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Extension Structures in the Central Arctic Submarine Elevations Complex

V.A. Poselov✉, V.V. Butsenko, S.M. Zholondz, A.A. Kireev

I.S. Gramberg All-Russia Scientific Research Institute for Geology and Mineral Resources of the Ocean (VNIIOkeangeologia), Angliiskii pr. 1, St. Petersburg, 190121, Russia

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Abstract—The available body of geological and geophysical data indicates that the morphologic structures of the Central Arctic submarine elevations complex (CAE) form a single complex block of continental crust that broke away from the Barents–Kara continental margin in the late Paleocene. Seismostratigraphic interpretation of the multichannel seismic reflection data acquired within the CAE, based on seismostratigraphic benchmarks confirmed by drilling and continuous tracing of pre-Cenozoic unconformities from the offshore North Chukchi Trough to its deep-water extension (Vilkitsky Trough), makes it possible to draw the following conclusions: The sedimentary-basin depocenters of the Vilkitsky Trough and Chukchi basin include pre-Upper Jurassic sediments in addition to Cretaceous complexes. However, the former are not common in the rest area of the CAE.

Synrift extension of the continental crust is the key factor that affected the tectonic evolution of morphologic structures of the Central Arctic basin. Multichannel seismic reflection data show the clearest signs of the synrift extension in the Lomonosov Ridge, Mendeleev Rise, Chukchi plateau, and their flanks sloping to the sedimentary basins of the Vilkitsky Trough and Chukchi basin. At the same time, the depocenters of these sedimentary basins formed by pre-Upper Jurassic deposits are characterized by an almost undisturbed bedding of all sedimentary complexes.

Pre-Upper Jurassic deposits might be interpreted as a relic of the Ellesmerian structural stage preserved in the deep-water extension of the North Chukchi Trough since the preoceanic evolution stage. Pre-Upper Jurassic complexes seem to be affected by deep rift activity only within the elevations of the Central Arctic area and near-flank zones of the depressions separating them. Pre-Upper Jurassic deposits in the sedimentary basin depocenters of the Vilkitsky Trough and Chukchi basin structurally linked to the shallow-water shelf were barely affected by the rifting processes. The tectonic evolution of the depocenters and their submergence relative to the flank zones might have been affected not only by crustal extension processes but also by compensation mechanisms.

Keywords: multichannel seismic reflection, seismic stratigraphy, sedimentary cover, extension, Arctic, Podvodnikov Basin, North Chukchi Trough, Vilkitsky Trough

INTRODUCTION

The Central Arctic submarine elevations complex (CAE) occupies a major area of the deep-water Amerasian basin. The complex includes not only major positive seafloor structures, such as Lomonosov Ridge, Mendeleev Rise, Alpha Ridge, Chukchi plateau, and Northwind Ridge, but also extensive bathymetric depressions that separate them, such as Podvodnikov and Makarov basins and Mendeleev and Chukchi troughs (Fig. 1).

The geology and origin of the CAE, similarly to the Amerasian basin in general (which typically includes the Canada basin in addition to CAE), have been a matter of discussion for over half a century, with a number of tectonic models proposed by various authors (Carey, 1958; Grantz et al., 1979, 2011; Forsyth, 1986; White and McKenzie, 1989; Jokat, 2003; Miller, 2006; Brumley et al., 2008; 2011; Miller and Verzhbitsky, 2009; Dove et al., 2010; Funck et al, 2011; Scotese, 2011; Lobkovsky et al., 2013; Vernikovsky et al., 2013; Petrov, 2016).

In 2005–2014, Russian researchers acquired regional bathymetric and seismic grids, which made it possible to study the key structures of the Central Arctic basin and their junctions with both the adjacent East Siberian shallow-water shelf and the oceanic rim in the form of the Eurasian basin in the west and Canada basin in the east. The database presently includes 35,000 km of bathymetric profiles, over 23,000 km of multichannel seismic reflection profiles, over 4000 km of wide-angle deep seismic sounding (DSS) profiles, and 150 seismic refraction and reflection surveys.

Processing and interpretation results of the latest geological and geophysical data indicate that the morphologic structures of the CAE form a single complex block of continental crust, which separated from the Barents–Kara continental margin in the late Paleocene. Elevations and troughs corresponding to these morphologic structures and their relationships with geological structures of the adjacent East Siberian shallow-water shelf (discussed below) are illustrated by the sedimentary cover thickness map plotted at the

✉Corresponding author.
E-mail adress: vap@vniio.nw.ru (V.A. Poselov)

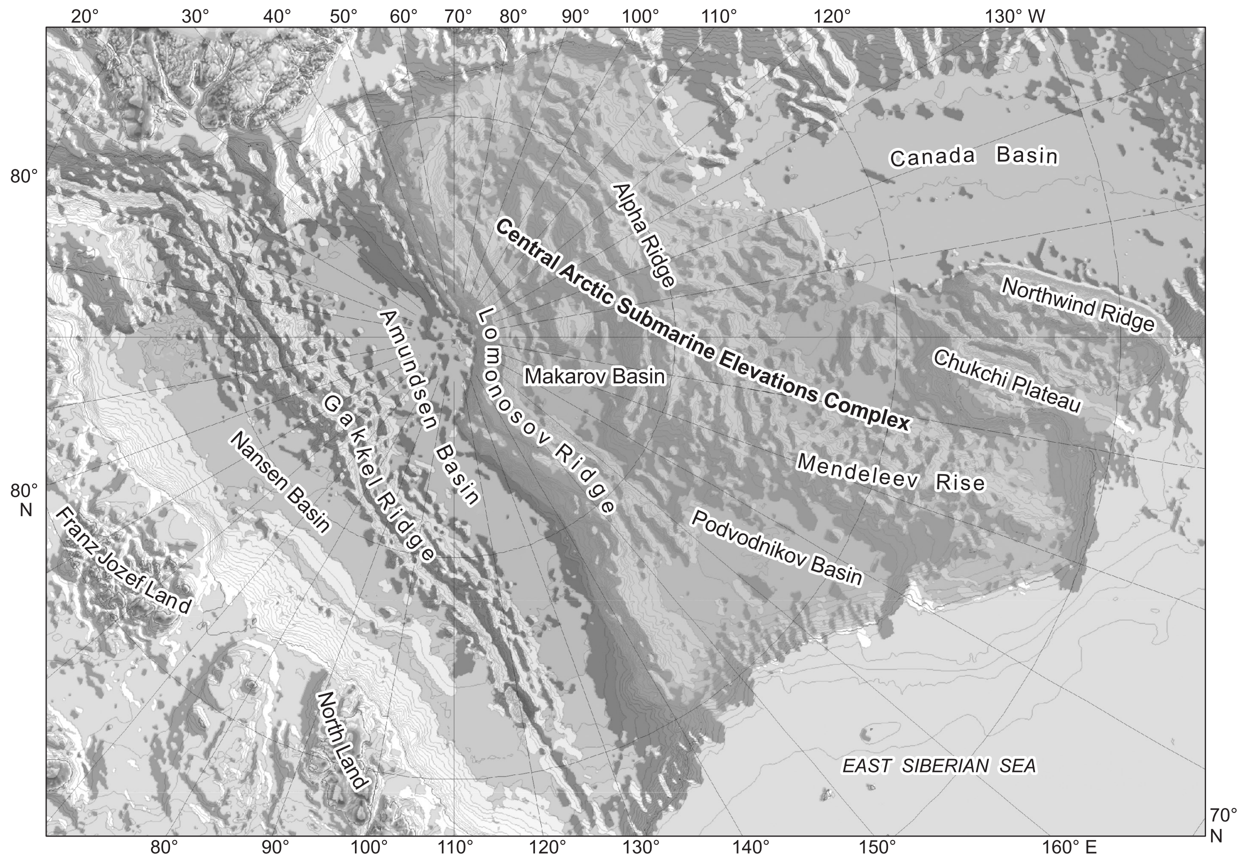

Fig. 1. The Central Arctic submarine elevations complex.

All-Russian Scientific Research Institute for Geology and Mineral Resources of the Ocean (VNIIOkeangeologiya) using the multichannel seismic reflection database (Fig. 2).

The evidence of continental nature of the Earth's crust in the CAE complex and signs of its extension as a key factor of the tectonic evolution of positive and negative morphologic structures in this megablock are considered in the present paper.

SEISMOSTRATIGRAPHIC INTERPRETATION OF MULTICHANNEL SEISMIC REFLECTION DATA

Reliable interpretation of the Cenozoic sedimentary cover in CAE was made possible as a result of ACEX drilling campaign (Expedition 302…, 2006). It was persuasively shown in (Butsenko, 2006; Butsenko and Poselov, 2006; Poselov et al., 2014) that two major Cenozoic unconformities in the studied sedimentary basin correspond to two major discontinuities in the well column, namely post-Campanian (pCU unconformity) and pre-Miocene (RU regional unconformity).

Interpretation of the pre-Cenozoic sedimentary section is complicated primarily by the lack of deep drilling data for the East Siberian shelf. A breakthrough was achieved as a result of the Russian 'Arktika-2014' campaign, which acquired multichannel seismic reflection data along profile No. 1401 (Fig. 3) using a 4.5 km towed streamer.

Profile 1401, which was proposed by VNIIOkeangeologiya and acquired by OAO MAGE is unique. It showed that all the main unconformities in the sedimentary cover of the offshore North Chukchi Trough (NChT) are continuously tracked to the Vilkitsky Trough (Fig. 4). Therefore, the latter is to be considered as a deep-water extension of the NChT.

Thus, the main unconformities in the sedimentary basin of the NChT should be tied to the US offshore wells or the wells at the Alaskan coast (Klemperer et al., 2002; Sherwood et al., 2002) (Fig. 3). It seems that a dense seismic reflection grid would make this well-tie possible, however the elevation between the NChT and Hanna Trough, where the most informative wells are drilled (Fig. 3), is complicated by the tectonics, which disturbs the regularity of the seismic reflection field, thereby making it impossible to continuously track the main unconformities from the wells to the NChT (only the Cenozoic sedimentary basement of the mBU may be tracked from the POPCORN well with a decent reliability).

Thus, the necessity arises for identifying regional seismostratigraphic markers confirmed by drilling to be projected onto the NChT.

The benchmarks confirmed by the INIGOK well (Bird, 1994) were identified in seismic reflection profiles R13, R8, R14 (SEG-Y sections are available at www.pubs.er.usgs.gov/publication/ofr00286) at the Alaskan coast (Figs. 3, 4).

The first benchmark is a progradational complex with downlapping paleoslopes (Fig. 4). According to the INIGOK data, it is dated as Aptian–Albian and is underlaid by the Brookian unconformity (BU), which often merges with the Lower Cretaceous unconformity (BU + LCU). Although the upper boundary of the complex is not a strong reflector, it is formed by clinoforms, which flatten towards the continent, and based on the INIGOK data corresponds to the Lower–Upper Cretaceous boundary. The lateral extension of the paleoshelf and formation of paleoslopes occurred during transgressions and regressions, and so the first benchmark may be referred to as a transgressive–regressive complex (TRC).

The second benchmark, according to the INIGOK data, is limited at the top by the LCU (or BU + LCU) and at the bottom by the Upper Jurassic unconformity JU and is represented by chaotic seismofacies of low-amplitude reflectors. It is interpreted in (Klemperer et al., 2002; Sherwood et al., 2002) as a synrift complex, which separates Brookian and Ellesmerian structural stages and is synchronous to the Neocomian opening of the Canada basin. The surface of the upper Ellesmerian complex (JU) is represented in the sections by the strongest double-phase reflector (Fig. 4).

Here, the regional status of the identified benchmarks is critically important. The authors believe it to be defined by a critical regional tectonic event, specifically the opening of the Canada basin. While the second benchmark is synchronous to the event, the first one (TRC) was formed after the opening as a result of transgressions and regressions of the coastal rim of the offshore area. Downlapping paleoslopes are a specific seismostratigraphic feature of the TRC.

Given the regional nature of the identified benchmarks, the progradational complex with clearly recorded paleoslopes in profile 1401 (Fig. 4) may be interpreted in the NChT as Aptian–Albian–Upper Cretaceous TRC (the first benchmark). Similarly to the Alaskan coast, the NChT has downlapping paleoslopes. Thus, the unconformity underlying the TRC is identified as BU, and the reflector picked below it as LCU. In addition, LCU overlaps chaotic seismofacies of low-amplitude reflectors (the second benchmark). The latter are underlaid in the NChT by a strong double-phase reflector identified as JU (Poselov et al., 2017).

It is important to note that a chaotic complex of nonextensive clinoforms is recognized in almost all seismic reflection profiles within the NChT by multiple authors. The nature of those clinoforms was unclear. It was only understood as a result of analyzing multichannel seismic reflection data along profile 1401 that it was how the first benchmark (TRC) appeared in the sections, when profile directions did not match with lateral extension of the Aptian–Albian paleo-shelf, i.e., from the NChT depocenter in the shallow-water shelf to the depocenter in its deep-water extension (Vilkitsky Trough) (Figs. 2, 3).

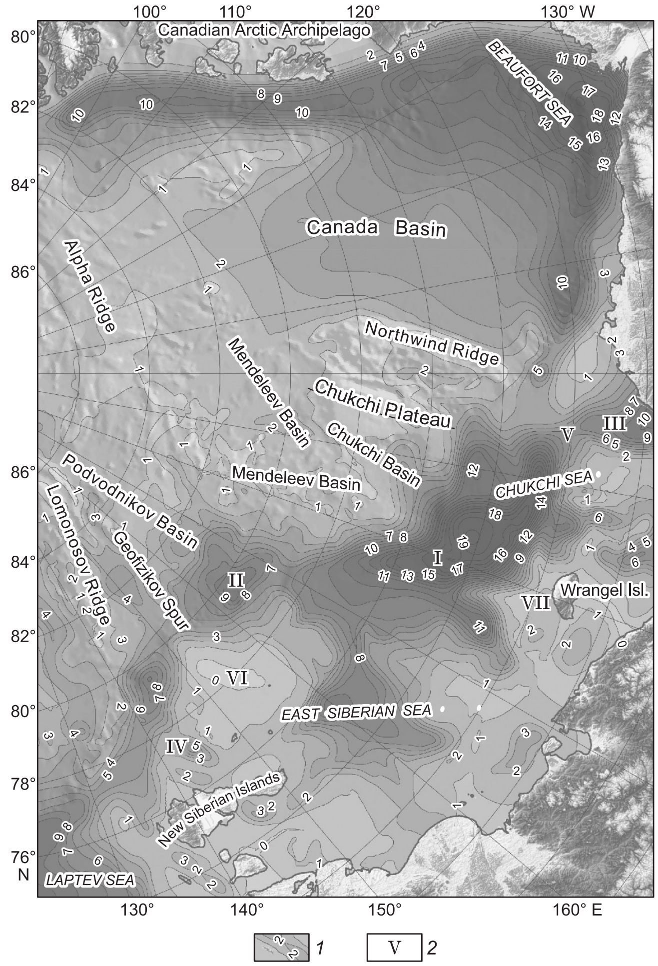

Fig. 2. Geostructures of the Central Arctic area and the adjacent East Siberian shelf superposed over the sedimentary cover thickness map. *1*, sedimentary cover isopachs (km); *2*, geostructures: I, North Chukchi Trough, II, deep-water continuation of the North Chukchi Trough (Vilkitsky Trough), III, Hanna Trough, IV, Anisinsky Trough, V, elevation between the North Chukchi Trough and Hanna Trough, VI, De Long Rise, VII, Wrangel-Herald arch.

When it comes to a possible source of terrigenous sediment drift, which formed the Aptian–Albian–Upper Cretaceous TRC in the NChT, we may conclude the following. POPCORN is the closest well to the NChT (Fig. 3). It is drilled in the elevation, which separates NChT and the Hanna trough. It is different from all other wells drilled in offshore Alaska as the thickness of the Aptian–Albian complex is reduced sharply in its well column (Sherwood et al., 2002). Given that the Upper Cretaceous complex is also absent from the well column of all the remaining wells, it is reasonable to assume that the elevations that bound the NChT basin from the east-south-east represent the sought source of the sedimentary drift that formed the TRC. Furthermore, the amount of these sediments in the TRC formation compared to Aptian–Albian deposits increases in paleoslopes towards the Vilkitsky Trough (accompanied by natural rejuvenation) as a result of complete erosion of the

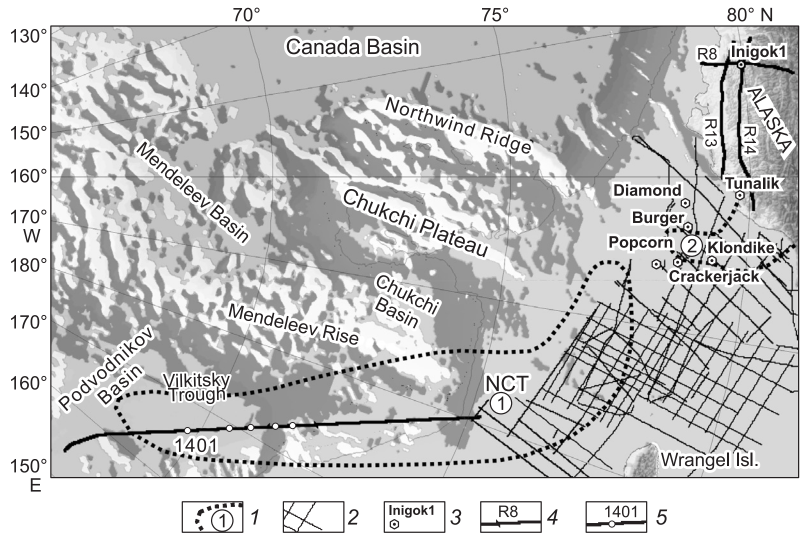

Fig. 3. Illustration for seismostratigraphic interpretation of seismic reflection data. *1*, outlines of the North Chukchi Trough (1) and Hanna Trough (2); *2*, MCS coverage of the study area; *3*, US wells; *4*, studied seismic reflection profiles; *5*, studied seismic reflection profile No. 1401 acquired by the Arktika-2014 campaign with seismic refraction/reflection sounding station locations.

Upper Cretaceous deposits in the drilled area in offshore Alaska (Fig. 4).

It is important to note that another, younger (upper) progradational complex is observed on the southeastern flank of profile 1401 above the pCU in the time range of 0.5–2.5 s (Fig. 4). Progradations at times of 0.5–2.5 s are also recorded in seismic reflection sections obtained in the neighborhood of the northern NChT flank by the R/V Polarstern campaign in 2008 (Hegewald and Jokat, 2013). According to the interpretation performed by German researchers, they are underlain by the middle-Brookian unconformity mBU (Cenozoic sedimentary basement similar to pCU). In addition, the researchers believed the formation of Cenozoic progradations to be linked with significant regional relative sea level fluctuations. It should be noted that the Chukchi shelf extension intensified the most following the breach of the Arctic Ocean isolation in the early Miocene (i.e., after RU) as a result of the Fram Strait opening, which caused a massive inflow of Atlantic waters (Hegewald and Jokat, 2013).

Another two important facts should be mentioned:

(1) The pCU (mBU) unconformity may be tracked from the POPCORN well throughout the whole seismic reflection grid within the NChT with a minor discontinuity (Fig. 3). It turned out that the Cenozoic sedimentary basement is picked in the offshore NChT at times of about 3.0 s, while the lower progradational basement is picked at 5.5–6.0 s (Fig. 4).

(2) The Cenozoic sedimentary basement of the pCU (or mBU in (Sherwood et al., 2002)), tracked from the POPCORN well in the offshore Alaska and from the deep-water ACEX well in the Lomonosov Ridge via a system of transregional seismic reflection profiles converges in the deep-water extension of the NChT (Vilkitsky Trough) with an accuracy up to phase correlation.

Since the majority of wells in offshore Alaska (POPCORN well in particular) penetrate thick Cenozoic sediments, the elevations, which bound the NChT basin from the south, rather than from the east (for instance, Wrangel-Herald arch), are considered the sources of the sedimentary drift that formed upper progradations in the NChT. A shift in the drift direction led to a shift in the lateral extension direction of the Chukchi paleoshelf from SE–SW for Aptian–Albian–Upper Cretaceous clinoforms to S–N for the Cenozoic ones. It is possible that this drift reorganization in the Chukchi shelf was associated with one of the key tectonic events in the Arctic Ocean history, i.e., the opening of the Eurasian basin.

Thus, identification of the basement of the upper progradational complex as a Cenozoic sedimentary basement validated by independent sources confirms the Aptian–Albian–Late Cretaceous age of the lower clinoform complex (TRC) within the NChT. Moreover, the amount of Late Cretaceous sediments in the extension of the TRC into the Vilkitsky Trough compared to Aptian–Albian deposits increases sharply.

The arguments presented above make it possible to draw a fundamental conclusion that the continuous tracking of BU, LCU, and JU from the offshore NChT to the Podvodnikov basin indicates the presence of pre-Upper Jurassic sediments in the depocenter of the deep-water extension of the NChT in addition to Cretaceous complexes (Poselov et al., 2017).

With regional seismic reflection grid and profile 1401 used as a seismostratigraphic benchmark, the main unconformities of the sedimentary cover were almost continuously picked throughout the whole Central Arctic basin area. It was found that pre-Upper Jurassic deposits only formed the Vilkitsky Trough and were not especially common in the remaining area of the CAE.

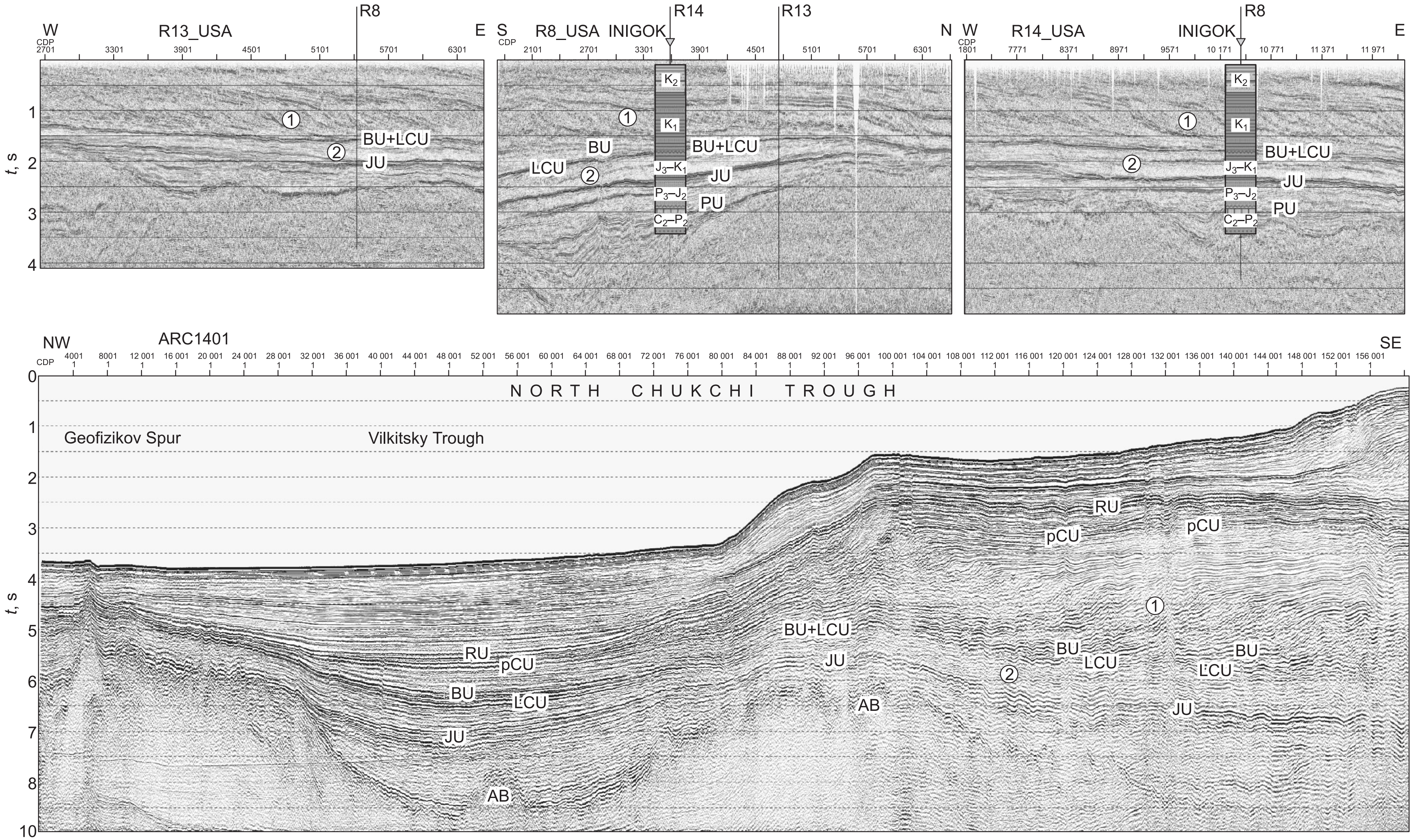

Fig. 4. Comparison of seismic reflection sections from the Alaskan coast (profiles R13, R8, and R14) and North Chukchi Trough (profile 1401). Symbols and ages of the major unconformities: RU, regional pre-Miocene; pCU, post-Campanian; BU, Brookian; LCU, Lower Cretaceous; JU, Upper Jurassic; PU, Permian; AB, acoustic basement; seismostratigraphic benchmarks: transgression–regression complex (1), chaotic complex of low-amplitude reflectors (2).

EXTENSION SIGNS IN SEISMIC DATA

Signs of the synrift extension of the continental crust in the main morphologic and Verzhbitsky structures of the CAE are clearly seen in the seismic reflection profile along the sublatitudinal transarctic profile from the Amundsen basin to the Chukchi plateau (Fig. 5).

Normal faults within the CAE are mapped with an approximate N–S orientation, the prevailing extension trend being E–W. Similar trends are recorded for tectonic faults in the adjacent lands of the Russian Arctic (Miller and Verzhbitsky, 2009).

Extension signs may be considered in more detail in individual morphologic structures of the Central Arctic basin.

Lomonosov Ridge. According to advanced paleoreconstructions, the Lomonosov Ridge is not considered a terrane. The ridge was involved in the movement of the North American lithospheric plate against the Eurasian plate as an integral part of the CAE ensemble (Poselov et al., 2014). Notably, this conclusion is currently supported by some western researchers as well, for example by W. Jokat (Jokat et al., 2013).

The continental nature of the Lomonosov Ridge is beyond any doubt. According to DSS data, the thickness of the Earth's crust in the ridge reaches 18–21 km with approximately equal thicknesses of the upper and the lower crust (Poselov et al., 2014; Kaminsky, 2017). The layer with transient seismic parameters conditionally named the "metasedimentary" layer overlies the crystalline basement. Its surface represents an acoustic basement for stratified deposits in seismic reflection sections.

The section of the sedimentary cover above the acoustic basement is characterized by the permanent presence of both lower synrift and upper cover complexes, which despite their variable thicknesses are steadily picked along the whole Ridge. The synrift complex is filled with Cretaceous–Paleogenic sediments deposited in neritic settings, according to ACEX well data. The cover complex is represented by Miocene–Quaternary hemipelagic deposits. The radical change in deposition settings at the Paleogene–Neogene boundary was presumably caused by the Fram Strait opening, the tectonic event (LMA 13) that resulted in massive inflow of Atlantic waters to the Arctic basin. The Paleogenic complex in the ridge is in the first hundreds of meters (thickness of ~200 m at the ACEX point). Therefore, the Lomonosov Ridge was above or close to the sea level before the early–middle Miocene (Poselov et al., 2014).

Seismic reflection data for the Lomonosov Ridge revealed multiple signs of synrift extension. Their clearest manifestations were observed on the eastern flank of the ridge, where a series of half-grabens bounded by normal faults with amplitudes of 1200 to 2300 m and slope angles of about 16º was recorded (Fig. 6*a*). According to the accepted seismostratigraphic model, synrift complexes are dated as Early or Late Cretaceous. A series of normal faults disturbing Paleogenic sediments is observed on the flank of the ridge leading to the Amundsen basin. It is possible that they were formed in process of Cretaceous fault reactivation during the ultraslow spreading in the Eurasian basin.

Podvodnikov basin. Under the geographical term Podvodnikov basin we imply (from a geomorphological perspective) two terraces (upper and lower) of a complex continental flank of the shallow-water East Siberian shelf in the direction of Makarov basin (where its basement is recorded). In terms of structural tectonics, the upper terrace corresponds to the extension of the NChT to the deep-water area (Vilkitsky Trough).

According to the DSS data, the Earth's crust structure in the Podvodnikov basin matches the description of the extended marginal-continental crust with thickness of 19–24 km (the upper crust of 2–5 km) (Lebedeva-Ivanova et al., 2006; Kaminsky, 2017). It is assumed that the upper crust of the basin was thinned as a result of rifting processes.

Seismic reflection data show that the flank of the acoustic basement of the Lomonosov Ridge stretches over the whole western part of the Podvodnikov basin to the interface with the Vilkitsky trough (Fig. 5). This feature is also noted by W. Jokat based on findings of the German R/V Polarstern campaign of 2008 (Jokat et al., 2013). A large graben-like trough between the Lomonosov Ridge and the Geofizikov spur (of the Lomonosov Ridge) is complicated by the system of half-grabens with normal fault amplitudes of 800–1000 m and slope angles of about 30º. Half-grabens are formed by pre-Cretaceous sediments and superposed by a thick Cretaceous sedimentary complex (Fig. 6*b*). Here, the thickness of the Paleogenic complex is almost insignificant. Paleogenic sediments with almost the same thicknesses are recorded by the ACEX well in the Lomonosov Ridge, where neritic deposition settings are identified based on the core sample. The upper part of the section is represented by Miocene–Quaternary hemipelagic sedimentary cover.

The western flank of the Vilkitsky Trough is represented by the Geofizikov spur. The increased thickness of the Upper Cretaceous complex presumably deposited in marine setting is a distinctive feature of sedimentary structures in the Vilkitsky Trough. At the same time, the thickness of Paleogenic sediments in the Vilkitsky Trough differs insignificantly from that in the graben-like trough between the Lomonosov Ridge and the Geofizikov spur, which most likely shows that deposition conditions in Paleogene were close to neritic. The upper part of the section is represented by Miocene–Quaternary hemipelagic sedimentary cover (Fig. 6*c*).

The central part of the Vilkitsky Trough (depocenter) is formed by a thick pre-Upper Jurassic sedimentary complex (below the Upper Jurassic unconformity), which stretches from the offshore NChT. It is characterized by flat and practically undisturbed bedding of all sedimentary complexes (Fig. 6*b*). Here, extension structures are very poorly manifested. Thus, it may be assumed that tectonic evolution of the depocenter of the Vilkitsky Trough and its submergence against flank zones were affected not only by crustal extension processes, but also by compensation mechanisms as-

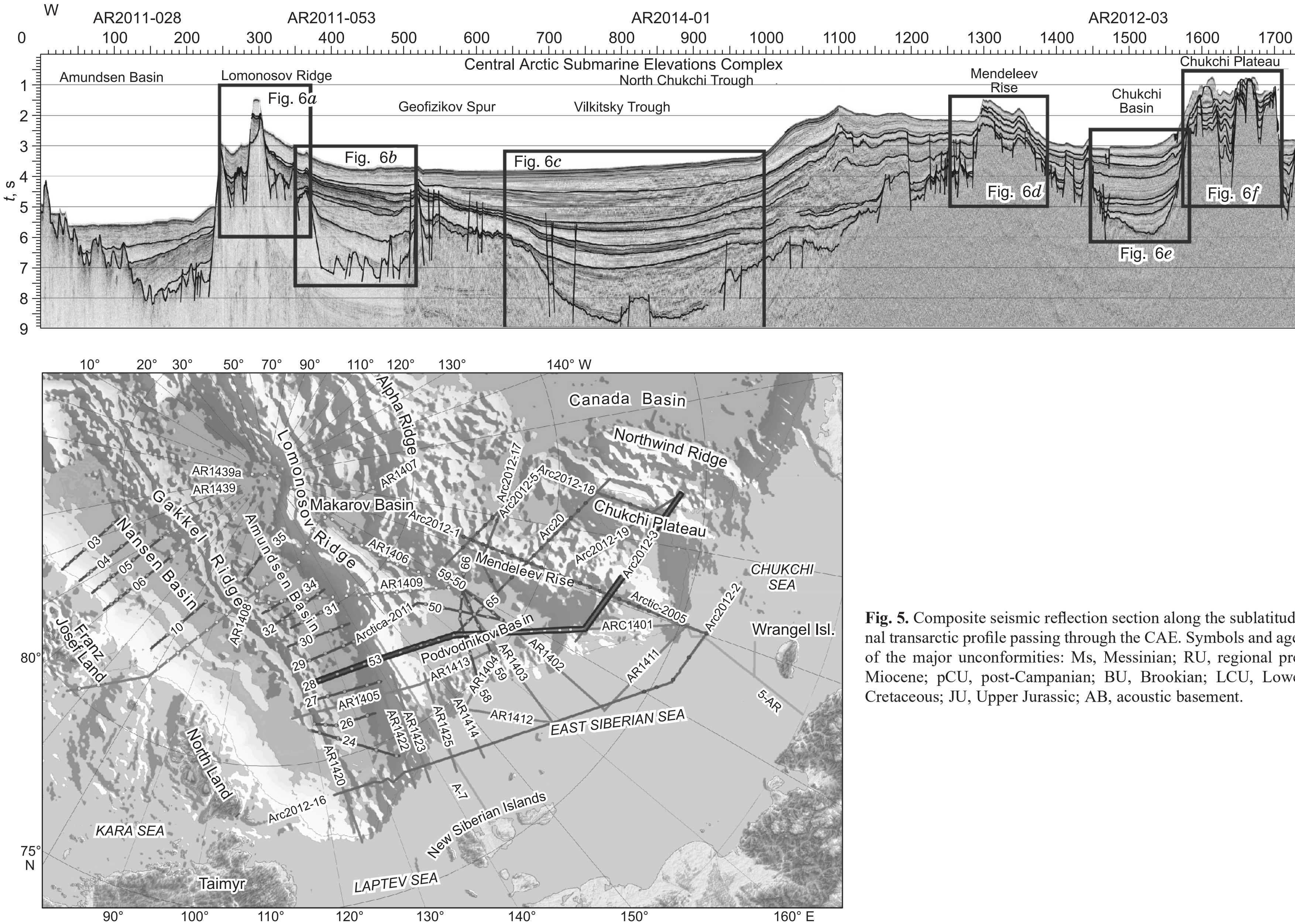

Fig. 5. Composite seismic reflection section along the sublatitudinal transarctic profile passing through the CAE. Symbols and ages of the major unconformities: Ms, Messinian; RU, regional pre-Miocene; pCU, post-Campanian; BU, Brookian; LCU, Lower Cretaceous; JU, Upper Jurassic; AB, acoustic basement.

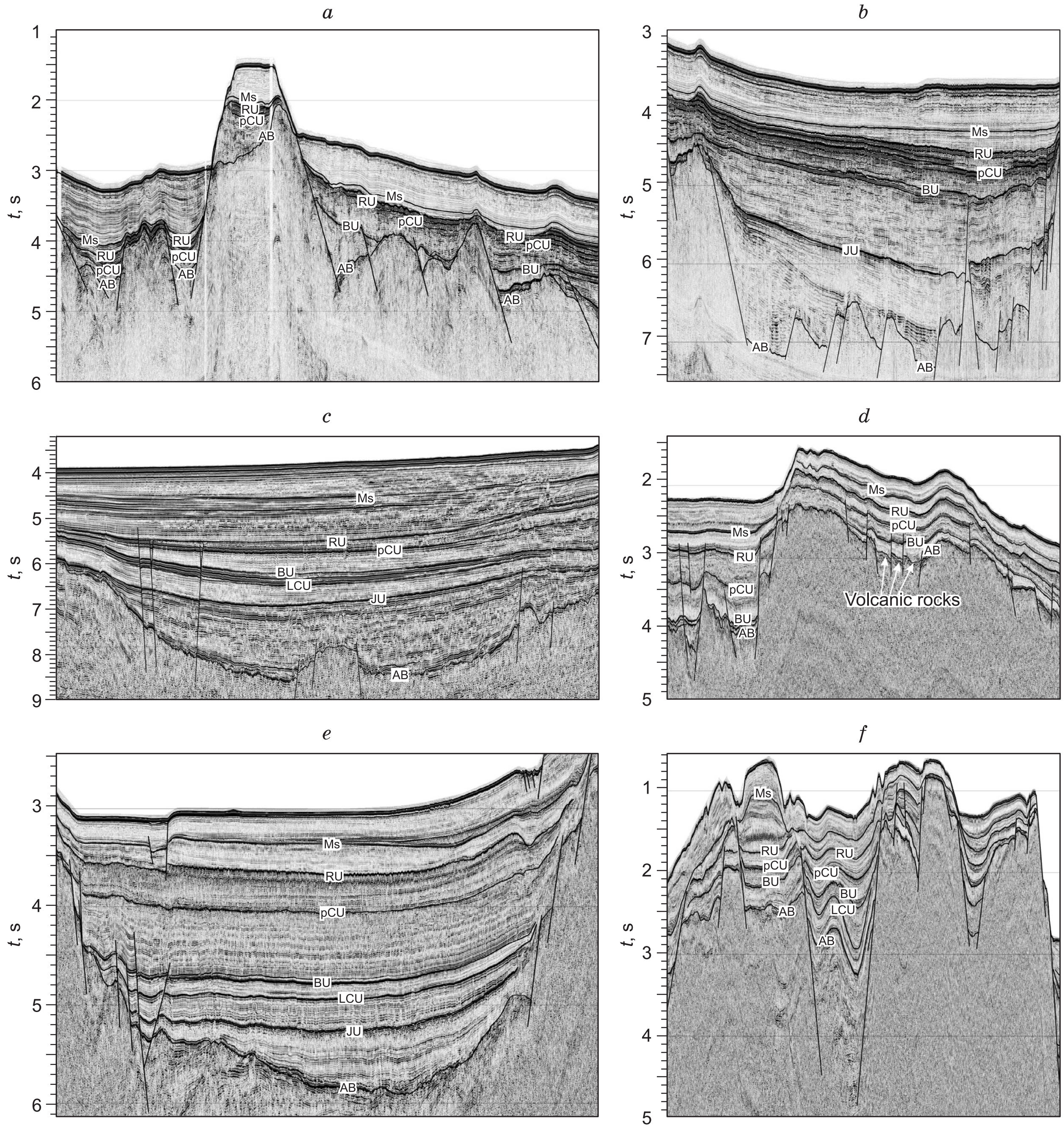

Fig. 6. Fragment of the seismic reflection section for the Lomonosov Ridge (*a*), the graben between the Lomonosov Ridge and Geofizikov spur (*b*), the deep-water continuation of the North Chukchi Trough (Vilkitsky Trough) (*c*), the Mendeleev Rise (*d*), the Chukchi basin (*e*), the Chukchi plateau (*f*). Fragment location in the composite section and ages of major unconformities are shown in Fig. 5.

sociated with changes in material composition of the lower crust. For example, the compensation mechanism of formation of deep-water troughs in the Amerasian basin as a result of eclogitization at the basement of the lower crust is suggested in (Artyushkov and Poselov, 2010).

Mendeleev Rise. The Mendeleev Rise borders with the Vilkitsky Trough on the west via a zone of stepped faults, with the NChT on the south, thereby forming its northern flank, and with Chukchi Trough in the east. A dense geomorphological link between the Mendeleev Rise and the shallow-water East Siberian shelf is confirmed by the presence of a continuous series of bathymetric terraces regularly submerging with a distance from the edge of the shelf.

The Earth's crust structure in the Mendeleev Rise matches the description of an extended marginal-continental crust. According to the DSS data, the crust thickness in the elevation reaches 30–32 km, the thicknesses of the upper and the lower crust being 4–8 km and 20–22 km, respectively (Poselov et al., 2012; Kaminsky, 2017). It is assumed that the upper crust thinning was the result of rifting processes.

Seismic reflection data revealed multiple extension structures in the Mendeleev Rise represented by grabens and half-grabens at the sedimentary cover basement (Fig. 6*d*). They are controlled by normal faults with amplitudes of 160–220 m and slope angles ranging from 15º to 30º. Maximum fault amplitudes (up to 500 m) with slope angles up to 40º are recorded at the junction of the Mendeleev Rise and the Vilkitsky Trough. Wide development of lower-Cretaceous synrift microbasins is observed as well. Short high-amplitude anomalies are identified in half-grabens near the acoustic basement surface, which may presumably be interpreted as volcanic rocks. The sample analysis indicated their Cretaceous age and neritic environment at the outcrops (Morozov et al., 2013). Similar extension signs are observed in the Alpha Ridge as well (Bruvoll et al., 2012). The Mendeleev Rise is covered by Miocene–Quaternary hemipelagic sediments along its whole length.

A common opinion on the solely volcanic origin of the Mendeleev Rise (Forsyth, 1986; Jokat, 2003; Dove et al., 2010; Funck et al., 2011; Bruvoll et al., 2012) is disproved by the analysis of rock samples collected using a manipulator arm from the escarpments of submarine mountains in the Alpha–Mendeleev Rise in 2012 and 2014–2016 by the Russian research submarine (NIPL) (Morozov et al., 2013; Gusev et al., 2017; Skolotnev et al., 2017). The vast majority of the samples were taken directly from the scarps formed by bed rocks and stone runs formed at terraces and scarp tops.

The following sedimentary rocks prevail in the samples collected: dolomites, limestones, quartzite sandstones, sandstones. Igneous rocks are represented by basalts, andesites, basaltic andesites, tuffs, dolerites, and gabbro. Same types of rocks collected using various techniques have no essential differences and show signs of paragenetic unity.

The age of sedimentary rocks was estimated using paleontological methods based on research of genera and species of acritarchs, spores, pollen, scolecodonts, dinocysts, conodonts, crinoids, foraminifera, and brachiopods. Three groups of sedimentary rocks were defined based on the paleontological research results: Late Ordovician–late Silurian (limestones and dolomites), Middle–Late Devonian (limestones and sandstone), and Early Cretaceous (Barremian–Aptian) (sandstone).

Certain representatives of Paleozoic paleofauna are typical for Siberian sediments of the same age. Bedding patterns in the rock masses extracted from the section and lithological properties of the rocks that form them (dolomites, limestones, sandstones, and quartzite sandstones) indicate that the sedimentary section of the Mendeleev Rise was formed in shallow-water continental settings of the epiplatform sea.

Chukchi basin. The flanks of the Chukchi basin in its junctions with the Mendeleev Rise and Chukchi plateau are complicated by the series of submeridional fault scarps.

According to the DSS data, the Earth's crust structure in the Chukchi basin matches the description of an extended marginal-continental crust with thicknesses of 19–20 km (the upper crust of 2–3 km) (Kashubin et al., 2016). It is assumed that the upper crust of the basin was thinned as a result of rifting processes.

The structural similarity between the sedimentary basins of the Chukchi basin and Podvodnikov basin is worth noting. Seismic reflection data show that the acoustic basement flank of the Mendeleev Rise stretches over the whole western part of the Chukchi basin (Figs. 5, 6*e*). Therefore, similarly to the Podvodnikov basin, it should be divided into two parts, i.e., the western and the eastern. The key differences between the two parts of the Chukchi basin lie in the degrees to which extension signs are manifested.

The western part of the Chukchi basin (a flank of the Mendeleev Rise) is underlain by a system of grabens and half-grabens controlled by normal faults with amplitudes of 300–400 m and slope angles of about 30º. According to our seismostratigraphic interpretation, they are formed by Lower Cretaceous sediments superposed by thick Upper Cretaceous sediments. Here, the Paleogenic complex is slightly thicker than in the Podvodnikov basin and is also affected by tectonic faults. The upper part of the section is represented by the Miocene–Quaternary hemipelagic sedimentary cover.

The eastern part of the basin is characterized by undisturbed bedding of all the sedimentary complexes (Fig. 6*e*). Here, similarly to the depocenter of the Vilkitsky Trough, extension signs are very poorly manifested. Normal faults with amplitudes up to 1100 m and slope angles of about 34º are only recorded at the interface between the Chukchi basin and the Chukchi plateau. The upper part of the section is represented by the Miocene–Quaternary hemipelagic sedimentary cover. The basin's depocenter is formed by a rather thick pre-Upper Jurassic sedimentary complex (below the upper Jurassic unconformity), which probably continues from the NChT.

Chukchi plateau. The Chukchi plateau is a shallowly submerged distal shelf elevation of the continental crust. According to the DSS data, the Earth's crust thickness in the plateau reaches 28–30 km with approximately equal thicknesses of the upper and the lower crust (Kashubin et al., 2016).

Seismic reflection data revealed synrift extension structures in the Chukchi plateau represented by a system of grabens and half-grabens at the sedimentary cover basement. They are controlled by normal faults, which successively displace the acoustic basement, sedimentary complexes (from Lower Cretaceous to Neogene), and seafloor (Fig. 6*f*). Fault amplitudes range from 600 to 900 m, and slope angles are 28–43º.

East Siberian shelf. According to some Russian and western researchers, the East Siberian shelf was affected by strong extension of the Earth's crust with approximate E–W direction (Miller et al., 2006; Miller and Verzhbitsky, 2009). It is shown in seismic reflection sections by the typical syn-

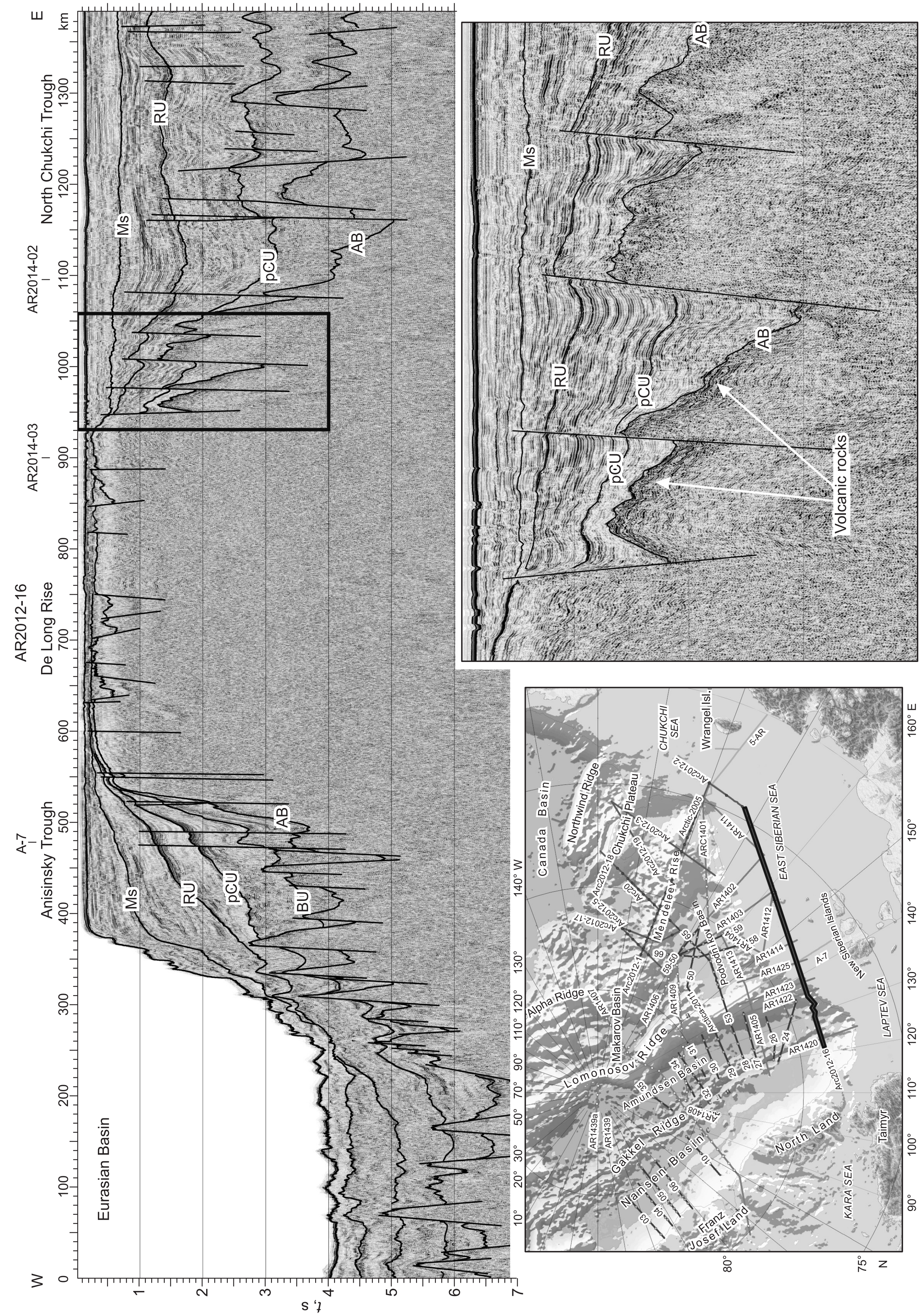

Fig. 7. Sublatitudinal seismic reflection section passing through the De Long Rise. Ages of major unconformities are shown in Fig. 5.

rift grabens and half-grabens recorded in the acoustic basement of the De Long Rise and its flanks leading to Anisinsky and North Chukchi Troughs (Figs. 2, 7), as well as development of synrift complexes with signs of volcanic rock formation in their basements (in the wave field) (Fig. 7). Extension structures are controlled by normal faults with amplitudes up to 3 km and slope angles ranging from 36º to 57º. Age range of synrift complexes varies from the Lower Cretaceous on the flank of the De Long Rise leading to the Anisinsky Trough to the Upper Cretaceous at the top of the elevation and on its flank leading to the NChT.

The High Arctic Large Igneous Province is identified (HALIP) within the CAE (White and McKenzie, 1989; Coffin and Eldholm, 1994; Bruvoll et al., 2012).

Seismic reflection data produced by Russian and western campaigns in 2012–2014 show that nonextensive high-amplitude anomalies are observed in the Mendeleev, Alpha, and De Long Rises near the acoustic basement surface. They are presumably interpreted as structures formed by basalt flows and sills with tuffaceous and sedimentary interlayers. Volcanic rock masses are developed within grabens and half-grabens, which may indicate that they were formed in process of rifting and basement extension controlled by fault tectonics.

The data available imply that the Central Arctic area was affected by two stages of intense polychronic volcanic activity typical for HALIP (Morozov et al., 2013).

The first, primarily Lower Cretaceous, stage was associated with continental rifting of the CAE at 130–120 Ma. The presence of this stage was confirmed during the ‘Arktika-2012’ campaign by geological sampling on the Mendeleev Rise, which revealed the age of volcanic rocks of 128 Ma based on uranium-lead dating (Morozov et al., 2013).

The younger, second stage of volcanic activity at about 90–80 Ma was represented by most samples collected in the Mendeleev–Alpha and Chukchi plateau areas (Morozov et al., 2013).

According to (Mukasa et al., 2009), the samples collected in the Mendeleev trough were represented by subalkaline basalts, in the Northwind Ridge by alkaline basalts, in topographic maximums of the Mendeleev Rise by subalkaline and alkaline basalts, and in Chukchi plateau by alkaline-subalkaline transitional basalts. Here, chemical parameters of all the samples were atypical for mid-oceanic ridges.

Basaltic volcanic activity in the Central Arctic basin is similar to manifestations with the same age and similar composition, recorded in the island rim of the Arctic basin, i.e., Spitsbergen, Franz Josef Land, De Long Islands, Ellesmere Island, and other islands in the Canadian Arctic archipelago (Morozov et al., 2013). Cenozoic volcanic activity was recorded in the Arctic as well. It is represented rather widely from the western Spitsbergen and Knipovich Ridge, to De Long Islands and Alaska through Gakkel Ridge (Korago et al., 2014). It is correlated in seismic reflection sections with numerous instances of Cretaceous fault reactivation in the Paleogene and Neogene, which indicates the extension of the continental crustal extension of the CAE in the Cenozoic.

Geodynamic model. The Amerasian basin in the Arctic Ocean has significant differences in morphology and deep structure from the Eurasian basin. It is more similar to the continental margin affected by rifting and broken into blocks submerged to various depths, rather than an oceanic structure (Gramberg, 2001).

In our opinion, the synrift extension of the CAE, similarly to other significant Mesozoic and Cenozoic tectonic processes in the Arctic, is currently the best geodynamic model for the upper mantle convection mechanism developed by L.I. Lobkovsky (Lobkovsky et al., 2013) and V.A. Vernikovsky (Vernikovsky et al., 2010, 2013).

These authors state that the opening of the Canada basin from the Late Jurassic onwards and the following collision of Chukotka, Siberia, and the Kolyma–Omolon superterrane are associated with subduction in the South Anyui (Angayucham) Ocean. The closure of the South Anyui Ocean ended in the Aptian. The subduction system was rearranged, and the stress field switched from submeridional to sublatitudinal. Subduction absorption of the oceanic crust started from the Pacific Ocean, which primarily drove the extension of the Earth’s crust in the Central Arctic.

The widely manifested intense episode of sublatitudinal regional extension of the Arctic lithosphere is dated as Aptian–Albian based on numerous seismic data. Extension conditions in the mid-Cretaceous were observed in Chukotka (Miller and Verzhbitsky, 2009) and in the north of Alaska.

The proposed geodynamic model of the upper-mantle convection associated with global subduction processes in the South Anyui and Pacific Oceans is recognized as a general mechanism controlling Mesozoic and Cenozoic tectonic evolution in the Arctic. It agrees with most known experimental facts and is, to a degree, universal.

CONCLUSIONS

The analysis of synrift extension signs within individual morphologic structures of the Central Arctic submarine elevations complex makes it possible to identify some regularities.

The clearest synrift extension signs in seismic reflection sections, namely graben and half-graben systems at the sedimentary cover basement and maximum normal fault amplitudes accompanied by minimum slope angles are recorded in the Lomonosov Ridge, Mendeleev Rise, Chukchi plateau, and the flanks of elevations leading to sedimentary basins of the Vilkitsky Trough and Chukchi basin. Essentially, the western parts of these basins are the flanks of the Lomonosov Ridge and the Mendeleev Rise, respectively. At the same time, eastern parts of sedimentary basins in the Vilkitsky Trough and Chukchi basin are characterized by almost undisturbed bedding of all the sedimentary complexes. In addition, according to our seismostratigraphic interpretation, depocenters of these basins are formed by a rather thick pre-Upper Jurassic sedimentary complex (up to 4 km in the Podvodnikov basin and up to 1.2 km in the Chukchi basin) continuing directly from the offshore North Chukchi Trough.

Thus, synrift extension of the continental crust indicated by two phases of Cretaceous volcanic activity in HALIP and Cenozoic volcanic activity on the periphery is the primary factor that affected the tectonic evolution of morphologic structures of the CAE. Pre-Upper Jurassic sediments are interpreted as a relic of the Ellesmerian structural stage (whether it is solely upper Ellesmerian or also includes lower Ellesmerian complexes is still unknown) preserved in the deep-water extension of the North Chukchi Trough from the preoceanic evolutionary stage. Pre-Upper Jurassic complexes seem to be affected by deep rift activity only in elevations of the CAE and near-flank zones of the depressions that separated them. Pre-Upper Jurassic sediments in depocenters of sedimentary basins of the Vilkitsky Trough and Chukchi basin structurally linked to the shallow-water shelf were barely affected by rifting processes. It seems that the tectonic evolution of the depocenters and their submergence compared to flank zones could be affected not only by crustal extension processes, but by compensation mechanisms as well.

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