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Paleovalleys and Paleodepressions of the Kara Sea Vostochno-Prinovozemelsky Area

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Abstract—U-shaped and V-shaped palleovalleys and paleodepressions are identified on multifrequency seismic data in near-surface section (NSS) within three study areas in Vostochno-Prinovozemelsky area. Valleys of the Late Cretaceous and Quaternary ages and of different genesis are found in the first area of study. The palleovalleys of the Late Cretaceous age are V-shaped and U-shaped by their characteristic morphological properties and are likely formed as a result of the rivers erosional activity. Genesis of the buried valleys filled with Quaternary glacial sediments is usually connected to glacial plucking of the Late Quaternary glaciation, and they are similar to U-shaped paleovalleys. The tunnel valleys of Quaternary age that most likely were formed as a result from impact of ice sheet located to the east of the Novaya Zemlya archipelago in the Late Quaternary age were observed in the second study area. In contrast to the first two sites, isometric depressions of Quaternary age and controversial genesis were observed in the third one. The direction of the identified paleovalleys in some cases coincides with the submarine valleys indicated on the USSR Northern Seas submarine valleys map (Lastochkin, 1977) and the Kara Sea geomorphological map (Miroshnikov et al., 2021).

Keywords: paleovalleys, paleodepressions, Valdai glaciation, multifrequency seismic, Vostochno-Prinovozemelsky area, Kara Sea

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INTRODUCTION

Currently, the interest in studying the Kara Sea geological structure has grown significantly due to high oil and gas potential and the lack of the knowledge about its territory. In order to minimize potential risks during production activities on the shelf, geological and geophysical surveys are carried out, which allows to study in detail the interval of the section up to about 1000 m below seafloor. Gas saturated sediments, faults, permafrost, paleovalleys and paleodepressions (Roslyakov et al., 2018) are considered hazardous for drilling. Geohazards identification in a study area contributes to minimizing risks during production activities and has a significant scientific importance. One of the issues of the paleogeography reconstruction of the Vostochno-Prinovozemelsky area in the Kara Sea is related to detection, genesis and development of the buried valleys and depression structures. A.N. Lastochkin (Lastochkin, 1977), E.E. Musatov (Musatov, 1987), N.N. Dunaev (Dunaev et al., 1995), D.A. Kostin (Kostin, 1998), S.I. Rokos (Rokos, 2009) et al. studied paleodepressions of different origins on the territory of marginal northern seas, and Kara Sea region in particular.

Nowadays, the problem of paleovalleys and paleodepressions investigation using seismic data is widely disclosed in foreign publications especially those where the North Sea region is represented (Livingstone and Clark, 2016). One of the first Russian papers was A.N. Lastochkin's article (Lastochkin, 1977), in which submarine valleys map covering the entire Kara Sea region is presented. The map was built by A.N. Lastochkin based on analysis of navigation maps (not similar to topographic).

The possibility to conduct modern geophysical surveys including multi-frequency seismic for the first time, in many respects, defines the relevance of our work. For the study, detailed seismic data analysis allowed to identify paleovalley and paleodepression systems, clarify their genesis and detect their morphological properties in the upper part of the cross-section (up to 200 m below sea level (b.s.l.)) of the Kara Sea Vostochno-Prinovozemelsky area.

Publications (Dunaev et al., 1995; Lavrushin and Epstein, 2001; Rybalko et al., 2020), where present information about structure of Quaternary sediments of the Barents-Kara region is explained, are analyzed in the study. This information allowed to make an assumption about the age and genesis of sediments infilling and overlapping identified buried negative landforms.

According to the investigation results of the Russian and foreign authors, negative landforms are identified on the glacial shelves as follows: (1) U-shaped (through) paleovalleys, (2) V-shaped paleovalleys; (3) paleodepressions of different genesis. The first type of submarine valleys is characterized by pronounced parabolic cross-profile with steep parallel walls and a broad, nearly flat bottom. Some authors (Bell et al., 2016) associate U-shaped (trough) valleys formation with glacial plucking. According to the paper (*Geomorfologicheskii…*, 2002), U-shaped valleys may have river genesis, in particular when bottom erosion is replaced by lateral one upon reaching an erosion-resistant layer.

This type of paleovalleys also includes tunnel valleys, the formation of which is presumably associated with the eroding activity of meltwater accumulating in the lower layers of the glacier during its retreat. According to studies conducted in the North Sea (Livingstone and Clark, 2016), these structures are characterized by an undulating long-profile, elongated, and slightly sinuous shape in plan. They also start and end abruptly on the study area. The depth of tunnel (subglacial) valleys thalweg varies in the range from several tens to several hundred meters, the length is about several dozen of kilometers, the average width is from several hundred of meters to several kilometers. Some researches (Andersen et al., 2015) distinguish three types of tunnel valleys: U-shaped, V-shaped and flat-bottomed, while noting that the origin of the latter type is not fully clear.

V-shaped valleys, in comparison to the first type of submarine valleys, have a cross-profile with steep sides and a narrow bottom. According to the paper (Bell et al., 2016), the formation of such valleys is associated with fluvial erosion. The third type of negative landforms is represented by paleodepressions with an isometric shape in plan. The genesis of these structures is ambiguous since they may be the fragments of eroded previously formed glacial or stream buried valleys, and their formation may also be due to other geological processes (thermokarst, for example).

DATA AND METHODS

The seismic data obtained by AMIGE within three research sites of the Vostocho-Prinovozemelsky area in 2019 are analyzed. The research sites are located in various geomorphological zones. The first site is located on the board of the Novaya Zemlya trough. The water depth of the trough varies from 243 to 283 m. The second site is located within local uphill of the seabed at the depth from 85 to 170 m. The third site occupies a shallow part of a flat plain and it is relatively shallow, the water depth within it is 30–32 m (Fig. 1). Seismic surveys included 2D high resolution (2D HR), 2D very high resolution (2D VHR) seismic, sub-bottom profiling (SBP) (Fig. 1). High and very high resolution seismic survey was performed with two source types—an air gun and a sparker. The receiver system consisted of seismic streamers with 192 and 48 receivers for low-frequency (2D HR) and higher-frequency (2D VHR) seismic surveys, respectively. The frequency range of 2D HR varied from several dozens to several hundred hertz (Hz).

The vertical resolution of 2D HR data is several meters, the depth is up to 1000 m. 2D VHR data is characterized by a frequency range from several hundred to 1500 Hz, a vertical resolution of 0.5–3 m and depth of up to 200 m. In order to study the first dozens meters of geological section SBP data characterized by a vertical resolution from 0.1 to 5 m and frequency range from 1500 to 16000 Hz is used.

RESULTS AND DISCUSSION

At the first stage of research, seismic–stratigraphic analysis of 2D HR, 2D VHR data is performed and, as a result, the studied section is divided into seismic sequences (SS) and the stratigraphic binding is performed within sites 1–3 (Fig. 2). Five seismic sequences (SS1–SS5) separated by key reflectors (KR) H0(1)–H4(1) are detected in the site 1. SS1–SS6, SS1–SS4 and KR H0(2) –H5(2), KR H0(3) – H3(3) are identified in the sites 2 and 3. A detail description of each seismic sequence with a stratigraphic binding made on the basis of comparison of seismic data and offshore wells Leningradskaya-1, 2, and Rusanovskaya-1,2 as well as taking into account all available geology and seismic stratigraphy data of the study area (Shipilov and Shkarubo, 2010) is presented in the paper (Zamotina et al., 2021).

It is not possible to determine the material composition of identified seismic sequences sediments due to the lack of deep drilling data within the research sites. As a result of the seismic data analysis it is revealed that the structure of the upper part of the section changes with distance from Novaya Zemlya trough where the research site 1 is located. In this site there is an absence of Paleogene deposits that overlap Upper Cretaceous sequences in the sites 2 and 3. It is important to note that the detailed analysis of changes of geo-

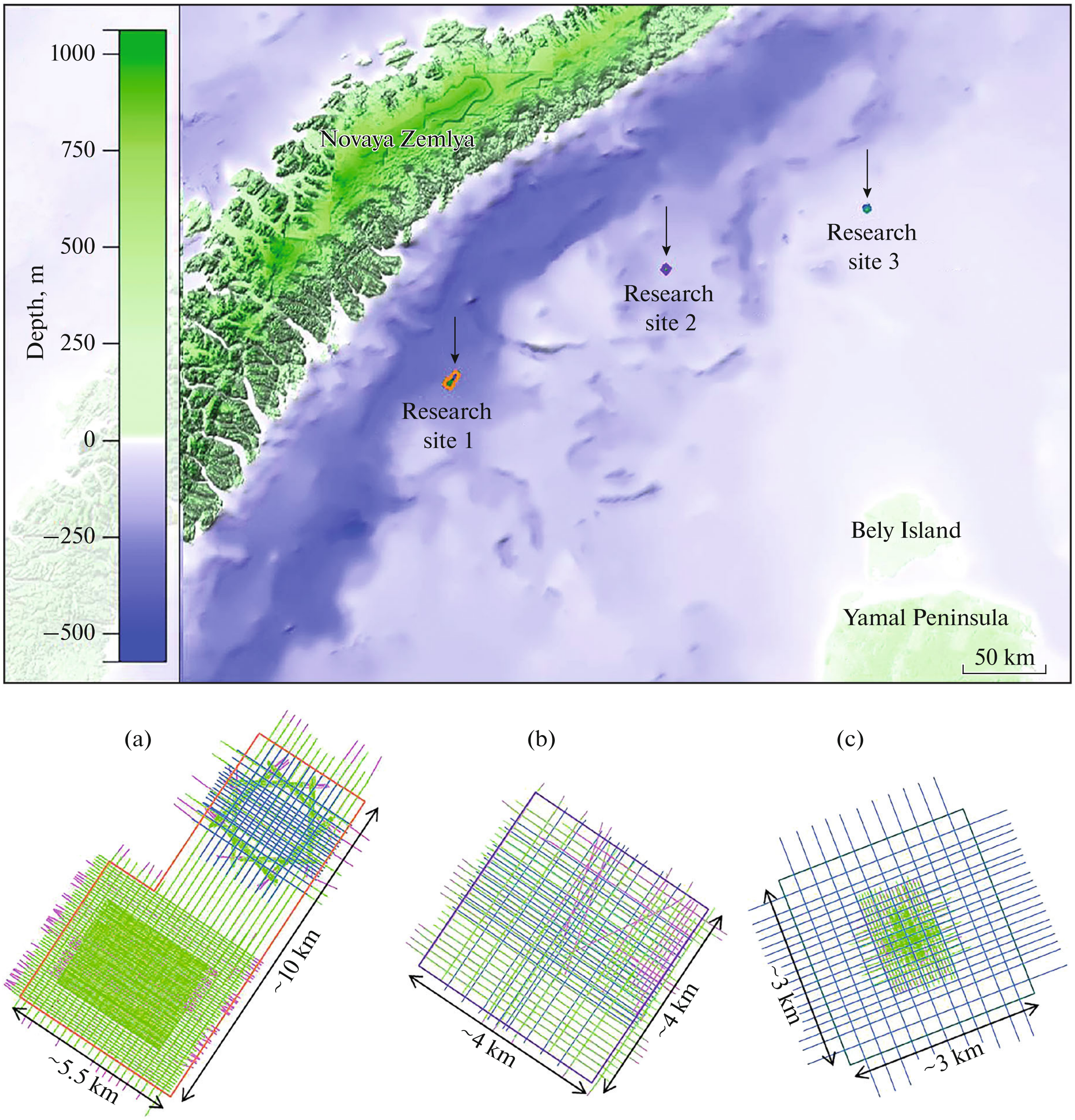

Fig. 1. Overview map of the study area (above). Coloured polygons with arrows show research sites 1–3, within which 2D HR, 2D VHR and SBP data were obtained; and positions of seismic lines within the research sites: (a) 1, (b) 2, (c) 3; 2D HR surveys shown as blue lines, 2D VHR—green lines, SBP—pink lines.

logical section including the depositional sequences presence or absence is a separate subject of research which is not included in the range of analyzed issues. The main interest is the study of morphological properties, spatial position and development history of buried valleys and depressions in the Kara Sea Vostochno-Prinovozemelsky area.

According to the results of a joint analysis of data obtained by different methods paleovalleys and paleodepressions incised in sediments of the presumably Cenomanian (SS3) and the Turonian-Santonian (SS2) in site 1 as well as the presumably Paleogene-Neogene age (SS2, SS3) and (SS2) in sites 2 and 3, respectively, are detected (Fig. 2). Below a detailed description of the identified buried landforms is presented.

Research site 1. The fragments of the oldest paleovalleys have depth ranging from 180 to 550 m below seafloor (b.s.f.) (P-wave velocity (V_p) is 2300 m/s) in the presumably Cenomanian sequence (SS3) in the site. An example of these paleovalleys on 2D VHR data is shown in Fig. 3. The observed negative land-

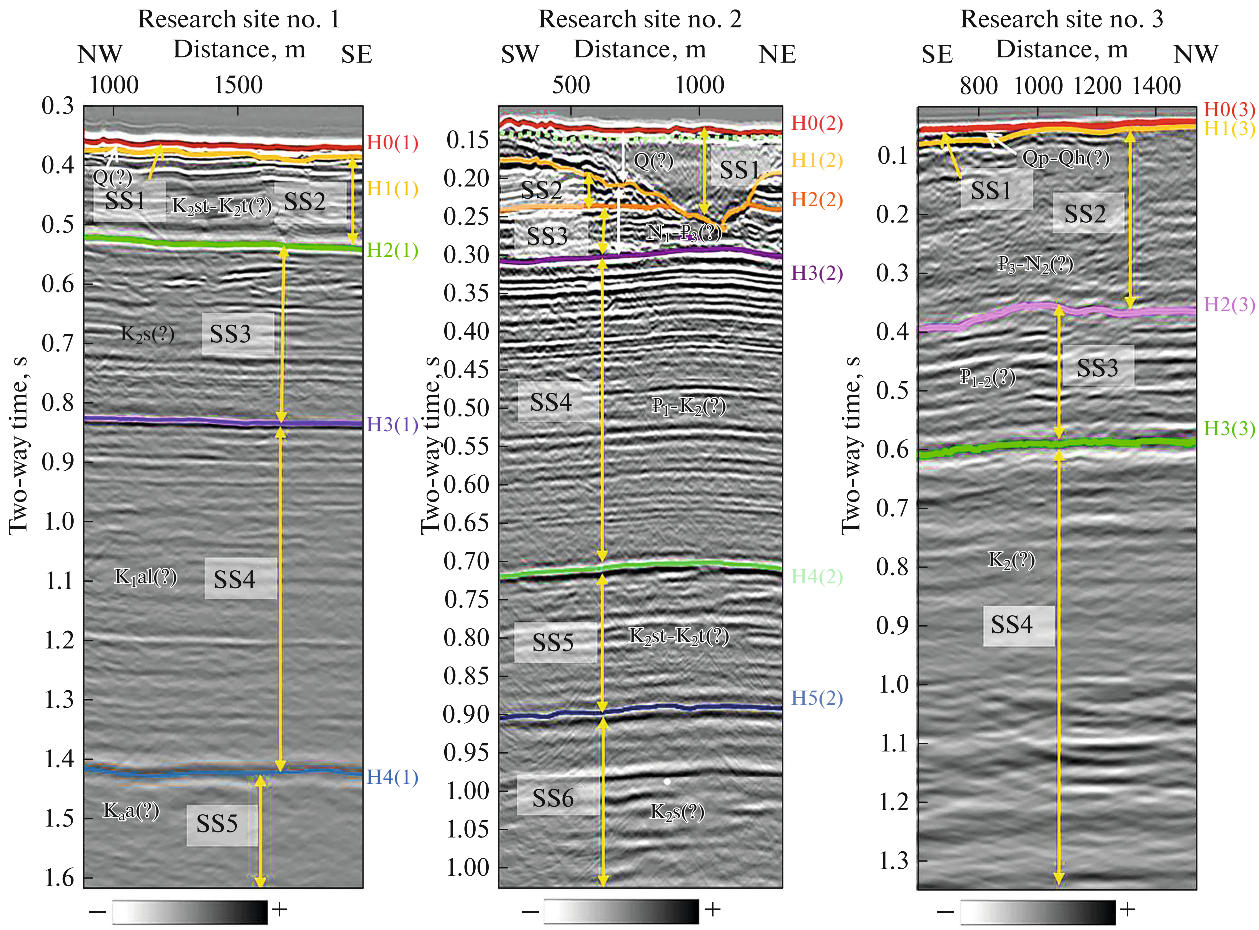

Fig. 2. An example of a 2D HR data with identification of the seismic sequences and the key reflectors separating them (shown by coloured lines) within research sites 1–3. White inscription—presumable age of SS.

forms are distinguished by the substrate erosional truncation in their bottom and flank parts, as well as the chaotic wave pattern of the infilled sediments. The valleys with depth about 400 m b.s.f. (V_p = 2300 m/s) are characterized by the angles of inclination of the flanks about 4° (north-west flank) and 8° (south-east flank) as well as a predominantly narrow bottom. The thickness of the sediments that infill these structures is about 40 m. Higher in the cross section there are valleys with depth about 320 m b.s.f. and relatively flat flanks (the angles of inclination are several degrees) and with less thickness of the infill sediments (about 20 m). During the cross section analysis, it was determined that the deepest valley is similar to V-shaped structures. Higher in the cross section there is U-shaped paleovalley. Cenomanian age depositional environment is analysed in order to identify potential genesis of the delineated paleovalleys. According to the paleogeographic reconstruction presented in the paper (Kontorovich et al., 2014) the Cenomanian age was the time of warm-temperate and humid climate as well as the stage of regional regression completion which began in the Late Albian age. According to the data presented in the paper there was a boundary between the areas of transitional sedimentation (coastal plain, sometimes flooded by the sea, floodplain, lacustrine-boggy, channel, deltaic etc deposits) and shallow sea (depth less than 25 m) in the Cenomanian age within the research site 1 where presumable the Late Cretaceous paleovalleys are located (near the Novaya Zemlya archipelago). Based on the reconstruction, it was assumed that the identified paleovalleys are formed as the result of the relict rivers erosional activity and they are overlapped by younger sediments during transgression.

The youngest paleovalleys incised in the Turonian-Santonian seismic sequence (SS2) and filled with presumable the Quaternary age sediments are revealed in the near-surface section, at the depth varying from the seafloor to 40 m below seafloor (V_p = 2000 m/s) (Fig. 2). The morphological properties of the paleovalleys are observed on the 2D VHR data fragment shown in Fig. 4. They are characterized by the reflectors erosional truncation in their bottom and flank parts on the seismic data. Two seismic sequences (SS1.2 and

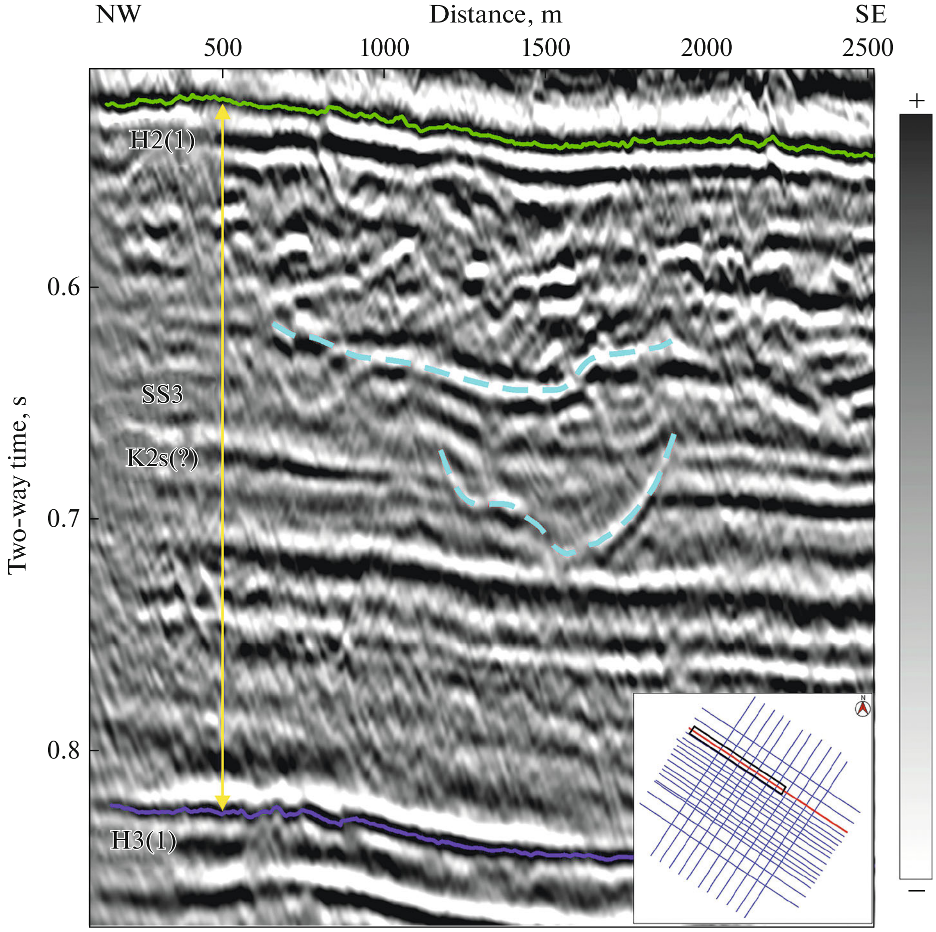

Fig. 3. V-shaped and U-shaped paleovalleys of fluvial genesis (blue dotted line) in the Cenomanian seismic sequence (coloured lines and double arrow) on the 2D HR seismic data. The position of the seismic profile is shown on the map. White inscription – presumable age of SS 3.

SS1.1) separated by continuous and pronounced key reflector H01(1) are identified in the sequence (SS1) infilling and overlapping these structures (Fig. 4). SS1.1 is characterized by uneven top, diffraction objects presence and lack of stratification. All the above features of wave pattern are mapping signs of glacial deposits characteristic to the Western Arctic basin (Starovoytov et al., 2018). SS1.2 infilling paleodepression in bedrock top is characterized by an acoustically transparent wave pattern with separate fragments of the reflectors and is presented by presumable glacial-marine sediments. Analysis of the Quaternary sediments showed the landscape forming moraine was formed in the Ostashkov (the Late Valdai) glaciation in the study area (Dunaev, 1995; Lavrushin and Epstein, 2001; Rybalko et al., 2020).

According to the 2D VHR data the following morphological properties of the paleovalleys are detected: a nearly flat and broad bottom as well as uneven flanks with angles of inclination less than 8°. The thickness of the infill sediments is about 40 m (V_p = 2000 m/s) (Fig. 4). Paleovalleys have predominantly isometric shape in plan. The paleovalleys with horizontal dimensions of 1 × 0.5 km and 970 × 640 m are observed in the southern and northeastern part of the research site. The largest fragment of the paleovalley is located in the southwest part of the research site and characterized by about 3 km length and about 1.4 km width (Fig. 4, map). The paleovalley is elongated in a north-east direction. It is also noted that paleovalleys are located in the corner parts of the research site which doesn't allow to analyze their shape in plan fully.

The history of the study area development in the Late Quaternary age, and specifically the alternation of the cold Pleistocene epochs with formation of a large ice sheet (Hughes et al., 2015), glacial and glacial-marine sediments infilling and overlapping the paleovalleys allows us to suppose their glacial genesis.

Research site 2. The paleovalleys system is revealed in the upper part of the cross section (up to 205 m b.s.l., V_p = 1600 m/s) of the site. Seismic profiles crossing the largest paleovalley (horizontal dimensions of 2.25 km × 730 m, thickness of sediments infilled is about 100 m) in two directions are shown on

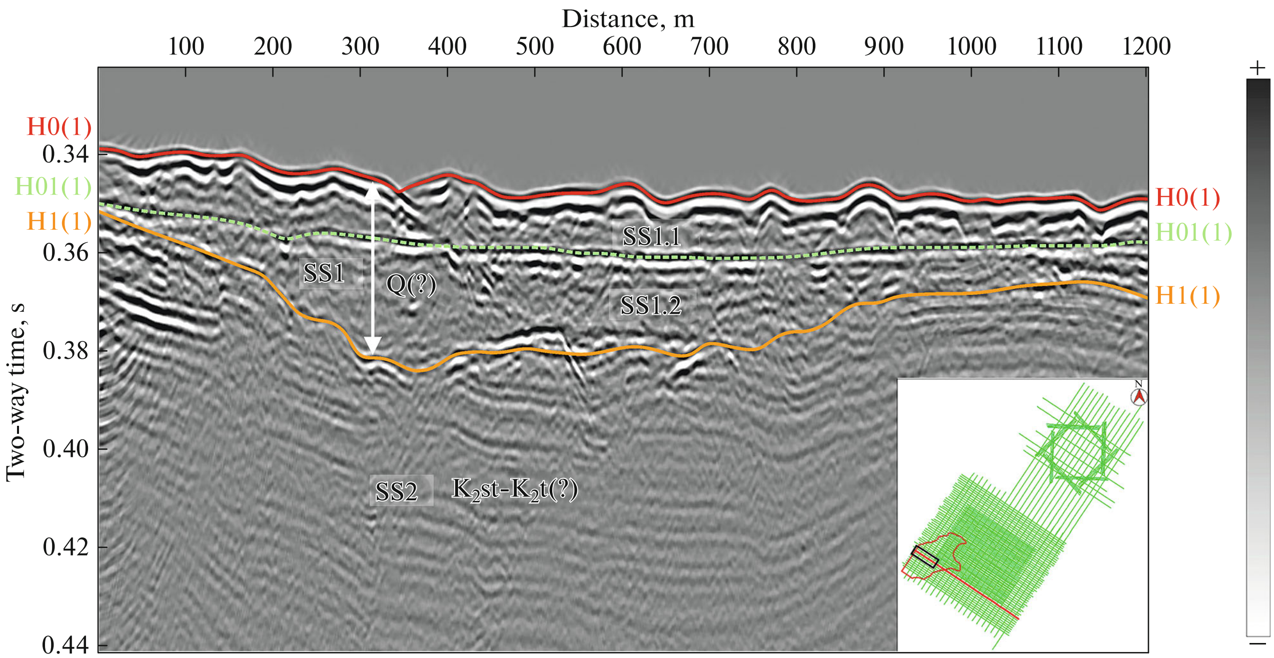

Fig. 4. An example of the trough valley of the Quaternary age (orange line) on the 2D VHR seismic data within the research site 1. The positions of the seismic profile (red line) and paleovalley (red polygon) are shown on the map. White inscription—presumable age of SS1 and SS2.

Fig. 5. The second profile (Fig. 5a) that is crossing paleovalley along the normal, shows the main features of its structure, in particular, steep flanks (up to 25°) and a relatively flat bottom which allows it to be attributed to U-shaped valley. The wave pattern of infill sediments of the buried valley (SS1.2) is acoustically transparent. Besides, up to the section a pronounced high-amplitude sub-horizontal reflector separating SS1.2 and SS1.1 is observed. SS1 have an uneven top and chaotic wave pattern. Morphological properties described above and the Quaternary age of SS1 (Shipilov, Shkarubo, 2010) are the evidences of the presence of glacial and glacial-marine sediments infilling SS1.1 and SS1.2 accordingly.

The buried valleys identified within research site are pronounced in the horizon H1(2) (Fig. 5b) which allows us to analyze their shape in plan. The Fig. 5b shows the largest paleovalley (2.25 km length and 730 m width, the thickness of the infill sediments is about 85 m, V_p = 1600 m/s) observed in the southwestern part of the research site is elongated in northwest direction. The buried valleys elongated in submeridional directions are revealed in the south-east and east of the research site. The horizontal dimensions of the valleys are 4.2 km × 280 m, the thickness of the sediments is about 36 m (V_p = 1600 m/s). A large isometric negative landform with dimensions of about 900 m along the long axis and about 700 m in cross-section is identified in the north-eastern corner of the research site. According the morphological properties the paleovalley is similar to other negative landforms identified within research site.

Undulating long-profile (the depth of thalweg is the range 3–5 m) is a feature of identified paleovalleys (see Fig. 5b).

The paleogeography of the study area in the Late Quaternary, in particular the supposed existence of an ice sheet (Hughes et al., 2015) as well as morphological features of the structure and orientation of the identified paleovalleys allow us to suppose their glacial genesis. The paleovalleys features like an undulating long-profile, elongated, slightly sinuous shape in plan and horizontal bedding of the sediments into which they are incised indicate the buried tunnel (subglacial) valleys exist in the study area. The complicated shape of the identified paleovalleys flanks may be explained by significant meltwater erosion forming in the lower layers of glaciers during its retreat (Livingstone and Clark, 2016).

Research site 3. The negative landforms located in the near-surface section (up to 16 m b.s.f., V_p = 1600 m/s) are also detected here. They are represented by shallow depressions with 10–16 m thickness of the infill sediments (V_p = 1600 m/s). According to the paper (Shipilov, Shkarubo, 2010), the paleodepressions complicate the Oligocene–Miocene sequence internal structure and are presumably filled with the Quaternary sediments. An example of the paleodepression identification using 2D HR, 2D VHR and SBP data is shown in Fig. 6. The sections of 2D HR and 2D VHR

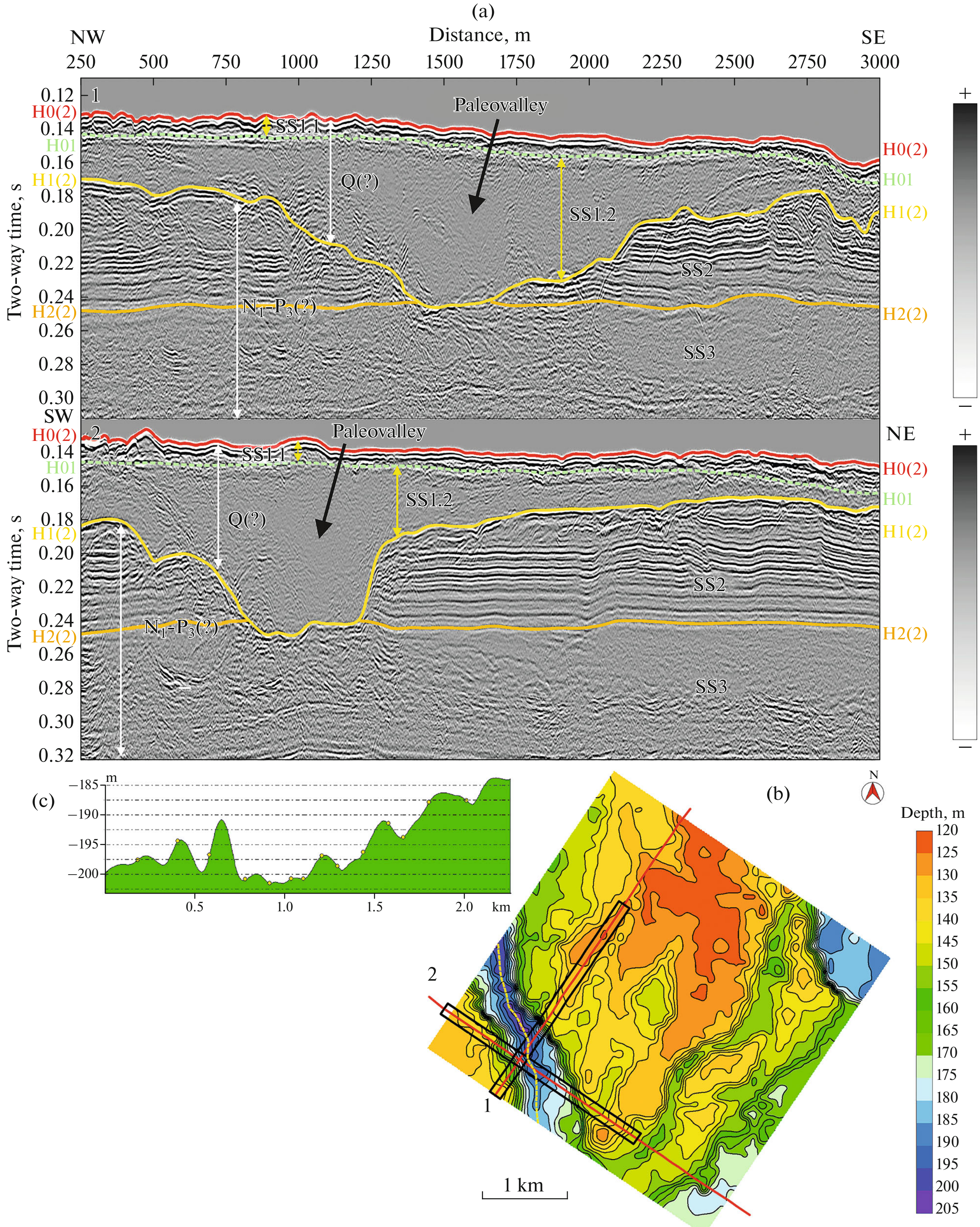

Fig. 5. Presumable buried tunnel (subglacial) valley of the Quaternary age on the 2D VHR data within research site 2: (a) 2D seismic profiles crossing the largest paleovalley (yellow solid line and black arrow); (b) the horizon H1(2); (c) longitudinal profile along the valley showing an undulating bottom profile (yellow dotted line in Fig. 5b). White inscription—presumable age of SS.

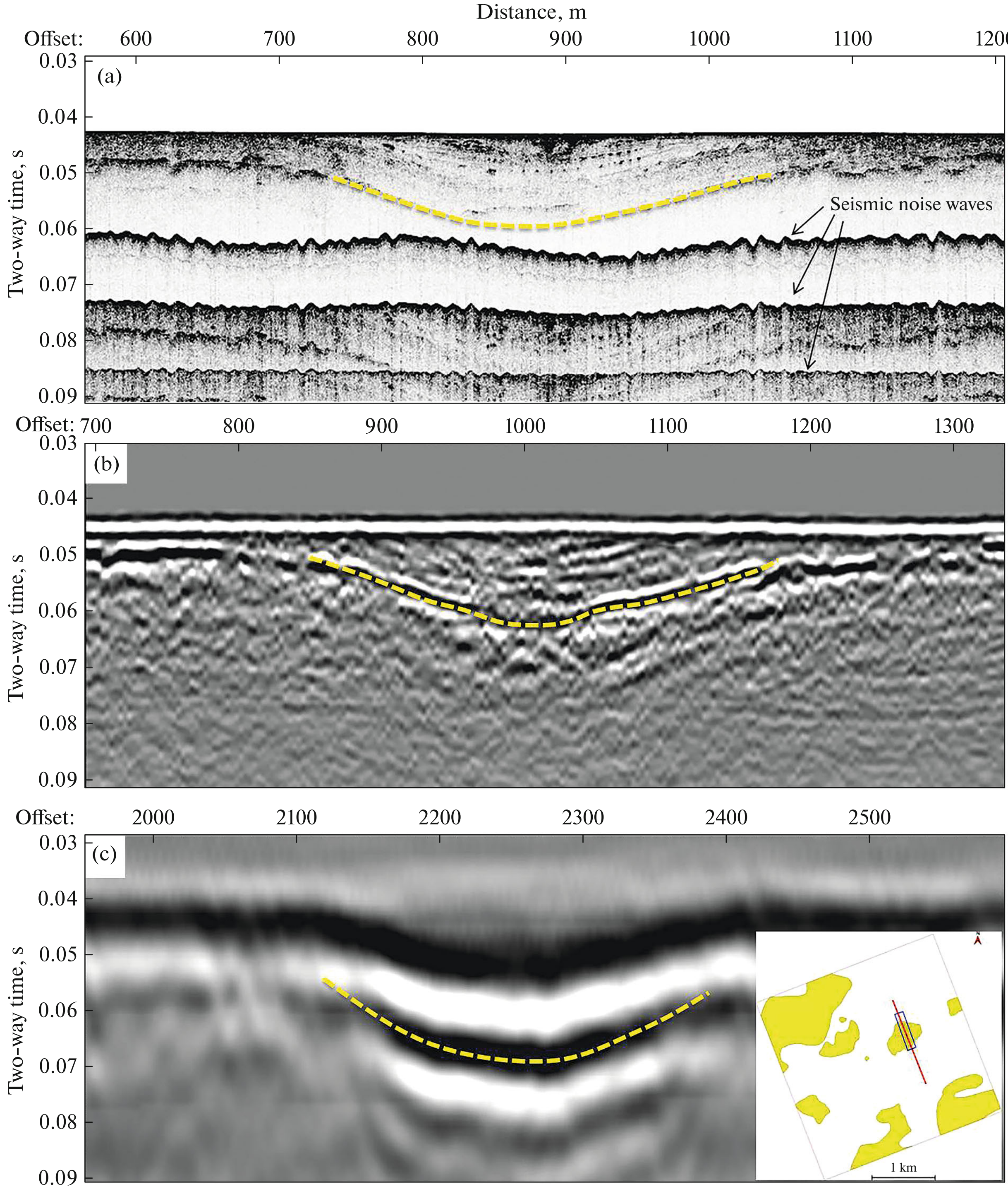

Fig. 6. Paleodepression on the SBP (a), 2D VHR (b), 2D HR (c) data within research site 3. The positions of the seismic profile (red line) and paleodepressions (yellow polygons) are shown on the map.

seismic data clearly illustrate that these structures are limited by a high-amplitude, pronounced, continuous reflector. Their wave pattern is predominantly acoustically transparent, sometimes parallel-layered. According to SBP data, a high-amplitude reflector is located near the bottom of the paleodepressions. It may be explained by coarse or gas-saturated sediments existence.

The paleodepressions are characterized by isometric or rounded shape in plan (Fig. 6, map). They have various horizontal dimensions. The minimum length and width are 70 and 60 m. The maximum ones are 1.4 km and 500 m. The genesis of these paleodepressions is unclear as the research area is limited, however, we may suppose their formation is associated

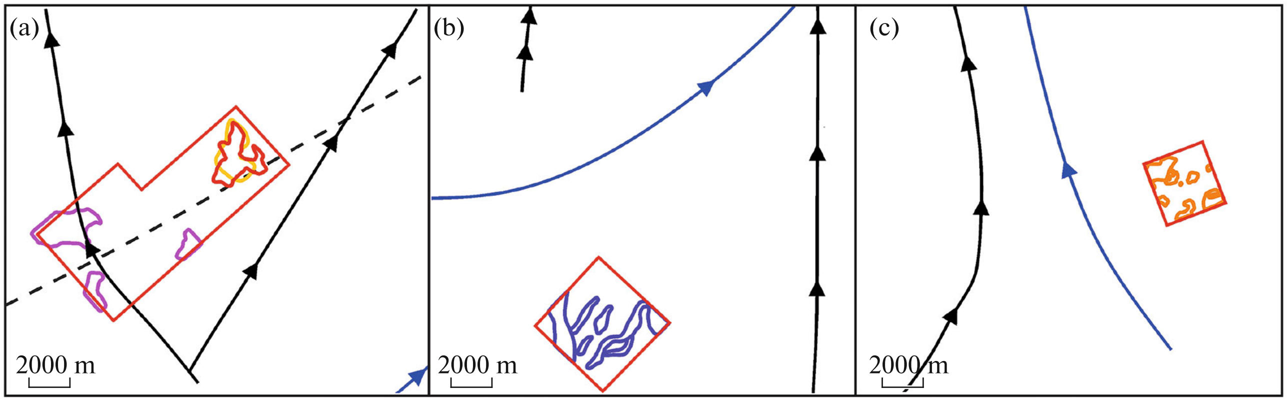

Fig. 7. The schemes of the paleovalleys and paleodepressions locations revealed by multi-frequency data with the plotted supposed thalwegs of submarine valleys according to the paper (Miroshnikov et al., 2021) (black arrows) and (Lastochkin, 1977) (blue arrows). The research sites ((a) 1, (b) 2, (c) 3) are shown by red polygons. The oldest and the youngest valleys incised into sediments of the Cenomanian sequence are marked with red and orange outlines in Fig. 7a. The valleys incised into sediments of the Turonian–Santonian sequence are shown by pink outline in Fig. 7a. Paleovalleys and paleodepressions of the Quaternary age are marked with violet and orange outlines in Figs. 7b, 7c. The border of the southeastern board of Novaya Zemlya trough is shown by the dotted line.

with thermokarst processes, the essence of which is the underground ice melting and soil subsidence. According to the paper (Mel'nikov and Spesivtsev, 1995), permafrost strata were formed in the Late Quaternary age severe climate epoch on a drained shelf area uncovered by the ice sheet. The processes of thermokarst depressions formation occurred during the climate warming in the post-glacial period.

It is important to note that the assumption about thermokarst genesis of identified depressions is fair in case the research site 3 is located within non-glacial area in the Late Quaternary period. Otherwise, it is possible that paleodepressions were formed in the result of the melt-out of isolated buried blocks of glacier ice, however, this topic requires further study.

The spatial distribution analysis of the paleovalleys and paleodepressions. The paleovalleys of different ages and genesis are mapped using data obtained within three research sites which allowed us to analyze their spatial distribution. The buried valleys incised into the presumably Late Cretaceous sediments and observed in the north-eastern part of the research site 1 have linear shape in plan and are elongated in the north direction. The younger buried negative landforms occupy the southwestern part of the site. The largest valley is elongated from southwest to northeast. In the eastern direction from it, the small fragments of valleys of presumably the same age are observed. It is difficult to analyze their shape and orientation fully due to them being located in the marginal part of the study area.

As part of the analysis of the spatial distribution of the identified paelodepressions they were compared with the USSR Northern Seas submarine valleys map complied by A.N. Lastochkin (Lastochkin, 1977) and the Kara Sea geomorphological map (Miroshnikov et al., 2021). Figure 7a shows the valleys incised into the Cenomanian sequence sediments are located close to the submarine valleys thalwegs plotted on the maps and are elongated in the same direction with them (from South to North). The paleovalleys of the Quaternary age, unlike above-mentioned structures, are less consistent with the direction of submarine valleys identified by authors of the paper (Lastochkin, 1977; Miroshnikov et al., 2021) (Fig. 7a). The largest one is elongated in the north-east direction which coincides with the assumed direction of the Novaya Zemlya glacier movement (Zamotina et al., 2021), the existence of which in the Ostashkov period is evidenced by terminal moraines revealed on some terraced levels of the Novaya Zemlya trough eastern slope and on isolated hills of the top surface near the west trough slope (Dunaev et al., 1995; Lavrushin and Epstein, 2001; Rybalko et al., 2020).

Most of the paleodepressions located within research site 2 are oriented in the same direction as the large buried valley within research site 1 (Fig. 7b). It is important to note that the direction in which they are elongated approximately corresponds to the one of thalwegs of submarine valleys identified by A.N. Lastochkin (Fig. 7b). The largest valley observed in the southwestern part of the site is elongated from southeast to northwest which roughly corresponds to the direction in which the submarine valleys indicated on the geomorphological map are elongated (Miroshnikov et al., 2021) (Fig. 7b).

The paleodepressions have predominantly isometric shape in plan in the research site 3 (Fig. 7c).

CONCLUSIONS

The presumably Late Cretaceous (Cenomanian) paleovalleys of the fluvial genesis and the Quaternary (the Late Pleistocene) ones of glacial genesis are analyzed. Analysis of the paleovalleys and paleodepressions spatial distribution using multi-frequency data in the Vostocno-Prinovozemelsky area showed that they are not entirely consistent with the submarine valleys indicated on the USSR Northern Seas submarine valleys map (Lastochkin, 1977) and the Kara Sea geomorphological map (Miroshnikov et al., 2021) and only in some cases coincide with them. Probably this is due to the fact that the maps were compiled on the basis of the seafloor data obtained by echo sounding measurements, geological sampling, without using detailed seismic surveys. The use of the new multi-frequency seismic data made it possible to analyze spatial distribution and characterize paleovalleys and paleodepressions not identified on the seafloor. The results presented in the article are the first step of the large-scale investigation of the paleovalleys in the Kara Sea.

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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