Transform margins of the Arctic: a synthesis and re-evaluation

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Abstract

Transform margin development around the Arctic Ocean is a predictable geometric outcome of multistage spreading of a small, confined ocean under radically changing plate vectors. Recognition of several transform margin stages in Arctic Ocean development enables predictions to be made regarding tectonic styles and petroleum systems. The De Geer margin, connecting the Eurasia Basin (the younger Arctic Ocean) and NE Atlantic during the Cenozoic, is the best known example. It is dextral, multi-component, features transtension and transpression, is implicated in microcontinent release, and thus bears close comparison with the Equatorial Shear Zone. In the older Arctic Ocean, the Amerasia Basin, Early Cretaceous counterclockwise rotation around a pole in the Canadian Mackenzie Delta was accommodated by a terminal transform. We argue on geometric grounds that this dislocation may have occurred at the Canada Basin margin rather than along the more distal Lomonosov Ridge, and review evidence that elements of the old transform margin were detached by Makarov-Podvodnikov opening and accommodated within the Alpha-Mendeleev Ridge. More controversial is the proposal of shear along the Laptev-East Siberian margin. We regard an element of transform motion as the best solution to accommodating Eurasia and Makarov-Podvodnikov Basin opening, and have incorporated it into a three-stage plate kinematic model for Cretaceous-Cenozoic Arctic Ocean opening, involving Canada Basin rotational opening at 125-80 Ma, Makarov-Povodnikov Basin opening at 80-60 Ma normal to the previous motion, and a Eurasia Basin stage from 55Ma to present. We suggest that all three opening phases were accompanied by transform motion, with right-lateral sense being dominant. The limited data along the Laptev-East Siberian margin is consistent with transform margin geometry and kinematic indicators, and these ideas will be tested as more data become available over less explored parts of the Arctic, such as the Laptev-Eastern Siberia-Chukchi margin.

Introduction

The Arctic Ocean, essentially an enclosed ocean "at the top of the world" (Figures 1 & 2), is ice-covered most of the year. For this reason, and because of inaccessibility and remoteness from major habitations, the deep Arctic Ocean and its periphery remain poorly explored in both general and geological terms. Compared to many of the world's oceans and margins, geological models are poorly substantiated, many in number, and still essentially unresolved. In the last two decades, however, geological understanding of the Arctic has improved and numerous geological studies have been performed (see for example Geological Society Memoir 35, Spencer et al,. eds., 2011). For specific regions of the Arctic (e.g. Alaska, Barents Sea) a large body of literature is now available. More remote areas, such as offshore eastern Siberia and the Chukchi Borderlands are far more sparsely covered in terms of data and studies. Significantly, since Ziegler (1988) there have been few pan-Arctic syntheses of geological development through time, with Golonka (2011) being a notable exception.

The Arctic is also one of the few remaining underexplored petroleum provinces in the world, and is considered by some authorities to house up to a quarter of the world's undiscovered resources (e.g. Gautier et al. 2011). It is bordered by two of the world’s major petroleum provinces (West Siberia and Alaska’s North Slope) and by unusually wide continental shelves (e.g. Barents, Kara and East Siberian Seas) in the Norwegian and Russian sectors. Interest in the potential of the Arctic margins was reflected in significant awards of prospecting rights offshore Russia, Norway and Greenland between 2011 and 2013. The present paper, with its emphasis on the shear margins, is part of a general update and petroleum geological synthesis of the Arctic carried out by Statoil in 2013-14, taking in all seismic data, literature and studies in the company’s database. The plate reconstructions were performed with G Plates software (Boyden et al., 2011, Williams et al., 2012) in a global EarthByte rigid plate model (based on Shephard et al., 2013).

At present day, limited connections exist between the Arctic Ocean and the Pacific Ocean and NE Atlantic via the Bering and Fram Straits respectively (Figures 1 & 2). In the geological past, likewise, the Arctic oceans have repeatedly been confined (e.g. Mann et al., 2009). The shape of the Arctic Ocean generally reflects the underlying plate configuration, with oceanic crust (or, locally, hyperextended continental crust or exhumed mantle) underlying the deep water areas. Large shallow sea areas, such as the Barents and Kara Seas are underlain by continental crust. Although uncertainty remains regarding the nature of the crust of some key Arctic elements, in particular the Alpha-Mendeleev Ridge, most of the area can today be reasonably defined based on gravity, magnetics, seismic refraction/reflection and outcrop data, and the interpretation can in turn be tested by plate reconstructions.

The Arctic oceanic realm consists of the following major physiographic areas (Figures 1 & 2): Canada Basin, Eurasia Basin, Makarov-Podvodnikov Basin, and fringing the central Arctic, the northern part of the NE Atlantic and Labrador Sea-Baffin Bay. Internally to these are at least two continental fragments, the Lomonosov Ridge and Chukchi Borderlands. Of more uncertain nature are the Alpha and Mendeleev Ridges that lie within the Amerasia Basin (combined Canada Basin and Makarov-Podvodnikov Basin), which may be entirely oceanic, or alternatively contain continental material overlain by basalt flows and/or recent sediments. Although basalts cover these ridges, extensional faults are quite widespread (e.g. Bruvoll et al., 2012) and may reflect underlying continental crust. Fairly well expressed continent-ocean-boundaries can be interpreted along the Siberian and North American margins, the Lomonosov Ridge, the Chukchi Borderlands, and the Barents-Kara Sea margin (Figure 3).

While numerous models exist for its opening and subsequent development, there is general consensus that the Arctic Ocean is essentially a Late Mesozoic-Cenozoic feature, and that spreading took place in several distinct stages (e.g. Churkin & Trexler 1980, Dutro 1981, Grantz et al., 1979, Herron et al., 1974, Lawver et al, 2001). It lies between the Atlantic and Pacific, and compared to these bordering pan-global oceans is a comparatively small ocean basin (Figure 1). Although influenced by the development of both the Atlantic and Pacific, it has been a discrete and separate entity for much of its existence. A natural concomitant of the size, multi-stage development and isolated nature of the Arctic Ocean is that it must be bounded on several sides by transform margins. Transform boundaries are common in plate tectonics and are fundamental to, and required by, plate motions on a sphere. Plate separation motion is defined by rotation around a point on the surface, the Euler pole, with the shear margin being a requirement at the distal end of the ocean from the pole. A small, multi-stage ocean should therefore be characterized by several shear margins in relatively close proximity to each other. What also typifies shear boundaries is that they, as well as oceanic fracture zones, follow small circle arcs described by the respective Euler pole of rotation. Opening of a small ocean around a nearby Euler pole will generate a pronounced V-shaped ocean and arcuate fracture zones, whereas a very distant Euler pole may generate a slightly arcuate shear.

These geometries are all either observed or postulated in the Arctic (Figure 4). They include the western Barents Sea margin, which includes major shear elements such as the Senja Fracture Zone and Hornsund Fault, and links the NE Atlantic and Arctic. This margin is part of a major trans-Arctic lineament sometimes termed the “De Geer Zone” (Harland 1965), which dates at least from the closing stages of the Caledonian orogeny at approximately 400Ma. With the exception of the Equatorial Shear Margin (e.g. Mascle et al., 1995, Nemčok et al., 2012 and papers in this volume) this may be the best studied shear margin on the globe (e.g. Faleide et al., 2010, Gabrielsen et al., 1990). The Eurasian side of the Amerasia Basin, generally (but not always) interpreted as a shear margin (e,g, Grantz et al., 1979) is less well understood, in terms of both scale and position. In this paper we also argue for the periodic existence of shear along the Siberian margin between the Laptev and Chukchi Seas. Each of these proven or proposed shear margins is described below, after which we integrate them into what we consider the most likely plate tectonic sequence of events. The sense of shear in the Arctic appears to be overwhelmingly dextral, which may be coincidence or may indicate a generic connection not yet clear to the authors. Additionally, an apparently intimate relationship between the development of the shear margins and the formation of microcontinents is evident in the Arctic, and appears to reflect a worldwide paradigm. This relationship is considered in context below, but is also examined in a companion paper in this volume (Nemčok et al., this volume).

Principal structural units of the Arctic Ocean

Eurasia Basin

The Eurasia Basin (Figures 1 & 2) is the prolongation of the Atlantic rift system, which through its Mesozoic-Cenozoic evolution has nearly divided the Mesozoic Pangean supercontinent. Northeast Atlantic-Eurasia Basin opening began at Isochron 24b-25 (54-56 Ma) time as the Nansen-Gakkel Ridge formed between the Lomonosov Ridge microcontinent and the northern Barents-Kara Sea margin. The two oceanic segments were linked by the De Geer transform margin until the end of the Eocene (Isochron 13 time, 33 Ma). The Eurasia Basin largely consists of abyssal plain, with maximum water depths between 4000 and 4500m. It is characterized by well-defined magnetic isochrons that reflect the age of the ocean floor. Well-expressed isochrons are to be expected at a high latitude, and the Arctic oceans have been at high latitude throughout their development. The use of the isochrons establishes that the Eurasia Basin is the world's slowest spreading ocean (e.g. Snow & Edmonds, 2007), and this fact has attracted a number of scientific studies, including sampling of the seafloor (e.g. Michael et al., 2003). The continent-ocean boundaries (COB) against the Barents-Kara margin and against the Lomonosov Ridge are well established by gravity, magnetic, and bathymetry data. The COB against the rift tip in the Laptev Sea is also well established and according to Drachev (1998), is marked by the Khatanga Shear or Severnaya Shear. The tectonic implications of this major transform (shown as Khatanga-Bering Transform, KBT on Figure 2) have not been widely discussed, and will be considered later.

Lomonosov Ridge

The Lomonosov Ridge (Figures 1 & 2) is an elongate feature of continental affinity extending 1800 km between the Canadian Arctic Islands and the Russian New Siberian Islands, and crossing the North Pole. It rises to minimum depths of about 950m, is steep-sided and is bounded on each side by the abyssal basins of the Eurasia Basin and the Amerasia Basin (Figure 1). The limited seismic evidence shows that the ridge is multiply segmented, but in general contains relatively undisturbed Cenozoic sediments overlying a faulted, presumed Mesozoic, basement (Jokat et al., 1992: Jokat, 2005). The ridge was cored by the ACEX (Arctic Coring Expedition) in 2004 (http://www.ecord.org/pub/ACEX), which found 420m of Cenozoic sediments, with the basal Early Eocene-Paleocene sediments resting on an angular unconformity with underlying Mesozoic sands. Of particular note is a major hiatus spanning from 44 to18 Ma. (Moran et al., 2006). The Lomonosov Ridge detached during the initial NE Atlantic-Eurasia Basin opening at Isochron 24b-25 (54-56 Ma) time (e.g. Brozena et al., 2003), as the Nansen-Gakkel Ridge formed between the microcontinent and the northern Barents Sea margin. Its significance as the largest of the Arctic microcontinents is discussed in Nemčok et al., (this volume).

Amerasia Basin

The Amerasia Basin (Figures 1 & 2) is far less understood. Although older and larger than the Eurasia basin, water depths are somewhat lower, attaining a maximum of about 3900m. With a few exceptions (Kristoffersen et al., 2008), the ocean floor is overlain by a very thick sedimentary succession, preventing sampling of the seafloor. The Amerasia Basin is subdivided into the Canada Basin and the Makarov-Podvodnikov Basin by an intervening diffuse rise, the Alpha and Mendeleev ridge system (e.g. (Bruvoll et al., 2010: Jokat et al., 2013). Notably, neither of these oceanic realms is characterized by well-defined magnetic isochrons. However, the Canada Basin has a well-defined gravity anomaly in its centre (e.g. Grantz et al., 2011), generally accepted to be the abandoned spreading axis. On either side of this axis is a single pair of magnetic isochrons. The pie-shaped Canada Basin has been suggested to reflect counterclockwise rotational opening, whereby Alaska (Figure 1) has moved away from the rifted Canadian margin. Carey (1958), well before acceptance of plate tectonics, suggested that the swing in the Cordillera-Brooks Range represented an oroclinal bend, i.e. a previously linear orogeny that became bent: this bend would now be viewed as associated with the rotation of Alaska away from the Canadian Arctic margin. A number of other plate models have been proposed (e.g. Churkin & Trexler 1980, Dutro 1981, Herron et al., 1974, Lawver et al, 2001) but the "windshield wiper" model (Grantz et al., 1979) remains the most generally accepted model for the Canada Basin. The amount of rotation, and the position of the bounding shear (here termed the Amerasia Basin Transform, ABT on Figure 4) are considered below.

The Makarov-Podvodnikov Basin is often ascribed a similar origin to the Canada Basin – i.e. formed by rotation along with the entire Amerasia Basin (e.g. Grantz et al., 1979 & 1998). Herein, we treat it as a separate basin analogous to the Eurasia Basin, although with its apex toward Greenland and with a different and younger origin. These arguments are made in the section on the Amerasia Basin Transform, below.

Alpha-Mendeleev Ridge System

The Alpha-Mendleev Ridge system (Figures 1 & 2) forms bathymetrically high elements, together some 1500 km long and 250-400 km wide, rising 2 km above the adjacent Canada Basin and Makarov-Podvodnikov Basins (Bruvoll et al., 2012). Strata subcrop directly at seabed on the Alpha Ridge, but this area has some of the harshest ice conditions in the Arctic, and is difficult to access.

The ridge system appears to contain continental elements (Vernikovsky et al., 2013), although velocity gradients from seismic refraction data also suggest an oceanic affinity and Bruvoll et al. (2012) point to similarities with intra-plate oceanic volcanic constructs. The Alpha Ridge has been proposed to be an element of an Arctic Large Igneous Province (LIP) formed at c. 125 Ma (e.g. Lawver et al. 2002). However, very few samples exist of the basalt that is assumed to form the acoustic basement. The only available geochronologic (Ar/Ar) date from the ridge is much younger - Coniacian, 89 ± 1 Ma (Jokat et al., 2013). A limited number of piston cores from the Alpha Ridge, collected from stations on the drifting Fletcher ice island in the late 1960s and 70s, reveal Campanian to mid- Late Maastrictian strata over acoustic basement (Jenkyns et al. 2004). Thus, the limited sampled portion of the ridge appears to be Late Cretaceous in age, with Coniacian or older acoustic basement and a sedimentary cover at least as old as Campanian. Both the Alpha and Mendeleev Ridges are cut by normal faults and have a distinct horst-and-graben geometry. Bruvoll et al. (2010) interpreted the age of faulting of the Alpha-Mendeleev Ridge to be Early Miocene, but noted that there is no strong candidate regional tectonic event to which the deformation can be linked. It appears possible that the extensional deformation is considerably older, since syn-rift wedges are primarily observed in the succession immediately above acoustic basement (basalt). A pronounced seabed relief of 500 m or more across some major normal faults suggests recent reactivation.

Other major elements of the Arctic

The Chukchi Borderlands (e.g. Grantz et al, 2011: Houseknecht & Bird 2011) are a piece of continental crust protruding into the Canada Basin from the westernmost part of Alaska (Figures 1 & 2). It rises very steeply from the abyssal plain to depths as shallow as 250m. In most reconstructions, including that of this paper, formation of the Canada Basin by rotation of Alaska away from the Canadian Arctic margin necessitates simultaneous rotation the Borderlands from a position parallel with the Alaska margin. This rotation has the opposite sense to the general rotation of Alaska, i.e. while the Canada Basin formed by counterclockwise rotation of Alaska away from the Canadian Arctic margin, the Borderlands rotated clockwise away from East Siberian margin. In this interpretation the North Chukchi Basin, in the space between the Siberian margin and the Borderlands created by the rotation, would probably be floored by either exhumed mantle or by oceanic crust. The extreme depth of the sedimentary basin, up to c. 18-20 km, has been remarked upon by Drachev (2011). Note, however, that a more radical interpretation by Nikishin et al. (2014) places the Amerasia Basin Transform (ABT, Figure 4) along the North American flank of the Borderlands, which would therefore not be rotated. Ultimately, only palaeomagnetic work on orientated cores from the sparsely-studied Borderlands is likely to resolve this issue.

The Morris Jessup and Yermak Plateaux (Figure 2) are paired, probably incipient microcontinental elements either side of the Fram Strait, which separates Greenland and Spitsbergen and links the Atlantic and Arctic oceans. The Yermak Plateau extends northwards from western Spitsbergen into the Eurasia Basin as a shallow area of sea floor, and has variously been interpreted as a continental fragment (e.g. Jokat et al., 2008) or anomalously shallow ocean floor derived from hotspot activity (Feden et al., 1979). The Morris-Jessup Rise on the opposing side of the Eurasia Basin is its mirror-image, and these features are cut off by post-Isochron 13 ocean floor, implying that the two plateaux were a single plateau prior to separation at the Eocene-Oligocene transition. The Yermak Plateau shows indications of late volcanism (Geissler et al., 2011), probably representing the propagation and conjoining of the Knipovitch (Atlantic) and Gakkel (Eurasia basin) ridges during the onset of passive drift.

Shear margins, proven and postulated

De Geer transform margin

The De Geer line or zone was a term coined by Harland (1965) for the remarkably straight lineament cutting across the Arctic from the northern coast of Norway, along the Svalbard and Greenland-Canadian Arctic margin, to the Mackenzie Delta, a distance of some 4000 km (Figures 2 & 3). The lineament is evident in the trend of the continental margins, in component NNW-SSE shear faults linking the NE Atlantic and Arctic (e.g. Hornsund Fault, Senja, Spitsbergen and Greenland fracture zones), and in major margin-parallel fractures on the western Barents shelf and on Spitsbergen (e.g. Gabrielsen et al., 1990: Worsley & Aga 1986).

This transform margin links two major Cenozoic ocean basins, the Northeast Atlantic and the Eurasia Basin of the Arctic Ocean. However, the greater De Geer zone almost certainly exploited a Paleozoic zone of weakness dating at least from the Caledonian orogeny at approximately 400Ma at the Silurian-Devonian transition (e.g. Harland, 1965: Faleide et al., 1993) (Figure 5). This event was the culmination of a long sequence of terrane accretion, finally resulting in the closure of the ancient Iapetus Ocean and the fusing of Baltica (mainland Norway, Sweden) with Laurentia (Greenland, North America). The Inuitian fold belt (Figure 5) running through Spitsbergen, North Greenland and Arctic Canada, is broadly contemporaneous with the Caledonian deformation (e.g. Ohta et al. 1989) and suggests that the NE-trending orogen turned NNW at the present Barents margin, or that the Inuitian was an important side-branch of the orogen. (e.g. Gee & Teben'kov 2004). A final phase of the Caledonian, the Svalbardian, took place in Late Devonian times. This phase has been proposed to represent major strike-slip along the line of the Caledonian-Inuitian orogen and the assembly of Svalbard from sinistral movement of originally widely separated terranes (e.g. Harland 1965). The magnitude and complexity of this movement is still a matter of debate (Torsvik 1985; Gee & Teben'kov 2004). Critical for the later transform margin evolution, however, is the fact that this late movement involved a series of extensive NNW-trending lineaments such as the Billefjorden Fault Zone on Spitsbergen, which were repeatedly reactivated through later geological time and defined the western margin of the Barents Sea.

A probable sequence of Cenozoic break-up events linking the NE Atlantic and Eurasia Basin is shown in Figure 6, adapted from the work of Faleide et al. (2010) and others. On the Mid-Norway and East-Greenland margins, separation to form the Mohn's Ridge in the Early Eocene (Isochron 24b time, 54 Ma) was predated by a period of crustal extension in the latest Cretaceous and Paleocene (e.g. Ren et al. 2003), accompanied by extensive basaltic magmatism. As break-up progressed, a dextral transform margin developed along the western Barents Sea margin, accompanied by severe contractional movements in the north and the formation of the West Spitsbergen fold and thrust belt, which extended northwestwards into the Eurekan fold belt of northern Greenland and Arctic Canada (see full description in Dallmann et al. 1993). The fold belt is usually dated as Paleocene to Eocene, but has also been suggested to have originated in the Late Cretaceous (Lyberis & Manby 1993), synchronously with contractional movements in the Wandel Sea Basin, North Greenland. The Paleocene-Eocene Central Basin of Spitsbergen developed immediately west of the Billefjorden

Fault Zone, as a foreland basin to the fold belt to the west, but also possibly as a response to pull-apart. Simultaneously, sedimentary basins probably attributable to pull-apart were formed on the southwestern Barents Sea margin: the Sørvestnaget Basin and Vestbakken Volcanic Province (e.g. Gabrielsen et al., 1990). The transit of a spreading ridge along the transform margin a short distance west of these basins gave rise to volcanism in the Vestbakken Volcanic Province between the Eocene and earliest Oligocene. Episodes of compressive stress occurred contemporaneously in the two basins, forming NW-SE trending intra-basinal folds and hanging wall anticlines. This complex interrelationship of Paleogene basins and highs along the western Barents Sea margin is illustrated in Figure 7.

At the Eocene-Oligocene transition (Isochron 13 time, 33 Ma) a significant change in the pole of rotation occurred such that the NW-directed spreading changed to a more westerly course (e.g. Faleide et al., 2010) . This resulted in the propagation of the Knipovitch Ridge between the Mohns and Nansen-Gakkel Ridges, and the separation of Greenland from the Barents margin. The change to passive drift terminated the West Spitsbergen compressional episode and brought a period of tectonic quiescence to the western Barents Sea. It is generally thought that at this stage, fragments of the former transform margin, the Hovgaard Ridge and the East Greenland Ridge along the northern part of the Greenland Fracture Zone, were separated from the Barents Sea margin and drifted westward as the Knipovitch Ridge spreading continued (e.g. Myhre & Thiede 1995: Døssing & Funck 2012). The true picture may, however, be more complicated. As pointed out by Myhre & Eldholm (1988) and others, it is likely that the microcontinental slivers were involved in a complex northeastwards propagation of the NE Atlantic via small spreading cells that may have begun as early as Isochron 22 time (50 Ma), and were rifted away from the Barents-Svalbard margin prior to the full development of the Knipovitch speading ridge (Figures 6 & 7: see also Nemčok et al., this volume).

The apparent extension of the De Geer Line along the Greenland-Canada Arctic margin could of course be a coincidental alignment. More likely, however, is that a general zone of shear existed in this region in the Paleozoic, associated with the NNW turn of the Caledonian orogen into the Inuitian system (e.g. Ohta et al., 1989: Gee & Teben'kov 2004). In the Canadian Arctic islands, the straight continental margin forms the northern limit of the Inuitian fold belt and is paralleled inboard by the Sverdrup Rim, an elongate basement high forming the northern boundary of the Late Paleozoic-Mesozoic Sverdrup Basin. These lineaments separated the Canada margin from Crocker Land, a significant terrane and source area to the Sverdrup Basin, generally presumed to be part of the Chukotka terrane now incorporated into the Siberian shelf (e.g. Embry & Beauchamp 2008). This unit was rotated away from the Canadian margin in the Early Cretaceous during the opening of the Canada Basin (see following section and Figure 6). It is thus quite plausible that early development of the Arctic Ocean (as well as the Cenozoic development) was facilitated by continental separation along the former shear zone. If this argument is accepted, the De Geer zone can claim a major role in the mega-structural history of the Arctic from the Caledonian to the present, and has been involved in orogen-parallel shear, fold-and-thust belts, convergent and pull-apart basins, volcanism, microcontinent release and passive plate separation

The Amerasia Basin Transform

The rotational model for the initial opening of the Amerasia Basin (Grantz et al, 1979) involves the rotation of a microcontinental block (Chukotka) away from the Canadian Arctic margin. As indicated above, this idea is widely accepted because of the relic spreading ridge detected on gravity data, the two paired apparent magnetic anomalies either side of it, and the generally triangular nature of the Canada Basin (Figures 2 & 8). The Canadian apex of this triangle lies in the Mackenzie Delta, representing the likely pole of rotation. While Grantz et al., (1979) and many other subsequent authors describe a c. 66º rotation around the pole, it is debatable how much of this opening represents true oceanic spreading. One view with a strong circumstantial basis is that the general absence of magnetic anomalies indicates spreading during the Cretaceous “quiet zone” (118-84 Ma). By this hypothesis, the single pair of anomalies would indicate a cessation of spreading at about 80 Ma, just after the reappearance of magnetic reversals. However, it is known that the margins of the Canada Basin represent initial slow spreading, are magma-poor and likely to feature wide zones of exhumed mantle (e.g. Grantz et al, 2011 and in-house potential fields modelling). This may provide another explanation for the absence of linear anomalies. A recent model for the Arctic Ocean (Nikishin et al.. 2014) focuses on the idea that the few central anomalies may represent a very limited spreading cell, with the remainder of the basin constituting foundered, hyperextended continent or exhumed mantle. However, we favour the wider, c. 66º rotation because of overall fit with the basin shape, general Arctic kinematics (including the Alaskan oroclinal bend) and independent paleomagnetic evidence of rotation of Alaska (Halgedahl & Jarrard, 1987).

Timing of crustal separation in the Canada Basin (whether by mantle exhumation or oceanic spreading) is, for similar reasons not accurately known. Wells along the Canadian Arctic, Beaufort-Mackenzie and North Slope margins constrain the pre-breakup rifting to Kimmeridgian through to Hauterivian (e.g. Dixon 1982). The Hauterivian unconformity is a pronounced regional break along the Canada Basin margins and marks the upper limit of rifting. Rifting of continents typically becomes younger towards the location of continental separation, and hence we deduce that the Hauterivian is a lower limit for break-up. Dike swarms and lava flows in the Canadian Arctic margin, Svalbard, Frantz Josef Land, and southern East Siberian Islands indicate a peak of magmatism at c. 125 Ma, i.e. at the end of the rift episode (in-house analysis and Corfu et al., 2013). This volcanism may therefore be associated with the initial Arctic break-up event, leading us to a best-guess interval of 125-80 Ma for the Canada Basin rotation.

The terminal shear of the rotational opening or "windshield wiper shear" must of course have been a transform margin during the Early Cretaceous, and like the De Geer Zone the sense will have been right-lateral (Figure 8). Grantz et al. (1979) proposed that this shear followed the edge of the Lomonosov Ridge (on the Canada Basin side) and continued into Siberia. The shear is generally terminated against the western tip of the South Anyui suture (Figure 8), a diffuse tectonic break associated with folding, thrusting and ophiolites (e.g. Sokolov et al, 2009) representing closure of a former oceanic element of the Pacific, the South Anyui Sea. The Canada Basin would thus have opened in concert with closure of the South Anyui Sea, so that the "windshield wiper" shear did not cut across Siberia to the Pacific plate, but instead continued into the suture between Chukotka and mainland Siberia.

A problem with this proposed location for the transform margin is the linear, non-curved nature of the Lomonosov Ridge. If its Amerasian flank marks the paleo-shear margin, it is neither sufficiently arcuate to correspond to the small circle centered about the Euler rotation pole in the Mackenzie Delta area (MD, Figure 2), nor to have been defined by the relic spreading ridge. This geometric problem has been pointed out by other authors (e.g. Rowley & Lottes 1988, Kuzmichev 2009) and alternative models involving a shear traversing the Siberian shelf in a more easterly position have been suggested (Figure 8). The validity of these alternatives hangs on the nature of the South Anyui Suture and basement structural continuity across the Siberian shelf.

Both seismic and sampling data are very sparse on the shelf, but outcrops have been studied on the New Siberian and De Long islands between the Laptev and East Siberian seas. Kuzmichev (2009) asserts that field evidence points to extension of South Anyui deformation offshore and as far west as Big Lyakhovsky Island (Figure 8), a view supported by the maps of Vernikovsky et al., (2013a). Given a simple one-to-one relationship between the suture and the rotational shear, this evidence would push the shear westwards and support the correlation with the Lomonosov Ridge. However, as shown by Figure 8, Sokolov et al., (2002) and Vernikovsky et al., (2013a), the suture zone is anything but simple, recording a history of terrane and ophiolite accretion on the margins of the South Anyui Sea dating back to the Late Paleozoic. Additionally, almost synchronously with the assumed collision of the rotating Chukotka block with Siberia in Early Cretaceous times, a further large terrane (Kolyma-Omolon) impinged westwards on the continent from the paleo-Pacific (e.g. Shephard et al., 2013), forming the Verkhoyansk Foldbelt immediately south of the present Laptev Sea (Figure 8). The close proximity and co-evolution of these elements illustrates the complexity of the Eastern Siberian plate tectonic collage, and the probable over-simplified nature of the rotation-collision model. The occurrence of major dextral shear along the line of the South Anyui Suture, as proposed by Sokolov et al., (2002), would further blur the entry position of the Amerasia Basin Transform.

Paleomagnetic work by Vernikovsky et al. (2013a & b) demonstrates apparent basement continuity between the New Siberian and De Long islands, and thus that a major shear is unlikely to have interposed between the two archipelagos. A clinching piece of evidence - for the position of the main transform west of the New Siberian Islands and the amount of lateral translation - would be paleomagnetic or polar wander data placing the islands adjacent to the Barents Sea Svalbard margin prior to rotation. To our knowledge, however, no such data exists.

A different location of the transform, closer to the Alpha Ridge (Figure 8), would allow a more arcuate margin, corresponding better with the Canada Basin rotation. This interpretation implies that the Makarov-Podvodnikov Basin, located between the Lomonosov Ridge and the Alpha-Mendleev Ridge, would include separate oceanic elements formed between cessation of Canada Basin rotation and Eurasia Basin initiation. Like the Eurasia Basin, opening would have been orthogonal to the Canada Basin spreading. A similar interpretation has been proposed by Arctic workers repeatedly in the past (e.g. Taylor et al., 1981, Drachev et al., 1998, Franke et al., 2004, Rowley & Lottes 1988, Sekretov 2001).

As indicated earlier, the curious array of normal faults cutting the Alpha-Mendeleev Ridge area (Bruvoll et al., 2010) currently lacks a candidate regional tectonic phase. The faults were active in the Cenozoic but, significantly, offset the acoustic basement with basal syn-rift wedges, and thus probably have an older origin. If this is the case, a best-fit timing for the faults may be the rift phase immediately preceding Makarov-Podvodnikov Basin opening, with some continental material entrained in the Alpha-Mendeleev Ridge, and with the Coniacian volcanic dates on the ridge (Jokat et al., 2013) representing pre-opening volcanism.

In summary, the sparse geophysical and geological data allows a wide range of interpretations for the location of the Amerasia Basin rotational transform margin. Our preferred view is that the Alpha-Mendeleev Ridge marks the approximate location of the shear, albeit subsequently significantly blurred by the volcanic signature. We favour this interpretation on the basis of geometries and kinematics, which become even more self-consistent if it is accepted that the oceanward position of the transform was displaced westwards along the Siberian margin by Makarov-Podvodnikov and Eurasia Basin spreading (see arguments below). Elements of the transform margin probably flaked off as microcontinents during Makarov-Podvodnikov rifting and spreading, and are now entrained in the Alpha-Mendeleev Ridge. Constrained by the age of the volcanics, and bracketed by Canada Basin and Eurasia Basin spreading episodes, Makarov-

Podvodnikov Basin opening probably took place in the Late Cretaceous at c. 80 Ma and lasted until c. 60 Ma. Margin-parallel shears probably helped to define the elongate Lomonosov Ridge microcontinent, but this feature essentially reflects the trend and spreading vector of the Nansen-Gakkel spreading ridge and can perhaps be regarded more as a product of detachment during Eurasia Basin formation, rather than a precise proxy for the paleo-transform margin.

Shear geometries on the Siberian-Alaskan margin

Whilst it is clear that the Laptev rift system is the tip of the Eurasia Basin, there appears to be a marked and abrupt discrepancy in extension between the oceanic domain and the rift. This is well expressed by the bathymetry. We argue below that the two domains are separated by a major transform.

The total width of the Laptev rift system as it abuts the Eurasia Basin is approximately 750 km (Figs. 9a and 9b) , and while seismic refraction data reveal significant crustal thinning under the most extended parts of the rift (Fig. 11), the crustal thinning is generally no more than ca 50% on average (D. Franke, Personal Communication, 2014). The width of the oceanic crust of the Eurasia Basin when it abuts the Laptev rift is approximately 600 km (Figs. 9a and 9b). In addition to this amount of plate separation, the bordering rifted margins must have been extended prior to break-up. A necking width of c. 100 km is probably reasonable, yielding a total extension in the Eurasia Basin just north of the proposed transform in the order of 700 km.

Rigid-plate plate reconstructions have been proposed that require approximately 600 km of extension in the Laptev rift (Gaina et al., 2002), a value also adopted by Shephard et al., (2013). However, this amount of extension appears difficult to document for the Laptev rift system. Gravity inversion (Alvey et al., 2008; Wienecke et al., 2011) reveals a remaining crustal thickness in the Laptev rift of approximately 20 km (Fig. 3), which is approximately what is revealed by refraction data (e.g. Franke et al., 2001) (Fig. 11). Summed fault heaves reveal even less extension (Fig. 11). In-house subsidence analysis and forward modelling based on summed fault heaves interpreted from seismic data suggest a stretching factor of approximately 1.25 (R. Kyrkjebø, Personal Communication, 2015). Given a total width of the Laptev rift system of c. 750 km just south of the Eurasia basin margin (excluding the Laptev horst) (Figs 9a and 9b), and a stretching factor of 2 (based on the remaining crustal thickness), this suggests that the rift has experienced no more than c. 350 km of extension where it is widest near the ocean margin. A recent extension estimate from gravity modelling (Mazur at al., 2015) suggests a larger extension value, in the order of 500 km, in the Laptev rift system. Such extension would probably imply hyperextension and complete absence of crust in places, an observation that appears to be in conflict with the shallow, shelfal water depths of the present day Laptev Sea (10-50 m). We note that this estimate hinges strongly on an assumed original crustal thickness of 40 km and appears to be measured on lines that run quite obliquely to the rift. Furthermore, this work assigns extension to both the Cretaceous and Cenozoic, and since the Eurasia Basin extension is entirely Cenozoic in age this would increase the Cenozoic discrepancy between the Eurasia basin and Laptev Shelf. Thus, at least for the Cenozoic, the Mazur et al. (2015) extension value appears to be an overestimate.

We conclude that approximately half of the extension required to open the Eurasia Basin remains unaccounted for in the Laptev rift. This discrepancy has previously been pointed out, particularly by Drachev and co-workers (e.g. Drachev 1998, Drachev et al., 2003, Franke & Hinz, 2005, Drachev 2011), but has generally been overlooked in plate kinematic reconstructions.

A zone of strike-slip motion between the Laptev Rift and Eurasia Basin, marked by both the abrupt bathymetric change and by a long lineament on the Bouger Anomaly map (Figure 9a), is the most likely explanation for the discrepancy, and is probably necessary for a geometrically satisfying plate model. A shear directed westward into the Yenisey-Khatanga Trough (Figure 2), eastward along the East Siberian margin, or both, has long been suggested and has been named the Khatanga Shear (Drachev, 1998), the Severnyi Transfer (Fujita et al., 1990), and the Khatanga-Lomonosov shear (Drachev, 2011). The Yenisey-Khatanga Trough, and the major West Siberia Basin at its western end are characterized by anticlines (Vyssotski et al., 2006) and strike-slip indicators (Gogonenkov & Timurziev 2012), both of which may in part represent accommodation of Arctic Cenozoic spreading in the Russian continental interior. In modern times a magnitude 6 earthquake with a strike-slip focal plane solution occurred along the proposed shear in the Laptev Sea (Franke et al., 2004). This type of structure is by no means unusual at the tip of propagating oceans. A strongly analogous case is the northern Red Sea, which is separated from the much less extended Gulf of Suez by the sinistral Dead Sea Transform (e.g. Freund 1970, Steckler & ten Brink 1986, Figure 12).

As argued above and by Taylor et al., (1981), Drachev et al., (1998), Franke et al., (2004), Rowley & Lottes (1988) and Sekretov (2001), the Makarov-Podvodnikov Basin can be regarded as separate from, and younger than, the remainder of the Amerasia Basin (i.e. the Canada Basin). The spreading vector would have been almost normal to that of the Canada Basin, analogous to the Eurasia Basin, although with the apex of the ocean towards Greenland and its broader distal margin towards East Siberia. This interpretation would predict i) shear margin architecture along the East Siberian margin and ii) precursor rifts to Makarov-Podvodnikov spreading on the adjacent East Siberian shelf, subsequently abandoned as the Late Cretaceous transform margin developed. These geometries have both been described by Sekretov (2001) (Figure 13). It is important to note that data is extremely sparse in this area, limited to regional potential fields and a few regional seismic lines across the margin and internal shelf. Nevertheless, in-house study and Sekretov's observations both suggest that the East Siberian margin, although now overstepped by thick Cenozoic sediments, was faulted and steep in the Cretaceous (Figure 13), a geometry characteristic of transform margins where abrupt crustal attenuation rather than gradual necking towards the ocean is typical (e.g. Mascle et al., 1995: Nemčok et al., 2012). At least two rifted and lightly inverted basins occur on the interior shelf, consistent with extension and later shear.

Shear along the Siberian Margin would have been relayed, again by right lateral motion, into the Chukchi Sea-Bering Strait region (Figure 9). As the plate reconstructions will show, this is an attractive solution since it restores Wrangel Island and the Brooks Range, and they in turn become aligned with the North American Cordillera when the Canada Basin is closed. The possible continuity between the Brooks Range and Wrangel Island has previously been remarked upon (Moore et al., 2002; Miller et al, 2006), but has remained controversial because the two are offset, dextrally, by c. 600 km. Arctic Ocean kinematics and right-lateral marginal shear provides a potential solution to this offset. Shear may have run along (and/or been expressed as) the Wrangel-Herald Arch, an offshore basement high and deformation zone running NE-SW between Wrangel and the Lisburne Hills at the western tip of the Alaska Peninsula (Verzhbitsky et al., 2008). Shear may also have exited the Arctic Ocean into the Pacific via the present day Bering Strait, where the position of the Mesozoic-Cenozoic Long Strait and Hope Basins again appear to show dextral offset. Potentially, both lineaments exist as splays where the shear margin dissipates into Alaska and the Pacific. A well-defined shear, probably dextral, running along the northern end of the Hanna Trough in the Alaskan Chukchi Sea, may be a further splay of the Khatanga-Bering Transform. It is expressed as a steep flower structure observed on seismic data. A dense "orthorhombic" conjugate fault set of Late Cretaceous-Early Cenozoic age mapped on 3D seismic immediately south in the Hanna Trough is usually attributed to 3D strain in a strike-slip regime (c.f. Krantz 1988), although the origin of such lateral motion has not been clear. The model of dextral shear along the margin related to Makarov-Podvodnikov and Eurasia Basin spreading provides a potential explanation for the orthorhombic faults. A testable hypothesis is that similar fault sets will be identified in the cover successions of other basins along the sheared Siberian margin as better data sets become available.

Our proposal therefore is that most of the Laptev and East Siberian Arctic COBs existed as transform margins for at least part of their geological history. On Figure 9 we show this margin as a composite or contiguous transform, which have termed Khatanga-Bering Transform. It is quite plausible however that two separate shears exist, one relaying Late Cretaceous Makarov-Podvodnikov and Cenozoic Eurasia Basin spreading dextrally via western Alaska and the Bering Strait into the Pacific, and one relaying Eurasia Basin spreading sinistrally via the Yenisey-Khatanga Trough into Western Siberia, as implied by Drachev (1998). In general, this zone can be viewed as the northernmost, terminating transform margin of Atlantic spreading, a trans-global system characterized by multiple major transform zones, generally dextral, separating oceanic segments of differing ages (Figure 14).

Opening of the Arctic Ocean in a regional transform setting

We have argued above that shear margins are commonplace around the Arctic, and are an inevitable product of accommodating opening along several vectors in a small, confined ocean. In this section we use these arguments to propose an integrated kinematic history, illustrated stepwise in Figures 15 to 18. The present day position of the main plate tectonic elements is shown in Figure 15. As we have been careful to point out, all of these kinematic elements including 3-stage models (e.g. Alvey et al., 2008) have been described in the Arctic literature, albeit not in this particular combination and timing, and with less emphasis on shear along the Laptev-Siberian continental margin.

Canada Basin stage 125-80 Ma

In the 125 Ma reconstruction (Figure 16) the Brooks Range and Wrangel Island are aligned with the trend of the North American Cordillera, i.e. predating the oroclinal bend that was imposed as Alaska-Chukotka rotated counter-clockwise away from the Canadian Arctic margin. Breakup-related mafic magmatism (red stars on Figure 15) occurred in the Sverdrup Basin area, Svalbard, Franz Josef Land, and East Siberian Islands, which all restore closely together (e.g. Corfu et al., 2013). Subduction and terrane accretion was taking place along the paleo-Pacific margin. The South Anyui Sea – the space into which Chukotka-Alaska rotated – was present as an embayment in the Pacific margin. Interestingly, the South Anyui Sea lines up rather precisely with the Uralian orogen, the largely Late Paleozoic fold and thrust belt representing closure between Siberia and Baltica (e.g. Puchkov 2009). This connection is also implicit in the reconstructions of Sokolov et al., (2002), which also demonstrate the Late Paleozoic initiation of the South Anyui Suture. The last compressional activity took place in Triassic-Jurassic time, recorded in the northernmost outpost of the Uralian chain, the Taimyr Peninsula and the adjacent Yenisey-Khatanga Trough (e.g. Kontorovich et al., 2013). The South Anyui Sea can perhaps, therefore, be regarded as an imperfect join between Baltica and Siberia that was annealed as subduction consolidated along the Pacific margin, with the early Arctic Ocean being a product of this reorganization.

Continued widening of the Canada Basin (100 Ma reconstruction, Figure 16) was accommodated by translation along the major dextral transform at the distal end of the Canada Basin as the South Anyui Sea was gradually subducted beneath the Chukotka terrane, with associated deformation along the South Anyui suture (e.g. Sokolov et al., 2009). The Brookian orogeny of Alaska began with accretion of island arcs to the North American Plate in the Jurassic, but the main crustal thickening in the Brooks Range occurred in the Early Cretaceous (e.g. Toro et al., 2002; Bird & Houseknecht 2011). The compression was driven by subduction on the Pacific side. However, simultaneous opening of the Canada Basin in the Early Cretaceous probably played a role in the deformation, and the Brooks orogeny can be viewed as part of the same general system of terrane consolidation that affected the South Anyui suture.

Simultaneously the future Chukchi Borderlands detached from the Canadian margin and rotated clockwise away from the East Siberian margin. Initially, the Borderlands formed a bridge between the Arctic Canadian margin and East Siberia, but continued opening of the Canada Basin resulted in cessation of Borderlands rotation, drifting away from the Canadian margin and development of the single through-going spreading axis that is seen abandoned today. By 90 Ma the Canada Basin was nearly completely open and the South Anyui Sea nearly completely subducted. A basaltic magmatic pulse around 80-90 Ma (red stars, Figure 17), affecting the eastern Sverdrup Basin (e.g. Døssing et al., 2013) and Alpha Ridge (Jokat et al., 2013), heralded opening of the Makarov-Podvodnikov Basin (respectively SB, AR and MPB, Figure 2).

Makarov-Podvodnikov Basin stage 80-60 Ma

At 80 Ma (Figure 17) the Canada Basin spreading had terminated, and the Makarov-Podvodnikov Basin started to break up with an axis almost normal to the Canada Basin spreading centre. Viewed on the large scale, the radical change in spreading vector can be regarded as propagation of Atlantic Pangean break-up northwards into the Arctic; specifically the Makarov-Podvodnikov Basin may have linked with the northward propagating Labrador Sea-Baffin Bay system. Initial rifting took place in the Labrador Sea in the Barremian and in Baffin Bay in the Aptian-Albian, followed by break-up, with mantle exhumation, in the Late Cretaceous, leading eventually to the first proper oceanic crust in the Paleocene around 61 Ma (Balkwill 1987: Larsen et al., 2009: Harrison & Brent 2011). Makarov-Podvodnikov opening may also have linked with latest Cretaceous extension on the margins of the developing NE Atlantic rift between Greenland and northern Norway (e.g. Ren et al. 2003).

As the Makarov-Podvodnikov Basin formed, volcanic constructs and continental fragments were rifted away from the former sheared margin of Canada Basin and incorporated into the Alpha-Mendeleev Ridge. Opening was relayed by right-lateral transform motion along the Siberian margin towards the Pacific margin, probably exiting the Arctic Ocean via the present day Bering Strait but with splays through the Wrangel-Herald Arch and north of the Hanna Trough. Wrangel Island and the Brooks Range gradually became more displaced from one another. In our model, the major plate motion at this time was assigned to Eurasia (reaching the active Tethyan margin) rather than North America, to avoid implying compression in the region of the Canada Basin margins. By 70 Ma the Chukotka orogen was no longer active and the South Anyui Suture was completely closed. There was also a cessation in activity on the Brooks Range orogen, but activity was renewed at c. 60 Ma (Late Brookian event), with the shedding of thick sediments northwards into its foreland basin, the Colville Trough (e.g. Houseknecht & Bird 2011).

A major basaltic magmatic pulse in the interval 62-58 Ma spanning 2000 km between Disco Island, Baffin Bay and the British Volcanic Province (e.g. Saunders et al. 1997) is generally taken to be the precursor of NE Atlantic spreading (see 60 Ma reconstruction, Figure 17). Notably however, the orientation of this magmatic belt was nearly perpendicular to the evolving NE Atlantic rift (e.g. Smallwood & White 2002, Lundin & Doré 2005).

NE Atlantic-Eurasia Basin stage 55-0 Ma

Opening of the NE Atlantic and Eurasia Basin is well established from magnetic isochrons in the NE Atlantic, ODP drilling of seaward-dipping reflectors marking the mid-Norwegian COB (Eldholm et al., 1989) and off SE Greenland (e.g. Larsen & Saunders 1998), and numerous other scientific studies. This event was marked by a pulse of magmatism between c. 56 and 53 Ma (e.g. Saunders et al., 1997). From 55 to 33 Ma both the Labrador Sea and NE Atlantic opened on either side of Greenland (see 33 Ma reconstruction, Figure 18). The simultaneous opening on two arms of spreading caused Greenland to move northwards, leading to collision between Greenland and Ellesmere Island in the Canadian Arctic (Eurekan Orogeny), and transpression between Greenland and Svalbard (West Spitsbergen Orogeny) associated with dextral translation along the NNW-SSE De Geer shear zone.

The relaying of motion between Baffin Bay and the Eurasia Basin is enigmatic. Baffin Bay terminates rather abruptly to the north, beyond which only small half-grabens exist in Lancaster and Jones Sounds. Accommodation of Labrador Sea-Baffin Bay opening has traditionally been visualized as the “Wegener Fault” (e.g. Harland 1965), a NE-SW sinistral shear, running along the Judge Daly Fault in the Nares Strait (e.g. Figures 2, 17 & 18). However, despite the Nares Strait forming an impressive NE-SW lineament, recent work on piercing points across the strait suggests limited lateral movement (Harrison 2004). Since the existence of shear is necessitated by the opening of an oceanic basin (on a sphere) in a rigid plate model, the best candidate location for this movement is within the Eurekan foldbelt on Ellesmere Island .

The large, elongate Lomonosov Ridge microcontinent separated from the Barents-Kara margin as the Eurasia Basin initiated, probably in part exploiting parallel fractures from the Amerasia Basin terminal transform zone. Eurasia Basin spreading terminated at the Laptev margin, where extension was partitioned between the Laptev Rift (Drachev et al., 1998) and strike-slip: westwards into the Yenisey-Khatanga Trough and eastwards as renewed right-lateral movement along the Eastern Siberian margin and into the Bering Strait (Figure 17).

Isochron 13 (33 Ma) marked a significant plate reorganization in the NE Atlantic and Arctic (Figure 18). Seafloor spreading terminated in the Labrador Sea and Baffin Bay (Kristoffersen & Talwani 1977). Consequently Greenland again became part of the North American plate, and the seafloor spreading became focused on a single spreading axis linking the NE Atlantic and Eurasia Basin. Greenland was therefore no longer forced northward and the Eurekan Orogeny terminated, as did the West Spitsbergen Orogeny. The spreading vector between Greenland and Eurasia changed by c. 30º, causing oblique opening of the pre-existing De Geer shear margin, release and outward drift of microcontinental shards (Hovgaard and East Greenland Ridges), inception of the Knipovich spreading ridge and passive drift between NE Greenland and the Barents Sea.

The Arctic gateway in the Fram Strait (between Greenland and Spitsbergen) became breached at c. 17.5 Ma and allowed oceanic circulation to start between the Arctic Ocean and the Atlantic (e.g. Jakobsson et al., 2007). Activity on the Khatanga-Bering Shear Zone may have diminished after this reorganization, with extension refocusing on the Laptev Rift from the Middle Miocene onwards (Drachev et al., 1998).

Implications for future Arctic work

Most models for Cretaceous-Cenozoic Arctic evolution, and especially the 3-stage model proposed above, imply that much of the oceanic area is bracketed by paleo-transform margins, and/or by transforms that have been reactivated as passive margins. This observation makes definite and testable predictions about geometries and basin modelling characteristics that will be encountered as more data becomes available in the lesser-known Arctic areas. Transform margins have unique geometries, distinct from those of rifted or active margins, and these structures have been studied in some detail on the Atlantic equatorial transform zone (e.g. Mascle et al., 1995, Nemcok et al. 2012). A similar array of structures has already been documented in parts of the Arctic, and should become further evident as more data is gathered.

Timing of continental break-up in shear margins is ambiguous, and depends on whether it is defined by passing of a given point on the continent by the spreading ridge, or by the time when already-formed oceanic crust passes by the margin. The ocean forms without much preceding extension, by lateral motion of one plate past the other, so margins tend to be expressed by an abrupt termination of normal or moderately thinned continental crust against oceanic crust. Abrupt terminations of this type are typical of parts of the Barents Sea western margin, for example along the Svalbard margin (e.g. Myhre & Thiede 1995) and on the western peripheries of the Sørvestnaget Basin and Vestbakken Volcanic Province (e.g. Gabrielsen et al., 1990) (Figure 7). Similar geometries are also evident on the few seismic profiles across the eastern Siberian margin, where Sekretov (2001) characterizes the Late Cretaceous paleo-margin via a "passive-transform model' associated with opening of the Makarov-Povodnikov Basin. His published lines show abutment of Late Cretaceous reflectors against steeply rising basement, albeit now buried beneath thick continental slope deposits of Cenozoic age (Figure 13). New, currently unpublished Russian seismic lines across the Laptev and East Siberian margin either side of the Lomonosov Ridge show further evidence of steep margins and strike-slip deformation, including flower structures (A. Nikishin, Personal Communication, 2015). We predict further confirmation of shear margin geometries along this little-known margin as better seismic data sets are obtained, along with further expressions of small-scale conjugate strike-slip fault assemblages of the type observed in the Hanna Trough, Alaska, described above (c.f. Reches 1978; Krantz 1988).

Although on the grand scale transform margins appear to be long, straight features, in detail they commonly consist of multiple parallel fractures, "horsetail' faulting and *en echelon* shear segments (e.g. Mascle et al., 1995). Transpression and pull-apart occur at constraining or releasing bends or between *the en echelon* segments, but also occur due to convergent or divergent motion across the margin associated with plate reorganization and changes in the spreading vector. The Sørvestnaget Basin and Vestbakken Volcanic Province are examples of Paleogene pull-apart basins at releasing bends along the De Geer transform margin (Figures 6 & 7). Pull-part basins promote ridge-jump by eventually developing spreading ridges in their axes (Nemcok et al. 2012), and this appears to have taken place in the Vestbakken Volcanic Province, where the segmented margin steps eastwards and the Eocene-Oligocene volcanism is probably associated with development of the ridge. It is worthy of note that the De Geer margin has an intermittent igneous signature, which also includes Quaternary volcanism documented on Spitsbergen (Treiman 2012). The association between volcanism and ridge propagation in a transform margin setting – or, in some cases, the lack of it - appears to have been little discussed in the literature (with a few exceptions, e.g. Mihut and Muller 1998) and is worthy of future investigation.

Changes in spreading vector on elements of the Equatorial Transform Margin such as the Romanche and St Paul fracture zones, associated with the development of transpressive structures, appear to have been in the order of 10-20 degrees (Nemcok et al. 2012). The De Geer shear margin, on the other hand, has seen more radical changes in plate motion. These began in the Early Eocene with the dextral shear occurring simultaneously with northwards convergence of Greenland with the Barents and Arctic Canada margin. Simultaneously, sinistral shearing probably occurred along the greater "Wegener fault" between Greenland and Ellesmere Island. The result was not just transpressive uplift but the development of mountain ranges and full-scale fold-and- thrust belts in Spitsbergen, North Greenland and Arctic Canada (Dallmann et al., 1993: Lyberis & Manby 1993). Conversely, the c. 30 degree change in spreading direction at the Eocene-Oligocene transition represented extreme divergence. This change resulted eventually in passive drift, although it is notable that transtensional tectonics are still active today on the western margin of Spitsbergen (Cianfarra & Salvini 2014). This area represents part of the De Geer Zone where the Knipovitch Ridge has only just penetrated through the Fram Strait between Greenland and the Barents platform, and where oblique ultra-slow spreading is taking place at present day (Snow et al., 2011) . The most radical change in spreading vector in the Arctic occurred between the opening of the Canada and Makarov-Povodnikov Basins. Here the change was almost 90 degrees, and in the view we have promoted above this resulted in major shedding of microcontinental material from the former shear margin during the late Cretaceous and Paleogene (see also Nemčok et al., this volume).

Transform margins have specific implications for basin modelling and thus for petroleum exploration (e.g. Nemčok et al., 2012). Reservoir deposition is affected by steep slopes with low sediment retention. Depositional fans are therefore likely to be separated from their shelf source area. Entry points for clastic sediments tend to be focused at releasing bends with thickest deposits in pull-apart basins. Because of the separation of source from depositional area by bypass, stratigraphic traps become important, as exemplified by discoveries along the Equatorial Transform Margin. In terms of thermal maturation history, modelling suggests that initial continental break-up in a shear setting results in a warming event due to thinning of crust in pull-apart basins. This peak is followed by cooling and then further warming as the spreading center passes along the margin instead of moving away from it. This second heat flow maximum is reached during the passage time of the spreading center. It is then followed again by cooling (see more detailed description of the thermal modelling in Nemčok et al., 2012). In addition to thermal maturation, hydrocarbon migration is also likely to be influenced by the margin type. Reactivation of strike-slip faults by different stress regimes (strike-slip faulting, transtension, transpression), can occur long after initial continental break-up. Therefore, fault-controlled hydrocarbon migration should be long-lasting and variable during the post-rift history.

Thermally-induced uplift should also increase with the passing of the spreading ridge, but both this type of uplift and uplift due to flexural unloading of the shear margin are exceeded by almost an order of magnitude by transpressional effects (Clift & Lorenzo 1999, c.f. Nemčok et al., 2012). Uplift and exhumation of a basin has radical, systematic effects on the petroleum system and requires a different approach to exploration (Doré et al., 2002). Recent uplift of the margins appears to be a pan-Arctic phenomenon, and, as might be expected, is most severe in the transpression-compression dominated areas of the De Geer zone such as the north-western Barents Sea margin (e.g. Henriksen et al., 2011) and Sverdrup Basin (e.g. Brooks et al. 1992).

The Equatorial and De Geer transform zones both represent globally-significant Atlantic transform margins. Both are dextral and both are complex with multiple parallel components, but they differ significantly in terms of plate kinematic evolution. These factors, plus the interest of the petroleum industry in both areas, suggest that a more detailed future comparison of the two zones would pay dividends in terms of understanding transform margin behaviour.

Conclusions

1. During the Cretaceous-Cenozoic opening history of the Arctic Ocean, transform margins existed on three sides of the developing ocean. Transform margin development was a natural outcome of opening around Euler poles in a relatively confined space, which is why all plate tectonic models for the Arctic involve significant strike-slip motion. Timings and locations of the transform margins were determined by spreading vectors, which changed radically during Arctic Ocean evolution.

2. A three-stage opening for the Arctic Ocean is argued to be the best kinematic fit and the most reasonable correspondence with observed structural geometries and pre-opening volcanic episodes. The model involves a Canada Basin rotational opening stage at 125-80 Ma, a Makarov-Podvodnikov Basin stage (with Eurasian-Tethyan plate convergence) at 80-60 Ma orthogonal to the Canada Basin spreading , and an adjacent, “mirror image” Eurasia Basin stage at 55-0 Ma. All of these opening stages have been previously proposed in the literature, albeit not with this precise combination and timing.

3. Canada Basin opening represents plate reorganization on the paleo-Pacific margin, specifically the annealing of the South Anyui Sea, an embayment in the margin conceivably remaining from the earlier (Late Paleozoic–early Mesozoic) Uralian closure. The radical change of break-up vector that resulted in Makarov-Podvodnikov and Eurasia basin spreading represents a quite different influence – northwards fragmentation of Pangea along the Atlantic trend. Makarov-Podvodnikov activity appears to correspond with rifting and hyperextension in the Labrador Sea and Baffin Bay, while Eurasia Basin spreading was synchronous with – and connected to – NE Atlantic activity.

4. The Grantz et al. (1979) rotational model still remains an excellent solution to early Amerasia Basin opening, but we propose a modification such that the dextral terminal shear margin tracks the arcuate Alpha-Mendeleev Ridge rather than the more linear Lomonosov Ridge. Volcanic dates on and adjacent to the Alpha-Mendeleev Ridge are consistent with a separate opening of the Makarov-Podvodnikov Basin, and this phase also provides a potential explanation for the widespread normal faulting on the ridge. Further seismic data across the East Siberian Shelf, and palaeomagnetic data documenting the rotation of the Chukotka/East Siberian shelf area, would help to pin down both the existence and position of the Amerasia Basin Transform.

5. The De Geer line is a global-scale lineament that almost certainly began its existence as a Late Paleozoic shear zone and was exploited during the separation of the Chukotka-Crocker Land terrane from the Canadian Arctic margin in the Early Cretaceous. During the Cenozoic it formed a major transform margin linking the Eurasia Basin and NE Atlantic, associated with transpression, pull-apart and volcanism. The De Geer transform margin is strongly analogous to the similarly dextral and extensive Equatorial shear margin, but experienced more radical changes in plate vector than the latter. More detailed comparison of the two margins in terms of geometries, ridge-margin interactions, volcanism and response to changing plate vectors would be fertile ground for future study.

6. The existence of Late Cretaceous-Early Cenozoic shear along the Laptev-East Siberian continental margin is highly likely as an outcome of, and accommodation to, Makarov-Podvodnikov and Eurasia Basin opening. We have expressed this concept via the “Khatanga-Bering Transform”, but readily accept that the shear may not be a single continuous feature. Although data is sparse in this part of the Arctic, the available evidence is consistent with transform margin development, including marginal geometries, lateral offsets and strike-slip fault assemblages. Transform motion along the margin probably waned after the end-Eocene plate reorganization at Isochron 13 time, 33

Ma. While we predict that more evidence of shear will emerge as data coverage improves, work should focus on two key factors; 1) further resolution of the amount of Cenozoic extension in the Laptev Rift compared to the Eurasia Basin, and 2) evidence for transform margin and/or strike-slip geometries on seismic lines across the Laptev margin, east Siberian margin, and within the Yenisey-Khatanga Trough.

7. There appears to be an intimate connection between the Arctic transform margins and microcontinent formation. Arctic microcontinents include the Hovgaard, East Greenland and Lomonosov ridges and, we propose, continental material entrained in the Alpha-Mendeleev ridge. In the Arctic, microcontinent escape appears to have taken place during, or as a result of, changes in spreading vector. This connection appears to be a worldwide phenomenon and is considered in more detail in a companion paper (Nemčok et al., this volume).

8. The sense of marginal transform motion in the Arctic appears to be overwhelmingly dextral, with the possible exceptions of sinistral shear through the Yenisey-Khatanga Trough (Russia), Nares Strait (Canada) and the theoretical (but unobserved) shear expressing the rotation of the Chukchi Borderlands. The entire Atlantic also seems to be characterized by dextral offset on the major transform margins, with the Arctic Ocean at the northern terminus of the system. This association may be pure coincidence, or may represent a generic connection not yet understood.

9. The similar Equatorial and de Geer transform margins have both attracted petroleum industry interest and include recent oil and gas discoveries. Recognition of a shear stage in the development of a continental margin makes specific predictions on the petroleum system, including reservoir deposition, traps, thermal history, migration, uplift and exhumation. Further detailed examination of similarities and differences between the two transform zones could pay dividends both academically and economically.

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Figure Captions

Figure 1

Bathymetry-topography map showing general physiographic elements of the Arctic.

Figure 2

Tectonic elements map of the Arctic. AB = Anabarsky Block, BAB = Baffin Bay, BB = Bjørnøya Basin, BI = Banks Island, BR = Brooks Range, BS = Baltic Shield, CAO = Caledonian Orogen, CB = Canada Basin, CFB = Coleville foreland basin, CO = Chukotka Orogen, DLH = De Long High, EBMB = Eastern Barents Megabasin, EO = Eurekan Orogen, FJL = Franz Josef Land, GFZ = Greenland Fracture Zone, HAB = Hammerfest Basin, HB = Hope Basin, HR = Hovgaard Ridge, HT = Hanna Trough, JM = Jan Mayen, KBS = Khatanga-Bering Transform, LH = Laptev Horst, LR = Laptev Rift, LSB = Long Strait Basin, MD = Mackenzie Delta, MJR = Morris Jessup Rise, MR = Mendeleev Ridge, NCB = North Chukchi Basin, NGS = Norwegian-Greenland Sea, NKB = Nordkapp Basin, NKS = North Kara Sea, NS = Nares Strait, SAS = South Anyui Suture, SB = Sverdrup Basin, SH = Stappen High, SKS = South Kara Sea, SV = Svalbard, TB = Thetis Basin, TFB = Taimyr Foldbelt, TRB = Tromsø Basin, VFB = Verkhoyansk Foldbelt, WI = Wrangel Island, WS = West Siberia Basin, YKT = Yenisey-Khatanga Trough, YP = Yermak Plateau.

Figure 3

Crustal thickness map to show main crustal elements of the Arctic. Potential continent-ocean boundaries are indicated by dotted lines. AR = Alpha Ridge, BB = Baffin Bay, CB = Canada Basin, EB = Eurasia Basin, LR = Lomonosov Ridge, MPB = Makarov-Podvodnikov Basin, MR = Mendeleev Ridge, NEA = Northeast Atlantic. The crustal thickness, supplied by A. Alvey, was inverted from gravity data according to techniques described in Alvey et al., (2008). Image courtesy Badley Geoscience Ltd and OCTek**.**

Figure 4

Bouger gravity map of the Arctic (from Gaina & Werner 2009) showing the proposed locations of principal shears. ABT = Amerasia Basin Transform, CBT = Chukchi Borderlands Transform, DGL = De Geer Line, EJMFZ = East Jan Mayen Fracture Zone, HT = Hanna Transform, UFZ = Ungava Fracture Zone, 64FZ = 64 Degree West Fracture Zone = WHA = Wrangel-Herald Arch, WJMFZ = West Jan Mayen Fracture Zone.

Figure 5

Principal basement domains of the Barents Sea area, showing probable late Paleozoic expression of the De Geer Line. Adapted from Gee & Teben'kov (2004).

Figure 6

Break-up and evolution of the western Barents Sea (De Geer) shear margin, adapted from Faleide et al. (2010) and others. Abbreviations: AR = Aegir Ridge, BB = Bjørnøya Basin, EFB = Eurekan Fold Belt, EGR = East Greenland Ridge, HAB = Harstad Basin, HR = Hovgaard Ridge, JM = Jan Mayen Microcontinent, JMFZ = Jan Mayen Fracture Zone, KNR = Knipovitch Ridge, KR = Kolbeinsey Ridge, MJR = Morris-Jessup Rise, MR = Mohn's Ridge, NR = Nansen-Gakkel Ridge, SVB = Sørvestnaget Basin, TB = Tromsø Basin, THB = Thetis Basin, VOB = Vøring Basin, VVP = Vestbakken Volcanic Province, WSFB = West Spitsbergen Fold and Thrust Belt, YP = Yermak Plateau.

Figure 7

Paleogene tectonic reconstruction of the western Barents Sea (De Geer) shear margin with seismic sections. The map is a composite for the Paleogene drawn on a 40 Ma (Eocene) base map. It does not indicate a precise time, but is designed to show the interrelationship between the shear margin, spreading cells, pull-apart basins and fold belts. Section A-A′ is across the Vestbakken Volcanic Province, from TGS survey NPD-BJV2-86R05, courtesy TGS. Section B-B′ is across the Sørvestnaget Basin. Abbreviations: BB = Bjørnøya basin, BFZ = Billefjorden Fault Zone, GFZ =

Greenland Fracture Zone, H = Hovgaard Ridge, L = Lomonosov Ridge, LH = Loppa High, OCT = Ocean-Continent Transition, SCB = Spitsbergen Central Basin, SFZ = Senja Fracture Zone, SH = Stappen High, SVB = Sørvestnaget Basin, VVP = Vestbakken Volcanic Province, WSFB = West Spitsbergen Fold and Thrust Belt, YP = Yermak Plateau.

Figure 8

Sketch maps showing potential tracks of the proposed Amerasia Basin rotational shear. Upper map: general relationship of the alternative shear tracks to the Canada Basin extinct spreading ridge and pole of rotation in the Mackenzie Delta. Lower map: generalized geological units of the Siberian margin showing relationship to New Siberian Islands, fold belts and terranes. AR = Alpha Ridge, B = Barents Sea, CBL = Chukchi Borderlands, ER = Extinct spreading ridge of the Canada Basin, ES = East Siberian shelf, G = Greenland, LR = Lomonosov Ridge, MD = Mackenzie Delta, MJR = Morris-Jessup Rise, MR = Mendeleev Ridge, NSA = North Slope of Alaska, NSB = New Siberian Basin, NSI = New Siberian Islands, SB = Sverdrup Basin, YP = Yermak Plateau.

Figure 9

Maps pertaining to the discussion on shear along the Siberian margin. a) Bouger gravity map (from Gaina & Werner 2009). b) Structural features. Abbreviations: AB = Anisin Basin; ABT = Amerasia Basin Transform; AR = Alpha Ridge, CBT = Chukchi Borderlands transform; ChP = Chukchi Plateau, COB = Continental-ocean boundary; Cz = Cenozoic; DF = Denali Fault ; ESB = East Siberian Basin; HB= Hope Basin; HT = Hanna Transform; INFF = Idatarod-Nixon Fork Fault; KaF = Kaltag Fault, KBT = Khatanga-Bering transform, KoF = Kobuk Fault, KuF = Kugruk Fault, LSB = Long Strait Basin; MR = Mendeleev Ridge, NCB = North Chukchi Basin; NSB = New Siberian Basin; SAS= South Anyui Suture; SCB = South Chukchi Basin; TF = Tintina Fault; ULR = Ust-Lena Rift; WHA = Wrangel-Herald Arch; WI = Wrangel Island.

Figure 10

Birdseye view of bathymetric-topographic map of the Eurasia Basin viewed from the Norway-Greenland side, illustrating termination against the Laptev shelf. Based on IBCAO map (Jakobsson et al.)

Figure 11

NE-SW crustal profile across Western Laptev Rift, the most extended part of the rift (from Franke et al. 2001). Note that the remaining crust is in the order of 10 km thick even where thinnest. A direct continuation of the Eurasia Basin into the Laptev Rift would require the continental crust to essentially be absent. Profile location is shown on Figure 9b.

Figure 12

Satellite image showing the termination of Red Sea spreading against the sinistral Dead Sea Transform, a suggested analogy for the termination of the Eurasia Basin against the Laptev Rift.

Figure 13

North-south profile (after Sekretov 2001) across the East Siberian continental margin. Note steep Cretaceous margin and candidate position of the Khatanga-Bering Transform at the site of substantial offset and pinch-out of the Cretaceous succession. Profile location is shown on Figure 9b.

Figure 14

Atlantic Ocean map showing series of transform faults and paleo-shear margins separating oceanic segments of differing ages and terminating at the proposed Khatanga-Bering Transform (KBT). AG = Azores-Gibraltar Fracture Zone, CG = Charlie Gibbs Fracture Zone, DGL = De Geer Line, E =Equatorial Shear Zone, F = Florianopolis Fracture Zone, FA = Falklands Fracture Zone.

Figure 15

Present day (0 Ma) plate tectonic setting and model. Abbreviations: AR = Alpha Ridge, CB = Chukchi Borderlands, JM = Jan Mayen Microcontinent, MPB = Makarov-Podvodnikov Basin, MR = Mendeleev Ridge, SAS = South Anyui suture, WI = Wrangel Island, WS = West Spitsbergen orogen.

Figure 16

Plate reconstructions at 125 and 100 Ma. For legend see Figure 15. Abbreviations: BR = Brooks Range; CAB = Canada Basin; CB = Chukchi Borderlands; NAC = North America Cordillera; SAS = South Anyui Sea; WI = Wrangel Island

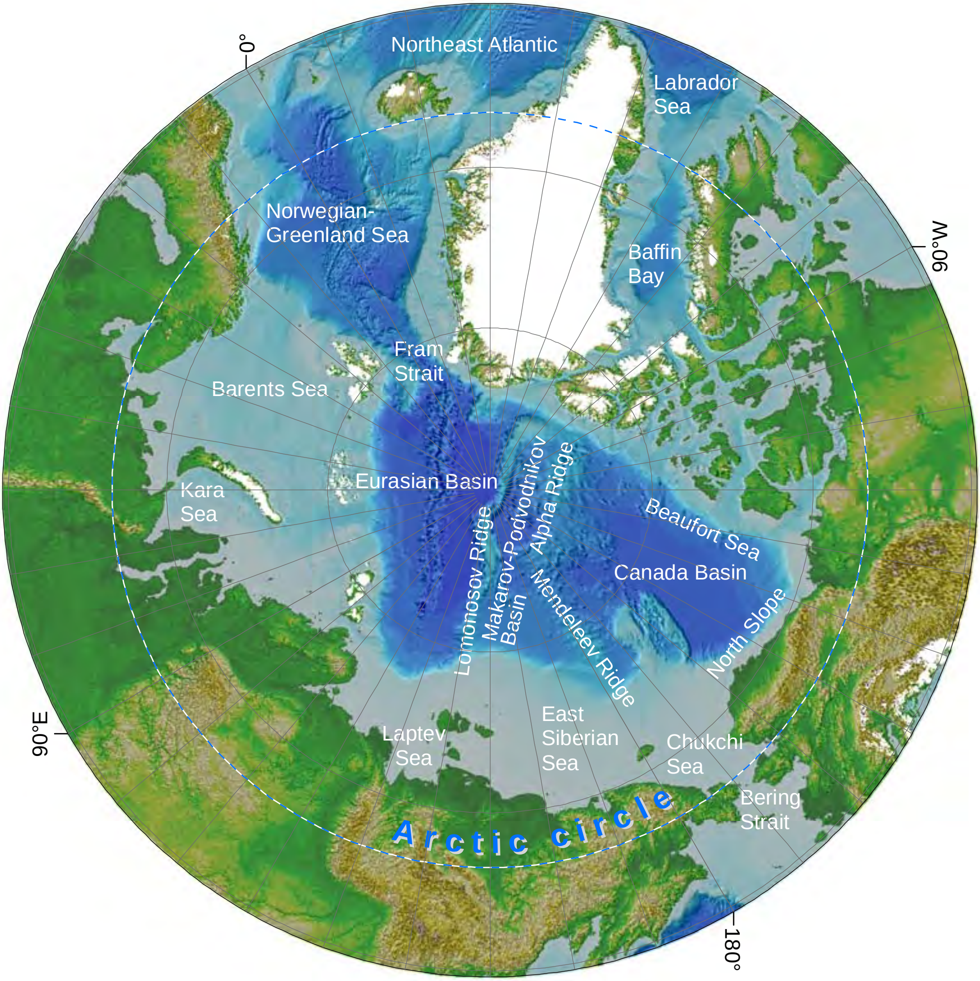
Figure 17

Plate reconstructions at 80 and 60 Ma. For legend see Figure 15. Abbreviations: AMR = Alpha-Mendeleev Ridge; BB = Baffin Bay; LS = Labrador Sea; MPB = Makarov-Podvodnikov Basin

Figure 18

Plate reconstruction at 33 Ma. For legend see Figure 15. Abbreviations: BB = Baffin Bay; LS = Labrador Sea; SV = Svalbard

1323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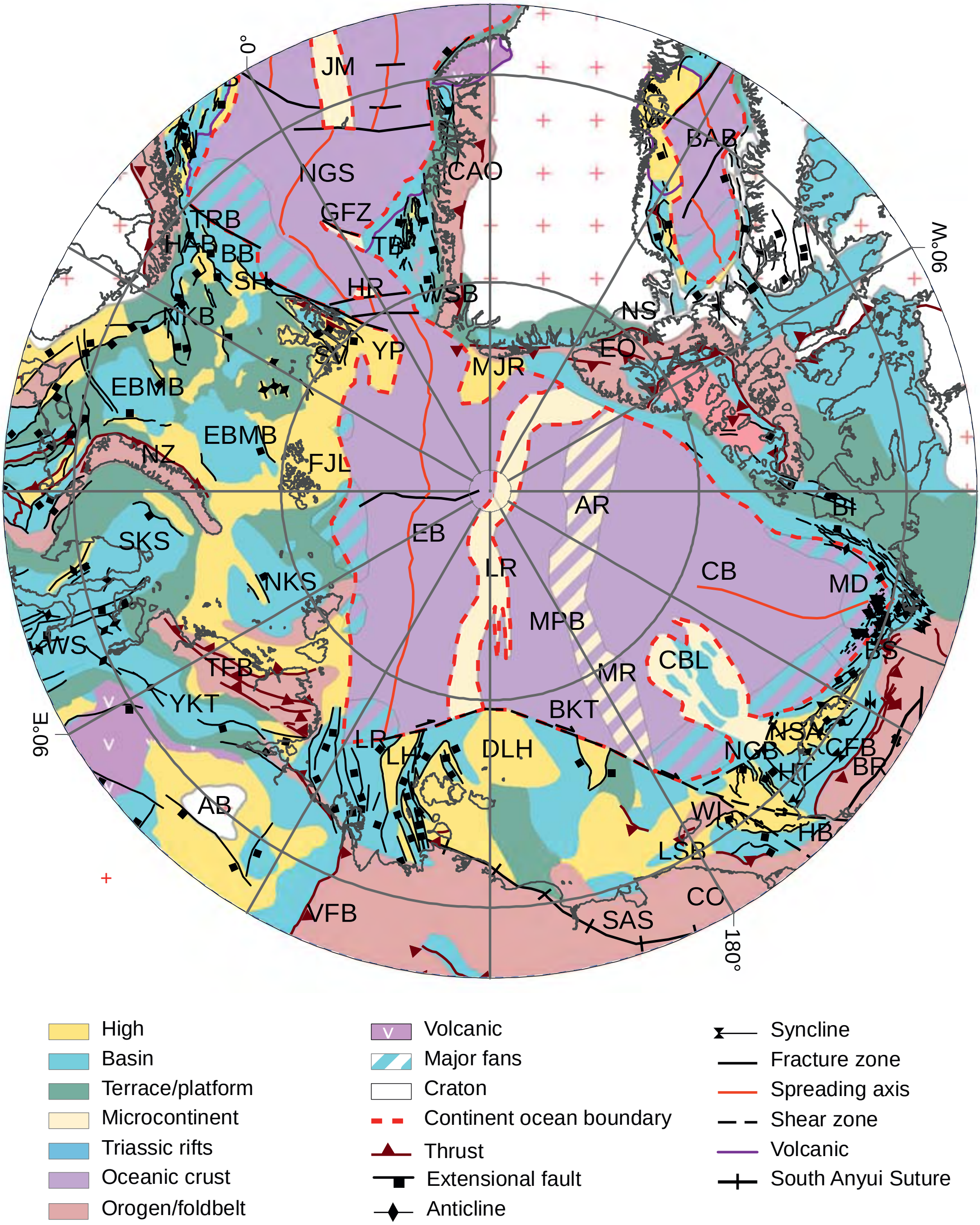
90°W
90°E
180°
Northeast Atlantic
Labrador Sea
Norwegian-Greenland Sea
Baffin Bay
Fram Strait
Barents Sea
Eurasian Basin
Kara Sea
Lomonosov Ridge
Makarov-Podvodnikov Basin
Alpha Ridge
Mendeleev Ridge
Beaufort Sea
Canada Basin
North Slope
Laptev Sea
East Siberian Sea
Chukchi Sea
Bering Strait
Arctic circle



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SV
YP
NS
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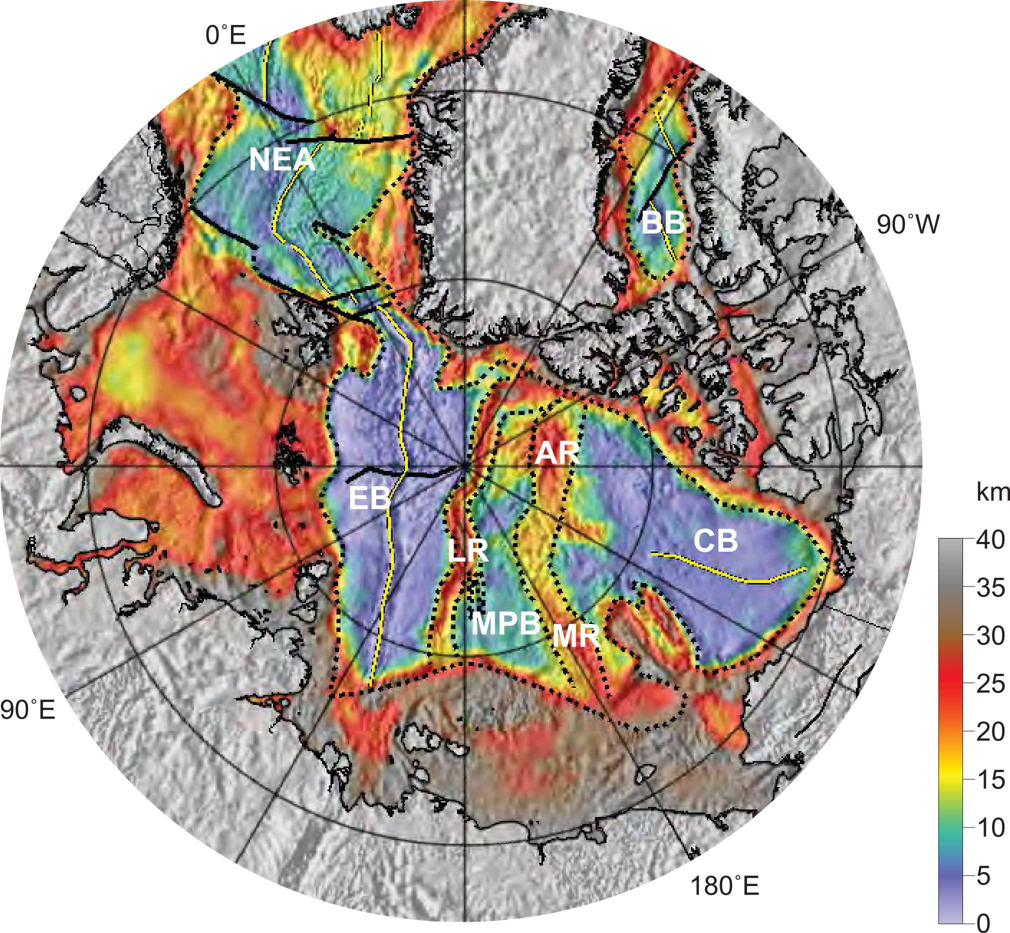
MJR
BAB
EBMB
EBMB
NZ
FJL
AR
EB
LR
CB
MD
BI
SKS
NKS
MPB
WS
TFB
MR
CBL
BS
YKT
BKT
NSA
CFB
LR
LH
DLH
NCB
HT
BR
AB
WI
HB
LSB
CO
VFB
SAS
High
Basin
Terrace/platform
Microcontinent
Triassic rifts
Oceanic crust
Orogen/foldbelt
Volcanic
Major fans
Craton
Continent ocean boundary
Thrust
Extensional fault
Anticline
Syncline
Fracture zone
Spreading axis
Shear zone
Volcanic
South Anyui Suture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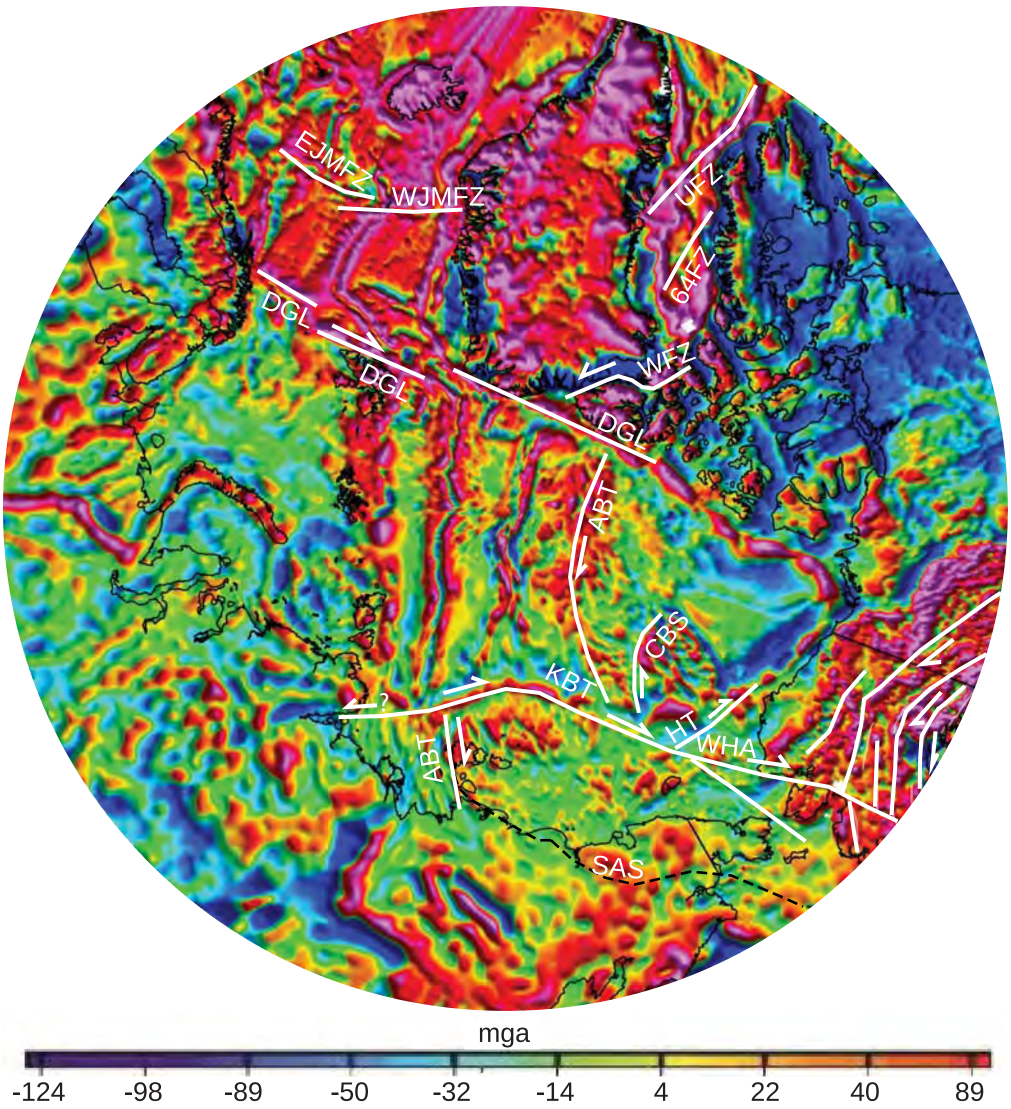
EJMFZ
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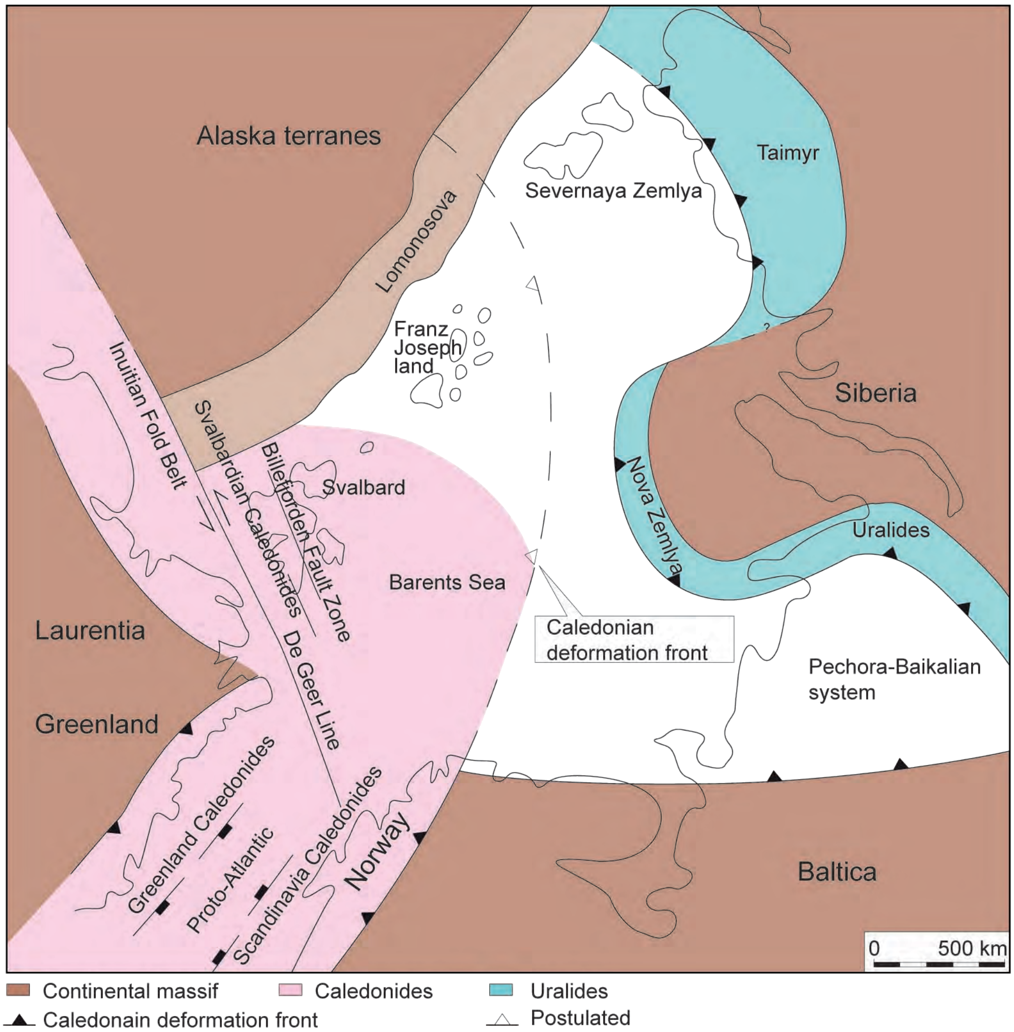
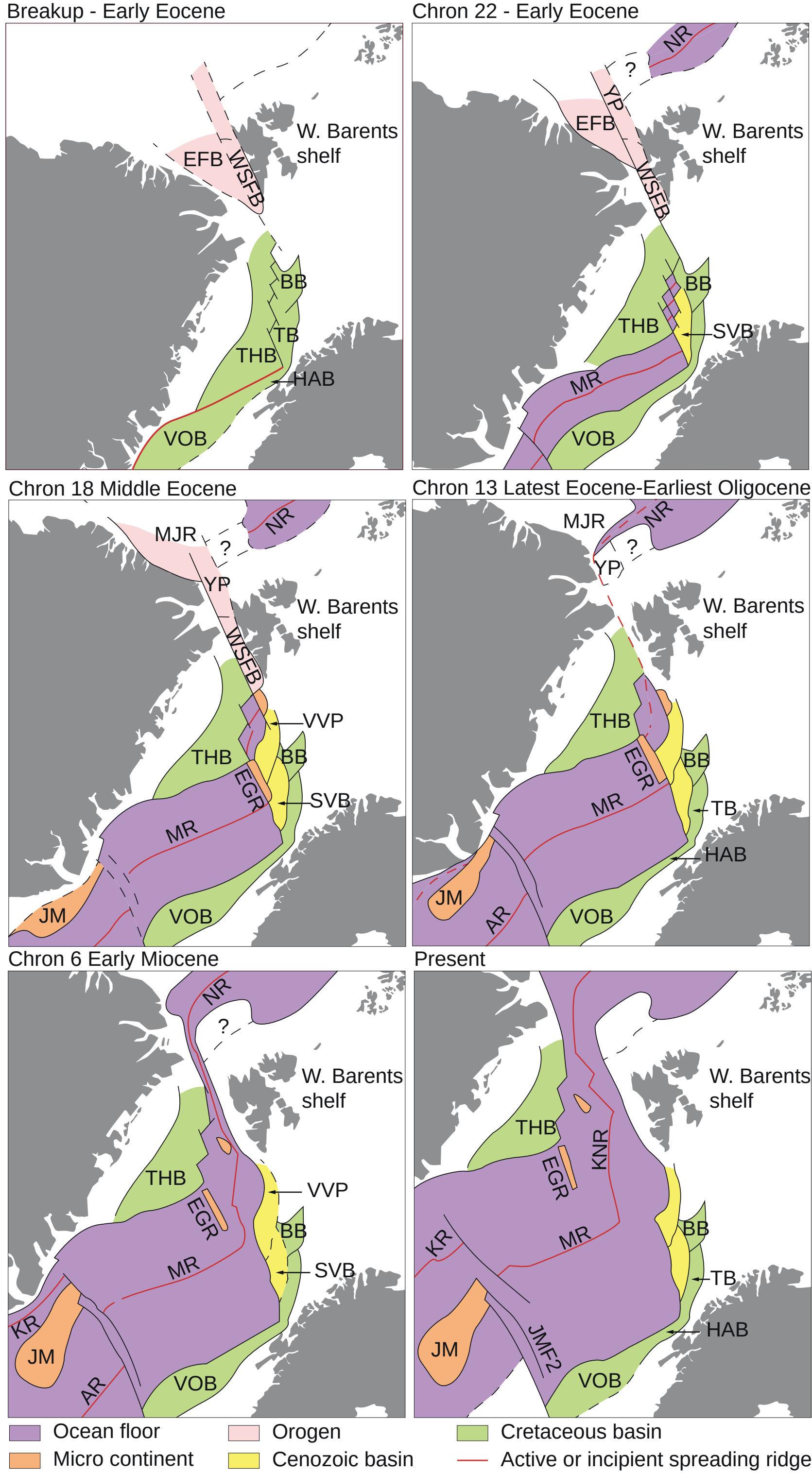


Alaska terranes
Lomonosova
Severnaya Zemlya
Taimyr
Franz Joseph land
Siberia
Inuitian Fold Belt
Svalbardian Caledonides
Billefjorden Fault Zone
Svalbard
Nova Zemlya
Uralides
Barents Sea
Caledonian deformation front
Laurentia
De Geer Line
Pechora-Baikalian system
Greenland
Greenland Caledonides
Proto-Atlantic
Scandinavia Caledonides
Norway
Baltica
0
500 km
Continental massif
Caledonides
Uralides
Caledonain deformation front
Postulated



Breakup - Early Eocene
EFB
WSFB
W. Barents shelf
BB
TB
THB
HAB
VOB
Chron 22 - Early Eocene
NR
?
YP
EFB
WSFB
W. Barents shelf
BB
THB
SVB
MR
VOB
Chron 18 Middle Eocene
MJR
?
NR
YP
W. Barents shelf
WSFB
VVP
THB
BB
EGR
SVB
MR
JM
VOB
Chron 13 Latest Eocene-Earliest Oligocene
MJR
NR
?
YP
W. Barents shelf
THB
EGR
BB
MR
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HAB
JM
AR
VOB
Chron 6 Early Miocene
NR
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W. Barents shelf
THB
VVP
EGR
BB
MR
SVB
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JM
AR
VOB
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W. Barents shelf
THB
KNR
EGR
BB
KR
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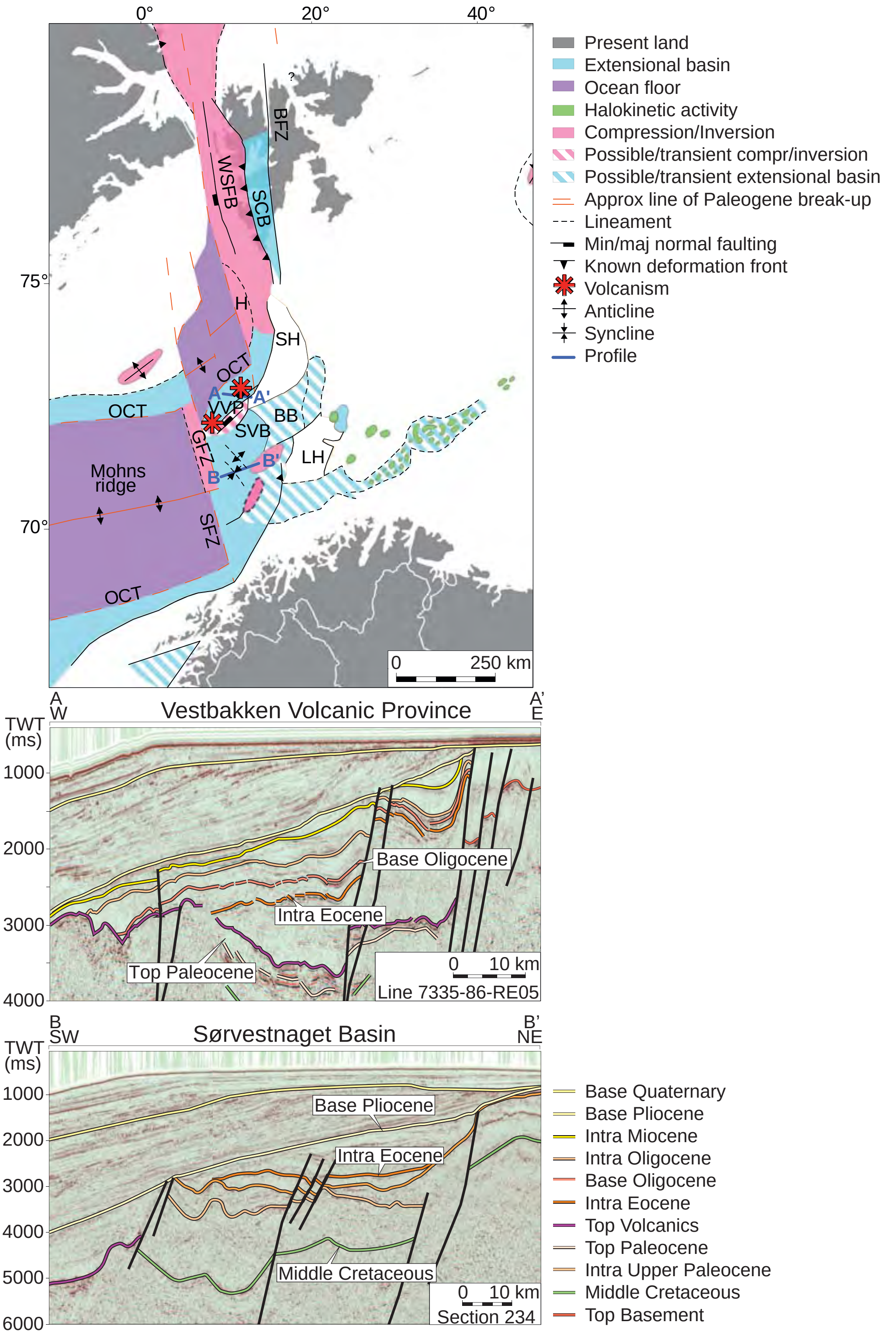
JM
JMFZ
VOB
Ocean floor
Orogen
Cretaceous basin
Micro continent
Cenozoic basin
Active or incipient spreading ridge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75°
70°
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Extensional basin
Ocean floor
Halokinetic activity
Compression/Inversion
Possible/transient compr/inversion
Possible/transient extensional basin
Approx line of Paleogene break-up
Lineament
Min/maj normal faulting
Known deformation front
Volcanism
Anticline
Syncline
Profile
BFZ
WSFB
SCB
H
SH
OCT
A
A'
VVP
SVB
BB
LH
GFZ
Mohns ridge
B
B'
SFZ
0 250 km
A W
A' E
Vestbakken Volcanic Province
TWT (ms)
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2000
3000
4000
Base Oligocene
Intra Eocene
Top Paleocene
0 10 km
Line 7335-86-RE05
B SW
B' NE
Sørvestnaget Basin
TWT (ms)
1000
2000
3000
4000
5000
6000
Base Pliocene
Intra Eocene
Middle Cretaceous
0 10 km
Section 234
Base Quaternary
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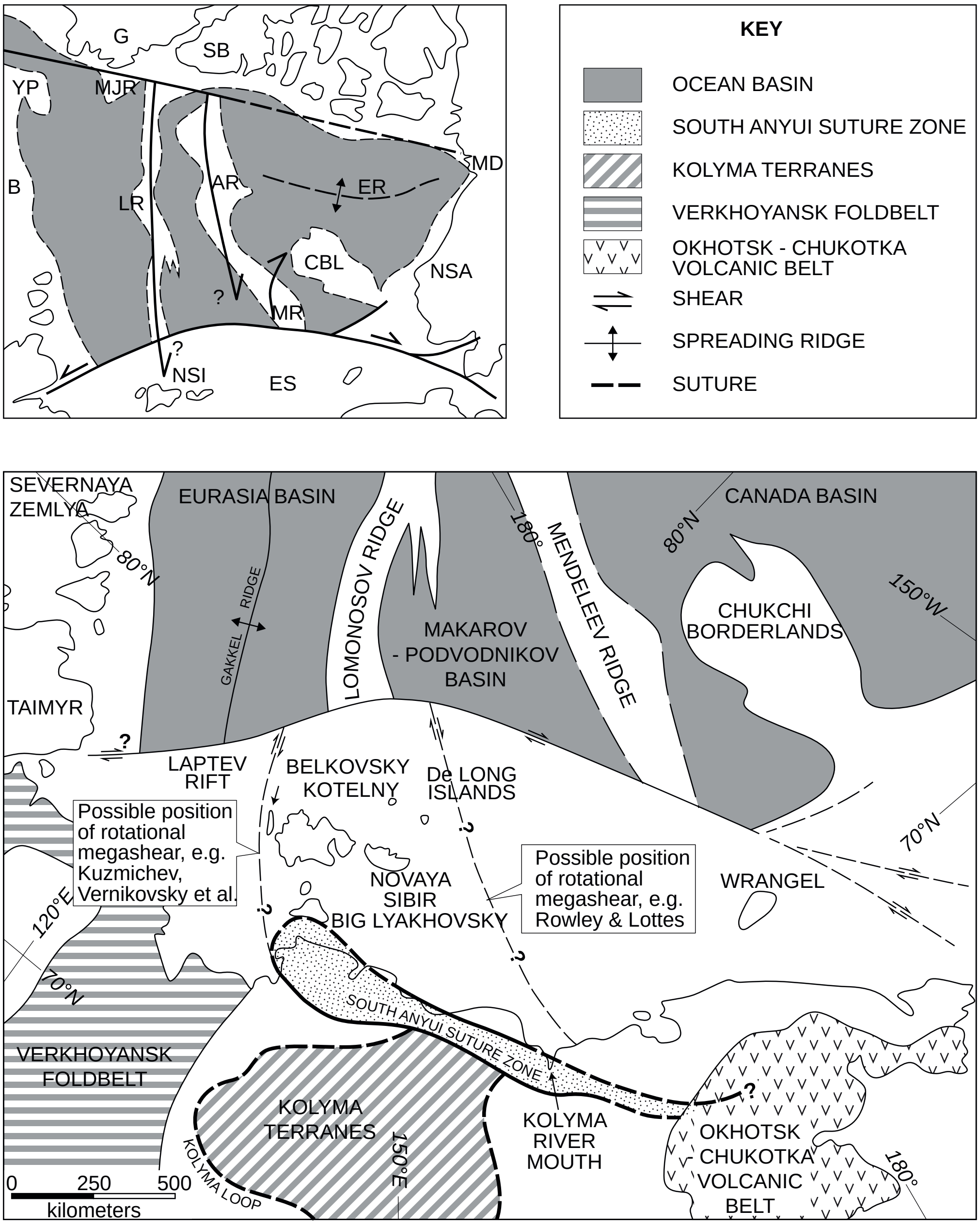
Top Basement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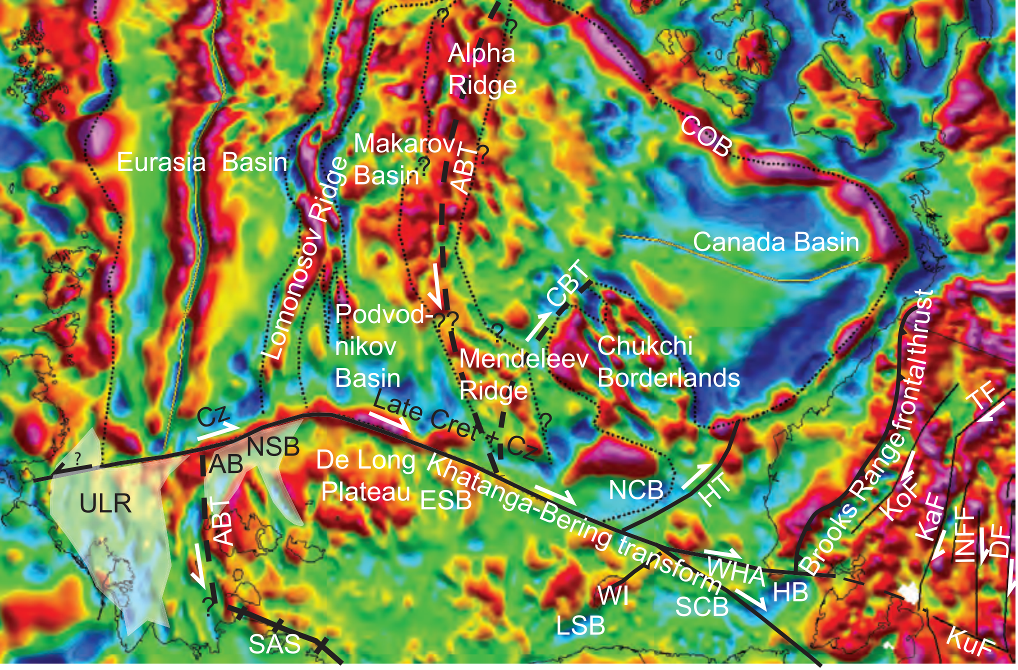
KOLYMA TERRANES
VERKHOYANSK FOLDBELT
OKHOTSK - CHUKOTKA VOLCANIC BELT
SHEAR
SPREADING RIDGE
SUTURE
SEVERNAYA ZEMLYA
EURASIA BASIN
LOMONOSOV RIDGE
180°
MENDELEEV RIDGE
80°N
CANADA BASIN
80°N
GAKKEL RIDGE
MAKAROV - PODVODNIKOV BASIN
CHUKCHI BORDERLANDS
150°W
TAIMYR
?
LAPTEV RIFT
BELKOVSKY KOTELNY
De LONG ISLANDS
Possible position of rotational megashear, e.g. Kuzmichev, Vernikovsky et al.
?
NOVAYA SIBIR BIG LYAKHOVSKY
Possible position of rotational megashear, e.g. Rowley & Lottes
WRANGEL
70°N
120°E
70°N
?
?
SOUTH ANYUI SUTURE ZONE
VERKHOYANSK FOLDBELT
KOLYMA TERRANES
150°E
KOLYMA RIVER MOUTH
?
OKHOTSK CHUKOTKA VOLCANIC BELT
180°
KOLYMA LOOP
0 250 500
kilometers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Lomonosov Ridge
Canada Basin
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Podvod-
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Basin
Mendeleev
Ridge
Chukchi
Borderlands
Brooks Range frontal thrust
TF
Cz
Late Cret + Cz
NSB
AB
De Long
Plateau
ESB
Khatanga-Bering transform
NCB
HT
ULR
ABT
KoF
KaF
INFF
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HB
WI
LSB
SCB
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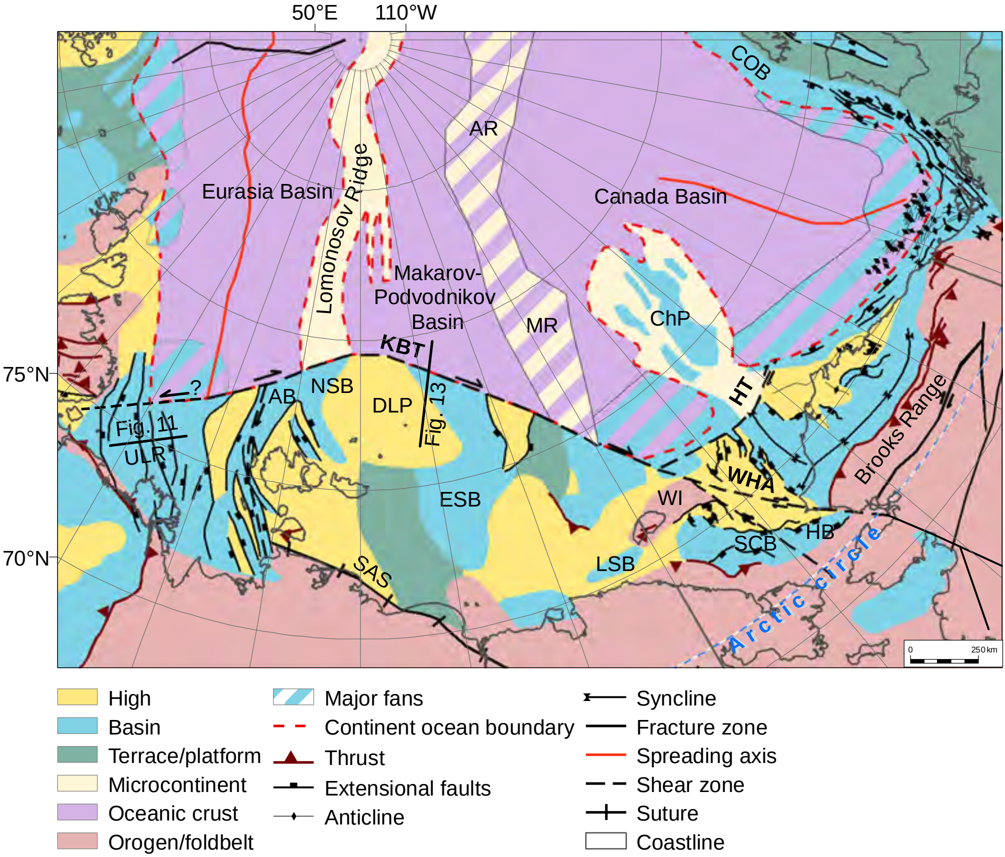

50°E
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75°N
70°N
COB
AR
Eurasia Basin
Lomonosov Ridge
Canada Basin
Makarov-
Podvodnikov
Basin
ChP
MR
KBT
HT
?
AB
NSB
DLP
Fig. 13
Fig. 11
ULR
ESB
WHA
WI
HB
SCB
LSB
SAS
Brooks Range
Arctic circle
0
250 km
High
Basin
Terrace/platform
Microcontinent
Oceanic crust
Orogen/foldbelt
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Continent ocean boundary
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Extensional faults
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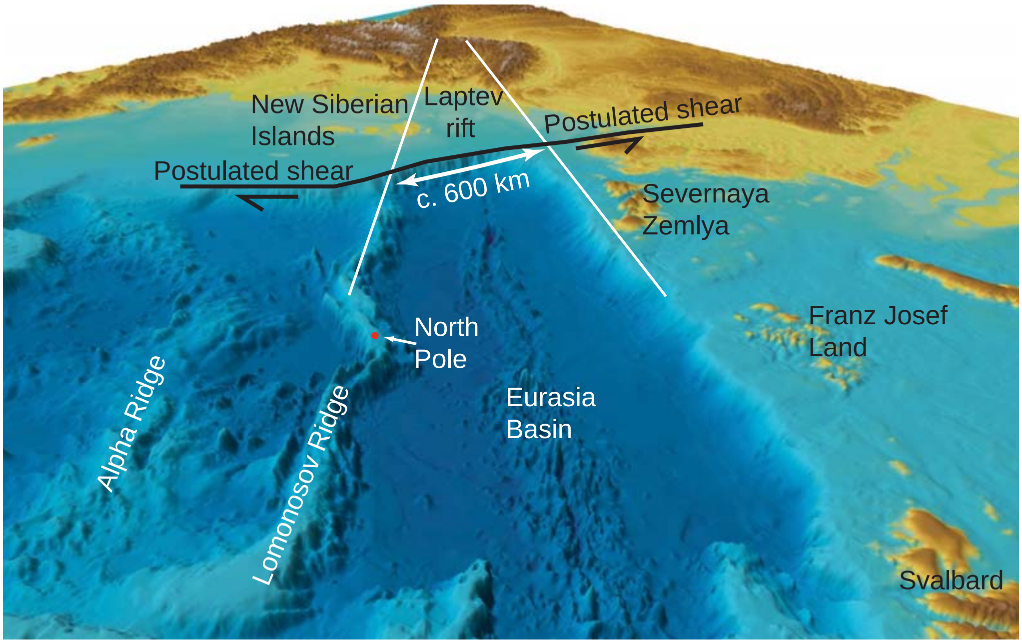
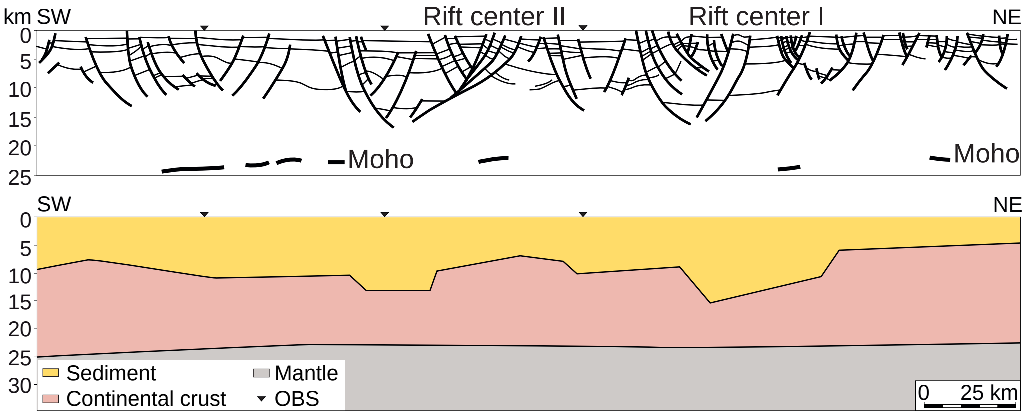
Syncline
Fracture zone
Spreading axis
Shear zone
Suture
Coastline



New Siberian
Islands
Laptev
rift
Postulated shear
Postulated shear
c. 600 km
Severnaya
Zemlya
Franz Josef
Land
North
Pole
Alpha Ridge
Lomonosov Ridge
Eurasia
Basin
Svalbard



km SW
Rift center II
Rift center I
NE
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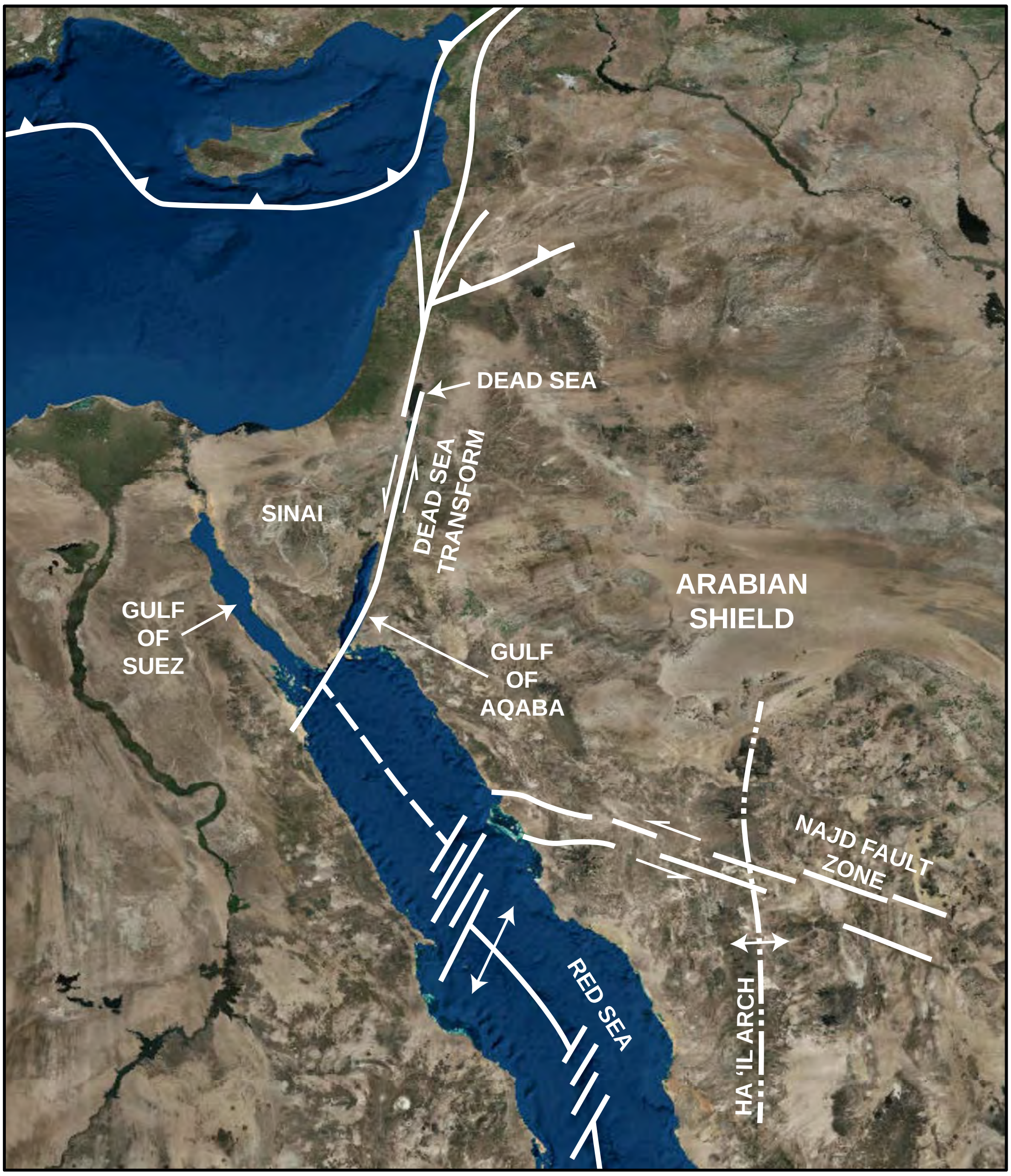
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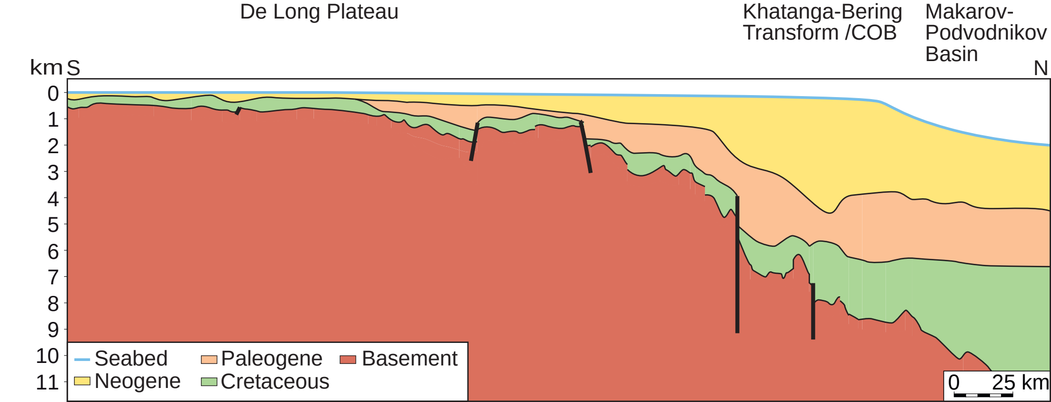
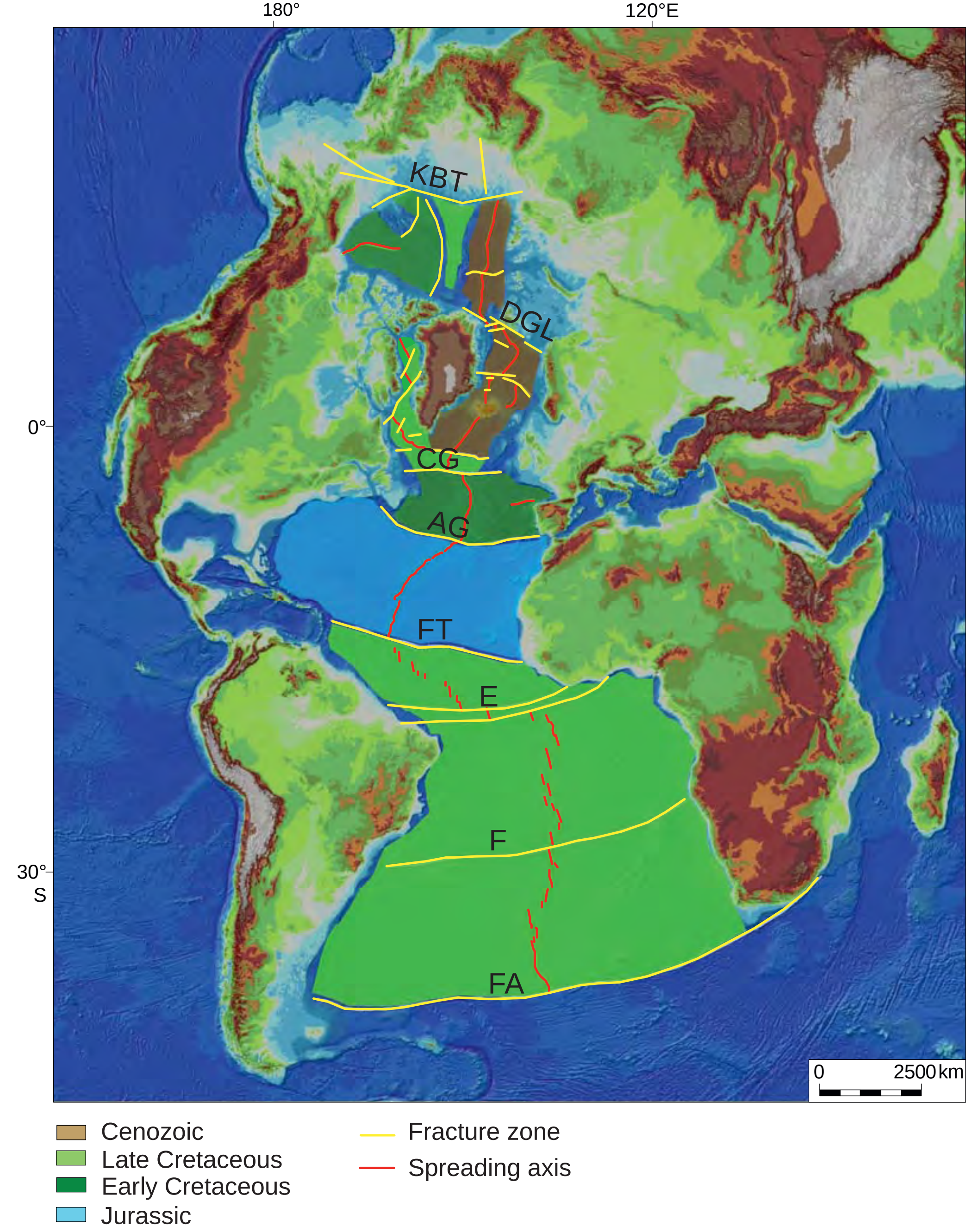
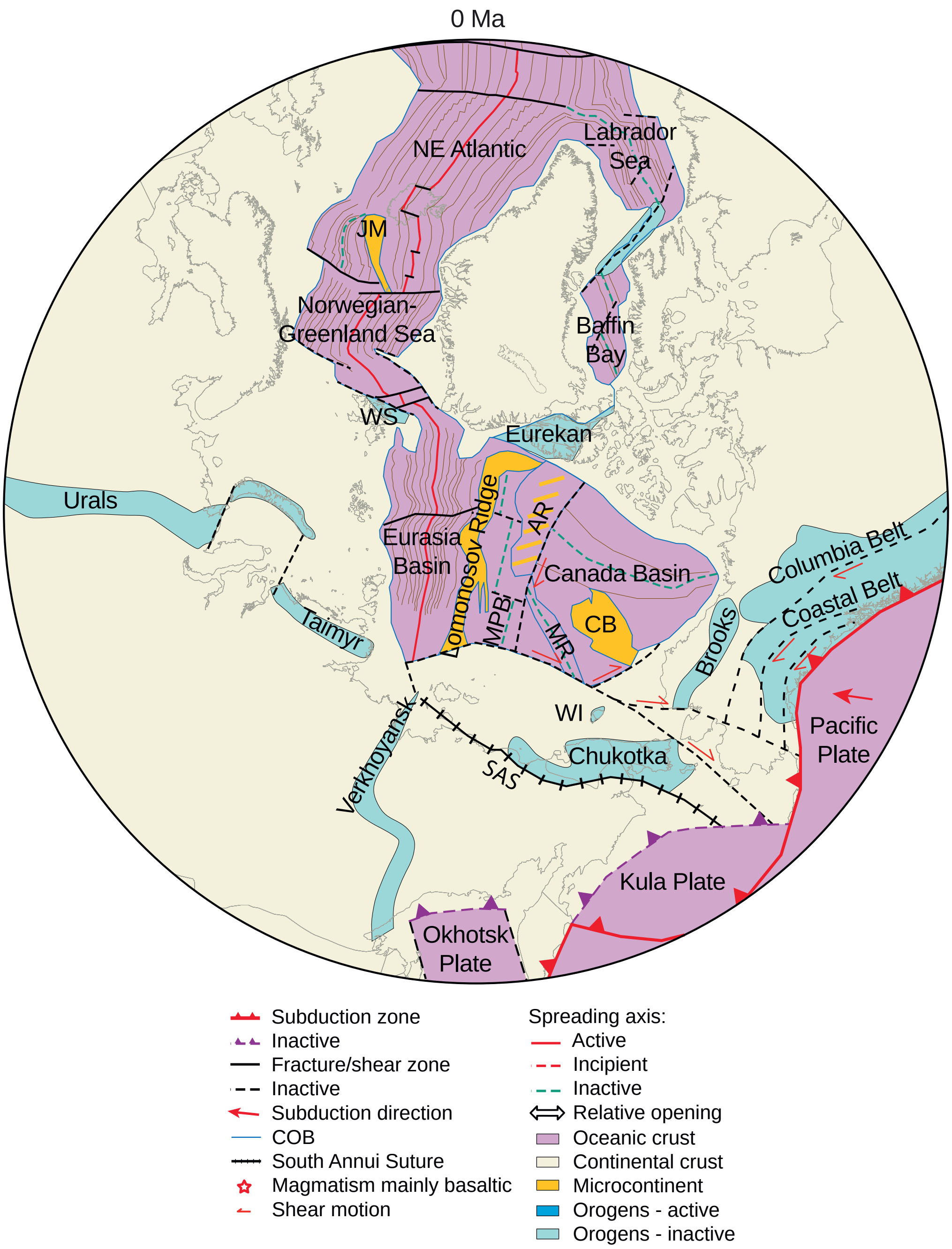
HA 'IL ARCH



De Long Plateau
Khatanga-Bering Transform /COB
Makarov-Podvodnikov Basin
km
S
N
0
1
2
3
4
5
6
7
8
9
10
11
Seabed
Neogene
Paleogene
Cretaceous
Basement
0
25 km

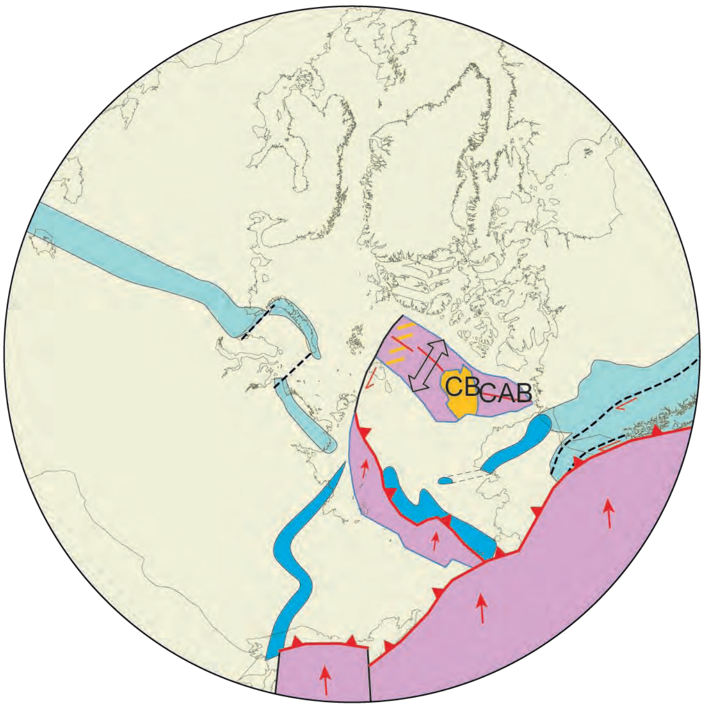


180°
120°E
0°
30°
S
KBT
DGL
CG
AG
FT
E
F
FA
0
2500 km
Cenozoic
Late Cretaceous
Early Cretaceous
Jurassic
Fracture zone
Spreading axis

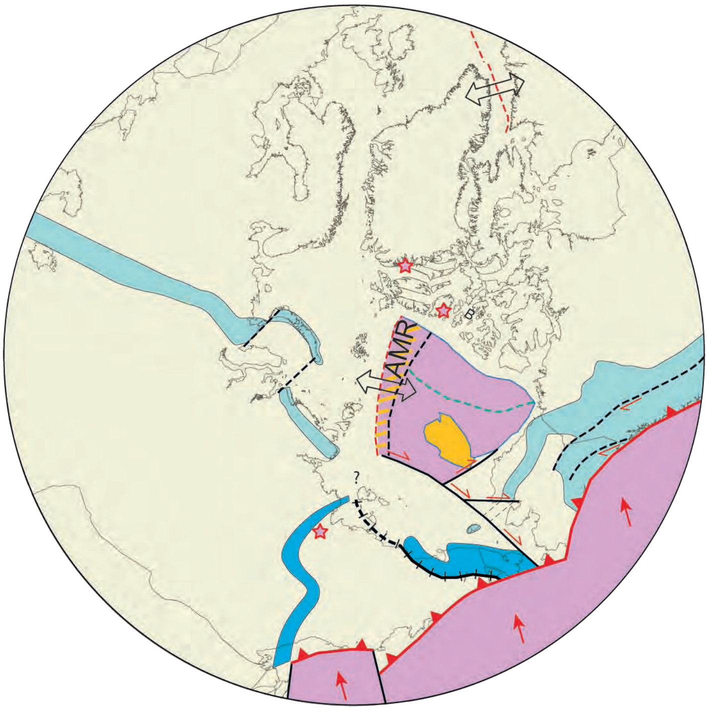

0 Ma
NE Atlantic
Labrador Sea
JM
Norwegian-Greenland Sea
Baffin Bay
WS
Eurekan
Urals
Eurasia Basin
Lomonosov Ridge
AR
Canada Basin
MPB
MR
CB
Taimyr
Columbia Belt
Coastal Belt
Brooks
WI
Chukotka
Pacific Plate
Verkhoyansk
SAS
Kula Plate
Okhotsk Plate
Subduction zone
Inactive
Fracture/shear zone
Inactive
Subduction direction
COB
South Annui Suture
Magmatism mainly basaltic
Shear motion
Spreading axis:
Active
Incipient
Inactive
Relative opening
Oceanic crust
Continental crust
Microcontinent
Orogens - active
Orogens - inactive

125 Ma

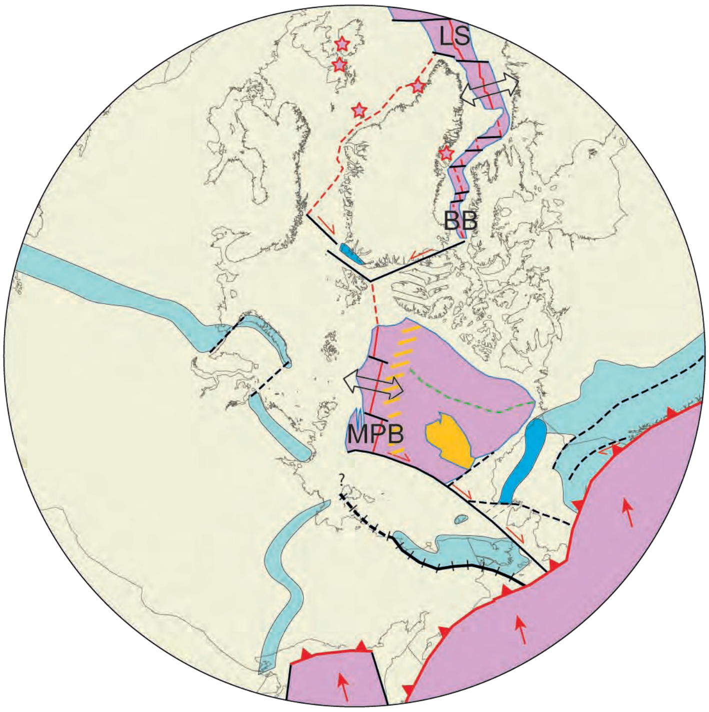
100 Ma

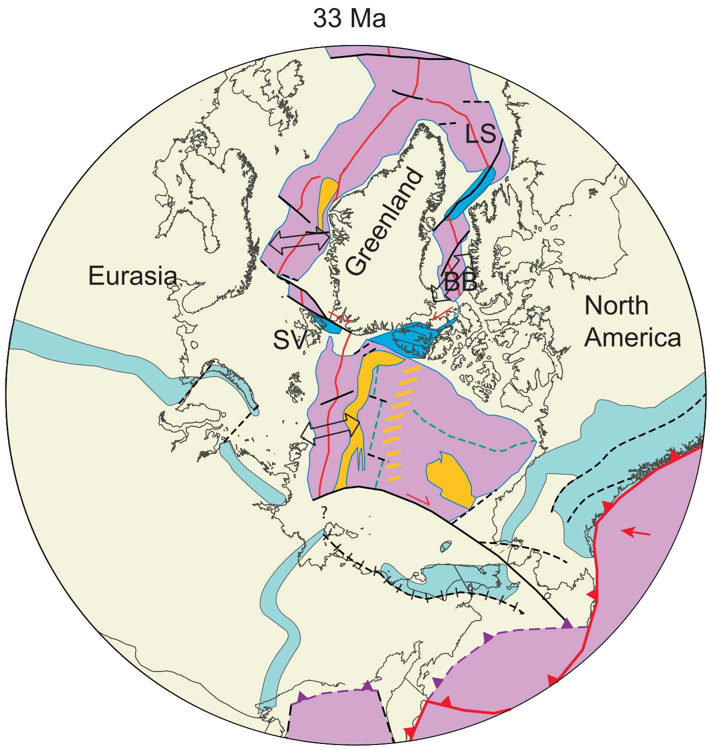


80 Ma



60 Ma




33 Ma
LS
Greenland
Eurasia
BB
North
America
SV
?