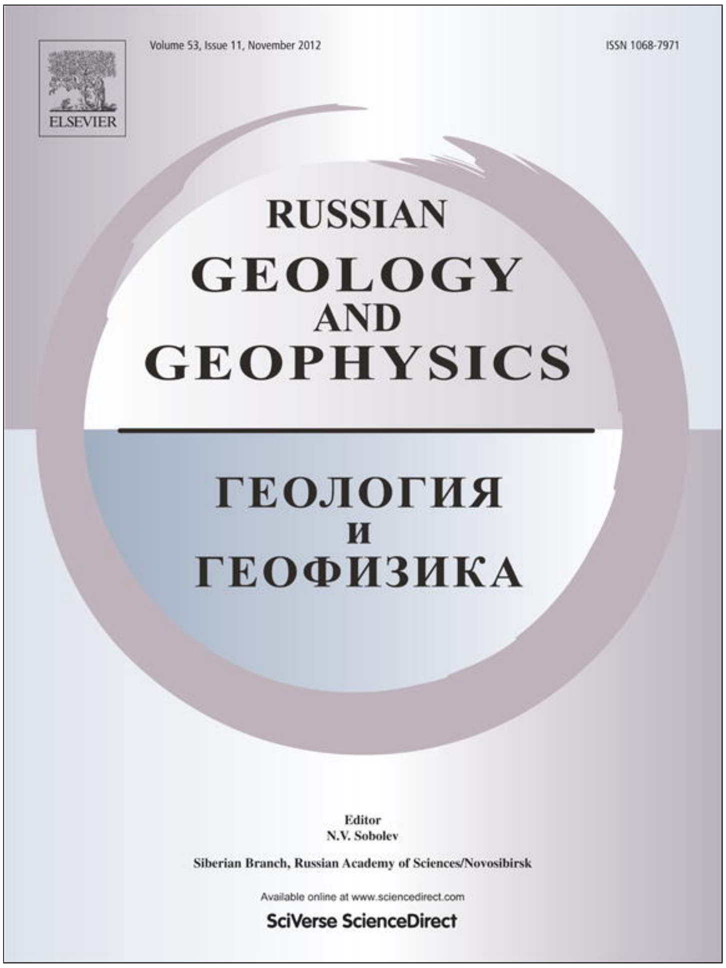
Volume 53, Issue 11, November 2012
ISSN 1068-7971
ELSEVIER
RUSSIAN
GEOLOGY
AND
GEOPHYSICS
ГЕОЛОГИЯ
И
ГЕОФИЗИКА
Editor
N.V. Sobolev
Siberian Branch, Russian Academy of Sciences/Novosibirsk
Available online at www.sciencedirect.com
SciVerse ScienceDirect

Available online at www.sciencedirect.com

SciVerse ScienceDirect

Russian Geology and Geophysics 53 (2012) 1150–1162

RUSSIAN GEOLOGY AND GEOPHYSICS

www.elsevier.com/locate/rgg

# Seismic geologic structure model for the sedimentary cover of the Laptev Sea part of the Lomonosov Ridge and adjacent parts of the Amundsen Plain and Podvodnikov Basin

P.V. Rekant [a,b], E.A. Gusev [a,b,*]

[a] *I.S. Gramberg All-Russian Scientific Research Institute for Geology and Mineral Resources of the Ocean, St. Petersburg, Angliiskii pr. 1, St. Petersburg, 190121, Russia*
[b] *St. Petersburg State University, Universitetskaya nab. 7, St. Petersburg, 199034, Russia*

Received 28 July 2010; accepted 23 April 2012

**Abstract**

Seismic data on the southern (Laptev Sea) extremity of the Lomonosov Ridge were used to develop a new structural model for the sedimentary cover. It permitted a correlation between the seismic cross-sections of the ridge crest and two deep-sea basins: the Podvodnikov Basin and the Amundsen Plain. It is the first time that a seismic model has taken into account both regional seismic-reflection profiles obtained from NP drifting ice stations and recent high-resolution CDP data. Our seismic model agrees both with geological data on the Laptev Sea continental margin and the data obtained from deep-sea drilling into the Lomonosov Ridge under the IODP-302 project. The sedimentary cover of the southern Lomonosov Ridge and adjacent parts of the Amundsen Plain and Podvodnikov Basin was dated at the Aptian–Cenozoic. The sedimentary section is divided by two main unconformities, of Campanian–Paleocene and Oligocene–Early Miocene ages. The cover contains a structurally complicated graben system, which is an extension of the New Siberian system of horsts and grabens, recognized in the shelf. Sedimentation began in the grabens in the Aptian–Albian and ended with their complete compensation in the Paleocene.


*Keywords:* seismic model; sediments; Lomonosov Ridge; Podvodnikov Basin

## Introduction

The first reflection surveys of the sedimentary cover of the Lomonosov Ridge were done in the middle 20th century. The present widely held views on the geologic structure of the sedimentary cover of the central Arctic region originated at this time. Surprisingly, the main features of the geologic structure of the Arctic basin and its evolution, confirmed by 2004 deep-water drilling into the ridge (Backman et al., 2006; Moran et al., 2006), were pointed out more than 30 years ago in (Demenitskaya and Kiselev, 1968; Demenitskaya et al., 1962; Kiselev, 1986; and others). The first seismic surveys (early 1970s) revealed evidence for shallow-water sediments in the Lomonosov Ridge and for the continental origin of the ridge. Also, it was hypothesized at that time that the sedimentary cover of the Lomonosov Ridge consists of two "structural stages" (platform and subplatform), which overlie the folded basement ("structural stage" 3) with an unconformity (Demenitskaya and Kiselev, 1968; Kiselev, 1986). At that time, the regional erosional unconformity separating the sedimentary cover from the folded basement (Fig. 1) was detected; later, it was named the Lomonosov Unconformity (LU) (Jokat et al., 1995) (Fig. 2). Although the above publications significantly influenced many modern seismic models (Butsenko, 2008; Butsenko and Poselov, 2004; Lebedeva-Ivanova et al., 2004; and others), they are now undeservingly forgotten.

Now there are several seismic models for the geologic structure of the Lomonosov Ridge (Butsenko and Poselov, 2004; Daragan-Sushchova et al., 2004; Jokat, 2005; Jokat et al., 1995; Kim and Glezer, 2007; Langinen et al., 2009; Lebedeva-Ivanova et al., 2004; Sweeney et al., 1982; Zamanskii et al., 2002), which differ both in the number of seismic sequences (SSq) and in their stratigraphical correlation (Fig. 2). The differences are often determined by the seismic data used for the model. For example, the models based on low-resolution reflection data from North Pole (NP) drifting ice stations (Butsenko and Poselov, 2004; Langinen et al., 2009; Lebedeva-Ivanova et al., 2004; Zamanskii et al., 2002)

* Corresponding author.
*E-mail address*: gus-evgeny@yandex.ru (E.A. Gusev)

1068-7971/$ - see front matter © 2012, V.S. Sobolev IGM, Siberian Branch of the RAS. Published by Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.rgg.2012.09.003

yield a rather simplistic division of the section. They show regional SSq distribution and relations, almost without reflecting their internal wave pattern. Attempts at doing seismic-facies analysis based on these data (Butsenko, 2008; Butsenko and Poselov, 2004) seem questionable to us.

The seismic models of B.I. Kim and Z.I. Glezer (2007) and L.A. Daragan-Sushchova et al. (2004) rely both on geological data and seismic data on several CDP profiles, obtained from the crest of the Lomonosov Ridge. The advantage of these models consists in the detailed subdivision of the lower part of the sedimentary cover. However, the use of only individual seismic profiles of the key sites does not reveal the regional component of tectonic events.

Other problems are the absence of a distinct correlation between the existing seismic models (see above) and the use of the same SSq and reflector notation by different authors with fundamentally different subdivisions of the seismic cross-section (Jokat et al., 1995; Kim and Glezer, 2007) (Fig. 2).

The most important regional seismic boundaries are the LU in the Lomonosov Ridge crest (Fig. 2) (Jokat, 2005; Jokat et al., 1995) and the well-defined regional reflector A (regional unconformity (RU) (Butsenko, 2008; Butsenko and Poselov, 2004; and others)) in the sedimentary cover of conjugated deep-water basins. Correlation of these key reflectors is a complicated problem, whose solution is crucial in understanding the geologic history of the region. The presence of large zones of noncorrelation on the western and eastern slopes of the Lomonosov Ridge precludes the direct tracing of reflector A from the Podvodnikov Basin and Amundsen Plain to the Lomonosov Ridge crest. Now this problem can be solved only by correlating CDP data with the deep-water drilling data on borehole M0004a, ACEX (IODP-302) project (Backman et al., 2008; Moran et al., 2006).

Solutions have been suggested in (Butsenko, 2008; Butsenko and Poselov, 2004; and others) and (Langinen et al., 2009), on one hand, and in (Chernykh and Krylov, 2011), on the other (Fig. 2). However, these models have their flaws.

For example, according to (Butsenko, 2008; Butsenko and Poselov, 2004), the RU (Fig. 2) is the main regional marker in the seismic cross-section, which divides it into the Cretaceous–Eocene and Miocene–Quaternary parts. The researcher V.V. Butsenko attributes the formation of this reflector to the transformation of the regional morphostructure and postulates its regional erosional character but correlates it with the contact between the LR-4 and LR-5 seismic complexes (in Jokat's interpretation) (Fig. 2). However, a thorough analysis of all the seismic data available shows no traces of a significant tectonic event at this stratigraphic level in the seismic cross-section, and the deep-water drilling data indicate that the unconformity here is concealed (stratigraphic). We think that the event which transformed the regional morphostructure must be reflected in a much more conspicuous unconformity and the corresponding reflector. Therefore, another weakness of this model seems to be the correlation of the LU with an indistinct seismic boundary, the Eurasian Unconformity (EU), fragments of which are localized within the filling complex of the troughs (Butsenko, 2008).

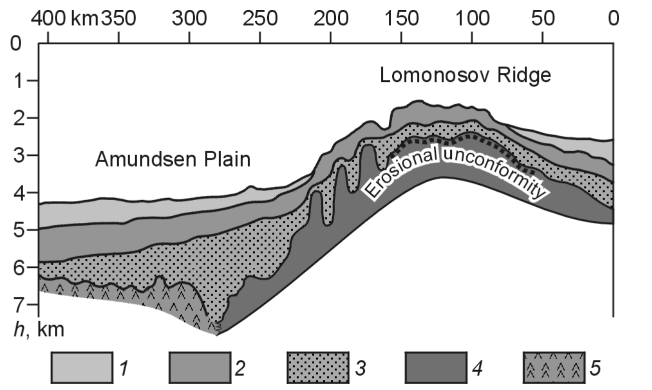


Fig. 1. Seismic geologic cross-section at 82° N, obtained at NP-24 (Kiselev, 1986). *1*, pelagic sediments of structural stage (SS) $1_1$ ($v_1$ = 1.5–1.6 km/s); *2*, neritic sediments of SS-$1_2$ ($v_1$ = 1.7–1.9 km/s); *3*, SS-2 rocks ($v_1$ = 2.5–4.5 km/s); *4*, SS-3 rocks ($v_1$ = 4.5–6.0 km/s); *5*, mafic complex ($v_1$ = 5.5–6.5 km/s). A distinct erosional unconformity is observed at the contact between the sediments of "structural stages" 2 and 3.

A somewhat different correlation scheme for the key reflectors is proposed in (Langinen et al., 2009) and (Chernykh and Krylov, 2011) on the basis of magnetostratigraphic dating and the similarity between the wave patterns of the seismic complexes in the uplifts and adjacent basins. Independently, these authors correlate the prominent regional reflector A in the basins with a very indistinct conformable seismic boundary at the LR-4 bottom and the Lomonosov angular unconformity with the bottom of the high-amplitude conformable unit below reflector A. Again, we do not think this is the optimum solution. The problem led us to develop our own model for the seismic division of the sedimentary cover.

## Materials and methods

The seismic model for the structure of the sedimentary cover in the southern Lomonosov Ridge is based on the analysis of the AWI-98550-98599 (Jokat, 2005), Oden-9613-16 (Kristoffersen, 1997), and UB-0103 (Backman et al., 2004) CDP profiles (Fig. 3). Also, we used the results of seismic reflection profiling at stations NP-21 and NP-24 (Kiselev, 1986; Poselov et al., 2007; Zamanskii et al., 2002). The stratigraphical correlation of the model was based on key seismic cross-sections AWI-91090 and AWI-91091 (Jokat, 2005) and their refined stratigraphical correlation with core from borehole M0004a (Backman et al., 2008).

In general, our seismic model preserved the SSq notation of Yu.G. Kiselev (1986). The names of the reflectors between the SSq were modified after (Langinen et al., 2009; Lebedeva-Ivanova et al., 2004). The seismic complexes in the circumpolar part of the region were described and identified after (Jokat, 2005).

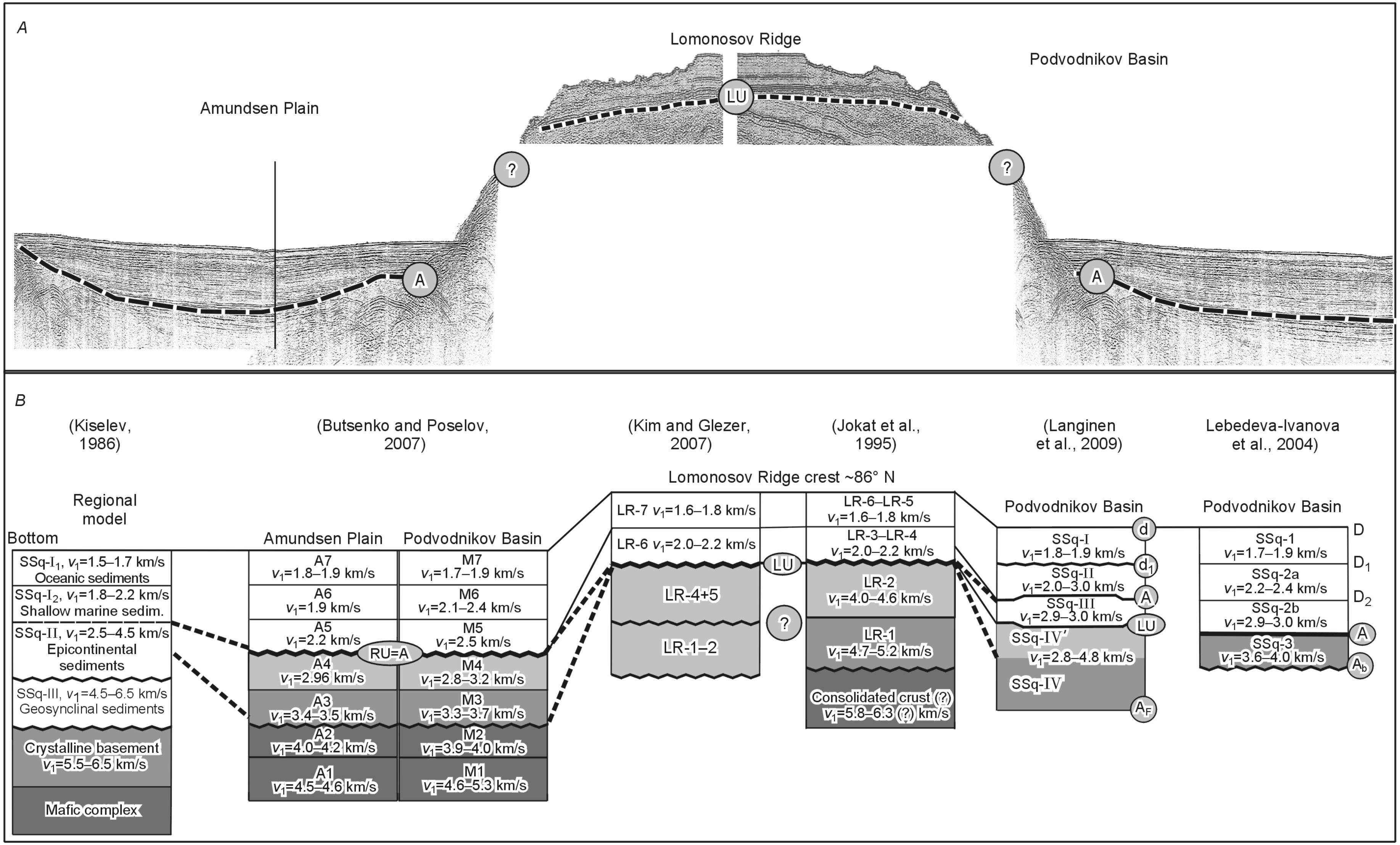


Fig. 2. General synthetical section of the Lomonosov part of the Arctic Ocean with the key reflectors (*A*) and a correlation scheme for the main regional seismic models (*B*). The prominent angular unconformity LU is observed in the Lomonosov Ridge crest on most of the seismic profiles, and the well-defined conformable reflector A is observed in the adjacent deep-water basins. Heavy dotted lines show the correlation scheme used in the study for the key reflectors.

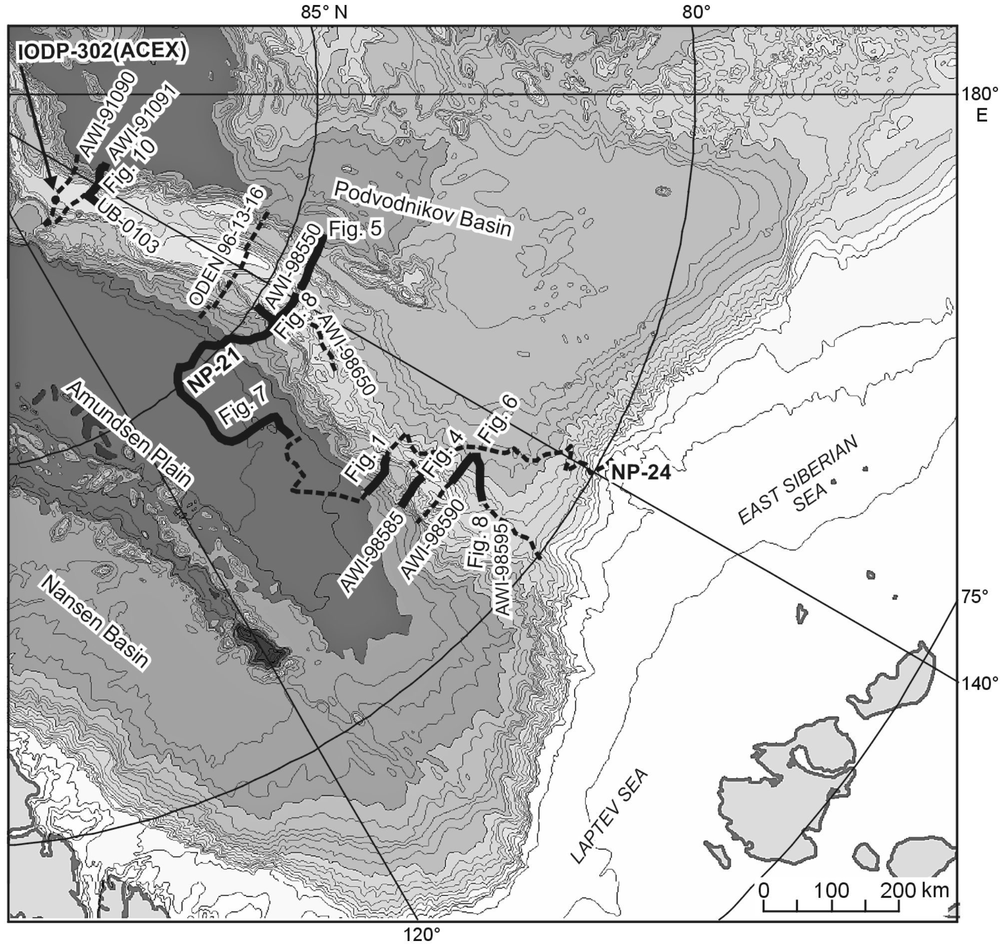


Fig. 3. The position of seismic profiles in the Laptev Sea part of the Lomonosov Ridge (Backman et al., 2004; Jokat, 2005; Kiselev, 1986; Kristoffersen, 1997; Poselov et al., 2007; Zamanskii et al., 2002) and that of borehole M0004a, drilled as part of the IODP-302 project (Backman et al., 2008; Moran et al., 2006). Heavy line shows fragments of the seismic profiles cited and the figure numbers.

## Results

Analysis of all the seismic data available and the existing summaries showed that the seismic cross-section of the Lomonosov part of the Arctic Ocean, both within the basins and the ridge, is divisible into five SSq over the acoustic basement (reflector $A_b$) (Fig. 4).

The upper SSq ($I_1$, $I_2$) form a bedded unit consisting of pelagic sediments and remain undisturbed in most of the water area. The lower ones ($II_1$, $II_2$, III) fill deep graben-like troughs on the ridge slopes and crest and consist of presumably littoral-marine and shallow-water sediments.

The wave pattern of the upper unit comprises high-frequency plane-parallel reflections, which envelop and level the roughness of the underlying relief. Note that their dynamic character and frequency considerably decrease down the section. Owing to the clear wave pattern, the unit is traced easily in the Podvodnikov Basin and Amundsen Plain and in the crest of the southern Lomonosov Ridge (Figs. 4–8). Its seismic stratigraphic volume correlates with “structural stage” 1 (Kiselev, 1986), or LR-3–LR-6 (Jokat et al., 1995) (Fig. 7). A layer velocity ($v_l$) of 1.5–2.2 km/s in the upper unit (Jokat et al., 1995; Kiselev, 1986) suggests the presence of loose and poorly lithified sediments.

In most of the area, SSq-$I_1$ and SSq-$I_2$ form a single sedimentary unit, divided by the $D_1$ conformable reflector. The unit thickmess increases regularly from north to south: from 300–500 m in the deep-water basins to 1500 m near the foot of the continental slope. In the acoustic-basement inliers, it decreases to 80–100 m owing to the missing upper part of SSq-$I_2$ (Fig. 5, PK no. 600–700), and reflector $D_1$ is here unconformable.

The SSq-$I_2$ bottom is bounded by the regional key reflector A, which coincides with the bottom of “structural stage” 1 (Kiselev, 1986) (Figs. 4–7).

The existence of this key reflector was pointed out long ago (Demenitskaya and Kiselev, 1968; Kiselev, 1986); it is easily recognizable in the vast territories of the central Arctic and has stable morphologic and dynamic characteristics. Such a prominent reflector, which is manifested in a stable regional change in the wave pattern, must correspond to a large sedimentation gap, accompanied by major changes in the paleogeographic situation.

Most of the authors who studied and interpreted later seismic data also use the above seismic horizon as a reference

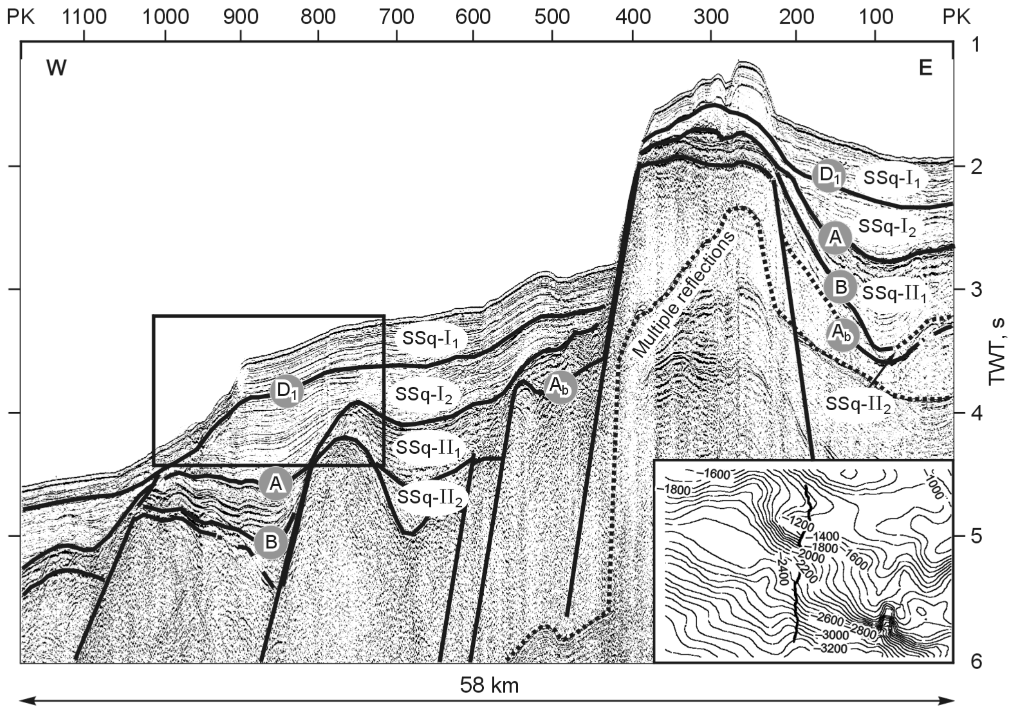


Fig. 4. Fragment of the AWI-98585 seismic profile (Jokat, 2005) with the interpretation scheme accepted in the paper. The seismic sequences and the reflectors which separate them are described in the text. The erosional character of reflector A in the most elevated parts of the Lomonosov Ridge crest (PK 200–300 TWT = 1.8–2.2 s) is evidenced by the absence of SSq-$II_1$ and the deep erosion of the underlying sediments.

for their models (Butsenko and Poselov, 2004; Jokat, 2005; Jokat et al., 1995; Langinen et al., 2009; Verba, 2008; Zamanskii et al., 2002). The horizon is conformable in most of the study area in the Makarov Basin (sea depths of >1500 m) and Amundsen Plain (>3000 m). This reflector acquires a well-defined erosional character (Figs. 4–8) in the basement inliers in the erosion zone of the sediments underlying SSq-$II_1$.

The SSq-$II_1$ roof is bounded by reflector A (Figs. 4–6); the bottom, by reflector B. This SSq is important for the stratigraphical correlation of seismic cross-sections. We think that it coincides with the upper "structural stage" 2 (Kiselev, 1986). Seismic sequence $II_1$ is marked by layer velocities of 2.5–3.5 km/s (Figs. 4–8), and its wave pattern, with slightly wavy high-amplitude parallel reflectors, is typical and easily identified in the vast territories of the Arctic Ocean up to the continental slope of the Laptev Sea–East Siberian Sea continental margin. Down the SSq-$II_1$ section, the internal-reflection amplitude shows a considerable decrease, and the lower part of the complex consists of acoustically semitransparent sediments.

Seismic sequence $II_1$ forms a well-defined structure filling the troughs on both ridge slopes (Figs. 4–8). It wedges out almost completely in the basement highs, and its thickness dramatically increases (to 1000 m) in the adjacent grabens and deep-water basins. This complex almost completely levels the roughness of the underlying relief and makes up the thicker part of the graben filling on the eastern slope. Most probably, SSq-$II_1$ accumulated during the erosion of the Lomonosov Ridge crest and sediment transport into the adjacent basins and local depressions on its slopes.

Seismic sequences $II_2$ and III are localized in the lower part of the graben filling. We correlate them with SSq-IV + IV′ (Langinen et al., 2009) or SSq-IV (Zamanskii et al., 2002). They are separated from the overlying sediments by the indistinct reflector B, whose fragments are observed on the seismic profiles. This boundary is most prominent in the grabens on the eastern slope of the Lomonosov Ridge (Fig. 6, PK 2400–3000, TWT = 4.5–5.0 s).

The wave pattern for SSq-$II_2$ and SSq-III is nonlayered, with short lineups and many diffracted waves in the roof. The latter clearly indicates that the upper part of the seismic complex over the basement inliers was eroded. The minimum thickness (50–100 m) is observed in the basement inliers, and the maximum thickness (>1800 m) is observed in the deepest graben on the eastern slope.

We correlate **the acoustic-basement** roof with reflector $A_b$. The latter often shows a conspicuous angular unconformity with inclined high-amplitude reflecting surfaces, which step along a fault series. It is most prominent in the elevated blocks on the western slope of the Lomonosov Ridge and at the bottom of the deepest grabens. The layer velocities (Jokat et al., 1995) in the sediments of the acoustic basement vary widely (4.5–5.2 km/s), and this suggests its heterogeneity. Apparently, the structurally complicated rocks of the folded basement are expected within this seismic complex.

Almost no seismic data are available on **the crystalline basement** of the study area. Only on the AWI-98550 profile (Fig. 5, PK no. 600–900), the prominent reflector $A_{cr}$, underlain by high-velocity sediments ($v_l$ > 5.9 km/s), is present in the seismic cross-section at 3–4 s TWT.

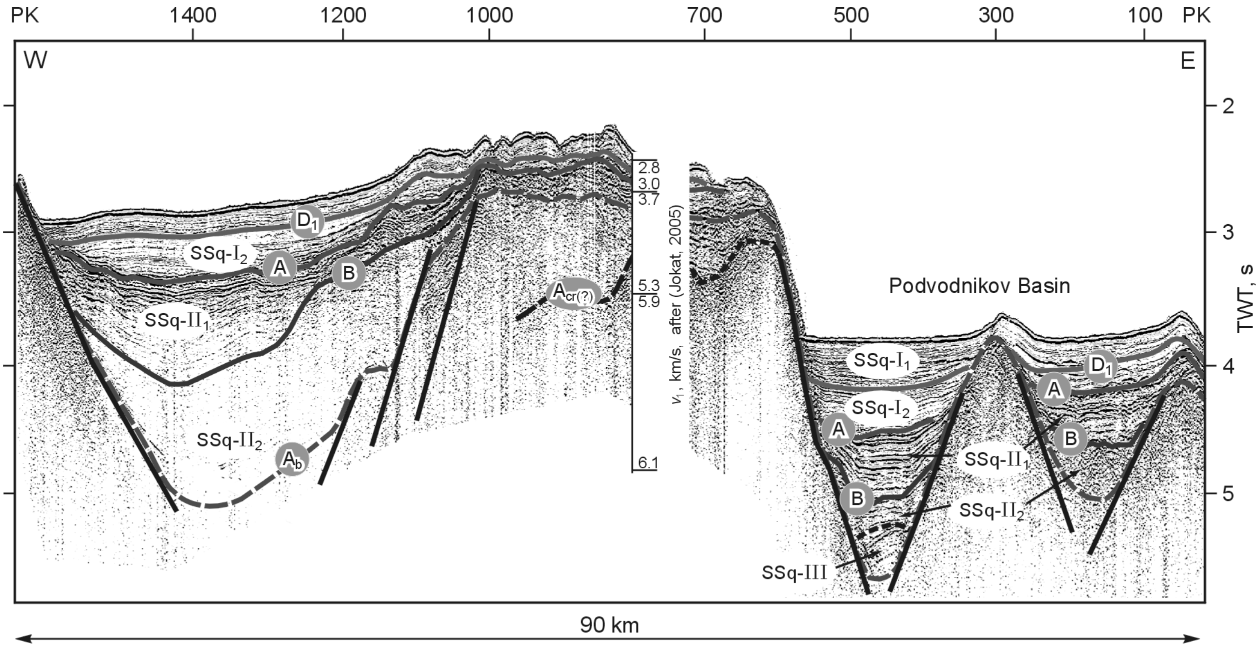


Fig. 5. Eastern part of the AWI-98550 seismic profile (Jokat, 2005) with the interpretation scheme accepted in the paper. The erosional character of reflector A is distinct over the basement inlier (center) (PK 1000–600, TWT = 2.6 s); here, the SSq-II1 sediments are almost missing from the section. Lower down the section, reflector $A_{cr}$ is observed, which might correlate with the crystalline-basement surface.

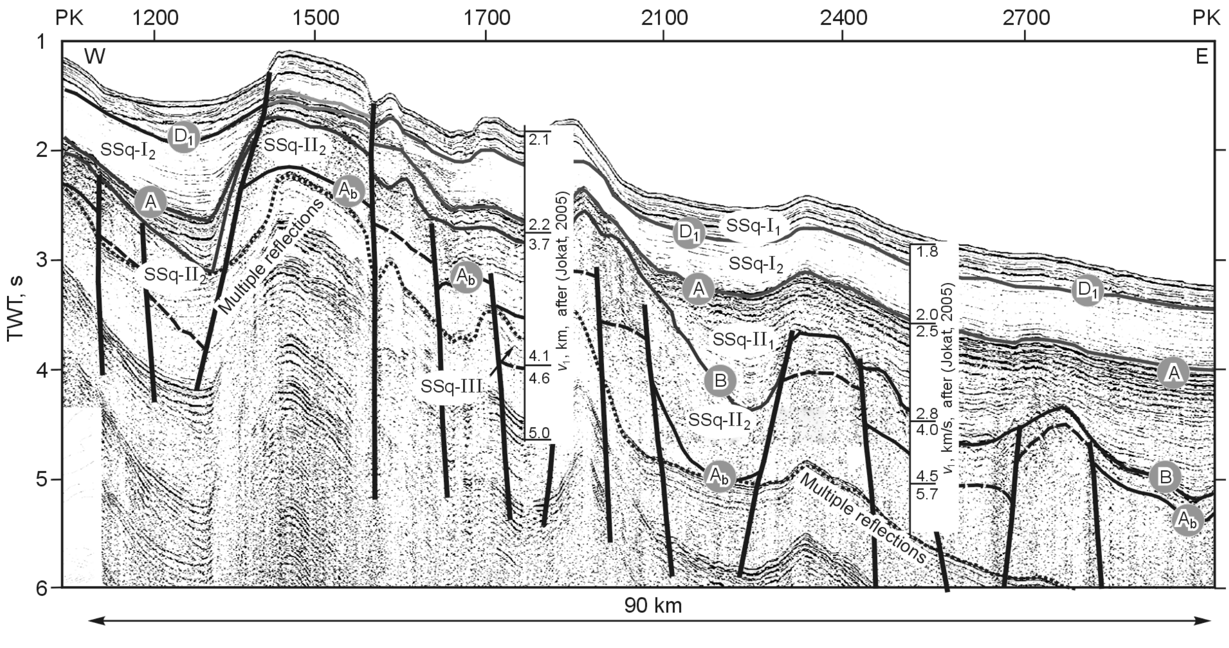


Fig. 6. Fragment of the AWI-98590 seismic profile (Jokat, 2005) through the Lomonosov Ridge crest with the interpretation scheme accepted in the paper. In the places with almost missing SSq-II1 sediments (~PK-1500–1700), reflector A becomes erosional and the layer velocities in the seismic field change dramatically.

## Stratigraphical correlation of the seismic model for the sedimentary cover

The stratigraphical correlation of the seismic model began with the identification of the key reflectors in the seismic cross-section and their correlation with the corresponding tectonic events, accompanied by considerable transformations of the regional morphostructure. It seems evident that traces of such tectonic events must be manifested throughout the region and differ radically in the uplifts and deep-water basins. The former were eroded actively and served as debris reservoirs, whereas the latter served as depocenters of eroded sediments. Consequently, the erosional contact in the ridge must correlate with the sedimentary complex filling the adjacent basins. We question the hypothesis about the development of a regional erosional unconformity in the ridge crest and in the basins to depths of 4000 m (Butsenko, 2008). Also, we think that the deep-water basins must have the most

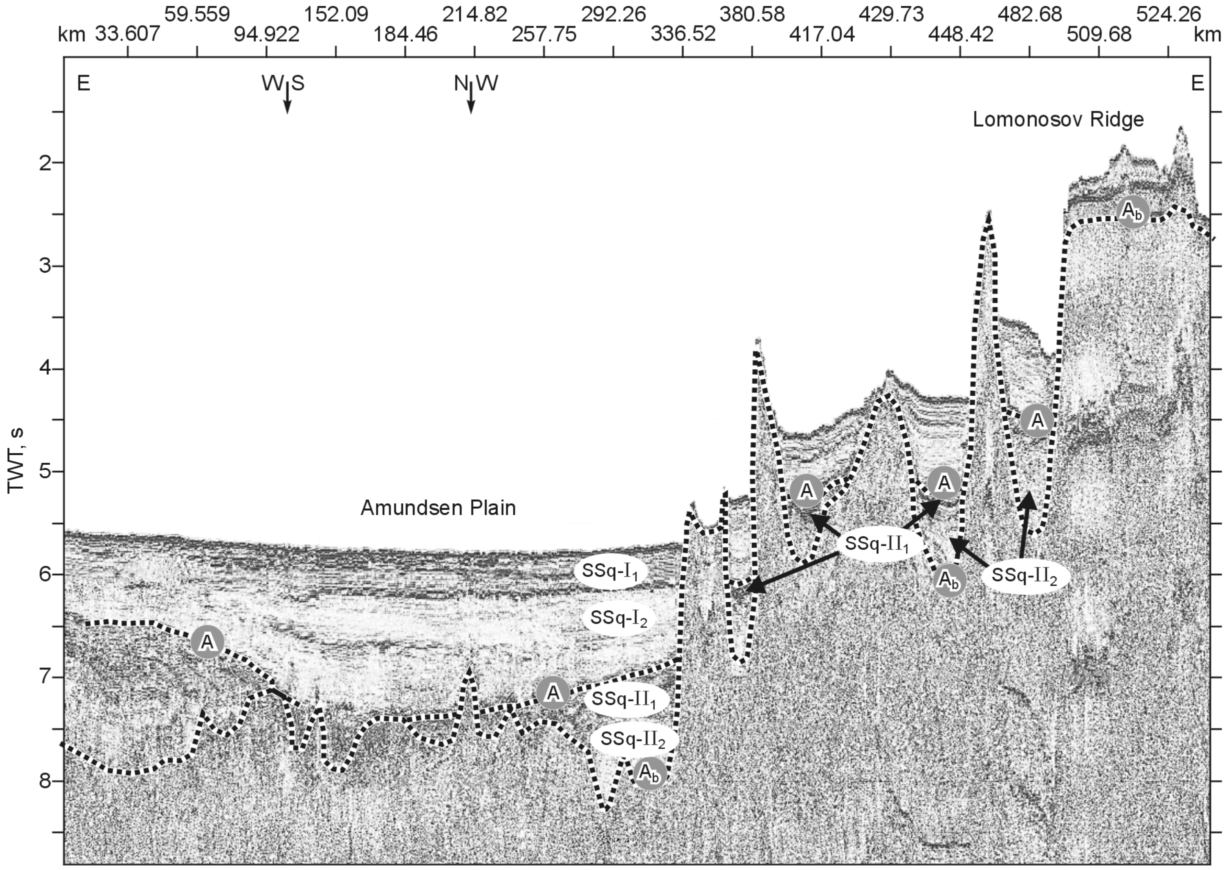


Fig. 7. Fragment of the seismic-reflection profile along the drift line of the NP-21 station in the Amundsen Plain (Butsenko and Poselov, 2004) with the interpretation scheme accepted in the paper. Seismic sequence $II_1$ wedges out above the basement inlier (PK 200, TWT = 7.5 s) approximately 150 km west of the Lomonosov Ridge foot, suggesting the Late Cretaceous age of the basement in the region.

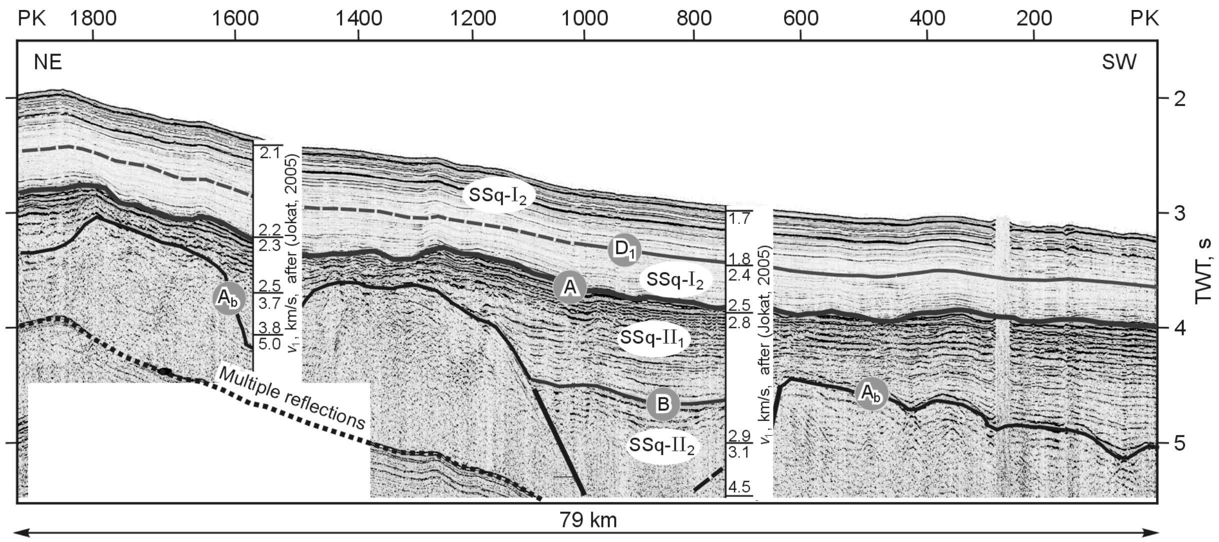


Fig. 8. Fragment of the AWI-98595 seismic profile (Jokat, 2005) with the interpretation scheme accepted in the paper. Seismic sequence $II_1$ is complete in the basins, and the layer velocities increase gradually down the section of the sedimentary cover.

complete stratigraphic section, which might contain even the sediments missing from the shelf (e.g., Paleocene ones).

Undoubtedly, the most prominent seismic marker in the arched part of the Lomonosov Ridge is the LU (Fig. 9), which was detected as far back as the 1980s (Kiselev, 1986) and described in detail by later CDP studies (Jokat et al., 1995). The LU correlates with the formation of the block–boulder structure of the ridge, accompanied by a considerable sedimentation gap, sediment erosion in the crest, and active tectonic movements. Preliminary estimates of the erosional truncation at this boundary show that at least 800 m sediments was eroded here (Jokat et al., 1995). This is also evidenced unambiguously by an angular unconformity and a drastic increase in the layer velocities at this boundary: from 2.2 km/s in the overlying layered unit to 4.5 km/s in the underlying dislocated unit (Jokat et al., 1995).

The age model for the section structure, based on studies of core from borehole M0004a (Backman et al., 2006; Moran et al., 2006), was chosen as the main stratigraphical reference for correlating the seismic complexes and their boundaries. It was characterized quite well by seismic (Jakobsson et al., 2007; Jokat et al., 1995; Kristoffersen, 1997; Weigelt, 1998) and direct geological evidence (Backman et al., 2006, 2008; Derevyanko et al., 2009; Krylov, 2005; Moran et al., 2006). The geological model obtained from integrated studies of core from this borehole is the most complete one and accepted by most researchers.

As is known from the drilling data (Moran et al., 2006), borehole M0004 in the ridge crest stripped the entire section of the horizontal-bedded unit corresponding to the LR-3–LR-6 seismic complexes (Jokat, 2005) and was driven for >20 m along the underlying sediments (Fig. 9) (Backman et al., 2008). However, the dislocated acoustic-basement rocks with layer velocities of >4.0 km/s, which were expected on the basis of the seismic profiling results, were not stripped.

The sediments at the bottom of the horizontal-bedded unit were dated on the basis of micropaleontological data at the Late Paleocene (56 Ma). Sediments with Turonian (Krylov, 2005), Campanian (Backman et al., 2006), or Maastrichtian (Derevyanko et al., 2009) fossils were stripped in the lowermost part of the section, within the very sandy litholigic complex 4 (Fig. 9). Such wide variation in the age correlations might be due to the presence of in-site and redeposited foraminifer, spore, and pollen assemblages.

Thus, we think that borehole M0004, which did not reach the acoustic basement, stopped in the base unit, formed by the erosion of Cretaceous underlying sediments. The thinness of this unit at the drilling site of borehole M0004 makes it unidentifiable in the adjacent part of the AWI-91090 profile. However, analysis of seismic data on the eastern and western peripheries of the ridge permitted the identification and a seismic description of a similar unit immediately below the LU. For example, a structurally complicated clinoform seismic filling unit (LR-2/3 in our interpretation) is traced at the intersection of the AWI-91091 and UB-0103 profiles (Fig. 9), between LR-2 (bottom) and LR-3 (top). It indicates that eroded sediments were removed from the ridge crest and accumulated in local sedimentation traps and the adjacent deep-water basins. A similar unit was detected in the western part of the ridge. Also, such a filling unit was described by B.I. Kim (Kim and Glezer, 2007) in a graben on the eastern slope of the Lomonosov Ridge.

The end of the erosion stage is marked in the seismic cross-section by the formation of the LU regional boundary in the late Late Paleocene (Backman et al., 2008). According to the paleontological data available (Backman et al., 2006; Derevyanko et al., 2009; Krylov, 2005), the sedimentation gap correlates roughly with the late Late Cretaceous–early Paleocene. Such a large gap, which gave rise to the angular unconformity and was accompanied by deep erosion of the Lomonosov Ridge summit surface, must have also changed the character of the sedimentation in the adjacent areas. The change must have given rise to a thick filling unit in the adjacent basins and a conspicuous seismic boundary marking the end of the erosion.

Indeed, as demonstrated above, the regional key reflector A, which coincides with the roof of the filling unit (SSq-II$_1$), exists in the Amundsen Plain and Podvodnikov–Makarov Basins and in the East Siberian Sea part of the Lomonosov Ridge. Thanks to its seismic prominence and stable dynamic characteristics, this boundary is identified easily within and outside grabenlike troughs in the central and southern Lomonosov Ridge (Figs. 4–7). Being conformable in the abyssal zone, reflector A acquires distinct features of an erosional unconformity in the uplifts (Figs. 4–6). Since most of SSq-II$_1$ (layer velocities of 2.5–3.5 km/s) is missing from the section, the SSq-I$_2$ low-velocity sediments ($v_l$ = 2.0–2.2 km/s) here overlie the eroded roof of the SSq-II$_2$ and SSq-III high-velocity sediments ($v_l$ = 3.5–4.5 km/s or more) (Fig. 6), and a drastic change in the layer velocities is observed within the seismic field (Jokat et al., 1995; Weigelt, 1998). Seismic sequence II$_1$ reaches the maximum thickness in the deep grabens near the ridge crest and in the adjacent parts of the basins (Figs. 4–8). As a result, the layer velocities in the seismic field show an almost continuous gradual stable increase down the section (Fig. 8).

In summary, the local filling units in the northern part of the ridge (LR-2/3) might correlate with the SSq-II$_1$ regional sedimentary complex, and the surfaces of the LU, which marks the end of the deep erosion of the Lomonosov Ridge, might correlate with the regional key reflector A (Fig. 9). In turn, this makes it possible to apply the geological model based on drilling data (Backman et al., 2008) to regional seismic data and to do the stratigraphical correlation of our seismic model (Figs. 9, 10).

We consider the Middle Eocene–Early Miocene unconformity in the section of borehole M0004a (Fig. 8) to be the second important stratigraphical reference, which divides the Cenozoic part of the sedimentary section. It coincides roughly with the boundary of LR-3 and LR-4, which are localized in the ridge crest (Backman et al., 2008). According to the model of J. Backman et al., the boundary marks a considerable change in the Arctic paleoenvironments from an isolated stagnant shallow-water sea basin to the deep ocean with active hydrodynamics and correlates with the opening of the Fram Strait (Thiede et al., 1990). Similar ideas were also expressed before. For example, in Kiselev's (1986) geological model for the section structure, shallow-water marine environments are replaced by oceanic ones in the seismic cross-section at the contact between the sediments of the upper (SS-1$_1$) and lower (SS-1$_2$) parts of "structural stage" 1 (Fig. 2). In our seismic model, this gap corresponds to reflector D$_1$, which separates

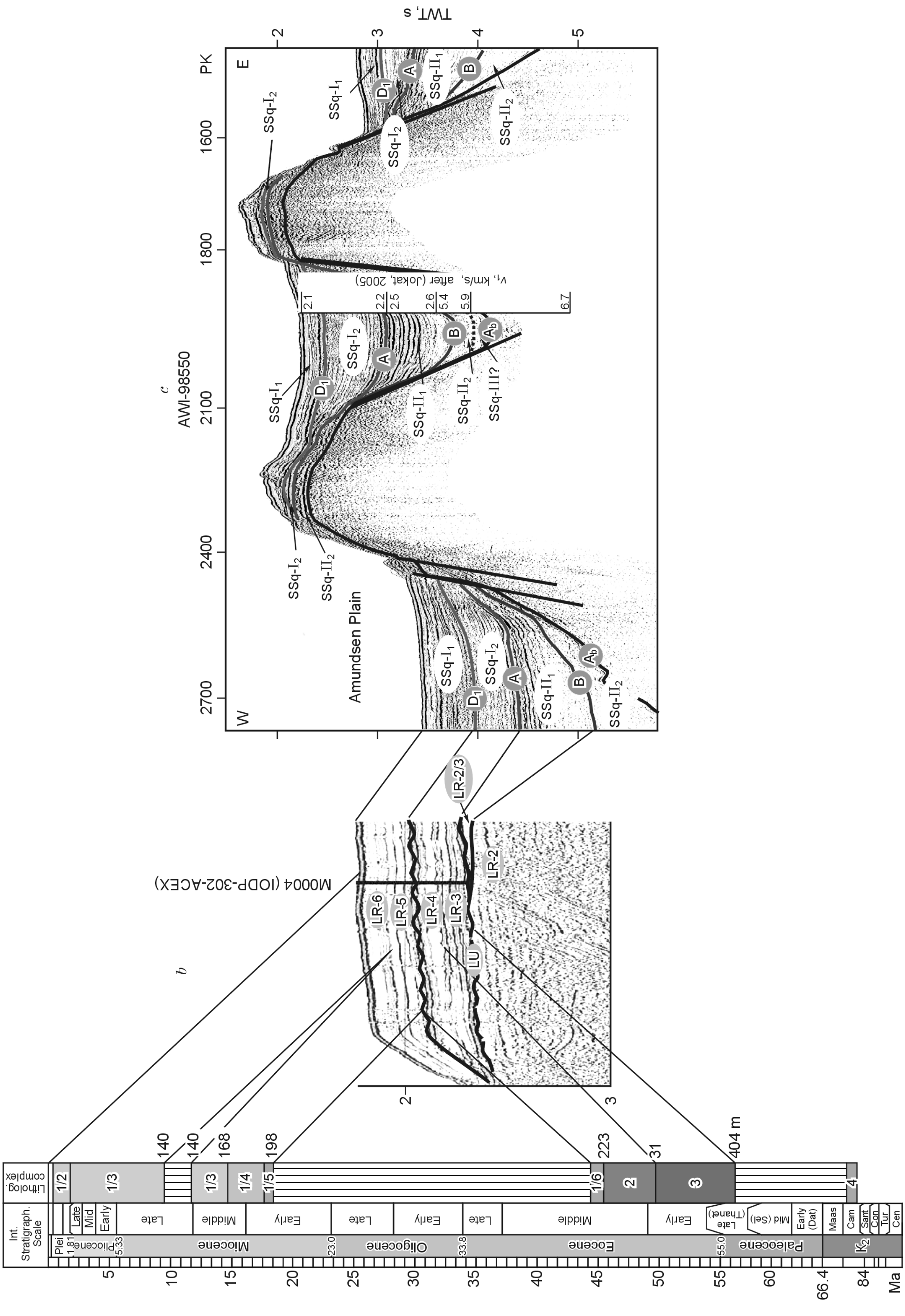


Fig. 9. Stratigraphical correlation of the seismic model: correlation of data from the M0004 deep-water borehole (Backman et al., 2008) (*a*) with fragments of the AWI-91091 (Jokat et al., 1995) (*b*) and AWI-98550 (Jokat, 2005) (*c*) profiles.

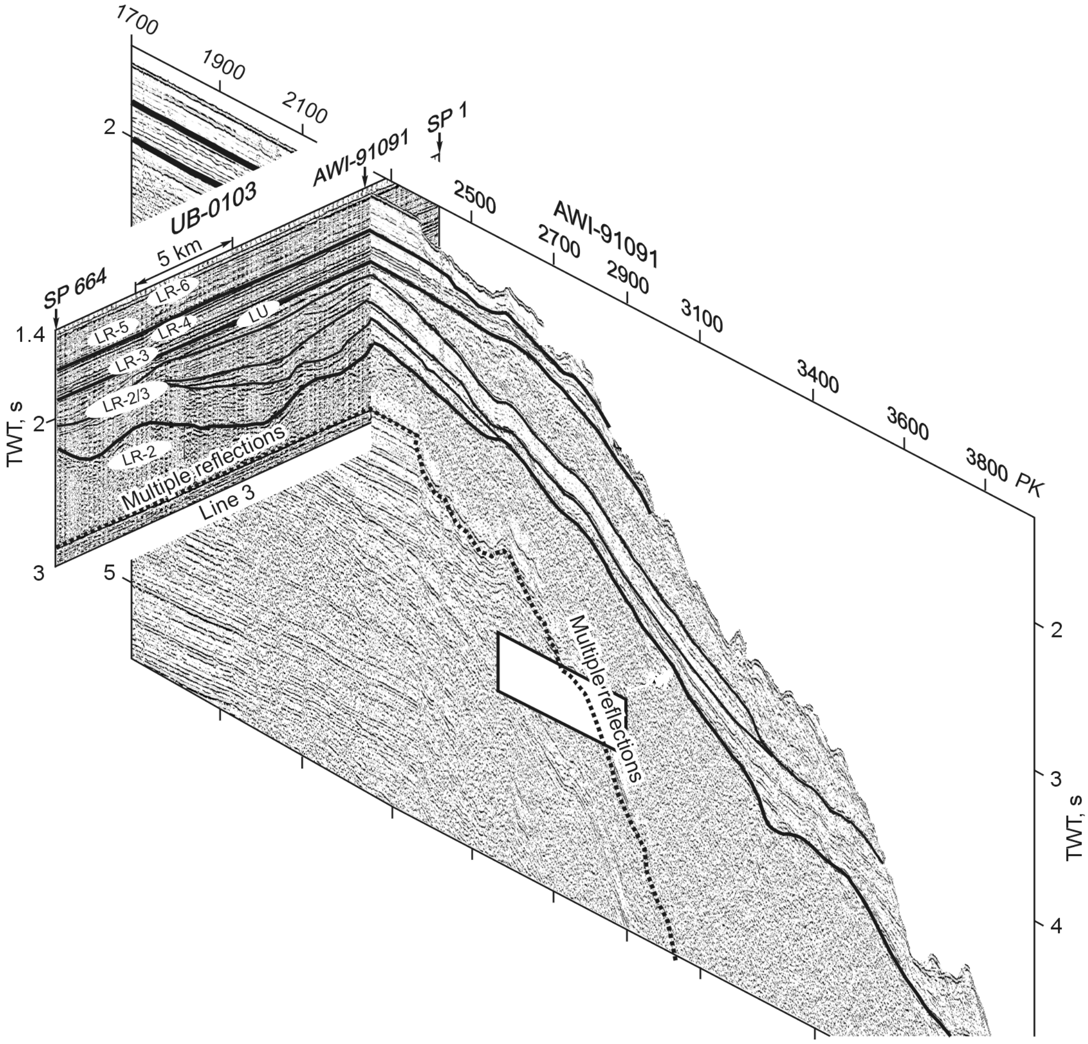


Fig. 10. Fragments of the UB-0103 (Backman et al., 2004) and AWI-91091 seismic profiles (Jokat, 2005). The interpretation scheme is supplemented after (Jokat et al., 1995). A complex filling unit (LR-2/3 in our interpretation) is observed in the depressions of the LR-2 eroded roof, below the LU, under the LR-3 + LR-6 horizontal-bedded unit. It might have formed in the Campanian–Paleocene owing to the erosion and redeposition of the underlying sediments.

SSq-I$_1$ and SSq-I$_2$, is conformable in the basins, and bears some signs of an erosional unconformity in the ridge slopes (Fig. 9).

After the stratigraphical correlation of two key reflectors (A(LU), D$_1$), we correlated the rest of the seismic complexes (Fig. 8). Note that the Mesozoic section, which was almost not drilled into, was correlated with the filling complex of the deepest grabens of the Laptev Sea–East Siberian Sea continental margin (State..., 2004; Vinogradov et al., 2005) (Fig. 11). Comparison showed a good correlation between the velocity parameters and the tectonic positions of the stratigraphic units as well as the inherited character of the main unconformities in the shelf and in the deep-water region (Rekant et al., 2011, 2012).

Seismic sequences III and II$_2$, localized at the very bottom of the graben filling complex, correlate with the Balyktakh Formation (K$_1$a-al) and Late Cretaceous rocks, respectively. Seismic sequence II$_1$ correlates mainly with Paleocene rocks. The lower part of SSq-I$_2$ might correlate with the Paleocene–Eocene sediments in the East Siberian Sea and Laptev Sea water areas, which correspond to the seismic complex bounded by reflectors L-IV and L-V and the Anzhu Formation of the New Siberian Islands (State..., 2004). The Nerpich'ya Formation, which consists of Late Oligocene–Early Miocene carbonaceous sediments (State..., 2004), correlates in our seismic model with the upper part of SSq-I$_2$. The uppermost part of the section in the study area is recognized as SSq-I$_1$ and spans the Middle Miocene–Holocene. This correlates with the Kanarchak Formation, which corresponds to the recent tectonic stage.

## Conclusions

The following conclusions are made on the basis of the stratigraphical correlation of our seismic model.

The following events took place in the Early Cretaceous: The structural outline of the Lomonosov Ridge began to form;

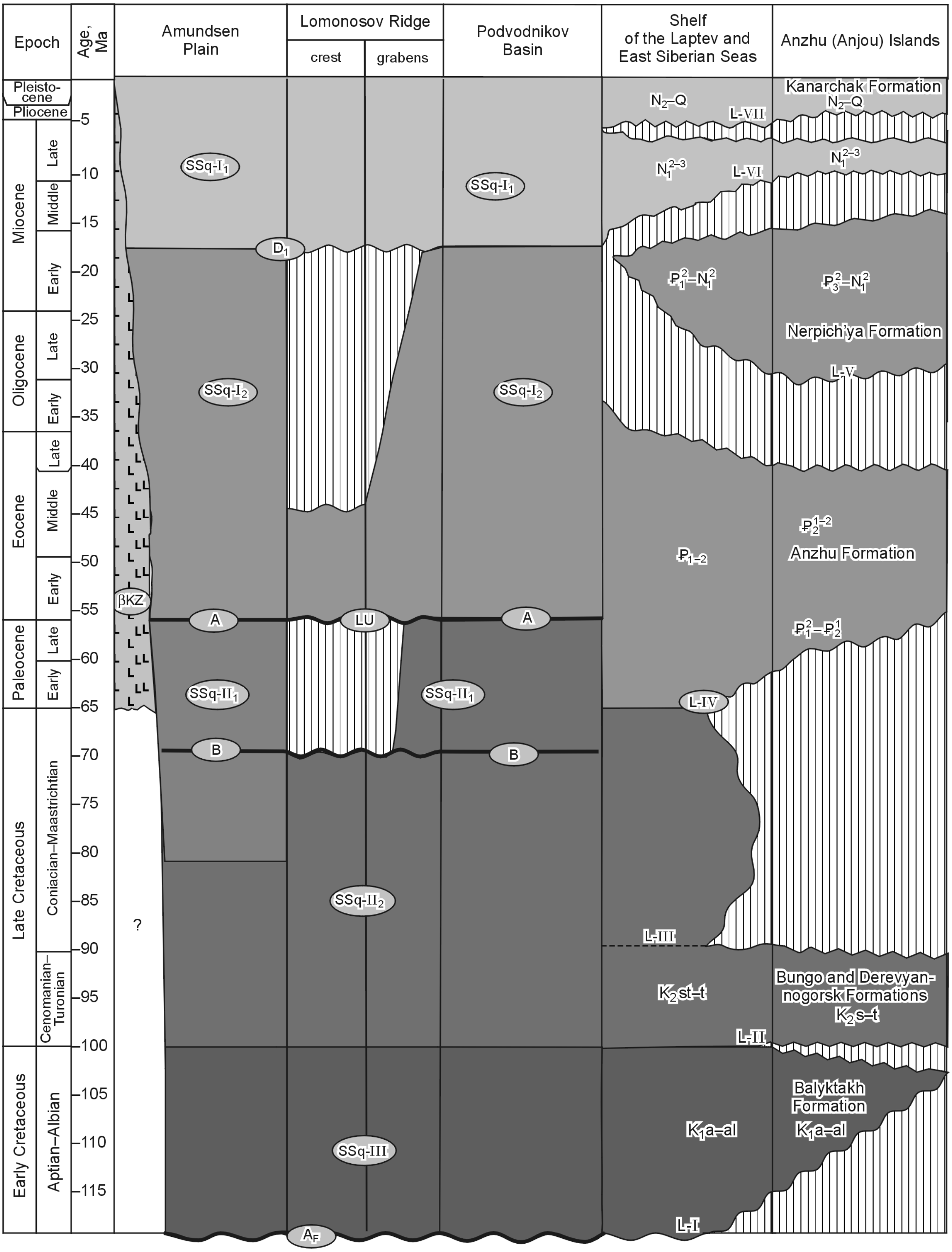


Fig. 11. Correlation scheme for the geologic sections of the Lomonosov Ridge and adjacent Laptev Sea–East Siberian Sea continental margin.

the horst–graben structure of the ridge was initiated and developed; and the fault zone bounding the future area of the Amundsen deep-water basin was formed. At that time, the Lomonosov Ridge was an epicontinental uplift surrounded in the west and east by shallow sea basins (Backman et al., 2008). In the Paleocene, sedimentation within the present area of the Lomonosov Ridge was followed by erosion. The elevated blocks in the ridge crest underwent intense erosion, and active sedimentation with the formation of correlative terrigenous sediments proceeded in the adjacent shallow sea basins, in place of which the Amundsen Plain and Podvodnikov Basin are now located. Anyway, leveled summit surfaces of horst structures were formed. In the Laptev Sea shelf and on insular and continental land, this time is marked by peneplanation and the formation of chemical-weathering crusts. Thus, sedimentation in the Lomonosov Ridge grabens began in the Aptian–Albian and ended with their complete compensation as late as the Paleocene. This age correlation of the graben filling complex is the main difference of our model from those in (Butsenko, 2008; Chernykh and Krylov, 2011; Langinen et al., 2009), which presuppose that the grabens were filled with younger (predominantly Cenozoic) sediments.

The main markers of the Cretaceous–Paleocene stage in the seismic sections are the LU, the LR-2/3 local filling units in the Lomonosov Ridge crest, and SSq-$II_1$, which has a regional occurrence in the adjacent basins. Analysis of the SSq-$II_1$ areas suggests that Cretaceous–Paleocene rocks were widespread in the Amundsen Plain. This is confirmed by CDP profiling in the Amundsen Plain (Jokat et al., 1995). The AB-1 and AB-2 seismic complexes, which correlate with the Paleocene erosion in the ridge crest, are traced for up to 400 km along the profile (~200 km along the orthogonal) from the Lomonosov Ridge to the Amundsen Plain.

In all probability, the active subsidence of the present-day basins to abyssal depths began no earlier than the late Oligocene and peaked in the Miocene–Pliocene. The intense formation of deep-water basins and the Lomonosov Ridge uplift which separates them began in the Late Oligocene–Early Miocene and is associated with gradual basin deepening and the replacement of shallow-water sediments by deep-water ones. The ridge morphostructure formed under general nonuniform subsidence, determined by the fault system which segmented the ridge. The subsidence amplitude and subsidence rate of the morphostructures which remained positive were considerably smaller and lower as compared with those of the actively subsiding neighboring blocks. In general, this was a peculiar system of structures consisting of parallel underwater grabens and horsts, which were sometimes filled with a small amount of sediments. This stage in the development of the region corresponds to reflector $D_1$, which is unconformable in the uplifts and belongs as a conformable boundary to a single parallel-bedded unit in the abyssal zone.

The tectonic structure of the ridge cannot be considered in isolation from the structure adjacent to the southern Laptev Sea–East Siberian Sea continental margin. The graben system in the sedimentary cover of the Lomonosov Ridge is the structural extension of the New Siberian system of grabens and horsts, which is recognized in the shelf (State..., 2004; Vinogradov et al., 2005). This is confirmed by the unity of the system of tectonic deformations and graben filling complexes.

## References


Backman, J., Moran, K., Evans, D., the Expedition 302 Project Team, 2004. ACEX—Arctic Coring Expedition "Paleoceanographic and tectonic evolution of the central Arctic Ocean," in: Integrated Ocean Drilling Expedition 302, Mission Specific Platform Sci. Prospectus, No. 1.

Backman, J., Moran, K., McInroy, D.B., Brinkhuis, H., Clemens, S., Cronin, T., Dickens, G.R., Eynaud, F., Gattacceca, J., Jakobsson, M., Jordan, R.W., Kaminski, M., King, J., Koç, N., Martinez, N.C., Matthiessen, J., Moore, T.C., Onodera, J., O'Regan, M., Pälike, H., Rea, B.R., Rio, D., Sakamoto, T., Smith, D.C., Stein, R., St. John, K.E.K., Suto, I., Suzuki, N., Takahashi, K., Watanabe, M., Yamamoto, M., 2006. Sites M0001–M0004, in: Backman, J., Moran, K., McInroy, D.B., Mayer, L.A. (Eds.), Proc. of the Integrated Ocean Drilling Program. Integrated Ocean Drilling Program Management Int., Inc., Vol. 302.

Backman, J., Jakobsson, M., Frank, M., Sangiorgi, F., Brinkhuis, H., Stickley, C., O'Regan, M., Løvlie, R., Pälike, H., Spofforth, D., Gattacecca, J., Moran, K., King, J., Heil, C., 2008. Age model and core-seismic integration for the Cenozoic Arctic Coring Expedition sediments from the Lomonosov Ridge. Paleoceanography 23 (1), doi: 10.1029/2007PA001476.

Butsenko, V.V., 2008. The Main Tectonic Events in the Arctic Ocean History (from Seismic Data). Extended Abstract Doctoral (Geol.–Mineral.) Dissertation. All-Russ. Sci. Res. Inst. for Geol. and Mineral Resources of the Ocean, St. Petersburg.

Butsenko, V.V., Poselov, V.A., 2004. Regional peculiarities of the seismic configuration of the sedimentary cover of the Arctic deep-water basin and the possibility of their paleotectonic interpretation, in: Geological and Geophysical Features of the Lithosphere in the Arctic Region [in Russian]. VNIIOkeangeologiya, St. Petersburg, Vol. 203, Issue 5, pp. 141–159.

Chernykh, A.A., Krylov, A.A., 2011. Sedimentogenesis in the Amundsen Basin from geophysical data and drilling results on the Lomonosov Ridge. Dokl. Earth Sci. 440 (2), 1372–1376.

Daragan-Sushchova, L.A., Poselov, V.A., Daragan-Sushchov, Yu.I., 2004. Seismogeological analysis of models for the development of the Eurasian basin, in: Geological and Geophysical Features of the Lithosphere in the Arctic Region [in Russian]. VNIIOkeangeologiya, St. Petersburg, Issue 5, pp. 111–124.

Dementskaya, R.M., Kiselev, Yu.G., 1968. The structure and morphology of the sedimentary cover of the central Lomonosov Ridge (from seismic data), in: Dementskaya, R.M. (Ed.), Geophysical Exploration Methods in the Arctic [in Russian]. Gostoptekhizdat, Leningrad, Issue 5, pp. 33–46.

Dementskaya, R.M., Karasik, A.M., Kiselev, Yu.G., 1962. Results of the geological structure studies of the Earth's crust in the central Arctic by geophysical methods, in: Problems of the Arctic and Antarctic [in Russian]. Morskoi Transport, Leningrad, Issue 11, pp. 91–95.

Derevyanko, L.G., Gusev, E.A., Krylov, A.A., 2009. Palynological characteristics of Cretaceous rocks in the Lomonosov Ridge. Problemy Arktiki i Antarktiki, No. 2 (82), 78–84.

Drachev, S.S., 2000. Tectonics of the Laptev Sea Rift System. Geotektonika, No. 6, 43–58.

Franke, D., Hinz, K., Reichert, C., 2004. Geology of the East Siberian Sea, Russian Arctic, from seismic images: Structures, evolution, and the implications for the evolution of the Arctic Ocean Basin. J. Geophys. Res. 109 (B07106), doi: 10.1029/2003JB002687.

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 (7147), 986–990.

Jokat, W., 2005. The sedimentary structure of the Lomonosov Ridge between 88°N and 80°N. Geophys. J. Int. 163 (2), 698–726.

Jokat, W., Weigelt, E., Kristoffersen, Y., Rasmussen, T., Schöne, T., 1995. New insights into the evolution of the Lomonosov Ridge and the Eurasian Basin. Geophys. J. Int. 122, 378–392.

Kim, B.I., Glezer, Z.I., 2007. Sedimentary cover of the Lomonosov Ridge: Stratigraphy, structure, deposition history, and ages of seismic facies units. Stratigrafiya. Geologicheskaya Korrelyatsiya 15 (4), 63–83.

Kiselev, Yu.G., 1986. Deep Structure of the Arctic Basin [in Russian]. Nedra, Moscow.

Kristoffersen, Y., 1997. Seismic reflection surveys during Arctic Ocean-96. Yearbook 1995/96. Swedish Polar Research Secretariat, pp. 75–77.

Krylov, A.A., 2005. Deep-water drilling in the Arctic, in: Expeditions of VNIIOkeangeologiya in the Arctic and in the World Ocean, 2004 (Annual Review) [in Russian]. VNIIOkeangeologiya, St. Petersburg, pp. 4–7.

Langinen, A.E., Lebedeva-Ivanova, N.N., Gee, D.G., Zamansky, Y.Y., 2009. Correlations between the Lomonosov Ridge, Marvin Spur and adjacent basins of the Arctic Ocean based on seismic data. Tectonophysics 472 (1–4), 309–322, doi:10.1016/j.tecto.2008.05.029.

Lebedeva-Ivanova, N.N., Langinen, A.E., Zamanskii, Yu.Ya., Sergeev, M.B., 2004. Seismic model for the Earth's crust along the De Long Islands–Makarov Basin geotraverse, in: Geological and Geophysical Features of the Lithosphere in the Arctic Region [in Russian]. VNIIOkeangeologiya, St. Petersburg, Issue 5, pp. 125–140.

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 (7093), 601–605.

Poselov, V.A., Verba, V.V., Zholondz, S.M., 2007. Typification of the Earth's crust of Central Arctic Uplifts in the Arctic Ocean. Geotektonika, No. 4, 48–59.

Rekant, P.V., Gusev, E.A., Chernykh, A.A., Zinchenko, A.G., Basov, V.A., Kupriyanova, N.V., Vinogradov, V.A., Bondarenko, S.A., Zykov, E.A., Kaban'kov, V.Ya., Suprunenko, O.I., Shustova, N.V., Usov, A.N., Korshunov, D.A., 2011. Geological Map, Scale 1 : 1,000,000 [in Russian]. Ser. Okeanskaya. Sheet U-53-56—Lomonosov Ridge. Explanatory Note. VSEGEI, St. Petersburg.

Rekant, P.V., Gusev, E.A., Vinogradov, V.A., 2012. Horst-graben structures in the Lomonosov Ridge sedimentary cover: history of formation and linkages with the Siberian shelf, in: Stone, D.B., Clough, J.G., Thurston, D.K. (Eds.), Geophysical Institute Report UAG-R. Univ. Alaska, Fairbanks, Alaska, pp. 165–167.

State Geological Map of the Russian Federation, Scale 1 : 1,000,000 (New Ser.). Sheet T-53-56—Zhokhov Island. Explanatory Note [in Russian], 2004. VSEGEI, St. Petersburg, p. 118.

State Geological Map of the Russian Federation, Scale 1 : 1,000,000 (New Ser.). Sheet S-1,2—Chukchi Sea. Explanatory Note [in Russian], 2005. VSEGEI, St. Petersburg.

Sweeney, J.F., Weber, J.R., Blasco, S.M., 1982. Continental ridges in the Arctic Ocean: Lorex constraints. Tectonophysics 89 (1–3), 217–238.

Thiede, J., Clark, D.L., Herman, Y., 1990. Late Mesozoic and Cenozoic paleoceanography of the northern polar oceans, in: Grantz, A., Johnson, L., Sweeney, J.F. (Eds.), The Geology of North America: The Arctic Ocean Region. GSA, Boulder, Colo., Vol. 50, pp. 427–458.

Verba, M.L., 2008. Comparative Geodynamics of the Eurasian Basin [in Russian]. Nauka, St. Petersburg.

Vinogradov, V.A., Lopatin, B.G., Burskii, A.Z., Gusev, E.A., Morozov, A.F., Shkarubo, S.I., 2005. Main results of the geological mapping of the Russian Arctic shelf, scale 1 : 1,000,000. Razvedka i Okhrana Nedr, No. 6, 45–52.

Weigelt, E., 1998. The crustal structure and sedimentary cover of the Eurasian Basin, Arctic Ocean: results from seismic and gravity measurements. Ber. Polarforsch., No. 261.

Zamanskii, Yu.Ya., Ivanova, N.N., Langinen, A.E., Sorokin, M.Yu., 2002. Seismic studies in the Arktika-2000 geotraverse, in: Geological and Geophysical Features of the Lithosphere in the Arctic Region [in Russian]. VNIIOkeangeologiya, St. Petersburg, Issue 4, pp. 24–31.

*Editorial responsibility:* A.E. Kontorovich