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Arctic Ocean Mega Project: Paper 3 - Mesozoic to Cenozoic geological evolution

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ABSTRACT

We present an atlas of paleogeographic and paleotectonic maps which documents major events in the Arctic for 0–157 Ma. We demonstrate that the Mendeleev Ridge has a continental basement. The following chronology of events in the history of the Arctic Ocean is proposed: (1) Jurassic: continental rifting in the area of the Sverdrup-Banks basins and in the area of the present-day Canada Basin; a system of continental-margin volcanic belts formed in the region of Chukotka and the Verkhoyansk-Omolon; (2) Berriasian-Barremian: formation of the continental-margin Verkhoyansk-Chukotka Orogen; fast opening of Canada Basin (~133–125 Ma); (3) Aptian-Albian: formation of continental igneous provinces, rifting and magmatism in the area of the Alpha-Mendeleev ridges; rifting in the Ust'-Lena, Anisin, North-Chukchi, Podvodnikov and Toll basins; (4) Cenomanian-Campanian: intraplate magmatism in the area of the Alpha-Mendeleev ridges; (5) Campanian-Maastrichtian: a likely start of compressional deformations in the area of the Chukchi Sea; (6) Paleocene: formation of the continental-margin orogen; continental rifting along the present-day Eurasia Basin and the Ust'-Lena Basin; (7) Early-Middle Eocene: onset of opening of the Eurasia Basin started; (8) Middle-Late Eocene: a major restructuring of paleogeography of the Arctic took place at ca. 45 Ma with subaerial emergence of the Barents and Kara Sea shelves and onset of ultra-slow spreading of the Gakkel Ridge, and start of the epoch of formation of normal and strike-slip faults on the Lomonosov and Alpha-Mendeleev ridges and on the shelves of the Chukchi and East Siberian seas. Paleoclimate is discussed in connection with changes in the paleogeography.

1. Introduction

Key information on concepts of the geological and tectonic history of the Arctic is presented in many studies (e.g., Grantz et al., 2011b, 2011a; Piskarev et al., 2019; Stein, 2008). Our objective is to analyze the onshore and offshore records within these time intervals and to develop paleogeographical and paleotectonic maps for different intervals of the geological history of the entire Arctic. Similar efforts have been made by many authors (e.g., Alvey et al., 2008; Hutchinson et al., 2017; Jokat and Ickrath, 2015; Kuzmichev, 2009; Laverov et al., 2013; Lawver et al., 2015, 2011; Lobkovsky, 2016; Metelkin et al., 2016; Miller et al., 2018b, 2018a; Miller and Verzhbitsky, 2009; Nikishin et al., 2017a, 2017b, 2015; Petrov et al., 2016; Petrov, 2017; Piskarev et al., 2019; Shephard et al., 2013; Shipilov, 2016; Sømme et al., 2018; Vernikovsky et al., 2013; Weigelt et al., 2014; Ziegler, 1989, 1988). The main challenge to develop these models resides in the lack of understanding of the structure of the Amerasia Basin. Two main groups of models for the tectonic history of the Amerasia Basin exist. The first group of models considers a rotational hypothesis in which the Amerasia Basin opened as an integral structure with a pole of rotation in the south and a transform segment along the Lomonosov Ridge (Evangelatos and Mosher, 2016; Grantz et al., 2011b, 2011a; Shephard et al., 2013). The South Anyui Ocean closed concurrently with formation of the accretionary-collisional Verkhoyansk-Chukotka orogen (Grantz et al., 2011b, 2011a; Piepjohn et al.,

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2018). The second group of models assumes that Canada Basin formed independently, while the region of the Alpha-Mendeleev ridges and the Podvodnikov Basin formed in a separate tectonic environment and at a different time than Canada Basin (Alvey et al., 2008; Doré et al., 2016; Hutchinson et al., 2017; Lobkovsky, 2016; Miller and Verzhbitsky, 2009; Nikishin et al., 2017a, 2017b; Nikishin et al., 2015; Shipilov, 2016). The models within each group may also differ significantly.

We refrain here from a discussion of the structure and geological history of Canada Basin. The new data have been well documented (Chian et al., 2016; Chian and Lebedeva-Ivanova, 2015; Coakley et al., 2016; Coakley and Ilhan, 2012; Hutchinson et al., 2017; Mosher et al., 2012). The formation time of Canada Basin is debatable and different models for the formation of this basin from Early Jurassic to Late Cretaceous have been proposed (Coakley et al., 2016; Dixon et al., 2019; Grantz et al., 2011a, 2011b; Houseknecht, 2019; Hutchinson et al., 2017; Miller et al., 2018b, 2018a; Mosher et al., 2012; Pease et al., 2014; Toro et al., 2016). In accordance with the model of Helwig et al. (2011), the breakup unconformity has an age ca. 133 Ma (the Valanginian/Hauterivian boundary) and oceanic crust was formed prior to mid-Aptian (ca. 117 Ma). This model is based on the notion that the rift/postrift boundary in the Sverdrup Basin has an age of about 135–130 Ma, while this boundary should corresponds to the breakup unconformity in Canada Basin (Hadlari et al., 2016). New data for Canada Basin (Chian et al., 2016; Coakley et al., 2016; Hutchinson et al., 2017; Mosher et al., 2012) show that its opening took place under cool mantle conditions.

A key challenge in the geological history of the Arctic Ocean is the issue of the basement of the Alpha-Mendeleev ridges (see Paper 2). In all models ridges are volcanic edifices, though the type of crust unambiguously identified upon which this volcanism did took place has not yet been identified (Brumley, 2014; Bruvoll et al., 2012, 2010; Kashubin et al., 2018, 2013). Our new data are indicative of a continental nature of the Alpha-Mendeleev terrane. Just after the completion of the Verkhoyansk-Chukotka Orogeny at ca. 125 Ma, formation of basaltic igneous provinces started throughout the Arctic. Basaltic provinces are well known on the Ellesmere Island, on Svalbard, on Franz Josef Land, and on the De Long Islands (Corfu et al., 2013; Drachev and Saunders, 2006). We identified a new hypothetical igneous province north of Wrangel Island (see Paper 2). These data show that the Alpha-Mendeleev Igneous Province was surrounded by igneous provinces on all sides (except the area of Canada Basin). The available data show that volcanism in the Alpha-Mendeleev Province also started at ca. 127–110 Ma. This implies that within the framework of the available data, an approximately synchronous onset of volcanism in a large area can be assumed. Our analyses of seismic lines show that the Arlis Gap Buried High is a continuation of the structure of the Mendeleev Ridge (see Paper 2). Our data also show that most part of the Makarov Basin's basement is a continuation of the structure of the Alpha Ridge. A similar conclusion is presented in Evangelatos and Mosher (2016). Summing up these data, it appears that the Alpha-Mendeleev Igneous Province started to form at the eastern margin of the Lomonosov Ridge. That is, the Alpha-Mendeleev Igneous Province started to form at ca. 125 Ma as a volcanic continental margin. This hypothesis is in good agreement with inferences from analysis of gravity and magnetic anomalies (Gaina et al., 2011; Oakey and Saltus, 2016).This hypothesis was mentioned in Dove et al. (2010) as one of the probable concepts. The Alpha-Mendeleev Igneous Province can be compared with the Kerguelen Plateau (Bénard et al., 2010; Borissova et al., 2003) in the Indian Ocean (Nikishin et al., 2015; Oakey and Saltus, 2016) or with the Vøring Plateau on the continental margin of Norway in the North Atlantic (see also Abdelmalak et al. (2016) and Omosanya et al. (2016)).

In 2014 and 2016, rock samples were taken with the use of a specially equipped submarine on three scarps on the Mendeleev Ridge (Skolotnev et al., 2019, 2017). As a result, three sections were studied, which are composed mainly of sedimentary rocks with Paleozoic fauna. These sections are pierced by basalt dykes and sills of Early Cretaceous age (110–115 Ma) (Petrov, 2017; Skolotnev et al., 2019, 2017). These data suggest that the Mendeleev Ridge is a continental terrane that experienced a strong extension and magmatism. Most recent geometrical reconstructions of the Arctic Ocean history with synchronous opening of the Amerasia Basin and closure of the South Anyui Ocean are probably not correct due to existence of a large-size continental Alpha-Mendeleev terrane which does not comply with such a model.

2. Data and methods

The bulk of our new data is presented in Papers 1 and 2. This applies in particular to the revised seismostratigraphy and tectonostratigraphy of the Arctic Ocean. In this paper, we aim to provide a synthesis of all our and published tectonostratigraphy data of the ocean jointly with the paleogeographic and paleotectonic history of the onshore regions surrounding the ocean with the objective to create a model for the geological history of the area of the Arctic Ocean in the Mesozoic and Cenozoic. We will also utilize published data on the geology of the onshore. We used all published data on detrital zircon ages from samples from different places to reconstruct a paleogeography (our zircon age data include also a number of unpublished results and data in industrial reports (Nikishin et al., in preparation)). We used G-Plates technology for paleotectonic restorations. By doing so, we are presenting a new atlas of the geological history of the Arctic Ocean.

3. Paleogeographic and paleotectonic history of the Arctic Ocean in the Mesozoic and Cenozoic

3.1. *Geometrical reconstructions of the Arctic region*

Many kinematic reconstructions of the geography of the Arctic Ocean exist. Global reconstructions with a focus on the Arctic region are widely known (e.g., Alvey et al., 2008; Golonka, 2011; Lawver et al., 2015, 2011; Shephard et al., 2013). We made kinematic reconstructions of the Arctic region taking into consideration that the Alpha-Mendeleev Terrane has a continental crust and was of great importance in the opening of the ocean (Freiman et al., 2018; Nikishin et al., 2015, 2017a, 2017b).

3.2. *Structure and age of the Pre Mesozoic basement of the region of the Arctic Ocean*

We constructed a map of basement age of the Arctic on a reconstruction for the Permian/Triassic boundary (Fig. 1). An area with Neoproterozoic-Cambrian basement (ca. 650–520 Ma) is wide-spread. These areas are usually named Timanides (Gee et al., 2006; Hoiland et al., 2018; Kuznetsov et al., 2010; Miller et al., 2018b, 2018a; Nikishin et al., 2015). Recent data show areas with a Timanian basement including Timan-Pechora Basin (Gee et al., 2006; Kuznetsov et al., 2010), Novaya Zemlya (Gee et al., 2006; Kuznetsov et al., 2010; Pease and Scott, 2009), the Severnaya Zemlya and Izvestiy Tsik Islands (the North Kara Sea region) (Gee et al., 2006; Nikishin et al., 2017b), the Zhokhov Island of the New Siberian Island (Akinin et al., 2015), the Wrangel Island in the Chukchi Sea (Gorodinsky, 1999a; Gottlieb et al., 2018; Kos'ko et al., 1993; Luchitskaya et al., 2017), the northern part of Chukotka (Gottlieb et al., 2018), and Seward Terrane on Alaska (Hoiland et al., 2018). A large number of detrital zircons with ages of ca. 650–520 Ma are encountered in Paleozoic sediments of the Arctic (e.g., Ershova et al., 2018, 2016a, 2016b, 2015b, 2015a; Gottlieb et al., 2014; Miller et al., 2018b, 2018a; V. A. Nikishin et al., 2017; Pease et al., 2014). It follows from this information that a large-size composite terrane did have a crust with an age of about 650–520 Ma (Kuznetsov et al., 2010; Miller et al., 2018b, 2018a; Nikishin et al., 2015; Pease et al., 2014). Existence of such a continental landmass was assumed by N. Shatskiy (Shatskiy, 1935) who named it the Hyperboreal Continent. This idea was developed by L. Zonenshain who named this continent

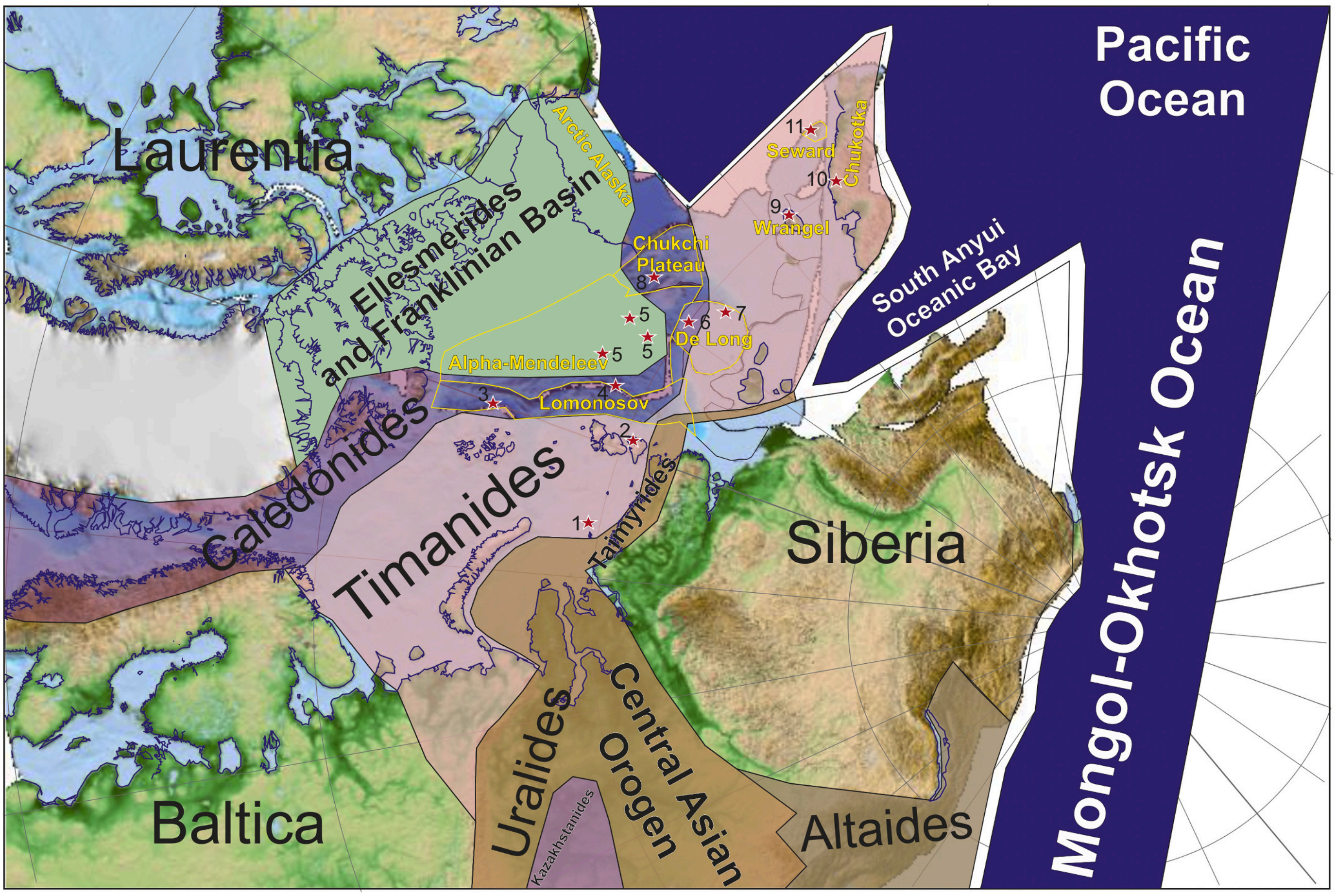

Fig. 1. Main basement provinces of the Arctic region compiled using kinematic restoration for Permian/Triassic transition (~250 Ma). Some key references: 1 - V. A. Nikishin et al., 2017; 2 - V. A. Nikishin et al., 2017; 3 - Knudsen et al., 2018; 4 - Rekant et al., 2019; 5 - Skolotnev et al., 2019; 6 - Ershova et al., 2016a; Prokopiev et al., 2018; 7 - Akinin et al., 2015; 8 - Brumley et al., 2015; O'Brien et al., 2016; 9 - Gottlieb et al., 2018; Luchitskaya et al., 2017; 10 - Gottlieb et al., 2018; 11 - Hoiland et al., 2018.

Arctida (Laverov et al., 2013; Zonenshain et al., 1990). A. Embry (e.g., 2011) called approximately this continental landmass Crockerland.

The classical belt of the Caledonides is known in the North Atlantic region. The Caledonides of Scandinavia, East Greenland and Svalbard belong to them (Gee et al., 2006; Lawver et al., 2011; Ziegler, 1989, 1988). The Caledonian Pearya Terrane on the Ellesmere Island is also well-known (Estrada et al., 2018; Gee et al., 2006). All these Caledonian terranes composed previously a single collisional belt (Ziegler, 1989, 1988). In recent years, rock samples were taken from subsea scarps of the Lomonosov Ridge (Knudsen et al., 2018; Rekant et al., 2019) and of the Chukchi Plateau (Brumley et al., 2015; O'Brien et al., 2016). It is assumed that these samples are indicative of the Caledonian basement. On the Henrietta and Jeanette Islands at the north of the New Siberian Islands, an Early Paleozoic volcanic arc is described and presence of Caledonides is assumed (Chernova et al., 2017; Ershova et al., 2016a, 2016b; Prokopiev et al., 2018). Caledonides are possible on Alaska (Hoiland et al., 2018). It has been assumed that a belt of Caledonides crossed the Arctic from the North Atlantic to Alaska, though accurate geometry of this orogen is not clear yet (Brumley et al., 2015; Gee et al., 2006; Miller et al., 2018b, 2018a; Nikishin et al., 2015; O'Brien et al., 2016; Ziegler, 1989, 1988).

The Ellesmere Orogen is well known for the northern part of the Canadian islands. The main collisional processes took place at the end of the Devonian and beginning of the Carboniferous (Colpron and Nelson, 2011; Golonka, 2011; Hadlari et al., 2014; Kumar et al., 2011; Lane, 2007; Piepjohn et al., 2015; Rippinton et al., 2010; Ziegler, 1989, 1988). The Ellesmere Orogen is composed mainly of Neoproterozoic-Devonian or Cambrian-Devonian sedimentary deposits (Hadlari et al., 2014; Kumar et al., 2011; Morrell, 1995). The so-called Franklinian Basin previously existed in its place (Embry et al., 2018; Harrison and Brent, 2005; Kumar et al., 2011; Morrell, 1995). This basin probably formed at the edge of the American continent (Cocks and Torsvik, 2011; Hadlari et al., 2014). After completion of the Ellesmere Orogeny, major rift basins of the type of Sverdrup Basin and Hanna Trough formed in the Early Carboniferous (e.g., Galloway et al., 2018; Kumar et al., 2011).

Rock samples were taken on three slopes of the Mendeleev Ridge (Skolotnev et al., 2019, 2017). The slopes samples are composed mainly of shallow-water carbonates and sandstones which form a folded structure. Late Ordovician-Silurian and Middle-Late Devonian fauna are found in the rocks. The Franklinian Basin probably was also situated within the Mendeleev Ridge in the Paleozoic. In this case, we assume that the continental margin of the American (Laurentia) continent forms the basement of the Mendeleev Ridge.

On Taimyr, the Paleozoic Taimyr Orogen is situated (Vernikovsky, 1996). In recent years many new data were obtained on the basis of studying the Paleozoic orogen itself (Ershova et al., 2016a, 2016b; Gee et al., 2006; Khudoley et al., 2018; Makariev, 2013; Pease, 2011; Pease and Scott, 2009; Proskurnin et al., 2014; Vernikovsky and Vernikovskaya, 2001; Zhang et al., 2013, 2016) and its Taimyr Foredeep in the South Taimyr zone (Afanasenkov et al., 2016; Khudoley et al., 2018; Pogrebitsky, 1971; Zhang et al., 2016, 2013). New data also were presented for the synorogenic molasse basins on islands of the Novaya

Zemlya Archipelago (Ershova et al., 2015b, 2015a; V. A. Nikishin et al., 2017). New seismic lines have been acquired for the shelf of the North Kara Basin on which the northern boundary of the Taimyr Orogen is observed (Malyshev et al., 2012; Nikishin et al., 2015). Many new seismic lines have also been acquired for the Yenisei-Khatanga Basin that is situated south of the Taimyr Orogen (Afanasenkov et al., 2016). Some seismic lines cross the South Taimyr zone (Late Paleozoic foredeep basin) (Afanasenkov et al., 2016). These data were synthesized by Nikishin et al. (2015, 2010) and Afanasenkov et al. (2016). Syncollisional granite intrusions in the northern part of Taimyr have an age ranging from 344 to 275 Ma (from the Visean to the end of Early Permian) (Khudoley et al., 2018; Pease, 2011; Vernikovsky, 1996). The Late Carboniferous – Early Permian Akhmatov Formation of the Bolshevik Island (the island of the Severnaya Zemlya Archipelago) forms a synorogenic molasse basin. Detrital zircons in sandstones have peak ages in the range of about 350–306 Ma (V. A. Nikishin et al., 2017). Carboniferous sandstones of the Novaya Zemlya islands have peak ages of detrital sandstones ca. 323 Ma (Nikishin et al., 2016). The possible provenance of these sandstones involved the Taimyr Orogen. Within the North Kara Basin, a distinct angular unconformity is observed on seismic lines which is dated as approximately the Devonian/Carboniferous boundary (Malyshev et al., 2012; Nikishin et al., 2015; Nikishin, 2013). On seismic lines for the South Taimyr zone, an angular unconformity is observed that is situated approximately within the Early Carboniferous. This unconformity corresponds to the onset of formation of the Taimyr Foredeep Basin (Afanasenkov et al., 2016). The age spectra of detrital zircons for Carboniferous deposits of the Taimyr Foredeep Basin (Zhang et al., 2013) and for the Carboniferous of Novaya Zemlya practically coincide, providing evidence for a single provenance of detrital material. In the area of the northern part of the Barents Megabasin, clinoforms and turbidite complexes are detected at the level of the Early Carboniferous with material transport from the side of the North Kara Basin and Taimyr (Nikishin et al., 2016; Startseva, 2018). As early as the Early Carboniferous, sediment transport from the Taimyr Orogen took place both to the north of the orogen (the area of the Barents Megabasin) and to the south of it (the area of the Taimyr Foredeep Basin). The main collision in the area of Taimyr may be thought to start at approximately the Devonian/Carboniferous boundary and in the Early Carboniferous (Nikishin et al., 2015). Collisional deformations continued until the end of the Early Permian (Khudoley et al., 2018). The main collision on Taimyr was in the Early Permian (Cocks and Torsvik, 2011) or in the Carboniferous (Ershova et al., 2016a, 2016b).

In the west, the Taimyr Orogen is overlain by the sedimentary cover of the South Kara Basin. No data are available for its structure and age. Data from commercial drilling demonstrated that the Lower Jurassic sedimentary cover overlies the basement. On the Novaya Zemlya islands, the change of carbonate sedimentation for clays and clastics took place at the Carboniferous/Permian boundary (Korago et al., 1992). In the Permian, the Novaya Zemlya area probably experiences subsidence as a foredeep basin. Upper Permian deposits are represented by alluvial and deltaic complexes. Our data on ages of Upper Permian detrital sandstones show that ages within the range of 280 Ma to 360 Ma dominate (Nikishin et al., in preparation). Transport of sediments in the Permian took place from the side of the South Kara Basin. Hence it follows that a collisional orogen was formed at the site of the South Kara Basin in the Permian. It merged the Central Asian Orogen (the Uralides) and the Taimyr Orogen into a single belt. We named the Late Paleozoic orogen in the area of the present-day South Kara Basin the Baydaratskiy Orogen (Nikishin et al., 2015).

In the east, the Taimyr Orogen is buried under shelf complexes of the Laptev Sea and it is unknown where its eastern continuation is situated. The Taimyr Orogen was probably situated on the Laptev Sea Shelf in the form of the Belkovsky collisional orogen; while further eastward it transited into the South Chukotka active continental margin of the Pacific Ocean (Nikishin et al., 2015). Over recent years, many data were collected on ages of detrital zircons for different islands of the Arctic, for Taimyr, and for Chukotka (Danukalova and Kuzmichev, 2018; Ershova et al., 2015b, 2015a; V. A. Nikishin et al., 2017). In the Late Devonian, Carboniferous and Early Permian, a deep trough was formed at the western edge of the New Siberian Islands (Danukalova et al., 2017, 2014; Ershova et al., 2015b, 2015a). Analysis of ages of detrital zircons in Devonian deposits of the New Siberian Islands, Severnaya Zemlya islands and Wrangel Island demonstrates that they have a similar character and had a single provenance in the form of the Laurentia-Baltica (Laurussia) paleocontinent (Ershova et al., 2015b, 2015a). A similar situation occurred in the Early Carboniferous as well (at least, in the Tournaisian). A sharp change in the source area of clastic material on the Belkovsky Island took place in the Permian with zircons ages ca. 284–298 Ma became strongly prevalent (Danukalova et al., 2017; Ershova et al., 2015b, 2015a; Pease et al., 2014). It is assumed that the Taimyr Orogen became the source area of clastic material (Danukalova et al., 2017; Ershova et al., 2015b, 2015a; Pease et al., 2014). In the Devonian, a hypothetical ocean existed in the place of the Paleozoic Taimyr Orogen (Khudoley et al., 2018; Pease, 2011; Vernikovsky, 1996). Hence, the areas of the New Siberian Islands and the Severnaya Zemlya Archipelago were situated north of this ocean (in the present-day coordinates). The Siberian continent was situated south of the mentioned ocean. It is conceivable that the collision of the Siberian continent with the Laurentia-Baltica (Laurussia) continent started approximately at the Devonian/Carboniferous boundary and was completed in the Permian. At that time, a marginal flexural basin was forming in the area of the Belkovsky Island for the Belkovsky collisional orogen in the Late Paleozoic. This foredeep was situated north-east of the orogen in present-day coordinates.

On Chukotka, Early Carboniferous subduction-related granites with ages of 352–359 Ma are established at different places (Luchitskaya et al., 2015). They could form a continental-marginal igneous belt of an active continental margin. It should also be noted that a large number of detrital zircons of Carboniferous and Permian age are encountered in Late Jurassic and Early Cretaceous sandstones of Chukotka (Vatrushkina, 2018). It is likely that the Taimyr Orogen transformed in the east into the active continental margin of Chukotka in the Late Paleozoic.

Summing up the data on probable ages of basement in the Arctic region, the following preliminary conclusions can be made: (1) basement is formed by orogens of Timanian, Caledonian and Late Paleozoic ages; (2) in the Cambrian, the Timanides became a part of the Baltica paleocontinent (Gee et al., 2006; Hoiland et al., 2018; Kuznetsov et al., 2010; Miller et al., 2018b, 2018a; Nikishin et al., 2015, 1996); (3) the Caledonian orogen was formed during the collision of Laurentia and Baltica (together with the Timanides); (4) the belt of Taimyrides together with the Ural Orogen and the Central Asian Orogen were formed during the collision of the Siberian paleocontinent and the Laurentia-Baltica (Laurussia) continent starting approximately from the Devonian/Carboniferous boundary (Nikishin et al., 2015); (5) the nature of the Ellesmere Orogeny is unclear; it was probably synchronous with the Taimyr Orogeny and was caused by the collision of the Siberian paleocontinent and the Laurentia-Baltica (Laurussia) continent.

3.3. *Late Jurassic history of the Arctic*

According to our model, the history of formation of the Arctic Ocean started from the Jurassic. That is why we will begin our discussion of this process from this time onward. At first we compiled a paleogeographical map of the Arctic for the Late Jurassic on the present-day geographic framework (Fig. 2). For the Russian part of the Arctic Ocean, we utilized our interpretation of federal and commercial seismic lines. Seismostratigraphy was tied to all available offshore boreholes. These data have been presented in the form of PhD theses (Mordasova, 2018; Nikishin, 2013; Startseva, 2018; Suslova, 2013). For the Norwegian Barents Sea, published data were utilized (e.g., Smelror et al., 2009; Torsvik et al., 2002; Torsvik and Cocks, 2017; Ziegler, 1988) along with our results of seismic data interpretation. For the European onshore and Siberia, the

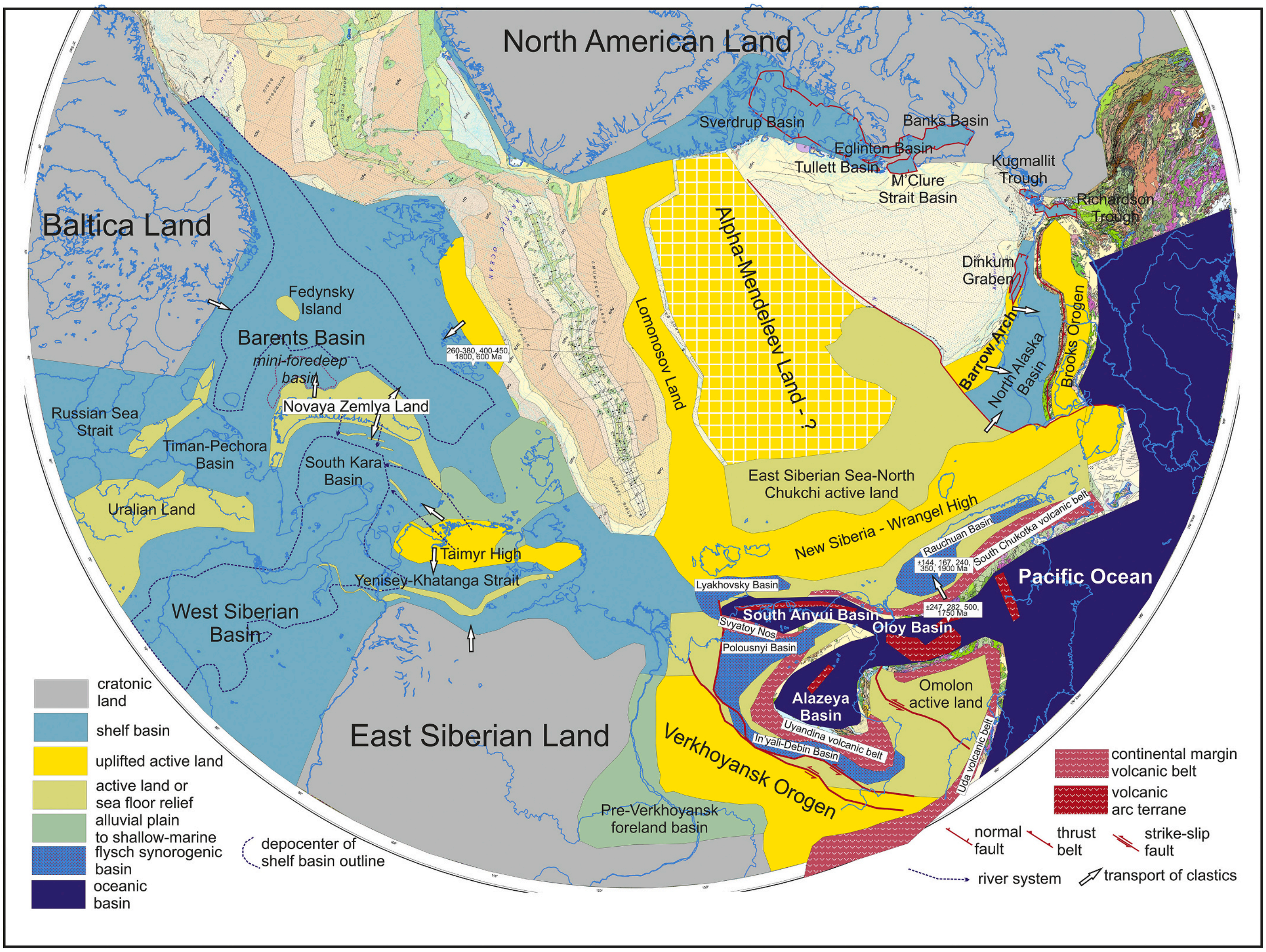

Fig. 2. Paleogeographic map of the Arctic for the Late Jurassic, Kimmeridgian to Tithonian (157–145 Ma), on the present-day geographic framework. Geographic base map is Geological map of the Arctic (Harrison et al., 2011). Ages in the white boxes – ages of peaks of detrital zircons (our data).

basis was the study of Vinogradov (1968) and numerous recent publications (e.g., Kontorovich et al., 2013). For North America, published data were utilized (e.g., Embry and Beauchamp, 2008; Houseknecht, 2019). For islands of the Russian Arctic, data of our field work were used also.

In the Late Jurassic, a single shelf basin existed which included the Barents Sea Basin, Timan-Pechora Basin, South Kara Basin, North Kara Basin, West Siberian Basin, Yenisey-Khatanga Basin, and Russian Sea Strait (Fig. 2). A system of uplifts was forming in this shelf sea. Interpretation of seismic data shows that transport of clastic material took place periodically from Novaya Zemlya toward the Barents and South Kara Basins (Nikishin, 2013; Suslova, 2013). Material was transported from the side of Taimyr in the South Kara Basin. In Upper Jurassic rocks of Franz Josef Land, peaks of detrital zircon ages have the following values: 260–380 Ma, 400–450 Ma, 1800 Ma, 600 Ma (Nikishin et al., in preparation). The abundance of zircons of the "Uralian" and "Caledonian" ages is indicative of the fact that an onshore landmass composed of Paleozoic orogens existed north of Franz Josef Land (in the present-day coordinates).

A system of inversion anticlines is present above Permo-Triassic rifts in the Yenisey-Khatanga Basin (e.g., Afanasenkov et al., 2016; Kontorovich et al., 2013; Unger et al., 2017). These anticlines were formed slowly in a compressional environment from the Callovian to the Aptian (Unger et al., 2017). Similar anticlinal folds were formed from the Callovian to the Aptian in the South Kara Basin (Nikishin et al., 2015; Nikishin, 2013) and in the West Siberian Basin (Kontorovich et al., 2013). In the Barents Sea, periodic uplift of the Fedynsky High took place (our seismic data). It is assumed that uplift of the Urals (Kontorovich et al., 2013) and Timan (Vinogradov, 1968) took place. It should be noted that from the Callovian until the Aptian, the main phase of folding and collision in the Verkhoyansk-Chukotka region of the Russian Far East took place (Parfenov, 1991, 1984; Parfenov and Kuzmin, 2001). The formation of compressional anticlines in the area of the Barents and Kara Seas and in West Siberia was probably associated with the Verkhoyansk-Chukotka Orogeny.

The Late Jurassic paleogeography and paleotectonics of the Russian Far East is a highly debatable issue (e.g., Amato et al., 2015; Didenko et al., 2002; Drachev, 2016; Kuzmichev, 2009; Miller et al., 2018a, 2018b, 2002; Parfenov, 1991, 1984; Parfenov and Natal'in, 1986; Sokolov et al., 2015; Toro et al., 2016). Our main hypothesis is that in the Late Jurassic, a subduction continental-marginal volcanic belt between Asia and the Pacific Ocean existed along the entire Far Eastern margin of Russia. Individual fragments of this belt have been known for a long time. In the south, the Uda (or Uda-Murgal) Late Jurassic – Neocomian volcanic belt is identified under the Okhotsk-Chukotka Cretaceous volcanic belt (Akinin, 2012; Miller et al., 2002; Parfenov, 1984; Tikhomirov, 2018; Toro et al., 2016). In the north, the Uda volcanic belt transits into the Oloy volcanic belt that is superimposed onto the edge of the Omolon Massif (Tikhomirov, 2018; Toro et al., 2016). On the northwestern continuation of the Oloy belt, the well-known Uyandina-Yasachnaya volcanic belt of Late Jurassic age is situated (Natapov and Surmilova, 1992; Parfenov and Kuzmin, 2001; Toro et al., 2016). New data show that the Uyandina-Yasachnaya volcanic belt is synchronous in age with the Main (Kolyma) granitoid belt of the Chersky Range and that it was a single continental-marginal igneous belt with subduction directed under the Asian continent (Didenko et al., 2002; Toro et al., 2016; Zonenshain et al., 1990; Prokopiev, personal communications). In the South of Chukotka, Tikhomirov (2018) identified the South Chukotka subduction-related volcanic belt with isotopic ages of volcanites at ca. 150–130 Ma, and with Tithonian-Berriasian paleontological ages (Tikhomirov, 2018; Vatrushkina, 2018). New data show that volcanic material (including pebbles) is present in Upper Jurassic – Berriasian sandstones of Chukotka for the Rauchuan Basin (Vatrushkina, 2018). Ages of detrital zircons have maxima in the intervals of 130–152 Ma and 152–190 Ma whereas the zircons are of igneous origin (Vatrushkina, 2018). The data for ages of detrital zircons demonstrate that a continental-marginal volcanic belt was situated along the southern edge of Chukotka in the Middle-Late Jurassic. This conclusion expressed in Tikhomirov (2018) contradicts the earlier concepts that a passive continental margin existed in the south of Chukotka in the Jurassic (e.g., Sokolov et al., 2015).

Along the southern edge in the west of the South Anyui Suture Zone described in Kuzmichev (2009), Sokolov et al. (2015), Amato et al. (2015), Toro et al. (2016), the Svyatoy Nos Zone is identified, which is considered as a Late Jurassic, Tithonian volcanic arc (Natapov and Surmilova, 1992). We assume that the Svyatoy Nos volcanic belt is a continuation of the continental-marginal Uyandina-Yasachnaya volcanic belt.

In the Late Jurassic, a system of sedimentary basins with accumulation of deep-water sediments, including turbidites, was formed between continental-marginal volcanic belts and the continent of Asia. Such basins include the In'yali-Debin Basin in the eastern part of the Verkhoyansk Orogen (Parfenov and Kuzmin, 2001; Vinogradov, 1968), the Polousnyi Basin south of the South Anyui Orogen (Kuzmichev, 2009; Natapov and Surmilova, 1992; Toro et al., 2016; Vinogradov, 1968), the Lyakhovsky Basin north of the South Anyuy Orogen (Kuzmichev, 2009; Nikishin et al., 2015), and the Rauchuan Basin on Chukotka (Gorodinsky, 1999b, 1999a; Miller and Verzhbitsky, 2009; Vatrushkina, 2018; Vinogradov, 1968). These troughs are usually considered as foreland basins (Kuzmichev, 2009), although they are poorly studied. In any of the models, these basins were considered as having a syntectonic origin.

The time of the onset of orogeny in the Verkhoyansk Orogen is not known exactly and is believed to start approximately in the Middle-Late Jurassic (Vinogradov, 1968). From this time on, the Verkhoyansk Foredeep Basin started to form, though its Late Jurassic subsidence was limited (Vinogradov, 1968).

The Upper Jurassic is absent in the area of the New Siberian Islands and Wrangel Island (Kuzmichev, 2009; Nikitenko et al., 2017; Sokolov et al., 2017; Vinogradov, 1968). This territory is considered to have experienced *syn*-compressional uplift (Kuzmichev, 2009; Miller et al., 2018b, 2018a; Sokolov et al., 2017; Verzhbitsky et al., 2012).

For the north of Canada and Alaska, the best known Jurassic basin is the Sverdrup Basin and its coeval analogs (Embry, 2011; Embry and Beauchamp, 2008; Hadlari et al., 2016; Houseknecht and Bird, 2011; Torsvik and Cocks, 2017; Ziegler, 1988). Examination of well data showed that synrift deposits have ages from Early Jurassic (Pliensbachian) to Early Cretaceous (Valanginian) (Hadlari et al., 2016). The Valanginian/Hauterivian boundary or a boundary within the Hauterivian is interpreted as a rift/postrift boundary. In regional context, it is considered as a breakup unconformity, which corresponds to the onset of opening of the Canada Basin ca. 135–130 Ma (Hadlari et al., 2016). This conclusion is in agreement with data on the structure of Canada Basin's continental margin (Helwig et al., 2011). Jurassic-Early Cretaceous rifts are known along the entire strip of the Canada Basin's continental margin. The Tullet Basin, Eglinton Basin, Banks Basin, M'Clure Basin, Kugmallit Basin, Richardson Trough, Dinkum Graben belong to them (Harrison and Brent, 2005; Houseknecht, 2019; Houseknecht and Connors, 2016; Hutchinson et al., 2017). They are blanketed by a sedimentary cover and are poorly studied yet. An important inference is that their development preceded opening time of the Canada Basin.

In the north of Alaska, the Kingak Shale shelf formation was formed in Jurassic times (Houseknecht and Bird, 2011).

A land mass was probably preserved in the Late Jurassic at the location of the Lomonosov Ridge. The fact that transport of sedimentary matter in the Barents Basin was from the north is evidential of this. A land mass was probably preserved at the location of the Alpha-Mendeleev ridges as well. This is evidenced by the fact that in the section of the Trukshin Seamount (Mendeleev Ridge) Paleozoic deposits are overlain by Aptian or Barremian-Aptian deposits with an angular unconformity (Skolotnev et al., 2019).

We developed kinematic tectonic reconstructions of the history of the Arctic for the Mesozoic and Cenozoic within the framework of the GPlates software (Freiman et al., 2018; Nikishin et al., 2015). The reconstruction for the Late Jurassic (150 Ma) is presented in Fig. 3. We superimposed data of our paleogeography onto the geometric reconstruction. In the present-day tectonic setting of the Verkhoyansk-Chukotka region, there are two major oroclines: the Kolyma and South Anyui. The first of them – the Kolyma Loop was identified by Zonenshain et al. (1990). The South Anyui Orocline was characterized in Kuzmichev (2009). Following Kuzmichev (2009), we straightened these two oroclines for the time of formation of volcanic belts. In contrast to the Kuzmichev model, we believe that these volcanic belts were continental-margin arcs and not intraoceanic volcanic arcs. It appears that in the Late Jurassic the entire area of the Russian Far East was in the rear of an active continental margin and experienced compression from the Verkhoyansk Orogen and Chukotka Orogen to the area of the Barents-Kara Sea and Taimyr. At that time, in the north of North America, extension took place and continental rifts were formed (Embry and Beauchamp, 2008; Houseknecht, 2019; Hutchinson et al., 2017). Continental rifting occurred probably at the site of the Canada Basin as well.

3.4. Berriasian-Barremian (Neocomian) history of the Arctic

Fig. 4 presents our paleogeographical map of the Arctic for the Neocomian on the present-day geological framework. For the Barents and Kara Seas, we utilized results of our interpretation of seismic lines and of drilling data. For the Barents Sea, data of the LoCrA (Grundvåg et al., 2017; Kairanov et al., 2018; Mordasova, 2018) were also extensively used along with other data (e.g., Nikishin, 2013; Smelror et al., 2009; Startseva, 2018; Torsvik et al., 2002; Torsvik and Cocks, 2017; Ziegler, 1988). For the South Kara Basin and for West Siberia, data in Borodkin and Kurchikov (2010), Kurchikov and Borodkin (2011), Kontorovich et al. (2014) and Nikishin (2013) were used. For the European onshore and for Siberia, the basis was the study of Vinogradov (1968) along with numerous recent publications. For North America, published data were utilized (e.g., Embry and Beauchamp, 2008; Houseknecht, 2019). For islands of the Russian Arctic, data of our field work were used also.

In the Neocomian, clinoform sedimentation with progradation of the shelf edge toward the residual shelf seas prevailed in the Barents-West Siberian region (Borodkin and Kurchikov, 2010; Grundvåg et al., 2017; Kontorovich et al., 2014). We identify two major megabasins: the Barents Basin and the West Siberian Basin (together with the South Kara and Yenisey-Khatanga basins). These two megabasins were separated by the Ural-Novaya Zemlya-Taimyr belt of uplifts. Clinoforms and their strikes are well observed on seismic lines. In the Barents Megabasin, the main transport of material took place from the north and northeast (in

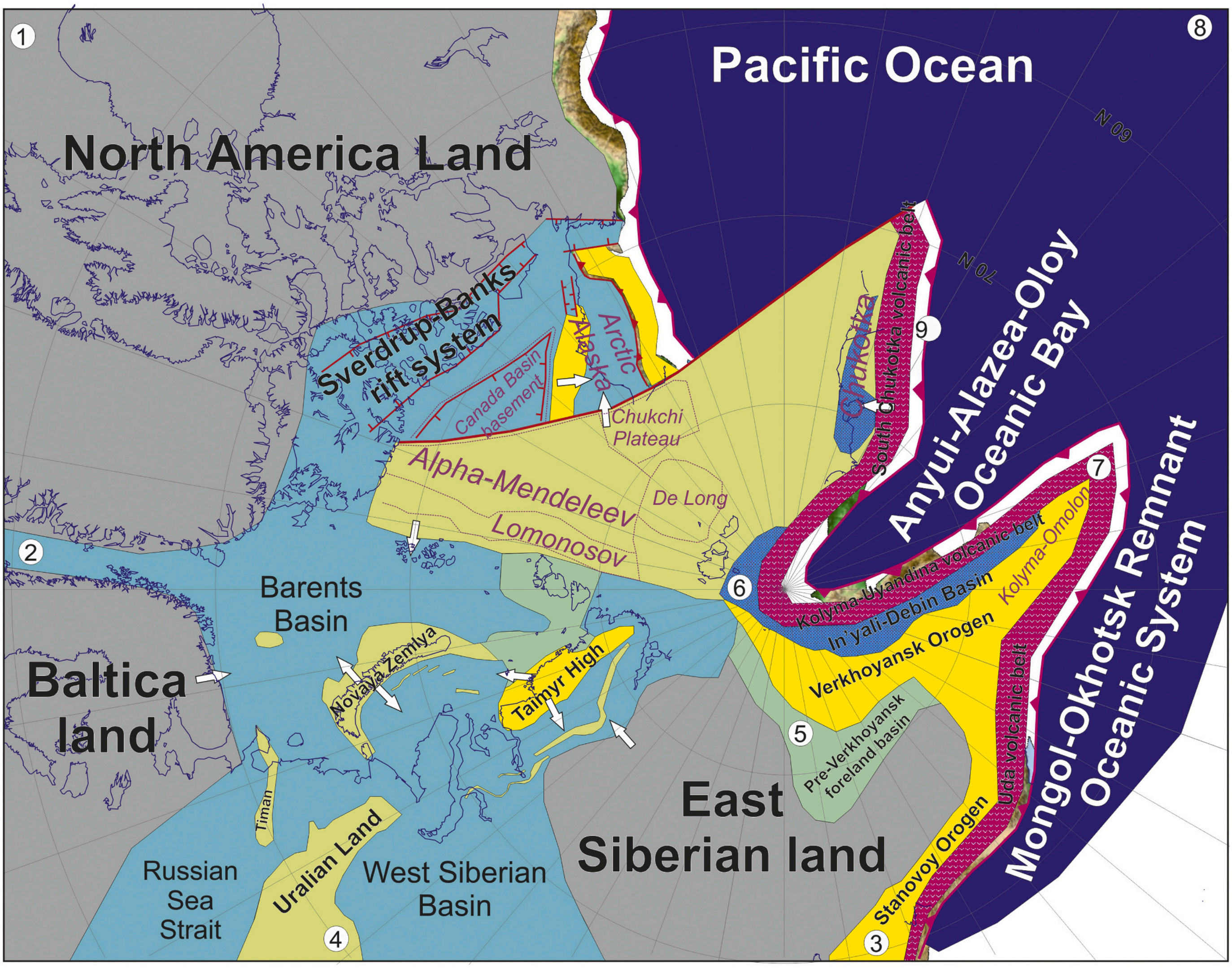

Fig. 3. Tectonic restoration of the Arctic region for the Late Jurassic, Kimmeridgian to Tithonian (157–145 Ma). Kinematic restoration for the 150 Ma. Restoration was performed using GPlates programme. Legend is similar to Fig. 2. 1 – cratonic land, 2 – shelf basin, 3 – uplifted active land, 4 – active land or sea floor relief, 5 – alluvial plain to shallow-marine, 6 – flysch synorogenic basin, 7 – continental margin volcanic belt, 8 – oceanic basin, 9 – subduction zone. Violet outlines and letters mark position of some terranes and their names. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

present-day coordinates). Sediments were partly transported from the Novaya Zemlya High. This finding is in agreement with the data in Grundvåg et al. (2017) and Mordasova (2018). Interpretation of seismic lines shows that in the Barents Megabasin, in the West Siberian, South Kara and Yenisey-Khatanga basins, many anticlinal highs are presumed with *syn*-tectonic sedimentation (Kairanov et al., 2018; Kontorovich et al., 2014; Mordasova, 2018; Nikishin et al., 2015). Where good seismic data are available, it appears that swells grew approximately from the Callovian until the end-Barremian. The examples are the Fedynsky High and Shtokman High in the Barents Sea (our seismic and drilling data, and data in Mordasova (2018)), Storbanken, Persey and Pinegin highs in the Norwegian Barents Sea (Kairanov et al., 2018), Universitetskaya High in the South Kara Basin (Nikishin, 2013), system of swells in the Yenisey-Khatanga Basin (Afanasenkov et al., 2016; Unger et al., 2017) and West Siberian Basin (Kontorovich et al., 2014). The time of development of these *syn*-compressional anticlinal highs coincides with the period of the main collision in the Verkhoyansk-Chukotka region. Therefore, we consider these two synchronous processes as related phenomena.

The Verkhoyansk-Chukotka Orogen was formed in the Neocomian in the Russian Far East (Amato et al., 2015; Didenko et al., 2002; Parfenov and Kuzmin, 2001; Puscharovsky, 1960; Shatskiy, 1935; Sokolov, 2010; Toro et al., 2016; Vinogradov, 1968; Zonenshain et al., 1990). The following two major problems exist within its boundaries: (1) a possible western continuation of the South Anyui accretional-collisional orogen (e.g., Kuzmichev, 2009; Piepjohn et al., 2018); (2) interrelationship of the Chukotka Orogen and Alaska (Amato et al., 2015; Miller et al., 2018b, 2018a).

A probable thrust front can be observed on seismic lines in the Laptev Sea and in the East Siberian Sea in the acoustic basement. The thrust front appears north of the New Siberian Islands and transits in the east into the known Zhokhov-Wrangel-Herald Thrust Belt (Drachev et al., 2010; Nikishin et al., 2017a, 2017b; Nikishin et al., 2015). No seismic data are available that would indicate that the South Anyui Suture proceeds northward into the Arctic. Our model is close to the study of Kuzmichev (2009). The conventional line of the Khatanga-Lomonosov fault inherits the northern boundary of the Early Cretaceous orogen. According to our data, we do not interprete Arctic Alaska as a part of the

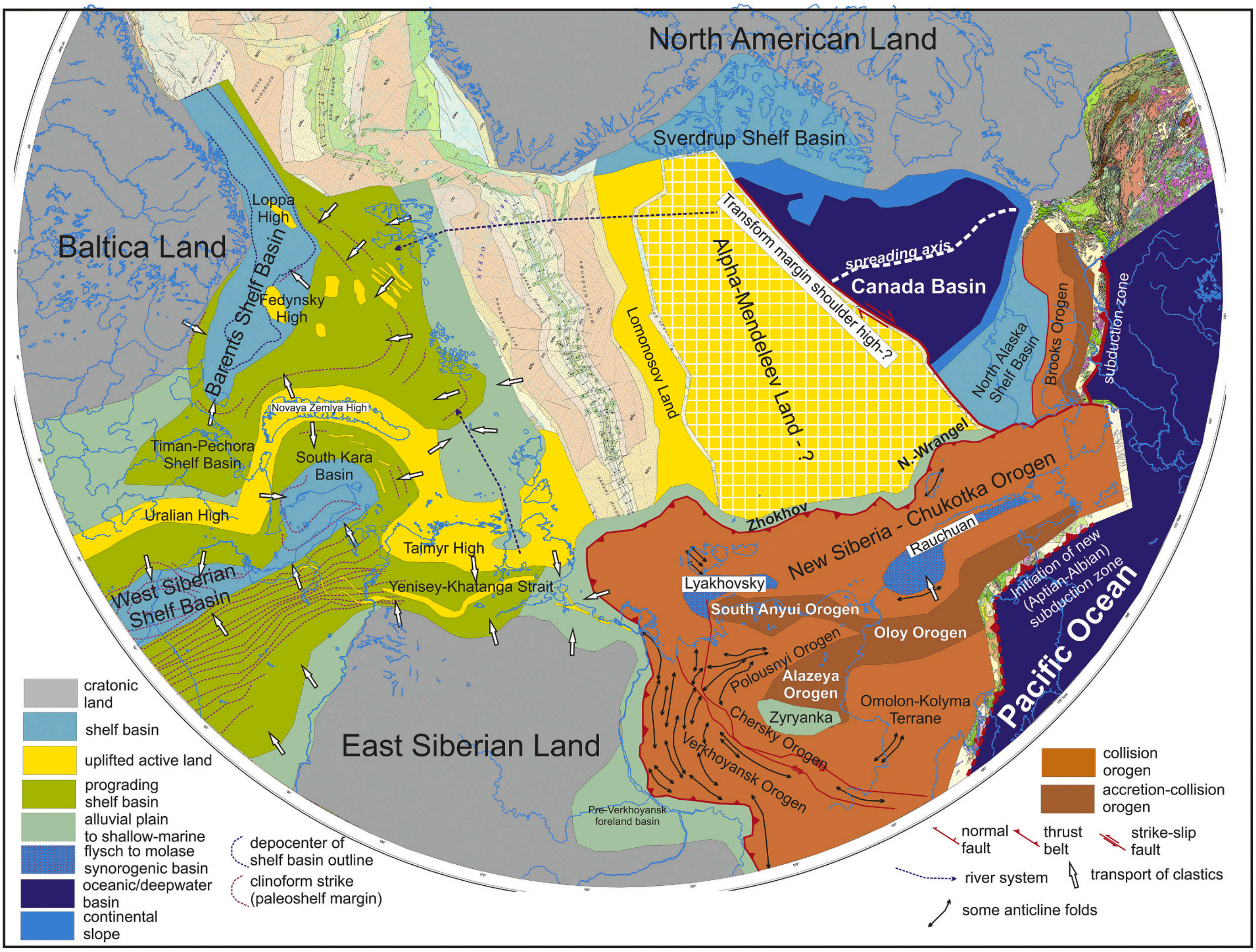

Fig. 4. Paleogeographic map of the Arctic for the Early Cretaceous, Berriasian to Barremian (145–125 Ma), on the present-day geographic framework. Geographic base map is Geological map of the Arctic (Harrison et al., 2011).

integrated Arctic Alaska-Chukotka Microplate. In our model, Alaska and Chukotka are separated by a major strike-slip zone (Nikishin et al., 2017a, 2017b; Nikishin et al., 2015).

The western boundary of the Verkhoyansk Orogen takes course along the Verkhoyansk Foredeep Basin that had its main subsidence phase in the Neocomian (Parfenov and Kuzmin, 2001). The possible northern boundary of the Verkhoyansk-Chukotka Orogen takes course along the Zhokhov-Wrangel-Herald thrust belt (Drachev et al., 2010; Nikishin et al., 2017a, 2017b; Nikishin et al., 2015). A belt of possible sedimentary wedges of Late Jurassic-Early Cretaceous deposits is observed on a number of published and commercial seismic lines just to the north of this thrust front, with thicknesses as up to 4 s TWT (Nikishin et al., 2015). The Verkhoyansk-Chukotka Orogen consists of collisional orogens as deformed edges of the Asian Paleozoic continent (the Verkhoyansk-Chersky and Chukotka-New Siberian regions), and a system of terranes that formed on an oceanic crust in the Pacific Ocean. It should, however, be noted that it still remains an intricate problem how to draw boundaries of different areas (terranes) (Amato et al., 2015; Parfenov and Kuzmin, 2001; Sokolov et al., 2015, 2002; Toro et al., 2016; Zonenshain et al., 1990). Along the outer boundary of the system of accretional terranes, a system of Neocomian molasse basins is identified, which can be considered as foredeeps or as *syn*-collisional basins. The Rauchuan (Vatrushkina, 2018), Lyakhovsky (Kuzmichev, 2009) and Zyryanka (Nikishin et al., 2017a, 2017b; Nikishin et al., 2015) basins belong to them. It should be noted that ages of detrital zircons from Neocomian sandstones of the Stolbovoy Island (the Lyakhovsky Basin) (Soloviev and Miller, 2014) and from sandstones of the Rauchuan Basin (Vatrushkina, 2018) mainly coincide: they have common peaks with values ca. 140–160 Ma, ca. 235–280 Ma, and ca. 1900 Ma.

In Alaska, the collision of the block of Arctic Alaska and the system of terranes of the Brooks Orogen started approximately at the Jurassic/Cretaceous boundary and the Colville Foredeep Basin started to form in the Neocomian (Houseknecht and Wartes, 2013; Moore et al., 2015; Toro et al., 2016).

As noted above, it is assumed for Canada Basin that the breakup unconformity has an age of about 135–130 Ma (Hadlari et al., 2016; Helwig et al., 2011; Nikishin et al., 2017a, 2017b). The time of opening of Canada Basin, as we already noted, is a highly debatable issue. According to our model, opening was completed at ca. 125 Ma, before the onset of emplacement of the HALIP superplume.

In the Neocomian, significant transport of clastic matter into the Barents Basin took place from the north. It is quite conceivable that the Lomonosov Ridge and the Alpha-Mendeleev ridges were uplifts and rivers transported clastic material from them toward the present-day Barents Sea.

We compiled a kinematic reconstruction of the Arctic for the

Fig. 5. Tectonic restoration of the Arctic region for the Early Cretaceous, Berriasian to Barremian (145–125 Ma). Kinematic restoration for the 128 Ma. Restoration was performed using GPlates programme. Legend is similar to Fig. 4. 1 – cratonic land, 2 – shelf basin, 3 – uplifted active land, 4 – prograding shelf basin, 5 – alluvial plain to shallow-marine, 6 – flysch to molasses synorogenic basin, 7 – continental slope, 8 – oceanic/deepwater basin, 9 – collision orogen, 10 – accretion-collision orogen, 11 – orocline, 12 – spreading axis. Violet outlines and letters mark position of some terranes and their names. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Barremian (128 Ma) within the framework of the GPlates software and our geodynamic concept (Freiman et al., 2018; Nikishin et al., 2015). The reconstruction is presented in Fig. 5. We superimposed data of our paleogeography onto the geometrical reconstruction.

According to our model, in the Late Jurassic, Chukotka and Alaska were part of a single continent with an active continental margin with the Anyui-Alazea-Oloy Oceanic Bay of the Pacific Ocean. In the Neocomian, this oceanic bay was closed as a result of movement of continental and oceanic terranes northwards and eastwards. At that time, the large-size Kolyma Orocline and South Anyui Orocline formed. We do not associate closure of the Anyui-Alazea-Oloy Oceanic Bay with opening of the Amerasia Basin. Our model is based on the concept that the continental Alpha-Mendeleev Terrane existed in the Neocomian which was situated north of the Verkhoyansk-Chukotka Orogen. In the Neocomian, final closure of the Mongol-Okhotsk Ocean took place and a major collisional orogen was formed along the southern edge of Siberia (Guo et al., 2017; Metelkin et al., 2010; Yang et al., 2015). The formation of the large Verkhoyansk-Chukotka and Mongol-Okhotsk orogens resulted in availability of a significant source of clastic material in the Neocomian. Therefore, clinoform sedimentation was typical of the West Siberian and Barents megabasins. The significant collision resulted in the situation that intraplate tectonics in the form of formation of compressional anticlinal highs widely manifested itself in sedimentary basins.

The Canada Basin was opened in the Hauterivian-Barremian as a back-arc basin of the Pacific Ocean's subduction system. The basin was bounded in the north by the transform boundary which is named by us the Amerasian Transform Fault. It separated Arctic Alaska from Chukotka and its course was east of the Chukchi Plateau (Nikishin et al., 2017a, 2017b; Nikishin et al., 2015).

3.5. *Aptian-Albian history of the Arctic*

Fig. 6 shows our paleogeography map for the Aptian-Albian. To a considerable extent, it is compiled for its offshore part on the basis of our interpretation of seismic data. For the Norwegian Barents Sea, various

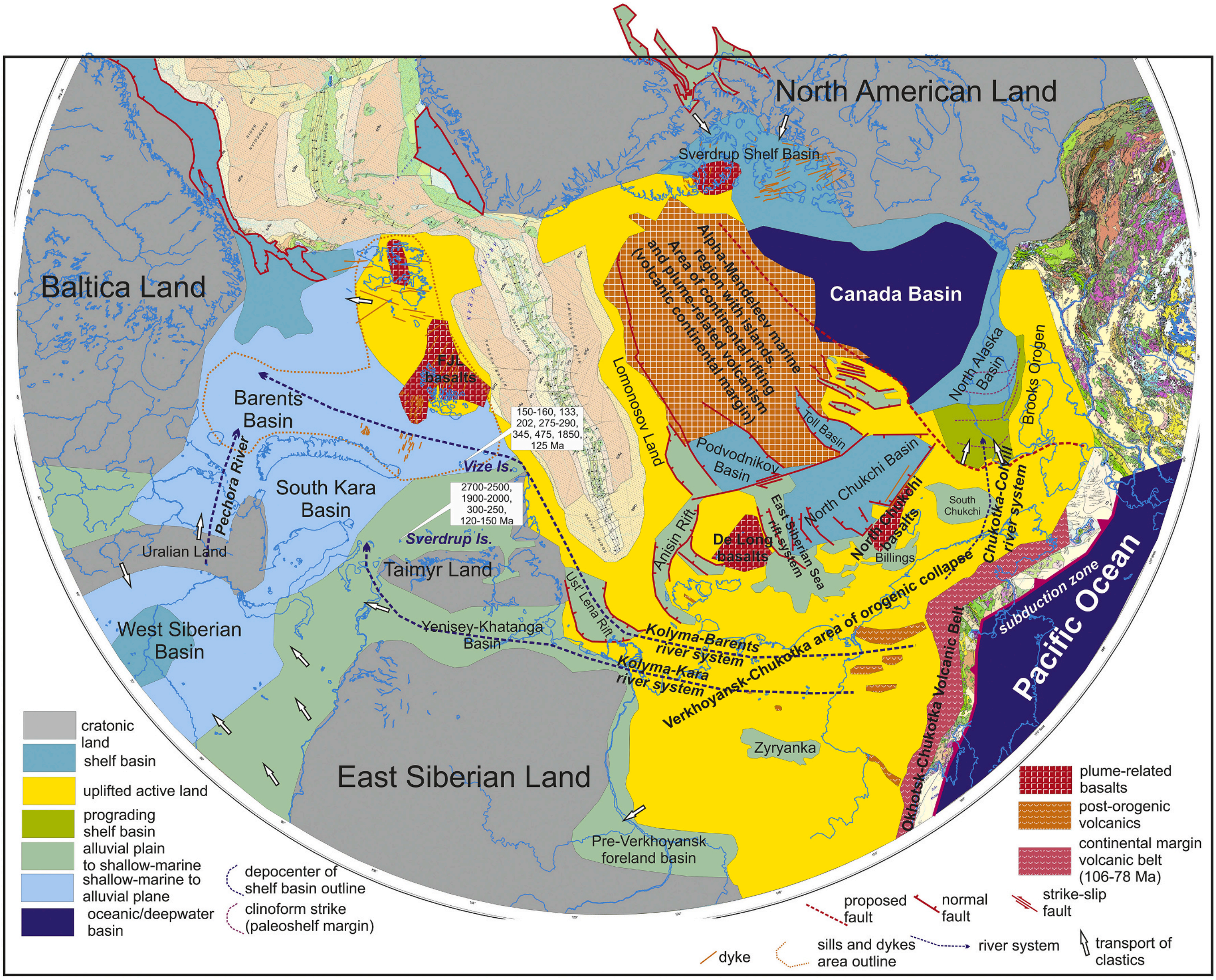

Fig. 6. Paleogeographic map of the Arctic for the Early Cretaceous, Aptian to Albian (125–100 Ma), on the present-day geographic framework. Geographic base map is Geological map of the Arctic (Harrison et al., 2011). Ages in the white boxes – ages of peaks of detrital zircons (our data), data for the Sverdrup Island are from Ershova et al., 2019.

studies (Blaich et al., 2017; Faleide et al., 2010; Grundvåg et al., 2017; Ziegler, 1988) were used. For the region of Alaska and Canada, the data in Houseknecht et al. (2009), Houseknecht and Wartes (2013), Moore et al. (2015) and Galloway et al. (2015) were used. For the onshore, the main studies were performed by Vinogradov (1968) and Kontorovich et al. (2014).

In the Russian part of the Barents Sea, the Neocomian clinofom complex is overlain by a sequence with horizontal layering which is considered by us as Aptian-Albian. The age of this seismostratigraphic complex is tied to available well data (Grundvåg et al., 2017; Midtkandal et al., 2016; Mordasova, 2018; Startseva, 2018). South and southwest of Franz Josef Land, approximately at the bottom of the horizontally layered Aptian sequence, a package with bright and chaotic reflections occurs. Its typical thickness is about 50–100 msec. We believe that this package of bright reflections corresponds to the strata of basalts on Franz Josef Land (see Paper 2, Fig. 56). This member of igneous rocks has an age of ca. 122–125 Ma (Corfu et al., 2013; Polteau et al., 2016). In the area of Svalbard, a horizon of bentonites with isotopic age of 123.1 ± 0.3 Ma is dated in the Cretaceous section (Midtkandal et al., 2016). These probable volcanites lay with an unconformity on the Neocomian clinoform complex. This unconformity approximately corresponds to the Barremian/Aptian boundary.

At the bottom of the Aptian, an angular unconformity is observed in the area of the Barents and Kara Seas. Aptian deposits covered all relative anticlinal highs, including Novaya Zemlya (Mordasova, 2018; Nikishin et al., 2015; Nikishin, 2013; Startseva, 2018). The pre-Aptian angular unconformity on anticlinal highs is well known for the Yenisey-Khatanga and West Siberian basins (Afanasenkov et al., 2016; Kontorovich et al., 2014; Unger et al., 2017). In the Aptian-Albian in the area of the Barents and Kara Seas, an environment of a shelf sea and alluvial plain prevailed (Grundvåg et al., 2017; Mordasova, 2018; Smelror et al., 2009; Startseva, 2018).

In the north of the Kara Sea on the Vize Island, sandstones with an Upper Barremian-Aptian age were sampled. Peaks of ages of detrital zircons have values in the range from 150 to 160, 133, 202, 275–290, 345, 475, 1850, 125 Ma (Nikishin et al., 2014). According to our data (Nikishin et al., in preparation), Jurassic and Neocomian sandstones from Franz Josef Land and from Barents Sea offshore wells have typical ages of detrital zircons of 290–230, 415–435, 520–560, 1700, 1000–1400, 230–250 Ma. I.e., the 'Uralian' source of clastic matter prevailed. From the Aptian on, the paleogeography pattern abruptly changed. The presence of Jurassic and Early Cretaceous zircons is indicative of a new source area from the Verkhoyansk-Chukotka Orogen (Nikishin et al., 2015), where Jurassic and Early Cretaceous magmatism widely manifested itself. The age data of detrital zircons for Aptian-Albian deposits of Chukotka coincide with ages for the Vize Island sandstones (Nikishin et al., 2014; Vatrushkina, 2018). Similar ages of detrital zircons are also available for Albian continental sandstones from the Kotelny Island of the New Siberian Islands, with peaks ca. 145, 240, 290, 330, 1700, 1880 Ma (Kuzmichev et al., 2018). Similar results were obtained for the Aptian sandstones of the South Kara Basin (Sverdrup Island) (Ershova et al., 2019). Hence, it is surmised that a major river system existed from Chukotka to the Barents-Kara Seas in the Aptian (see Fig. 6).

An Aptian-Albian deltaic system with clinoforms is identified in the Colville Basin on Alaska (Houseknecht et al., 2009; Houseknecht and Wartes, 2013; Moore et al., 2015). The river system had its start on Chukotka. The data in Moore et al. (2015) show that ages of detrital zircons in the Alaskan Aptian-Albian deposits almost coincide with ages of zircons on Chukotka and on the Vize Island. This topic requires special analysis, but the hypothesis assumes that in the Aptian-Albian time, rivers from Chukotka were running both toward the Canada Basin and toward the area of the Barents Sea.

Within the Verkhoyansk-Chukotka region, collapse of the Early Cretaceous orogen took place and numerous post-collisional granitoids were formed in the Aptian-Albian (Amato et al., 2015; Khanchuk et al., 2019; Kuzmichev, 2009; Miller et al., 2018b, 2018a, 2010, 2008; Parfenov and Kuzmin, 2001; Sokolov et al., 2002; Toro et al., 2016). In the area of the strip of the South Anyui zone, a system of volcanic belts in an extensional environment was formed synchronously with collapse of the orogen (125–112 Ma). These belts are consisting of basalts, andesites, rhyolites and sedimentary rocks. The largest of these belts is the Tytylveyem belt (Tikhomirov, 2018; Tikhomirov et al., 2017). Similar volcanites are also encountered on the New Siberian Islands (Kos'ko and Trufanov, 2002; Nikitenko et al., 2017).

In the Arctic from the Laptev Sea up to the Chukchi Sea, continental rift systems were formed in the Aptian and Albian. The North Chukchi Basin, East Siberian Sea Basin, Anisin-Novosibirsk Basin, and Ust' Lena

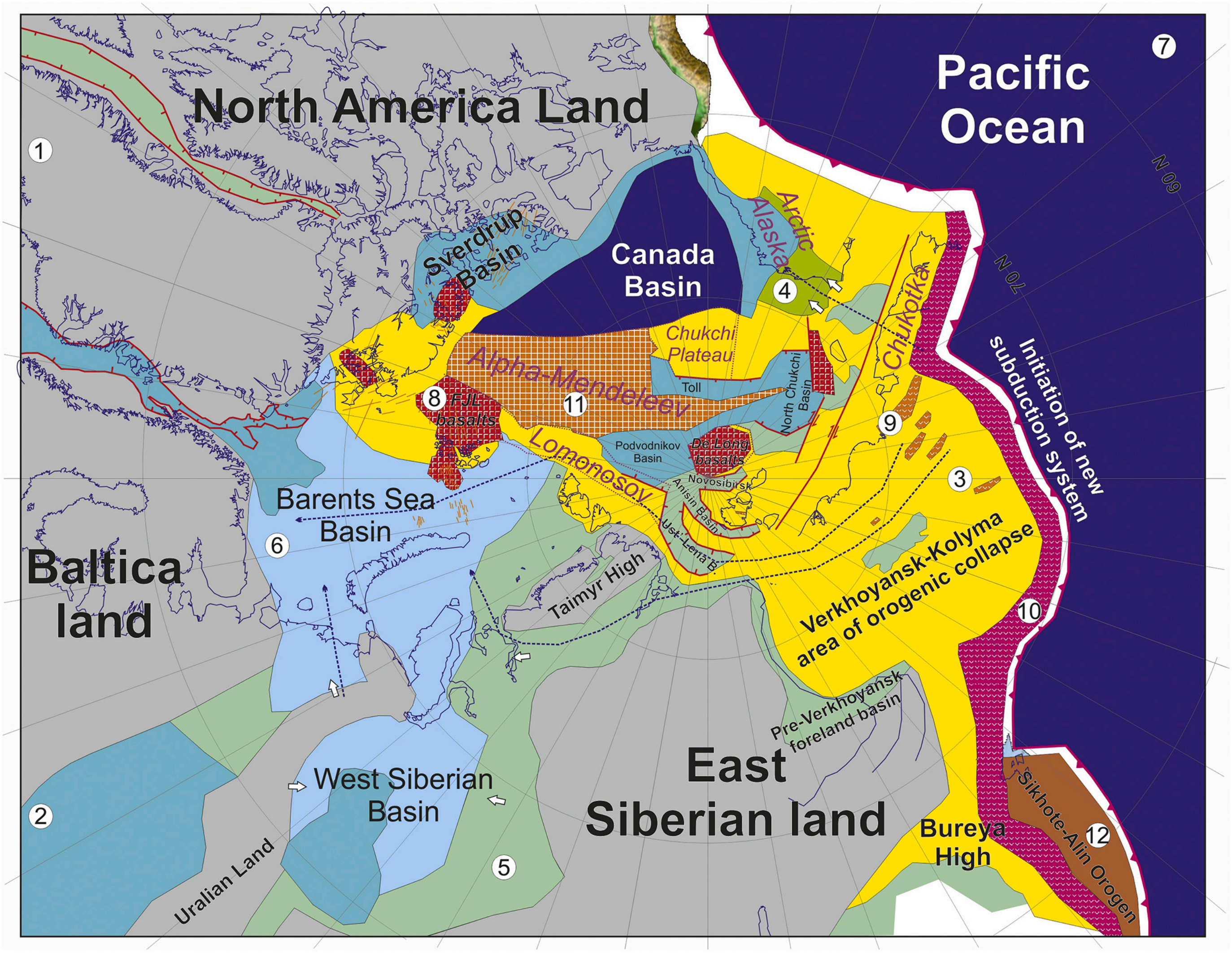

Fig. 7. Tectonic restoration of the Arctic region for the Early Cretaceous, Aptian to Albian (125–100 Ma). Kinematic restoration for the 115 Ma. Restoration was performed using GPlates programme. Legend is similar to Fig. 6. 1 – cratonic land, 2 – shelf basin, 3 – uplifted active land, 4 – prograding shelf basin with clinoform sedimentation mainly, 5 – alluvial plain to shallow-marine, 6 – shallow-marine to alluvial plane, 7 – oceanic/deepwater basin, 8 – plume-related basalts, 9 – post-orogenic volcanics, 10 – continental margin volcanic belt, 11 – area of continental rifting and plume-related volcanism, 12 – accretion orogen. Violet letters mark position of some terranes and their names. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Basin belong to them. On seismic lines, we observe normal faults of dominantly near north-south trends; we also observe possible strike-slip faults with dominantly near east-west trends. The Podvodnikov and Toll Basins probably started to form since the Aptian.

Aptian-Albian rifts are well known in the North Atlantic region (Ziegler, 1988) and in the Baffin Bay (Dickie et al., 2011; Gregersen et al., 2013).

We compiled a kinematic reconstruction of the Arctic for the Aptian (115 Ma) within the framework of GPlates software and our geodynamic concept (Freiman et al., 2018; Nikishin et al., 2017a, 2017b; Nikishin et al., 2015), presented in Fig. 7. We charted our paleogeography data onto the geometric reconstruction. For the Aptian, five areas of basaltic magmatism are identified on the shelf: Franz Josef Land, Svalbard, Sverdrup, De Long and North Chukchi areas. Ages of the onset of magmatism are not exactly dated, though they are likely close to 122–125 Ma. Probably magmatism started approximately simultaneously in all of the five igneous provinces.

The data for the area of the De Long Plateau show that basalts are present at the base of many rifts in the area of the Laptev Sea and the East Siberian Sea (see Paper 2). It is likely that after start of the magmatism, continental rifting widely manifested itself in the shelf areas from the Laptev Sea to the Chukchi Sea, as well as in the North Atlantic and in the Baffin Bay region. For the Alpha-Mendeleev ridges, isotopic ages of basalts are known in the interval of 127–110 Ma. The volcanic Alpha-Mendeleev ridges were together with the volcanic Franz Josef Land Plateau and the volcanic De Long Plateau at the onset of its formation (e.g., Døssing et al., 2013; Nikishin et al., 2015). Such an interrelationship is typical for known volcanic continental margins (e.g., Geoffroy, 2005). Therefore, we assume that in the Aptian the Alpha-Mendeleev ridges were formed as a volcanic continental margin on a continental crust. Such a hypothesis was discussed in Dove et al. (2010). Volcanic margins are typically associated with SDRs (e.g., Clerc et al., 2018; Geoffroy, 2005; Stica et al., 2014). In the area of the Toll Basin situated between the Mendeleev Ridge and the Chukchi Plateau, half-grabens with probable SDRs were identified on two seismic sections (Ilhan and Coakley, 2018; Nikishin et al., 2015). This result shows that volcanism on the Alpha-Mendeleev ridges was accompanied by continental rifting in the Aptian-Albian.

We find no indication for the presence of an oceanic spreading axis for the Aptian-Albian in the Alpha-Mendeleev ridges. Extension in the area of the Alpha-Mendeleev ridges and the rift systems of the Laptev-Chukchi Seas was probably associated with major strike-slip faults. These strike-slip faults might reach the Pacific Ocean and its subduction zone.

For the Aptian-Albian, many dyke belts and areas of development of sills are well known in the Arctic (e.g., Buchan and Ernst, 2018; Dockman et al., 2018; Døssing et al., 2013; Estrada et al., 2016; Kingsbury et al., 2018; Minakov et al., 2018; Shipilov, 2016). We refined these data for the Barents and Chukchi Seas on the basis of new seismic data and magnetic anomalies (Fig. 6).

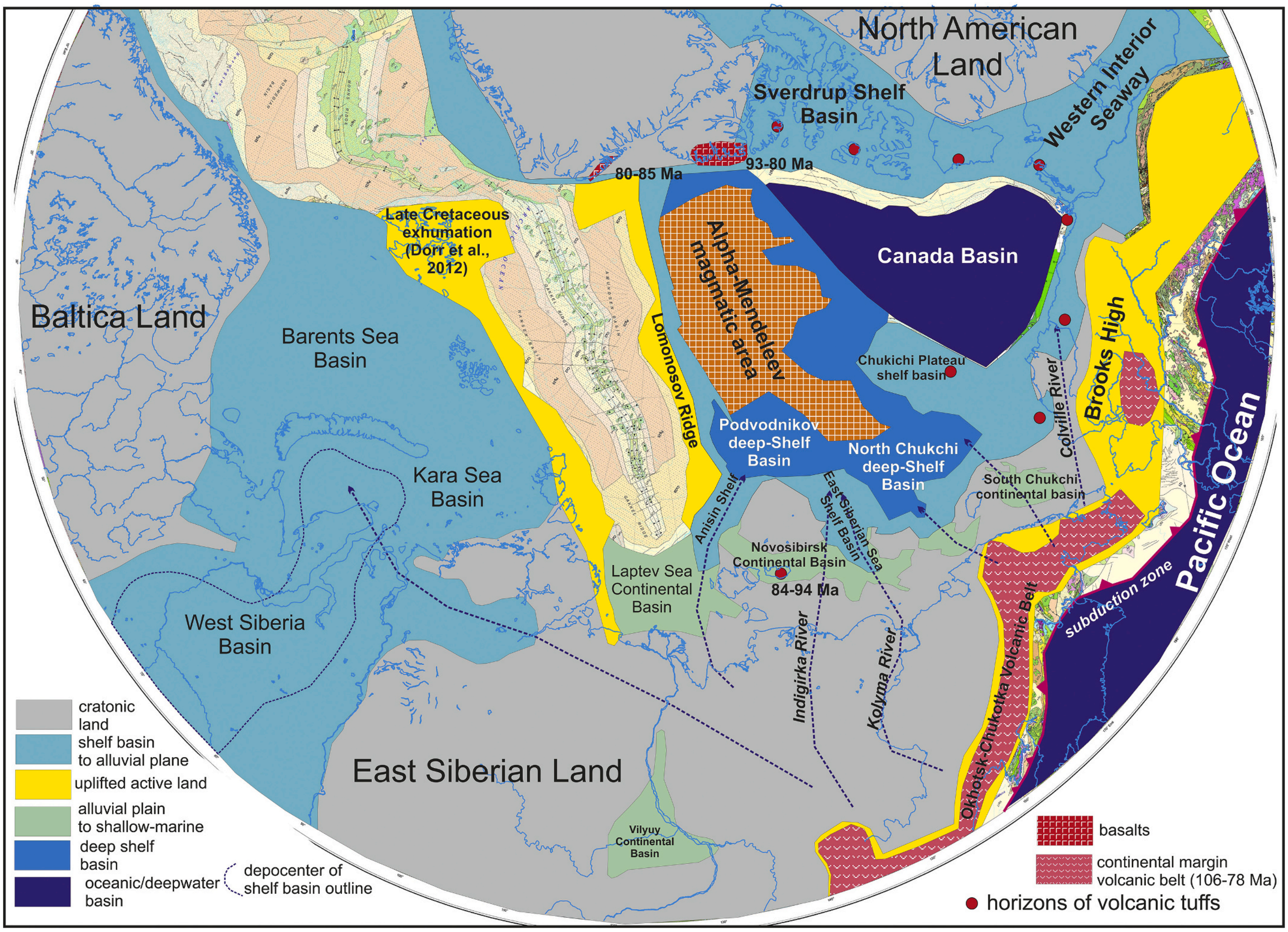

Fig. 8. Paleogeographic map of the Arctic for the Late Cretaceous, Cenomanian to Campanian (100–80 Ma), on the present-day geographic framework. Geographic base map is Geological map of the Arctic (Harrison et al., 2011).

3.6. Late Cretaceous history of the Arctic (100–80 Ma)

Fig. 8 shows our paleogeography map for the Late Cretaceous (Cenomanian – Middle Campanian). For its offshore part, it is compiled to a large extent on the basis of our interpretation of seismic data. For the Norwegian Barents Sea, the studies of Ziegler (1988) and Faleide et al. (2010) are used. For the region of North America, the data in Houseknecht and Connors (2016), Craddock and Houseknecht (2016), Moore et al. (2015), Schröder-Adams et al. (2014), Schröder-Adams et al. (2014) and Pugh et al. (2014) are utilized. For the Russian onshore, the main studies of Vinogradov (1968) and Kontorovich et al. (2014) are used.

Data of commercial drilling in the Russian part of the Barents Sea and in the South Kara Basin demonstrated that the Upper Cretaceous was widespread, but in the Barents Sea it was considerably eroded during the Quaternary glaciations (e.g., Henriksen et al., 2011a, 2011b).

In the South Kara Basin, the Upper Cretaceous is studied by several boreholes (Leningradskaya and Rusanovskaya, etc.) (Nikishin et al., 2015; Nikishin, 2013; Shishkin et al., 2015). Similar Upper Cretaceous deposits are penetrated by wells on Yamal (Kontorovich et al., 2014; Shishkin et al., 2015). In the South Kara Basin, the thickness of Upper Cretaceous deposits is about 700–1300 m, determined by drilling data. The Upper Cretaceous is represented mainly by marine and continental clays and siltstones including biosilica horizons. The Cenomanian is characteristic of sandstones (e.g., Nikishin, 2013; Shishkin et al., 2015).

The Upper Cretaceous is penetrated by several wells in the East Barents Megabasin. The most complete description is available for the Severo-Murmanskaya-1, Arkticheskaya, Shtokmanovskaya-1, Ledovaya-2 -1 wells (Mordasova, 2018). Thickness of Upper Cretaceous deposits in the wells reaches 300 m. Deposits are represented mainly by shelf clays and siltstones. It is observed on seismic lines that the thickness of Upper Cretaceous deposits exceeds more than 1 km (Mordasova, 2018; Nikishin et al., 2015; Startseva, 2018). The Upper Cretaceous biostratigraphy is poorly studied. On the Kolguyev Island, marine fauna from Cenomanian to Campanian are encountered in Upper Cretaceous deposits (Zhuravlev et al., 2014). Hence, it appears that shelf marine environments prevailed in the Barents Basin for this interval of time.

In the Norwegian part of the Barents Sea, a shelf sea was mainly present in the Late Cretaceous in the Cenomanian-Campanian, though these deposits have been eroded to a considerable extent (Faleide et al., 2010; Henriksen et al., 2011b, 2011a; Ziegler, 1988). Maastrichtian deposits are almost absent in the Barents Sea. It is assumed that a phase of regional erosion took place in the Maastrichtian (Henriksen et al., 2011b, 2011a).

Based on the available seismic data and analysis of lithofacies distribution in Upper Cretaceous deposits we assume that in the Upper Cretaceous all main uplifts in the region of the Barents and Kara Seas were covered by sediments. It is likely that integrated shelf basins existed which comprised the basins of the Barents Sea, Kara Sea and West Siberia.

A phase of uplift and exhumation occurred on Svalbard in the Late Cretaceous (Dörr et al., 2012). However, this issue is debatable at present. The Upper Cretaceous deposits of the Barents-Kara seas have no typical clinoforms. As a result, it is still unknown where the main sources of clastic material were situated.

In the Russian Far East, a well-known structure is the Okhotsk-Chukotka continental-marginal volcanic belt with an age of about 106–78 Ma (Akinin, 2012; Khanchuk et al., 2019; Parfenov, 1984; Tikhomirov, 2018). This belt separated the Asian continent form the Pacific Ocean. In the Artic in the area of the Laptev, East Siberian and Chukchi Seas, formation of post-rift basins was underway. Data for the Upper Cretaceous are available for the New Siberian Islands only. Cenomanian, Turonian and Coniacian deposits are present there. Cenomanian deposits are probably represented by continental sandstones, while Turonian-Coniacian deposits form a coastal coal-bearing member up to 95 m thick (Kostyleva et al., 2018; Nikitenko et al., 2017). In Turonian-Coniacian sandstones, many detrital zircons are present, with ages of ±82–94 Ma, whereas horizons of rhyolitic tuffs are also identified (Danukalova and Kuzmichev, 2014; Kostyleva et al., 2018). In the north of Siberia and south of the Lena River delta in the area of the town of Tiksi, volcanic centers and dykes composed of basalts were discovered. U—Pb SHRIMP zircon dating of 3 dykes yielded crystallization ages of 86 ± 4, 86.2 ± 1.3 and 89 ± 2 Ma (Turonian to Santonian) (Prokopiev et al., 2013). In the Russian Far East, no marine Upper Cretaceous deposits are present. The only mountain belt appears to be the Okhotsk-Chukotka volcanic belt. It is likely, therefore, that the main river system was from the Okhotsk-Chukotka volcanic belt into the shelf sea of the North Chukotka Basin and into the Podvodniov Basin (Fig. 8).

A Late Cretaceous shelf of the Sverdrup Basin is located in northern Canada (Hadlari et al., 2016; Pugh et al., 2014; Schröder-Adams et al., 2014). It consists of shelf clays and sandstones. Volcanites are known from the Cenomanian and Campanian (Hadlari et al., 2016; Schröder-Adams et al., 2014). The maxima of dyke volcanism are of 95 ± 4 Ma and 81 ± 4 Ma (Buchan and Ernst, 2018; Dockman et al., 2018). For the Mackenzie Delta Basin and Arctic Alaska Basin, the Upper Cretaceous is mainly represented by shelf clays (Houseknecht and Bird, 2011).

Volcanic tephra of Cenomanian-Coniacian age (ca. 100–86 Ma) are widely known in Upper Cretaceous on the Alaskan Shelf. It is assumed that the volcanic material entered from the Okhotsk-Chukotka volcanic belt (Houseknecht and Connors, 2016; Houseknecht and Bird, 2011).

Late Cretaceous ages of basalts are known for the Alpha-Mendeleev ridges (Coakley et al., 2016). We assume that a possible source of volcanic material for Late Cretaceous shelf deposits of the Arctic region was the area of the Alpha-Mendeleev ridges (see Fig. 8). Volcanoes of rhyolitic composition are inferred for the Alpha Ridge based on seismic data (Brumley, 2014). We compared the Mendeleev Ridge with the Vøring Plateau on the Norwegian continental margin in the North Atlantic. The Vøring Plateau is composed of basalts, but volcanites of acidic composition (dacites, ignimbrites), and pyroclastic material in the form of tuffs are also present (Abdelmalak et al., 2016). Thus, basaltic magmatism with possible acidic-composition, occurred in the area of the Alpha-Mendeleev ridges in Late Cretaceous. Acidic composition is characteristic of plume magmatism on a continental crust, as known for the Vøring Plateau.

We compiled a kinematic reconstruction of the Arctic for the Late Cretaceous (88 Ma) within the framework of GPlates software and our geodynamic concept (Freiman et al., 2018; Nikishin et al., 2017a, 2017b; Nikishin et al., 2015), presented in Fig. 9. We superimposed our paleogeographic data onto the geometric reconstruction. It is likely that the main event in the Late Cretaceous was magmatism on the Alpha-Mendeleev ridges. This magmatism was possibly accompanied by rifting on a not well-constrained scale. Magmatism manifested itself within shelf basins of the Arctic Ocean as well. It is likely that intraplate tectonics dominated in the Arctic Ocean in the Late Cretaceous.

3.7. Paleocene history of the Arctic

Fig. 10 shows our paleogeography map for the Paleocene. For its offshore part, it is to a considerable extent based on our interpretation of seismic data. For the Norwegian Barents Sea, the studies of Ziegler (1988), Faleide et al. (2010), Henriksen et al. (2011b), and Lasabuda et al. (2018) are used. For the North American region, various data (Craddock and Houseknecht, 2016; Dixon et al., 2019; Houseknecht, 2019; Houseknecht and Connors, 2016) are used. For the Russian onshore, we compiled the main studies presented by Grossgeym and Korobkov (1975), Akhmetiev and Zaporozhets (2014), Yakovleva (2017) and Vasilieva (2017).

As in the Barents and Kara seas, Paleocene deposits were eroded to a considerable extent, making it difficult to restore paleogeography of this period of time. Paleocene deposits are penetrated by wells in West Siberia (Akhmet'ev et al., 2010; Grossgeym and Korobkov, 1975; Vasilieva, 2017; Volkova, 2014; Yakovleva, 2017; Zyleva et al., 2014). In the

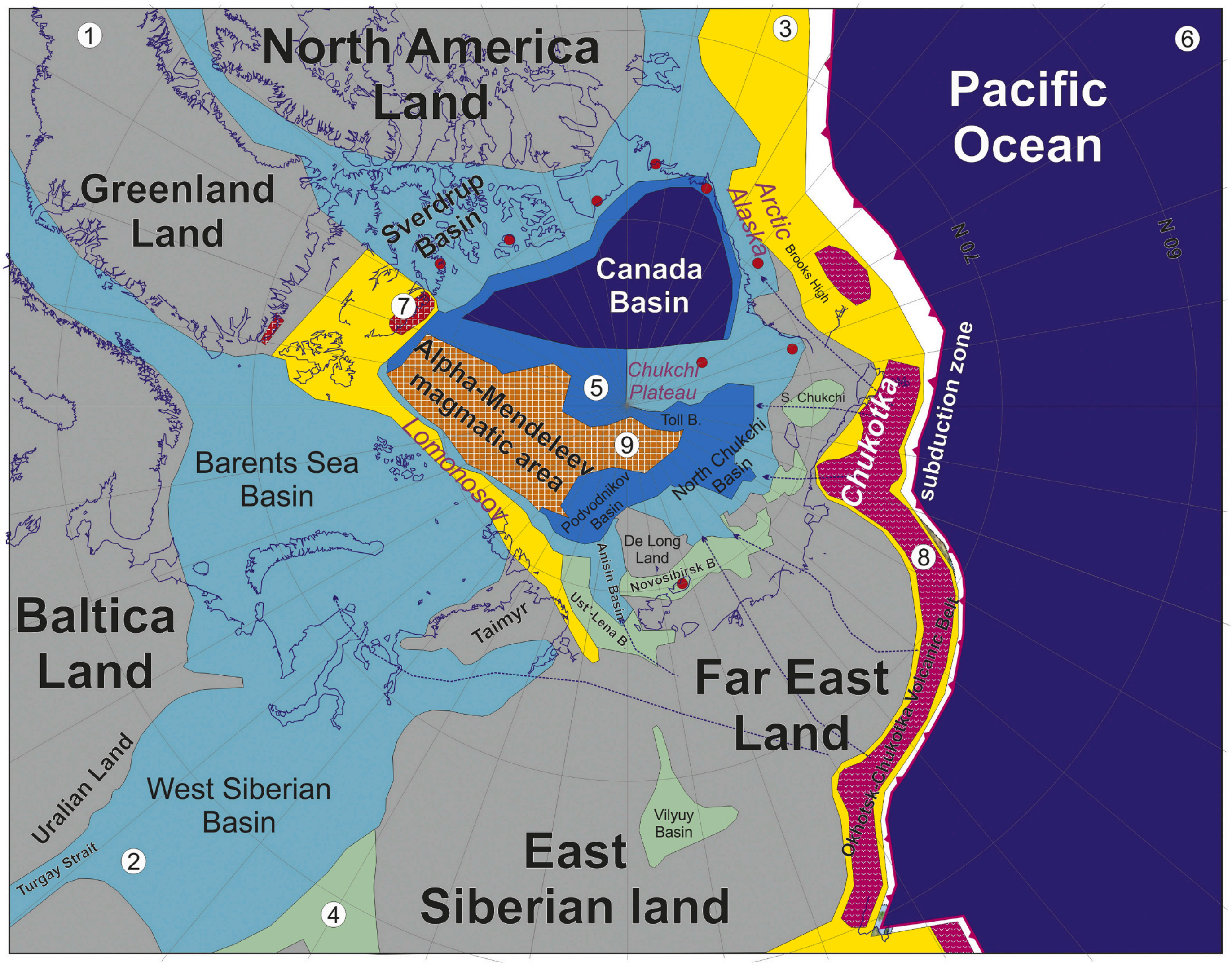

Fig. 9. Tectonic restoration of the Arctic region for the Late Cretaceous, Cenomanian to Campanian (100–80 Ma). Kinematic restoration for the 88 Ma. Restoration was performed using GPlates programme. Legend is similar to Fig. 8. 1 – cratonic land, 2 – shelf basin, 3 – uplifted active land, 4 – alluvial plain to shallow-marine, 5 – deep shelf basin, 6 – oceanic/deepwater basin, 7 – basalts, 8 – continental margin volcanic belt, 9 – Alpha-Mendeleev intraplate magmatic area. Violet letters mark position of some terranes and their names. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Paleocene, shelf diatomites play an important role. Paleocene deposits are known from wells in the South Kara Basin and on Yamal (the Leningradskaya-1 well and others) (Shishkin et al., 2015). They are represented by continental and shelf deposits with horizons of diatomites. In the upper part of the Paleocene (the Serov Formation), horizons of volcanic ash with volcanic glass are known (Shishkin et al., 2015). In the Timan-Pechora Basin, Paleocene sections are studied in several wells (Oreshkina et al., 1998). The Paleocene is represented by shelf diatomites and clays. Marine shelf sediments are known for the western part of the Barents Sea, with a hiatus at the base of Paleocene in the Hammerfest Basin (Lasabuda et al., 2018). No adequate data on the presence of Paleocene are available for the Russian part of the Barents Sea (e.g., Smelror et al., 2009). The presence of marine Paleocene deposits in the West Siberian, Timan-Pechora and South Kara Basins makes it likely that the entire Barents-Kara region in the Paleocene was a shelf sea. Periods of emergence and desiccation are interpreted for this region. This region was situated in a stable intraplate tectonic setting.

On Svalbard, horizons of bentonites are encountered in the Paleocene Basilika Formation. Within these bentonites, ages of detrital zircons are studied (Elling et al., 2016). Many zircons have ages in the range of 200–650 Ma, though rare zircons are encountered with ages of about 88, 152, 154, 162 and 188 Ma (Elling et al., 2016). Cretaceous and Jurassic magmatic zircons in the Arctic are widely known in the Verkhoyansk-Chukotka region. That is why a probability exists that they were transported to the Svalbard region from the Russian Far East in the Paleocene (Elling et al., 2016). Our data on ages of detrital zircons in the North Kara Sea showed that many Cretaceous and Jurassic zircons with ages of ca. 150–160, 133, 202, 275–290 Ma are present within Aptian and Albian deposits (see Fig. 6). It can be assumed that erosion of Cretaceous sandstones took place in the north of the Barents-Kara Seas in the Paleocene. A shoulder of the Paleocene continental rift was possibly uplifted along the recent margin of the Eurasia Basin.

In the north of Greenland and on the Canadian Islands, the Eurekan Orogeny started in the Paleocene and the Central Tertiary Basin on Spitsbergen started to form as a foredeep basin (Elling et al., 2016; Lasabuda et al., 2018; Petersen et al., 2016; Piepjohn et al., 2015; Saalmann et al., 2005). At that time, a continental rift system was formed in the North Atlantic (Faleide et al., 2010).

In the Russian Far East within the Verkhoyansk-Chukotka region, the Paleocene is only known in the Lower Kolyma Basin and in the north of

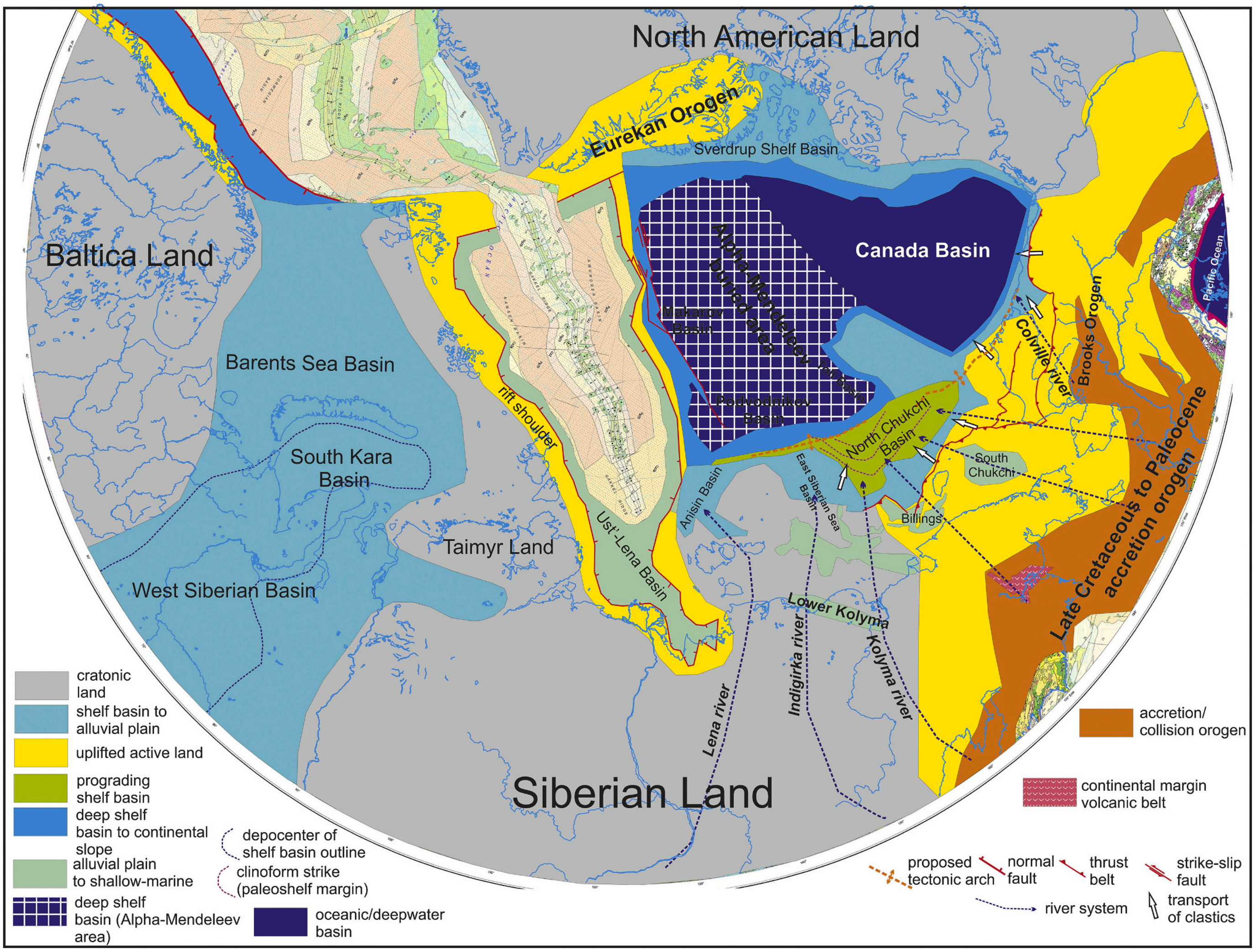

Fig. 10. Paleogeographic map of the Arctic for the Paleocene (66–56 Ma) on the present-day geographic framework. Geographic base map is Geological map of the Arctic (Harrison et al., 2011).

the Verkhoyansk Range near the Lena River delta (the Sogo Basin, Omoloy Basin, Ust'-Yana Basin). Paleocene deposits are known mainly from drilling data. The Paleocene is represented by continental deposits up to 200–300 m thick with horizons of coals (Gertseva et al., 2016; Grinenko, 1989; Grinenko et al., 1997; Grossgeym and Korobkov, 1975; Shulgina and Bashlavin, 2000). A regional weathering crust is well known at the Paleocene base; the Paleocene with erosional bottom overlies deposits of various ages (Grinenko, 1989; Grinenko et al., 1997). It is likely that a regional uplift phase took place at the Cretaceous/Paleocene boundary.

A well is available north of Chukotka on the Ayon Island in the area of the Rauchuan Basin. A weathering crust with kaolin clays is present in the well at the base of the Paleocene, Danian deposits are absent. The Selandian and Thanetian are represented by continental sediments with horizons of coals, with total thickness of about 50 m. Marine sediments might be present in the upper part of the Thanetian (Aleksandrova, 2016).

On the New Siberian Islands, a stratum of Thanetian age, up to 30 m thick, is known. It is represented by continental sediments with horizons of coal (Kos'ko and Trufanov, 2002; Kostyleva et al., 2018).

On the Alaska Shelf, three wells with Paleocene deposits are available. These are Klondike-1, Crackerjack-1, and Popcorn-1 (Craddock and Houseknecht, 2016; Houseknecht and Bird, 2011; Ilhan and Coakley, 2018; Sherwood et al., 2002). In these wells, the Mid-Brookian Unconformity (MBU) is identified to which a major erosional boundary corresponds whose age has not been determined exactly though it is close to the Cretaceous/Paleogene boundary (Craddock and Houseknecht, 2016; Sherwood et al., 2002). In the Popcorn-1 well, Lower Paleocene deposits overlie Aptian deposits (Sherwood et al., 2002). The magnitude of erosion is evaluated to be on the order of hundreds of meters. The Paleocene is represented by clays with sandstone horizons. Marine fauna is present in the sediments.

In the Russian part of the North Chukchi Basin, the "lower" clinoform complex belongs to the Paleocene in accordance with our seismostratigraphy model (see Paper 2). We identified clinoforms on seismic data and traced their strikes (see Fig. 10). Transport of clastic material took place from the south from the Verkhoyansk-Chukotka region and from the side of West Alaska. North of the Wrangel and Herald islands, is a thrust belt, the Herald-Wrangel Ridge is situated to the south (Drachev et al., 2010; Nikishin et al., 2017a, 2017b; Nikishin et al., 2015). North of the Herald-Wrangel Thrust Belt, the MBU seismic boundary overlies a low-angle folded complex (Ikhsanov, 2014; Nikishin et al., 2017a, 2017b; Nikishin et al., 2015). Our analysis of seismic profiles shows that folding was accompanied by sedimentation with variable thicknesses in synclines. The folding took place not long before the MBU boundary. On the Chukchi Plateau, it is observed on seismic lines that Cretaceous grabens experienced inversion accompanied by syntectonic sedimentation prior to the MBU boundary (Nikishin et al., 2015). As shown in Ilhan and Coakley (2018) in the eastern part of the North Chukchi Basin, significant erosion and, locally, an angular unconformity corresponds to the MBU boundary.

AFT data for the Brooks Range show that syntectonic uplift with kilometer-scale erosion took place at 60–65 Ma. This erosion encompassed the territories of the Alaska North Slope as well (Craddock et al., 2018; O'Sullivan et al., 1997). Modeling of subsidence history of the Alaska North Slope based on interpretation of seismic lines showed that an erosion phase with an amount up of 2–3 km took place at ca. 60 Ma (Peters et al., 2011). Our analysis of seismic lines for the MBU boundary shows that north of the Wrangel-Herald Thrust Belt, the amount of erosion below the MBU boundary reached the equivalent of 1–2 s TWT (the study was performed by M. Skaryatin). AFT data for the Wrangel Island show that a significant phase of erosion and uplift took place at about 72–64 Ma (Verzhbitsky et al., 2015, 2012). AFT data for the Herald High show that its uplifting started at ca. 74 Ma (Craddock and Houseknecht, 2016). It is likely that active uplift and erosion of the Wrangel-Herald High started earlier than uplift of the Brooks Range area.

At the base of the Paleocene, an erosional boundary is identified on the Chukchi Plateau (Ilhan and Coakley, 2018). The Andrianov High is located in the eastern part of the North Chukchi Basin. On this high, a small angular unconformity is also present at the bottom of the MBU boundary (Ikhsanov, 2014; Nikishin et al., 2015). It is likely that this high experienced uplift in the Paleocene in the course of regional compression.

The following scenario of the Paleocene history can be is proposed for the area of the Chukchi Sea. Regional compression and upthrusting of the Wrangel-Herald High and the Brooks system onto the North Chukchi Basin and the Chukchi Plateau started at the end of the Late Cretaceous at ca. 80–70 Ma, before the MBU boundary. The compression was accompanied by formation of mountain relief in the Wrangel-Herald and Brooks system strip of highs. The mountain belt became a source of a large amount of clastic material and a thick clinoform complex started to form in the North Chukchi Basin in the Paleocene.

In the area of the Laptev Sea, Paleocene deposits are exposed onshore

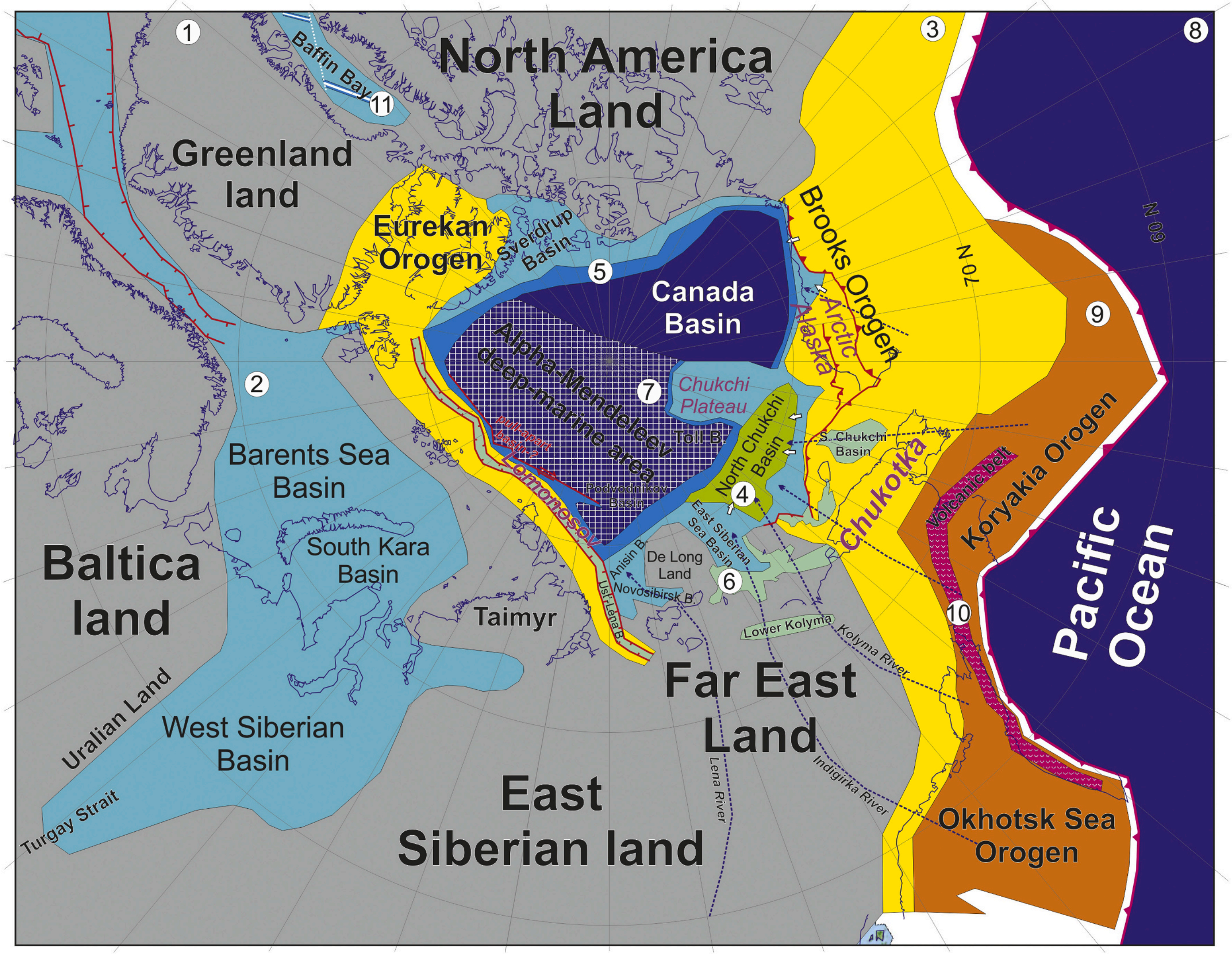

Fig. 11. Tectonic restoration of the Arctic region for the Paleocene (66–56 Ma). Kinematic restoration for the 65 Ma. Restoration was performed using GPlates programme. Legend is similar to Fig. 10. 1 – cratonic land, 2 – shelf basin, 3 – uplifted active land, 4 – prograding shelf basin with clinoform sedimentation mainly, 5 – deep shelf basin to continental slope, 6 – alluvial plane to shallow-marine, 7 – deep shelf basin, 8 – oceanic/deepwater basin, 9 – accretion/collision orogen, 10 – continental margin volcanic belt, 11 – spreading axis. Violet letters mark position of some terranes and their names. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

east of the Lena River delta (the Sogo Basin, Omoloy Basin, Ust'-Yana Basin). These Paleocene deposits are known from well drilling data. These are continental sediments with horizons of coals. The typical thickness of the deposits is about 100–300 m (Gertseva et al., 2016; Grinenko, 1989). These basins are bounded by faults and probably are a continuation of the Laptev Sea rift system (the Ust'-Lena Basin).

In the Laptev Sea, the Paleocene is identified by interpretation of seismic lines (see Paper 2). In the Paleocene, the large-size Ust'-Lena Rift formed and postrift subsidence of the Anisin and New Siberian Basins continued; facies of shelf, alluvial plains and slopes are identifiable. The deepest-water portion of the marine basin was the area of the Anisin Basin which transited into the continental slope of the Podvodnikov Basin in the north.

We compiled a kinematic reconstruction of the Arctic for the Paleocene (65 Ma) within the framework of GPlates software and our geodynamic concept (Freiman et al., 2018; Nikishin et al., 2017a, 2017b; Nikishin et al., 2015), presented in Fig. 11. We superimposed our paleogeography data onto the geometric reconstruction.

At the end of Cretaceous and in the Paleocene, a major continental-marginal orogen formed which comprised the area from the Okhotsk Sea Orogen and the Koryak Orogen to the Brooks Orogen on Alaska (O'Sullivan et al., 1997; Sokolov, 2010; Soloviev, 2008). Formation of the thrust belt of the Brooks Orogen system and the Wrangel-Herald Orogen is associated with formation of this orogen. Growth of mountain systems resulted in fast filling of the North Chukchi Basin with clinoform complexes. Synchronously with this "Laramide" Orogeny, the Eurekan Orogeny was taking place.

In the North Atlantic and along the present-day Eurasia Basin, continental rifting took place in the Paleocene. For the Eurasia Basin, parts of these rifts remained on the slope of the Lomonosov Ridge (see Paper 1). A Paleocene rift system (the Ust'-Lena Rift) was formed in the Laptev Sea as well. Formation of the Ust'-Lena Rift and the Paleocene "pre-Gakkel Rift" was associated with the history of the Atlantic Ocean opening. The West Makarov Basin was formed in the Paleocene as a pull-apart basin and as a part of the Paleocene Gakkel (or "pre-Gakkel") rift system.

3.8. *Early-Middle Eocene history of the Arctic*

Fig. 12 shows our paleogeography map for the Early-Middle Eocene time interval (56–45 Ma). For its offshore part, it was developed to a considerable extent on the basis of our seismic data interpretation. For the Norwegian Barents Sea, the studies by Ziegler (1988), Faleide et al. (2010), Henriksen et al. (2011b) and Lasabuda et al. (2018) were used. For the Alaska region, the data in Houseknecht and Connors (2016) and Craddock and Houseknecht (2016) were used. For the Russian onshore,

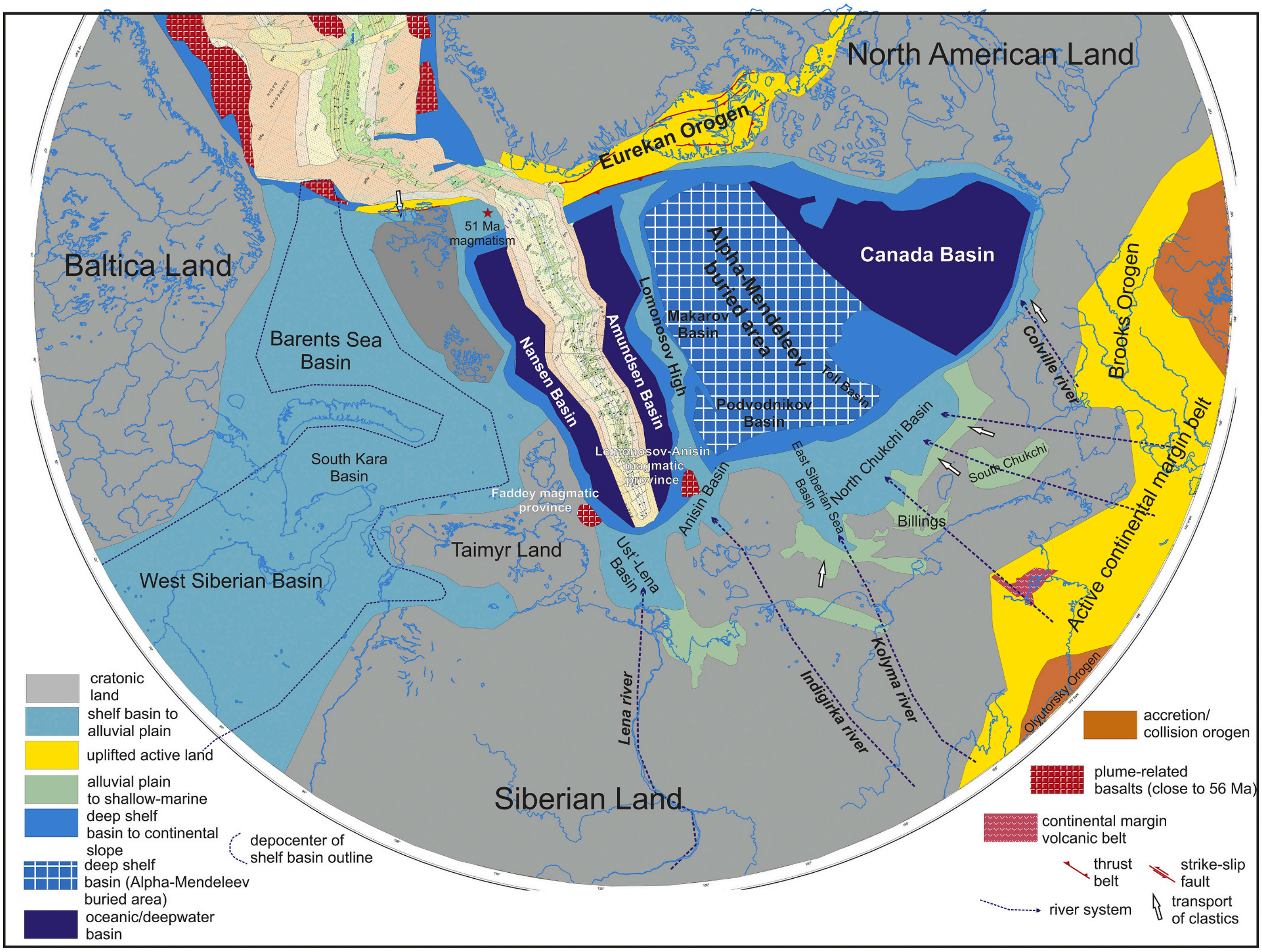

Fig. 12. Paleogeographic map of the Arctic for the Early-Middle Eocene (56–45 Ma) on the present-day geographic framework. Geographic base map is Geological map of the Arctic (Harrison et al., 2011).

the main studies are Grossgeym and Korobkov (1975), Akhmet'ev and Zaporozhets (2014), Yakovleva (2017) and Vasilieva (2017).

In the North Atlantic region, plume magmatism widely manifested itself at the end of Paleocene and beginning of Eocene, which transited into formation of volcanic continental margins and subsequent formation of the North Atlantic Ocean in the Eocene. This classical history is described in numerous publications (e.g., Abdelmalak et al., 2016; Faleide et al., 2010; Funck et al., 2017; Gaina et al., 2017; Torsvik et al., 2002; Wilkinson et al., 2017; Ziegler, 1988). We identified two new magmatic provinces at the boundary of the Laptev Sea Shelf and the Eurasia Basin on the basis of analysis of seismic profiles and magnetic field anomalies (see Paper 2). They are situated symmetrically relative to the Gakkel Ridge. Based on analysis of linear magnetic anomalies, the opening of the Eurasia Basin is assumed to start at ca. 56 Ma (e.g., Glebovsky et al., 2006). It appears that volcanic passive margins might form at the Siberian termination of the Eurasia Basin.

On the Lomonosov Ridge slope from the side of the Amundsen Basin, a breakup type boundary is readily identified on seismic lines (see Paper 1). In the Ust'-Lena Rift, a breakup type boundary is also well expressed on the side of Taimyr (see Paper 2).

On shore, Early Eocene deposits form several grabens (Gertseva et al., 2016; Grinenko, 1989). The best studied of them is probably the Kengday Basin situated east of the Lena River delta. Its deposits are presented by Ypresian-Lower Lutetian which overlies Paleozoic deposits with an angular unconformity (Grinenko, 1989; Grinenko et al., 1997). The graben is filled with continental coal-bearing sediments of about 500–700 m thickness with individual horizons of marine deposits in the form of marls. The main phase of rifting was in the Ypresian-Early Lutetian (ca. 56–45 Ma) in accordance with the available stratigraphy schemes (Gertseva et al., 2016; Grinenko, 1989). Early Eocene coal-bearing deposits are present in the Lower Kolyma Basin as well (Grinenko, 1989; Shulgina and Bashlavin, 2000).

Analysis of seismic lines for the Laptev Sea demonstrates that the Lower-Middle Eocene deposits (56–45 Ma) are thickest in the Ust'-Lena Basin (about 1 s). A phase of rifting took place in this basin. Analysis of seismic facies shows that in the Ust'-Lena Basin, the Lower-Middle Eocene is likely to be represented by non-marine and shallow marine deposits. A weak phase of rifting possibly took place in the Anisin-New Siberian Basin.

On the New Siberian Islands, Lower Eocene (Ypresian) deposits are known on the New Siberia Islands. They are represented by continental coal-bearing deposits of about 50 m thickness (Kos'ko and Trufanov, 2002; Kostyleva et al., 2018).

In the Chukchi Sea on the Ayon Island north of Chukotka, Ypresian deposits of about 25 m thickness are known from drilling data. They are represented by non-marine deposits (Aleksandrova, 2016).

Analysis of seismic lines for the North Chukchi Basin shows that Lower-Middle Eocene deposits (56–45 Ma) form a sedimentary cover of approximately even thickness (see Paper 2). Analysis of seismofacies shows that in the North Chukchi Basin, Early-Middle Eocene deposits have a facies transition from non-marine facies in the south to shelf ones in the north.

On the Alaskan Shelf, Lower-Middle Eocene non-marine and shallow marine deposits were sampled by wells (Ilhan and Coakley, 2018; Sherwood et al., 2002).

For the Arctic Beaufort-Mackenzie Basin, Lower-Middle Eocene deposits have been studied in the offshore well Natsek E-56 (Neville et al., 2017). They are represented mainly by clays with horizons of siltstones and conglomerates, with a total thickness of about 2 km. Sediments were formed on the continental shelf and slope and contain marine fossils. On the whole, the Lower-Middle Eocene is represented for the Alaskan and Canadian shelf by continental and shelfal sediments (Helwig et al., 2011; Houseknecht and Bird, 2011; Peters et al., 2011).

In the Early-Middle Eocene, the Eurekan Orogeny manifested itself in the north of Canada and Greenland (Elling et al., 2016; Lasabuda et al., 2018; Petersen et al., 2016; Piepjohn et al., 2016, 2015; Saalmann et al., 2005; Tegner et al., 2011). At that time, ca. 53–47 Ma, a transpressional orogen was formed in the north of Canada and Greenland, while a collisional orogen was formed in the west of Spitsbergen (Piepjohn et al., 2015). In the Eocene, the main phase of formation of the Central Tertiary Basin of Spitsbergen as a foredeep basin took place. Analysis of ages of detrital zircons in this basin shows that it was from the early Eocene. At this time the transport of sediments into the Central Tertiary Basin of Spitsbergen was from the side of the Eurekan Orogen (Petersen et al., 2016). Prior to this time the main transport of sediments took place from the Barents region (Elling et al., 2016; Petersen et al., 2016).

Within the Barents and Kara seas and West Siberia, Early-Middle Eocene deposits (56–45 Ma) overlie Paleocene deposits and form continuous stratigraphic sections. Paleogeography environments were on the whole constant. In the Early-Middle Eocene, an integral sedimentary basin probably existed in the area of the Barents and Kara Seas and in West Siberia. Eocene deposits are penetrated by wells in West Siberia (Akhmet'ev et al., 2010; Grossgeym and Korobkov, 1975; Vasilieva, 2017; Volkova, 2014; Yakovleva, 2017; Zyleva et al., 2014). Eocene deposits are known from wells in the South Kara Basin and on Yamal (Shishkin et al., 2015). They are represented by continental and shelf deposits with horizons of diatomites. In the Timan-Pechora Basin, Early-Middle Eocene sections are studied in several wells (Oreshkina et al., 1998). The Eocene is represented mainly by shelf diatomites. Marine shelf sediments are known for the western part of the Barents Sea only (Lasabuda et al., 2018). No reliable data are available on the presence of Eocene strata in the Russian part of the Barents Sea (Smelror et al., 2009). The presence of marine Early-Middle Eocene deposits in the West Siberian, Timan-Pechora and South Kara Basins suggests that the entire Barents-Kara region in the Early-Middle Eocene (56–45 Ma) was a shelf sea, that periodically desiccated and became a sub-aerial flatland.

Early-Middle Eocene deposits are studied for the Lomonosov Ridge based on data of ACEX boreholes (Backman et al., 2008; Backman and Moran, 2009; Brinkhuis et al., 2006). The lower unit with an age of ca. 56–50 Ma is represented by silty clay and clay. The upper unit with an age of ca. 50–45 Ma is represented by biosiliceous ooze. In the Early-Middle Eocene, euxinic shelf sedimentation prevailed (Backman et al., 2008; Backman and Moran, 2009; Brinkhuis et al., 2006; Moran et al., 2006).

In the Eurasia and Amerasia basins, Early-Middle Eocene deposits (56–45 Ma) are well traced as a package with bright reflections (see Paper 1). This distinctive acoustic signature is probably a result of a lithologic composition that is distinct from overlying and underlying deposits. We believe that siliceous deposits may be present in the composition of Lower-Middle Eocene deposits.

In the Early-Middle Eocene, an active orogeny along the Pacific margin of Asia and Alaska formed. A continental-marginal orogen was formed in the strip from Sakhalin and the Sea of Okhotsk to Koryakia and along the Brooks Range (Sokolov, 2010; Soloviev, 2008).

We compiled a kinematic reconstruction of the Arctic for the end of Paleocene and the Early-Middle Eocene (~56 Ma) within the framework of the GPlates software and our geodynamic concept (Freiman et al., 2018; Nikishin et al., 2017a, 2017b; Nikishin et al., 2015), presented in Fig. 13. We superimposed our paleogeography data onto the geometrical reconstruction. Three major tectonic events took place at that time: (1) opening of the North Atlantic Ocean and of the Eurasia Basin started after the epoch of plume magmatism; (2) the Eurekan Orogen developed; (3) a continental-marginal orogen was formed along the Pacific margin of Asia and North America.

3.9. Middle-Late Eocene history of the Arctic

Fig. 14 displays our paleogeography map for the Middle-Late Eocene for the time interval of 45–34 Ma. For the offshore part, it is developed to a considerable extent on the basis of our seismic data interpretation. For the Norwegian Barents Sea, the studies of Ziegler (1988), Faleide et al.

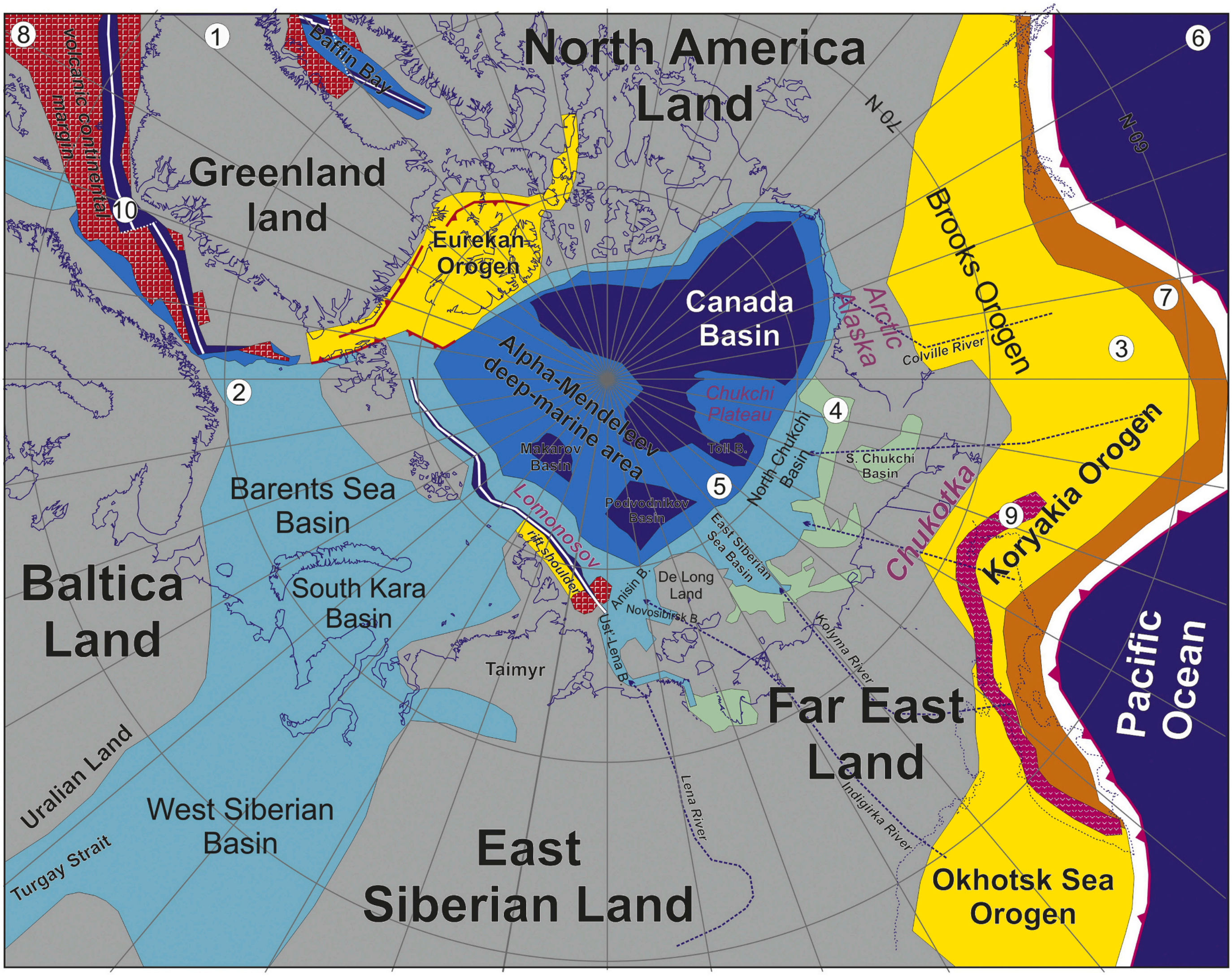

Fig. 13. Tectonic restoration of the Arctic region for the Early-Middle Eocene (56–45 Ma). Kinematic restoration for the 56 Ma. Restoration was performed using GPlates programme. Legend is similar to Fig. 12. 1 – cratonic land, 2 – shelf basin, 3 – uplifted active land, 4 – alluvial plain to shallow-marine, 5 – deep shelf basin to continental slope, 6 – oceanic/deepwater basin, 7 – accretion/collision orogen, 8 – plume-related basalts, 9 – continental margin volcanic belt, 10 – spreading axis. Violet letters mark position of some terranes and their names. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(2010), Henriksen et al. (2011b), and Lasabuda et al. (2018) were used. For the North American region, the data in Houseknecht and Connors (2016), Craddock and Houseknecht (2016) were used. For the Russian onshore, the main data are presented in Grossgeym and Korobkov (1975), Akhmetiev and Zaporozhets (2014), Yakovleva (2017) and Vasilieva (2017).

This interval of time is characterized by the diversity of tectonic processes. In the Arctic, there were three zones of formation of oceanic crust with spreading axes: the North Atlantic, Baffin Bay, and Eurasia Basin (e.g., Ziegler, 1988). In the Eurasia Basin, ultraslow spreading started at ca. 45 Ma (e.g., Glebovsky et al., 2006; Nikishin et al., 2018), which continues until the present time. The time interval of 45–34 Ma is characterized by the main compressional phase of the Eurekan Orogen and formation of the Central Tertiary Basin of Spitsbergen as a foredeep basin (Døssing et al., 2014; Elling et al., 2016; Gaina et al., 2015; Kleinspehn and Teyssier, 2016; Lasabuda et al., 2018; Petersen et al., 2016; Piepjohn et al., 2015; Saalmann et al., 2005).

Within the Barents and Kara Seas and the north of West Siberia and Yamal, Middle-Late Eocene deposits (45–34 Ma) are absent. Middle-Late Eocene deposits are penetrated by wells in the central and southern parts of West Siberia (Akhmet'ev et al., 2010; Grossgeym and Korobkov, 1975; Vasilieva, 2017; Volkova, 2014; Yakovleva, 2017; Zyleva et al., 2014). They are represented mainly by marine clays and siltstones (siliceous deposits disappear at ca. 45 Ma) (Akhmet'ev et al., 2010; Vasilieva, 2017; Yakovleva, 2017). Marine shelf sediments are known for the westernmost part of the Barents Sea (Lasabuda et al., 2018; Smelror et al., 2009). Recent paleogeography reconstructions show that the West Siberian Basin was separated by a vast land mass from the Arctic water basin in the Lutetian time at ca. 48–43 Ma (Akhmet'ev et al., 2010; Shatsky, 1978; Vasilieva, 2017; Yakovleva, 2017).

In the area of Yamal and South Kara Basin, wells penetrated Paleocene and Eocene deposits (Kontorovich et al., 2010; Shishkin et al., 2015; Viskunova et al., 2004).The youngest Paleogene sediments are strata with diatomites with ages from the Thanetian to Middle Ypresian (about 58–52 Ma) (the Serov and Irbit Formations) (Shishkin et al., 2015; Viskunova et al., 2004; Yakovleva, 2017). Up the section, Pliocene strata occur with an angular unconformity. In the South Kara Basin, it is assumed on the basis of seismic data interpretation that Early Eocene

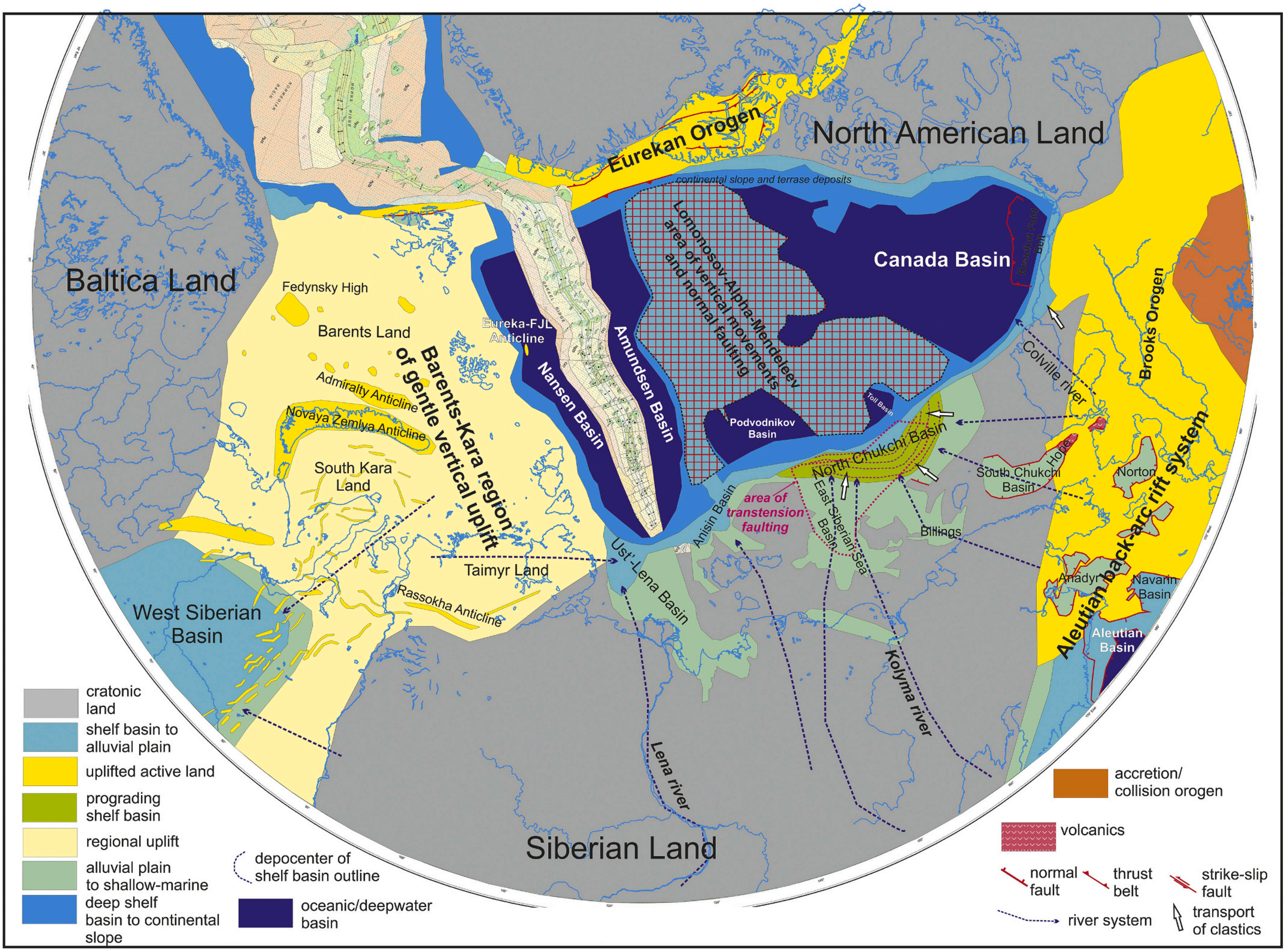

Fig. 14. Paleogeographic map of the Arctic for the Middle-Late Eocene (45–34 Ma) on the present-day geographic framework. Geographic base map is Geological map of the Arctic (Harrison et al., 2011).

deposits are overlain by thin Oligocene strata with an angular unconformity (Petrov, 2012; Viskunova et al., 2004). Data for the Yamal and the South Kara Basin show that starting from the Lutetian time, these areas experienced uplift and erosion. Probable low-angle folding took place before the Oligocene as presumed Oligocene deposits overlie the Paleocene-Eocene deposits with an angular unconformity. However, Oligocene deposits are not penetrated by wells at the present time and no stringent substantiation for this hypothesis is available yet. In West Siberia, a regional pre-Oligocene unconformity is known (Akhmet'ev and Zaporozhets, 2014; Grossgeym and Korobkov, 1975; Volkova, 2014; Volkova et al., 2016; Yakovleva, 2017). Oligocene and Miocene deposits are formed by a single series of mainly continental sedimentary rocks (Grossgeym and Korobkov, 1975; Volkova et al., 2016).

Within the West Siberian, Barents and South Kara basins, many anticlinal folds and anticlinal highs formed after the Cretaceous (Nikishin et al., 2015). In West Siberia, such anticline-like swells have been identified for a long time and they are known to have formed in the Cenozoic (exact time is not known) (Brekhuntsov et al., 2011; Kontorovich et al., 2010; Kontorovicha et al., 2016). In the Yenisey-Khatanga Basin, Mesozoic, Paleocene and Early Eocene deposits make part of the stratigraphic section of swells (Afanasenkov et al., 2016; Unger et al., 2017). The last phase of their growth was after the Early Eocene. A large number of anticline-like swells are located in the South Kara Basin. Deposits from Jurassic to Late Cretaceous age make part of the structure of these folds (Kontorovich et al., 2010; Nikishin et al., 2015; Nikishin, 2013) (Fig. 15). Since in the South Kara Basin, Paleocene and Lower Eocene deposits conformably overlie Cretaceous deposits, we anticipate that deposits up to the Lower Eocene were present in structure of these anticlinal swells. Analysis of seismic profiles shows that an angular unconformity is present in the South Kara Basin. Late Cenozoic sediments overlie Cretaceous and Paleocene-Lower Eocene sediments with an angular unconformity. Although ages of the Late Cenozoic (pre-Quaternary) deposits are not exactly dated, we assume an Oligocene age for this unit. In the Barents Sea, a large number of anticlinal swells are present; in which Upper Cretaceous deposits constitute part of the structure (presence of the Cenomanian is proved (e.g., Mordasova, 2018)). The following known structures belong to them: the Admiralty Swell, Fedynsky High, Shtokman High (e.g., Henriksen et al., 2011b, 2011a; Nikishin et al., 2015; Stoupakova et al., 2011) (Fig. 16). Our reconstructions show that deposits of the entire Upper Cretaceous and, possibly, of the Paleocene-Lower Eocene took part in the formation of these anticlinal highs. In the Barents Sea north of Novaya Zemlya, based on interpretation of commercial seismic lines, Jurassic-Cretaceous deposits are locally overlain by Cenozoic (pre-Quaternary) deposits with an angular unconformity. Although their age is not strictly dated, we assume that these are Oligocene-Neogene deposits. Seismic data interpretation shows that the time of formation of anticlinal highs was determined as between the middle of the Late Cretaceous and the

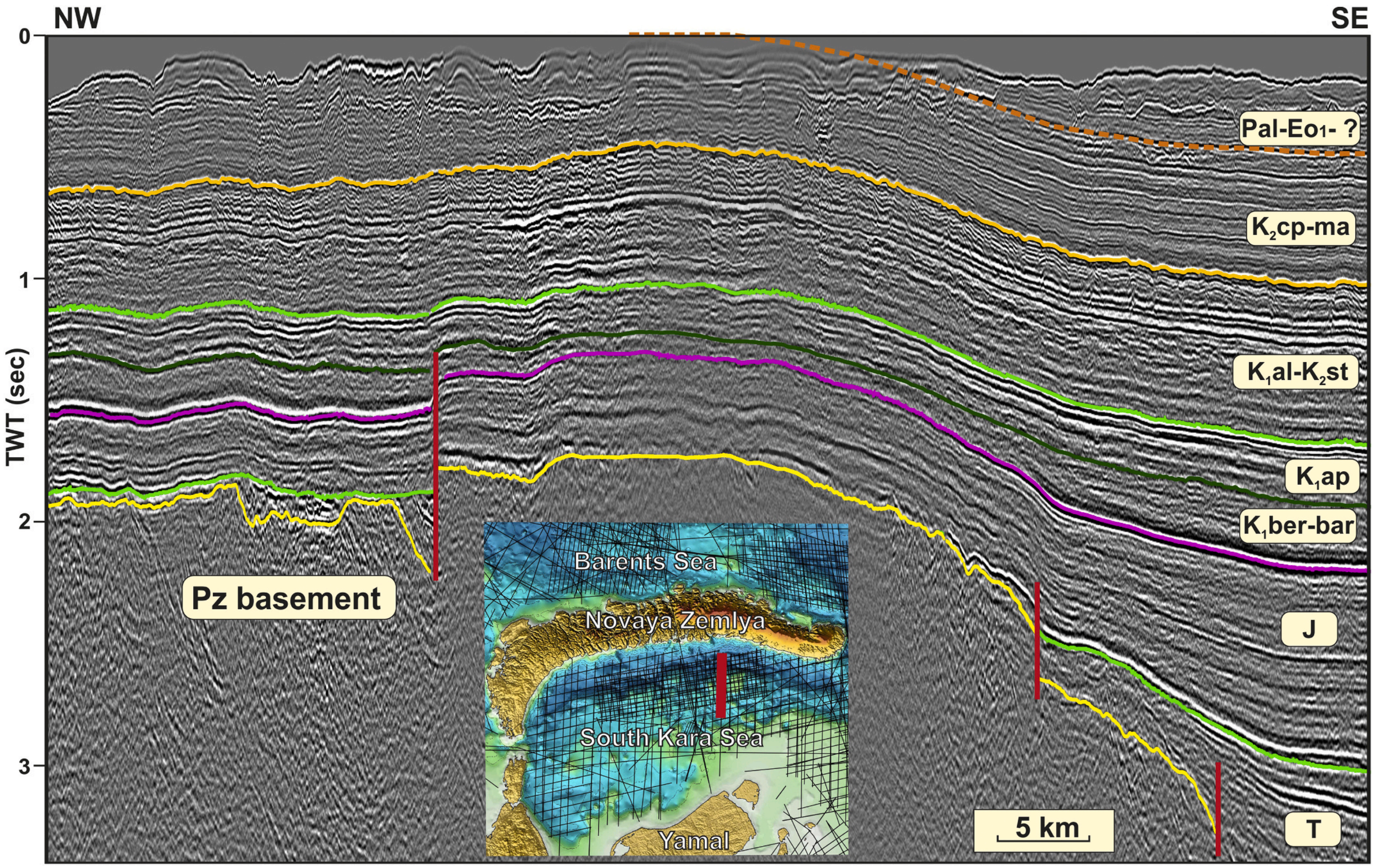

Fig. 15. Interpretation of seismic line for the Universitetskaya Swell, South Kara Basin (Nikishin et al., 2015; Nikishin, 2013, modified). The anticline structure originated after Late Cretaceous time, and possibly after Early Eocene time.

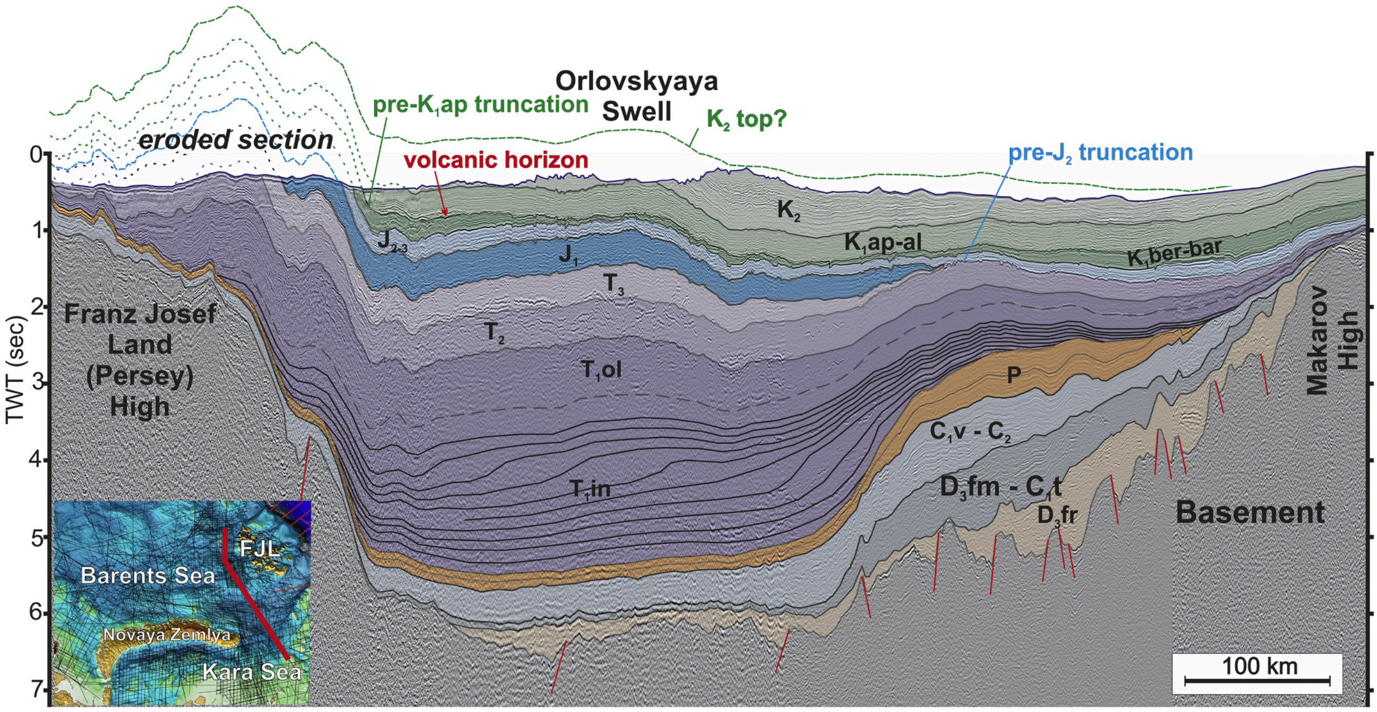

Fig. 16. Interpretation of regional seismic line 4-AR for the East Barents Magabasin. Modified after (Nikishin et al., 2015; Startseva et al., 2017). The anticline structures originated after Late Cretaceous time. Volcanic horizon is observed on a number of seismic lines. This is a prolongation of the Franz Josef Land volcanic province.

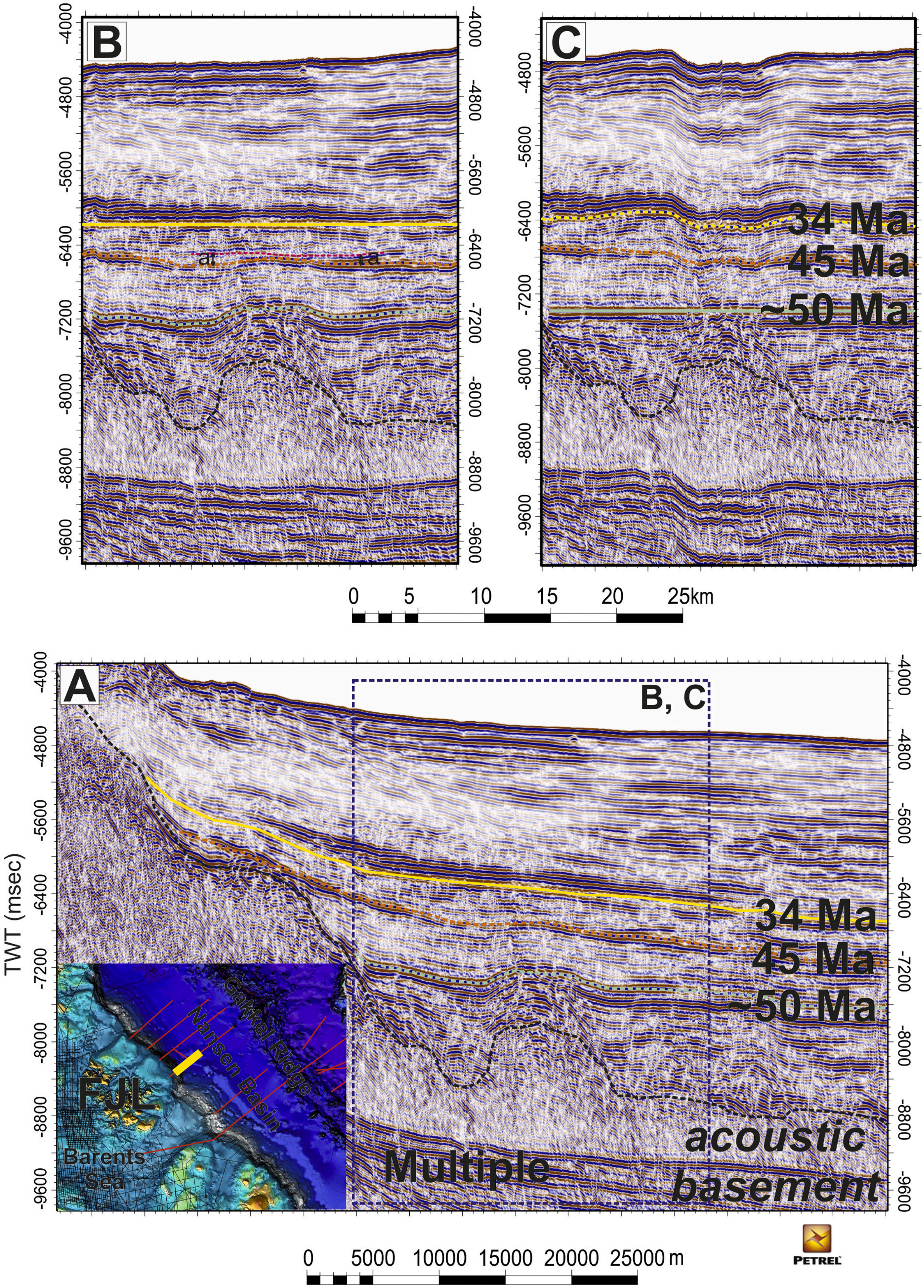

Fig. 17. A. Interpretation of seismic line ARC11–006 for the Amundsen Basin. Based on Nikishin et al. (2018) with additional data. A small anticline of the Eocene time origin can be recognized. B and C. Flattening for horizons 34 Ma and 50 Ma.

Neogene. The available data suggest that the main epoch of anticlinal folds formation was between the Lutetian (Eocene) and the Oligocene. The main argument in favor of our hypothesis is the observation that regional uplift in the north of West Siberia started in the Lutetian. In West Siberia, the Oligocene unconformably overlies Eocene and Paleocene deposits. Our preliminary and unpublished AFT data for Franz Josef Land show that maximum subsidence occurred in the Maastrichtian-Eocene. Regional uplift started from the end of Eocene and took place in the Oligocene-Neogene. AFT data available for the Fersmanovskaya-1 well on the Fersman High, show that uplift started in the Early Paleocene at ca. 60 Ma (Sobolev and Soloviev, 2013). These AFT data do not contradict our hypothesis that the main formation time of anticlinal highs was between the Lutetian and the Oligocene.

We studied seismic profiles for the Nansen Basin (Nikishin et al., 2018). Only seismic line ARC11-006 shows evidence for Cenozoic tectonic compressional deformation. Interpretation of this line demonstrates a small anticline structure originated before the Oligocene. Preliminary seismic stratigraphy based on linear magnetic anomalies points to a timing of anticline growth between 50 Ma and 34 Ma (Fig. 17).

The hypothetical time of formation of anticlines-swells in the vast area from West Siberia to the Barents and Kara Seas, and Nansen Basin coincides with the epoch of maximum of the period of compression during the Eurekan Orogeny.

In the Laptev Sea Basin, Middle-Upper Eocene deposits are known along the Laptev Sea coast and also in the Lower Kolyma Basin (Gertseva et al., 2016; Grinenko, 1989; Grinenko et al., 1997; Shulgina and Bashlavin, 2000). These are thin-thickness continental deposits (the Tenkichen and Parshinsky Horizons) which unconformably overlie underlying Early-Middle Eocene deposits. It is likely that a restructuring of the paleogeography took place at the Laptev Sea coast at circa 45 Ma.

Within the Laptev Sea, Upper Eocene deposits are known on the Belkovsky Island (Kuzmichev et al., 2013). Devonian deposits are overlain by strata of Upper Eocene – Lower Miocene continental deposits, of about 40 m thickness.

For the Laptev Sea Basin, it appears from our seismic data interpretation that continental and shelf sediments accumulated within it. The northern part of the basin is characteristic of clinoforms directed toward the Eurasia Basin. The time interval of 45–34 Ma is characterized by a weak manifestation of normal faults, i.e. a small-scale rifting was taking place, possibly in a transtensional tectonics regime.

Within the North Chukchi Basin and the East Siberian Sea Basin, the

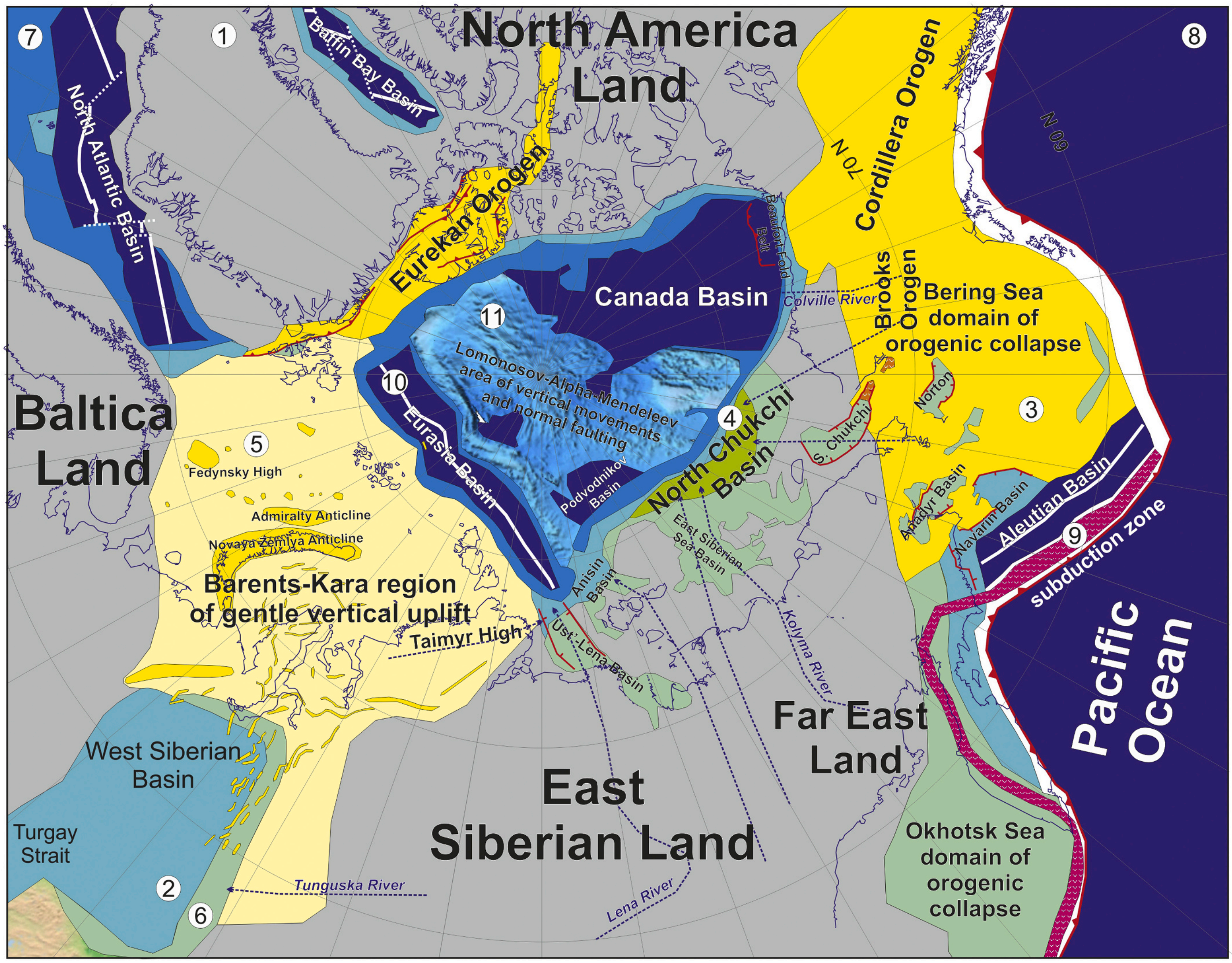

Fig. 18. Tectonic restoration of the Arctic region for the Middle-Late Eocene (45–34 Ma). Kinematic restoration for the 45 Ma. Restoration was performed using GPlates programme. Legend is similar to Fig. 14. 1 – cratonic land, 2 – shelf basin, 3 – uplifted active land, 4 – prograding shelf basin with clinoform sedimentation mainly, 5 – region of gentle vertical uplift, 6 – alluvial plain to shallow-marine, 7 – deep shelf basin to continental slope, 8 – oceanic/deepwater basin, 9 – continental margin volcanic belt, 10 – spreading axis, 11 area of vertical movements and normal faulting (main time of recent bathymetry generation).

main event in the Middle-Late Eocene (45–34 Ma) was formation of the “upper” clinoform complex with strongly pronounced progradation toward the Amerasia Basin (see Paper 2). At approximately 45 Ma, the shelf edge moved landward. As this transgression cannot be explained by eustasy alone, a short-term tectonic event is likely, which resulted in a rapid subsidence of the shelf area. Analysis of seismic data shows that within the North Chukchi Basin and East Siberian Sea Basin a facies transition takes place from continental deposits to shelf deposits and subsequently to deep-water deposits with turbidites.

Within the North Chukchi Basin and East Siberian Sea Basin, a large number of low-amplitude normal faults are identified, with ages of about 45 Ma (see Paper 2). We suppose that they formed during a short-term intensive regional phase of transtensional tectonics.

In the Chukchi Sea in the Ayon well on the Ayon Island, Lutetian and Bartonian deposits (48–38 Ma) are absent. The main hiatus occurs just at this time. Thin Priabonian deposits (38–34 Ma) are represented by continental sediments (Aleksandrova, 2016).

On the Alaska Shelf, Middle-Upper Eocene deposits are penetrated by the Crackerjack-1 and Popcorn-1 wells (Sherwood et al., 2002). They are represented by sampled continental and shallow-water marine sediments.

The tectonic event at ca. 45 Ma and the onset of accumulating deposits of the “upper” clinoform complex of the North Chukchi Basin corresponds in time to the uplift phase of the Brooks Range in Alaska (~45 Ma) (Craddock et al., 2018; O’Sullivan et al., 1997).

In the South Chukchi Basin, continental sedimentation is inferred for the Middle-Late Eocene based on seismic data interpretation in the South Chukchi Basin. The Hope Basin is situated at the eastern continuation of the South Chukchi Basin. Wells are available within this basin. The Paleozoic basement is overlain by Middle-Upper Eocene strata with volcanites and tuffs. Isotopic ages of 42.3 Ma and 40.7 Ma are known for the volcanites (Sherwood et al., 2002). It is likely that rifting took place

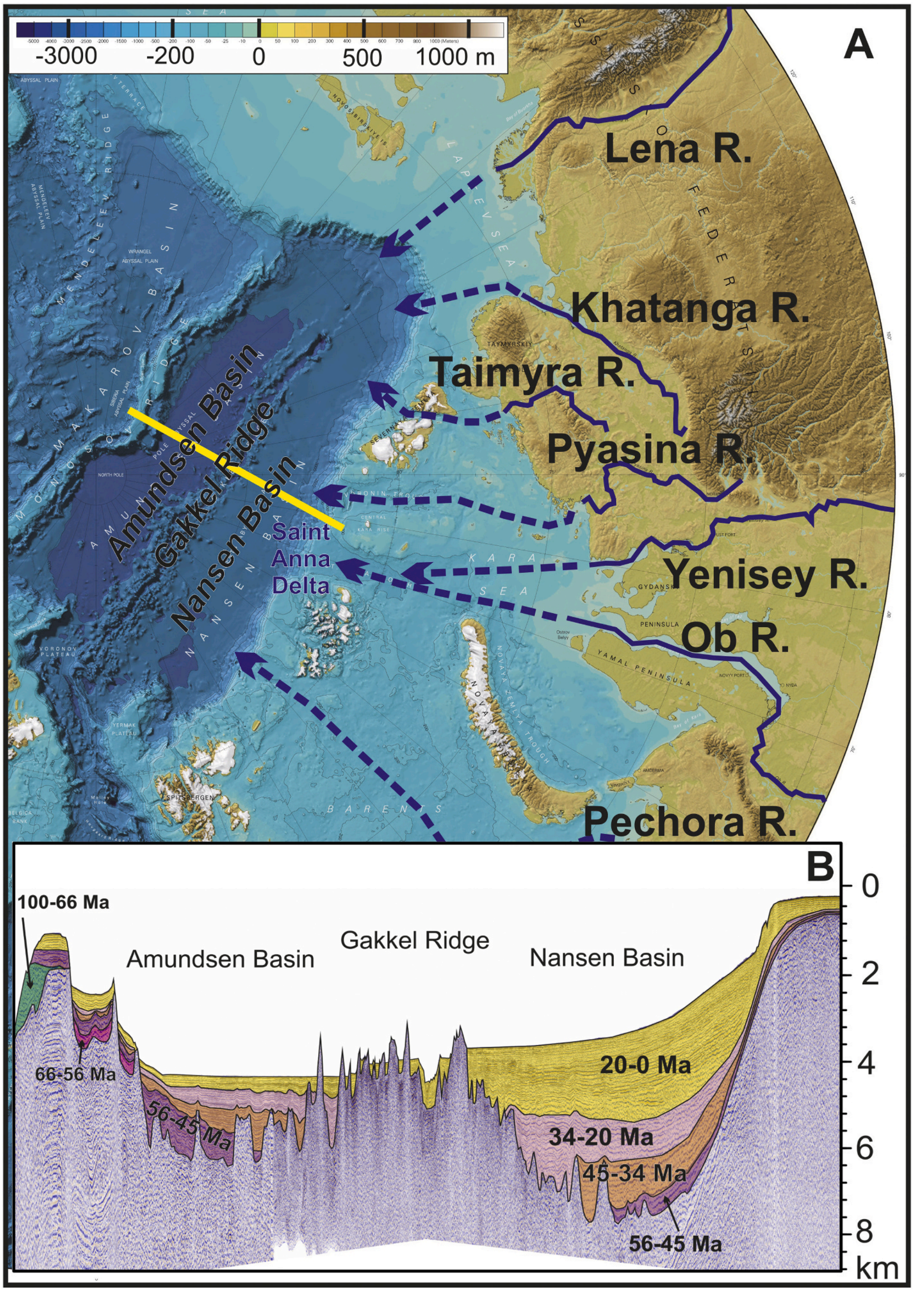

Fig. 19. **A**. Topographic map of part of Arctic region with proposed river systems for the Neogene to Quaternary time. **B**. Interpretation of seismic line ARC 14–07 for the Eurasian Basin. Location is yellow line in “A”. Asymmetry of the Eurasian Basin is well observed. Topographic map after Jakobsson et al. (2012). Saint Anna Delta is in our hypothesis partly based on limited seismic data. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

during formation of the basin.

A system of Eocene sedimentary basins is situated within the Bering Sea Shelf and the Russian onshore area of Chukotka and Koryakia. The Anadyr Basin and Norton Basin belong to them (Kharakhinov et al., 2014; Klemperer et al., 2002; Nikishin et al., 2015). The Eocene Khatyrka and Navarin Basins are a part of the passive continental margin of the Aleutian Basin (Kharakhinov et al., 2014; Nikishin et al., 2015). Basic information concerning these basins, with wells and seismic lines, is presented in Kharakhinov et al. (2014). All these basins are characteristic of the lower rift complex represented by the Mainitsky stratigraphic horizon of Lutetian-Oligocene age. This is a synrift complex with prevalence of continental deposits. Rifting in these basins was probably synchronous with rifting in the Hope Basin. Rifting in the Khatyrka and Navarin Basins in the Late Eocene or Oligocene probably transited into opening of the back-arc Aleutian Basin with an oceanic crust.

Low-amplitude normal faults formed in Amerasia Basin on the Alpha-Mendeleev and Lomonosov ridges in the Middle-Late Eocene (see Paper 2).

We compiled a kinematic reconstruction of the Arctic for the Middle-Upper Eocene (~45 Ma), presented in Fig. 18.

During this time, the following major tectonic events took place: (1) The Gakkel Ridge became an ultraslow spreading center after 45 Ma. (2) The maximum of the Eurekan Orogeny took place in the north of Greenland and the Canadian Arctic Archipelago Islands. (3) The vast area of the Barents and Kara seas and the north of West Siberia experienced syncompressional uplift and numerous anticline-like swells formed. (4) Within the Amerasia Basin on the Alpha-Mendeleev and Lomonosov ridges and the Chukchi Plateau, low-amplitude faults were formed in extensional and transtensional environments together with differential vertical movements. (5) At circa 45 Ma, within the sedimentary basins of the Chukchi, East Siberian and Laptev seas, a restructuring of paleogeography occurred with vertical movements and formation of low-amplitude normal faults. (6) A continental rifting phase took place in the areas of the Chukchi and Bering Seas (e.g. Hope Basin and Anadyr Basin). It started with collapse of the orogen in the area from the Sea of Okhotsk and Kamchatka to the Bering Sea.

3.10. *Oligocene-Neogene history of the Arctic (34–2.6 Ma)*

The Oligocene-Neogene history of the Arctic is relatively well known and this topic is beyond the scope of the present paper. Here we will note three principal points. (1) Oligocene-Quaternary sediments are thicker in the Nansen Basin than in the Amundsen Basin (Fig. 19). A thick series of Neogene-Quaternary sediments is present in the Nansen Basin (see Paper 2). We suppose that at that time the main rivers of Siberia of the type of the Ob, Yenisey, etc. together with paleo-ice streams flowed into the Nansen Basin and formed numerous deltaic systems. We identify a major Saint Anna Delta. (2) Activation of several normal faults on slopes of Lomonosov and Alpha-Mendeleev ridges continued (see Paper 2). (3) Within the East Siberian and Chukchi Seas, many faults and transpression zones were active post-34 Ma (Ikhsanov, 2014; Nikishin et al., 2015). Analysis of seismic profiles showed that there are many more of such zones than previously thought.

4. Discussion

In this study, we present new data together with a synthesis of published data on the geology of the Arctic. These data allow to resolve the history of the Arctic Ocean. Here we present several new concepts and approaches.

The new models presented in this study show that it is difficult to use the classical "rotational" model to explain the opening of Amerasia Basin with the main transform along the Lomonosov Ridge (e.g., Grantz et al., 2011b, 2011a). There are two groups of principal arguments against this model. (1) The Alpha-Mendeleev ridges have continental (pre-Ordovician) basement and the Paleozoic cover was preserved within it. It follows from this that in the course of opening of Canada Basin; the main transform boundary might run along the edge of these ridges rather than along that of the Lomonosov Ridge. (2) Preliminary data from interpretation of seismic lines show that in the area of the Alpha-Mendeleev ridges and of contiguous basins of the type of Podvodnikov and Toll Basins, the main strike of structures is perpendicular relative to the strike of the spreading axis in Canada Basin. A similar conclusion was suggested in Hegewald and Jokat (2013).

The opening of Canada Basin, according to our model, had no geometrical relation with closure of the South Anyui Ocean (Orogen) as usually assumed in many recent studies (e.g., Grantz et al., 2011b, 2011a). The Verkhoyansk-Chukotka Orogen which includes the South Anyui Suture was a continental-marginal orogen of the "Cordillera" type. In the course of its formation, terranes were moving toward Asia and the Arctic accompanied by formation of oroclines. Synchronously with the Verkhoyansk-Chukotka and Mongol-Okhotsk orogenies, inversion tectonics with growth of numerous anticlinal highs manifested itself in the vast area of the Barents, South Kara, West Siberian and Yenisey-Khatanga Basins.

We consider the Alpha-Mendeleev ridges as a volcanic edifice on a continental crust. Around this ridge, as a minimum five volcanic plateaus are identified: Sverdrup on the Canadian Islands, Svalbard and Franz Josef Land in the north of the Barents Sea, De Long in the north of the East Siberian Sea, and the proposed North Chukchi Plateau north of the Wrangel Island. Magmatism in these areas started at about ±125 Ma. Near the same time, magmatism started on the Alpha-Mendeleev ridges as well. Synchronously with the start of magmatism or somewhat later, large-scale continental rifting started in the North Chukchi Basin, in the Laptev Sea Basin, in the North Atlantic, and in the Baffin Bay. In the course of formation of the North Chukchi rift basin, strike-slip tectonics widely manifested itself. Magmatism within the Alpha-Mendeleev Ridge was completed at ca. 80 Ma. We assume that the Alpha-Mendeleev ridges started to form as a rift system with wide-scale magmatism, but rifting had not transited into oceanic crust spreading. We propose to classify the Alpha-Mendeleev ridges as an aborted volcanic passive continental margin. Foulger et al. (2019) proposed a new geodynamic model for the Greenland-Iceland-Faroe Ridge. We propose that the early stage of the history of the Greenland-Iceland-Faroe Ridge represents a possible geodynamic model for the Alpha-Mendeleev ridges.

Approximately at the Cretaceous/Paleocene boundary and in the Paleocene, formation of the major continental-marginal orogen was going on in the strip from the Sea of Okhotsk and West Kamchatka to Koryakia and the Brooks Orogen. Filling-up of the North Chukchi Basin with the thick sedimentary cover with clinoform structure was connected with this event. At that time, thrust belts were actively forming in the Chukchi Sea and on Alaska. Approximately simultaneously, continental rifting was underway in the Ust'-Lena Basin of the Laptev Sea and along the future Eurasia Basin.

At the Paleocene/Eocene boundary, plume basaltic magmatism widely manifested itself in the area of the North Atlantic, which was followed by opening of the North Atlantic Ocean and prevalence of volcanic continental margins (e.g., Torsvik et al., 2002; Ziegler, 1988). We have revealed two possible igneous provinces in the north of the Laptev Sea. The formation of these two provinces probably preceded opening of the Eurasia Basin. In this case, we observe similarity in the geodynamics of opening of the North Atlantic and Eurasia oceanic basins. Anomalies in the upper mantle in the eastern part of the Eurasia Basin (approximately at the place where we identify igneous provinces) on the whole resemble anomalies in the North Atlantic according to new seismic tomography data (Lebedev et al., 2018). This is an additional argument in favor of our hypothesis concerning new igneous provinces in the east of the Eurasia Basin.

At circa 45 Ma, a very interesting superregional complex tectonic event occurred; the chronology of which is uncertain: 1) the Gakkel Ridge started to experience ultraslow spreading (e.g., Glebovsky et al., 2006); 2) the maximum collision in the Eurekan Orogen started (e.g.,

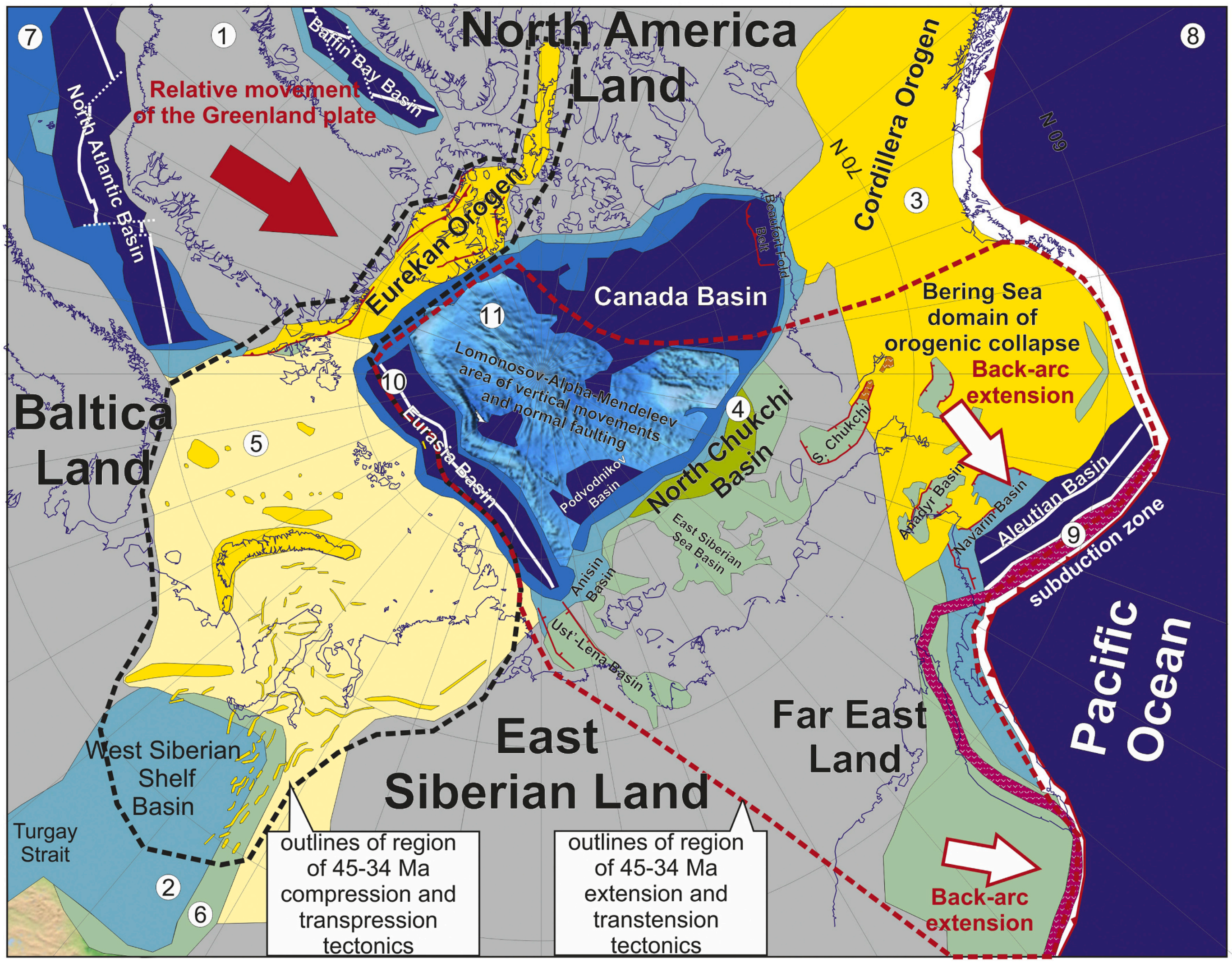

Fig. 20. Two superdomains of the 45–34 Ma regional intraplate tectonics in the Arctic region (see Fig. 18 for the legend). Relative movement of the Greenland plate led to Eurekan Orogeny and intensive compression/transpression intraplate tectonics in the Barents-Kara-West Siberia region. Gakkel Ridge, Alpha-Mendeleev Ridge, and Chukchi-Bering-Okhotsk seas region underwent extension and transtension intraplate tectonics as a back-arc region for the Pacific subduction system.

Gaina et al., 2015). In the North Chukchi Basin, after a short-term tectonic event, the shelf edge sharply moved southward by 200–300 km; 3) in the area of the North Chukchi Basin, formation of low-amplitude normal faults in a possible transtensional environment widely manifested itself; 4) in the area of the Chukchi and Bering Seas, continental rifting widely manifested itself; 5) in the area of the Lomonosov and Alpha-Mendeleev ridges, numerous normal faults reactivated in extension and transtensional environments. At that time, a paleogeographic restructuring with regional uplifting took place in the vast area of the Barents-Kara Seas and West Siberia. In the course of this process, growth of numerous intraplate anticlinal highs started in compressional or transpressional environments. On the whole, we see that the tectonic regime on either side of the Eurasia Basin was quite different. In the Barents-Kara region, compression prevailed, while in the area of the Amerasia Basin and the shelves of Siberia, extension prevailed. The simplest explanation comes down to the idea that the collision of the Greenland and Eurasian lithosphere plates in the area of Spitsbergen resulted in compression of the Barents-Kara region. This collision did not propagate to the area of the Amerasia Basin and its Russian-Alaskan shelf. The Amerasia-Chukotka-Bering superdomain had a possibility to stretch out toward the Pacific Ocean in a regional "back-arc" environment (Fig. 20). This issue obviously deserves further special analysis.

We do not know well the structure of the continental basement of the Arctic region. In accordance with the model presented in Fig. 1, the Eurasia Basin had opened along a possible Caledonian suture. The Caledonian suture was widely utilized for formation of strike-slip faults in the course of formation of the North Chukchi Basin. The Canada Basin probably formed along fabrics of the former Ellesmere Orogen.

The Arctic Ocean was always in the polar regions during the entire Cretaceous and Cenozoic time (e.g., Shephard et al., 2013). Sedimentation in polar regions is strongly dependent on paleoclimate. Therefore, study of the sedimentary cover will help us restore the history of global climate (e.g., Stein, 2008). Different types of sediments have different velocity characteristics on seismic sections. In the section of the Arctic Ocean, we observe as a minimum two sequences on seismic profiles with regionally developed bright reflection: HARS in the upper part of the section (Nikishin et al., 2015; Weigelt et al., 2014) and HARS-2 in the lower part of the section (see Paper 2). In accordance with our stratigraphic model, the HARS sequence corresponds to an age of 56–45 Ma and siliceous deposits, which are known for the ACEX boreholes, are present in its section. The epoch of 56–45 Ma is characteristic for several intervals of time with significant climate warming (Cramer et al., 2009; Gradstein et al., 2012; Stein, 2008).

The HARS-2, in accordance with our seismic stratigraphy model, has an age of about 80–100 Ma. This period also corresponds to a time of global warming (e.g., O'Brien et al., 2017). It is probable that in the Arctic, rocks of this stratigraphic level have a special lithology. For example, siliceous deposits may be present. Deposits of the HARS and HARS-2 can be considered as regional source rocks in analysis of hydrocarbon systems of the Arctic. This is proven for deposits of the HARS (Mann et al., 2009).

According to our model for the paleogeographical history of the Arctic, significant changes in paleogeography happened at circa 45 Ma (see Fig. 18). The main event was connected with sub-aerial exposure of the shelves of the Barents and Kara Seas and the north of West Siberia. This event resulted in abrupt cooling in the Arctic and cessation of siliceous sediment production (e.g., Stein, 2008; Stein et al., 2015).

5. Conclusions

An atlas of paleogeographic and paleotectonic maps showing main events in the history of the Arctic during the period of 0–157 Ma is presented in this paper. The following main conclusions obtained by us are:

1. There are Timanides, Caledonides, Ellesmerides, and Uralides-Taimyrides terranes within continental basement rocks underlying the greater Arctic Basin.
2. The Mendeleev Ridge has a possible continental pre-Ordovician basement.
3. The classical rotational model for opening of the Amerasia Basin with the main transform fault along the Lomonosov Ridge likely can revised. The data suggesting that the Mendeleev (or Alpha-Mendeleev) Ridge possibly has a continental basement contradicts this model. Additional investigations are needed to resolve this question.
4. The following chronology of events in the history of the Arctic Ocean is proposed since Kimmeridgian: (**1**) Kimmeridgian-Tithonian (157–145 Ma): continental rifting occurred in the area of the Sverdrup-Banks basins and in the area of the present-day Canada Basin; a system of continental-margin volcanic belts was formed in the area of Chukotka and the Verkhoyansk-Omolon area; closure of the hypothetical South Anyui Ocean was not associated with opening of Canada Basin; (**2**) Berriasian-Barremian (145–125 Ma): formation of the Verkhoyansk-Chukotka continental-margin orogen with the South Anyui and Kolyma oroclines; fast opening of Canada Basin (~133–125 Ma); intraplate compressional and transpressional tectonics in the basins of the Barents and South Kara Seas and in the north of West Siberia; (**3**) Aptian-Albian (125–100 Ma): formation of continental igneous provinces (for the Aptian, five areas of basaltic magmatism are identified on the shelf: Franz Josef Land, Svalbard, Sverdrup, De Long and North Chukchi areas); rifting and magmatism in the area formed the Alpha-Mendeleev ridges; rifting in the Ust'-Lena, Anisin, North-Chukchi, Podvodnikov and Toll Basins; synchronous rifting in the North Atlantic and in Baffin Bay; (**4**) Cenomanian-Campanian (100–80 Ma): intraplate magmatism in the area of the Alpha-Mendeleev ridges; basaltic magmatism in the north of North America; (**5**) Campanian-Maastrichtian (80–66 Ma): a likely start of compressional deformations in the area of the Chukchi Sea; a likely start of transtensional tectonics in the area of the Makarov and Ust'-Lena Basins; (**6**) Paleocene (66–56 Ma): in the wide strip from the Sea of Okhotsk to Koryakia and Alaska, formation of a continental-margin orogen; continental rifting took place along the present-day Eurasia Basin and the Ust'-Lena Basin; the Makarov Basin was likely formed as a pull-apart basin; (**7**) Early-Middle Eocene (56–45 Ma): after the epoch of plume magmatism, opening of the North Atlantic Ocean and of the Eurasia Basin started; a continental-margin orogen was formed along the Pacific margin of Asia and North America; the Eurekan Orogen was actively developed; (**8**) Middle-Late Eocene (45–34 Ma): at about 45 Ma, a major restructuring of the Arctic's paleogeography and paleotectonics took place with subaerial emergence of the Barents and Kara Sea shelves, onset of ultra-slow spreading at Gakkel Ridge, formation of normal and strike-slip faults on Lomonosov and Alpha-Mendeleev ridges and on the Chukchi Sea and East Siberian Sea shelves; collapse of orogens in the Bering and Okhotsk seas; maximum compression in the Eurekan Orogen; (**9**) Oligocene-Neogene (34–2.6 Ma): formation of the Eurasia Basin continued; activation of normal faults in the Amundsen Basin and on the Lomonosov, Alpha-Mendeleev ridges.
5. We assume that the Alpha-Mendeleev ridges started to form as a rift system with wide-scale magmatism, though rifting had not progressed into oceanic crust spreading. These processes were connected with possible HALIP mantle plume. We propose to classify the Alpha-Mendeleev ridges as an aborted volcanic passive continental margin.
6. The ~45 Ma event in the Arctic is a unique short-duration event in the history of the Earth: the ultra-slow spreading of the Gakkel Ridge started and approximately synchronously therewith, a major part of the lithospheric plate experienced intraplate compression and transpression, while another part of the lithospheric plate, probably synchronously, experienced intraplate tension and transtension. This short-duration tectonic event resulted in a considerable restructuring of paleogeography and climate.
7. Analysis of seismic stratigraphy of the Arctic suggests that the intervals of 100–80 Ma and 56–45 Ma are characteristic for the formation of sediments with some specific lithology. These sediments are possibly presented not by clay but, for instance, characterized by deposition of siliceous sediments. We assume that a climatic warming took place in the Arctic at these times. These periods coincide with global intervals of a relatively hot climate.

Declaration of Competing Interest

Reviewer-3 disagrees with our model of the Arctic history. Reviewer-3 believes to the classical rotation model, it is very difficult to discuss with him any alternative tectonic scenarios.

He sent a political paper to editors with the title: "Worrisome Political Overtones of the Nikishin et al papers". We do not want political discussions in the scientific journal.

We have no any other conflicts of interest.

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