Soc. Lond. Mem. 35, 49–60. https://doi.org/10.1144/M35.4.
Shephard, G.E., Müller, R.D., Seton, M., 2013. The tectonic evolution of the Arctic since Pangea breakup: integrating constraints from surface geology and geophysics with mantle structure. Earth-Sci. Rev. 124, 148–183. https://doi.org/10.1016/j.earscirev.2013.05.012.
Sherwood, K.W., Johnson, P.P., Craig, J.D., Zerwick, S.A., Lothamer, R.T., Thurston, D. K., Hurlbert, S.B., 2002. Structure and stratigraphy of the Hanna Trough, U.S. Chukchi Shelf, Alaska. In: Miller, E.L., Grantz, A., Klemperer, S.L. (Eds.), Special Paper 360: Tectonic Evolution of the Bering Shelf-Chukchi Sea-Artic Margin and Adjacent Landmasses. Geological Society of America, Boulder. Colorado, pp. 39–66. https://doi.org/10.1130/0-8137-2360-4.39.
Skolotnev, S., Aleksandrova, G., Isakova, T., Tolmacheva, T., Kurilenko, A., Raevskaya, E., Rozhnov, S., Petrov, E., Korniychuk, A., 2019. Fossils from seabed bedrocks: Implications for the nature of the acoustic basement of the Mendeleev Rise (Arctic Ocean). Mar. Geol. 407, 148–163. https://doi.org/10.1016/j.margeo.2018.11.002.
Skolotnev, S.G., Fedonkin, M.A., Korniychuk, A.V., 2017. New data on the geological structure of the southwestern Mendeleev Rise, Arctic Ocean. Dokl. Earth Sci. 476, 1001–1006. https://doi.org/10.1134/S1028334X17090173.
Smelror, M., Petrov, O.V., Larssen, G.B., Werner, S. (Eds.), 2009. Geological History of the Barents Sea. Atlas. Geological Survey of Norway, Trondheim.
Stein, R., 2008. Arctic Ocean Sediments: Processes, Proxies, and Paleoenvironment, 1st ed. Elsevier Science.
Van Wagoner, N.A., Williamson, M.-C., Robinson, P.T., Gibson, I.L., 1986. First samples of acoustic basement recovered from the Alpha Ridge, Arctic Ocean: new constraints for the origin of the ridge. J. Geodyn. 6, 177–196.
Vernikovsky, V.A., Morozov, A.F., Petrov, O.V., Travin, A.V., Kashubin, S.N., Shokal'sky, S.P., Shevchenko, S.S., Petrov, E.O., 2014. New data on the age of dolerites and basalts of Mendeleev Rise (Arctic Ocean). Dokl. Earth Sci. 454, 97–101. https://doi.org/10.1134/S1028334X1402007X.
Vogt, P.R., Jung, W.Y., Brozena, J.M., 1998. Arctic marine gravity highs remain puzzling. EOS Trans. Am. Geophys. Union 79 (601), 605–606.
Weber, J.R., 1990. The structures of the Alpha Ridge, Arctic Ocean and Iceland-Faroe Ridge, North Atlantic: comparisons and implications for the evolution of the Canada Basin. Mar. Geol. 93, 43–68.
Weber, J.R., Roots, E.F., 1990. Historical background; Exploration, concepts, and observations. In: Grantz, A., Johnson, G.L., Sweeney, J.F. (Eds.), The Arctic Ocean region (pp. 5–36). The Geology of North America DNAG L. Geological Society of America, Boulder.
Ziegler, P.A., 1988. Evolution of the Arctic-North Atlantic and the Western Tethys. Am. Assoc. Pet. Geol. Mem. 43, 1–198.
Zonenshain, L.P., Kuzmin, M.I., Natapov, L.M., 1990. Geology of the USSR: A Plate-Tectonic Synthesis, Geodynamics Series. American Geophysical Union, Washington, D. C. https://doi.org/10.1029/GD021.