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Tectonic history and petroleum geology of the Russian Arctic Shelves: an overview

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Abstract: The Eastern Barents, Kara, Laptev, East Siberian seas and the western Chukchi Sea occupy a large part of the Eurasian Arctic epicontinental shelf in the Russian Arctic. Recent studies have shown that this huge region consists of over 40 sedimentary basins of variable age and genesis which are thought to bear significant undiscovered hydrocarbon resources. Important tectonic events controlling the structure and petroleum geology of the basins are the Caledonian collision and orogeny followed by Late Devonian to Early Carboniferous rifting, Late Palaeozoic Baltica–Siberia collision and Uralian orogeny, Triassic and Early Jurassic rifting, Late Jurassic to Early Cretaceous Canada Basin opening accompanied by closure of the South Anyui Ocean, the Late Mesozoic Verkhoyansk–Brookian orogeny and Cenozoic opening of the Eurasia Oceanic Basin. The majority of the sedimentary basins were formed and developed in a rift and post-rift setting and later modified through a series of structural inversions. Using available regional seismic lines correlated with borehole data, onshore geology in areas with no exploration drilling, and recent Arctic-wide magnetic, bathymetry and gravity grids, we provide more confident characterization of the regional structural elements of the Russian Arctic shelf, and constrain the timing of basin formation, structural styles, lithostratigraphy and possible hydrocarbon systems and petroleum play elements in frontier areas.

Keywords: Eurasian Arctic, Barents Sea, Kara Sea, Laptev Sea, East Siberian Sea, Chukchi Sea, sedimentary basin, rift, petroleum potential, hydrocarbon system

A significant part of the Arctic is represented by the Eurasian epicontinental shelf which is the largest shelf on Earth. Its major portion (about 3.5 million km^2) is located in the Russian Arctic and is occupied by the eastern part of the Barents, Kara, Laptev, East Siberian and a western part of the Chukchi seas (Fig. 1). A systematic geological study and airborne gravity and magnetic measurements of the vast Russian Arctic shelves (RAS) was commenced soon after the end of the World War II, by the Research Institute of Arctic Geology (NIIGA, former Leningrad) and later by State Research Enterprise 'SevMorGeo' (see references below). The general results were summarized by Vol'nov *et al.* (1970), Vinogradov *et al.* (1974, 1977), Gramberg & Pogrebitskiy (1984), and recently by Suprunenko & Kos'ko (2005), Petrov *et al.* (2008), and Burlin & Stoupakova (2008).

The main exploration effort over the entire RAS was undertaken during the latest period of the Soviet era, when extensive coverage of refraction and 2D reflection seismic lines was acquired over the eastern Barents and southern Kara seas by Polar Marine Geological Expedition (PMGRE, St Petersburg), Marine Arctic Geological Expedition (MAGE, Murmansk), SevMorGeologiya (SMG, St Petersburg) and SevMorNefteGeofizika (SMNG, Murmansk) (Fig. 2). Some of the large prospects were successfully tested during the 1980s and several large discoveries were made, including the gigantic Shtokman, Rusanovskoe and Leningradskoe gas and gas condensate fields. Today the Russian Barents and southern Kara shelves represent the most explored petroleum provinces of the RAS, bearing *c.* 130×10^9 barrels of oil equivalent (BBOE) of proven resources.

The Siberian shelves, which are the most remote from the present-day markets, remain poorly explored. They represent one of the most promising petroleum frontiers worldwide. They have been explored by an irregular grid of wide-angle refraction and 2D regional multichannel seismic reflection (MCS) lines acquired mostly between 1975 and 1997 by PMGRE, MAGE, Laboratory of Regional Geodynamics (LARGE, Moscow) and SMNG in cooperation with German Federal Institute for Geosciences and Natural Resources (BGR, Hannover) in the Laptev Sea; and by LARGE and DalMorNefteGeofizika (DMNG, Sakhalin) in cooperation with Halliburton Geophysical Services, in the East Siberian and Chukchi seas. A recent seismic survey by the TGS-Nopec Geophysical Company AS provided modern high-quality data acquired with a 6 km long streamer in the Russian Chukchi Sea (Verzhbitsky *et al.* 2008).

Although the post-Soviet period did not bring new offshore discoveries due to suspended exploration activity, it was generally a time of broad regional compilation of the Soviet-era data. These became publicly available, and were incorporated into Arctic-wide digital bathymetric, gravity and magnetic grids through implementation of several international projects: International Bathymetric Chart of the Arctic Ocean (IBCAO, http://www.ibcao.org), Arctic Gravity Project (AGP, http://earth-info.nga.mil/GandG/wgs84/agp/index.html) and several compilations of the Arctic magnetic and gravity fields (Verhoef *et al.* 1996; Glebovsky *et al.* 2000; Maschenkov *et al.* 2001). Interpretation of these digital gravity and magnetic grids in combination with MCS lines allowed much more confident and accurate mapping and characterization of the Arctic regional structural elements and sedimentary basins (Ivanova *et al.* 1990; Warren *et al.* 1995; Drachev *et al.* 1998, 1999, 2001; Franke *et al.* 2000, 2001, 2004; Glebovsky *et al.* 2000; Sekretov 2000, 2001; Sherwood *et al.* 2002; Franke & Hinz 2005; Sharov *et al.* 2005; Grantz *et al.* 2009).

Sedimentary basins of the RAS are thought to bear significant volumes of undiscovered hydrocarbon (HC) resources which are still difficult to estimate due to limited geological and geophysical data. According to a recent assessment by the Russian Ministry of Natural resources, the RAS could contain as much as 700 BBOE of

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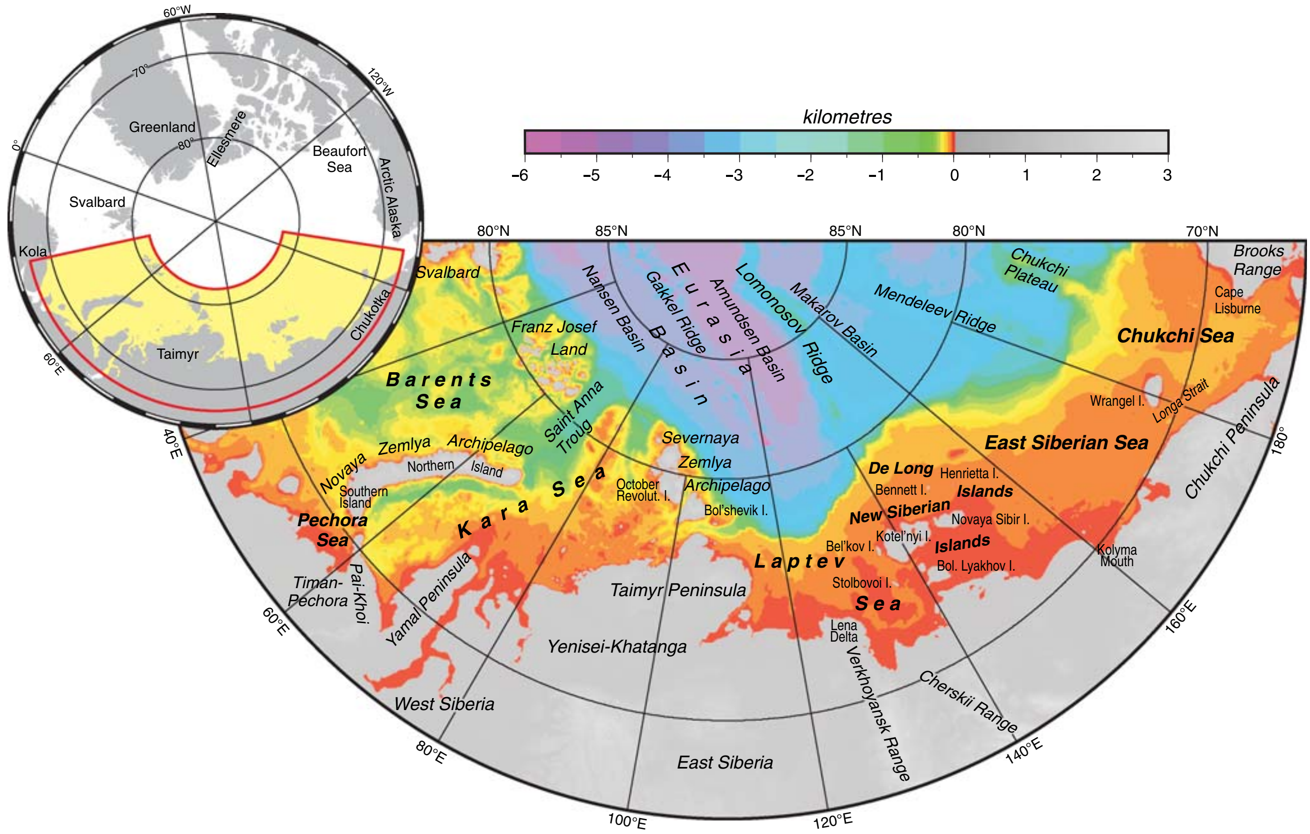

Fig. 1. Physiography of the Russian Arctic shelf. Topography is given after International Bathymetric Chart of the Arctic Ocean (IBCAO; http://www.ibcao.org). The inserted map in the upper left corner shows the location of the study area (red outline) in the Circum-Arctic.

total (discovered and undiscovered) resources. Data describing the age, composition and structural styles of the rocks composing the Arctic continental masses and islands remain a principal source of information about undrilled pre-Jurassic HC plays of the Barents–Kara region and the entire section of the Siberian Arctic shelves. This paper presents a brief overview of the RAS regional and petroleum geology. Based on available seismic, gravity/magnetic and geological data, we describe the main structural features of the East Barents, North and South Kara, Laptev, East Siberian Sea and western Chukchi provinces. The paper also summarizes the most important data on the evolution of these basins, and their known petroleum systems, and tries to apply general tectonic

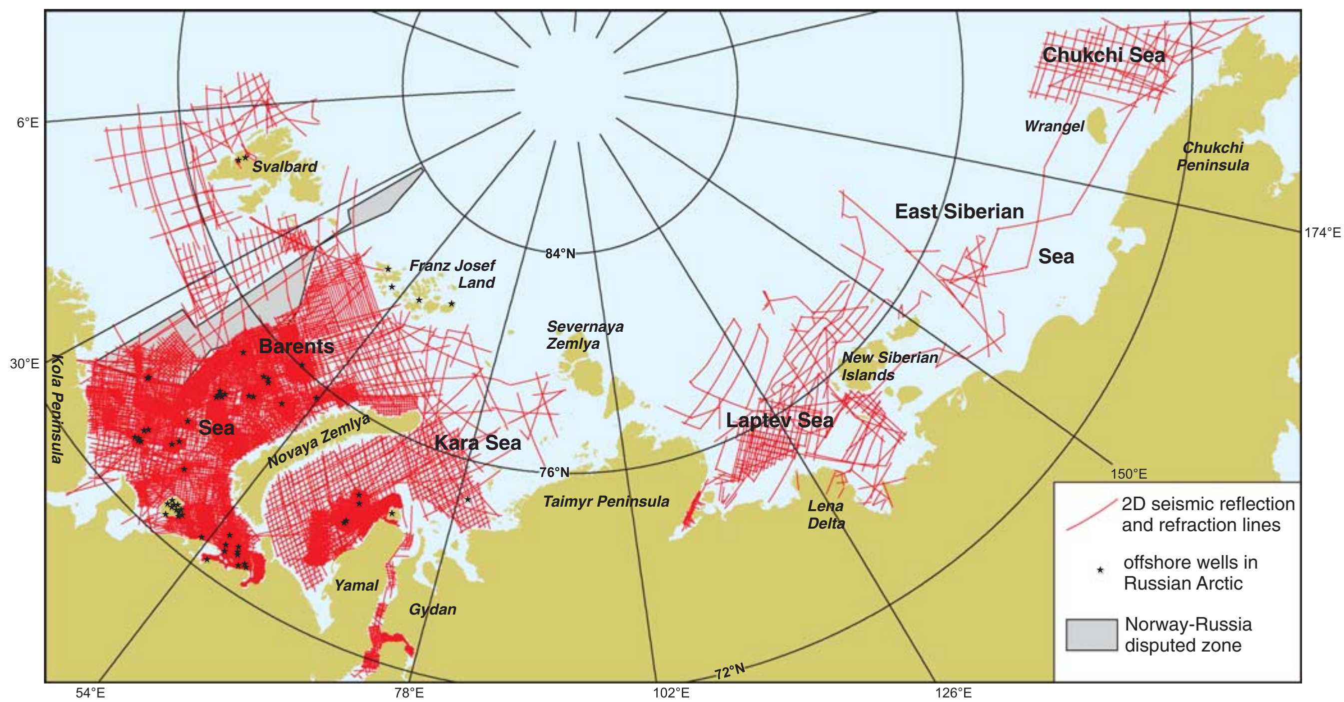

Fig. 2. Location of the 2D seismic reflection and refraction surveys and offshore wells in the Russian Arctic.

models and trans-regional correlations to draw some conclusions for those parts of the shelves where no direct observations exist to infer their geology.

Tectonic setting

As is consistent with modern plate-tectonic ideas of Arctic evolution, the structure of the consolidated continental crust underlying the Eurasian continental margin was formed during much of the Phanerozoic as a result of a series of collisions between the Laurentia, Baltica and Siberia continents and with a number of smaller microcontinents. Sedimentary basins post-dating the main Phanerozoic collisions mainly formed in response to initial rifting related to post-orogenic collapse and/or to the formation of Arctic spreading basins, for example, Eurasia and Amerasia basins. Many of these sedimentary basins were later modified through a series of intraplate structural inversions.

The formation of the RAS basins has generally been migrating over time east- and northeastward (present-day coordinates), thus basin complexity and age decrease in the same direction. The oldest Early Palaeozoic basins formed in the western sector of the RAS, and then the basin formation progressed through the Palaeozoic in the east Barents and north Kara shelves, and throughout the Early–Mid Mesozoic in the South Kara Sea and the Yenisei–Khatanga region.

The latest phase of basin formation in the RAS took place in the Laptev Sea region, where a series of rift-related basins have been evolving due to the opening of the Eurasia oceanic basin and the development of the present-day boundary between the Eurasian (EUR) and North American (NA) lithospheric plates. The Cenozoic plate-tectonic history of the Arctic is well constrained due to the decipherable set of seafloor spreading magnetic anomalies in the North Atlantic and Eurasia basins (Karasik 1968, 1974; Pitman & Talwani 1972; Vogt *et al.* 1979; Savostin & Karasik 1981; Karasik *et al.* 1983; Savostin *et al.* 1984*a*; Srivastava 1985; Cook *et al.* 1986; Harbert *et al.* 1990; Kristoffersen 1990; Glebovsky *et al.* 2006), and we refer to these publications when more details are required with regard to the Cenozoic plate-tectonic framework of the Arctic.

Therefore the basins of the Barents–Kara region, which rest on continental crust of the Palaeoproterozoic craton and Palaeozoic accreted crust, are mostly composed of Neoproterozoic, Palaeozoic and Mesozoic–Cenozoic carbonate and siliciclastic sequences, whereas most of the Siberian Arctic basins (the Laptev, East Siberian and Chukchi shelves) are underlain by the younger crust of the Late Mesozoic fold belts, and are filled with the Cretaceous (Aptian–Albian and younger) and Cenozoic siliciclastic sediments.

The most important tectonic events controlling the structure and petroleum geology of the entire Eurasian Arctic shelf are:

(1) Neoproterozoic to Early Cambrian Timanian orogeny;
(2) Caledonian orogeny followed by a phase of orogen collapse and crustal extension in Late Devonian–Early Carboniferous;
(3) Late Palaeozoic (Uralian) collision of the Baltica and Siberian continents;
(4) Permo-Triassic plume-related volcanic event and associated crustal extension;
(5) Jurassic rifting and subsequent opening of the Canada oceanic basin, accommodated by separation of the Arctic Alaska–Chukchi Microplate (AACM) from the Canadian margin of North America and its movement towards Siberia;
(6) Early Cretaceous closure of the Anyui Ocean due to convergence of the AACM with the Verkhoyansk-Omolon Siberian margin along the South Anyui Suture;
(7) Late Cretaceous to Paleocene opening of the Labrador Sea and Baffin Bay basins, which may also have affected the Central Arctic region between the Lomonosov and the Alpha-Mendeleev ridges;
(8) Greenland–Ellesmere and Greenland–West Barents margin convergence at 55–33 Ma and related crustal microplate re-adjustment in the Barents–Kara region;
(9) opening of the Eurasia oceanic basin at 55–0 Ma and related rifting and crustal microplate re-adjustment in the Laptev–East Siberian seas sector;
(10) the India–Eurasia collision at 40–10 Ma, causing large-scale crustal re-adjustment throughout Asia and NE Asia, which may also have reached the Eurasian Arctic continental margins.

The Cenozoic development of the RAS was controlled by continuous interaction of the NA and EUR lithospheric plates, which caused a drastic impact on the Siberian Arctic shelves. Since this region has always been in an intra-plate setting near the pole of plate rotation, even small changes in the plates' rotation have resulted in drastic changes in the basins' tectonic development and depositional environments.

Main characteristics of the RAS consolidated basement

Structurally the RAS is bordered on the south by the Baltica (also called East European, or Russian) and Siberian (also called East Siberian) cratons and adjoining Neoproterozoic, Palaeozoic and Mesozoic fold-and-thrust belts (hereinafter called fold belts). All of these first-order structures approach the Eurasian Arctic coast, and apparently extend farther offshore, where they form a tectonic basement (hereinafter also called basement) underlying sedimentary basins (Fig. 3). (By a tectonic basement we mean strongly deformed and/or metamorphosed units of rocks and their associations, compared with generally undeformed/weakly deformed and unmetamorphosed sedimentary successions existing within a sedimentary basin.)

The fact that the Eurasian Arctic onshore fold belt domains extend offshore is also supported by a number of MCS lines located close to the shoreline, as well as by gravity and magnetic maps. However, due to the lack of reliable data, there are as many points of view on possible offshore basement tectonics as there are researchers. However, many agree that a fundamental difference in tectonics and geological history exists between the western and eastern sectors of the RAS, as was earlier recognized by Vinogradov *et al.* (1974, 1977), Gramberg & Pogrebitskiy (1984), Savostin *et al.* (1984*b*), Zonenshain *et al.* (1990) and others.

Figure 3 illustrates our understanding of large-scale crustal structural pattern of the RAS based on geological data from coastal areas, published and unpublished MSC lines and publicly available gravity and magnetic grids.

Western sector of the RAS (eastern Barents and Kara shelves)

The western RAS is dominated by pre-Cambrian, Palaeozoic and Early Mesozoic crustal domains: the Neoproterozoic Timan–Varanger Fold Belt (Timanides by Gee & Pease 2005), Scandinavian Caledonides, a hypothetical Mesoproterozoic Svalbard Massif, Late Palaeozoic Uralian and Taimyr fold belts (Uralides and Taimyrides, respectively), the Early Mesozoic Novaya Zemlya and, to a small extent, South Taimyr fold belts (Fig. 3). There are still many highly disputed issues concerning possible outlines and relationships of these first-order structural domains beneath thick sedimentary cover of the Arctic seas (for the latest review see Pease 2011). Below we provide a short description of the main structural domains of the offshore basement relevant to understanding the formation and evolution of the RAS sedimentary basins.

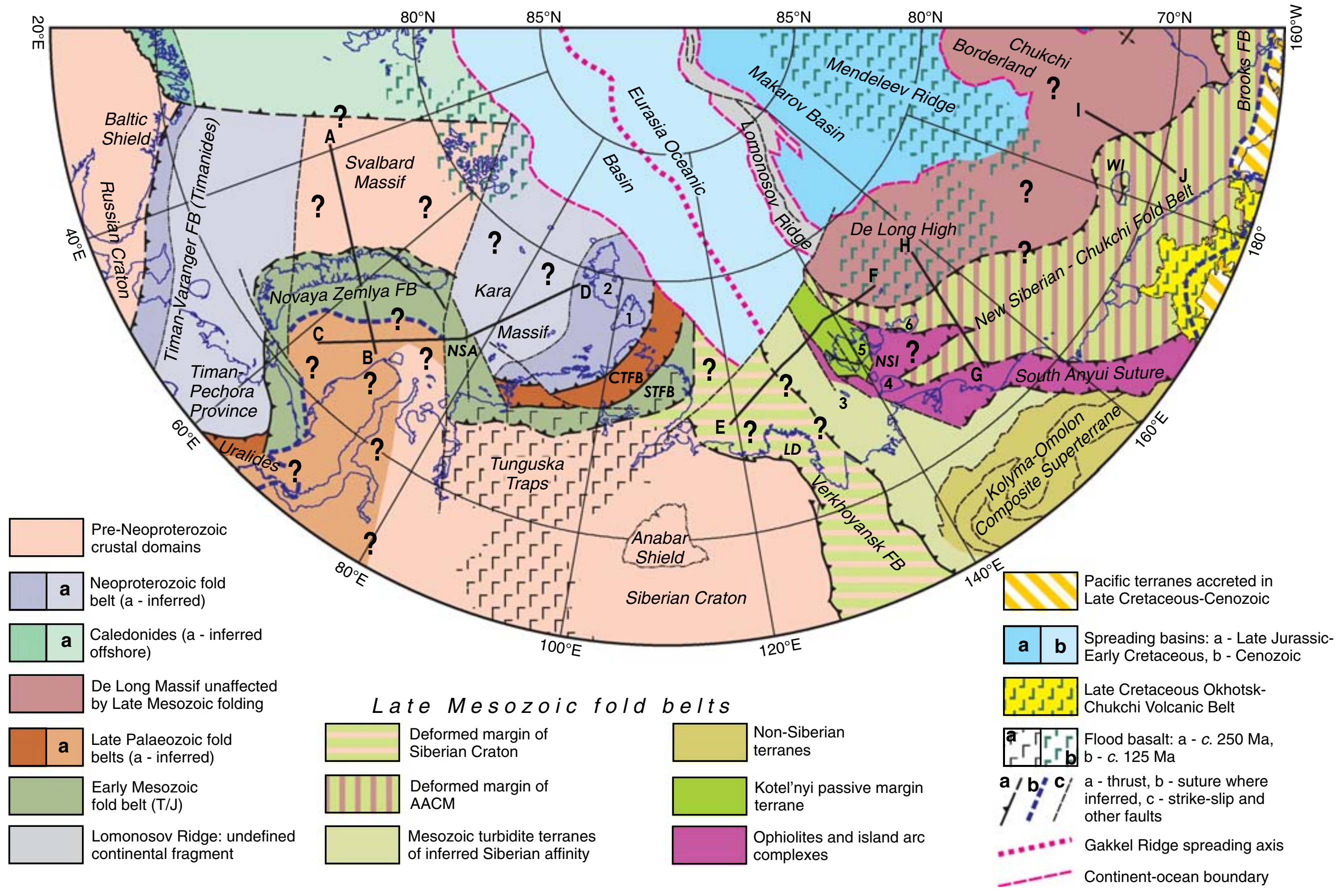

Fig. 3. Crustal tectonics of the Russian Arctic shelf and adjacent onshore and offshore regions. Bold solid lines labelled A–B, C–D, E–F, G–H and I–J show the location of crustal cross-sections given in Figures 6a, b, 11b, 14 & 16, respectively. The bold italic letters denote: NSA, North Siberian Arch; CTFB, Central Taimyr Fold Belt; STFB, South Taimyr Fold Belt; LD, Lena Delta; NSI, New Siberian Islands; WI, Wrangel Island. The bold numbers denote the following islands: 1, Bol'shevik; 2, October Revolution; 3, Stolbovoi; 4, Bol'shoi Lyakhov; 5, Kotel'nyi; 6, Novaya Sibir'. For other geographic names see Figure 1. Bold question marks denote the areas with least constrained interpretation of the basement type and age. FB denotes fold belt.

The Novaya Zemlya Fold Belt (NZFB) has a critical significance for understanding the tectonic history of the western RAS. It was formed at a very complex junction of the Baltica and Siberian cratons with the northern part of the Late Palaeozoic Uralides. It also divides two major HC provinces – East Barents and Northwest Siberian – and thus is the only area where the Palaeozoic HC systems of both provinces are exposed and thus available for direct studies.

As shown by Bondarev (1982), Lopatin *et al.* (2001), Pogrebitskiy (2004), Korago *et al.* (2004, 2009) and Vinokurov *et al.* (2009), the NZFB is mostly composed of Palaeozoic to Early Triassic successions deposited in a shelf to basin transition setting with shallow shelf facies developed along the western flank of the fold belt. The total thickness of the known section exceeds 13 km. The entire section was severely deformed at the end of the Triassic–earliest Jurassic to form a west-verging arcuate fold belt (Scott *et al.* 2010).

The basement of the NZFB is exposed locally and consists of Meso- and Neoproterozoic metaclastic and metacarbonate rocks, compressionally (east–west trending) deformed and metamorphosed in epidote–amphibolite and greenschist facies, and intruded by Neoproterozoic granite and granodiorite rocks (Korago *et al.* 2004). The recent study of metaclastic turbidites, which underlie a sharp angular unconformity at the base of unmetamorphosed variegated clastic sediments of Early Ordovician at Southern Novaya Zemlya Island, revealed the presence of Cambrian ages of detrital zircons (Pease & Scott 2009). This implies that at least some of the previously inferred Neoproterozoic rock complexes have, in fact, Cambrian age, and that the age of 'Timanian' unconformity is not older than Late Cambrian to Early Ordovician. Therefore, according to Pease (2011), the Timanian orogeny on southern Novaya Zemlya lasted until the end of Cambrian time, and the regional limit of the Timanian deformation probably extends beyond the Novaya Zemlya Archipelago into the Northern Kara region, where a contemporaneous unconformity between Cambrian and Ordovician is present on October Revolution Island (see below). A similar point of view about possible Cambrian extent of the Timanian orogeny was proposed by Bogolepova & Gee (2004).

The east–west compressed and unmetamorphosed Palaeozoic to Lower Triassic strata were deposited along the eastern margin of the Baltica (present-day orientation). The southern and central parts of the NZFB are composed of the following tectonostratigraphic rock assemblages, or complexes (Lopatin *et al.* 2001):

(1) Cambrian to Middle Devonian shallow water sandstones, dolomites, limestones, shales, siltstones, gravelites and conglomerates.
(2) Late Devonian to Early Carboniferous shallow water limestones, calcarenites, bioherms and calcareous sandstones.
(3) Middle to Late Devonian assemblage of clastic, volcanic and volcaniclastic rocks – claystones, siltstones, shales, polymictic sandstones, gravelites, conglomerates, tholeiitic basalts and tuffs. The intrusive analogues are represented by sills and dykes of gabbro-dolerites. The rock geochemistry suggest their intracontinental rift affinity.
(4) Late Devonian to Permian open marine and deepwater claystones, siltstones, rhodochrosite-bearing siliceous rocks, turbidites, olistostromes.

(5) Late Permian siliciclastic deepwater turbidites with horizons of olistostromes and calcareous sandstones.
(6) Later Permian to Lower Triassic shallow water and continental coarse-grained clastic rocks.

These rock complexes are intruded by a few small bodies of granitic rocks with Late Triassic to Early Jurassic isotopic ages (Pogrebitskiy 2004).

Baltica Timanide sources for the Palaeozoic clastic rocks are determined by detrital zircon ages (Pease & Scott 2009). Korago *et al.* (2009) suggested that the Upper Silurian clastic sediments, in contrast to the underlying beds, were derived predominantly from a northwesterly located Caledonian orogen. However, the Caledonian source is still highly debated (Pease 2011).

The northern part of the NZFB reveals a different type of stratigraphy. According to Lopatin *et al.* (2001), Pogrebitskiy (2004) and Korago *et al.* (2004), it is composed of a continuous *c.* 10–13 km thick Neoproterozoic to Lower Devonian section, which lacks any significant unconformities. The deepwater fine-grained siliciclastic metaturbidites are predominant within the Neoproterozoic to Lower Silurian successions. The overlying Upper Silurian to Lower Devonian strata are composed of shallow marine clastic and coarse clastic sediments, and the uppermost part of the section consists of Lower to Middle Devonian shallow water carbonate succession. Thin Upper Devonian and Carboniferous shallow water clastic and carbonate sediments occur sporadically and reveal a number of stratigraphic gaps. This interval could be related to the Late Palaeozoic orogenic event, which strongly affected the Taimyr Peninsula, and apparently the adjacent Kara Massif. Upper Carboniferous to Permian shallow-marine and continental coarse-grained clastic sediments coeval to main phase of the orogeny cap the section of the northern part of the fold belt.

The absence of unconformities within the Neoproterozoic to Lower Palaeozoic section of the northern block of the NZFB, which could be expected in proximity to the Timanian and possibly Caledonian (see Gee *et al.* 2006) deformation fronts, is one of the enigmas of the Arctic geology. One possible explanation given by Korago *et al.* (2004) is that this block had an independent Neoproterozoic and Palaeozoic history and became a part of the fold belt during its formation in Permian–Triassic.

The age of compressional deformations associated with the NZFB was for a long time one of the most disputed issues of the Arctic geology (see Pease 2011). The youngest strata recognized to be involved into the deformations are the Lower Triassic, which could assume a younger age of the deformations. Modern MCS data acquired in the vicinity of the western coast of Novaya Zemlya show a sharp angular unconformity at about the Triassic–Jurassic boundary, which probably corresponds to the main deformation phase (Pavlov *et al.* 2008).

The Kara Massif, or Microcontinent (KM) is traditionally outlined in the northern part of the Kara Sea. Structurally it is separated from the Late Palaeozoic to Early Mesozoic structural assemblage at the basement of the South Kara Basin (SKB) by a prominent linear North Siberian basement arch (or Step in the Russian literature). As depicted by the gravity field (Fig. 4, number 11), the arch strikes from the northern tip of the Novaya Zemlya Archipelago to the northwestern coast of the Taimyr Peninsula, indicating a structural relationship between the Novaya Zemlya and Taimyr fold belts. Its origin may be related to the Early Mesozoic compressional event and, given almost orthogonal orientation of the arch

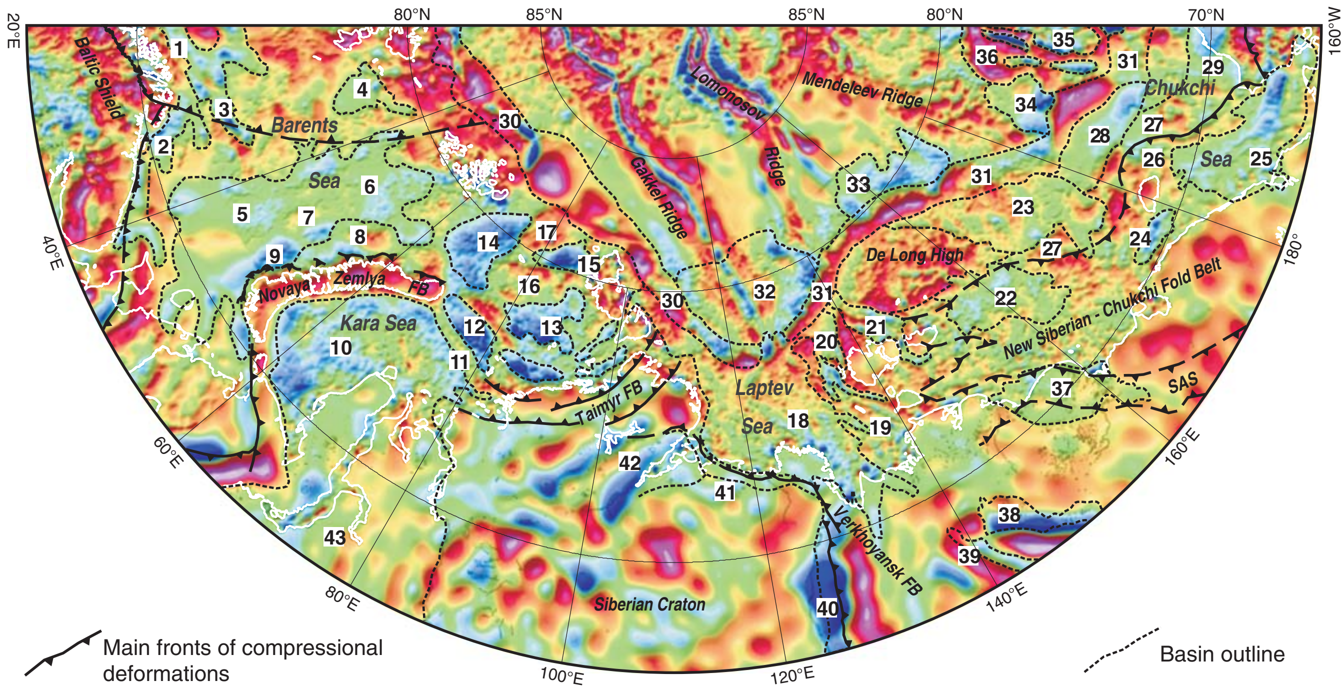

Fig. 4. Free-air gravity field over the Russian Arctic shelf and adjacent areas with outlines of the main sedimentary basins and basement highs (gravity data source is Arctic Gravity Project, http://earth-info.nga.mil/GandG/wgs84/agp). Numbers denote the following structural elements: *Barents Sea* – 1, Hammerfest Basin; 2, Varanger Trough; 3, Nordkapp Rift; 4, Olga Basin; 5–7, East Barents Megatrough (5, South Barents Basin; 6, North Barents Basin; 7, Ludlov Saddle); 8, Admiralty High; 9, Pri-Novaya Zemlya Basin. *Kara Sea:* 10, South Kara Basin; 11, North Siberian Arch; 12, Litke Trough; 13, North Kara Basin; 14, St Anna Trough; 15, Schmidt Trough; 16, Central Kara High; 17, Ushakov High. *Laptev Sea:* 18, Ust' Lena Rift; 19, Stolbovoi Horst; 20, Anisin Rift; 21, New Siberian Rift. *East Siberian Sea:* 22, East Siberian Sea Basin (East Siberian Depocentre); 23, Vil'kitskii Basin; 24, Longa Basin. *Chukchi Sea:* 25, South Chukchi (Hope) Basin; 26, Wrangel-Herald Structural Arch; 27, New Siberian-Wrangel Basin; 28, North Chukchi Basin; 29, Colville Basin. *Eurasian Continental Margin:* 30, Barents–Kara–West Laptev marginal basin; 31, East Laptev–East Siberian–Chukchi marginal basin. *Oceanic deepwater basins:* 32, South Eurasia Basin; 33, Podvodnikov Basin; 34, Chukchi Abyssal Plane Basin; 35, Northwind Basin; 36, Chukchi Plateau. *Continental realm:* 37, Lower Kolyma Basin; 38, Zyryanka Basin; 39, Moma Rift; 40, Priverkhoyansk Basin; 41, Lena-Anabar Basin; 42, Yenisei–Khatanga Basin; 43, West Siberian Basin. SAS is South Anyui Suture.

with regard to the NZFB, a considerable dextral strike-slip deformation may be expected.

The KM remains poorly studied and its geology is mainly projected from the Severnaya Zemlya Archipelago and northern Taimyr Peninsula. The first reliable isotopic data constraining the ages of magmatic, metamorphic and, therefore, tectonic events were obtained by Vernikovsky (1995, 1996). Recently new data on geology of Severnaya Zemlya were published by Metelkin *et al.* (2005), Lorenz *et al.* (2006, 2007, 2008), and Männik *et al.* (2009). Lorenz *et al.* describe the KM as the North Kara Terrane.

Tectonic basement of the KM is exposed in the northern part of the Taimyr Peninsula, and on northerly located Bol'shevik Island (Fig. 3). It is represented by a succession of Neoproterozoic siliciclastic turbidites that are commonly attributed to a passive margin of the KM (Vernikovsky 1996; Lorenz *et al.* 2006–2008). The detrital zircon ages provide solid argument for a Timanian Baltica source of the clastic sediments and therefore constrain Neoproterozoic setting of the KM as a part of the Baltica Continent (Lorenz *et al.* 2008; Pease & Scott 2009). The rocks are intensively deformed and regionally metamorphosed to lower greenschist (Bol'shevik Island) and amphibolite (Northern Taimyr) facies and intruded by Late Palaeozoic syn- and post-collisional granites (300–265 Ma, Vernikovsky 1995; Vernikovsky & Vernikovskaya 2001). While the Northern Taimyr metamorphism is related to the Late Palaeozoic Uralian orogeny (Vernikovsky 1995; Pease & Scott 2009), the data on the Neoproterozoic metaturbidites of Bol'shevik Island may suggest a Neoproterozoic (Vendian, according to Proskurnin (1999), or Riphean, according to Lorenz *et al.* (2008)) phase of compressional deformation and metamorphism, which may be related to a 740–600 Ma collision of the KM with an island arc terrane (currently the Central Taimyr Fold Belt; Vernikovsky & Vernikovskaya 2001).

Cambrian marine siliciclastic sediments occur on eastern October Revolution Island. The lower part of the section is represented by unfossiliferous turbidites which, according to Proskurnin (1999), reveal some similarities with the Neoproterozoic turbidites of Bolshevik Island, and therefore may have Neoproterozoic age. The fossiliferous Cambrian strata are composed of shallow marine and basinal clastic sediments with some limestone beds in the Upper Cambrian. The section is compressed in north–south trending tight folds, but the rocks are unmetamorphosed as compared with the Neoproterozoic rocks of the Bol'shevik Island (Lorenz *et al.* 2007, 2008).

The Ordovician shallow water clastic sediments overlie Cambrian strata with a prominent angular unconformity on eastern October Revolution Island (the Kan'on River Unconformity). Lorenz *et al.* (2006) consider the deformations of the Neoproterozoic turbidites and Cambrian clastics as manifestations of a Caledonian compressional phase. The Kan'on River Unconformity is a coeval analogue to the Cambrian–Ordovician unconformity on Northern Novaya Zemlya Island, and therefore may be attributed to the latest stage of the Timanian orogeny, as suggested by Pease & Scott (2009) and Pease (2011).

Multi-coloured poly-facial Early Ordovician to Late Devonian calcareous, evaporite and clastic successions form an unmetamorphosed *c.* 3.5–5 km thick cover of the KM. Accumulation of the Ordovician to Silurian strata was taking place in shallow-water semi-restricted basins (Männik *et al.* 2009). In the Early Ordovician time a magmatic event took place with emplacement of intrusive and extrusive rocks: alkaline gabbro, syenite, granite, andesite, rhyolite and trachytes. The rock geochemistry is consistent with their origin in an intracontinental rift setting (Proskurnin 1995; Gramberg & Ushakov 2000). The Mid-Ordovician section is dominated by dark shales and gypsiferous limestones. The Late Ordovician quartz-sandstones probably related to a local uplift of the KM, which was followed by deposition of carbonate rocks through most of the Silurian. Lorenz *et al.* (2008) correlate the Devonian shallow water and fluvial sandstone dominated clastic strata to the Old Red Sandstone Formation.

In the earliest Carboniferous, the whole Early to Middle Palaeozoic KM cover within present-day limits of the Severnaya Zemlya was affected by slight to moderate compressional or transpressional deformation, and intruded by post-orogenic granites with U–Pb zircon ages 342 ± 3.6 and 343.5 ± 4.1 Ma. This Severnaya Zemlya folding is regarded by Lorenz *et al.* (2007, 2008) as Caledonian related. Another coeval compressional tectonic event, which could be a potential cause of the Severnaya Zemlya deformations, is Ellesmerian, or Innuitian, folding in the Canadian Arctic (Trettin 1991).

The Carboniferous and Permian shallow marine and continental clastic sediments, post-dating compression, occur locally on the Severnaya Zemlya. These strata do not reveal any deformation, assuming this part of the KM was not affected by a compression during its collision with the Siberian continent in Late Palaeozoic, which formed a south verging Central Taimyr Fold Belt.

An Early Mesozoic phase of compression has also been reported for the South Taimyr Fold Belt (Inger *et al.* 1999). In the Southern Taimyr Peninsula, the Tunguska-like flood basalts with $^{40}Ar/^{39}Ar$ ages *c.* 229–227 Ma are folded together with Carboniferous to Lower Triassic continental clastic rocks, and are unconformably overlain by Early Jurassic strata that constrain the age of the compressional event to the Late Triassic time (Walderhaug *et al.* 2005). Therefore, the Early Mesozoic compression occurred across a large domain of the RAS, which is almost 2000 km in the east–west direction, from the Novaya Zemlya Archipelago to the eastern coast of the Taimyr Peninsula. The regional extent and the magnitude of the folding are comparable to other first-order tectonic events which occurred in the Arctic, like the Caledonian, Late Palaeozoic and Late Mesozoic events.

Eastern sector of the RAS (east of Taimyr Peninsula)

The eastern Siberian shelves of the RAS are considered to be mostly underlain by Late Mesozoic fold belts (Vinogradov *et al.* 1974; Drachev *et al.* 1999; Drachev 2002), which occupy a huge onshore region between the Lena River in the west and the Mackenzie River in Alaska in the east. These fold belts originated in Late Jurassic to Early Cretaceous in the course of several collisional episodes of large terranes (AACM, Omolon) with Siberian margin, and were finally consolidated in Aptian during so-called Verkhoyansk–Brookian (or Chukotka–Brookian) orogeny. The fold belts are inferred to continue offshore where the Late Mesozoic folded structural domains are exposed on New Siberian and Wrangel islands (Fig. 3).

The Verkhoyansk Fold Belt and its western branch, the Olenek fold zone, surround the Siberian Craton in the east and NE. Their sections consist of over 10 km of Upper Palaeozoic to Lower Cretaceous (Hauterivian) siliciclastic sediments, known also as a Verkhoyansk Complex, which vary from fluvial to shallow marine sediments in the proximity to the craton to deepwater turbidites in the distal zones of the fold belts. The Verkhoyansk Complex is underlain by Riphean to Middle Palaeozoic carbonate and clastic–carbonate formations, belonging to the marginal parts of the Siberian Craton. This Palaeo-Siberian passive continental margin was compressionally deformed in the Early Cretaceous (*c.* 130–125 Ma) in the course of collisions with Kolyma–Omolon Composite Superterrane (Kolyma Structural Loop) and the AACM. Based on available MCS and gravity data, Vinogradov & Drachev (2000) and Drachev (2002) outlined the possible offshore extent of the Verkhoyansk and Olenek fold belts beneath the Laptev Sea rifted basins post-dating the Late Mesozoic compressional deformation (Figs 3 & 10).

The Kotel'nyi Terrane is defined in the western part of the New Siberian Archipelago *c.* 350–500 km north from onshore Late Mesozoic fold belts (Fig. 3). It provides solid evidence of a major Late Mesozoic compression event affected eastern portion of the RAS. The terrane is prevailed by Middle Ordovician to Upper Devonian and Mesozoic sedimentary rocks deposited in a passive margin setting. Three main tectonostratigraphic rock assemblages were defined (Kos'ko & Nepomiluev 1975; Kos'ko *et al.* 1990; Kos'ko 1994):

(1) A 3–5 km thick Middle Ordovician to Middle Devonian succession of carbonate rocks, mainly represented by lagoonal and shallow water marine fossiliferous limestones; basinal facies of black limestones and shales are known within Lower Silurian and Lower Devonian.
(2) A 7–9 km thick Upper Devonian to lowermost Carboniferous succession of grey mudstones and siltstones with minor carbonates and sandstones occurring within a prominent NW elongated synform-like structure (the Bel'kov-Nerpalakh Trough by Kos'ko *et al.* 1990), which may represent an infill of a structurally inverted Late Devonian rift. The share of carbonates and sandstones increases in the uppermost Devonian to Carboniferous interval, where the variegated rocks appear.
(3) A 1200–1300 m thick Triassic to Jurassic succession of claystone, clayey siltstone, siltstone and sandstone. The fine-grained clastic rocks occur predominantly within the Jurassic part of the section while the Triassic interval reveals an almost total absence of clastic material and is abundant in calcite and phosphorite nodules, which may be an evidence of deepwater sedimentation (Egorov *et al.* 1987).

The Carboniferous to Permian rocks occur sporadically, and are absent over most of the terrane. Their known sections are represented by very thin (30–130 m) beds of Serpukhovian and Bashkitian shallow water fossiliferous limestones, and by *c.* 200 m thick Lower Permian black shales with siltstone and limestone interbeds. Both the Carboniferous and Permian strata overlie, with a prominent unconformity at their base, the Ordovician to Devonian strata. In several localities the unconformity is characterized as an angular unconformity (Kos'ko & Nepomiluev 1975). Therefore, these facts may suggest an occurrence of a compressional phase at earliest Carboniferous time, which may be related to Ellesmerian orogeny in the Canadian Arctic. Another possible cause for the deformation may be the tilting of blocks of lower Palaeozoic rocks during the formation of the Bel'kov–Nerpalakh Trough. At present, the lack of structural data does not allow any further conclusions to be drawn on the possible nature of the Mid Palaeozoic deformation.

The whole section of the terrane is intruded by numerous sills and dykes of gabbro-diabases that closely resemble in age and composition the Permian–Triassic Tunguska flood basalts (Kuzmichev & Pease 2007). The whole rock package of the terrane was intensively compressed in the Early Cretaceous, prior to Aptian, with clear dextral transpression component.

A narrow and highly deformed *South Anyui ophiolitic suture (SAS)* separates the New Siberian–Chukchi and Verkhoyansk–Kolyma fold belts. As shown by aeromagnetic data (Rusakov & Vinogradov 1969; Vinogradov *et al.* 1974; Spektor *et al.* 1981), it extends from the Kolyma River mouth onto the shelf where dismembered ophiolites and island-arc volcanic complexes are exposed on Bol'shoi Lyakhov Island (Drachev & Savostin 1993; Kuzmichev 2009). The further offshore continuation of the suture, though obscured by younger extensional structures, is still definable by magnetic data, which show two branches of positive anomalies: between Stolbovoi and Kotel'nyi islands and ENE of the latter (Fig. 3).

The suture formed as a result of the closure of the Anyui Ocean – a large embayment of the Late Palaeozoic–Mesozoic Pantallassa to the Pangaea II – in the course of collision between the AACM and the Siberian margin in the Late Jurassic–Early Cretaceous (prior to Aptian) time (Savostin *et al.* 1984*b*; Parfenov & Natal'in 1986; Zonenshain *et al.* 1990; Sokolov *et al.* 2002).

The Siberian portion of the *Arctic Alaska–Chukchi Microplate*, or microcontinent, is inferred to consist of two parts (Fig. 3):

(1) the New Siberian–Chukchi Fold Belt, which constitutes the southern, adjacent to the South Anyui Suture, deformed margin of the microcontinent;
(2) the De Long Massif located north of the Late Mesozoic deformation front and composed of Lower and Middle Palaeozoic complexes.

The New Siberian–Chukchi Fold Belt occupies the Chukchi Peninsula and provisionally extends offshore to include the Late Mesozoic folded complexes of Wrangel Island, and a broad area of the East Siberian Sea north of the proposed limits of the South Anyui Suture. The northern offshore limit of the fold belt has been identified on several MCS lines south of the De Long Islands and north and east of Wrangel Island, where it follows the northern flank of the Wrangel–Herald Arch (Drachev *et al.* 1999, 2001; Verzhbitsky *et al.* 2008).

Stratigraphic and structural relationships between various lithostratigraphic units of Wrangel Island remain poorly understood, although ongoing studies may illuminate its tectonic evolution. The oldest Neoproterozoic Wrangel Complex is composed of metavolcanic, metavolcanoclastic and metaclastic rocks, intruded by basic dykes and sills and small granitic bodies with isotopic ages 600–700 Ma (Kos'ko *et al.* 1993). The rocks were intensively deformed prior to deposition of thick sedimentary successions of Upper Silurian–Devonian and Carboniferous to Permian shallow marine siliciclastic rocks and shales, with some carbonate units deposited in a continental shelf setting. The uppermost part of the section is represented by an over 1–1.5 km thick unit of Triassic siliciclastic turbidites (medium to fine-grained sandstone alternating with shale and siltstone), which contrast with the older Palaeozoic shelfal strata (Kos'ko *et al.* 1993; Miller *et al.* 2010). Data on the U–Pb age of detrital zircons from Wrangel sections reveal similarities between the Upper Palaeozoic rocks of the island and the Lisburne Hills area (Western Alaska). Zircon populations from the Triassic turbidites differ significantly from both older Palaeozoic rocks of the island and from coeval rocks of the Lisburne area, although they are similar to the Triassic turbidites of the Chukchi Peninsula (Miller *et al.* 2010). All sedimentary successions were deformed in the latest Jurassic to Early Cretaceous, probably simultaneously with deformations in the Lisburne Hills area (132–115 Ma, according to Moore *et al.* 2002). On the Chukchi Peninsula and probably Wrangel Island the orogenic event was followed by an uplift and profound erosion between *c.* 117 and 95 Ma (Miller & Verzhbitsky 2009).

The De Long Massif has a very contrasting expression in gravity and magnetic fields, due to the occurrence of highly uplifted and eroded basement, and the presence of the Early Cretaceous flood basalts. The massif has repeatedly been attributed by Soviet geologists to a pre-Cambrian craton, often named the Hyperborean, or East Arctic Platform (Obruchev 1934; Shatskii 1935; Pushcharovskii 1963; Atlasov *et al.* 1970 and many others). However, today we have more evidence in favour of either Caledonian or Ellesmerian (Late Devonian) age for this feature (see below).

On Bennett Island, a 1.5 km thick succession of Middle Cambrian to Middle Ordovician fossiliferous shales and distal siliciclastic and clastic carbonate turbidites reveals rather weak deformation and a lack of metamorphism (Vol'nov *et al.* 1970; Drachev 1989). This section is quite unique since no similar rocks are known from the nearest Siberian Arctic. The closest occurrences of the Cambrian to Ordovician rocks to which the Bennett succession could be correlated are deepwater turbidites exposed in the Northern Greenland and the Northern Ellesmerian Island (Trettin 1991).

Henrietta Island is composed of moderately deformed clastic and volcano-clastic complexes and a unit of calc-alkaline basalts of unclear stratigraphic setting (Vinogradov *et al.* 1975). The section is intruded by diabase and diorite sills and dykes whose unpublished $^{40}Ar/^{39}Ar$ dates could possibly reveal a Caledonian age for the magmatism (Kaplan *et al.* 2001), while rock chemistry points to their island-arc affinity. The other two occurrences of the Caledonian-age structural domains in the High Arctic are at Spitsbergen and northern Ellesmere Island (Peary Terrane and adjacent area of the island). Therefore, based on the possible Caledonian age of the Henrietta magmatic rocks, we infer that a location of the De Long Massif was close to Northern Ellesmere Island prior to the Late Jurassic to Early Cretaceous opening of the Canada Basin.

On Bennett Island, Aptian coal-bearing muddy sediments, and a 200–300 m thick unit of plume-like flood basalts are separated from the underlying Lower Palaeozoic section by a sharp basal unconformity. A few K–Ar radiometric dates in the range of $119–112 \pm 5$ Ma constrain the age of the basalts to the Aptian to Albian (Drachev 1989; Drachev & Saunders 2006).

The above characterization of the RAS's heterogeneous folded tectonic basement points to some major uncertainties regarding the areal extent and structural relationships of the basement domains. These are:

(1) existence and extent of the Svalbard Massif (Microcontinent) and adjoining Scandinavian Caledonides and Timanides;
(2) relationships between the Kara and Svalbard massifs, and their relationship with the Baltica Continent;
(3) relationships between Late Palaeozoic Uralides and Taimyrides; extent of the Early Mesozoic Novaya Zemlya Fold Belt, and the mechanism of its formation;
(4) offshore extent of the Late Mesozoic fold belts, structural factors controlling their formation;
(5) palaeorelationships of the Kotel'nyi Terrane and the De Long Massif with Siberia, Arctic Canada, and Arctic Alaska;
(6) occurrence of Caledonian and/or Ellesmerian deformations on Kotel'nyi and Wrangel islands;
(7) offshore extent and magnitude of Permian–Triassic and Aptian–Albian flood basalt magmatic.

Presently no reliable data exist to constrain these uncertainties. However the fact that the western sector of the RAS is generally dominated by Neoproterozoic crustal domains, and the eastern sector by Late Mesozoic and, to a smaller extent, by Palaeozoic fold belts, is well supported by the modern geological and geophysical data. This has fundamental implications for characterizing the RAS sedimentary basins, history of their formations and their established and inferred HC systems.

RAS sedimentary basins and their petroleum geology

According to Grantz *et al.* (2009), as many as 37 large sedimentary basins of variable age and genesis exist over the entire RAS and adjoining deepwater areas. Figure 4 shows their outlines derived from MCS and gravity data. Based on the age of the basins, inferred mechanisms of their formation, composition of sedimentary infill, and known and inferred HC systems, we describe six groups of basins, or provinces, which generally fit into geographically isolated shelves: the East Barents (including offshore continuation of Timan–Pechora Basin), South Kara, North Kara, Laptev, East Siberian and Chukchi Sea (Russian sector).

East Barents Province

The structure, lithostratigraphy and petroleum geology of the East Barents and Pechora shelves are known due to the relatively dense grid of 2D seismic surveys, and a number of offshore wells (Gramberg & Pogrebitskiy 1984; Gramberg 1988; Verba *et al.* 1992; Bogdanov & Khain 1996; Shipilov & Tarasov 1998; Kogan *et al.* 2004). Shtokman, Ludlov, Ledovoe, Murmanskoe, Severo–Kildinskoe gas and gas condensate fields, Prirazlomnoe, Severo–Gulyaevskoe, Varandey–More and other oil fields are the biggest among those discovered so far.

The East Barents Province is dominated by the gigantic East Barents Megabasin (EBMB) which, due to its elongated shape, is often called a megatrough. It is bounded by the Central and North Barents platforms in the west and NW, respectively, and by the Novaya Zemlya Fold Belt in the east (Fig. 5). The southern rim of the EBMB is formed by a steep slope of the Fennoscandian Shield (Kola Monocline) and a series of NW-elongated horsts of the Timanian basement. In the north, it is limited by a high-standing block of basement of the Franz Josef Land Archipelago (Fig. 5). Some researchers also include the St Anna Trough in the EBMB. However, this basin is located in the North Kara Shelf, and is isolated from the East Barents Province by a zone of high-standing basement (the Al'banov-Gorbov Arch), and thus may have a different geological history.

The *East Barents Megabasin* extends south–north for over 1000 km, while its west–east width reaches 400–450 km. Despite a large amount of 2D MCS and refraction data and drilled wells, the EBMB is still poorly imaged beneath Jurassic strata due to the great thickness of Triassic and Upper Permian successions. Its internal structure and lithostratigraphic architecture are therefore disputable.

The EBMB is composed of two smaller depocentres: the South Barents and the North Barents basins divided by a basement high named the Ludlov Saddle (Fig. 5). Crustal velocity data show that in the central parts of the depocentres, where the total thickness of presumed post-Middle Devonian sediments reaches over 22 km, the underlying consolidated continental crust is highly attenuated or even could be completely absent (Kogan *et al.* 2004; Kaminsky *et al.* 2009). This fact is used by several researchers to propose that the EBMB is underlain by an oceanic lithosphere formed due to a failed spreading episode (Aplonov *et al.* 1996), or trapped during the Uralian collision event (Ustritsky 1989). As imaged by the deep seismic refraction data (Kogan *et al.* 2004; Ivanova *et al.* 2006), the EBMB generally resembles rift/post-rift basins with significant post-rift cover exceeding 20 km, for example the Pricaspian Basin.

MCS data supported by well ties both within the basin and along its southern margin in the Pechora Sea provide a good basis for understanding of the basin tectonostratigraphy. Six main seismic stratigraphic units have been identified so far (Fig. 6a). These are correlated to the siliciclastic sequences of Cretaceous (1), Jurassic (2), Triassic (3) and Late Permian (4) age, to the Late Carboniferous–Early Permian carbonate rocks (5), and to the Late Devonian to Early Carboniferous syn- and pre-rift clastic and carbonate rocks (6). The first three are well documented by numerous offshore wells that penetrated these stratigraphic intervals. Beneath the unit (6), on the flanks of the megabasin, an older pre-rift seismic stratigraphic unit is visible in seismic data (number 7 in Fig. 6a), which we correlate to Lower Palaeozoic strata known in the Timan–Pechora Basin.

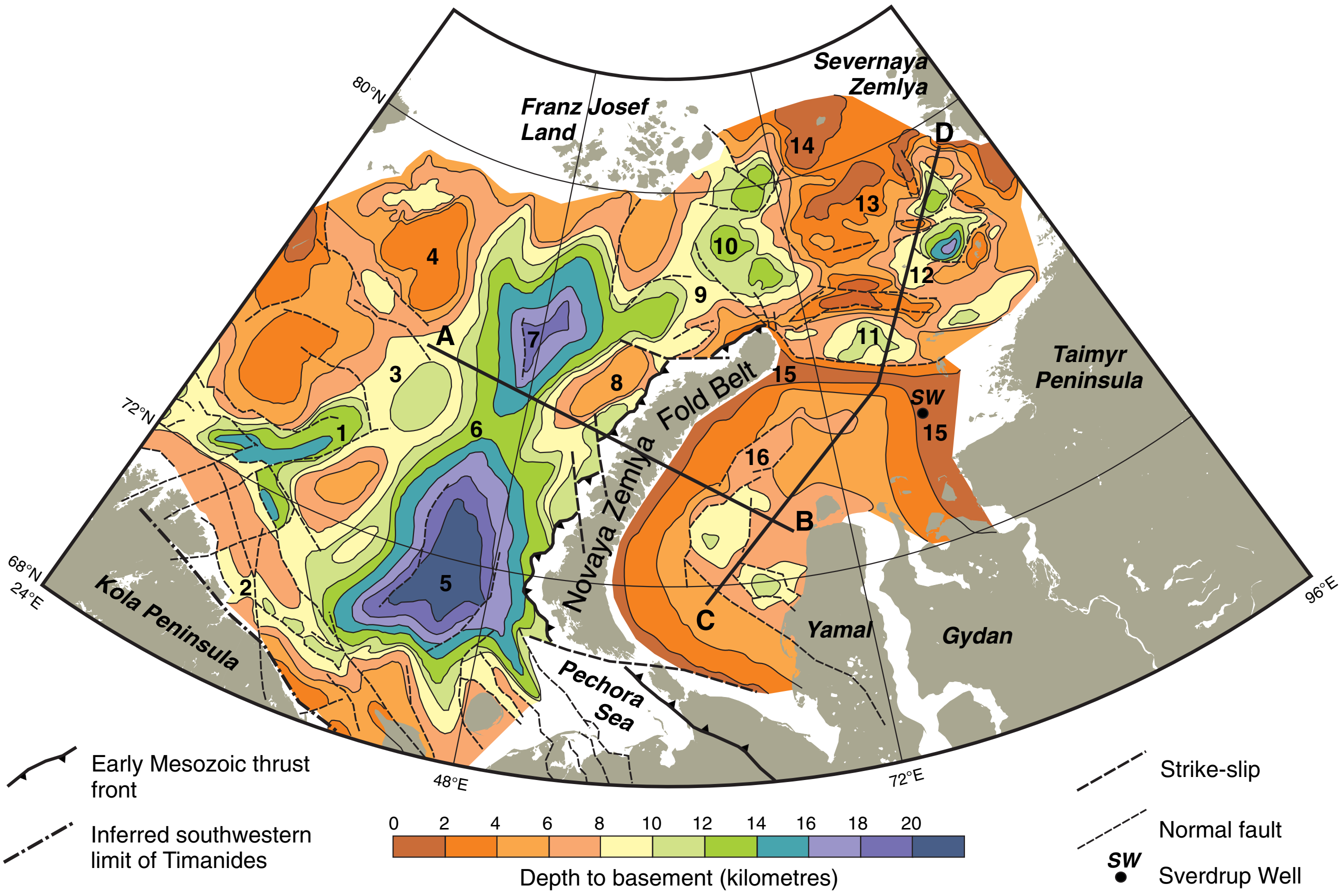

Fig. 5. Simplified depth-to-basement map of the Barents–Kara shelf based on seismic reflection and refraction data and ERS-2 gravity field (see text for the references). Numbered structures are: 1, Nordkapp Basin; 2, Varanger Basin; 3, Central Barents Platform; 4, North Barents Platform; 5, South Barents Basin; 6, Ludlov Saddle; 7, North Barents Basin; 8, Admiralty High; 9, Al'banov-Gorbov Arch. 10, St Anna Trough; 11, Litke Trough; 12, North Kara Basin; 13, Central Kara High; 14, Ushakov High; 15, North Siberian Arch; 16, South Kara Basin. Bold solid lines labelled A–B and C–D show location of cross-sections given in Figure 6.

Because of uncertainties with the stratigraphic correlation of the lower seismic horizons, the timing of basin formation is highly disputed. Proposed models differ significantly with regard to the age of the main rift event, which varies from Mezo-Neoproterozoic to Permo-Triassic (Gramberg & Pogrebitskiy 1984; Gramberg 1988; Nikishin *et al.* 1996; Shipilov & Tarasov 1998; Malyshev 2002; Sharov *et al.* 2005 and references contained therein). We support the point of view proposed in Lopatin (2000), and infer the main rifting phase to occur at Frasnian–Early Carboniferous time based on the following facts: (1) Late Devonian and Early to Mid Carboniferous rift episodes are well documented in the Norwegian Barents Shelf (Gudlaugsson *et al.* 1998); (2) Caledonian compressional deformation affecting the western Barents Shelf in Ordovician–Silurian terminated by Frasnian (Gee & Stephenson 2006).

The tectonic history of the EBMB can be described as a succession of the following events (Fig. 7):

(1) In Cambrian to Silurian, the basin may have been developing mainly in a shelf setting adjacent to the Uralian palaeocean. Its western (present-day) margin may have been subjected to compression and developing of a foreland basin in front of the Caledonides. Depositional environments may have varied though the EBMB from continental and fluvial–deltaic systems in the west, to carbonate platforms and deepwater conditions along its eastern flank. In the Late Silurian, clastic sediments derived from Caledonian orogen may have dominated the entire basin (Korago *et al.* 2009).

(2) In the latest Silurian to beginning of Devonian, large-scale strike-slip deformation and the formation of small pull-apart basins may have occurred in the southern part of the EBMB (by analogy with the Timan–Pechora Basin), followed by regional uplift and erosion during Middle to Late Devonian, prior to Frasnian. The latter could be correlated to a Svalbard Late Caledonian compressional phase, and therefore a compressional setting and basin inversion could be inferred for EBMB at the Middle to Late Devonian.

(3) Frasnian to Early Carboniferous was a time of a main rift phase accompanied by syn-rift basaltic volcanism. Continental crust was severely attenuated and formation of initial oceanic lithosphere could have taken place in the deepest parts of the megabasin. Geodynamic factors controlling the rifting are unknown. A possible association with a mantle plume event could be inferred as proposed earlier for the Russian Craton (Nikishin *et al.* 1996; Wilson & Lyashkevich 1996; Wilson *et al.* 1999). The collapse of the Caledonian orogen could also provide a possible mechanism for crustal extension. Some analogues could be drawn to the Sverdrup Basin in Canadian Arctic to explain crustal attenuation within the EBMB.

(4) The Late Carboniferous to Early Permian was a period of thermal subsidence. Carbonate platforms and buildups formed along the basin flanks while its central parts were dominated by deposition of basinal carbonates and shales.

(5) In Late Permian to Triassic, a rapid subsidence of the entire EBMB took place, accompanied by accumulation of large volume of siliciclastic sediments. Permian clinoforms show

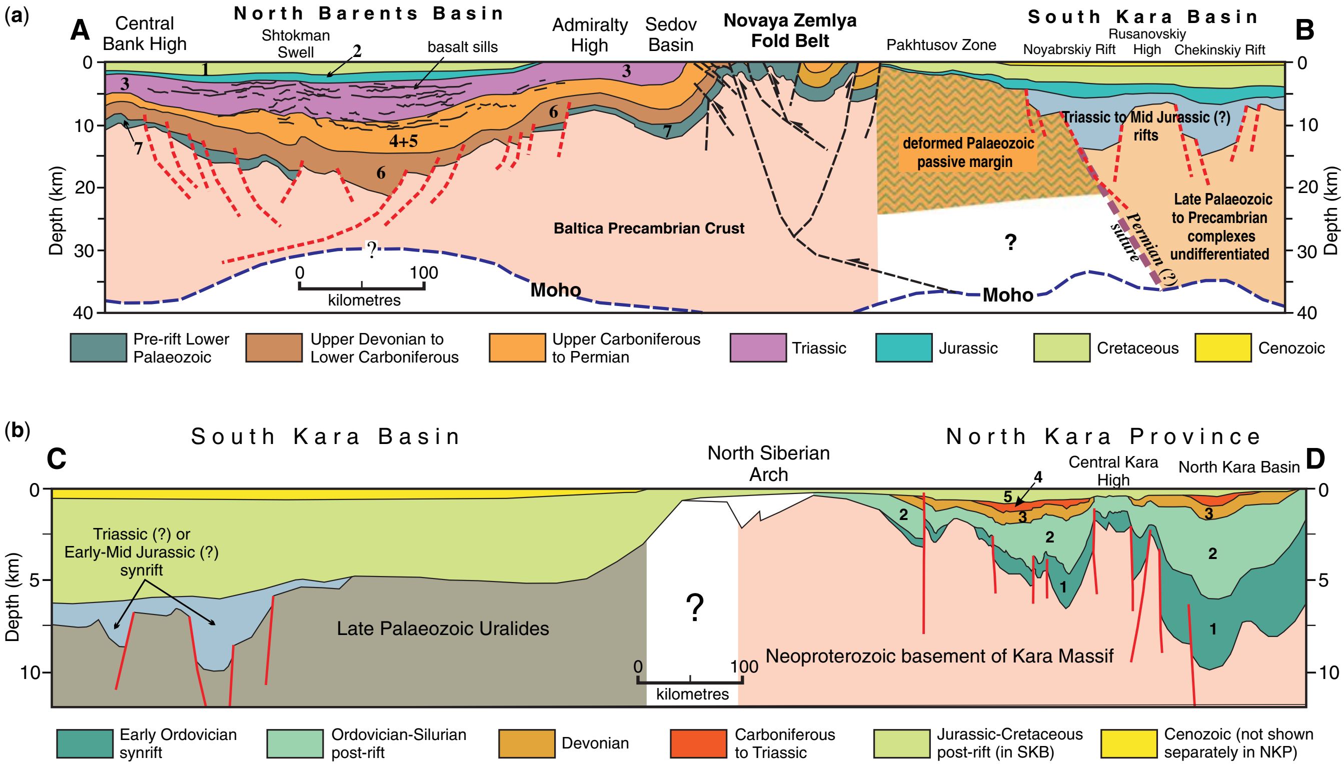

Fig. 6. Schematic geological cross-sections based on re-interpretation of deep seismic reflection and refraction data acquired and published by SMG (Sharov *et al.* 2005; Ivanova *et al.* 2006): (**a**) through the Eastern Barents and South Kara basins based on seismic transect 2-AP, (**b**) though the North Kara Province based on seismic transect 3-AP. Location is shown in Figures 3 and 5. Bold numbers from 1 to 6 in (a) and from 1 to 5 in (b) denote seismic stratigraphic units (see the text for the details).

that the main provenance areas were in the Russian Craton–Timan Pechora–Urals to the SSE of the EBMB, and to the NE within the present North Kara Shelf. Both of these regions were affected by the Late Palaeozoic Uralian orogenesis. Central and eastern parts of the EBMB remained uncompensated through the Late Permian to Early Triassic, and were probably part of a deepwater depression extending and deepening toward the present SKB. Many MCS lines approaching the Novaya Zemlya Fold Belt from the west show thickening of the Upper Permian and Lower Triassic intervals eastward, that is basinward. At the Permian–Triassic boundary, a plume-related basaltic volcanism affected some parts of the EBMB as indicated by basalts of the Pai–Khoi and Timan–Pechora (Nikishin *et al.* 2002). By the end of the Triassic the basin was probably completely filled with clastic sediments.

(6) At the Triassic–Jurassic boundary, the main Novaya Zemlya orogenic phase occurred, accompanied by inversion of the EBMB eastern flank in a foreland setting. Jurassic strata are eroded in the vicinity of the Novaya Zemlya, suggesting that the EBMB eastern flank was uplifted and subjected to erosion during most of Jurassic time.

(7) In Jurassic to Cretaceous, the central part of the EBMB continued to subside and received clastic sediments. During the latest Jurassic, the subsidence became undercompensated by sediment supply, and the EBMB became a starved basin accumulating marine organic rich sediments. By this time, the Novaya Zemlya orogen was probably completely eroded and had subsided below sea-level, uniting the EBMB with the SKB. Both of these became a part of the huge West Siberian depression and were gradually filled up in Early Cretaceous by easterly and northerly derived clastic sediments, as shown by the orientation of the Early Cretaceous clinoforms.

(8) In Aptian to Albian, there was a plume-related magmatic event that caused broad eruption of flood basalts known on Franz Josef Land and Eastern Svalbard (Amundsen *et al.* 1998).

Post-Cretaceous sediments are generally absent over most of the EBMB, which may be related to: (1) tectonic uplift during the Eocene-Oligocene and probably Early Miocene; and/or (2) recent glacial erosion. Cenozoic erosional phases were probably triggered by plate interactions in the North Atlantic and High Arctic, and by hard collision between India and Eurasia beginning around Eocene and continuing through Oligocene and Miocene. These global plate-tectonic factors caused the growth of a series of inversional swells and anticlinal structures (Fig. 8). Some of these inverted features (e.g. the Admiralty High) were formed at the Triassic–Jurassic boundary, and then re-activated in the Cenozoic time. Simultaneously, the Novaya Zemlya orogen was uplifted and became again the major divide between the Barents and Kara provinces.

The formation of the EBMB, as a whole, and especially the mechanisms of its rapid subsidence in the Triassic, remains highly debatable. Several models have been published by Nikishin *et al.* (1996), Artyushkov (2005), Levshin *et al.* (2007), Ritzmann & Faleide (2009) and others (for more comprehensive review see Gee & Stephenson 2006), and we refer readers to these publications and references contained therein for further details on the subject. In this paper we support a concept proposed by Sullivan *et al.* (2007) and by Scott *et al.* (2010), which involves the trapping of Uralian oceanic lithosphere in a pre-existing embayment of Baltica margin (present-day South Kara) during the main Late Palaeozoic collision, and following westward roll-back and pulldown of the trapped lithospheric slab, accompanied by slab to cause rapid subsidence of the adjacent Barents margin (Fig. 9).

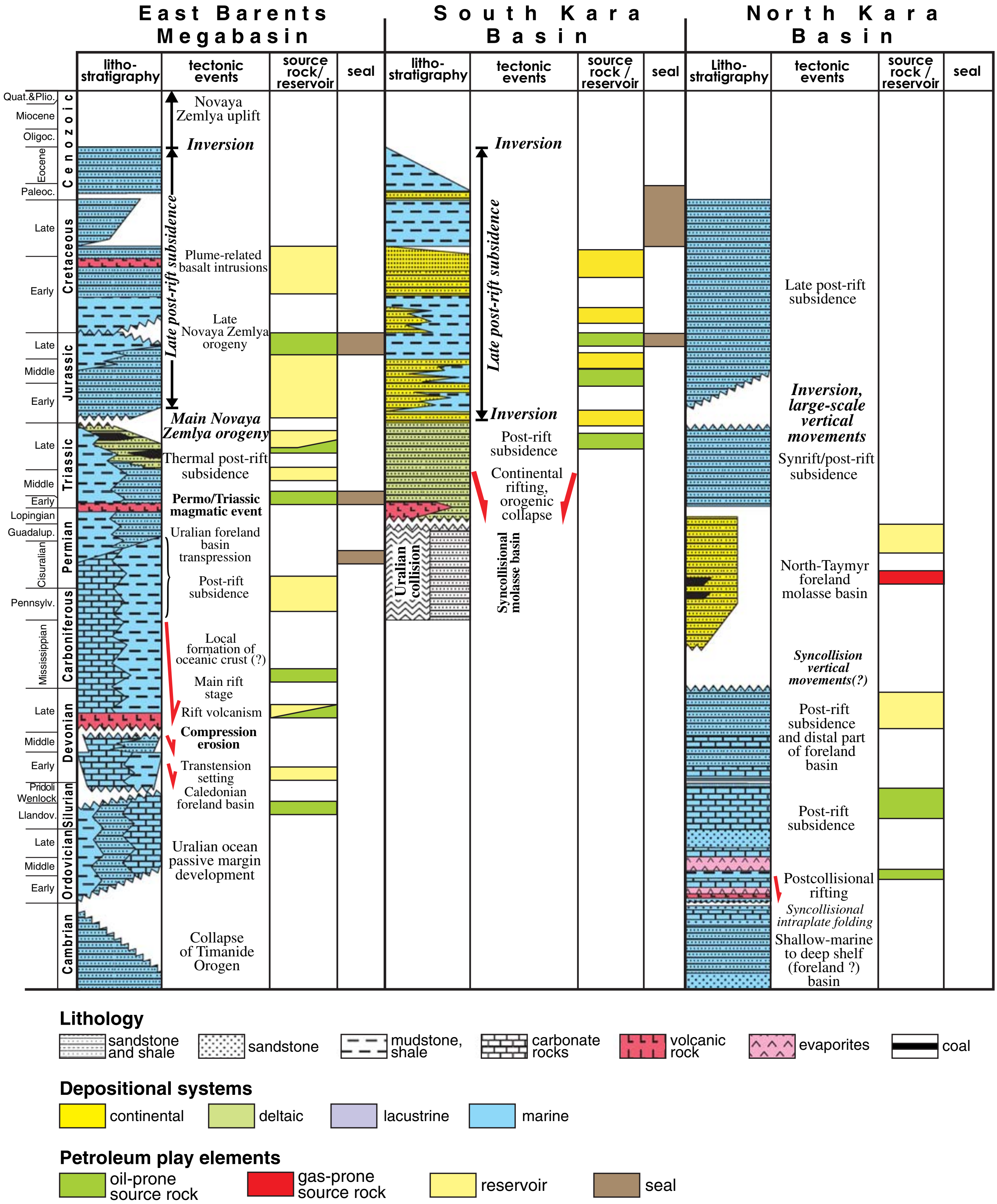

Fig. 7. Summary chart of tectonostratigraphy and petroleum play elements for the Barents–Kara Region.

Petroleum geology. HC systems and petroleum plays of the East Barents Province are known from numerous offshore wells (Fig. 2). The Palaeozoic and Lower Mesozoic plays, which occurred at greater depths throughout the basin and are currently undrilled, were tested in the Pechora Sea, and have been used to decipher the petroleum geology of the lower part of the EBMB infill. The younger Jurassic and Cretaceous plays are well studied in the EBMB where they have accumulated significant gas resources. Many data on the petroleum geology of the Barents–Pechora Shelf were summarized by Ulmishek (1982), Johansen *et al.* (1993), Ostisty & Fedorovsky (1993) and Doré (1995), and we refer readers to these publications for more detailed information. A summary of the petroleum systems and play elements of the East Barents province is given in Figure 7.

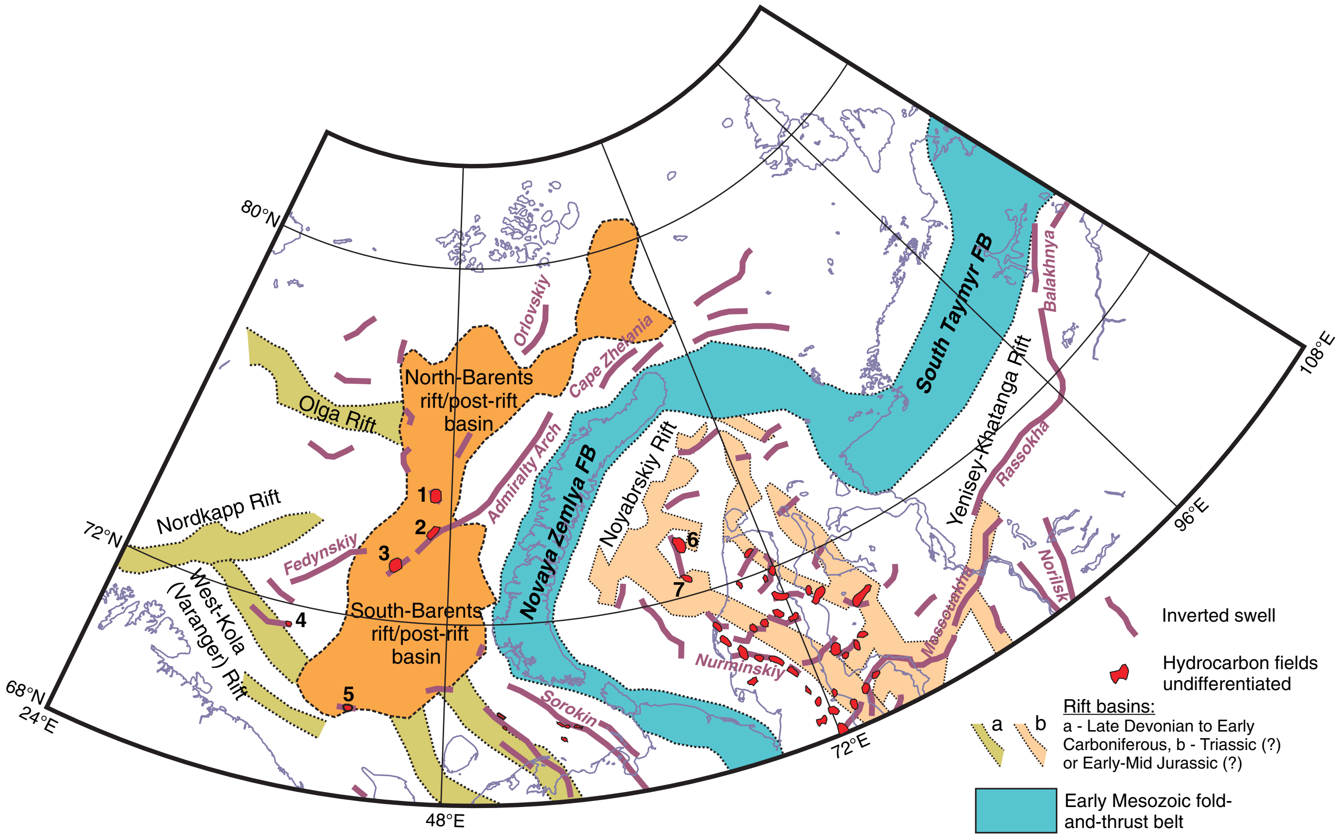

Fig. 8. Areal occurrence of main Mesozoic and Cenozoic intraplate inversional swells in the Barents–Kara Region. Bold numbers denote main gas and gas condensate fields: 1, Ludlov; 2, Ledovoe; 3, Shtokman; 4, Severo-Kil'dinskoe; 5, Murmarskoe; 6, Rusanovskoe; 7, Leningradskoe.

In the Timan–Pechora Basin, the Palaeozoic oil-prone source rocks are represented by:

(1) Upper Silurian shales;
(2) Devonian (lower Frasnian) carbonates and shales (Domanic Formation);
(3) Lower to Middle Carboniferous coaly-argillaceous sediments with mixed kerogen types.

The Lower Permian shaly sediments reveal high content of total organic carbon (TOC) in some sections, and thus could also be a local oil source.

The main reservoirs include:

(1) the Lower Devonian limestones and dolomitized limestones (encountered by a few wells at the lower levels of the Medyn–More and Prirazlomnoe fields);
(2) the Upper Carboniferous and Lower Permian carbonate rocks, especially carbonate buildups and organo-clastic limestones (the Prirazlomnoe Field);
(3) The Upper Permian to Triassic sandstones.

The properties of the Lower Devonian carbonate reservoirs are mainly controlled by highly irregular secondary porosity (7–8%) and low permeability. The Upper Carboniferous to Lower Permian carbonate rocks are the main reservoir for oil accumulations over the entire Timan–Pechora Basin. They also host the Medyn–More and Prirazlomnoe oil fields offshore. These rocks have good properties due to higher porosity, which reaches 25% in fossiliferous layers.

The main seals within the Palaeozoic and Lower Mesozoic plays of Timan–Pechora Basin are represented by:

(1) the Upper Devonian (Kynovsk–Sargaev) argillaceous succession;
(2) the Lower Carboniferous (Visean–Serpukhovian) evaporate succession;
(3) the Lower Permian (Kungurian–Upper Artinskian) carbonate–shale succession;
(4) the Lower Triassic shaly–argillaceous succession.

The Kynovsk–Sargaev and Kungurian–Upper Artinskian are the regional seals which developed throughout most of the Timan–Pechora Basin, while the others have a more limited occurrence.

The main phase of HC generation in the Timan–Pechora Basin occurred in the Permo-Triassic when about 70% of total source rocks entered the oil maturation window (Malyshev 2002).

In the EBMB, the main HC source rocks, which are inferred to charge the gigantic gas accumulations, are the Triassic organic-rich (up to 4.7–6.5% TOC) gas-prone coal-bearing shaly sediments of continental, lagoonal and shallow-marine origin. Their potential for oil generation is unknown, but cannot be ruled out, since marine facies with type II kerogen could have been deposited in the central parts of the EBMB. Marine Upper Jurassic organic rich shales (an analogue of the Bazhenov Suite of the West Siberian Basin) with TOC reaching 16% are widespread within the basin but are generally thermally immature.

The main Mesozoic petroleum plays in the EBMB are related to the Middle–Upper Jurassic (Shtokman, Ledovoe) and Lower–Middle Triassic (Severo-Kil'dinskoe and Murmansk fields) fluvial–deltaic and shallow-marine sandstones. The main pay

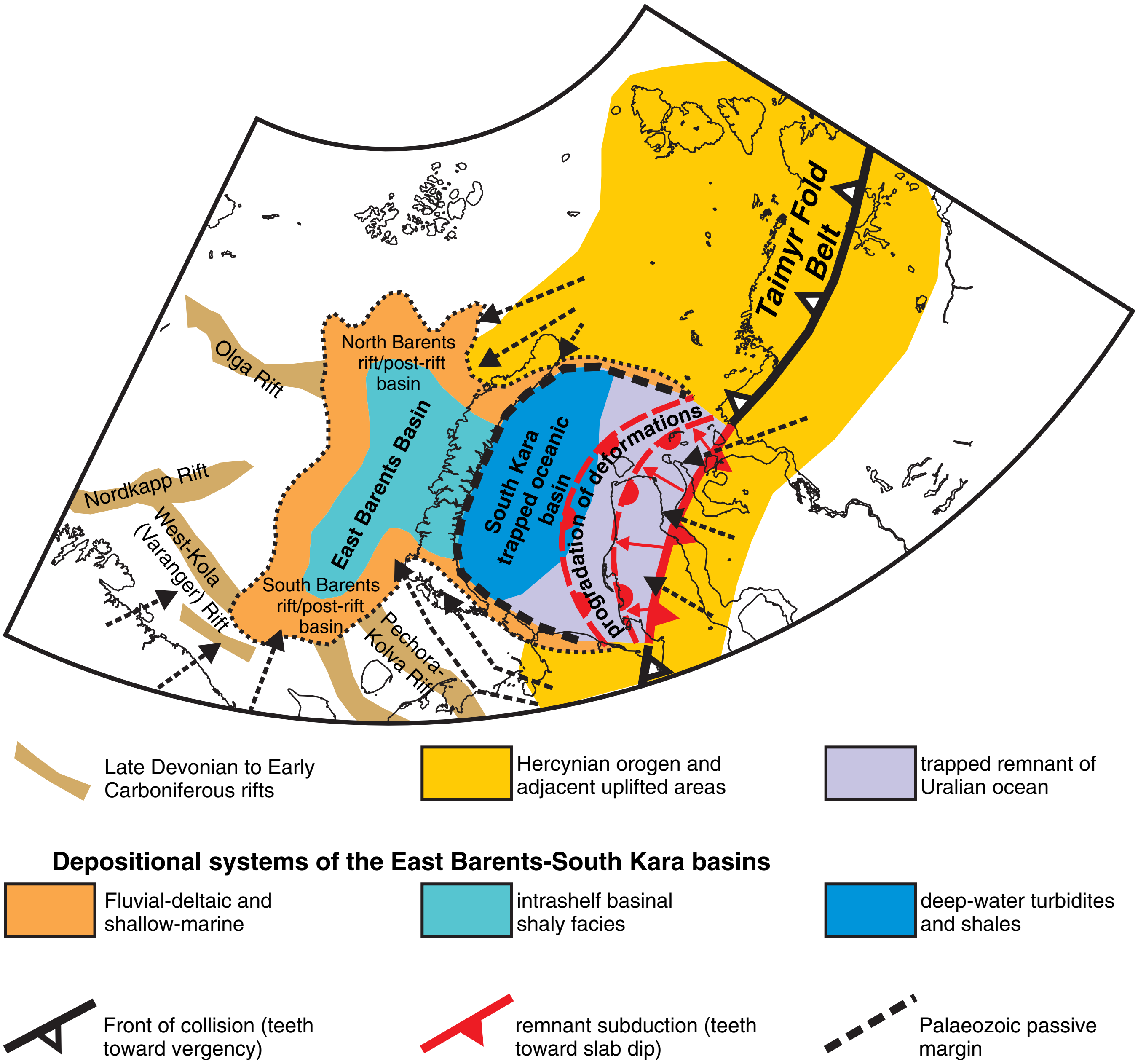

Fig. 9. Schematic chart illustrating the plate-tectonic setting and depositional environments of the East Barents and South Kara basins in Permian–Triassic and possible structural mechanism of the Novaya Zemlya Fold Belt formation. Black dashed arrows show main directions of sedimentary supply into the basins. Red arrows indicate direction of the subducted lithospheric slab roll-back.

interval of the Severo-Kil'dinskoe gas field occurs at 2440 m depth, and is hosted by Lower Triassic sandstones with porosity of *c.* 20%. Potential reservoirs can also be inferred within the Upper Permian siliciclastic successions forming clinoforms along the southern and northern margins of the EBMB, as well as within the Palaeozoic carbonate rocks, where these occur at drillable depths.

The only regional seal occurring throughout the EBMB is composed of the Upper Jurassic immature organic rich shales. In some parts of the basin the seal extends down-section to include the Callovian shales.

Oil and gas trap formation in the East Barents region is generally related to two inversion events:

(1) the Triassic–Jurassic orogeny;
(2) the Early Cenozoic (Eocene to Oligocene) crustal adjustment triggered by the Greenland–EUR–NA plate interactions in the North Atlantic and the Arctic.

The former has a greater impact on the eastern margin of the EBMB affected by a Novaya Zemlya foreland deformation, while the latter resulted in formation of large anticlinal quasi-isometric or elongated arches throughout the basin (Fig. 8).

The main phase of the HC generation in the EBMB started around 55–50 Ma, when the Triassic coaly source rocks became mature. Charge timing was favourable for both the traps formed in Early Cenozoic and for any older traps.

South Kara Province

The SKB is the second most petroliferous province in the RAS with established HC resources. Two large HC accumulations were discovered there at the end of the 1980s: the Leningranskoe gas and the Rusanovskoe gas condensate fields (Fig. 8). Generally the basin is fairly well explored, and many leads and prospects are known (Gramberg 1988; Shipilov

& Tarasov 1998; Kontorovich *et al.* 2001; Sharov *et al.* 2005; Vinokurov *et al.* 2009).

The SKB is located at a junction of the Baltica and East Siberian cratons and the intervening northern termination of the Late Palaeozoic Uralides and western flank of Taimyrides (Figs 3 & 5). It is also located at the hinterland of the Early Mesozoic Novaya Zemlya Fold Belt separating it from the EBMB (Fig. 6). Although it is generally accepted that the SKB is underlain by a basement consisting of these structural domains, the structural pattern of this tectonically complex region is not properly understood. The precise timing of the basin origin, as well as a tectonic regime causing its initiation, also remain unclear. There have been four structural mechanisms proposed so far:

(1) trapped lithosphere of Palaeozoic Uralian Ocean (Ustritsky, 1985);
(2) Late Permian to Early Triassic (Post-Uralian) abandoned small oceanic basin (Aplonov *et al.* 1996);
(3) Late Permian to Early/Mid Triassic intracontinental rifting (Surkov *et al.* 1997, and many others);
(4) Late Permian/Early Triassic subduction rollback and simultaneous crustal extension (see references below).

MCS data reveal extensional structures, dominated by half-grabens, beneath thick sedimentary cover post-dating the extension (Shipilov & Tarasov 1998; Sharov *et al.* 2005; Vyssotski *et al.* 2006). Because of the great thickness of the post-rift sediments, their lower stratigraphic intervals have not been penetrated by drilling, which results in a lack of clarity with regard to the age of the crustal extension affecting the basement beneath the basin. By analogy with the far better studied West Siberian Basin, where the age of crustal extension is considered to be Late Permian to Early Triassic (Kontorovich *et al.* 1975; Surkov & Zhero 1981; Nikishin *et al.* 2002), many researchers attribute the SKB rifts to the same Permo-Triassic extensional event. However, bearing in mind the magnitude of the Triassic–Jurassic compression, which resulted in the formation of the Novaya Zemlya and South Taimyr fold belts, we do not exclude a younger age for the South Kara rifting. Although this does not preclude the existence of the older Permo-Triassic rifts, the latter might have been affected by the Early Mesozoic compression and become a part of a folded basement underlying the SKB. The SKB grabens and half-grabens could be attributed to a crustal extension post-dating the main Triassic–Jurassic orogeny, and could therefore have originated in Early to Middle Jurassic, since the Upper Jurassic Bazhenov horizon is a well-defined seismic marker in the lower part of the post-rift cover. Indirect evidence in favour of this model is derived from the SE–NW strike of the Noyabrskiy Rift in the SKB – almost orthogonal to the dominant direction of the West Siberian rifts (Fig. 8), which suggests that these rifts could have originated independently.

The following events are considered to contribute to the origin of the SKB and its petroleum potential:

(1) the Permian Baltica–Siberia collision and possible trapping of oceanic lithosphere in the future SKB;
(2) the Permian–Triassic plume-related magmatic event;
(3) the Triassic–Jurassic compression and orogeny;
(4) the Early to Middle Jurassic rifting probably related to a collapse of the Early Mesozoic orogen.

Since the Middle Jurassic the SKB became an area of a post-rift thermal subsidence, providing room for accumulation of more than 6 km of fluvial–deltaic, shallow-marine and deepwater siliciclastic sediments. The main sedimentary supply into the basin was from the east (through the Yenisei–Khatanga Depression) and from the north.

Possible models for the SKB formation have to deal with explanation of the rapid subsidence of the EBMB in the Late Permian–Triassic, and remarkable curvature of the Novaya Zemlya Fold Belt. We believe that all these events could be integrated in the model shown in Figure 9. According to this, the slab rollback would be continuously accommodated by the westward expansion of the Uralian orogenic front into the remnant oceanic basin, which could have been completely consumed by the end of the Triassic. Modern seismic tomography data seem to support the existence of an oceanic lithospheric slab beneath the Eastern Barents and Southern Kara shelves (Levshin *et al.* 2007).

Petroleum geology. HC systems of the SKB are projected from the onshore West Siberian Basin. The main source rocks are the bituminous shales of the Bazhenov Formation. In addition, based on well data from the Yamal Peninsula, organic-rich beds are also present in older Early–Mid Jurassic marine shaly succession, and especially in the Tyumen Formation. Aptian–Albian deltaic coals of the Tanopchin Formation are one of the major gas sources (see Fjellanger *et al.* 2010). If the Triassic sediments survived the post-Triassic orogeny, they, by analogy with the East Barents Province, can also be considered as a potential source of HC.

The main gas and gas condensate accumulations of the SKB occur in the Cretaceous Tanopchin and Pokur fluvio-deltaic sandstones and pelitic sandstones. In the Rusanovskoe Field, 12 pay zones with average effective porosity *c.* 20% were established in Cenomanian (one zone), Albian (three zones) and Aptian (eight zones) strata. In the Leningradskoe Field, pay zones with average effective porosities of 26% were tested in Cenomanian (one zone), Albian (three zones) and Aptian (three zones) sediments. Potential clastic reservoirs may occur within the Lower Cretaceous (Neocomian) clinoforms and within the Jurassic Vasyugan Formation.

Regional seals within the SKB are represented by Turonian–Paleocene and Albian marine shaly successions. The former is a seal over 50 m thick for the Leningradskoe Field, while the latter is a 100 m thick seal in the Rusanovskoe Field. Upper Jurassic–Neocomian shales and shaly sediments form another basin-wide seal for the deeper undrilled prospects.

Numerous anticlinal structures, identified by the MCS data in the SKB, affect the Cenozoic sediments. This suggests inversion at the latest stages of the basin's formation. As shown by Vyssotski *et al.* (2006), the inversion in the West Siberian basin could have started as early as Campanian–Maastrichtian and culminated in the Oligocene. The existence of two systems of inverted anticlines striking to the eastnortheastern and northwestern directions, almost orthogonal one to another (Fig. 8) suggests at least two main directions of tectonic stress. Many researches refer to the far-field stresses sourced by the India–Eurasia collision to explain the West Siberia Basin inversion (e.g. Allen & Davies 2007). We believe that there could also be a more proximal source for inversion caused by convergence of the EUR–Greenland and EUR–NA plates in Early Cenozoic time.

HC generation in the SKB could have started as early as Barremian, when Tyumen Formation first entered the oil window, and persisted through the Late Cretaceous with the main HC generation from the Bazhenov Formation. One important difference between the West Siberian Basin and its offshore continuation is that all the pre-Bazhenov sources and most of the Bazhenov Formation are deeply buried within the SKB, and thus are located in the gas maturation window. Therefore, the potential for oil generation is limited to the marginal parts of the basin. According to Fjellanger *et al.* (2010), gas accumulations in the gigantic fields of the Yamal–Tazov Region and SKB can only be explained by the combined charge from all possible sources, including biogenic gas.

North Kara Province

North Kara Province (NKP) is the least explored part of the western RAS (Fig. 2). Current understanding of its geology is mostly based on a few published MCS lines (Shipilov & Tarasov 1998; Sharov *et al.* 2005; Ivanova *et al.* 2006), potential field data and geological observations from the Severnaya Zemlya Archipelago (Kaban'kov & Lazarenko 1982; Bogolepova *et al.* 2001; Metelkin *et al.* 2005; Lorenz *et al.* 2006–2008).

Tectonically the NKP is separated from the South Kara Basin by the North Siberian Arch (see above). As shown by the seismic reflection and refraction data along the 3-AP line (Sharov *et al.* 2005; Ivanova *et al.* 2006), the post-rift, especially Jurassic, sediments filling the SKB thin dramatically towards the arch. Sverdrup Well, drilled on a small same-named island in the eastern Kara Sea (Fig. 5), located just on the North Siberian Arch, penetrated about 1350 m of the Lower Cretaceous sediments and only 170 m of the Upper Jurassic sediments, which rest unconformably on metamorphic rocks of inferred pre-Cambrian age. This implies that the basement arch existed during most of the post-rift history of South Kara Province. MCS data do not show any significant faulting associated with the arch.

There are four contrasting gravity lows in the Northern Kara Sea corresponding to the main depocentres: St Anna Trough (Fig. 4, number 14; & Fig. 5, number 10), Litke Trough (Fig. 4, number 12; & Fig. 5, number 11), Schmidt Trough (Fig. 4, number 15) and North Kara Basin (Fig. 4, number 13; & Fig. 5, number 12). As shown by the MCS data, they have an extensional origin and contain *c.* 10 km of syn-rift and post-rift sediments (Shipilov & Vernikovsky 2010). Age calibration of the MCS data is highly controversial and can only be based on lithostratigraphic correlations with the sections described from northern part of the Novaya Zemlya and Severnaya Zemlya archipelagos.

Based on MCS data interpretation correlated with the above-described stratigraphy of the Severnaya Zemlya, we infer the following seismic stratigraphic units within the NKP offshore basins (Fig. 6b):

(1) Early Ordovician syn-rift unit consisting of shallow-marine clastic rocks and volcanic rocks;
(2) Ordovician–Silurian post-rift unit dominated by clastic rocks and shales (Ordovician), carbonate and evaporate rocks;
(3) Devonian unit dominated by syn-orogenic continental clastic molasses;
(4) Carboniferous to Triassic unit dominated by continental clastic sediments synchronous with the Taimyr orogeny;
(5) Mesozoic to Cenozoic unit composed of continental and shallow-marine sediments overlying older units with a sharp basal unconformity.

Whether the Neoproterozoic to Cambrian strata are present within the NKP sedimentary basins remains unclear. Considering data on the Northern Block of the NZFB, the pre-Cambrian siliciclastic rocks may, together with the Lower to Middle Palaeozoic strata, participate in the sedimentary cover of the KM, while the data on Severnaya Zemlya Archipelago evidences their involvement into folded Neoproterozoic basement.

Geological and MCS data suggests that the main structural inversion of the NKP basins took place in post-Triassic time, perhaps at the Triassic–Jurassic boundary, synchronous with the formation of the Novaya Zemlya Fold Belt. The inversion was accompanied by large-scale vertical movements of basement blocks, and may have generally had a transpressional character.

Petroleum geology. HC systems of the North Kara Sea and adjacent islands are not studied, and thus can only be inferred based on lithological composition and depositional environment observed in the Severnaya Zemlya sections. However, natural bitumen is reported from Silurian, Devonian and Triassic–Jurassic sediments, which may indicate the presence of source rocks generating these HCs. Oil-prone source rocks are inferred in the Middle Ordovician dark shales and Silurian carbonates, while clastic reservoirs could be expected within Devonian and Late Palaeozoic strata. The main trap formation phase may have occurred at the Triassic–Jurassic boundary, and the related structures could have been charged from Palaeozoic sources. The main exploration risks are related to seal presence, as perhaps Upper Jurassic–Lower Cretaceous (Neocomian) regional seals might not have been formed due to post-orogenic uplift of the entire NKP in Mesozoic time.

Laptev Sea Province

The Laptev Shelf is the most studied of the Siberian shelves (Fig. 2). Tectonically it represents a large, about 500 km wide and 700 km long, rift system that has been developing since Late Cretaceous time in response to the Eurasia oceanic basin breakup and consequent spreading along the Gakkel Ridge (Figs 4 & 10). Its geology has been described in detail by Drachev *et al.* (1998, 1999), Drachev (2000), Franke *et al.* (2000, 2001, 2004), Sekretov (2000) and Franke & Hinz (2005), and therefore we refer the reader to these publications for more comprehensive insight into structure and seismic stratigraphy of the Laptev shelf.

The Laptev Rift System (LRS) consists of a series of wide extensional basins and relatively narrow grabens, as shown in Figures 4, 10 and 11. These are (from west to east): the SW Laptev (Fig. 11a, number 1), Ust' Lena (Fig. 4, number 18; & Fig. 11a, number 2), Anisin (Fig. 4, number 20; & Fig. 11a, number 6), Bel'kov (Fig. 10, number 5; & Fig. 11a, number 7) and Svyatoi Nos (Fig. 11a, number 8), separated by high-standing blocks of underlying Late Mesozoic basement (East Laptev, Stolbovoi, Shiroston, and Kotel'nyi horsts, or highs; see Fig. 11a). The New Siberian Rift (Fig. 4, number 21; & Fig. 11a, number 10) occurring NE of Kotel'nyi Island is structurally isolated from the LRS, and thus is considered as a structural element of the East Siberian Shelf.

The internal structure of the LRS is controlled by a series of large-offset listric normal faults, with the main extensional detachments generally located at the eastern shoulders of the rifts (Fig. 11b). Inverted structures are widespread and occur along the listric faults; they are considered the result of compression, due to slight convergence between the EUR and NA plates in the Oligocene to Early Miocene (Savostin & Drachev 1988).

Stratigraphic correlation of the rift infill is disputable. Ivanova *et al.* (1990) and Sekretov (2000), based on the earlier idea of extension of the Siberian Craton far offshore (Vinogradov 1984), speculated that the rifts contain Neoproterozoic, Palaeozoic and Lower Mesozoic rocks, which represent a lithostratigraphic analogue of the craton's sedimentary cover. This concept suffers from lack of geological evidence supporting the offshore continuation of the Siberian Craton. An opposing point of view, supported in this paper, is based on a fact that the Laptev Shelf is surrounded by the Late Palaeozoic and Late Mesozoic fold belts, which apparently continue offshore and form a pre-rift basement of the rift system (Vinogradov & Drachev 2000; Drachev 2002). Therefore this concept limits the total stratigraphic range of the Laptev rift basins infill to the Upper Cretaceous and Cenozoic, and is in agreement with onshore stratigraphy of the Laptev region (Grinenko 1989; Alekseev *et al.* 1992).

The rift infill is composed of mainly siliciclastic non-marine, deltaic and shallow marine sediments whose total thicknesses vary from 1.5–3 to 8–10 km, and reach 13–14 km in the deepest parts of the Ust' Lena Rift (Fig. 11a, b). A clear eastward decrease of thickness and stratigraphic completeness of the syn-rift

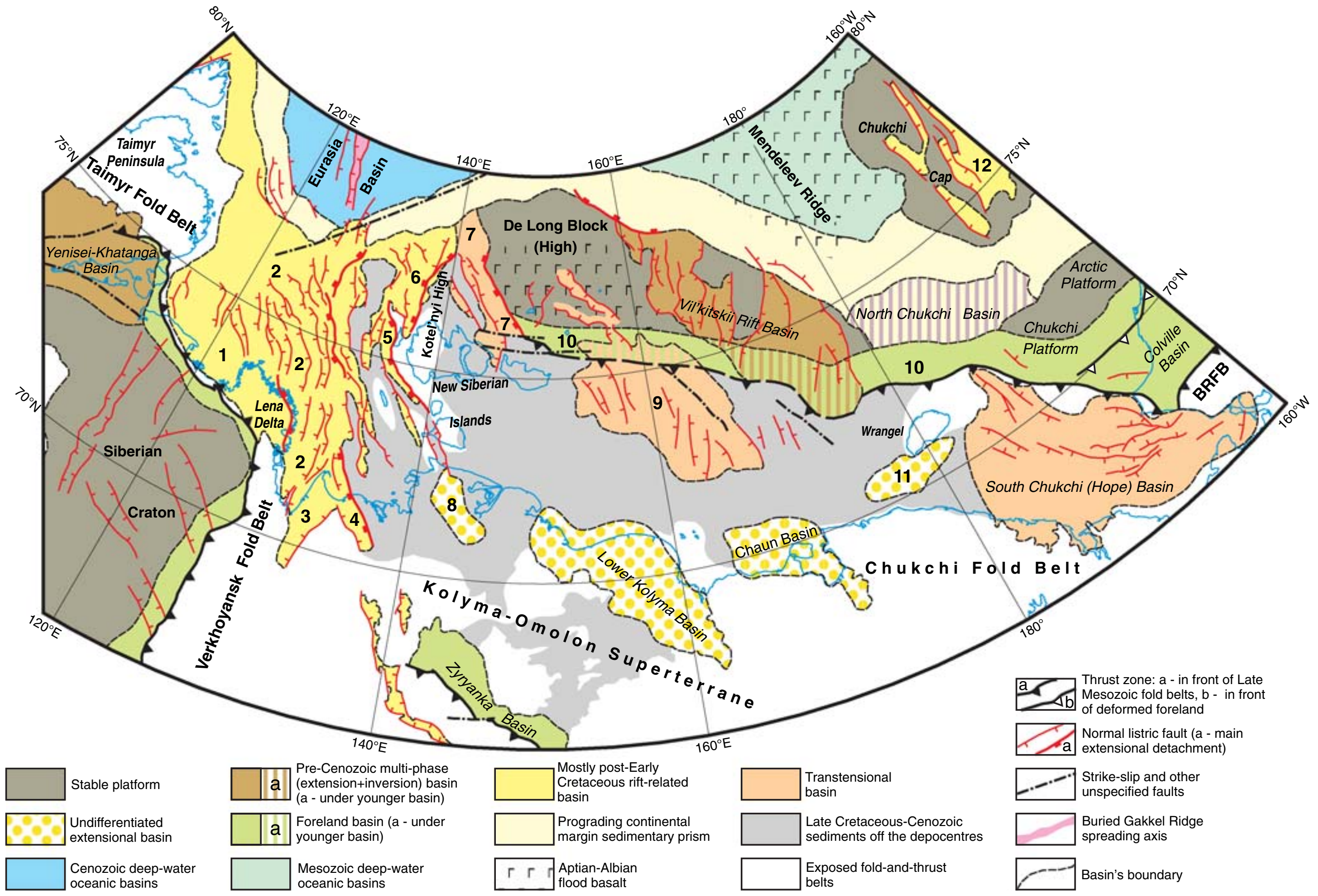

Fig. 10. Main sedimentary basins of the Siberian Arctic Shelf (modified from Grantz *et al.* 2009). Bold numbers denote the following basins: 1, Southwest Laptev Basin; 2, Ust' Lena Rift; 3, Omoloy Graben; 4, Ust' Yana Graben; 5, Bel'kov Rift; 6, Anisin Rift; 7, New Siberian Rift; 8, Tas–Takh Depression; 9, East Siberian Sea Basin; 10, New Siberian–Wrangel Basin; 11, Longa Basin; 12, Northwind Basin. BRFB, Brooks Range Fold Belt.

sequences, as well as a decrease in structural complexity of the rifts, may indicate an eastward rejuvenation of the rifts.

Based on the known history of the NA–EUR plate interaction in the Arctic, the following scenario for the evolution of the LRS is proposed (Fig. 12):

(1) In the Late Cretaceous to Paleocene, an initial rifting culminated in a breakup event and the onset of seafloor spreading in the Eurasia Basin at *c.* 55 Ma.
(2) In the Eocene, a non-rift setting existed as a result of the accommodation of the Eurasia Basin opening by the Khatanga–Lomonosov shear zone, which then became a segment of the plate boundary, and thus prevented the penetration of extensional strain onto the Laptev Shelf.
(3) During the Oligocene to Early Miocene, a non-rift or compressional setting existed, caused by global plate re-arrangement at 33 Ma.
(4) During the Late Miocene to Pleistocene, a re-activation of crustal extension occurred, representing the Second Rift Stage.

Interpreted MCS data correlated with onshore lithostratigraphy support this model and show the presence of successions deposited in a non-rift setting. These units truncate many of the earlier normal faults, and a sharp seismic stratigraphic unconformity at their base is regarded as a break-up unconformity at 55 Ma. The high reflectivity pattern on MCS data may be related to a high coaly material content. This is supported by a widespread occurrence onshore of Eocene and Oligocene strata abundant in brown coals and lignites deposited in low coastal plains during warm climatic conditions (Grinenko 1989; Stein 2008).

Petroleum geology. Data on HC systems of the Laptev Sea Province are generally absent. However, based on the lithostratigraphy of the onshore Cenozoic sections, and the inferred tectonic history of the LRS, we can speculate on possible source/reservoir/seal rock occurrences within the offshore rift basins (Fig. 12).

The main potential sources of HCs in the LRS can be attributed to:

(1) Paleocene to Eocene and, to some extent, Oligocene sediments with abundant terrestrial organic matter are potential gas-prone sources. However, Paleocene and Mid-Eocene marine organic-rich beds should not be excluded within the rift depocentres. They could be analogues of organic-rich marine shales recently encountered on the Lomonosov Ridge (Moran *et al.* 2006). Despite the uncertainty as to whether these beds could produce oil or not, their great contribution into the total HC potential of the Arctic deepwater basins and adjacent shelves cannot be ignored in future assessments.
(2) The Late Cretaceous and Paleocene syn-rift successions may contain both terrestrial and lacustrine organic-rich beds. These potential sources are presently buried at depths generally greater than 4–5 km in the main rift depocentres, and hence are likely to be mainly gas-prone.

Oligocene and particularly Lower Miocene sediments in many onshore localities are dominated by coarse-grained clastic sediments and thus can be considered as reservoir-prone successions. Little is known about the mineral composition of the sands, but considering the Palaeo-Lena River as a major supplier of the clastic sediments into the rift depocentres, especially into the Ust' Lena

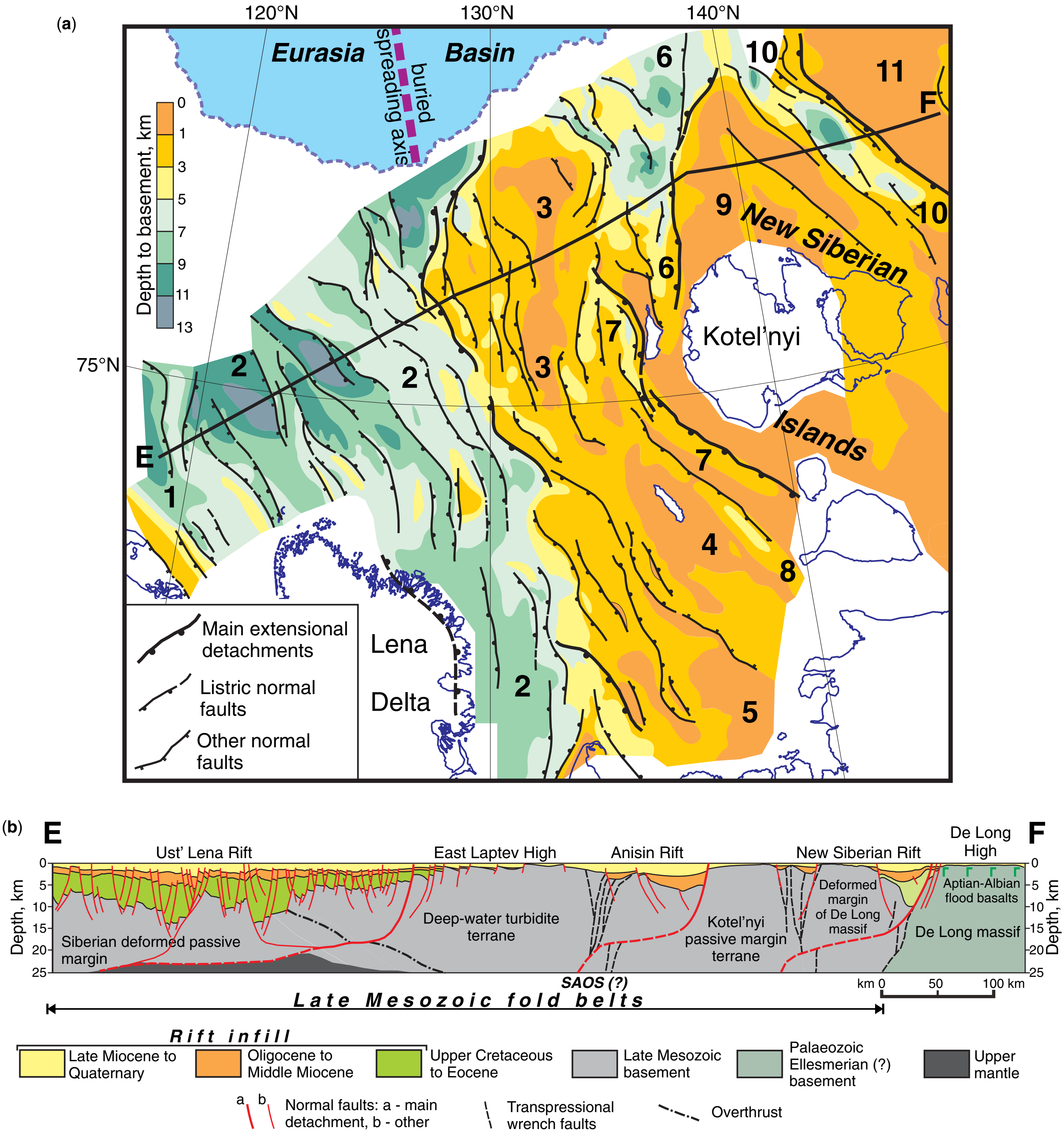

Fig. 11. Structure of the Laptev Rift System: (**a**) simplified depth-to-basement map of the Laptev Shelf based on 2D seismic and ERS-2 gravity data; (**b**) cross-section based on geological data and published BGR regional seismic lines (Franke *et al.* 2000, 2001). Location of the cross-section is shown in (a). Bold numbers in (a) denote following elements of the rift system: 1, Southwest Laptev Rift Basin; 2, Ust' Lena Rift; 3, East Laptev Horst; 4, Stolbovoi Horst; 5, Shiroston Horst; 6, Anisin Rift; 7, Bel'kov Rift; 8, Svyatoi Nos Graben; 9, Kotel'nyi High; 10, New Siberian Rift; 11, De Long High. *SAS (?)* in (b) denotes possible offshore projection of the South Anyui Suture.

Rift, we conclude that the reservoirs may potentially be of good or very good quality. Based on the broad areal extent of the Oligocene to Lower Miocene fluvial clastic sediments around the Laptev Shelf, we can predict their widespread occurrence offshore. That, in turn, makes this interval a main future HC exploration play.

In the onshore sections the Upper Miocene to Quaternary strata are dominated by clastic material against the suppressed accumulation of terrestrial organic matter. However, offshore sections are generally dominated by marine fine-grained muddy sediments, allowing the Upper Miocene and especially Pliocene to Quaternary sediments to be considered as a main regional seal.

Earliest oil generation could have started *c.* 13 Ma ago in the main rift depocentres of the western Laptev Shelf, and progressed until the end of Miocene time when the source rock is estimated to leave the oil maturation window, and the whole petroleum system became gas generating. The second phase of oil generation could have begun along the rift flanks during Late Miocene time, and has progressed up to the present.

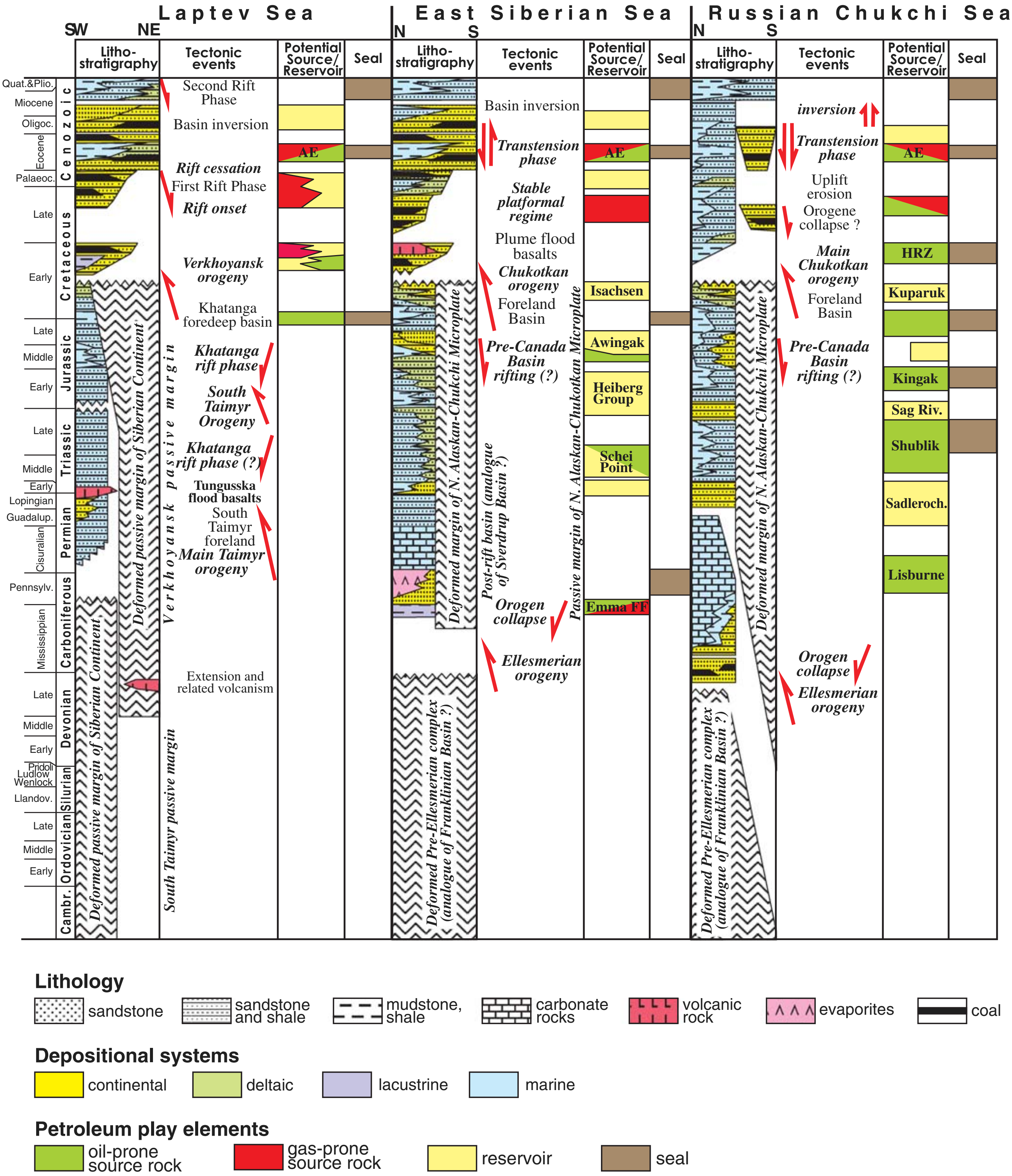

Fig. 12. Summary chart of tectonostratigraphy and petroleum play elements of the Siberian Arctic Shelf. AE denotes Azolla Event. Other bold italic words in Potential source/Reservoir columns denote names of analogue formations in the Sverdrup Basin (East Siberian Sea column) and the Alaskan Northern Slope (Chukchi Sea column). Emma FF denotes Emma Fiord Formation, and HRZ denotes Highly Radioactive Zone.

The estimated time of primary oil generation phases is quite favourable in terms of the capturing of migrating HCs in pre-existing structural traps, formed during the Oligocene to Early Miocene basin inversion, and the onset of the Second Rift Phase (Fig. 12). In most cases the traps are represented by tilted blocks and faulted rollover anticlines, as well as inverted anticlines and drapes over basement highs. The width of the structural traps is controlled by the distance between normal faults, which commonly varies around 5–7 km, while the length of the traps could be in the range of 10–20 km.

Older pre-rift HC plays may have a lesser contribution to the overall HC potential of the Laptev Shelf, as compared with the syn-rift plays. One of the pre-rift plays could be inferred in the southwestern part of the shelf, where marine organic-rich beds of latest Jurassic to earliest Cretaceous age are known to crop out along the shore in a foreland setting (Kaplan *et al.* 1973). There, a younger Neocomian succession is formed by reservoir-prone fluvial and deltaic/shallow marine facies, correlative to a set of Neocomian clinoforms that are well developed throughout the entire Yenisei–Khatanga Basin (Baldin 2001). If this basin extends offshore beneath syn-rift sedimentary cover, then the shelf area between the Lena Delta and Khatanga Bay could be favourable for both oil and gas pre-rift HC plays.

East Siberian Sea Province (ESSP)

The ESSP is the largest part of the Siberian Arctic shelf extending for over 1000 km from New Siberian Islands to Wrangel Island (Fig. 1). It is also the least studied part of the RAS (Fig. 2), and thus only general conclusions on its geology and possible HC systems can be drawn based on limited MCS, gravity and magnetic data, supported by the offshore projection of onshore geology. Earlier tectonic concepts published by Vinogradov *et al.* (1974, 1977), Kos'ko (1984) and Kos'ko *et al.* (1990) were recently reviewed with the use of regional MCS data (Roeser *et al.* 1995; Drachev *et al.* 1999, 2001; Franke *et al.* 2004; Franke & Hinz 2005). The following description summarizes the tectonic concepts of the ESSP history drawn from our interpretation of the available MCS data.

Two main crustal domains are recognized within the ESSP (Figs 10 & 13):

(1) the De Long Massif representing a northern (present-day) part of the AACM unaffected by the Late Mesozoic Verkhoyansk–Brookian orogeny;
(2) the New-Siberian–Chukchi Fold Belt – a southern part of the AACM involved in the Late Mesozoic compression deformation and orogeny.

Consequently, we outline two main generations of the basins whose occurrence is controlled by the above basement domains:

(1) Palaeozoic (post-Devonian?) to Mesozoic basins preserved north of the Late Mesozoic frontal thrusts (stratigraphic analogue of the US Chukchi Ellesmerian Sequence);
(2) Early Cretaceous (Aptian–Albian) to Quaternary basins, post-dating the Verkhoyansk–Brookian orogeny, and evolving mainly over the New-Siberian–Chukchi Fold Belt (stratigraphic analogue of the US Chukchi Brookian Sequence).

The 70–100 km wide New Siberian Rift is clearly expressed in the gravity field (Fig. 4, number 21). It occurs between two high-standing blocks of tectonic basement – Kotel'nyi High on the west and De Long High on the east (Fig. 10). The rift sedimentary infill thickens from 5 km in the southern part of the rift, where it onlaps onto the Late Mesozoic folded basement of the Kotel'nyi High (Fig. 11b), to 10 km in the northern part of the rift, and is composed of several seismic units forming two main sets of strata:

(1) a syn-rift sequence correlates with Upper Cretaceous and Paleocene–Eocene siliciclastic terrestrial and shallow-marine sediments containing abundant coaly material;
(2) a set of post-rift seismic sequences interpreted as Oligocene to Lower Miocene, Middle to Upper Miocene and Pliocene to Quaternary sequences, deposited mainly in shallow-marine conditions.

Drachev *et al.* (1998, 1999) proposed that the New Siberian Rift was formed in response to a postulated divergent plate-tectonic boundary linked to the Late Cretaceous–Paleocene Labrador Sea–Baffin Bay spreading axis. Generally the rhomboid-like shape of the rift, its rather limited extent and evidence of strike-slip dislocations within its interior, are interpreted as evidence of a pull-apart origin.

The East Siberian Sea Basin (ESSB) is a NW–SE elongated 450 km long by 350 km wide depocentre, occurring in the central part of the ESSP (Fig. 4, number 22; Fig. 10, number 6; & Fig. 13). Its structural style differs significantly from the severely rifted Laptev Shelf, and is interpreted as being transtensional in origin (Franke *et al.* 2004; Franke & Hinz 2005). A possible cause for the transtensional regime can be inferred from the tectonic setting of the ESSP within a broad region of Early Cenozoic crustal re-adjustment between the NA and EUR lithospheric plates.

The basin is filled with siliciclastic sediments exceeding 8 km in the deepest depocentres. Their stratigraphic range is inferred to be Late Cretaceous to Quaternary in age. Based on reflection MCS data, the basin infill is subdivided into three main units (Fig. 14):

(1) a Lower Unit correlated to Upper Cretaceous (Cenomanian to Turonian), and Paleocene successions of coal-rich continental and deltaic clastic sediments exposed on Novaya Sibir' Island;
(2) a Middle Unit inferred to consist of Eocene to Middle Miocene fluvial–deltaic and shallow-marine successions, accumulated during the main stage of basin subsidence;
(3) an Upper Unit post-dating the main subsidence stage, and truncating the majority of faults identified within the Middle Unit. We correlate the Upper Unit to a set of Late Miocene to Pleistocene sequences dominated by shallow-marine shaly clastic sediments, which occur widely throughout northeastern Asia.

Considering the tectonic history of the ESSB, we can distinguish the following stages:

(1) Late Cretaceous and Paleocene – a tectonically 'quiet' platformal regime existed with accumulations of the Lower Unit, which is abundant in terrestrial organic matter.
(2) Eocene to Middle Miocene – rapid subsidence of the basin occurred in a transtensional setting controlled by dextral divergence of the NA and EUR plates. By the end of Oligocene to Early Miocene a change in the interaction of the plates caused the compression and structural inversion of some parts of the basin.
(3) Late Miocene to Pleistocene – the active tectonic movements ceased across the entire East Siberian Sea as the main zone of interaction between the EUR and NA plates moved over to the Laptev Sea region. During this sag phase the entire ESS shelf experienced thermal subsidence, and experienced broad marine transgressions.

The *New Siberian–Wrangel Foreland Basin* is recognized below the northern limb of the ESSB (Fig. 10, number 10). This narrow west–east trending basin is traced by a few lines across the ESS and north of Wrangel Island (see below) into the US Chukchi shelf, where it possibly merges into offshore prolongation of the Colville Foreland Basin (Grantz *et al.* 2009).

The MCS data along seismic line LARGE-8901 show the presence of two wedge-shaped packages of seismic reflectors beneath the Lower Unit north of the Late Mesozoic frontal thrust (Fig. 14). The reflectors of the upper package progressively onlap northward onto the lower wedge-shaped package, and both packages are involved into compressional deformations in the vicinity of the frontal thrust. We interpret the upper package as a siliciclastic coal-bearing infill of the foreland basin formed at terminal stages of the Verkhoyansk–Brookian orogeny (Drachev *et al.* 2001). The lower package may represent the Lower Mesozoic and/or Late Palaeozoic strata of the De Long Massif – analogues of the Ellesmerian Sequence of the Arctic Alaska. Alternatively, it could consist of the Lower Cretaceous flood basalts cropped

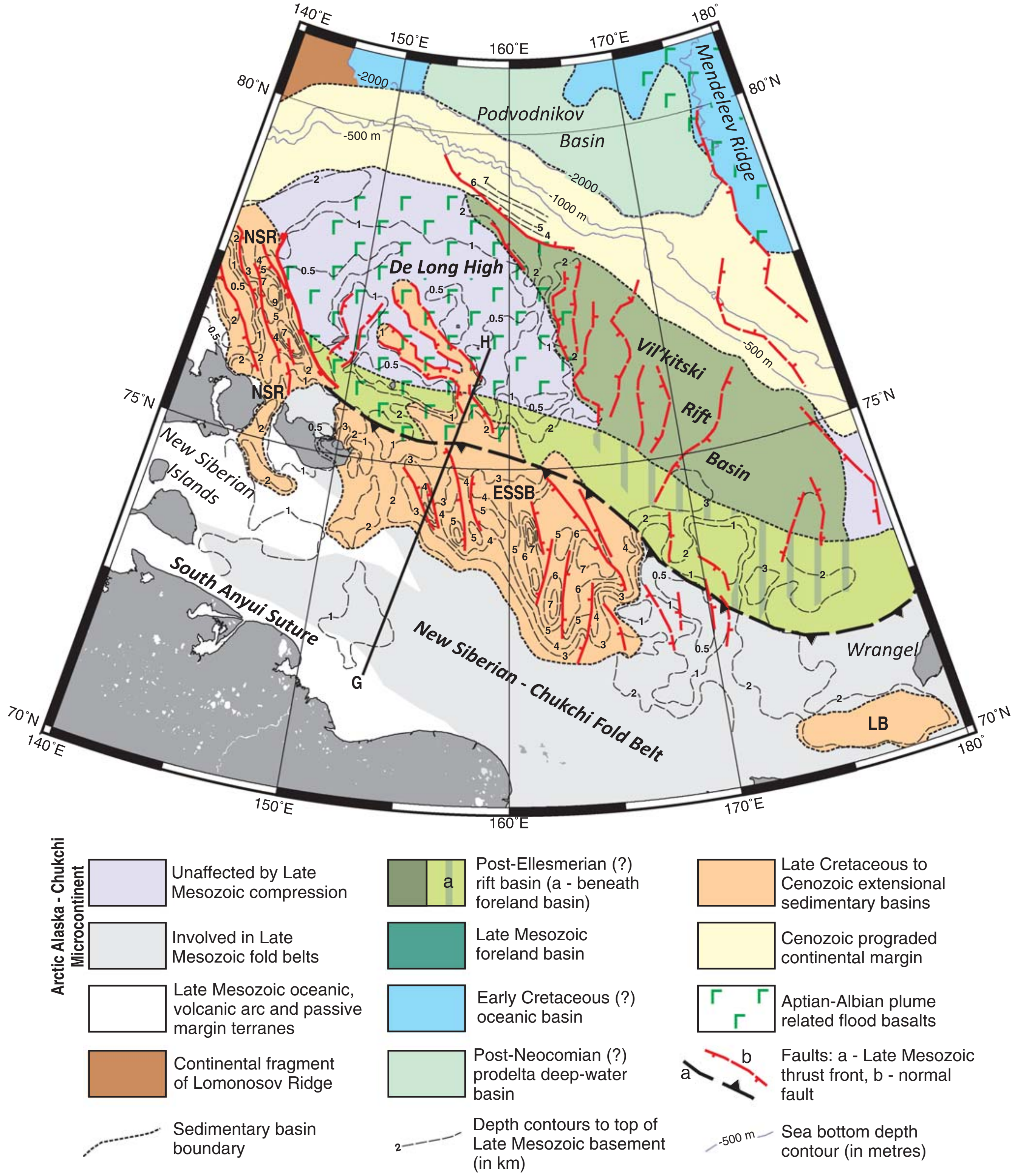

Fig. 13. Main structural features of the East Siberian Sea Shelf. NSR, ESSB and LB denote New Siberian Rift, East Siberian Sea Basin and Longa Basin accordingly. Bold line indexed G–H shows location of a cross-section given in Figure 14. The italic capital letters index the following islands: KT, Kotel'nyi; NS, Novaya Sibir'; BL, Bol'shoi Lyakhov. The accuracy of the scale bar increases towards 75°N.

out on Bennett Island. Presently we do not have data to constrain these possible interpretations.

The northeastern ESSP remains virtually unexplored, since no seismic data exist east of the De Long Archipelago (Fig. 2). The tectonic pattern of this vast area can only be inferred from the study of geophysical fields. The gravity field reveals a series of closely spaced SSE trending linear and rhomboid-shaped lows (Fig. 4, number 23) interpreted as an expression of extensional crustal features called the Vil'kitskii Trough by Kos'ko (1984), Fujita & Cook (1990) and Kos'ko *et al.* (1990) or the Vil'kitskii Rift System by Drachev *et al.* (1999). There are no data to infer the sediment age and composition in the Vil'kitskii Rift System, or to infer the scale and timing of possible crustal extension. Based on the suggested proximity of the northern ESS shelf to the Canadian Arctic prior to opening of the Canada Basin, we can only speculate as to the possible structural and stratigraphic relationships between the Vil'kitski Rift Basin and the Sverdrup Basin. If these basins are tectonically related, then

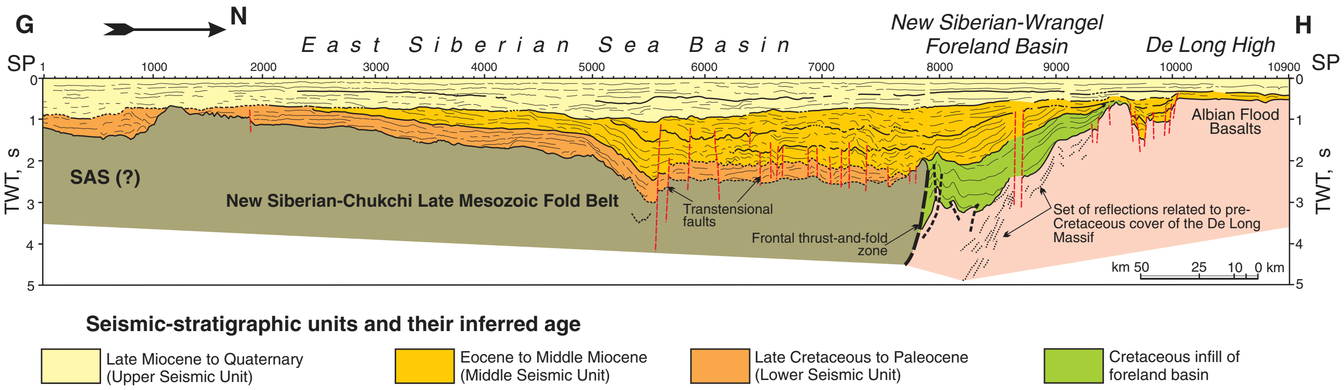

Fig. 14. Geological cross-section along seismic reflection line LARGE-89001 showing structural style and inferred seismic stratigraphy of the East Siberian Sea Basin (modified from S. Drachev *et al.* 1999). For location see Figures 3 and 13. SAS(?) denotes an offshore extent of the South-Anyui Suture.

the following tectonostratigraphic history can be proposed for the former:

(1) Early Carboniferous – the collapse of the Ellesmerian orogen, and formation of the rift system;
(2) Carboniferous to Mid Jurassic – post-rift thermal sagging and deposition of shelf carbonates, evaporates and clastic sediments, an analogue of Sverdrup Basin infill;
(3) Mid-Late Jurassic – a phase of crustal extension and initial rifting culminated probably during latest Jurassic to earliest Cretaceous, with continental breakup and spreading in the Amerasia Basin;
(4) Early Cretaceous (Neocomian) – the southern part of the basin became involved in Late Mesozoic compressional deformation and structural inversion occurred in its northern part;
(5) End Early Cretaceous – a plume-related magmatism influenced the northern part of the basin;
(6) Late Cretaceous to Early Cenozoic – followed the same development stages as the ESS Basin.

Petroleum geology. Two distinct differences exist between lithostratigraphy and, therefore, depositional environments of the Laptev and East Siberian Sea provinces:

(1) Cenomanian–Turonian terrestrial coal-bearing sediments deposited in a fluvial coastal plain setting are present on Novaya Sibir' Island, suggesting marine conditions existed northward in early Late Cretaceous time.
(2) In the Oligocene to Early Miocene, in contrast to the Laptev Province that experienced tectonic uplift and long-term regression with a prevalence of continental fluvial depositional systems, the ESSP, in turn, experienced a long period of subsidence and a dominance of marine and coastal plain environment with accumulation of mainly fine-grained sediments with abundant terrestrial organic matter and coaly material as far south as the present-day coastline (Patyk-Kara & Laukhin 1986).

This suggests that marine depositional environments were widespread through the entire Late Cretaceous and Cenozoic history of the ESSP, and therefore the corresponding sequences could be more favourable for the occurrence of marine organic rich beds – potential oil sources.

Based on this, the main potential HC sources could be expected in (Fig. 12):

(1) Upper Cretaceous to Paleocene sediments with abundant terrestrial organic matter (Lower Seismic Unit) – most probably a gas-prone source;
(2) Eocene and possibly Oligocene to Early Miocene sections.

Based on simple analysis of basin subsidence, initiation of HC generation could have started as early as 54 Ma when potential Lower Cretaceous source rocks entered the oil maturation window and may have continued until 23 Ma. Given the mainly terrestrial composition of organic matter, most of the generated HCs are probably in the gassy fraction, although the possibility of oil generation cannot be excluded. At approximately 23 Ma, possible Oligocene source rocks may have entered the oil maturation window and the period between 23 Ma and present time could represent the main phase of HC generation.

Presently, we do not have data to constrain possible HC systems and petroleum plays of the completely unexplored Vil'kitskii Rift Basin. Speculating on possible pre-Jurassic relationships between the Canadian Arctic and ESSP, we may infer an analogue to the Sverdrup HC systems to be present in the Vil'kitskii Basin north of the Late Mesozoic deformation front (Fig. 12). However, considering the magnitude of the Cenozoic tectonically driven subsidence in better known depocentres, preservation of the oil-prone Late Palaeozoic and Early Mesozoic source rocks at the depths not exceeding the oil window becomes very questionable.

Russian sector of Chukchi Sea Province (CSP)

The Russian sector of the Chukchi Shelf has much better seismic coverage compared with the East Siberian Sea (Fig. 2), and hence its geology is better constrained. The geology and tectonic history of this region were considered by Vinogradov *et al.* (1974, 1977), Pol'kin (1984), Grantz *et al.* (1986, 1990) and recently by Verzhbitsky *et al.* (2008) and Petrovskaya *et al.* (2008), and some data on petroleum geology were summarized by Haimila *et al.* (1990) and by Warren *et al.* (1995).

Tectonically the Russian CSP is similar to the East Siberian Sea shelf (Fig. 13). Two main tectonic domains divided by a zone of frontal thrusts of the Wrangel–Herald Arch are outlined (Fig. 15):

(1) the northern part of the AACM with preserved pre-Late Cretaceous (pre-Barremian?) basins mostly filled with stratigraphic analogues of the Ellesmerian Sequence of the US Chukchi Shelf;
(2) the southern part of the AACM affected by the Late Mesozoic Chukotka–Brookian compressional event and orogeny. It comprises basins post-dating the orogeny and filled with stratigraphic analogues of the Brookian Sequence of the US Chukchi Shelf.

Three first-order basins are outlined in the Russian CSP with use of the MCS and gravity data. Two of them, the New Siberian–Wrangel and the North Chukchi basins (Fig. 4, numbers 27 and 28), occur within the older crustal domain north of the

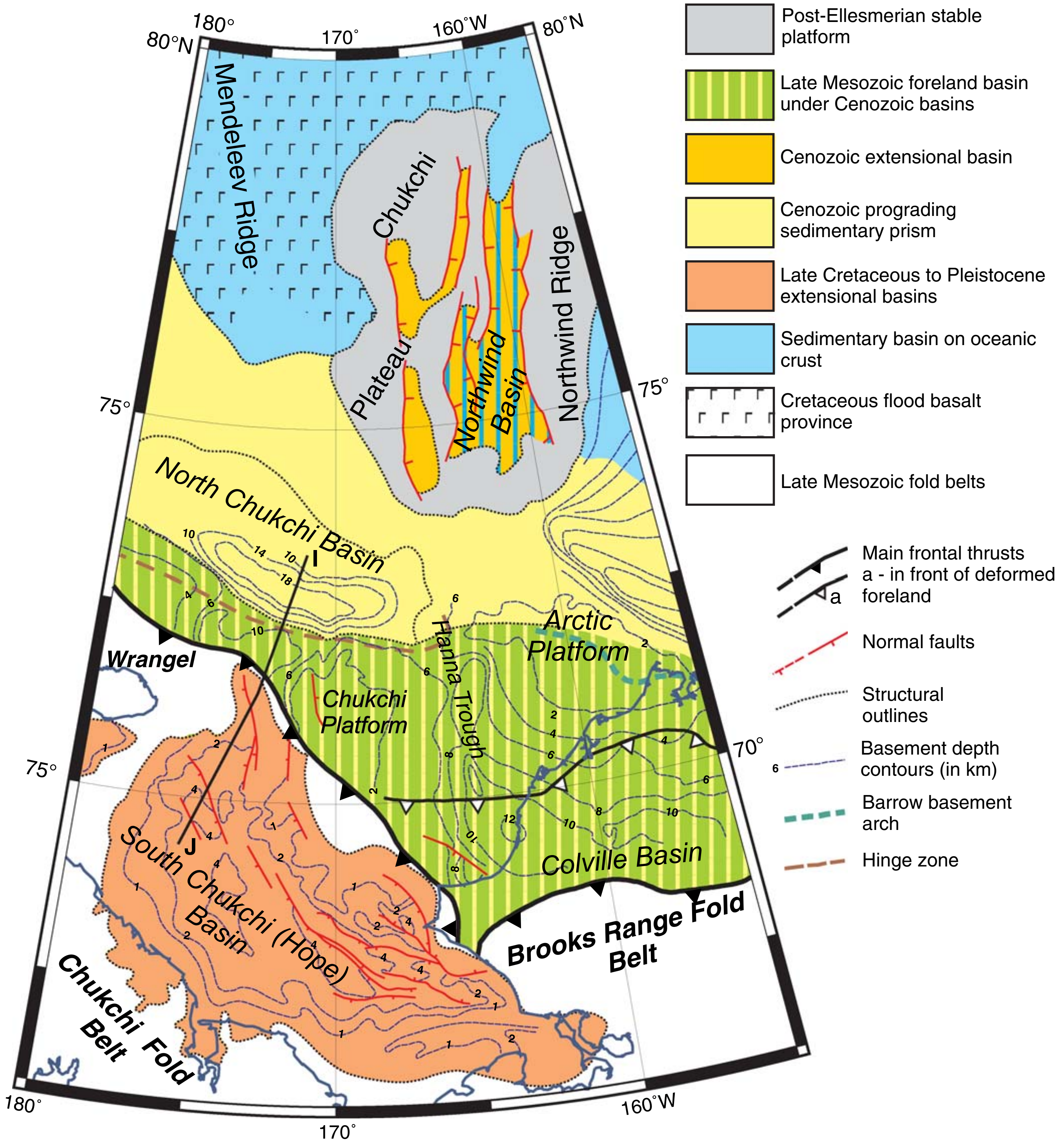

Fig. 15. Main structural elements of the Chukchi Shelf (modified from Grantz *et al.* 2009). Bold solid line labelled 'J–I' shows location of cross-section given in Figure 16. Capital italic letters denote: HT, Hanna Trough; SCB, South Chukchi Basin; KSB, Kotzebue Sound Bay. The accuracy of the scale bar increases towards 75°N.

deformational front, and the South Chukchi (Hope) Basin exists south of the Wrangel–Herald Arch (Fig. 15). A similar view on the Russian CSP tectonics was presented earlier by Grantz *et al.* (1990) and Warren *et al.* (1995).

The eastern part of the New Siberian–Wrangel Foreland Basin is well mapped by the numerous DNMG (Petrovskaya *et al.* 2008) and TGS–Nopec (Verzhbitsky *et al.* 2008) MCS lines north of Wrangel Island between the late Mesozoic deformational front and the North Chukchi Basin. From the latter it is divided by a sharp basement surface break which is assumed to be an analogue of the Hinge line by Grantz *et al.* (1990). Existence of a basin in this location was first proposed by Pol'kin (1984), who named it the North Wrangel Trough. Most of the basin infill is represented by the seismic stratigraphic units CS-2 and CS-3, which are inferred to be composed of Upper Jurassic to Lower Cretaceous clastic rocks (Fig. 16). These units are underlain by the CS-1 unit interpreted to represent Upper Palaeozoic to Lower Mesozoic sedimentary rocks, which may be analogues of the Ellesmerian Sequence of Arctic Alaska. The CS-3 forms the upper part of the basin infill and continues over the hinge line into the North Chukchi Basin. All these units are affected by moderate fold-and-thrust deformations in the vicinity of the Late Mesozoic compressional front.

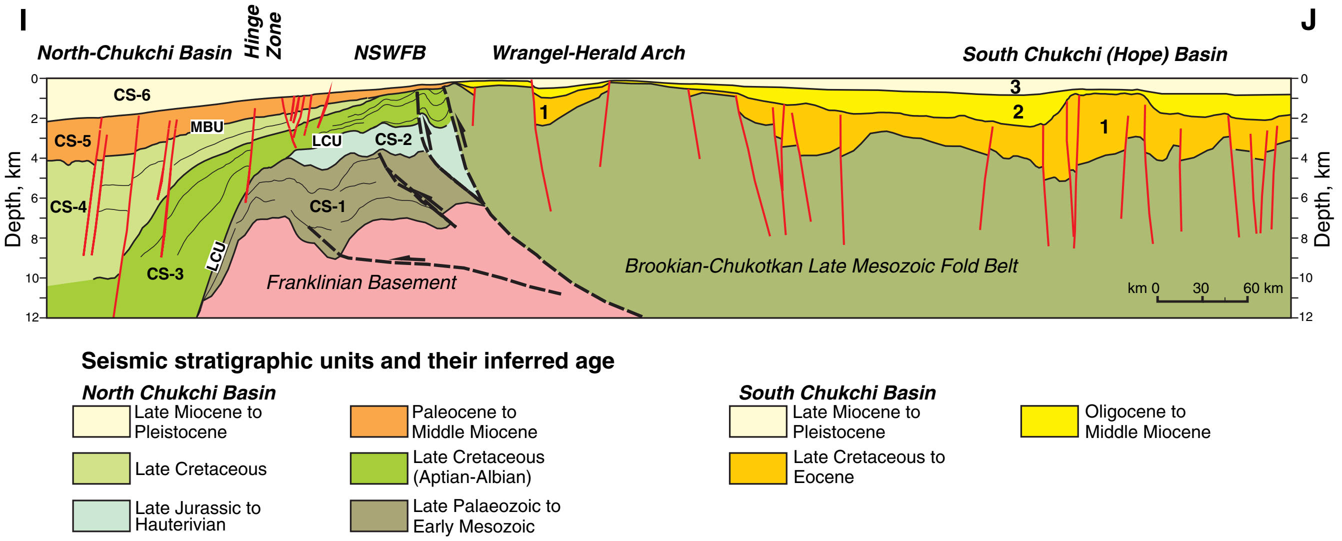

Fig. 16. Simplified cross-section illustrating internal structure and inferred stratigraphy of the South Chukchi and North Chukchi basins. Based on seismic data acquired and published by DMNG and TGS-Nopec (Petrovskaya *et al.* 2008; Verzhbitsky *et al.* 2008) and ERS-2 gravity data. Location is given in Figures 3 and 15. The bold numbers are indexes of the seismic sequences in the South Chukchi Basin after Tolson (1987). The alpha-numeric indexes CS-1 through CS-6 denote seismic sequences identified in the North Chukchi and the New Siberian–Wrangel basins (see text for further details). LCU, Lower Cretaceous Unconformity; MBU, Mid Brookian Unconformity. NSWFB denotes the New Siberian–Wrangel Foreland Basin.

The *North Chukchi Basin* extends east for more than 500 km from the 180° meridian towards the North Slope of Alaska (Figs 10 & 15). Its full extent is depicted by a prominent gravity low of −40 to −60 mGal (Fig. 4, number 28). According to interpretations of the MCS data, the basin can contain over 12 km thick sedimentary fill, which can locally reach 18 or even 20 km. Most of the basin fill is inferred to be composed of Cretaceous to Cenozoic clastic strata (Thurston & Theiss 1987; Grantz *et al.* 1990), although the presence of older sediments in the most subsided parts of the basin is highly likely.

Several seismic units have been identified within the basin and interpreted to reflect the main development stages (Fig. 16). A sharp unconformity is observed at the bottom of the seismic unit CS-3 along the steep southern slope of the basin. It deepens sharply from *c.* 3 to 12 km and more to the north, towards the basin interior. To the south, the unconformity extends into the New Siberian–Wrangel Foreland Basin, where it forms the top of seismic unit CS-2 corresponding to an early stage of the foreland deformations (Fig. 16). Therefore, we interpret this prominent seismic stratigraphic unconformity to be related to onset of the main orogenic phase which, based on geological data from the Chukchi Peninsula (Sokolov *et al.* 2002), occurred around Hauterivian to Barremian time (130–125 Ma). We further correlate this unconformity with the Lower Cretaceous Unconformity (LCU), which is one of the most distinct regional unconformities in the US Chukchi–Beaufort shelf (Craig *et al.* 1985; Thurston & Theiss 1987). A similar interpretation has been proposed by Grantz *et al.* (1990), and more recently by Verzhbitsky *et al.* (2008). The seismic stratigraphic units above the LCU form the main infill of the North Chukchi Basin, which is thus interpreted to be mostly a post-Barremian basin.

Another sharp seismic stratigraphic unconformity at the top of the seismic unit CS-4 truncates folds in the foreland basin, and extends into the central part of the North Chukchi Basin (Fig. 16). The closest analogue in the US Chukchi Sea is the well established regional Mid Brookian Unconformity (MBU) at the Cretaceous–Cenozoic boundary (Thurston & Theiss 1987). The well-laminated seismic pattern of the CS-4 unit between the LCU and MBU allows for conclusion that the post-Barremian Cretaceous infill can be dominated by marine facies, reflecting the main phase of the subsidence within the North Chukchi Basin.

The *South Chukchi (Hope) Basin* extends for over 1000 km from the Longa Strait up to the Western Alaska coast, and is limited by the transpressional Wrangel–Herald Arch in the north, and by the Chukchi Peninsula in the south (Fig. 4, number 25; Fig. 10, number 8 & Fig. 15). The basin is underlain by folded complexes of the Chukotka–Brooks Fold Belt exposed on Wrangel Island, Chukchi Peninsula and along the Alaskan rim of the basin. Two onshore exploration wells near Kotzebue in the southern US Hope Basin encountered basement of Palaeozoic schists and marbles (Thurston & Theiss 1987). In the US Chukchi Sea this basin is known as the Hope Basin, whose geology and petroleum systems were characterized by Tolson (1987) and Haimila *et al.* (1990).

MCS data reveal an asymmetric geometry of the basin. Its southern limb is formed by a gradual southward basement rise while the northern fractured limit, at the junction with the Wrangel–Herald Arch, is rather steep (Fig. 16). The internal structure of the basin is formed by a series of NW–SE trending grabens, half-grabens and dividing horsts, whose assemblage was described by Tolson (1987) as transtensional. Sediment thickness in the basin does not exceed 5–6 km in its deepest parts. Three main seismic stratigraphic units are interpreted (Fig. 16):

(1) A Lower Unit is inferred to be represented by Paleocene (perhaps, Upper Cretaceous) to Eocene continental coal-bearing and fluvial, lacustrine and shallow marine clastic sediments. In the Alaskan onshore extent of the basin, a lower stratigraphic interval penetrated by two exploration wells is known to consist of volcanic and non-marine volcaniclastic rocks, possibly of Eocene age. However, there is no direct tie of the seismic horizons with these wells, and therefore the well data may not be indicative for the offshore lithostratigraphy of the basin (Thurston & Theiss 1987).
(2) A Middle Unit is inferred to be represented by Oligocene–Middle Miocene predominantly continental clastic sediments.
(3) An Upper Unit is represented by Miocene to Quaternary mainly shallow-marine clastic and shaly sediments.

Based on the above characteristics of the Russian CSP geology, we draw the following conclusions about the tectonic history of its sedimentary basins:

(1) The North Chukchi Basin was probably initiated as a rift basin in the Early to Middle Jurassic during an extensional stage precursor to the Canada Basin opening (Grantz *et al.* 1998). However this remains a speculative assumption since the rocks coeval with the early stage of the North Chukchi Basin formation are buried below the depths imaged by MCS data.
(2) In latest Jurassic to Barremian, a major collision occurred between the AACM and the Siberian margin, followed by orogeny and formation of a foreland basin north of the deformation front.
(3) In Aptian to Albian, the North Chukchi Basin was affected by a drastic subsidence resulting in accumulation of a *c.* 10 km thick succession of clastic sediments. This event is coeval to a severe erosion which occurred at Western Alaska around 115 Ma (Moore *et al.* 2002).
(4) In the Late Cretaceous, formation of the South Chukchi Basin began in response to a post-orogenic collapse. The end of the stage was marked by an uplift and erosion caused by convergence of the NA and EUR plates.
(5) Paleocene to latest Eocene/earliest Oligocene – the basins evolved in an intraplate setting controlled by dextral motion between the NA and EUR plates. This is also the main phase of subsidence in the South Chukchi Basin.
(6) Oligocene to Miocene – the South Chukchi Basin was affected by NE–SW plate convergence compression causing transpressional growth of the Wrangel–Herald Arch.

Petroleum geology. Petroleum systems and HC play elements of the South Chukchi Basin can be projected from the drilled and thus to some extent better known Hope Basin. According to Haimila *et al.* (1990) the petroleum potential of the latter is considered to be rather limited with no identified oil-prone source and only thermally immature terrestrial organic rich beds identified in nearby onshore wells. However, offshore depocentres that subsided to significant depths may still be more prospective for generation and accumulation of HCs. During the main Eocene to Oligocene phase of tectonic subsidence, the basin remained structurally isolated from marine environment existing to the north by the Wrangel–Herald basement arch, and therefore the presence of the marine source beds in this inland basin is highly unlikely.

The older North Chukchi Basin is much more prospective for oil generation. The structural setting of the basin is quite similar to the Alaska North Slope and therefore a number of HC plays prospective for both gas and oil can be expected in this part of the Chukchi Shelf (Fig. 12).

As described above, the entire seismically imaged section of the North Chukchi Basin down to the depths of 12 km, and possibly greater, is apparently composed of Cretaceous and Cenozoic strata only. Depth to the Cenozoic base increases rapidly from a few hundred metres along the southern flank of the basin, up to 4–5 km at the basin's axial depocentre (Fig. 16). This suggests that any possible oil source rocks beneath the MBU in the central North Chukchi Basin would have already passed way below the conventional oil maturity window.

The section above the MBU has a much greater chance for the presence of lower Cenozoic marine organic rich beds – analogues of the Middle to Upper Eocene oil-prone Richards sequence in the Beaufort-Mackenzie region. However, an almost complete absence of tectonic structures within this part of the aggraded section significantly limits future exploration potential over the main part of the North Chukchi Basin axial depocentre to the stratigraphic traps.

Greater chances of finding large oil accumulations are more likely along the southern margin of the basin at the hinge zone, and to the south of the hinge zone, where pre-LCU strata occur at drillable depths for exploration wells – around 4–5 km. As illustrated in Figure 16, a basement high dividing the North Chukchi depocentre from the New Siberian–Wrangel Foreland Basin resembles the Barrow Arch. Therefore, mature HC plays existing along the Arctic coast of Alaska could be considered as the closest analogues of the potential untested petroleum plays of the southern flank of the North Chukchi Basin in the Russian CSP.

Summary and conclusions

The vast Russian Arctic Shelf is, to a large extent, sparsely explored due to its harsh environment, high cost of operations and remoteness from modern markets, and its undiscovered HC potential is still highly unconstrained. We have summarized the results of many regional geological and geophysical studies accomplished over the past few decades. Based on 2D regional seismic surveys correlated with borehole data and with onshore geological data in the areas where no exploration wells have yet been drilled, as well as on low-resolution gravity and magnetic data, we have outlined the main sedimentary basins and constrained their structural styles, lithostratigraphy and possible HC systems. Concluding this review of the RAS, we would like to highlight the following major points:

- The Barents and South Kara seas have the largest discovered gas resources in the Russian Arctic, and thus are commonly considered as gas-prone provinces. However, the chances for finding oil plays in the marginal zones of these basins are relatively high, and thus these could be of future exploration interest.
- The NKP is virtually unexplored, and its tectonostratigraphy is mainly constrained by available geological data from adjacent land areas. Several mid-sized depocentres inferred from gravity data are considered to be of mostly Early to Middle Palaeozoic age, and probably experienced inversion related to the Late Palaeozoic and Early Mesozoic orogenic events. Petroleum systems of the North Kara Shelf are unconstrained.
- The Siberian Arctic shelves were severely affected by the Late Mesozoic (Neocomian) orogeny, which largely shaped their tectonic basement and also had a dramatic impact on their potential petroleum systems.
- The Laptev rift province provides solid evidence of high HC potential. The basins are filled with thick Late Cretaceous to Cenozoic terrestrially sourced clastic sediments with abundant coaly matter, and thus are inferred to be mainly gas prone. However, if the pre-rift Bazhenov-type source rocks were not destroyed by the Late Mesozoic orogeny in the southwestern part of the Laptev shelf, or if the Early Cenozoic marine oil-prone source rocks accumulated within the rift depocentres, the Laptev shelf could also be prospective for the presence of oil plays. As the Laptev Shelf was the site of active rifting in Late Cretaceous to Paleocene and Recent times, and many normal faults reach the sea bottom, significant exploration risks may be related to the seal integrity.
- The East Siberian and Chukchi shelves are dominated by two generations of basins: (1) the Late Cretaceous to Cenozoic basins occurring south of the offshore extent of the Late Mesozoic deformational front; and (2) older (Late Palaeozoic(?) to Early Cretaceous) basins occurring north of the Late Mesozoic deformation front.
- The Late Cretaceous to Cenozoic basins are interpreted to have originated in a transtensional setting caused by dextral relative

motions of the NA and EUR lithospheric plates. Lithostratigraphy and possible HC systems of these basins are inferred from the better studied Hope Basin in the US Chukchi Sea, and are also constrained by onshore sedimentary sections. Their potential is considered to be mainly related to gas-prone terrestrial sources, although the presence of Early Cenozoic thermally mature lacustrine or shallow marine oil-prone sources cannot be disregarded.

- The inferred Late Palaeozoic to Early Mesozoic basins may be similar tectonostratigraphically to the Sverdrup Basin in the Canadian Arctic. The petroleum geology of the latter has been used to constrain possible HC systems of the Vil'kitsky Basin, which is identified on the basis of gravity and magnetic data only.
- The New Siberian–Wrangel Foreland Basin occurs in front of the Late Mesozoic compressional deformations. Its tectonostratigraphy is inferred to resemble the basins of the Alaska's North Slope and thus the petroleum geology of the latter with its rich oil potential has been projected north of Wrangel Island to highlight possible oil potential of this foreland basin.
- North Chukchi Basin dominates the Russian Chukchi Sea and is mainly filled with post-Neocomian siliciclastic sediments with a total thickness exceeding 18 km. Its petroleum plays may be similar to the known Late Cretaceous and Cenozoic plays of the Beaufort Sea.

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ERRATUM

S. S. Drachev, N. A. Malyshev and A. M. Nikishin

Drachev, S. S., Malyshev, N. A. & Nikishin, A. M. 2010. Tectonic history and petroleum geology of the Russian Arctic Shelves: an overview. In: Vining, B. A. & Pickering, S. C. (eds) Petroleum Geology: From Mature Basins to New Frontiers—Proceedings of the 7th Petroleum Geology Conference, 591–619; doi: 10.1144/0070591.

The updated versions of Figures 6, 10, 11, 13, 15 and 16 were not included in the print version of the proceedings. The updated versions are shown here.

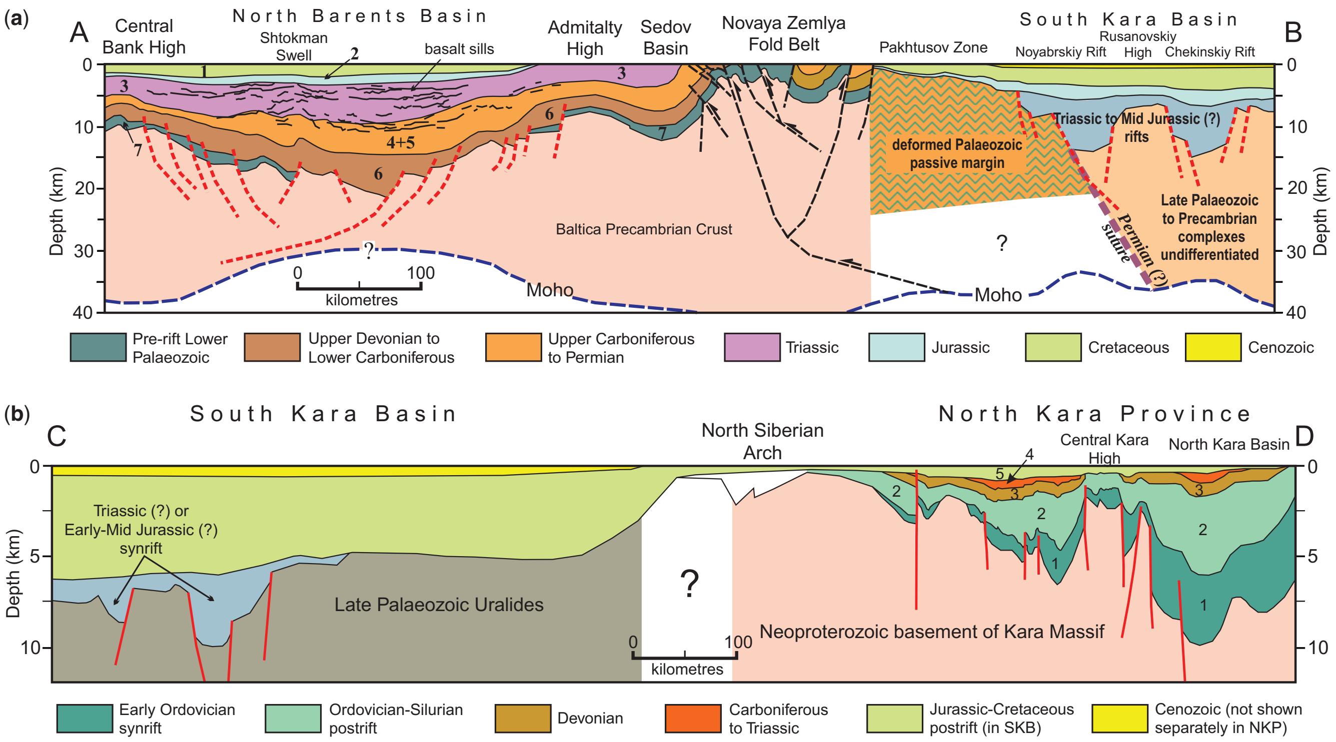

Fig. 6. Schematic geological cross-sections based on re-interpretation of deep seismic reflection and refraction data acquired and published by SMG (Sharov et al. 2005; Ivanova et al. 2006): (a) through the Eastern Barents and South Kara basins based on seismic transect 2-AP, (b) though the North Kara Province based on seismic transect 3-AP. Location is shown in Figures 3 and 5. Bold numbers from 1 to 6 in (a) and from 1 to 5 in (b) denote seismic stratigraphic units (see the text for the details).

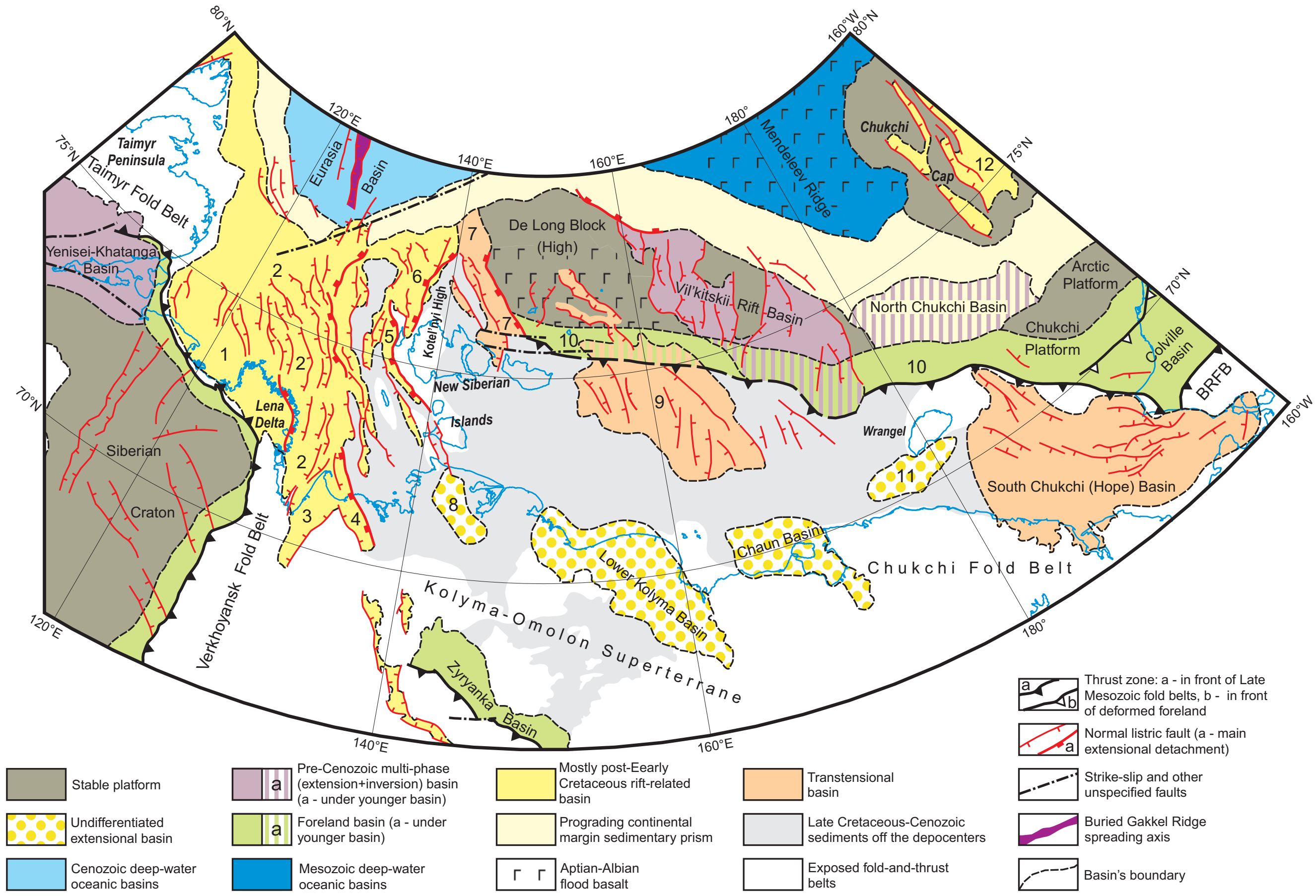

Fig. 10. Main sedimentary basins of the Siberian Arctic Shelf (modified from Grantz et al. 2009). Bold numbers denote the following basins: 1, Southwest Laptev Basin; 2, Ust' Lena Rift; 3, Omoloy Graben; 4, Ust' Yana Graben; 5, Bel'kov Rift; 6, Anisin Rift; 7, New Siberian Rift; 8, Tas–Takh Depression; 9, East Siberian Sea Basin; 10, New Siberian–Wrangel Basin; 11, Longa Basin; 12, Northwind Basin. BRFB, Brooks Range Fold Belt.

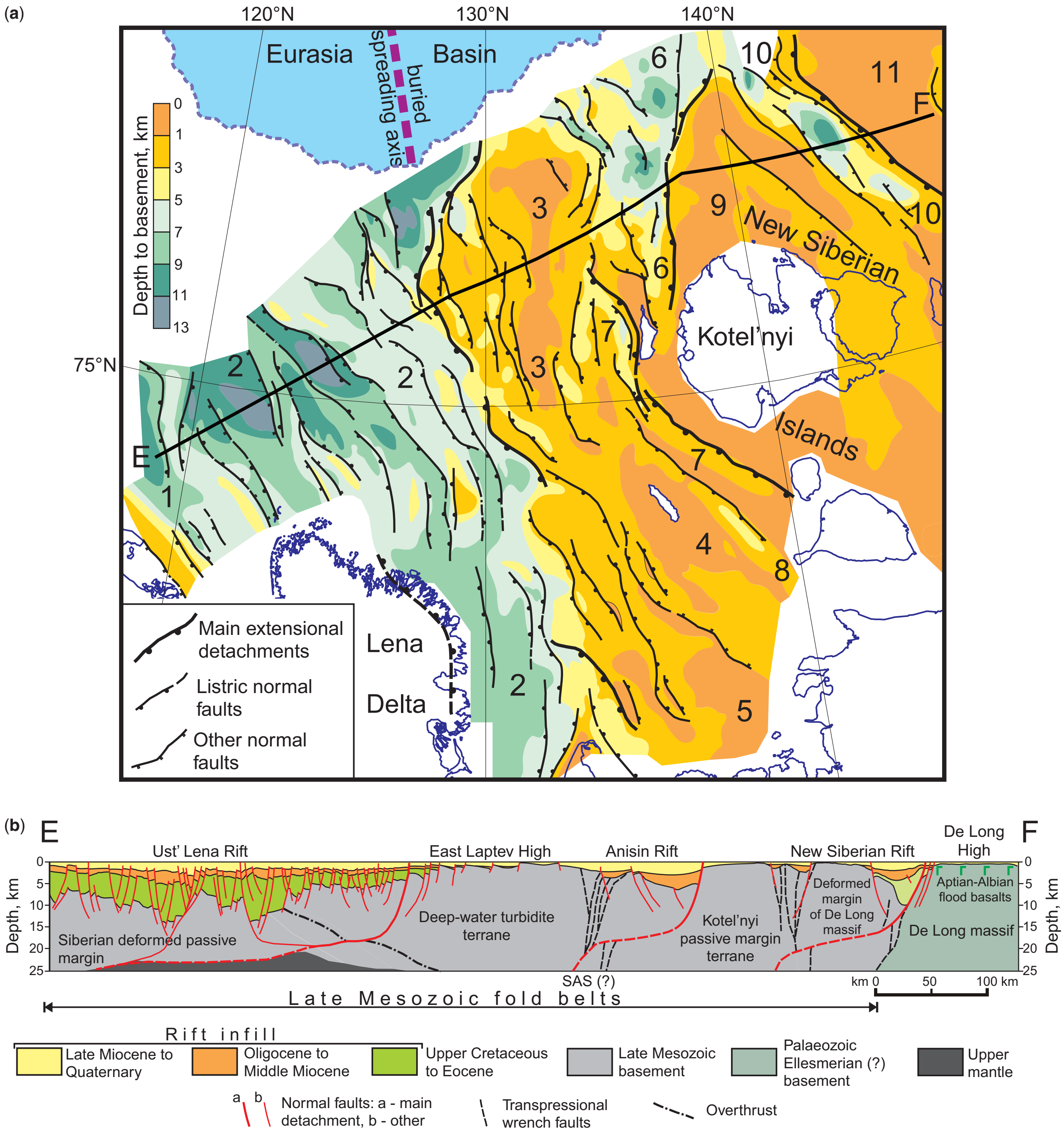

Fig. 11. Structure of the Laptev Rift System: (a) simplified depth-to-basement map of the Laptev Shelf based on 2D seismic and ERS-2 gravity data; (b) cross-section based on geological data and published BGR regional seismic lines (Franke et al. 2000, 2001). Location of the cross-section is shown in (a). Bold numbers in (a) denote following elements of the rift system: 1, Southwest Laptev Rift Basin; 2, Ust' Lena Rift; 3, East Laptev Horst; 4, Stolbovoi Horst; 5, Shiroston Horst; 6, Anisin Rift; 7, Bel'kov Rift; 8, Svyatoi Nos Graben; 9, Kotel'nyi High; 10, New Siberian Rift; 11, De Long High. SAS (?) in (b) denotes possible offshore projection of the South Anyui Suture.

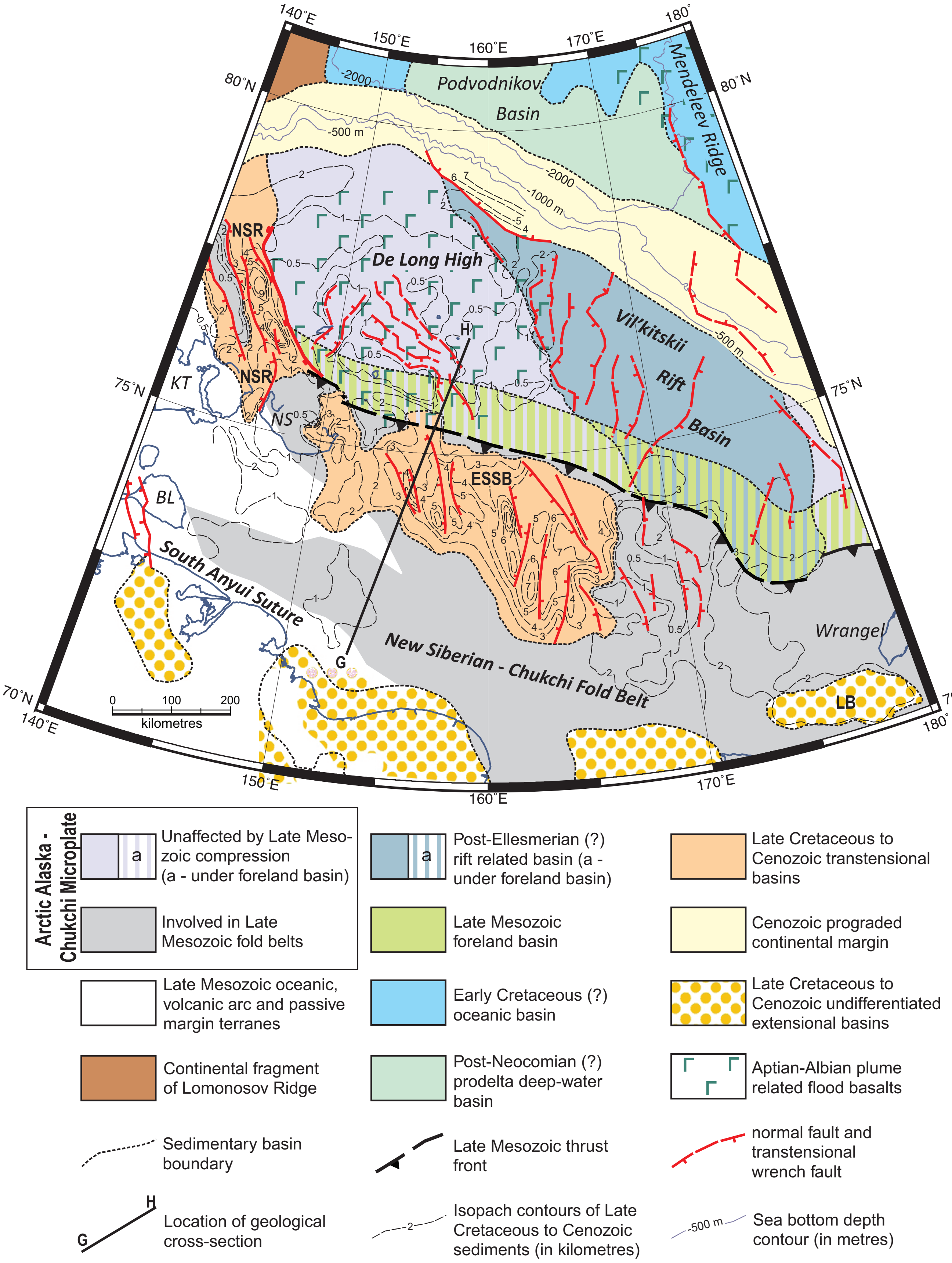

Fig. 13. Main structural features of the East Siberian Sea Shelf. NSR, ESSB and LB denote New Siberian Rift, East Siberian Sea Basin and Longa Basin accordingly. Bold line indexed G–H shows location of a cross-section given in Figure 14. The italic capital letters index the following islands: KT, Kotel'nyi; NS, Novaya Sibir'; BL, Bol'shoi Lyakhov. The accuracy of the scale bar increases towards 75°N.

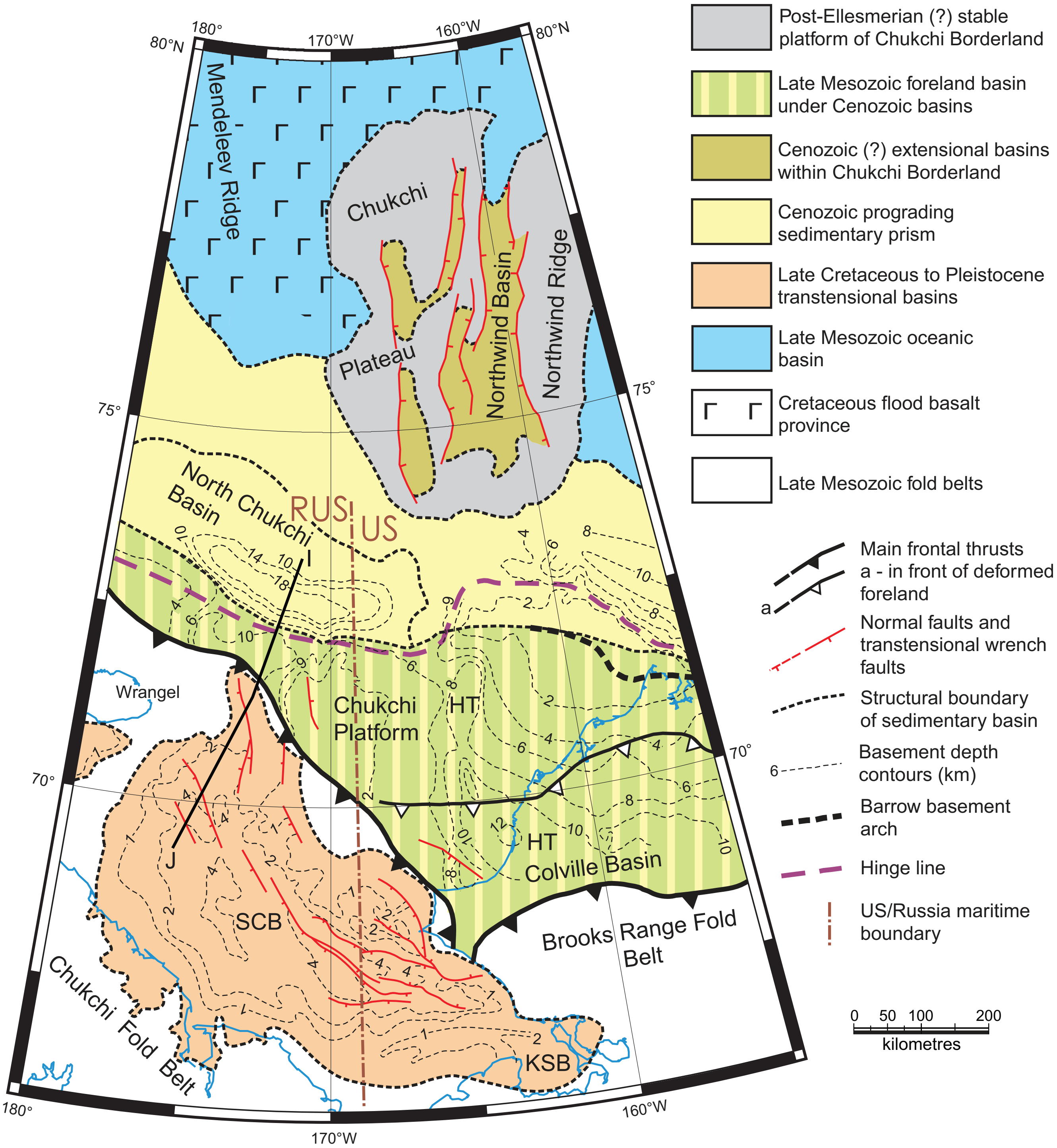

Fig. 15. Main structural elements of the Chukchi Shelf (modified from Grantz et al. 2009). Bold solid line labelled ‘J–I’ shows location of cross-section given in Figure 16. Capital italic letters denote: HT, Hanna Trough; SCB, South Chukchi Basin; KSB, Kotzebue Sound Bay. The accuracy of the scale bar increases towards 75°N.

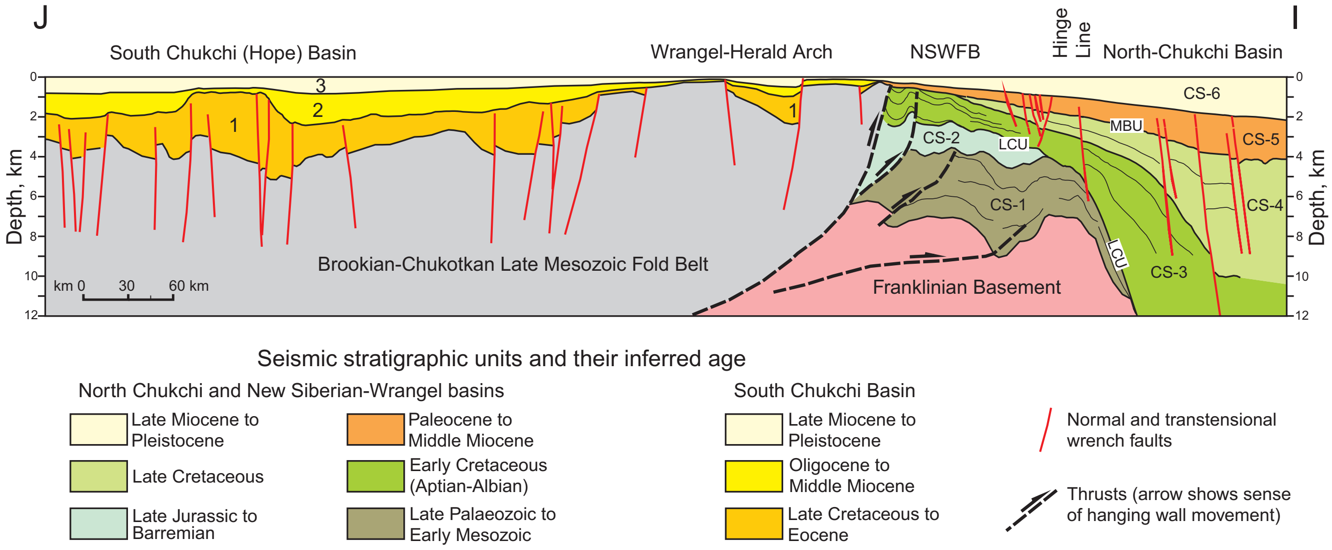

Fig. 16. Simplified cross-section illustrating internal structure and inferred stratigraphy of the South Chukchi and North Chukchi basins. Based on seismic data acquired and published by DMNG and TGS-Nopec (Petrovskaya et al. 2008; Verzhbitsky et al. 2008) and ERS-2 gravity data. Location is given in Figures 3 and 15. The bold numbers are indexes of the seismic sequences in the South Chukchi Basin after Tolson (1987). The alpha-numeric indexes CS-1 through CS-6 denote seismic sequences identified in the North Chukchi and the New Siberian–Wrangel basins (see text for further details). LCU, Lower Cretaceous Unconformity; MBU, Mid Brookian Unconformity. NSWFB denotes the New Siberian–Wrangel Foreland Basin.