Crustal architecture of the East Siberian Arctic Shelf and adjacent Arctic Ocean constrained by seismic data and gravity modelling results

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Abstract

The Eastern Siberian Arctic Shelf (ESAS) represents a geologically complex realm with a history related to the final stages of the Pangaea supercontinent formation during the Mesozoic and its subsequent disintegration during Late Cretaceous and Cenozoic times. It is a key region to constrain the origin of the deep-water basins and intervening ridges of the Amerasia Basin. We present results of gravity modelling of published OBS refraction data and seismic reflection profiles acquired between 1989 and 2012 in the ESAS and adjacent Arctic Ocean along five composite geotransects using Getech satellite altimeter derived gravity data. Our main goal was to examine published crustal models and to present new models for the ESAS that are constrained by both seismic data and 2D gravity forward modelling. We consider several topics important for understanding of the Arctic geology: (i) hyperextension within the Laptev Rift System and possible extent of the exhumed mantle, (ii) relationship between the New Siberian Shelf and the Lomonosov Ridge, (iii) nature of the collapsed late Mesozoic fold belt in the southern part of the East Siberian Sea, (iv) character of transition between the De Long Massif and the deep-water Podvodnikov Basin, (v) lateral extent of the hyperextended North Chukchi Basin and nature of its basement, and (6) relationship between the Mendeleev Ridge and Chukchi Plateau crustal domains. Our results do not confirm the previously inferred extent of continental crust beneath the oceanic realm. The latter is dominated by either exhumed mantle regions and/or HALIP igneous crust. We discuss the existence of a dismembered continental Bennett-Barrovia block currently represented by three smaller fragments, or massifs. This block when restored to its possible single state, can play a crucial role in reconstructing the pre-Canada Basin Arctic.

Key words: Arctic, Siberian shelf, Earth crust, rifts, gravity data, seismic refraction and reflection profiles

Introduction

The vast East Siberian Arctic Shelf (ESAS) stretches for ~2,500 km from the eastern coast of the Taimyr Peninsula across the Laptev, East Siberian and Chukchi Seas to the US/Russia maritime boundary in the Chukchi Sea, including a number of islands grouped into the New Siberian and De Long Archipelagos, and a stand-alone Wrangel Island (Fig. 1). The ESAS borders deep-water basins and subsea ridges and plateaus of the Arctic Ocean. This remote and hard-to-access part of the Arctic has, for a long time, remained one of the least geologically studied regions of the Earth with just a few long-offset seismic profiles published by the beginning of this century and no single deep penetrating offshore well drilled so far. As a result, concepts of its tectonic origin and geological history have been mainly based on a rather sparse seismic data coverage and geological data from the adjacent mainland and islands. Many of these concepts, proposed by Soviet and more recently by Russian geoscientists extend Precambrian continental crust from the shelf across the continental margin into the deep-water oceanic domain (Gramberg and Pogrebitskiy, 1984; Morozov et al., 2013; Petrov et al., 2016a,b; Piskarev et al., 2016; Poselov et al., 2011;).

Since the 1990s, we have witnessed a steady progress in seismic data acquisition in the High Arctic icy seas as part of the Russian UNCLOS (United Nations Convention on the Law of the Sea) research program. It started from the ambitious seismic refraction project ‘Transarctic 89-91’ by PMGRE (Polar Marine Arctic Expedition) that resulted in acquisition of a composite profile (or a ‘geotransect’ as often referred to in the Russian literature) extending for ~1500 km from Zhokhov Island in the De Long Archipelago to the Lomonosov Ridge in the vicinity of the North Pole (Gramberg et al., 1993), and a 1992 profile ‘Transarctic-92’ across the Lomonosov Ridge (Poselov et al., 2011). The Russian program of the Arctic seismic geotransects continued successfully through the 2000s resulting in acquisition of the ~490 km-long ‘Arctic-2000’ and ~600 km-long ‘Arctic-2005’ profiles both crossing different parts of the Mendeleev Ridge, and the ‘Arctic 2007’ crossing a junction zone between the shelf north of the New Siberian Islands and the Lomonosov Ridge and extending further north along the ridge’s crestal part for a total length of ~835 km. The most recent 750 km-long ‘Arctic-2012’ profile crosses the Mendeleev Ridge and the Chukchi Plateau in the W-E direction (Piskarev et al., 2016; Poselov et al., 2011).

Since 2005, there has been a significant increase in the multichannel seismic reflection (MCS) data acquisition throughout the Russian Arctic shelves mainly funded by the state as part of the Russian UNCLOS application and hydrocarbon-related exploration activities, and, since 2012 – by the Russian State Oil company Rosneft in partnership with ExxonMobil, Statoil and ENI. The Russian seismic companies ‘Marine Arctic Geological Expedition’ (MAGE), ‘SevMorGeologiya’ (SMG) and ‘Dal’MorNefteGeofisika’ (DMNG), as well as western seismic companies TGS and ION have acquired a significant amount of the state-of-art high-quality and long-offset reflection and refraction seismic profiles.

In the recent years, several studies have been published revising the geology of the Russian Arctic shelves including the ESAS, which are based on the recent seismic data (Drachev et al., 2010; Drachev 2011, 2016; Morozov et al., 2013; Nikishin et al., 2014, 2017; Pease et al., 2014; Petrov et al., 2016a,b; Piskarev, 2016; Poselov et al., 2011). Yet, despite all this outstanding progress in the deep penetrating long-offset seismic data acquisition, the tectonic concepts explaining the origin and history of this part of the Arctic remain highly controversial. All crustal models published by several Russian research groups and summarized by Poselov et al. (2011); Petrov et al. (2016a,b), and Piskarev et al. (2016) project continental crust across the continental margin far north beneath the deep-water basins and submarine ridges while many other authors proposed quite different views on the High Arctic tectonics (Chian et al., 2016; Doré et al., 2016; Grantz et al., 2011a,b; Gottlieb et al., 2014; Oakey and Saltus 2016; Pease 2011; Pease et al., 2014). One of the reasons for such discrepancies in these interpretations is often related to the fact that the gravity data has not been routinely used to constrain and verify the proposed models.

In this paper we use published Russian seismic data along five composite geotransects (Fig. 1) and the Getech's large-scale compilation of satellite altimeter derived gravity data (Fig. 2) to examine the published crustal models and to present our new crustal models for the ESAS that are constrained by both seismic data and 2D gravity forward modelling.

Geological setting and main crustal domains of the ESAS

The ESAS represents a geologically complex realm with its history related to the final stages of the Pangaea supercontinent formation in the early Mesozoic and its subsequent disintegration during the Late Cretaceous and Cenozoic times. This is a key region to constrain the origin of the deep-water basins and intervening ridges of the Amerasia Basin. The geology of the islands and adjoining mainland provides evidence of the main contractional deformation phases which occurred during the Late Jurassic to Early Cretaceous (Verkhoyansk and Chukotka-Brookian, Early Brookian by Moore et al. (1994), late Mesozoic orogenies). These resulted from collisions between the north-eastern Asian margin of Laurasia and two large microcontinents: the Kolyma-Omolon and Arctic Alaska-Chukotka terranes (Grantz et al., 2011; Pease, 2011; Pease et al., 2014; Sokolov, 2010; Zonenshain et al., 1989, 1990). These events formed major fold-and-thrust belts (shortened to 'fold belts' herein), the North Verkhoyansk, Cherskii, Chukotka Fold Belts, dominating geology of the mainland (Drachev, 2016; Oksman, 2003; Parfenov, 1991; Toro et al., 2016 and the references therein). At earlier stages of the ESAS exploration in the 20th century, many researchers speculated that these fold belts do not continue offshore, and the shelves are mostly occupied by old cratons (platforms in the Russian nomenclature) such as the East Siberian and Asian cratons (Atlasov et al., 1970; Muratov 1981) or their large fragments, with the Hyperborean Platform being the most discussed since the discovery of a slightly deformed Cambro-Ordovician section on Bennett Island by Edward Toll in 1903 (Wollosowitsch, 1909). Modern seismic results provide overwhelming evidence supporting an opposite concept, first proposed by Kropotkin and Shatalov (1936) suggesting that the late Mesozoic fold belts of the Northeast Asia extend offshore where, based on seismic data, they underlie the entire Laptev Shelf and southern parts of the East Siberian Sea and the Russian Chukchi Shelf (Drachev, 2002, 2011, 2016; Franke et al., 2004, 2008; Shkarubo et al., 2014; Zavarzina et al., 2014). The northern part of the western East Siberian Sea is occupied by the so-called De Long Massif, which represents a Neoproterozoic fold belt partially overprinted by a Caledonian-age contractional event (Ershova et al., 2016). Caledonian-age deformation has been recently also identified in the northern part of the Chukchi Borderland (Brumley et al., 2015; O'Brien et al., 2016).

Following the late Mesozoic orogeny, the ESAS continental basement subsequently underwent several extensional deformation phases related to the formation of deep-water oceanic basins. In the Laptev Sea, the Late Cretaceous and early Cenozoic extension preceded the opening of the Eurasian oceanic basin and formed a vast rift system (Drachev et al., 1998; Franke et al., 2001; Drachev, 2011). As shown recently by Mazur et al. (2015), Drachev and Shkarubo (2017) and Drachev et al. (2017), the thinning of the continental crust beneath the Ust' Lena Rift in the western part of the shelf may have resulted in a complete rupture of the continental crust and upper mantle exhumation.

The northern parts of the East Siberian and Chukchi Seas are occupied by the North Chukchi Basin, which extends for ~850 km in a W–E direction from the De Long High to the US Chukchi Sea. Seismic and gravity data show that the total sediment thickness reaches ~20 km in the most subsided part of the basin north of Wrangel Island and may be underlain by severely attenuated lower continental crust and/or exhumed upper mantle (Drachev, 2016).

Near the Aptian/Albian transition, almost the entire Amerasia Basin and northern part of the ESAS was affected by mantle plume-related magmatism that resulted in large volumes of mafic intrusive and extrusive rocks emplaced into the pre-existing crust during formation of a so-called High Arctic Large Igneous Province (HALIP; Maher, 2001). This province is well-manifested in the magnetic field, and volcanic rock samples have been obtained (Mühe and Jokat, 1999; Vernikovsky et al., 2014, Morozov et al., 2013; Petrov et al, 2016a). The HALIP magmatism severely modified the pre-existing crust masking its original crustal affinities, presenting many challenges in interpreting the Arctic pre-Aptian tectonics.

To aid gravity modelling, we compiled a map of main ESAS crustal provinces (Fig. 2). Their offshore tectonic boundaries were mainly derived from the magnetic, gravity and published seismic data and geological observations, similar to the results of tectonic analysis by Drachev (2011, 2016) and Pease et al. (2014). Based on age, structure and crustal affinities, we recognize six main crustal types of these domains:

(i) Domains underlain by old Neoproterozoic crust partially overprinted by younger contractional deformation (Lomonosov Ridge; southern part of the De Long Massif and the North Wrangel Block including its southern part involved into late Mesozoic fold belt; Kotel'nyi Terrane, where Neoproterozoic basement is inferred).
(ii) Late Mesozoic fold belts developed over proximal passive paleocontinental margins underlain by Precambrian crust (North Verkhoyansk and Chukotka-Wrangel Fold Belts).
(iii) Late Mesozoic fold belts that developed over regions with severely thinned continental crust or exhumed mantle such as the distal Paleo-Siberian continental margin (Kular-Nera-Polousnyi Turbidite Belt) and hyperextended basins (Novaya Sibir' Fold Belt).
(iv) Hyperextended continental margins and basins that may be underlain by severely thinned lower continental crust and/or by exhumed serpentinised mantle. These include peripheral parts of the Amerasia Basin and the North Chukchi Basin, as well as the central part of the Ust' Lena Rift Basin in the Laptev Sea.
(v) Oceanic crust affected by the HALIP magmatism (Makarov Basin).

(vi) The Alpha-Mendeleev Large Igneous Province domain (HALIP) composed of flood basalts underlain by thick igneous mafic crust that may also include fragments of thinned continental crust and serpentinised mantle heavily intruded by mafic rocks.

These crustal domains form a tectonic framework that helps to constrain densities and thicknesses of the proposed crustal models and so verify first-order tectonic fabric of the ESAS.

Seismic and gravity data used in the study

For the purpose of this study, we used 12 seismic refraction and reflection profiles that are grouped into 5 long composite profiles, or geotransects, crossing the major crustal domains: ***I***, Northern Laptev Shelf Geotransect, ***II***, Kotel'nyi Island—Lomonosov Ridge Geotransect, ***III***, Indigirka Bay—Makarov Basin Geotransect, ***IV***, Chukotka Peninsula—Mendeleev Ridge Geotransect, and ***V***, Mendeleev Ridge—Chukchi Plateau Geotransect (Figs. 1-3). Table 1 provides some general information about the seismic profiles used and the related published sources.

Table 1. General information about published seismic profiles used in this study.

Seismic profile	**Geo-transect**	**Company*/Year**	**Length (km)**	**Streamer or Receiver/Record lengths**	**Data source**
MCS ARS10F04	***I***	TGS/2010	547	7,950 m/12 s	Drachev & Shkarubo (2018), Drachev et al. (2017)
MCS A4	***I***	MAGE/2008-2009	660	8,100 m/12 s	Drachev & Shkarubo (2018), Drachev et al. (2017)
MCS A7	***II***	MAGE/2007	832	8,100 m/12 s	Poselov et al. (2012a), Piskarev et al. (2016)
OBS ARCTIC-2007	***II***	VNIIO & PMGRE /2007	650	460 km	Poselov et al. (2012a)
MCS LARGE8901	***III***	LARGE/1989	580	3,000 m/6 s	Drachev (2011)
MCS Arctic 2011-059	***III***	VNIIO-ROSNEDRA/ 2011	320	600 m/9 s	Piskarev et al. (2016)
OBS TRANSARCTIC 89-91	***III***	PMGRE/1989-1991	1487		Lebedeva-Ivanova et al. (2011)
MCS 5-AR	***IV***	SMG & MAGE/2008-2010	540	8,087.5 m/14 s	Sakoulina et al. (2011)
OBS 5-AR	***IV***	SMG & MAGE /2008-2010	540	540 km	Sakoulina et al. (2011)
OBS ARCTIC-2005	***IV***	VNIIO & PMGRE /2005	600	465 km	Poselov et al. (2011), Poselov et al. (2012b)
MCS ARCTIC 2012-3	***V***	/2012	692	4,500 m/15 s	Piskarev et al. (2016)
OBS ARCTIC-2012	***V***	SMG/2012	750	480km/60s	Kashubin et al. (2016), Piskarev et al. (2016)

** TGS, TGS Seismic Company ; MAGE, Marine Arctic Geologic Expedition (Murmansk, RF) ; VNIIO, VNIIOkeangeologiya (St. Petersburg, RF); PMGRE, Polar Marine Geologic & Prospecting Expedition (Lomonosov, RF); LARGE, Laboratory of Regional*

Geodynamics; SMG, SevMorGeologiya (St. Petersburg, RF); ROSNEDRA, Russian Federal Agency for Management of Subsoil Resources

We used two-way-time (TWT) pre-stack time migrated MCS profiles for the interpretation, which then were depth-converted using proprietary pre-stack migration velocities along with the published OBS and sonobuoy refraction velocities (Jokat et al., 2013).

The gravity data used for the 2D models and for the map in Figure 3 were derived from merging the Getech reprocessed satellite altimeter gravity data offshore with gridded gravity data onshore (Green and Fairhead, 1996; Fairhead et al., 2004). Public-domain data from the Arctic Gravity Project (Kenyon et al., 2008) were also incorporated into the final grid. The data sets were merged into a single coherent 2 km grid that includes Bouguer anomaly and Free-Air anomaly data onshore and offshore, respectively. The Bouguer reduction density of the final grid (onshore part only) was 2.67 g/cm^3. It should be noted that although the gravity is presented as a 2-km grid, the initial resolution of the satellite gravity data set is ~12 km minimum wavelength, with increasing noise at wavelengths below 20 km. The magnetic data used in the study (Fig. 18) are after Verhoef et al. (1996) and they were low-pass filtered with a cut-off wavelength of 120 km.

Gravity Modelling

The 2D/2.5D gravity modelling permits testing of geological/seismic models against the observed gravity field. For this study, we used the Geosoft GM-SYS 2-D forward-modelling package with model layers of infinite length. This approach is justified if the presence of point-source density anomalies such as evaporite bodies or volcanic centers that may produce out-of-plane effects influencing the gravity response along the models is unlikely. Though salt accumulations are known in the Canadian Arctic and North Kara (Malyshev et al. 2013; Stephenson et al. 1992), there is no seismic or geological data proving their occurrence in the ESAS. Volcanic centers may be expected in the HALIP domain but since the flood basalt provinces are known for a great lateral extent of rather homogeneous basalt flows fed through a dense array of dykes rather than through stand-alone central vents, we assume that influence of possible volcanic buildups could be negligible. Also, a dozen km spatial resolution of the original satellite gravity data allows exclusion of possible shallow point-source density anomalies.

Since the modelled sections are located entirely offshore, we used the free-air gravity anomalies. The modelling technique enabled conversion of the interpreted seismic units/horizons into geological bodies. Each of these bodies is modelled as a polygon with an assigned density value. The software calculates the gravity response of the model using the technique outlined by Talwani and Ewing (1960). The gravity response from a proposed model was compared with the observed gravity; the model was then interactively adjusted until a satisfactory fit was obtained between the synthetic response and the observed gravity profile.

Gravity models are non-unique, which means that there are a multitude of density and geometrical configurations that can produce the same amplitude and wavelength anomaly. However, by using seismically constrained boundaries and densities for the modelled bodies down to the Moho, we can minimize the number of possible solutions. The range of rock densities is calculated from seismic interval velocities using a Nafe-Drake formula (Ludwig et al., 1970; Brocher, 2005). The boundaries of the modelled bodies down to the top of basement inclusive are guided by seismic interpretation. Long-offset MCS data in combination with seismic refraction data provide the most reliable constraint over depth and geometry of top basement (top consolidated crust) horizon and so we preserved the geometry of this horizon while performing the modelling. The depth to the Moho and Mid-Crust Discontinuity (MCD, top of lower continental crust) is also well constrained by seismic data along some sections of refraction profiles. In our approach we avoided introducing prism-shaped bodies in crustal layers to replicate a lateral density gradient that have no geological or seismic control.

We also introduced some density contrasts across the boundaries of crustal domains shown in Figure 2. This is mainly based on an assumption that the old continental crust of the Precambrian and Palaeozoic domains as well as at the deformed proximal passive continental margins (domains 1 to 7 in Fig. 2) is generally thicker and denser than the crust below the deformed distal passive continental margins and hyperextended rift basins (domains 8 to 11). The HALIP crust containing extensive mafic magmatic additions is generally treated as denser one as compared to other crustal domains. Also, the exhumed upper mantle below the hyperextended basins is inferred to be serpentinised and therefore of a lower density as compared to the ‘normal’ upper mantle.

For the purpose of this study, we present three groups of 2D gravity models for every seismic transect except for the Geotransect I that was published by Drachev et al. (2017) and is reproduced here for a completeness of tectonic characterization of the ESAS. The first group, the ‘initial’ models, is built using published refraction profiles, with no modifications to crustal geometries and densities that were derived from seismic velocities. These initial models allow us to evaluate the consistency of previous geologic interpretations with gravity data and to identify where important misfits exist between the observed gravity and the synthetic response of the models. The second group, the ‘intermediate’ models, is based on a new enhanced geologic interpretation produced by us utilizing both results of our interpretation of seismic reflection data published by Piskarev et al. (2016) (mostly intrasediment and top basement horizons) and boundaries constrained by seismic refraction data, such as Moho and MCD. These models demonstrate the effect of the improved geologic interpretation without any adjustments guided by misfits between the observed and modelled gravity profiles. The third group, the final models, represents the best fit between the modelled and observed gravity achieved through a sequence of iterations. In the course of modelling, we were focused on reproducing long-wavelength anomalies caused by the Moho or MCD since the higher horizons are seismically well constrained. To smooth out short-wavelength anomalies caused by the top basement geometry that are not reproducible by the satellite gravity data, the gravity profiles are low-pass filtered using a 20-km cut-off wavelength.

Results

Geotransect I: Northern Laptev Shelf

The Geotransect I is based on two long-offset MCS profiles, TGS ARS10 and MAGE A4 that provide reliable constraint on the crustal structure of the shelf down to the Moho. The gravity modelling results for these profiles were published by Drachev et al. (2017) and so we refer readers to this publication for more details. For this study, we have merged TGS ARS10 and MAGE A4 models to produce a 765 km-long composite profile that crosses the northern part of the shelf and reveals a character of crustal extension across the Laptev Rift System (Fig. 4).

The Geotransect I crosses all major elements of the northern part of the rift system, which are (from west to east): the Ust' Lena Rift, the East Laptev Horst and Graben Province, the Anisin Rift, the Kotel'nyi High and the New Siberian Rift.

The Ust' Lena Rift is the main locus of extension within the Laptev Shelf with a total thickness of presumably Late Cretaceous to Quaternary syn-rift and post-rift sediments reaching over 14 km in its axial zone. The resulting model along the ARS10F04 profile is based on the initial seismic interpretation by Drachev and Shkarubo (2017) and allows for the continental crust to be entirely thinned out in the axial part of the rift, where the sedimentary fill may be directly underlain by the exhumed and serpentinised upper continental mantle. To accommodate a complete removal of the crust, the modelled Moho ascends from ~27 km beneath the rift flanks to ~13-14 km beneath the rift axis.

The main extensional detachment fault is inferred to coincide with the MCD below the entire eastern flank of the Ust' Lena Rift, and with the modelled interface between the exhumed serpentinised mantle and the rift sedimentary fill. Further to the west, it is inferred to deepen below the lower continental crust of the North Verkhoyansk Fold Belt developed on the Paleo-Siberian proximal passive continental margin.

Geotransect II: Kotel'nyi Island to Lomonosov Ridge

This geotransect is based on a single 832 km-long MAGE MCS profile A7 and a 650 km-long refraction profile Arctic-2007 that was acquired using 30 OBS receivers deployed with 5 km interval along the MCS line (Piskarev et al., 2016; Poselov et al., 2011, 2012a); the southern 175 km of the geotransect do not have seismic refraction coverage and thus have less data to constrain the crustal structure. Both seismic reflection and refraction profiles cross the shelf break and continue along the crestal part of the Lomonosov Ridge providing a unique opportunity to examine the structural relationship between the ridge and the continental margin.

The refraction model of the Arctic-2007 profile by Poselov et al. (2011, 2012a) demonstrates a tectonic continuity of the continental crust between the shelf and ridge allowing the authors to conclude that there is 'no evidence that the Lomonosov Ridge moved as a terrane with respect to the shelf' and the ridge 'should be regarded as a natural prolongation of the continental margin'. However, this conclusion is in the conflict with the fact that during the opening of the Eurasia Basin, the 'Siberian' end of the ridge has drifted away from the Taimyr margin for over 500 km and thus could be expected to experience a significant displacement relative to the southerly located Laptev Sea continental margin. That right-lateral movement is inferred to have been accommodated by the Khatanga-Lomonosov Fracture Zone (Drachev et al., 2003; Drachev 2011). Therefore, the Geotransect II is aimed to test both these models.

For the initial model, we used the Arctic-2007 crustal cross-section by Poselov et al. (2012a). The resultant model shows a significant misfit between the observed and calculated gravity with a considerable mass deficit over the continental shelf and a mass excess over the ridge (Fig. 5a). This is mostly related to the Moho being generally too shallow underneath the Lomonosov Ridge and too deep underneath the continental shelf. This problem has been recognized by the authors of the refraction model, and they attempted to modify the crustal structure to achieve a better calculated gravity response (see Fig. 9b in Poselov et al., 2012a). For this, they allowed a significant deviation from their refraction model both in the geometry of the crustal layers and in their densities, and introduced a series of seismically uncontrolled vertical prism-shaped bodies. In attempt to replicate the published model, we have modelled the same cross-section with the same densities as in Poselov et al. (2012a) but could not achieve a satisfactory fit between the observed and calculated gravity (Fig. 5b).

To improve the crustal model along the Geotransect II, we have performed interpretation of the MAGE A7 MCS profile (Fig. 6). We have traced the two most prominent seismic horizons that are: (i) the top of a tectonic (acoustic) basement interpreted as the pre-rift unconformity and (ii) the top of a high reflective unit that corresponds to the early Eocene horizon 'A' of Langinen et al. (2009) and is dated at ~48 Ma based on Backman et al. (2008). The seismic unit bounded by these two horizons is inferred to consist of mostly Upper Cretaceous to Paleocene sedimentary rocks according to the ACEX results (Backman et al., 2008). In some places along the profile, laterally and vertically limited packages of discontinuous reflectors were observed below the interpreted top of basement horizon that could potentially represent poorly imaged syn-rift sediment patches (Fig. 6). However, the most important observation was the discovery of a ~6 s TWT-thick package of discontinuous reflectors between ~380 and 560 km of the profile. This package is bounded by the top of basement horizon and by the inferred Moho discontinuity at the ~10 s TWT depth (Fig. 6). Therefore, the package has a significant thickness and lateral extent and is interpreted as a body of deformed and poorly imaged sediments that are located between two solid (acoustically transparent) basement blocks: the De Long Massif to the south and the Lomonosov Ridge to the north. The southern limit of this package coincides with the projection of the Khatanga-Lomonosov Fracture Zone as proposed by Drachev with the co-authors (Drachev et al., 2003; Drachev, 2011; Drachev and Shkarubo, 2017). As this package occurs beneath the top of basement horizon, the corresponding rocks are apparently older than Cretaceous, and could possible represent a Palaeozoic-Mesozoic clastic succession, a remnant of the Paleo-Siberian passive continental margin (see Discussion for more details).

An over10 km-thick unit of moderately (?) deformed sedimentary material that extends laterally for ~180 km between two solid crustal blocks should, if present, correspond to a significant crustal heterogeneity and thus has to be detectable by both the gravity and seismic refraction data. The latter do not seem to reveal any significant crustal velocity anomaly between the Lomonosov Ridge and the continental shelf (Fig. 5a) though Poselov with co-authors point to a 'dramatic decay of the P-waves' in two crustal zones beneath the continental slope, which coincide with the inferred deformed sediment patch (see Fig. 6 in Poselov et al., 2012a).

To test this hypothesis, we have started with a model that combines the interpreted MAGE A7 seismic horizons and the refraction crustal boundaries (Fig. 7a). The crustal densities in this model are the same as in the initial model in Figure 5a, and are constrained by the seismic velocities; the sediment densities are somewhat different from those given in Figure 5a and are based on sonobuoy velocities by Jokat (2005). The model demonstrates a significant misfit between the observed and calculated gravity with a mass deficit in the area of continental shelf and a mass excess over the Lomonosov Ridge. The long wavelength of the misfit suggests that it is mainly caused by the Moho geometry, and is generally inherited from the refraction model.

In the third, final model (Fig. 7b), we have utilized a scenario with the presence of a 2.65 g/cm^3 body in the middle of the cross-section that emulates the inferred deformed sedimentary package based on our interpretation of the MAGE A7 MCS profile (Fig. 6). We have also assumed that this body is underlain by the exhumed serpentinised upper mantle with the density of 3.0 g/cm^3, which mostly occupies the lower crust level at depths between 16 and 23 km below sea level. The base of this serpentinised mantle coincides with the 'refraction' Moho. In addition to these changes, we have increased the Moho depth below the Lomonosov Ridge by ~1.5 to 3.8 km and decreased its depth by 1.7-4.6 km below the region of the thinnest crust in the area of the outer continental shelf; also we have increased the density of the sedimentary fill from 2.35 to 2.5 g/cm^3 in the lower part of the basin between 280 and 420 km of the transect. Finally, omitting many local sediment patches inferred from the MCS data below the top of basement horizon helped to improve the fit for the 40-60 km long wavelengths. All these modifications have resulted in a much tighter fit between the observed and calculated gravity with the mean error of 4.7 mGal.

Geotransect III: Indigirka Bay-De Long Islands – Makarov Basin

Geotransect III is designed to examine the crustal structure of the western ESAS, the adjoining Podvodnikov Basin and the northerly located Makarov Basin. This is a composite geotransect consisting of two MCS profiles, the LARGE 8901 and Arctic 2011-059 and the refraction profile Transarctic 89-91 (Figs. 1-3). It starts ~80 km north of the Indigirka River mouth and goes north for ~2000 km crossing all the major crustal domains, such as the Novaya Sibir' Fold Belt, De Long Massif, the western Amerasia deep-water basins and the Lomonosov Ridge margin (Fig. 2). Because of the large length of this transect, the gravity models are shown in two parts: the southern based on the LARGE 8901 profile (Fig. 9), and the northern based on the Transarctic 89-91 profile (Fig. 10).

The LARGE 8901 MCS profile was the first ever seismic data acquired in the East Siberian Sea in 1989 by the first private Soviet seismic company LARGE Ltd. It crosses the Novaya Sibir' Fold Belt and the southern margin of the De Long Massif, and is the first profile that revealed a compressional deformation zone south of the De Long Islands, which was interpreted as a northern front of the late Mesozoic contractional deformation (Drachev et al., 2001). For the purpose of modelling, we use the geological interpretation published by Drachev (2011).

The LARGE 8901 profile has a limited record length of 6 s TWT and so it is not informative for deeper crustal levels below the top of basement horizon. To constrain these, we have used a published fragment of the long-offset 12 s TWT-deep ION ru2-2050 profile (Nikishin et al., 2014) and Dream Line refraction profile by Sakulina et al. (2016).

The ION ru2-2050 profile intersects the LARGE 8901 profile ~40 km south of the deformation front providing unique insights into the structure of the fold belt buried underneath ~2 to 6 km (2-4 s TWT) of Upper Cretaceous and Cenozoic post-orogenic sediments (Fig. 8). In our interpretation, the seismically transparent body beneath the undeformed sedimentary cover represents the deformed rocks of the fold belt that are overthrusted onto the southern margin of the De Long Massif along a north-vergent frontal thrust. The latter is traced down to depths of ~22 km, where it merges into a prominent 1 to 2 s TWT-thick high-reflective package interpreted as tectonically imbricated crust (Fig. 8).

The Dream Line 1 refraction profile provides a reliable velocity and depth control at the intersection with both, the LARGE and ION profiles (Figs 8, 9). It reveals a somewhat unusual velocity profile of the crust. An inferred deformed sediment body has the refraction velocity of 5.85 km/s and is underlain by a thin 7.1 km/s layer; typical crystalline continental crust velocities in the range of 6.2-6.8 km/s are not documented. Therefore, we infer that the high-velocity layer underlying the low-velocity deformed sedimentary rocks may include tectonised and serpentinised ultramafic rocks. Published seismic profiles (Nikishin et al., 2017) located in the area occupied by the hyperextended North Chukchi Basin east of the LARGE-8901 profile show the same but thinner high reflective package underlying a thick undeformed sedimentary fill of the basin. Based on this observation, it appears that the North Chukchi Basin is involved in late Mesozoic compressional deformation along and south of a 550 km stretch of the frontal thrust zone in the central East Siberian Sea (Fig. 2). This observation allows us to conclude that the fold belt in the central and western East Siberian Sea (the Novaya Sibir' Fold Belt in Fig. 2) is composed of deformed sediments of the North Chukchi Basin underlain by the compressionally imbricated basin's basement, that used-to-be thinned lower continental crust and/or exhumed serpentinised upper mantle.

Figure 9 shows the starting and final gravity models of the LARGE 8901 profile. The former uses an arbitrary crustal thickness below 20 km depth. The latter adapts the crustal architecture scenario derived from the ION MCS profile (fold belt) and the Transarctic profile for the De Long crust. To achieve a satisfactory fit between the observed and calculated gravity for the final model (Fig. 9b), we introduced a 12 to 20 km-thick body of deformed sediments with an average density of 2.69 g/cm^3 and the underlying 6 to 12 km-thick layer of rocks with a density of 3.0 g/cm^3 that emulates the high-reflective seismic package and represents either lower crust metamorphic rocks or serpentinised ultramafic rocks.

North of the deformation front, below seismically documented foreland basin sediments and underlying older rocks potentially including Aptian-Albian flood basalts, we infer an additional ~10 km-thick sedimentary unit that may represent a preserved underthrust remnant of the North Chukchi Basin sedimentary fill underlain by the exhumed mantle (Fig. 9b). It is worth noting that in this model, the inferred edge of the De Long Massif Neoproterozoic continental crust coincides with a prominent positive magnetic anomaly, a phenomenon that is also observed along the 5-AR transect (see below).

The continental crust of the De Long Massif is assumed to have structure and thickness similar to that imaged by the Transarctic 89-91 profile, i.e. 29-33 km-thick with MCD located at depths from ~13 km to ~20 km.

The Transarctic 89-91 refraction profile is the longest one ever acquired in the Arctic and thus represents a key dataset that has an immense importance for testing tectonic concepts. It crosses all the major tectonic domains identified in this part of the Arctic, namely: (i) 36-41.5 km-thick continental crust of the De Long Massif, (ii) 10 to 26 km-thick crust of the deep-water Podvodnikov Basin, Arlis Gap and western fringes of the Alpha Ridge with the thickest crust occurring in the middle of the deep-water basin and the thinnest – below the continental slope area, and (iii) 6-13 km-thick crust of the Makarov deep-water basin (Fig. 10). The crustal velocity profile below the Podvodnikov Basin very closely resembles the velocity profiles of intraoceanic volcanic ridges and plateaus with a typical triple-layer structure of the crust dominated by a thick high-velocity and low-gradient lower crust (Gladczenko et al., 1997; Gohl et al., 2011). We use this resemblance to assume that the crustal province (ii) corresponds to typical magmatic (igneous) crust of HALIP, instead of continental crust as earlier inferred by Gramberg et al. (1993), Poselov et al. (2011), and Lebedeva-Ivanova et al. (2004, 2011).

For the initial model in Figure 10 we have used the most recent version of the Transarctic seismic refraction velocity cross-section by Lebedeva-Ivanova et al. (2011). This cross-section has been further modified to incorporate recent seismic observations in this part of the Arctic, which are the Russian UNCLOS MCS profiles Arctic 2011-59, 2011-50, 2011-58-66, 14-09 and 14-06 (Piskarev et al., 2016), and the US-Canada LSSL2011-03/04 profile (Evangelatos et al., 2017; Mosher 2012); the location of these MCS profiles is given in Figure 1.

The Arctic 2011-59 profile runs parallel to and just ~5 km east of the Transarctic 89-91 transect between kms 419-618 in the continental slope area (Fig. 2.2.6 in Piskarev et al., 2016). It reveals the top of basement horizon at depths up to 12 km below sea-level and the sediment thickness totaling up to 10 km in the continental slope depocenter. We have used this profile to correct the ‘refraction’ top basement (‘AF’ boundary by Lebedeva-Ivanova et al., 2011), that appeared to be up to 3 km shallower as compared to the same reflection horizon (Fig. 10). The ‘reflection’ top basement is also located ~1 km deeper at the crossings with the Arc 2011-050 and Arc 2011-058-66 and less than 0.5 km deeper at the intersection with the 14-09 and 14-06 profiles while all the refraction boundaries are in a good agreement with those picked along the LSSL2011-03/04 profile in the Makarov Basin. Sediment thickness at the intersection with the AWI 81°N transect is 4.3 km that is in a good agreement with the published data (Jokat and Ickrath, 2015).

As imaged by the MCS profiles, the sediment fill of the continental slope depocenter along and around the Geotransect II decreases northward from 10-12 km at the deepest part of the depocenter to 1-2.5 km awhile sediments pinching out against a prominent basement high (Fig. 10, around 600 km). The latter coincides with a high-amplitude magnetic anomaly featuring the HALIP magmatic province. Therefore the sediments overlying the top basement horizon are inferred to be not older than Early Cretaceous Aptian (~125-120 Ma).

The gravity response of the initial model produced a considerable misfit between the observed and calculated gravity (Fig. 10). The obvious reason for the misfit is too thick continental crust of the De Long Massif and too thin igneous crust of the Alpha Ridge. This misfit could, at least partially, be a result of poor seismic data coverage at both flanks of the transect and between kms 960 and 1080 where there is a gap between 1989 and 1990 segments of the profile (see Lebedeva-Ivanova et al., 2011 for details).

To produce a better fit for the long wavelength gravity field component, we have implemented significant modifications to the Moho, MCD (continental crust) and the top of the middle crust discontinuity (the HALIP province) as shown in Figure 11a. The Moho was consistently raised beneath the De Long Massif with its depths reduced to 35 km (average) and below the Podvodnikov Basin where the Moho became 3-4 km shallower than in the starting model. On the contrary, below the Alpha Ridge and flanks of the Makarov Basin the Moho was deepened by 7 to 32 km. In the central part of the Makarov Basin, where the crust is the thinnest in all the models, a depth to Moho remained the same. In this central part of the basin, we infer the presence of oceanic crust that is in agreement with the previous interpretations by Sorokin et al. (1999), Astafurova et al. (2006), Lebedeva-Ivanova et al. (2011) and Evangelatos et al. (2017). Some minor modifications were also implemented to the top and base of the middle igneous crust that drastically improved the fit of middle- and short wavelength gravity anomalies.

Since the model in Figure 11a allows for preservation of a very thin lower continental crust below the continental slope depocenter, we have decided to test an alternative scenario with the exhumed serpentinised mantle flooring this depocenter (Fig. 11b). Replacing thinned lower crust with a 4 km thick body of serpentinised mantle resulted in the Moho shallower by 1.5 km, the slightly deeper continental slope depocenter (13.5 km) and a better fit to the observed gravity data.

Geotransect IV: Chukotka coast – Mendeleev Ridge

The Geotransect IV stretches for 1,140 km in S-N direction from the Chukchi Peninsula coast to the Mendeleev Ridge and crosses the major tectonic domains of the East Siberian Sea west of Wrangel Island (Fig. 2). It is another key composite seismic transect that consists of the Arctic-2005 OBS refraction profile, the 5-AR OBS refraction and 5-AR MCS profiles (Fig. 1; Tab. 1). The latter two completely overlap since they were acquired along the same line, and thus provide much better control over the seismic model of the shelf portion of the geotransect.

To test the earlier seismic interpretations, we have merged two published cross-sections: by Sakulina et al. (2011) for the 5-AR profile and by Poselov et al. (2012b) for the Arctic-2005 profile. As shown in the Figure 12, the gravity response of this merged cross-section resulted in a significant up to ~90 mGal misfit between the observed and calculated gravity that was mostly caused by a mass deficit underneath the North Chukchi Basin and a mass excess underneath the Mendeleev Ridge.

To produce a better seismically constrained crustal model (Fig. 13a), we interpreted the published MCS 5-AR profile and merged the derived reflection horizons with the refraction boundaries from Sakulina et al. (2011) and Poselov et al. (2012b). The main difference between the published cross-sections and our interpretation are: (i) the extent of the Chukotka-Wrangel Fold Belt that is rather vertically limited in the Sakulina et al. (2011) model, (ii) the structural relationship between the fold belt and the North Chukchi Basin – in our interpretation the boundary between the two is represented by a sharp compressional thrust front that is also documented by other seismic profiles located nearby (Drachev, 2011; Nikishin et al., 2014), and (iii) the stratigraphy of the North Chukchi Basin sedimentary fill is much younger in our interpretation, with most of the lower section represented by Cretaceous terrestrial siliciclastic sediments onlapping onto the ~120 Ma igneous crust of the Mendeleev Ridge, and the upper 5–6 km of the section represented by a Cenozoic passive margin clastic wedge prograding towards the Canada Basin.

Despite the improvements applied, the intermediate model still shows a major misfit above the North Chukchi Basin, the spin-off effect of which was also misfits above the Mendeleev Ridge and the Chukotka-Wrangel Fold Belt (Fig. 13a). This was the case as we preserved the 12-km-thick (thinned) continental crust below the North Chukchi Basin as suggested by the published refraction velocity profiles. Therefore, the gravity response of the starting model showed even greater misfit between the observed and calculated gravity reaching ~120 mGal over the North Chukchi Basin.

In the final model (Fig. 13b) we achieved a much better fit mainly by raising up the Moho by 12 km below the axial part of the North Chukchi Basin that required a complete removal of the continental crust and its replacement with a body of serpentinised upper mantle rocks (3.1 g/cm^3). Significant modifications were also introduced to the Moho and MCD along the basins' margins, and less remarkable – to the flanks of the model, except for the 920-1040 km stretch of the profile below the Mendeleev Ridge where the Moho and the top of lower crust were deepened by up to ~6 and 5.5 km, respectively. An important constraint on the thickness and density of the crustal layers beneath the Mendeleev Ridge was derived at the intersection point of the Arctic-2005 profile with the Arctic-2012 profile as the latter provides a more reliably refraction data set. While depths to the main crustal boundaries and the Moho are close in both refraction models, there is a notable difference in the lower crust velocity: 7.8 km/s in Arctic-2012 vs 6.8 km/s in Arctic-2005.

Geotransect V: Mendeleev Ridge – Chukchi Cap

This geotransect is composed of the 750 km-long Arctic-2012 OBS refraction profile and a shorter MCS Arctic 2012-3 profile as both datasets were acquired along the same line (Figs. 1, 3). Both the profiles run across the Mendeleev Ridge and the Chukchi Plateau in the W-E direction approximately along 77°N and hence provide unique data for examining the HALIP crustal architecture. They also reveal possible differences between the igneous crust of the latter and the continental crust of the plateau. The data and results were published by Kashubin et al. (2016) and Piskarev et al. (2016). Another important aspect of this transect is that it crosses the Arctic-2005 OBS refraction profile and thus both intersecting profiles provide a better control over the proposed models.

For the initial model (Fig. 14a), we used the Arctic-2012 OBS refraction profile by Kashubin et al. (2016). The model demonstrates two-layer continental crust below both the Mendeleev Ridge and the Chukchi Plateau overlain by a stratified sedimentary cover and metasedimentary rocks of so-called 'Intermediate Layer' (according to Kashubin et al., 2016). The average densities for this model were derived from the refraction seismic velocities. The gravity response of the initial model resulted in a noticeable misfit in the range of 20-60 mGal between the observed and calculated gravity over the Mendeleev Ridge (mass deficit) and the Chukchi Plateau (mass excess) (Fig. 14a).

As Kashubin et al. (2016) also published a gravity model demonstrating a close match between the observed and calculated gravity along the Arctic-2012 profile, we have replicated this model to test the provided parameters such as densities and crustal boundaries. However, the resulted gravity response from this model appeared to be even worse as compared to the response from the initial model constrained by the refraction data only (Fig. 14b).

As the next step, we build an intermediate model by merging the main seismic horizons along the MCS profile Arctic 2012-3 and the OBS refraction boundaries (Fig. 15a). The former were obtained by re-interpreting the published MCS profile (Piskarev et al., 2016), and the latter were transferred from the initial refraction model. As shown in Figure 15a, the main difference between the initial (published) and the starting model was more accurate geometry of the top basement horizon. We also introduced a high density body at the lower part of the Mendeleev Ridge crust as suggested by Kashubin et al. (2016) gravity model to test an underplating scenario, and also used a more accurate sea-bottom topography derived from the latest IBCAO-3 dataset (Jakobsson et al., 2012). All these changes, however, were not critical to the long wavelength anomalies of the synthetic gravity profile that still showed similar misfits as those produced by the initial model.

In order to improve the fit between the observed and calculated gravity, we modified the deeper refraction boundaries while preserving the densities constrained by the refraction velocities, and introduced two different crustal domains: (i) the three-layer HALIP igneous crust beneath the

Mendeleev Ridge, and (ii) the two-layer continental crust of the Chukchi Plateau. Though the density of the HALIP upper crust layer remains the same as density of the 'Intermediate Layer' in the initial model (Fig. 14a), we consider it not as metasedimentary rocks but rather as upper igneous crust. The changes of the Moho depth were in the range of 0.3 km to 5.0 km beneath the Mendeleev Ridge and up to 3.8-4.0 km beneath the western flank of the Chukchi Plateau. The changes implemented to the top of the Mendeleev lower igneous crust were from a few hundred meters to 1.5-2.8 km, and those applied to the top of the middle igneous crust - in the range of 0.2-0.5 km to 2.8 km. The MCD depth below the Chukchi Plateau was adjusted in the range of a few hundred meters to 2.3 km. The resultant gravity model demonstrated a far better gravity fit as compared to both, the initial and starting modes (Fig. 15b). This was primary the effect of splitting the crust into two contrasting domains characterized by a dissimilar density structure.

Discussion of the results

The results of the gravity forward modelling of the OBS refraction and MCS profiles acquired between 1989 and 2012 in the ESAS and adjacent Amerasian sector of the Arctic Ocean revealed some significant inconsistencies between the published crustal models and the gravity response in the form of long-wavelength (150-250 km-long) gravity anomalies. The main causes of these inconsistencies are: (i) the presence of reduced (thinned) continental crust below the major depocenters with a sediment thickness exceeding 12 km, and (ii) the presence of variable thicknesses of continental crust below the most parts of the western Amerasia Basin except for the central part of the Makarov Basin. In order to produce crustal models that are guided by both seismically constrained interfaces and observed gravity anomalies, we modified the published models in the following ways:

(i) Incorporating into the crustal refraction models the MCS reflection horizons, which were obtained by re-interpreting the published MCS profiles acquired along the geotransects, as well as more accurate IBCAO-3 sea bottom relief.
(ii) Modifying the geometries of the deep crust refraction boundaries, such as MCD and the HALIP top lower and middle igneous crusts, and the Moho discontinuity.
(iii) Introducing the serpentinised upper mantle doming below deep sedimentary depocenters.
(iv) Adjusting the rock densities to make them consistent with two types of the Earth's crust: the lighter continental crust below the Lomonosov, De Long, North Wrangel and Chukchi Plateau blocks, and the heavier HALIP igneous crust below most of the deep-water Podvodnikov Basin, Arlis Gap and the Alpha and Mendeleev Ridges.

The first procedure (re-interpreting the published MCS profiles) mostly impacted the short-wavelength anomalies produced by the top of basement horizon relief. These anomalies are often shorter-wavelength than the satellite-derived gravity field that is insufficient to resolve the anomalies with the half-wavelength of 10 km and lesser. There are two main exceptions though where the reinterpreted top basement (top consolidated crust) horizon had a significant impact on the resulting models: the western Laptev Sea (the Geotransect I) and the transition zone between the ESAS and Lomonosov

Ridge (Geotransect II). In the Laptev Sea, previous interpretations inferred thinned but yet continuous continental crust underlying the entire rift system (Drachev et al., 1998; Franke et al., 2001; Shkarubo et al., 2014). New geologic interpretation of the long-offset MCS profile ARS10F04 by Drachev and Shkarubo (2017) inferred that the Ust' Lena Rift Basin sedimentary fill may be underlain by serpentinised mantle, and that the rifting there has evolved to the stage of the complete crustal rupture and the upper mantle exhumation; the forward gravity modelling (Drachev et al., 2017) has shown that this interpretation is consistent with the observed gravity (Fig. 4).

The interpretation results of the MCS profile A7 allow us to consider a scenario with complete decoupling of the Lomonosov Ridge crust from the New Siberian continental margin. To achieve a satisfactory gravity response from this model that would provide a fit with the observed gravity, the continental crust has been replaced by a ~12-14 km -thick and ~190 km-wide in S-N direction body of what we interpret as a deformed sedimentary succession based on the seismic reflection data. This deformed sediment package is inferred to be underlain by a body of serpentinised upper mantle rocks; the modelled contact between the two is located at a depth of ~16 km.

The existence of this body that is inferred to represent deformed sedimentary rocks may be related to a pre-drift location of the Lomonosov Ridge and a pre-rift location of the shelf edge north of the Kotel'nyi Island with regard to the Eurasia continental margin. Figure 16 demonstrates a scenario in which the Lomonosov Ridge has been restored to its pre-Eurasia Basin position using finite rotation parameters by Glebovsky et al. (2006), and the Laptev Rift System has been shortened to undo the Cretaceous-Cenozoic extension in two steps: (i) moving the De Long Block by ~65 km in a SW direction to close the New Siberian Rift between the De Long and New Siberian blocks, and (ii) moving both blocks as an intact microplate in a SW direction to shorten the Ust' Lena Rift by 300 km in the north and 210 km in the central part of the shelf.

In the resultant reconstruction, the southern edge of the Lomonosov Block is positioned close to the late Mesozoic compressional deformation front mapped offshore the Taimyr Peninsula by Drachev and Shkarubo (2018). As revealed by MCS profiles (Fig. 17), there is an inferred zone of weaker deformed stratigraphy in the 'acoustic basement' between the late Mesozoic North Verkhoyansk and early Mesozoic South Taimyr compressional fronts. This V-shaped, in map view, zone is traced in the NE direction towards the continental shelf break and could be projected further to include the southern part of the restored Lomonosov block where the ~200 km-wide deformed sedimentary body is inferred by the Geotransect II. The existence of this very thick pre-Cretaceous sedimentary body that experienced some degree of compressional deformation could be related to a pre-late Mesozoic (pre-collisional) Eurasian passive margin and could potentially represent a remnant of the latter that survived intense compressional deformation that first affected the South Taimyr Fold Belt in the latest Triassic or earliest Jurassic (Khudoley et al., this volume) and then was followed by late Mesozoic compression that in the entire Laptev Shelf region (Fig. 17).

Another important observation is that the proposed 'sediment filled gap' is expressed in the magnetic field by a prominent magnetic anomaly, which may be a result of a considerable emplacement of igneous material (Fig. 18a). This zone is also documented by a dramatic decay of the top of lower crust reflected P-waves (Poselov et al., 2012a), which together with the potential presence of a thick body of deformed sediments with potentially significant amount of magmatic addition could be jointly interpreted as a manifestation of profound crustal decoupling between the ridge and the continental margin. If this decoupling existed prior to the spreading onset in the Eurasia Basin then it could have acted as a crustal-scale zone of weakness that became the Khatanga-Lomonosov sheared fracture zone during the Lomonosov Ridge displacement along the Laptev Sea rifted continental margin.

The second procedure (modifying the geometries of deeper boundaries) revealed a high sensitivity to depths to the Moho and the top of lower crust discontinuities. The applied changes vary from a few hundred of meters to a 1-2 km in the most cases, with a maximum deviation reaching ~4, 6 and 7 kilometers at some parts of the Geotransect II, IV and III, correspondingly. These changes were needed in order to achieve a satisfactory fit between the observed and calculated gravity that is lacking by all the examined published crustal models. Though we are fully aware that these modifications are not unique and that there are other possible models that would satisfy the observed gravity, by doing so we have illustrated significant inconsistencies in the published crustal cross-sections and tried to minimize these by testing alternative models.

The third procedure (introducing upper mantle doming below deep sedimentary depocenters) was required to accommodate mass deficits in the areas where more than 14 km of sedimentary fill existed in the inferred hyperextended basins, e.g. the Ust' Lena Rift Basin, the North Chukchi Basin, the Podvodnikov continental slope depocenter and the proposed sediment-filled gap between the Lomonosov Ridge and the De Long Massif. In all our final models, the inferred serpentinised mantle bodies occupy the space that is considered to be the lower continental crust in the published refraction models. As it is a well-established phenomenon that the seismic velocities in serpentinised ultramafic rocks vary significantly (as do rock densities) and mimic the whole spectrum of velocities and densities of crustal rocks (see Fig. 3 in Oakey and Saltus, 2016), one of the major challenges is to identify these bodies based solely on seismic refraction data. Also, this phenomenon limits gravity models of hyperextended basins and continental margins to a point when it becomes vague to speculate upon whether lower continental crust is completely absent below deep depocenters. Introducing serpentinised mantle bodies in our models resulted in a much tighter fit between the observed and calculated gravity but same time it led to major diversions between the modelled and seismic interfaces. Allowing for these alterations of the seismic boundaries, we believe that they are still within the uncertainty range of seismic refraction models though we could not verify this assumption as we do not have access to the original seismic data.

Finally, the fourth procedure (adjusting rock densities to be geologically consistent with either continental or mafic – HALIP – crust) brings consistency to the geotransects. As documented by the OBS refraction experiments, the HALIP Mendeleev and Alpha ridges and the continental Lomonosov Ridge and Chukchi Plateau have comparable crustal thicknesses in our gravity modelling results. If the HALIP ridges were continental fragments, we would expect to observe the same water depths as for their continental siblings. However, the depths to the sea floor are generally greater for the Alpha and Mendeleev Ridges, which is expected if their crust is denser (consider water depth contrast between ~33 km thick crusts of the Chukotka-Wrangel Fold Belt and the Mendeleev Ridge in Fig. 13). Based on this reasoning, and also on the observations by Oakey and Saltus (2016)crustal densities applied to igneous crustal layers within the HALIP are somewhat higher than those of the continental Lomonosov and Chukchi blocks.

The procedures (ii) to (iv) may raise some questions if this is a justified approach to alter crustal densities and boundaries constrained by the seismic refraction data. In the best case scenario, one would perform refraction data modelling coupled with the gravity modeling as the latter provides a good control over crustal model. As we do not have access to the original seismic data, we are unable to determine uncertainties of the published refraction models we used in our study. However, analysis of published refraction and gravity models for the Arctic-2007 by Poselov et al. (2012a), Arctic-2005 by Poselov et al. (2012b), and Arctic-2012 by Kashubin et al. (2016) profiles provides us with some qualitative insight in these uncertainties. In the case of the published Arctic-2007 models, there is a significant discrepancy between the refraction and density boundaries (Fig. 5b) as well as between seismically constrained densities (Fig. 5a) and those used for a gravity model (Fig. 5b). Based on this fact, we conclude that there is an uncertainty in the published refraction model that allowed its authors to deviate from seismically constrained velocities and depths to obtain a better fit between the observed and calculated gravity. This conclusion is also justified when considering the intersection of the published Arctic-2005 and Arctic-2012 models. The intersection reveals a significant misfit between the refraction velocities in the lower crust (see the text above). Therefore, at this stage of our study, we believe that our approach is reasonable and allows us to examine published refraction models and propose alternative scenarios.

The anomalous magnetic field provides a good spatial control over contours of the proposed crustal domains. Figure 16a illustrates the Getech magnetic grid along with the outlines of the crustal domains drawn based on magnetic field pattern and our final crustal models (see Table 2 for the main characteristics of these domains). The HALIP magnetic region dominates the central and northern part of the map, but there are also several smaller but quite well pronounced groups of anomalies indexed from A to D that correspond to continental blocks with the inferred Neoproterozoic crust modified in some domains by the Palaeozoic and late Mesozoic compressional events, such as the Kotel'nyi (A), De Long (B), North Wrangel (C) and Chukchi Borderland (D) blocks. The magnetic anomalies over these blocks are similar in size, shape and intensity, with positive anomalies generally along the margins of the blocks. In the area of the northern East Siberian and Chukchi Seas, these blocks are separated by a magnetically quiet domain that is clearly coincides with the North Chukchi hyperextended basin (domains 7 and 11a of Fig. 16a). Southern flanks of the magnetic domains B and C, as well as the intervening 'quiet' magnetic domain 7-11a occur to the south of the late Mesozoic compressional front suggesting that the corresponding crustal domains are affected by late Mesozoic fold and thrust deformation as inferred by the LARGE 8901 final model for the southwestern part of the North Chukchi Basin (magnetic domain 7; Geotransect III, Fig. 9b). Based on the published geologic and seismic data

(Drachev, 2011, 2016; Drachev and Shkarubo, 2018; Drachev et al., 1998, 2010; Franke et al., 2001, 2004, 2008; Ershova et al., 2016; Gottlieb et al., 2018; Kos'ko et al., 2013; Miller et al., 2006, 2018; Natal'in et al., 1999; Nikishin et al., 2014, 2017; Piepjohn et al., 2018; Sakulina et al., 2016), the results of crustal gravity modelling presented in this paper, and the distribution of magnetic anomalies, we propose that the Kotel'nyi, De Long, North Wrangel and Chukchi Borderland blocks represent fragments of once single continental block with the Precambrian crust; we call it Bennett-Barrovia Block after Natal'in et al. (1999). This block was probably part of the Arctic Alaska-Chukotka Microcontinent, and was separated from the latter and dismembered by the intense crustal thinning and formation of the North Chukchi hyperextended basin. Presently, we do not have data to constrain the timing of this extensional event, but its relationship with the opening of the Canada Basin sometime in the Jurassic and the earliest Cretaceous is possible. Figure 16b shows a schematic reconstruction of the Bennett-Barrovia Block based on magnetic patterns.

Following the Canada Basin breakup and fragmentation of the Bennett-Barrovia Block, the fragments of the latter have been drifted away from their pre-rift location and docked to the Eurasian margin along the South Anyui Suture Zone. The time of the docking is documented by the latest Jurassic-Early Cretaceous supra-subduction Oloi-Svyatoi Nos magmatic arc (Sokolov et al., 2009, 2015), and the cessation of the collision is bracketed by youngest compressionally deformed Hauterivian-Barremian sedimentary rocks and the oldest 116.9±2.5 Ma (Miller et al., 2009) granite pluton cross-cutting the deformed rocks. During this Early Cretaceous collision, the southerly located Kotel'nyi and North Wrangel crustal blocks together with the southern part of the hyperextended North Chukchi Basin were affected by compressional deformation and became part of the vast Verkhoyansk-Chukotka-Brooks orogen. Younger age of compressional deformation with regard to the extension that formed the North Chukchi Basin is documented by a frontal thrust zone north of Wrangel Island and its western prolongation in the East Siberian Sea (Fig. 13; see also Drachev, 2011, 2016).

Conclusion

The ESAS forms a continental rim of the least geologically understood part of the Arctic Ocean, the Amerasia Basin. It is a tectonically unique region that includes, the Gakkel spreading ridge in the Eurasia Basin and the major Arctic submarine ridges (the continental Lomonosov Ridge, the Mendeleev Ridge of disputed origin, and the continental Chukchi Plateau along the East Siberian continental margin). Due to its unique position, the ESAS is a place for geoscientists to address a broad spectrum of topics related to the formation of the present-day Arctic Ocean.

In this study, we focused on examining tectonic relationships of the main structural features of the Arctic Ocean with the Siberian continental margin, as well as crustal architecture of the ESAS itself using published seismic refraction and reflection profiles grouped into five geotransects. Using Getech gravity grid, we tested the proposed crustal models and generated the new ones, which demonstrate internally consistent geological and geophysical interpretations. Our results help addressing the following scientific topics:

- Hyperextension within the Laptev Rift System and possible extent of the exhumed mantle;
- Relationship between the New Siberian Shelf and the Lomonosov Ridge;
- Nature of the collapsed late Mesozoic fold belt in the southern part of the East Siberian Sea;
- Character of transition between the De Long Massif and the deep-water Podvodnikov Basin;
- Lateral extent of the hyperextended North Chukchi Basin and nature of its basement;
- Relationship between the Mendeleev Ridge and Chukchi Plateau crustal domains.

Our main observations are the following:

1. The Geotransect I crustal model in the Laptev segment of the ESAS shows that the extension in the Laptev Rift System resulted in a complete rupture of the continental crust, accompanied by upper mantle exhumation beneath the Ust' Lena Rift that probably preceded the 53 Ma breakup event;
2. Modelling along Geotransect II which crosses the ESAS north of Kotel'ny Island and its junction with the Lomonosov Ridge allows us to propose a new concept, in which the ridge is completely detached from the continental margin. The gap between the two is inferred to be filled with the deformed sediments underlain by the exhumed upper mantle.
3. The collapsed fold belt in the western part of the East Siberian Sea Shelf (Geotransect III) formed over the hyperextended North Chukchi Basin and thus is lacking a well-developed thick continental crust;
4. The continental crust of the De Long Massif does not extend north of the continental margin being sharply truncated at the area of the lower continental slope. The sedimentary depocenter beneath the slope is underlain either by extremely thin igneous crust or by the exhumed upper mantle. Further north along the Geotransect III, the continental crust is replaced by the thick HALIP igneous crust;
5. The North Chukchi Basin in the northern part of the ESAS can be modeled by the thinned lower continental crust and exhumed upper mantle. This prevents thicker continental crust of the southerly located North Wrangel Block to be continuously traced across this basin into the Mendeleev Ridge area.
6. The two gravity models across the Mendeleev Ridge demonstrate that its crustal section can be modeled to resemble crust of typical 'volcanic' intraoceanic ridges. Its thickness is almost equal to the thickness of the adjoining continental crust of the Chukchi Plateau, but because of its inferred 'magmatic' crust dominated by mafic rocks, the Mendeleev Ridge occurs in greater water depths.

An overall result of our study is to show that consistent gravity modeling provides an alternative interpretation for the crustal architecture of the ESAS. The 'central' role in formation of the ESAS belongs to the large North Chukchi hyperextended basin whose 15-20 km-thick sedimentary fill can be modeled with highly attenuated lower continental crust or the exhumed and serpentinised upper continental mantle. Three large tectonic fragments of Neoproterozoic continental crust can be identified: the De Long and North Wrangel Massifs and the Chukchi Plateau block. These blocks have similar crustal affinities documented by the geological data and can be modeled with a consistent crustal density and thickness. We speculate that these crustal blocks once were united into a single Bennett-Barrovia microcontinent before its disintegration in the course of the North Chukchi Basin formation. The southern margins of the De Long and North Wrangel Massifs and intervening North Chukchi Basin were then involved into compressional deformation during Early Cretaceous and were incorporated into the Chukotka Fold Belt.

The proposed existence of this now-dismembered Bennett-Barrovia microcontinent can play a crucial role in the paleotectonic analysis of the Arctic, and in reconstructing the Mesozoic pre-Canada Basin Arctic in particular. In a number of recent publications (Drachev 2011, 2016; Miller et al., 2006; Pease 2011; Pease et al., 2014), the East Siberian Sea and Chukchi Sea shelves are included into a large crustal block, the Arctic Alaska-Chukotka microcontinent that is considered to be moved to its current position in the course of late Mesozoic opening of the Amerasia Basin. The shape and size of this microcontinent are the key parameters that influence pre-Canada Basin Arctic reconstructions. Once re-united, the Bennett-Barrovia microcontinent would be much smaller in size compared to what is usually speculated to be the 'Siberian' portion of the Arctic Alaska-Chukotka Microcontinent. There could be even more blocks that were part of this Bennett-Barrovia microcontinent that are currently masked by the HALIP. However, considering the recent results of the seismic investigations and our present attempt to model the crust below the HALIP, the solution of this important scientific problem may lie beyond capacities of non-unique geophysical methods. The solution may need a more comprehensive sampling/drilling campaign to answer the question whether any continental masses exist below the region occupied by the HALIP magnetic anomaly.

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Figure captures

Fig. 1. Main physiographic features of the East Siberian Arctic Shelf and adjacent deep-water and mainland territories. Orange lines show location of the seismic profiles. The black roman numerals are the indexes of the following geotransects: I, Northern Laptev Shelf, II, Kotel'nyi Island—Lomonosov Ridge, III, Indigirka Bay—Makarov Basin, IV, Chukotka Peninsula—Mendeleev Ridge, V, Mendeleev Ridge—Chukchi Plateau. The topography is by Jakobsson et al. (2012). Lambert Azimuthal Equal Area projection, central meridian 130°E.

Fig. 2. Getech gravity grid (Bouguer onshore and Free-air offshore) used for the purpose of this study and the location of the seismic profiles. Lambert Azimuthal Equal Area projection, central meridian 130°E.

Fig. 3. Crustal domain map. Modified from Drachev (2016) and Pease (2014). Location of seismic profiles is shown by the black lines, and dark blue roman numerals are the indexes of the geotransects (names are given in the Fig. 1). Lambert Azimuthal Equal Area projection, central meridian 130°E

Fig. 4. Crustal gravity model along the North Laptev Geotransect I. Compiled using results by Drachev et al. (2017). Note: vertical scales of the gravity charts in this figure and in Figures 5, 7, 9-15 are different.

Fig. 5. Kotel'nyi Island—Lomonosov Ridge Geotransect II: Initial gravity models of the Arctic-2007 profile by Poselov et al. (2012a): (a), based on the seismic refraction data; (b), model reproducing gravity model by Poselov et al. (2012a).

Fig. 6. Fragment of the MAGE A7 MCS profile crossing conjugation zone between the New Siberian Shelf and the Lomonosov Ridge and illustrating the presence of package of discontinuous reflectors in the middle of the section that we interpreted as moderately deformed sedimentary rocks. The seismic record is from Piskarev et al. (2016).

Fig. 7. Kotel'nyi Island—Lomonosov Ridge Geotransect II: Gravity forward models based of the Arctic-2007 refraction data by Poselov et al. (2012a) and our interpretation of the MCS A7 profile. (a), starting model; (b), final model. White lines in (b) show seismic boundaries from (a) to highlight differences between the two models.

Fig. 8. Fragment of the ION RU2-2050 MCS profile crossing the late Mesozoic compressional deformation front south of the De Long Islands (modified from Nikishin et al., 2014). The imbricated tectonic basement is interpreted to be composed of lower crust rocks or serpentinised ultramafic rocks representing formerly exhumed upper mantle below the used-to-be North Chukchi Basin.

Fig. 9. Indigirka Bay—Makarov Basin Geotransect III: Gravity forward models of the LARGE 8901 MCS profile utilizing geologic interpretation by Drachev (2011). (a), starting model; (b), final model. Location of the profile is given in Figs 1-3.

Fig. 10. Indigirka Bay—Makarov Basin Geotransect III: Initial gravity model of the Transarctic 89-91 refraction profile utilizing a refraction model by Lebedeva-Ivanova et al. (2011) and seismic reflection horizons derived from the MCS profile Arctic 2011-59 (Piskarev et al., 2016).

Fig. 11. Indigirka Bay—Makarov Basin Geotransect III: Final gravity forward models of the Transarctic 89-91 refraction profile; (a), model with a thin lower crust beneath the continental slope depocenter; (b), model with a body of exhumed mantle beneath the depocenter. White lines in (b) show seismic boundaries from (a) to highlight differences between the two models.

Fig. 12. Chukotka Peninsula—Mendeleev Ridge Geotransect IV: Gravity forward models of the 5-AR and Arctic-2005 refraction and reflection profiles by Sakulina et al. (2011) and Poselov et al. (2012a) correspondingly.

Fig. 13. Chukotka Peninsula—Mendeleev Ridge Geotransect IV: Gravity forward models of the 5-AR and Arctic-2005 refraction and reflection profiles based on our interpretation of the 5-AR MCS profile from Nikishin et al. (2017); (a), Starting model utilizing seismic refraction (crust) and reflection (top basement and intra-sediment horizons) data; (b), final model.

Fig. 14. Mendeleev Ridge—Chukchi Plateau Geotransect V: Gravity forward models of the Arctic-2012 refraction model by Kashubin et al. (2016).

Fig. 15. Mendeleev Ridge—Chukchi Plateau Geotransect V: Gravity forward models of the Arctic-2012 refraction and reflection profiles based on our interpretation of the MCS-3 profile from Piskarev et al. (2016). (a), starting model utilizing seismic refraction (crust) and reflection (top basement and intra-sediment horizons) data; (b), final model. White lines in (b) show seismic boundaries from (a) to highlight differences between the two models.

Fig. 16. Interpreted composite migrated MAGE seismic profile A9 illustrating the presence of moderately deformed sedimentary accumulation between two frontal thrusts, an inferred remnant of the Paleo-Siberian passive continental margin (modified from Drachev and Shkarubo, 2018).

Fig. 17. Reconstruction to be completed…

Fig. 18. Magnetic data and plate tectonic reconstruction. (a) Map showing main crustal domains superimposed on the magnetic field of the ESAS and adjacent regions (Getech grid based on Verhoef et al. 1996). Tectonic boundaries of the domains were updated using results of our study. The black Arabic numerals denote: 1, North Wrangel and South De Long blocks: inferred fragments of Neoproterozoic fold belt; 2, Northern De Long Massif and Chukchi Borderland: inferred fragment of Arctic mid-Palaeozoic fold belt; 3, Lomonosov Ridge (microcontinent): detached fragments of Neoproterozoic, late Palaeozoic and Mesozoic fold belts; 4, Kotel'nyi cratonic terrane; 5, Verkhoyansk late Mesozoic Fold Belt developed over the Paleo-Siberian margin; 6, Chukotka-Wrangel Fold Belt developed over the Arctic Alaska – Chukotka Microcontinent; 7, Western Chukotka Fold Belt developed over the hyperextended North Chukchi Basin; 8, Kular-Nera-Polousnyi Turbidite Belt and its offshore

extent; 9, West Laptev zone of hyperextension (including exhumed mantle); 10, deformed sedimentary basin between the Lomonosov Ridge and De Long Massif (based on MCS A7 profile); 11, Amerasia Basin margins underlain by hyperextended continental crust and exhumed mantle; 12, Makarov Oceanic Basin; 13, Alpha-Mendeleev (High Arctic) Large Igneous Province (HALIP); 14, Eurasia Oceanic Basin; 15, South Anyi-Oloi Suture Zone. The bold capital letters A to D denote major positive anomalies related to the dismembered Bennett-Borrovia microcontinent.

(b) Provisional reconstruction of the Bennett-Borrovia microcontinent based on the magnetic pattern of crustal blocks. Blue dashed contours show original position of the blocks as per (a) map. Grey arrows show applied rotations and translations. Blue bold letters denote the following crustal blocks: K, Kotel'nyi; DL, De Long, ChP, Chukchi Plateau; WCh, Wrangel-Chukotka. The WCh block remained fixed.