Seismostratigraphy of the Siberian Sector of the Arctic Ocean and adjacent Laptev Sea Shelf

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Abstract
A new seismostratigraphic model has been established within the Arctic Ocean adjacent to the East Siberian Shelf on the basis of multichannel seismic reflection data acquired along a transect at 81°N. Ages for the sedimentary units were estimated via links to seismic lines and drill site data of the US Chukchi Shelf, the Lomonosov Ridge, and the adjacent Laptev Shelf. Two distinct seismic units were mapped throughout the area and are the constraints for dating the remaining strata. The lower marker unit, a pronounced high-amplitude reflector sequence (HARS), is the most striking stratigraphic feature over large parts of the Arctic Ocean. It indicates a strong and widespread change in deposition conditions. Probably, it developed during Oligocene times when a reorientation of Arctic Plates took place, accompanied by the gradual opening of the Fram Strait, and a widespread regression of sea level. The top of the HARS likely marks the end of Oligocene/early Miocene (23 Ma). An age estimate for the base of the sequence is less clear but likely corresponds to base of Eocene (~56 Ma). The second marked unit detected on the seismic lines parallels the seafloor with a thickness of about 200 ms two-way travel time (160 m). Its base is marked by a change from a partly transparent sequence with weak amplitude reflections below to a set of continuous high-amplitude reflectors above. This interface likely marks the transition to large-scale glaciation of the northern hemisphere and therefore is ascribed to the top Miocene (5.3 Ma).

1. Introduction
The knowledge about the geological and glacial history of the East Siberian part of the Arctic over the Cenozoic Era remains poorly constrained. A common problem in this part of the Arctic is that any direct age constraints from drilling are missing for the strata in the Siberian sector of the Arctic Ocean and that stratigraphic dates are only available from distant sites. The objective of this study is to establish a seismic chrono-stratigraphy transferred via seismic marker horizons, reflection pattern, and reflector configuration into the Siberian part of the Arctic Ocean from distant calibration points. The basis for the correlation is multichannel seismic reflection lines collected around the eastern end of the Lomonosov Ridge (Figure 1). These provide an insight into the sedimentary cover and crustal fabric of the ridge and the adjacent Laptev Sea. Drill site data of the US Chukchi Sea [Sherwood et al., 2002], the Lomonosov Ridge (ACEX) [Jakobsson et al., 2007; Moran et al., 2006], and results from onshore investigations on the New Siberian Islands [Franke et al., 2001, 2004; Kos'ko and Korgo, 2009] are incorporated. Linking these data sets provides a more consistent seismostratigraphic model which (1) constrains the sedimentation history along the East Siberian margin and (2) provides a framework for future scientific drilling on the Lomonosov Ridge.

2. Regional Setting
The Arctic Ocean has a complex tectonic history, and is divided into two primary basins, the Eurasia and Amerasia basins separated by the Lomonosov Ridge (Figure 1). The older Amerasia Basin developed during late Jurassic/Early Cretaceous [Emby, 1990; Grantz et al., 1998], and the younger Eurasia Basin has expanded by seafloor spreading along the Gakkel Ridge since Paleocene times (58–56 Ma) [e.g., Karasik, 1968; Vogt et al., 1979; Brozena et al., 2003; Glebovsky et al., 2006], coincident with the opening of the North Atlantic.

The Lomonosov Ridge is interpreted as a continental fragment, which was attached to the Barents Shelf before the Eurasia Basin opened [Heezen and Ewing, 1961; Lawver et al., 1988; Jokat et al., 1992]. At present it is unclear whether the Ridge moved as a part of the North American Plate [Srivastava and Tapscott, 1986] or
whether it moved as an independent plate until at least Early Oligocene [Jackson and Gunnarsson, 1990; Brozena et al., 2003]. Seismic reflection profiles across Lomonosov Ridge show a cover of a few hundred meters to a kilometer thick sedimentary succession probably of Cenozoic age, which overlies unconformable older strata [Jokat et al., 1992, 1995; Jokat, 2005]. Langinen et al. [2009] describe this regional angular discordance as the Lomonosov Unconformity (LU). Drilling data acquired on the central Lomonosov Ridge by the Arctic Coring Expedition (ACEX) in 2004 confirmed the Cenozoic age of the sedimentary units on top of the Ridge [Backmann et al., 2008; Moran et al., 2006; Jakobsson et al., 2007]. Surprisingly, a large hiatus spanning from 44 to 18 Ma was found [Moran et al., 2006], which suggests that the Ridge may have subsided below sea level in earliest Eocene but remained in shallow-water depth until Miocene [Sangiorgi et al., 2008; Minakov and Podladchikov, 2012]. Alternatively, the hiatus may be a consequence of a pronounced sea level fall during this time [Hegewald and Jokat, 2013] and/or strong erosive currents [Jokat et al., 1992].

On the adjacent Laptev Shelf, the existence of wide and up to 15 km deep offshore rift sedimentary basins around the New Siberian Islands is documented on the basis of seismic data [Drachev et al., 1998, 1999; Franke et al., 2001, 2004; Sekretov, 2001, 2002; Vinogradov et al., 2003]. These basins are likely the sites of petroleum generation and accumulation [Cramer and Franke, 2005]. A variety of interpretations have been proposed for the sedimentary cover of the Laptev Shelf, ranging in age from the Proterozoic to the Cenozoic [Kos’ko and Trufanov, 2002].

3. Data and Methods

For our study we use multichannel seismic (MCS) reflection lines collected during RV Polarstern cruise ARK XXIII/3 along an almost 1200 km long transect at 81°N, crossing the Canada Basin, Mendeleev Ridge, Makarov Basin, Lomonosov Ridge, and Amundsen Basin [Jokat et al., 2009] (Figure 1). MCS data from the Laptev Shelf into the Amundsen Basin, recorded in 1993 of the Bundesanstalt für Geowissenschaften und Rohstoffe (BGR) [Roeser et al., 1994; Franke et al., 2004], are also incorporated in this study.

The seismic survey setup of ARK XXIII/3 (Figure 1, red lines) comprised a 300 m streamer with 48 channels, and a 32 l air gun array. Shots were fired every 15 s corresponding to a shot point spacing of 40 m. The sea ice coverage was in general 80% and worse, which precluded the usage of a longer streamer, and in turn, prevented a detailed velocity analysis by normal moveout (NMO) corrections. Data were recorded for 12 s at a
The seismic data processing comprised sorting (25 m CDP interval = fold 25) and a detailed velocity analysis (every 100 CDP = 2.5 km). Depth-velocity information from sonobuoys was incorporated to improve the velocity model for NMO corrections. After the removal of noisy traces and spherical divergence correction the traces were stacked and migrated with a finite-difference time migration. For display the data were filtered with a band pass of 5–90 Hz, and an automatic gain control with a gate length of 1000 ms was applied. The signal-to-noise ratio is sufficient to image the sedimentary column down to a sub-bottom depth of more than 4500 m, and with a vertical resolution of about 12 m.

Sample rate of 2 ms. The seismic data processing comprised sorting (25 m CDP interval = fold 25) and a detailed velocity analysis (every 100 CDP = 2.5 km). Depth-velocity information from sonobuoys was incorporated to improve the velocity model for NMO corrections. After the removal of noisy traces and spherical divergence correction the traces were stacked and migrated with a finite-difference time migration. For display the data were filtered with a band pass of 5–90 Hz, and an automatic gain control with a gate length of 1000 ms was applied. The signal-to-noise ratio is sufficient to image the sedimentary column down to a sub-bottom depth of more than 4500 m, and with a vertical resolution of about 12 m.

The seismic equipment of the BGR1993 cruise (Figure 1, yellow lines) on the continental shelf comprised a 2400 m long streamer with 48 channels and a 28 l air gun array. Data were recorded for 12 s at a sample rate of 4 ms. For processing the traces were sorted in a CDP interval of 50 m, and velocity analysis was made every 100 CDP (5 km). An overcorrection of primary signals before stacking and the removal of the remaining...
energy enabled a successful suppression of seafloor multiples on the shallow shelf regions. For display the data were filtered with a band pass of 5–45 Hz, and an automatic gain control with a gate length of 300–500 ms was applied. The dominant frequency of the seismic signals is about 35 Hz, which enables a vertical resolution of 25 m. The sub-bottom is imaged down to a depth of more than 6000 m.

Depth-velocity information for the sedimentary layers was derived from eight sonobuoys deployed during ARK XXIII/3 cruise [Ickrath, 2010], and interval velocities were calculated from stacking velocities of selected CDP gathers. Seismic units were defined on the base of reflection character, reflection strength, and termination geometries. Depths and thicknesses were calculated from velocity models as described above. Prominent reflectors and units were correlated with those of studies in other regions of the Arctic Ocean, which allowed us to infer an age control.

4. Age Control

As no deep offshore drill holes exist for the Siberian part of the Arctic Ocean, the age and nature of seismic horizons and units are uncertain. To derive constraints on ages we compiled different published seismostratigraphic models as summarized in Figure 2. We suggest that the disparate data sets can be linked via seismic reflection characteristics even over large distances.

Our first source for age constraints to date the seismic sequences defined on the 81°N-Transsect (Figure 3) bases on a data set of five exploration wells from the US Chukchi Shelf [Sherwood et al., 2002] and seismic lines acquired between 1969 and 2008 (Figure 4, index map). Hegewald [2012] and Hegewald and Jokat [2013] dated seismic interfaces by correlating the logging information to seismic lines crossing the drilling locations. We transferred and extrapolated the ages of these marker horizons through the existing seismic network to the 81°N-Transsect (Figure 4).

In a second approach, we correlated seismic strata identified at the south-eastern end of the Lomonosov Ridge at 81°N (Figure 5a), seismic records recorded along the Ridge [Jokat, 2005], and the stratigraphy for the central Ridge [Jokat et al., 1995] with incorporated data of the ACEX drilling sites [Moran et al., 2006; Jakobsson et al., 2007; Backmann et al., 2008] (Figure 5b).
For dating the sequences on the Laptev Shelf slope, we refer to Franke et al. [2001, 2004], and in addition to onshore datings on the New Siberian Islands [Kos'ko and Trufanov, 2002; Kos'ko and Korago, 2009] (Figure 6). These studies reveal a seismostratigraphy for the Laptev Shelf which is transferred into the southeasternmost Amundsen Basin [Franke, 2013] and further can be linked to the westernmost section of the 81°N-Transect (Figure 6d).

As another approach to define the age of strata, we tested an attribution via magnetic spreading anomalies as undertaken in the studies of Chernykh and Krylov [2011] and Jokat et al. [1995] for the central Amundsen Basin. However, the profiles of our study are far away from these magnetic anomalies which are still identifiable in the southeasternmost Amundsen Basin [Franke, 2013] and further can be linked to the westernmost section of the 81°N-Transect (Figure 6d). For the central Amundsen Basin, age control on strata via magnetic anomalies succeeded [Chernykh and Krylov, 2011]. We incorporated some of these age estimations, even the gap to our seismic data set in the southeastern Amundsen Basin is quite large (ca. 1000 km).

5. Seismostratigraphic Framework

The seismic lines of the ARK XXIII/3 and BGR1993 cruises provide images of the sedimentary sequences of the Siberian part of the Arctic Ocean and the bordering Laptev and East Siberian shelves. All profiles show a similar
reflection characteristic for the upper sedimentary succession, which enabled a correlation to seismic profiles recorded in other regions of the Arctic Ocean. We describe the seismic data in three legs: (1) the 81°N-Transect, (2) lines across the Lomonosov Ridge, and (3) the lines across the Laptev Shelf and slope. The subsequent chapters comprise the results, age model, and interpretation of each region.

5.1. Transect at 81°N

5.1.1. Results

The MCS data recorded along the Transect at 81°N (Figure 1) display the whole sedimentary cover down to the acoustic basement (Figure 3a). Figure 3b shows the corresponding depth-converted section with interval velocities and sedimentation rates of the units. The seismic data indicate sedimentary thicknesses of almost 1.5 s two-way travel time (twt) (4500 m) in the Canada Basin, 1.5 s twt (1500 m) on the western flank of the Mendeleev Ridge, almost 4 s twt (7000 m) within the deepest part of the Makarov Basin, a cover of 1.5 s twt (1200–2000 m) on the Lomonosov Ridge, and a roughly 1.5 s twt (2000 m) thick sequence in the Amundsen Basin (see Figure 3a for two-way travel times (s), and Figure 3b for depths in meters, respectively).

P wave velocities increase from 1.6 to 5.7 km/s from the sedimentary cover down to the lowermost units in filling the basement topography (Figure 3b). In this chapter we concentrate on the description of the sedimentary sequences in the Makarov Basin. According to Ickrath [2010] the sedimentary cover is subdivided into six seismic units, named MB 1–6 (MB = Makarov Basin) from bottom to top.

5.1.1.1. Basement Surface

The acoustic basement is characterized by scattered reflections, with low signal frequencies and the absence of any conformable reflectors (Figure 3a). Its surface can be well identified along the entire 81°N-Transect, and P wave velocities below range between 6.1 and 6.9 km/s.

5.1.1.2. UNIT MB 1

The lowermost unit consists of several continuous and faulted reflectors with medium to strong amplitudes indicating variations in density and/or P wave velocities in the deposited material. It fills the basement topography in the Makarov Basin and reaches in parts a thickness of more than 1.2 s twt (almost 3000 m) in the Basin (Figures 3a and 3b). On the western slope of the Mendeleev Ridge and on the eastern slope of the Lomonosov Ridge the unit onlaps.
5.1.1.3. UNIT MB 2
The unit is the lowermost seismic sequence on the Lomonosov and Mendeleev Ridge. Low reflection amplitudes and a scattered reflection pattern characterize the unit on the slopes of both Ridges (Figure 3a). Toward the center of the Makarov Basin, however, reflection amplitudes increase and show several continuous and faulted reflectors (Figure 3a). The unit has a maximum thickness of 0.75 s twt (1500 m) in the Basin (Figures 3a and 3b). It continues across the Lomonosov Ridge with a thickness decreasing below 0.3 s twt (500 m). The unit onlaps on the western slope of the Mendeleev Ridge, and on the Ridge it fills the ridges basement topography.

5.1.1.4. UNIT MB 3a, b
The unit presents a prominent sequence of six to seven high-amplitude reflectors (Figure 3a). This striking high-amplitude reflector sequence (HARS) parallels the basement topography and can be observed throughout large parts of the Arctic Ocean (Figures 3a, 4, and 5a). In the Makarov Basin, the unit thickens up to 0.6 s twt (1200 m) and splits up into a lower subunit (MB 3a) with transparent reflection pattern, and an upper subunit (MB 3b) consisting of high-amplitude reflectors (Figure 3a). Onto the Lomonosov and Mendeleev Ridge the sequence merges, and the lower reflectors onlap on the slopes and basement elevations of the ridges.
5.1.1.5. Unit MB 4
Continuous low-amplitude reflectors reveal an almost 1 s twt (1200 m) thick and well-stratified sedimentary unit in the center of the Makarov Basin (Figures 3a and 3b). The reflection pattern changes to an almost transparent style toward the Lomonosov and Mendeleev Ridges. On the Lomonosov Ridge the thickness decreases to 0.5 s twt (440 m), and on the Mendeleev Ridge it drops below 0.2 s twt (100 m).

5.1.1.6. Unit MB 5
This unit is almost transparent with some weak continuous internal reflectors of low amplitudes (Figure 3a). It has a maximum thickness of 0.4 s twt (550 m) in the Makarov Basin (Figures 3a and 3b) and shows pronounced top-lap truncations toward the Mendeleev Ridge.

5.1.1.7. Unit MB 6
The uppermost unit defined on the 81°N-Transect consists of three to four continuous, high-amplitude reflectors (Figure 3a). It has an almost constant thickness of 0.2 s twt (160 m) and can be traced on all seismic lines from the Siberian part of the Arctic Ocean (Figures 3, 4, and 5a), as well as on the slope of the Laptev Shelf (Figures 6a and 6c).

5.1.2. Age Model and Interpretation
The ages we suggest for the seismic units MB 1 to MB 6 in the Makarov Basin are derived from a seismostratigraphic model developed for the US-Chukchi region by Hegewald [2012] and Hegewald and Jokat [2013]. The authors identified and dated marker horizons between Lower Cretaceous and top Miocene via a link of seismic data to well data.

The striking similarity of reflection patterns enables us to extrapolate these dated marker horizons over several data gaps across the Mendeleev Ridge into the Makarov Basin, across the Lomonosov Ridge, and finally into the Amundsen Basin (Figure 4). The HARS in this connection presents an important reference point because it can be traced throughout the whole 81°N-Transect.

5.1.2.1. Unit MB 1
These sediments may represent syn-rift deposits, which filled troughs and grabens of the rugged basement. Age correlations to the Canada Basin [Hegewald and Jokat, 2013; Hegewald, 2012] indicate that the top of the unit might represent the base of Tertiary (65 Ma).

5.1.2.2. Unit MB 2
The low-amplitude reflection pattern points to a low impedance contrast, which in turn, indicates a homogenous matrix of the deposits or a strong mixing and reworking of sediments. Age correlations with the study of Hegewald and Jokat [2013] suggest the Base of Tertiary (65 Ma) as age for the base of the unit (Figure 4). Presumably, Unit MB 2 developed during times, when the Lomonosov Ridge was close to sea level and only minor sedimentation took place on the ridge or even material was eroded from the Ridge and transported into the Makarov Basin and deposited there in well stratified layers. Thus, we suggest that the unit formed before the breakup of the Lomonosov Ridge off the Siberian Shelf at 56–58 Ma.

5.1.2.3. Unit MB 3a, b
The high-amplitude reflectors characterizing the sequence indicate strong and recurring variations in sedimentation conditions and might be a consequence of repeated erosional/depositional processes close to sea level. The presence of the HARS along the entire transect reflects large changes in deep water circulation which involved large parts of the Arctic Ocean. The intercalated sub-unit MB 3a (Figure 3a) points to increased sediment input and deposition into the center of the Makarov Basin, presumably due to erosion of sediments from the East Siberian Shelf in the south, and potentially also from the Lomonosov Ridge.

The distinct similarity between the reflector succession on the 81°N-Transect and the reflection pattern recorded in the Chukchi Region [Hegewald and Jokat, 2013] suggests that the age of the top of the HARS is the end of Oligocene (23 Ma) (Figure 4). This is in good agreement with age estimations based on seismic profiles recorded along the crest of the Mendeleev Ridge [Dove et al., 2010; Bruvoll et al., 2010]. Furthermore, these studies reveal striking similarities in the reflection pattern to the 81°N-Transect. Dove et al. [2010] and Bruvoll et al. [2010] describe a regional unconformity separating two primary sedimentary sequences on the Mendeleev Ridge, which we consider to correspond to the HARS. Using sedimentation rates from the Lomonosov Ridge Dove et al. [2010] dated the unconformity tentatively to 19 Ma. However, they consider that the unconformity may be older, because sedimentation rates on the Lomonosov Ridge probably were higher than on the Mendeleev Ridge. Bruvoll et al. [2010] related the discordance to sediment instability, generated by a phase of tectonic activity and contemporaneous enhanced bottom circulation due to the initial opening of the Fram Strait. Consequently, they estimated 22 Ma for the top of the pronounced reflection sequence, which agrees well to our dating.
The age of the base of the prominent unit is less clear. It could be (1) Base of Eocene (56 Ma) corresponding to the breakup, (2) Early Eocene (49 Ma), when the Azolla-Fresh-water event occurred marking the start of a transition to “icehouse” conditions [Brinkhuis et al., 2006], or (2) Top of Eocene (34 Ma) when a reorganization of plates in the Arctic took place [e.g., Hinz et al., 1993] accompanied by a strong sea level regression [Haq et al., 1988]. Both events may have had a great impact to the circulation system in the Arctic Ocean and could be the cause for the formation of the HARS.

5.1.2.4. Unit MB 4

Continuous, and low-amplitude reflectors indicate uniform deposition conditions during the genesis of the unit. Toward the Lomonosov and Mendeleev ridges reflection pattern changes to an almost transparent style, which emphasizes a steady accumulation of homogenous or well-mixed material. The age correlations indicate an age of about 10 Ma for the top of the unit. Thus, this sedimentary package has been deposited after the opening of the Eurasian Basin and the subsidence of the Lomonosov Ridge well below sea level.

5.1.2.5. Unit MB 5

This unit is almost transparent with some weak continuous internal reflectors of low amplitudes. Like unit MB 4 below, it indicates quiet and uniform depositional conditions between Middle/Late Miocene (10 Ma) and Top Miocene (5.3 Ma) as inferred from units of similar reflection pattern identified in the Canada Basin [Hegewald, 2012; Hegewald and Jokat, 2013] (Figure 4). Distinct top–lap truncations of this unit indicate a change from deep marine current-controlled deposition to the following onset of glacio-marine deposition [e.g., Dove et al., 2013; Niessen et al., 2013].

5.1.2.6. Unit MB 6

As the youngest marker unit we defined in correspondence to Hegewald [2012] and Hegewald and Jokat [2013] a cover of three to four continuous, strong amplitude reflectors present on all lines from the Siberian part of the Arctic Ocean, as well as on the slope of the Laptev Sea. The strong reflectors indicate pronounced variations in density and/or P wave velocity in the sedimentary layers and thus are associated with the onset of glacio-marine deposition since the end of Miocene (5.3 Ma).

5.2. Lomonosov Ridge and ACEX

5.2.1. Results

The westernmost leg of the 81°N-Transect crosses the Lomonosov Ridge and includes the south-eastern corner of the Amundsen Basin (Figure 1). The seismic profiles show that the units MB 3 to MB 6 defined for the Makarov Basin continue over the ridge and can be traced as well in the Amundsen Basin (Figure 3). All sedimentary sequences parallel the basement topography. The total sedimentary thickness is 1.5 s twt (2000 m) on the ridges crest (Figure 5a).

5.2.2. Age Model and Interpretation

The ages we suggest for the seismic units on the southeastern Lomonosov Ridge are derived from ages of the ACEX sites drilled on the central ridge (Figure 5, index map). On the base of the ACEX data the sedimentary sequence on the central Lomonosov Ridge is subdivided into the lithostratigraphic units U1 to U3 [Backmann et al., 2008] (Figure 5b). The seismic sequences on the central ridge are divided after Jokat et al. [1995] into the six units LR 1 to LR 6 (LR = Lomonosov Ridge). The lowermost and regionally most important seismic boundary on the crest of the central ridge is the Lomonosov Unconformity (LU) (Figure 5b), indicating the subsidence of the ridge below sea level [Jokat et al., 1995]. The correlation between synthetic seismograms calculated from core data and seismic profile AWI-91090 show a good fit, and it is suggested that LR 3 correlates with ACEX unit 3, LR 4 with unit 2, and LR 5 and LR 6 with unit 1 [Backmann et al., 2008] (Figure 5b). Consequently, the base of LR 3 or LU is dated to 56.2 Ma, and Unit LR 4 comprises roughly the Early Eocene in the time interval between 56.2 and 49.7 Ma, and the base of LR 5 corresponds to the top of a hiatus at 18.2 Ma (Figure 5b).

It is difficult to identify and trace these units defined for the central Lomonosov Ridge further south along the Ridge, because the sedimentation style changes significantly. But an important clue is a distinct loss of reflection amplitudes from seismic unit LR 4 to unit LR 5 above (Figure 5b). Such a pronounced change in reflection pattern appears also on 81°N-Transect across the southeastern Lomonosov Ridge and further in the Makarov Basin between seismic unit MB 3 and MB 4 (Figures 3 and 5). We suggest that the base of LR 5 presents the top of the hiatus and also corresponds to the top of the prominent reflector sequence on the southeastern Lomonosov Ridge (Figure 5a, marked by purple line). Consequently, we imply that unit LR 5 on the central Lomonosov Ridge and unit MB 4 in the Makarov Basin are related. The low reflection amplitudes indicate that both units likely consist of sediments deposited since Early Miocene times, when a quieter depositional realm prevailed.
On the central Lomonosov Ridge, the uppermost unit LR 6 drapes conformable the lower units and has a thickness of about 0.1 s twt (80–100 m) (Figure 5b). Backmann et al. [2008] suggested an age of about 5.8 Ma for the base of LR 6. This date corresponds well with the age of unit MB 6 (Top Miocene, ~5.33 Ma), although the different reflection pattern indicates an unequal depositional regime for the eastern and central Lomonosov Ridge. High-amplitude reflectors characterize the uppermost unit on the 81°N-Transsect, whereas the reflector amplitudes on the central ridge beside a strong cover reflector remain low (Figure 5). This indicates much stronger lateral variations in sediments deposited on the eastern Lomonosov Ridge, presumably due to the proximity to the shelf.

5.3. Laptev Shelf and Slope

5.3.1. Results

Seismic units for the Laptev Sea Shelf and slope are named LSU-1 to LSU-6 (LSU = Laptev Shelf Unit) from bottom to top (Figures 2 and 6a–6c). Below the outer shelf and slope the surface of the acoustic basement indicates faulted and rotated blocks. The reflection sends permit an interpretation of listric faults bounding the faulted blocks and penetrating the lowermost sedimentary sequence LSU-1 (Figures 6a–6c). Unit LSU-1 with an interval velocity of 3.9 km/s is the lowermost sedimentary sequence on the slope. The unit drapes the acoustic basement with a few hundred meters on the slopes and expands to more than 3 km below the shelf edge. Above, in unit LSU-2, the reflection pattern is scattered, and reflectors are less continuous and also indicate faulting. The thickness of unit LSU-2 varies from 200 to 500 ms twt (340–850 m), as it infills the topography of the strata below. Its internal velocity increases to 3.4 km/s. Unit LSU-3 differs from the strata below as a sequence of continuous, high-amplitude reflectors. With an interval velocity of 2.6 km/s, its thickness decreases from 900 ms twt (1200 m) at the slopes base to less than 500 ms twt (600 m) in the Amundsen Basin. We correlated the top of unit LSU-3 to the top of the HARS mapped on the 81°N-Transsect and other seismic records of the Arctic Basin (Figures 3 and 6d). Unit LSU-4 is characterized by a broken reflection pattern with high amplitudes, but several continuous reflectors can be traced through this unit. Its thickness on the shelf is more than 1 s twt (1100 m), decreasing slightly to 700 ms twt (800 m) toward the slope and increasing again to more than 1 s twt (1100 m) in the Amundsen Basin. Its internal velocity is 2.2 km/s. Above, in unit LSU-5, the reflection pattern is discontinuous with weak amplitudes and in most parts transparent. The interval velocity is 1.8 km/s. The thickness of unit LSU-5 varies from 50 to 200 ms twt (50–180 m), and its lower boundary to unit LSU-4 is less clear. The uppermost unit LSU-6 consists of three to five continuous, strong amplitude reflectors and covers with an almost constant thickness of 200 ms twt (170 m) the southeastern end of the Amundsen Basin of the Eurasia Basin and the lower Laptev Shelf slope (Figures 6a–6d). The unit has an interval velocity of 1.7 km/s. The reflectors from the lower boundary of the unit are in some parts discontinuous or undulated. Upslope, the reflectors merge at the shelf edge to a single strong-amplitude reflector, which extends onto the Laptev Shelf (Figures 6a and 6b).

5.3.2. Age Model and Interpretation

Franke et al. [2001, 2004] defined the major seismic unconformities LS1–LS3 on the Laptev Sea Shelf, and ESS1–ESS3 on the east Siberian shelf, and tentatively linked them to the main tectonic events documented in the onshore geology of the New Siberian Islands (Figure 2). The structural pattern of pre-Cretaceous rocks is mainly due to the Early Cretaceous tectonic events, and the lack of compressional structures in the offshore sedimentary strata suggests a post-Hauterivian (Early Cretaceous) age of the rifts. The lowestmost interface ESS1 may have an age between about 130 and 66 Ma. This interface was suggested to mark the initial rifting of the Lomonosov Ridge, or even likely the end of plutonism in the Verkhochansk-Chukotka region [Franke et al., 2004].

From the work of Franke et al. [2001, 2004] and Franke [2013] close to our survey area, we suggest that reflector ESS1 corresponds to the base of unit LSU-1 on line BGR 93-090 (Figure 2a), and to the top of seismic unit MB 1 in the Makarov Basin even though we cannot trace this marker horizon directly across the Lomonosov Ridge (Figures 3a and 6a).

The seismic interface ESS2 (33.6 Ma) corresponding to unconformity LS2 is described by Franke et al. [2004] as a highly reflective horizon, probably representing an erosional surface. It forms the top of a seismic unit characterized by a pronounced internal layering of high-amplitude reflectors, similar to the high-reflective sequence found on Lomonosov Ridge, close to the ACEX well. Because of this reflection pattern we suggest that horizon ESS2 corresponds to the top of unit LSU-3 we defined on the Laptev Shelf (Figure 2a) and the
adjacent Amundsen Basin (Figures 6c and 6d). Based on similarities in reflection amplitudes we further extrapolate horizon ESS2 to the top of the marked reflection band MB 3 in the Makarov Basin. Franke et al. [2004] suggest an age of about 33.6 Ma for ESS2, referring to an erosional event in the beginning of the Oligocene and known from several sites on the New Siberian Islands [Kos’ko and Trufanov, 2002]. At the same time a significant reorientation of relative plate motions around the Arctic Ocean initiated the opening of the Eurasian Basin to the North Atlantic [e.g., Hinz et al., 1993], accompanied by a widespread sea level regression in early Oligocene [Haq et al., 1988]. In a revision Kos’ko and Korago [2009] correlated horizon ESS2, present as regional reflector in the western East Siberian Sea, with the base of Upper Oligocene-Miocene strata on the New Siberian Islands. Thus, their age assignment is in good agreement with our interpretation, that the top of the marked reflection sequence is related to the top of the Oligocene (Figure 2a).

Horizon ESS3 is tentatively interpreted by Franke et al. [2004] as base of the late Miocene (10 Ma). This interface is associated with an abrupt change in the reflection pattern, from high-amplitude subparallel strata below to a low-amplitude reflection pattern above, indicating a significant change in the depositional environment. Probably, the strata above were deposited under the influence of large-scale glaciation [e.g., Myhre and Thiede, 1995; Zachos et al., 2001 and references therein]. We suggest Horizon ESS3 to represent the top of seismic unit LSU-4 (Figure 2a). The marked loss in reflection amplitudes is evident between seismic units LSU-4 and LSU-5 on the profiles across the Laptev Shelf Slope (Figure 6a) and of the easternmost Amundsen Basin (Figure 6c). However, this change is not as evident on the slope of the Lomonosov Ridge (Figure 6d), and in the Makarov Basin the setting is even different (Figure 3a). In the basin, the most striking change in reflection pattern marks the top of unit MB 3 (Figure 3a). A relation to interface ESS3 seems unlikely to us, because it would imply that almost half of the strata in the Makarov Basin were deposited during the last 10 Ma, and the other half over a period of 110 Ma since the opening of the basin in the late Early Cretaceous. For this reason, we prefer to correlate horizon ESS3 of the Laptev Shelf with the top of unit MB 4 in the Makarov Basin. The reflection pattern of unit MB 4 to unit MB 5 above shows as well a clear loss in reflection amplitude, which might be an indication for a changing environment due to enhanced glaciation since the Late Miocene as proposed by Franke et al. [2004].

Some additional constraints on the age of marker interfaces can be derived from magnetic spreading anomalies in the Eurasian Basin even they are distant from our 81°N-Transect. In a study on the sedimentary sequences in the central Amundsen Basin Chernykh and Krylov [2011] defined six seismostratigraphic complexes, named SSC1–SSC6 from bottom to top (Figure 2a). The authors described a striking change in a reflection pattern from seismic unit SSC4, a rather transparent unit with low reflection amplitudes, to unit SSC5 above, consisting of continuous high-amplitude reflectors. With the help of magnetic anomalies they dated the interface between these two seismostratigraphic complexes to 25–28 Ma (Figure 2a), which does not really correspond to a marker interface in the southeasternmost Amundsen Basin. Better, the top of sequence SSCS dated to 21–23 Ma by Chernykh and Krylov [2011] corresponds to the age we suggest for the top of the HARS. SSC5 is suggestetd to be composed of a terrigenous material, whereas SSC6 above developed under the influence of an open Fram Strait which changed the sedimentation style from neritic to modern ocean type [Chernykh and Krylov, 2011]. In accordance we suggest that this profound change in the depositional environment is also the reason for the striking loss of reflection amplitude from the HARS to unit MB 4 above in the Makarov Basin. We take this as a further argument to assign latest Oligocene/Early Miocene as an age to the top of the HARS.

6. Discussion

6.1. Origin of the Distinct High-amplitude Reflector Sequence (HARS)

We propose a seismo-stratigraphic framework for the sedimentary cover of the Siberian sector of the Arctic Ocean from basin-wide similarities of the reflection patterns and strata geometries (Figure 2). In particular, a sequence of high-amplitude reflectors (HARS) is conspicuous in all analyzed seismic profiles, indicating contemporaneous changes in the depositional regime over large parts of the Arctic Ocean. The top of this HARS gives us a reference point for our age model, and here we discuss possible tectonic and climate-driven scenarios which may have impacted regional sedimentation and led to the development of this geographically extensive sequence.
1. The oldest possible event apparent on the seismic data described here is the breakup of the Lomonosov Ridge from the Siberian and Barents shelves between 65 and 56 Ma ago and the subsequent onset of spreading in Eurasia Basin [Karasaki, 1968; Vogt et al., 1979]. Franke [2013] interpreted such breakup unconformity on the Laptev Sea Shelf and correlated it with the onset of seafloor spreading in the Eurasia Basin and with the fact that weathering and planation continued up to the end of the Paleocene on the New Siberian Islands. However, a flat-lying reflector package filling the space between basement heights can be observed farther in the Amundsen Basin [Figure 6d] and on the Eurasian side of the Lomonosov Ridge [Jokat, 2005]. The internal reflectors are parallel and do not onlap on the ridge crest. This indicates a predominantly marine sedimentation style and implies an advanced opening of the Eurasia Basin. Consequently, the HARS must be considerably younger than 56 Ma.

2. In the Early Eocene, a phase of profound palaeoenvironmental changes occurred in Arctic Ocean. The climate turned cooler, and the transition to an “icehouse” Arctic started as indicated by the find of a dropstone, and the massive occurrence of Azolla fern [Moran et al., 2006]. Later, in middle Eocene first evidence of ice-rafter debris appeared and suggested a further shift from “greenhouse” to “icehouse” Arctic [Moran et al., 2006]. As well, paleoceanography changed in the Early Eocene, as manifested in the Azolla event. Plenty of fern indicate that episodic fresh surface waters were present at 48–49 Ma, probably depending on an oceanic exchange between the Arctic Ocean and adjacent seas [Brinkhuis et al., 2006]. Backmann et al. [2008] suggest the boundary of Early Eocene to Middle Eocene to be onset of the development from an isolated stagnant shallow-water sea basin to a deep Arctic ocean with active hydrodynamics. Further, tectonic events had an impact to the region. In the earliest Eocene the Lomonosov Ridge subsided slowly below sea level [Moran et al., 2006]. So the crest was easily susceptible to changes of climate or current controlled deposition changes. All these climate, paleoceanographic, and tectonic events must have left an imprint on the sediments, which we propose is manifested in the HARS. Likely, the lowermost strong-amplitude horizons are of early Eocene age.

3. The era of marked paleoceanographic changes continued through the entire Eocene and Oligocene until the Early Miocene. During Oligocene times a significant reorientation of Arctic Plates took place, which resulted in the opening of the Fram Strait and initiated a deep water connection from the Atlantic to the Eurasia Basin [e.g., Hinz et al., 1993]. The opening of this gateway likely enabled enhanced bottom water activity, which might have caused a major hiatus between Middle/Late Eocene to Early Miocene (44 to 18 Ma) as defined from ACEX drilling samples Jakobsson et al., 2007; Backmann et al., 2008; Poirier and Hillaire-Marcel, 2011]. This hiatus is regarded to mark the transition from poorly oxygenated to fully oxygenated (“ventilated”) conditions in the Arctic Ocean completed by 17.5 Ma [Jakobsson et al., 2007]. As well, during the same time the Lomonosov Ridge was close to sea level as revealed by various shallow-water clays detected in the drilling samples [Moran et al., 2006; Sangiorgi et al., 2008]. At this depth the ridge was probably exposed to repeated erosion and deposition, also because a strong regression in sea level occurred at about 28 Ma in the Oligocene, followed by some smaller rises and falls [Haq et al., 1988; Hegewald and Jokat, 2013]. We suggest that the top of hiatus recorded on the central Lomonosov Ridge is associated with the top of the HARS detected on its Siberian end and the adjacent basins (Figure 5). Thus, we conclude that the top of the marked reflection package presents likely the top of Oligocene or earliest Miocene.

4. In the middle Miocene the deep water connection through the Fram Strait to the North Atlantic was completed and the modern current system established in the Arctic Basin [Jakobsson et al., 2007]. The Lomonosov Ridge subsided well below sea level, and pelagic deposition conditions started to prevail [Moran et al., 2006]. This depositional regime is expressed in the transparent and uniform reflection pattern with low reflection amplitudes of units MB 4 and MB 5, indicating only minor changes in the deposition regime. Consequently, we suggest that the top of the HARS must be clearly older than the Middle Miocene.

In a number of studies, a much earlier age than top of Oligocene is proposed for the top of the distinct reflection sequence (Figure 2b). For example, Rekant and Gusev [2012] propose the reflection band to correspond to the regional marker reflectors A [Langinen et al., 2009] in the Amundsen and Makarov Basins, and to the Lomonosov Unconformity LU [Jokat et al., 1995] on the Lomonosov Ridge. They suggest the unconformity to mark the end of an erosional stage, and assigned late Paleocene to early Eocene age (56 Ma) to it. Langinen et al. [2009] suggested the top the reflector band (named A) to be of early middle Eocene age (44 Ma). The base of the package they referred to the Lomonosov Unconformity LU of late Paleocene to early Eocene age (> 56 Ma). Franke et al. [2001] described on the Laptev Shelf a distinct unconformity (LS2) within the rift basins that forms the top of a high-reflective sequence. They inferred an age of 33 Ma for it, which is suggested to result from a major sea level fall in early Oligocene [Haq et al., 1988].

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On the other hand, several studies are in good agreement with our interpretation that the top of the HARS corresponds to the Top of Oligocene (Figure 2b). For example, Butsenko and Poselov [2004] suggest that a transformation of the regional morphostructure formed a reflector of regional erosional character and correlate it with interface LR4/LR5 at about 23 Ma [Jokat et al., 1995]. Chernykh and Krylov [2011] described a sequence horizon in the central Amundsen Basin which has an age of about 21–23 Ma (SH5, Figure 2b) The authors relate this interface to a change from terrigenous influenced deposition to a more marine sedimentations style as a result of the progressive opening of the Fram Strait in late Oligocene. As well, our dating of the HARS correlates to studies of Dove et al. [2010] and Bruvoll et al. [2010] on the Alpha-Mendeleev Ridges (Figure 2b). Both studies describe a high-amplitude reflector succession to form a regional unconformity. Bruvoll et al. [2010] relate it to sediment instabilities generated by a phase of tectonic activity and contemporaneous enhanced bottom circulation due to the initial opening of the Fram Strait. They estimated 22–14 Ma as time frame for the deposition. Dove et al. [2010] interpret the unconformity to mark the end of extensional deformation of the ridge. Tentative dating of the unconformity, applying sedimentation rates from the Lomonosov Ridge, revealed an age of about 19 Ma, which would imply that tectonism might have persisted into the Cenozoic. However, the authors consider the unconformity to be older, because sedimentation rates on the Lomonosov Ridge were probably higher than on the Mendeleev Ridge.

7. Conclusion

The objective of the study was to develop a seismostratigraphy for a number of seismic profiles at 81°N across the Canada Basin, the Mendeleev Ridge, Makarov Basin, Lomonosov Ridge, and the Amundsen Basin. The present interpretation has been made on the assumption that seismic characteristics, as reflection pattern and reflector configuration, allow to link the distant data sets. The mapped seismic sequences vary in combined thickness from 1 s twt (2 km) on the Lomonosov Ridge to 3.5 s twt (~7 km) in the Makarov Basin. In spite of these variations, the strata show a regionally consistent seismic stratigraphy across the Siberian sector of the Arctic Ocean, which indicate that depositional processes impacted the region in a comparable manner in response to basin-wide paleoenvironmental conditions. This enabled us to extrapolate age information from three remote sites (1. drill sites on Chukchi Shelf, 2. ACEX-drilling on central Lomonosov Ridge, 3. onshore geology from the New Siberian Islands/Laptev Shelf) onto the 81°N-Transect. Several distinguishable seismic units and interfaces were mapped throughout the Siberian part of the Arctic Ocean, which provide information on the development of sedimentary cover under the influence of climate and tectonic changes (Figure 2a).

The two lowermost units MB 1 and MB 2 in the Makarov Basin, filling the basement topography, are likely of Late Cretaceous and Paleocene age, respectively, as inferred from age correlations to the Canada Basin [Hegewald and Jokat, 2013]. Numerous normal faults indicate the influence of intense extensional tectonic activity during this period. The striking high-amplitude reflectors sequence (HARS), termed MB 3 in the Makarov Basin, is taken as reference for dating both strata above and below the sediment package. The marked reflectors likely indicate strong changes of the depositional realm. The sequence likely developed during Eocene-Oligocene times after the breakup of the Eurasian Basin (58–56 Ma), followed by a reorientation of Arctic plates in Oligocene [e.g., Hinz et al., 1993], and accompanied by a widespread regression of sea level [Haq et al., 1988]. During the Oligocene the Fram Strait opened gradually, and a modern current system evolved in the Arctic Ocean since Early Miocene times [e.g., Moran et al., 2006]. Corresponding to the top of a hiatus recorded on the Lomonosov Ridge, we assign an age of latest Oligocene/Early Miocene to the top of the reflector sequence, because no traces of such profound tectonic and oceanographic events were detected in the seismic units above. Instead, the transparent and uniform reflection pattern of units MB 4 and MB 5 indicates relatively slow bottom circulation, which prevailed after the Middle Miocene. For the base of the uppermost unit MB 6 we suggest an age of early Pliocene. At those times the Northern Hemisphere was glaciated in wide style with intensification in middle Pliocene [e.g., Zachos et al., 2001]. On the Siberian part of the Arctic Ocean this must have had a strong effect on the deposition regime, as indicated by a set of high-amplitude reflectors in this uppermost unit MB 6.

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