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Frontier Science and Exploration: the Atlantic – Arctic

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REPORT

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Summary:

A new kinematic model from the pre-breakup to present day has been developed for the Arctic-North Atlantic region. Using potential field data (magnetic and gravity), published seismic interpretation and geological records we have re-interpreted the continent ocean boundaries and transition zones. Seafloor spreading has been quantitatively determined and new palaeo-age grids have been constructed for the oceanic area. Kinematic parameters have been used in the case of a triple junction to estimate the errors of continent ocean boundary location. For the Jurassic-Cretaceous evolution of the Arctic we have explored several scenarios of oceanic basin evolution and used the predicted present day age configuration for estimation of crustal thickness. A new plate tectonic model of the North Atlantic-Barents Sea area have been used for modelling the Late Triassic-Early Jurassic compression in the Novaya Zemlya and eastern Barents Sea basins.

We have constructed the first hybrid ’absolute’ reference frame model since the Carboniferous: we use a moving hotspot reference frame based on Atlantic and Indian Ocean hotspots for the last 100 Ma and for earlier times, we use the global paleomagnetic frame adjusted 5 degrees in longitude to smooth the frame transition. It has been observed that there is a clear correlation between downward projected Large Igneous Province (LIP) eruption sites of the past 200 My and the margins of the Large Low Velocity Provinces (LLVPs) at the base of the mantle. Using the new global reference frame we have restored the Skagerrak-Centered Large Igneous Province (SCLIP-about 297 Ma volcanic activity observed in the NW Europe) and concluded that it is the product of a deep-seated mantle plume: the Skagerrak Mantle plume.

Hotspot tracks of the plume conduits and the plume head of Iceland were calculated and compared to actual bathymetry of the North Atlantic. It has been concluded that plume models having a source at the 660 km discontinuity are only influenced by flow in the upper mantle and transition zone and hence rather yield westward hotspot motion. A plume head of 120 K anomalous temperature gives the best match between plume head track and bathymetry.

Keywords: Geophysics	Geology	Plate kinematics
North Atlantic	Magnetics	Arctic
Gravity	Large Igneous Provinces	Basin evolution

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    6.3. *Long term stability in deep mantle structure: Evidence from the ~300 Ma Skagerrak-centered Large Igneous Province (the SCLIP)* Torsvik et al., (in review) - abstract

APPENDICES (CD attached**)**
A. (To be) submitted/in review papers
1. *Integrated Crustal Thickness Mapping & Plate Reconstructions for the High Arctic,* Alvey et al. (in prep)
2. Plate tectonic reconstructions predict part of Hawaiian hotspot track to be preserved in Bering Sea, Steinberger and Gaina (submitted to Geology)
3. *The Extrusion of Alaska: Past, Present, and Future,* Redfield and Scholl (in prep)
4. *North Atlantic fits with implications for the Barents Sea* Torsvik et al., (in prep)
5. *Middle Miocene Ice Sheet Expansion in the Arctic – Views from the Barents Sea,* Knies and Gaina (submitted to Geology)
6. *The effect of the large-scale mantle flow field on the Iceland hotspot track* Mihalffy et al., (in press)
7. *Breakup and early seafloor spreading between India and Antarctica in the light of new data: a Mesozoic magnetic anomaly sequence and an extinct spreading center in the Enderby Basin, Antarctica,* Gaina et al., (JGI, in review)
8. *Large Igneous Provinces generated from the margins of the large low velocity provinces in the deep mantle*, Torsvik et al (GJI, in press)
9. *Global plate motion frames: Toward a unified model* Torsvik et al., (ESR, in review)
10. *Long term stability in deep mantle structure: Evidence from the ~300 Ma Skagerrak-centered Large Igneous Province (the SCLIP)* Torsvik et al., (in review)

B. GIS format revised Arctic/North Atlantic/South Atlantic COBs and tectonic feature outline

This compilation of papers reflects the studies that have been undertaken by the GEODYNAMICS group in order to address the following objectives of the FRONTIER SCIENCE AND EXPLORATION: THE ATLANTIC – ARCTIC project:

- Refine Plate Reconstructions and Basin Evolution models
- Identification and Characterization of Continental Ocean Boundaries
- Interpreting Relationships between Large Igneous Provinces and Plate Tectonics in the Atlantic-Arctic
- Age and distribution of LIPs
- Origin and stability of hotspots
- Deep mantle vs. shallow sources

1. ARCTIC

1.1. Introduction

The tectonic evolution of the Arctic represents a challenge for the geodynamic community because of his remoteness and complicated history. Significant constraints could be placed upon the development of the margins of Alaska's North Slope, the Canadian Arctic Islands, the East Siberian platform, Barents Sea and other areas. Because the physical confines of the circum-Arctic are small, their histories are inter-related: for example, reconstructing the history of the Canada Basin requires an understanding of the plate trajectories of the continental Chuckchi Borderlands and Northwind Ridge crustal bodies as well as the closure of the ancestral South Anyui Ocean. Given the vast petroleum potential of the entire Arctic region ~ recently estimated by to be some 25% of the world's remaining resources ~ the wild cards posed by the Amerasian basins must be addressed as fully as possible.

1.2. Regional Setting

The Arctic Ocean itself can be physiographically divided into the *Eurasian* and *Amerasian* basins, separated by the Lomonosov Ridge (Fig. 1.2.1.). Well-preserved magnetic lineations are interpreted to have formed as an extension of Atlantic mid-ocean spreading on the Gakkel Ridge between 57-55 Ma and the present day (Gaina et al., 2002; Brozena et al., 2003). The Amerasian basin may be subdivided into the *Makarov*, *Podvodnikov*, and *Canada* Basins. Here, geophysical and geological data remain sparse. Many data are difficult to interpret unequivocably: for example, marine magnetics display complicated, commonly conflicting patterns. Only in the Canada Basin can linear magnetic fabrics be interpreted as isochrons, but their exact ages are difficult to interpret (Grantz et al., 1998, Lane, 1997, Grantz, 2006).

In the Amerasian basin there are several bathymetric highs of continental nature (Northwind Ridge and Chucki Plateau) and of controversial nature (i.e. volcanic overprinted oceanic or continental, Alpha-Mendeleev Ridge).

The Arctic Ocean passive margins formed either in the Late Jurassic-Cretaceous (North America, Canada and East Siberia) or Early Tertiary (Barents/Kara Sea). The Barents and North Kara margins preserve a prolonged pre-breakup depositional history spanning almost the entire Paleozoic and Mesozoic, resulting in generous sedimentary basins with considerable hydrocarbon potential. Along the North American margin (Sverdrup Basin and Beaufort Sea), Late Paleozoic-Mesozoic passive margins with proven Mesozoic source rocks in sedimentary basins were affected by Late Cretaceous-Tertiary compressional regimes. New geophysical data from the Chukchi Sea have been controversially interpreted to suggest that it has a similar tectonic history as the Northern Alaskan/Beaufort Sea region (Grantz et al., 1998). The least explored margin is the East Siberian margin; located at the boundary between the Tertiary Eurasian Basin and Laptev Sea shelf and the enigmatic Amerasian Basin, its history is also highly controversial (Lawver et al., 2002; Miller et al., 2006).

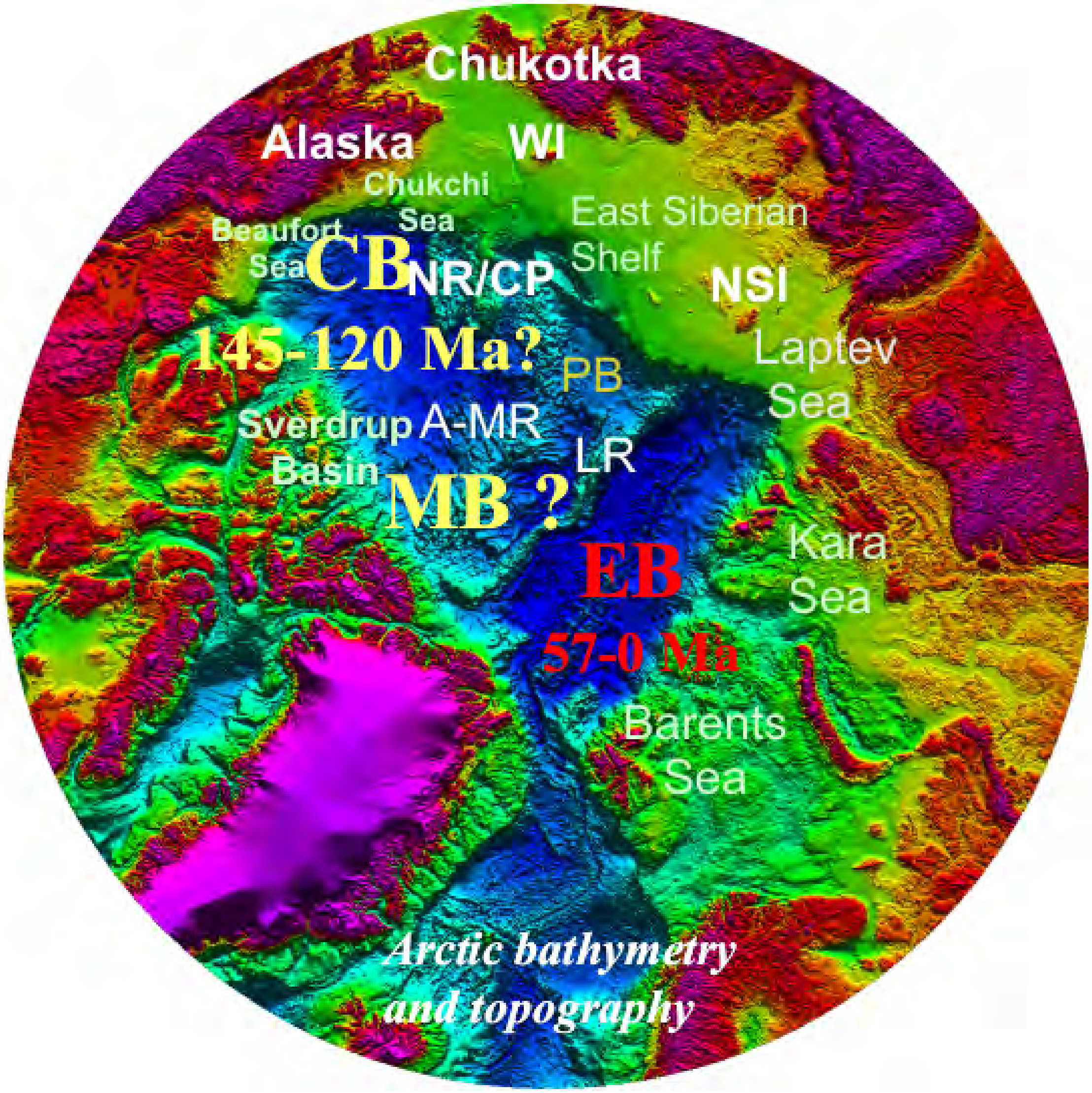


Fig. 1.2.1: Arctic present day bathymetry (Jakobsson et al. 2003) drapped on Arctic free air gravity (ArcGP project, 2001). Abbreviations: CK – Chukotka, NWR-Northwind Ridge, NR/CP-Northwind Ridge Chucki Plateau, MR – Mendeleev Ridge, LR-Lomonosov Ridge, A-M R – Alpha Mendeleev Ridge, NSI – North Siberian Islands, AB – Amerasian Basin, EB – Eurasian Basin, MB– Makarov Basin, PB – Podvodnikov Basin.

1.3. Review of tectonic models for oceanic areas

Three major oceanic basins are preserved in the present day Arctic region: the Canada, Makarov and Eurasian basins (Fig. 1.2.1.). A summary of our current understanding of the tectonic evolution of these basins and adjacent areas is presented below.

Amerasian Basin (Canada and Makarov basins)

Before the opening of the Canada Basin, an older oceanic basin, the South Anyui Basin, occupied the area between the North American and North Eurasian margins. This basin was gradually consumed by subduction along the South Anyui (N Siberia) subduction zone until the Chukotka plate in NE Russia collided with Siberia (e.g. Sokolov et al. 2002). The most commonly accepted model for explaining the opening of the Canada Basin involves counterclockwise rotation of Arctic Alaska away from the Canadian Arctic islands (Carey 1955), although a more unconventional model, like a trapped Pacific crust (Churkin & Trexler 1981), has also been postulated. The rotational model is based on paleomagnetic data (Halgedahl & Jarrard 1987), stratigraphic studies of the North Slope and Sverdrup basin margins, and a fan-shaped magnetic pattern observed in the southern Canada basin. New paleomagnetic data presented by Lewchuk et al. (2004) also concludes that the North Alaska terrane might have been involved in rotation during the opening of the Canada basin. However, in modern reviews of the age and geology of the rifted margins (i.e. North Slope of Alaska and Canadian northern margin), and more recent studies on the stratigraphy of Northwind Ridge, Lane (1997) and Grantz et al. (1998) proposed more complex models that include orthogonal or strike-slip motion, combined with a rotation in the later stages of opening. These models differ in the proposed age of opening (Early-Mid Cretaceous – Granz et al. 1998 vs. Late Jurassic-Late Cretaceous - Lane, 1997). A new study by Miller et al. (2006) used detrital zircon data to show that the Chukotka microplate originated closer to the Taimyr and Verkhoyansk and not from the Canadian Arctic, therefore experiencing only a small, local rotation and translation during the opening of the Amerasian Basin.

In the oceanic Makarov basin, the seafloor spreading record has been largely obstructed by volcanism. Despite the complexity of this region, there are few studies that debate the age of the Makarov Basin. Weber and Sweeney (1990) suggest an age between 118 and 56 Ma, Mickey (1998) 95 to 67 Ma, and recently, Lebedeva-Ivanova and Gee (EGU abstract, 2005) suggests a Cretaceous age for the Makarov Basin interpreting the Arlis Rise as an extinct spreading center 128 Ma old.

Eurasian Basin

Well-preserved magnetic isochrons that are relatively easy to identify have allowed a straightforward interpretation of the Eurasian Basin. Most authors have identified chron 24 (c. 54 Ma) as the oldest magnetic isochron, spawned by seafloor spreading between the Lomonosov Ridge and the Eurasian margin. Other studies have identified an abandoned extinct ridge (c. 55 Ma) in the proximity of Lomonosov Ridge. If correct, this structure implies that the opening of the Eurasian Basin may was linked to the evolution of Baffin Bay and the Labrador Sea (Brozena et al. 2003). This additional plate boundary might also have acted as a paleo-gateway between the Arctic and the Labrador Sea.

Evolution of oceanic plateaus and ridges

Numerous plateaus and ridges are distributed throughout the two Arctic basins. Northwind Ridge and Chukchi Borderland have been identified as slivers of continental origin rifted from the Canadian margin. Data from cores collected from the southern Northwind Ridge show that Triassic and older strata were attached to both Arctic Canada and Alaska prior to the rifting that created the Canada Basin. Younger sediments show that this continental sliver was isolated in Early Jurassic (Grantz et al. 1998). Northwind Ridge later underwent Paleocene uplift, perhaps related to relative convergence, while extension relative to the Chukchi Borderland created the Northwind basin.

The nature of both the Alpha and Mendeleev Ridges remains speculative, extensive volcanism having overprinted and complicated their original geophysical signatures. Maastrictian fossils have been recovered (Clark 1980), providing a minimum age constraint for the Alpha Ridge. Volcanic material of mid-Cretaceous age has been described from the Alpha-Mendeleev Ridge, leading Lawver & Müller (1994) to postulate a 'hotspot' origin. However, material recovered from piston cores show MORB affinity (Jokat 2003), suggesting a fundament of oceanic crust. Recently, Kaminsky et al. (2005) and Lebedeva-Ivanova et al., (2006) presented new seismic data acquired on Mendeleev Ridge, claiming a continental origin. If confirmed, Mendeleev Ridge could be another continental block that rifted away from the northern American margin, further complicating the geometry of the reconstruction and its role in the opening of Arctic.

The western boundary of the Eurasian margin, the Lomonosov Ridge, indisputably rifted away from the northern Barents Sea during the Paleocene (c. 55 Ma). However, other bathymetric highs remain controversial. Similar to Mendeleev, the Yermak and Morris Jessup plateaus, located in the southern Eurasian basin, have been described as volcanic constructs with a possible hotspot origin. However, from seismic data Jokat (2003) showed that at least the southern part of the Yermak Plateau is continental material, again placing definite spatial constraints upon Arctic paleogeography.

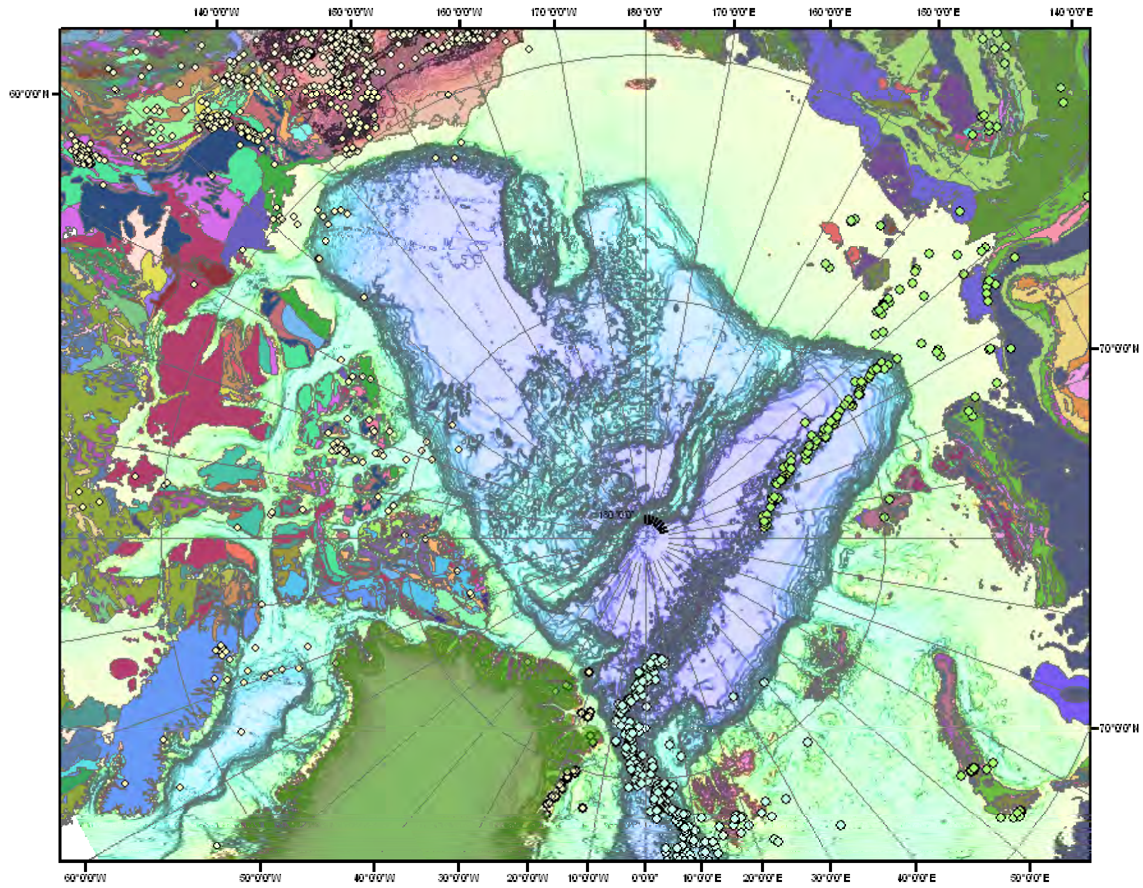


Fig. 1.3.2. Bathymetry of the Arctic region (Jakobsson et al., 2003), geological provinces and seismicity (USGS compilation, Hearn et al., 2003)

Based on new datasets (gravity and magnetics) and new studies published on the origin and evolution of Amerasian and Eurasian margins, we propose a novel model for the evolution of the High Arctic oceanic areas.

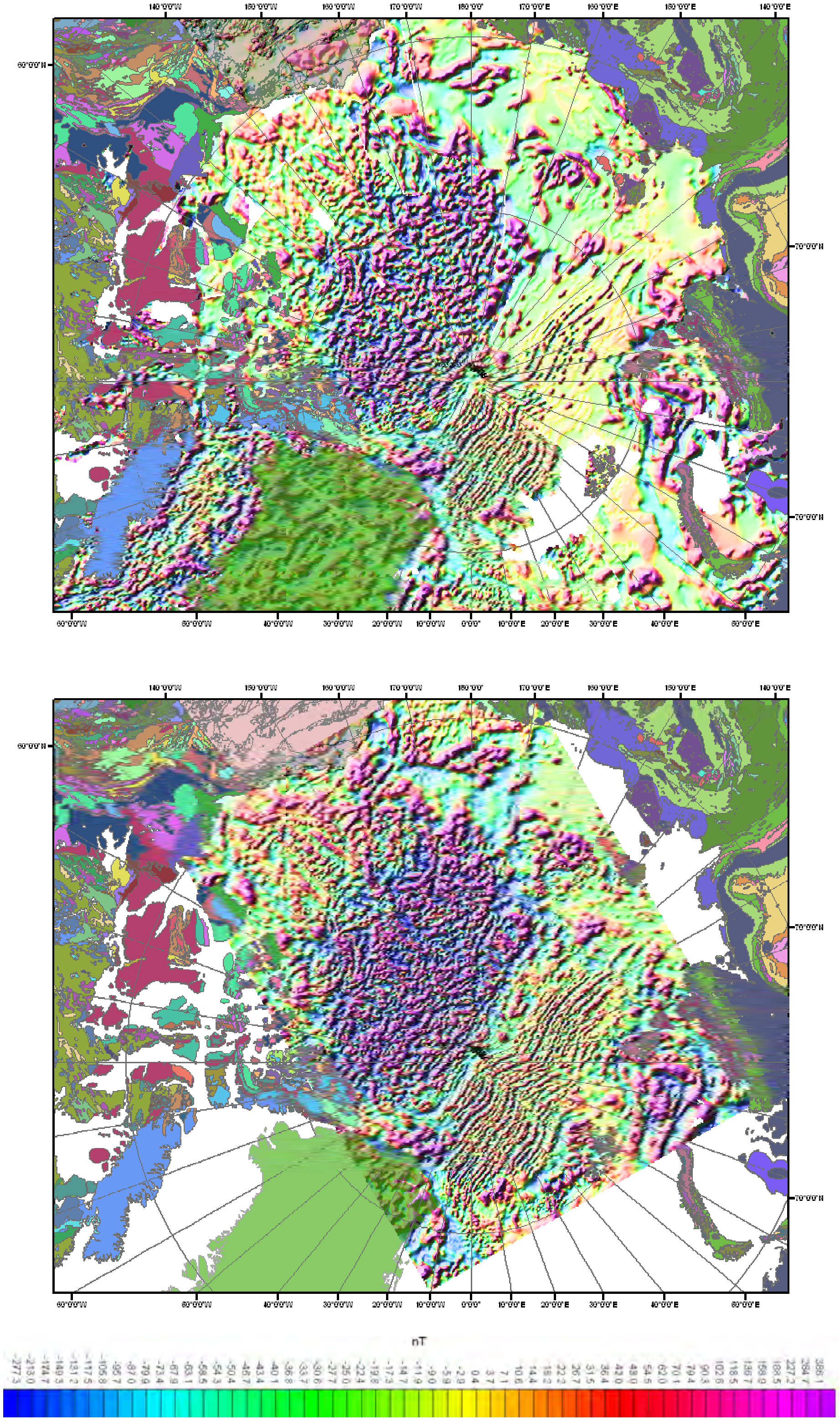


Fig. 1.3.3. Gridded magnetic data of the Arctic –upper image Verhoef et al., 1997, lower image Glebovki et al., 1998, 2000)

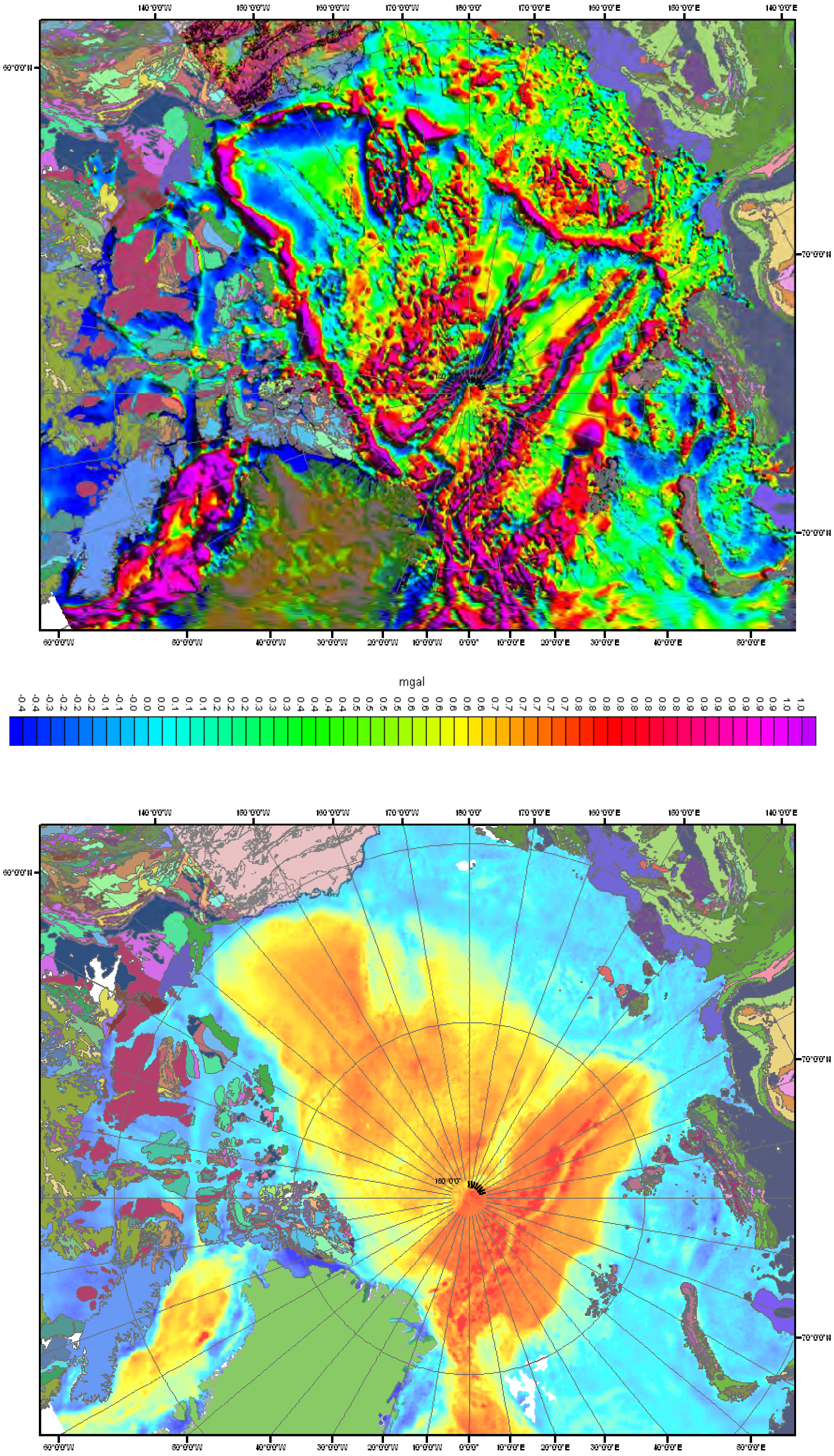


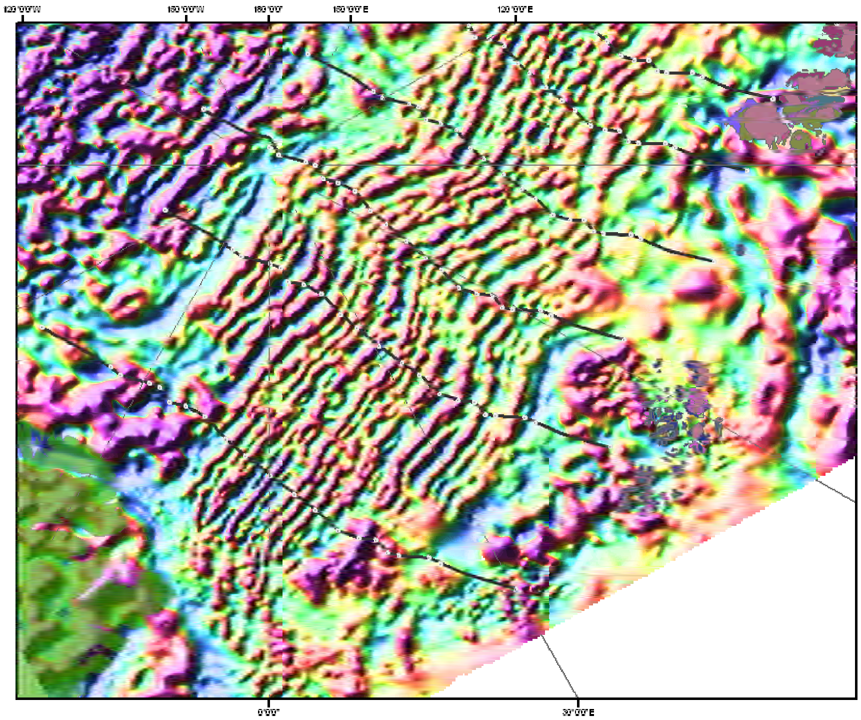
Fig. 1.3.4. Free air gravity (ArcGP gravity project) and Bouguer anomaly for the Arctic region

1.3.1.Eurasia Basin

Magnetic data

We have used both the Verhoef et al., (1996) and Glebovsky (2000) magnetic gridded data (5x5 km) to re-interpret the magnetic anomaly patterns in the Eurasia basin. For chrons 5-24b we have guided our interpretations on the Gaina et al., (2002) identifications for the southern part of basin (where line data was available). Isochrons in the northern part of the basin are based on the Glebovsky et al. (2000) gridded data and flowlines computed from the Gaina et al., (2002) model (see fig. 1.3.1.1.).
The new compilation of Russian and American magnetic data (Glebovsky et al., 2000 and Brozena et al., 2003) highlights an additional normal magnetic stripe in the southern part of the Eurasian Basin on both Lomonosov Ridge and Eurasian margins that has been identified as chron 25 by Brozena et al., (2003). Although they claimed that the identification of cron 25 on the Eurasian margin could not be clearly discerned due to an early ridge jump, their interpretation lacks the conjugate chron 25 on the Lomonosov Ridge.

Our model for the evolution of the Eurasian margin suggests that the Lomonosov Ridge was a separate plate during the early opening of the basin (chron 25-24b time). As no seafloor spreading magnetic anomaly has been recorded in the Greenland Sea at chron 25 time, the opening of the Eurasian Basin might have been connected to the Labrador Sea spreading system (although the magnetic record in the Baffin Bay is hard to interpret) as Brozena et al. (2003) also argued.



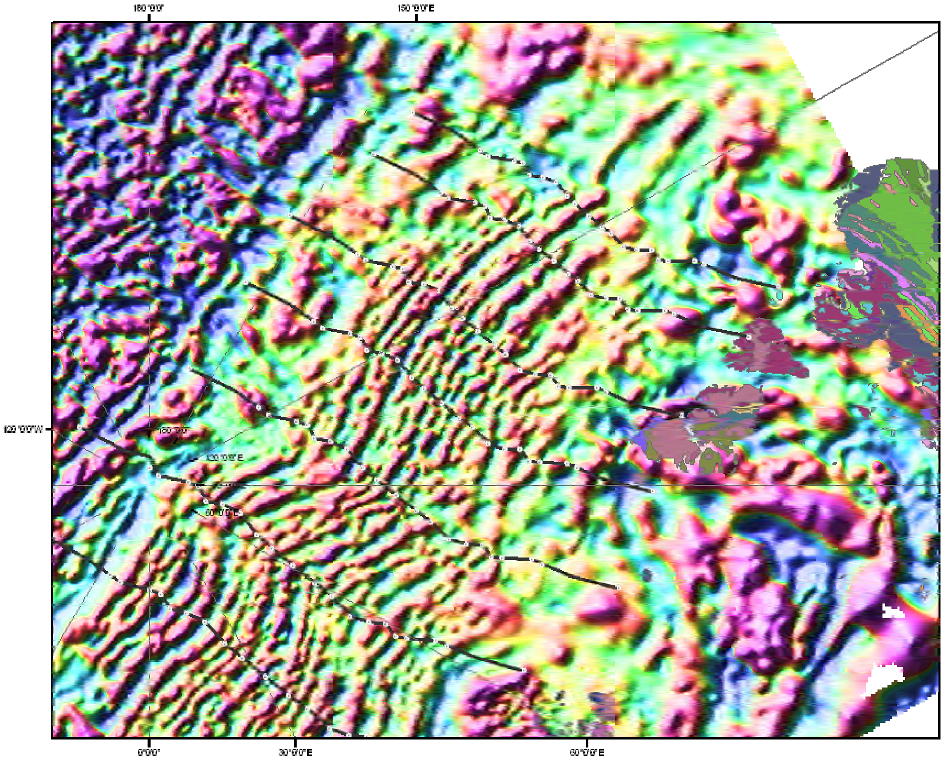


Fig. 1.3.1.1. Gridded magnetic data (Glebovski et al., 2000) and flowlines (south of Eurasia Basin –upper figure, north of the basin lower figure) from chron 26 to present day based on our kinematic model for the Eurasian Basin (Lomonosov Ridge is considered a separate plate after break-up until chron 24 old time – i.e. from 57 to 53.3 Ma).

Gravity data

The Arctic Gravity Project (ArcGP) gridded data has been used to compute the Bouguer anomaly and a series derivatives in order to better define the transition between the continental and oceanic crust.

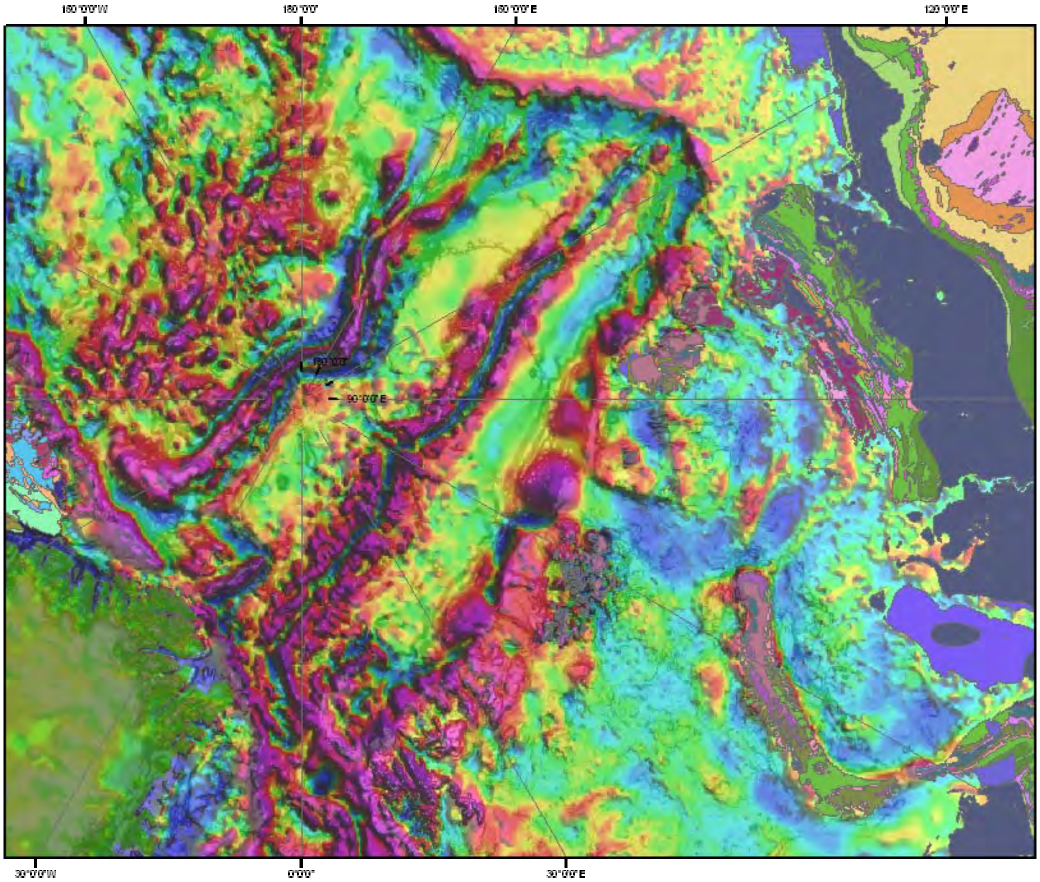


Fig. 1.3.1.2. Free air gravity data (ArcGP) draped on the Arctic bathymetry (Jakobsson et al., 2003). Note that Lomonosov Ridge seems to have several distinct tectonic blocks (gravity highs separated by pronounced gravity lows).

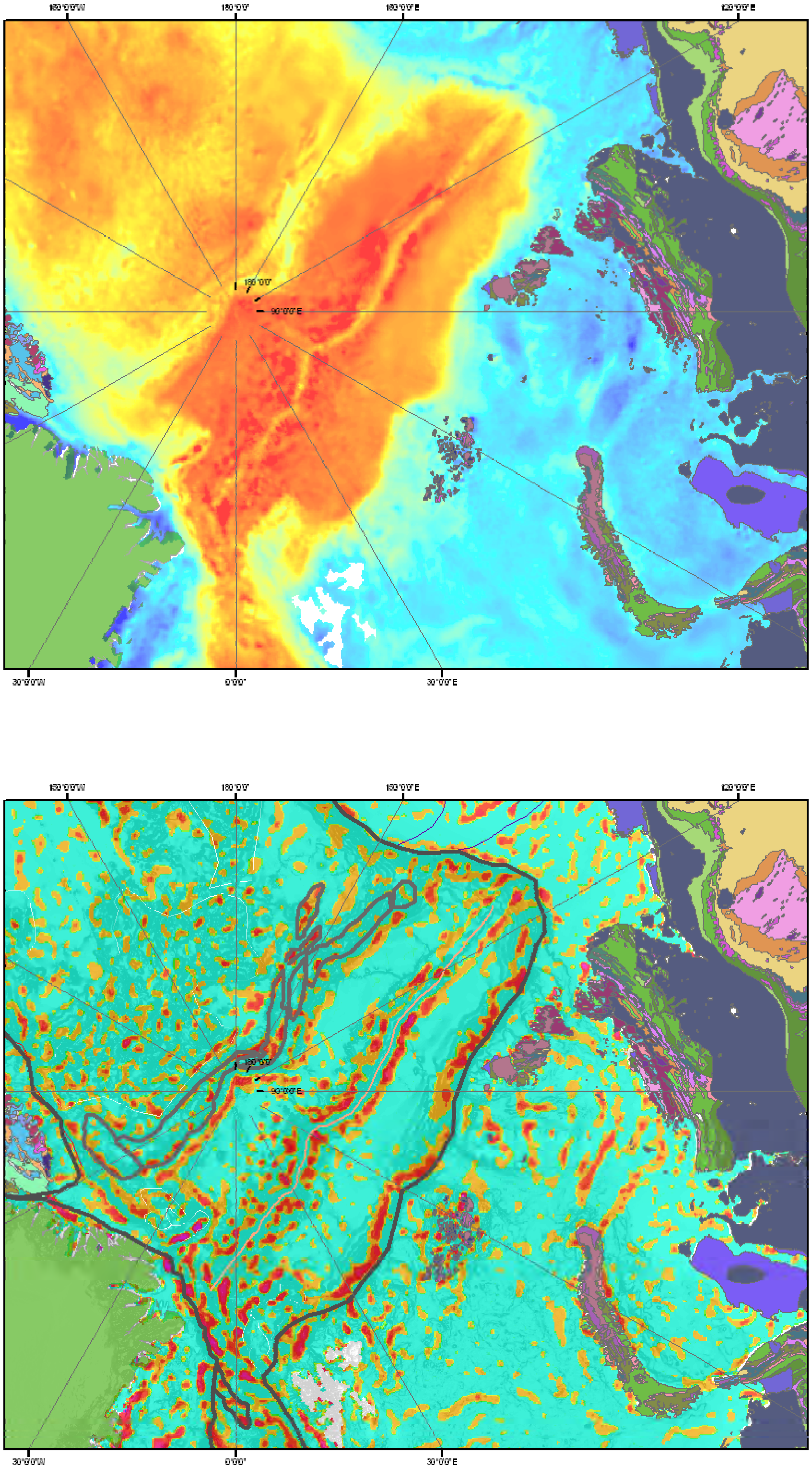


*Fig. 1.3.1.2.*Eurasian Basin – Bouguer anomaly and second derivative of upper continued gravity residuals. Thick gray lines show the present study continent ocean boundary.

Canada Basin

Lawver et al., (AGU 1999) described a new set of aeromagnetic data acquired in the Canada Basin and Brozena et al., (1999) suggested a three stages opening that would have formed a more complex pattern of magnetic lineations than the previously accepted fan-shaped evolution. However, they claim that this basin opened by the rotation of the Alaskan North Slope and the attached Northwind and Chucki Borderland. In a recent abstract, Grantz (2006) proposes that the Amerasian basin is the product of two phases of anti-clockwise rotation: one that produced transitional crust between 195 and 131 Ma, followed by a period of seafloor spreading between 131 and 127.5 Ma.

We have analysed the gridded magnetic data from the Canadian Basin and adjacent margins and modelled the following successions of events that led to the formation of the present day oceanic crust in the Canada basin:

- Pre-breakup extension before 145 Ma
- Seafloor spreading between 143 and 126 Ma (see Table 1 for finite rotation poles) by rifting the Alaskan Northern Slope off the Canadian Margin
- Convergence between the Northwind Ridge and northern part of the Canada basin

Age of rifting

Grantz et al. (1990) list a series of events recorded in the Jurassic-Early Cretaceous that formed rifted margins on both Alaska Beaufort shelf and Banks Island of the Canadian Beaufort margin. This seem to be contemporaneous with uplift and deformation in the region of the present central southern Brooks Range that records an initial stage of subduction of the North American plate beneath the intraoceanic Koyukuk arc (Box and Patton, 1987). However, numerous stages of deformation of the Brooks Range from the Jurassic toTertiary and their correlations with the North Pacific tectonics cannot be directly related to the inferred ages of break-up and seafloor spreading in the Canada Basin. In addition, Late Cretaceous tectonic instability recorded within the Beaufort Sea margins (Dixon and Dietrich, 1990) led to the conclusion that either seafloor spreading in the Canada Basin is younger (Mid to Late Cretaceous) or spreading continued until Late Cretaceous (Lane, 1997).

Age of SouthAnnyui suture

It has been suggested that the (Jurassic ?) South Anyui Ocean that formed north of the Siberian Craton and North American margin has been completely subducted due to the opening of the Amerasian Basin and collision of several terranes (among them Chukotka) with the Northern margin of the Eurasian plate. This is documented by the South Anyui suture that can be traced by ophiolite emplacements from the Chukotka peninsula to the East Siberian Islands. The age of the collision was estimated to be Mid Aptian (Sokolov et al., 2002); new Ar/Ar dating gave a 117-124 Ma age to the collision related deformation recorded in the Chokotka peninsula (Toro et al., 2003).

Magnetic data

As the magnetic record in the Canada Basin show a complex pattern one could infer at least two different stages of oceanic crust formation (Fig. 1.3.2.1 and 1.3.2.3.). An earlier fan-shaped magnetic lineations seem to be gradually replaced by parallel isochrons that would indicate the change in the pole of opening to a more distal place. The northwestern part of the basin, proximal to the Northwind Ridge show a deformed zone that is probably due to a later clockwise rotation of this ridge (Fig. 1.3.2.3).

The age of the magnetic lineations could be inferred only in conjunction with the geology of the margins and tectonic events succession. Considering that break-up occurred around Late Jurassic-Early Cretaceous and seafloor spreading ceased in the Aptian, then the most prominent normal polarity magnetic lineations could be identified as chrons M17, M16, M14, M10 and probably M5. Grantz (GSA abstract, 2006) proposed seafloor spreading occurring only between 131 and 127.5 Ma, which would result in an unrealistically high spreading rates (about 200 mm/yr). The magnetic pattern does not record the Aptian-Campanian Cretaceous Normal Superchron (CNS), therefore we argue that seafloor spreading probably ceased in Early Aptian as a result of the North Asian collision.

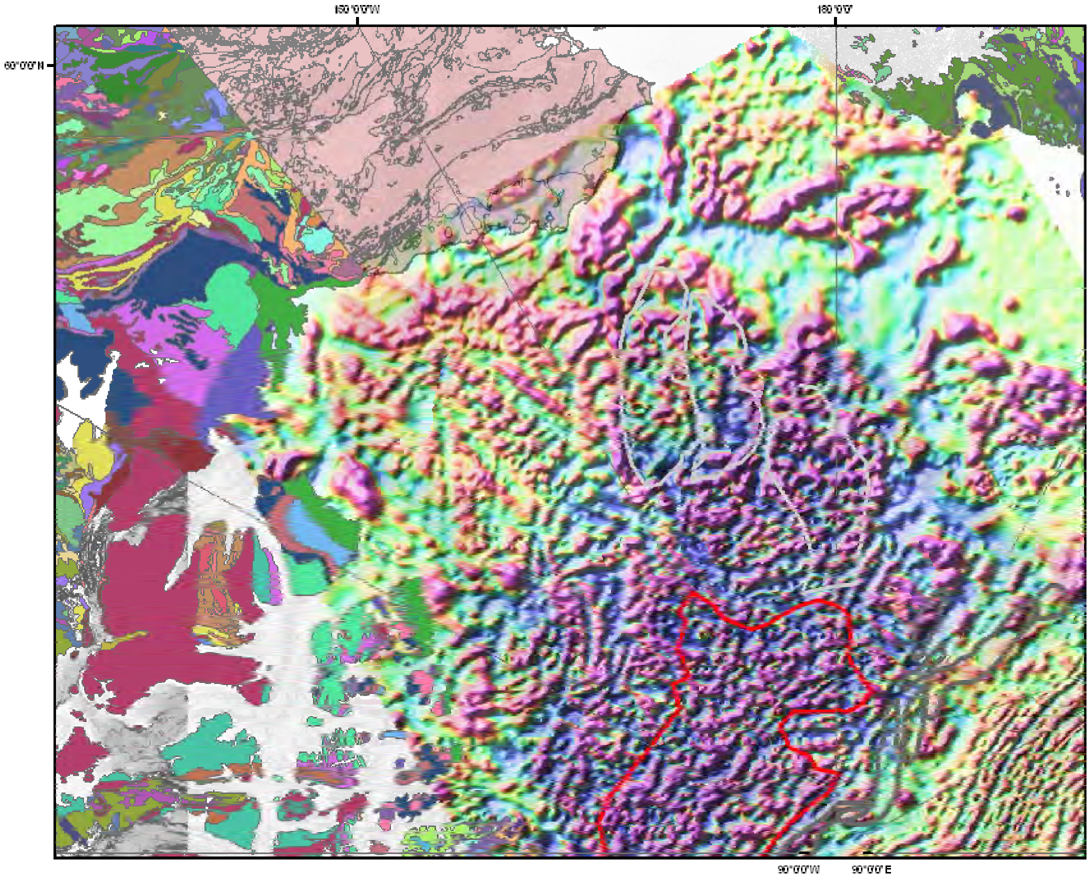


Fig. 1.3.2.1. Amerasian Basin – Magnetic anomaly grid (Glebovski et al., 2000). Grey lines outline the location of continental fragments, red line show the extent of the volcanic Alpha Ridge.

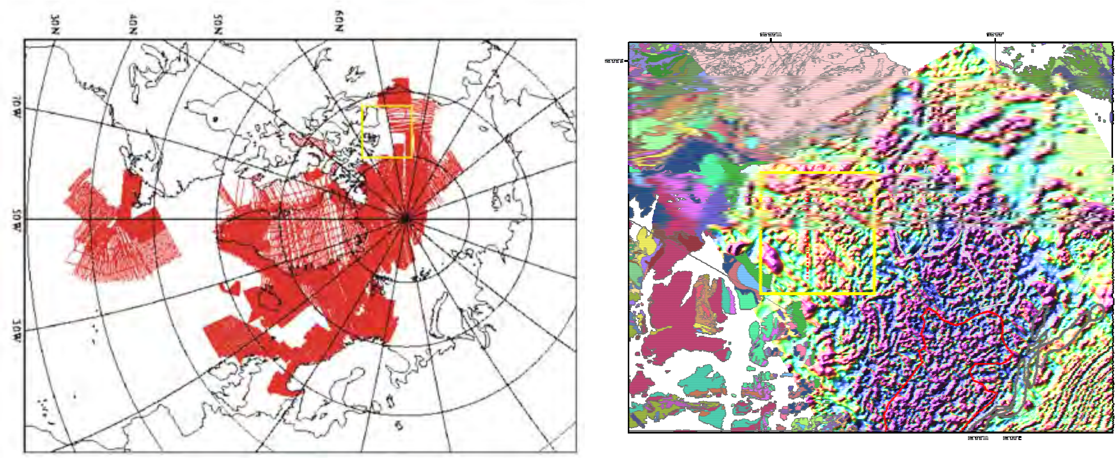


Fig. 1.3.2.2. Left-Location of aeromagnetic surveys in the Arctic-North Atlantic (GSC report).. Right-gridded magnetic data in the Canada Basi. Note the artifacts generated by the interpolation of data in the area poorly covered that cross he extinct ridge and magnetic lineations area. Yellow box shows the coverage of data in the Canada Basin.

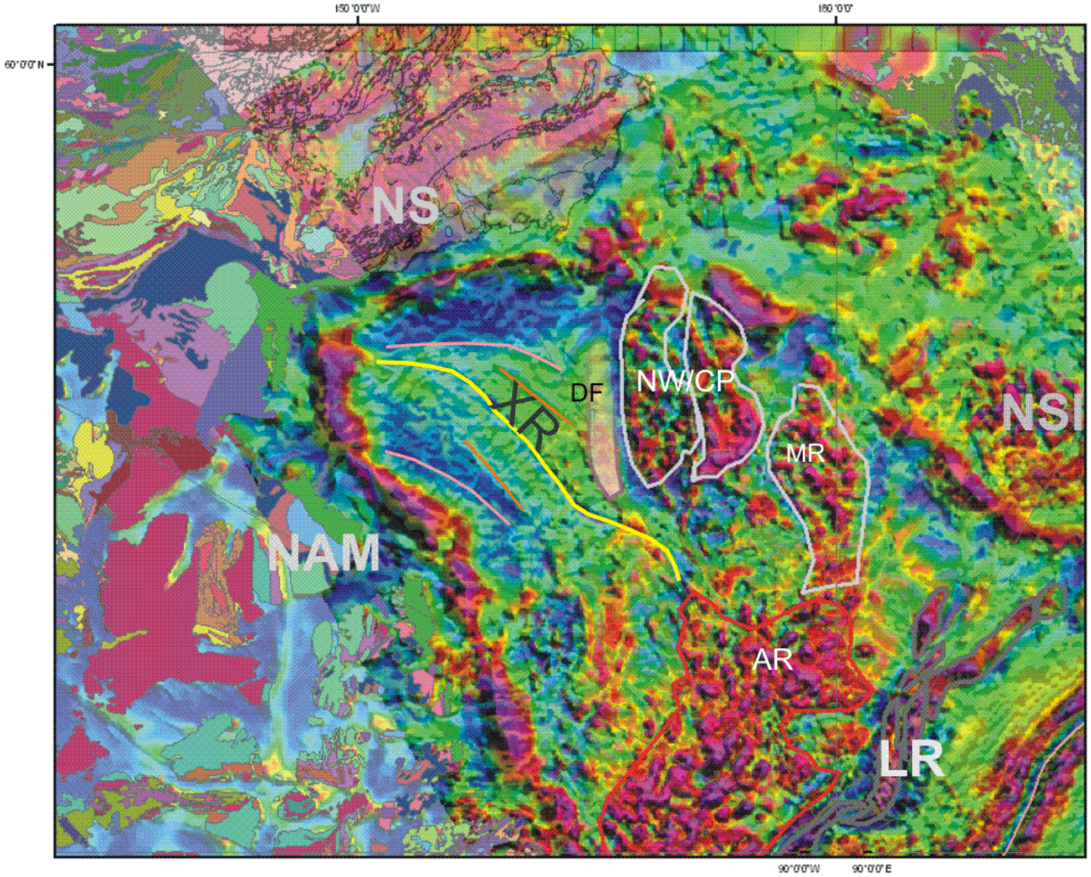


Fig. 1.3.2.3. Amerasian Basin – Free air gravity anomaly draped on gridded magnetic anomaly grid (Glebovski et al., 2000). Grey lines outline the location of continental fragments(NW/CP – Northwind/Chucki Plateau, MR – Mendeleev Ridge, LR-Lomonosov Ridge), red line show the extent of the volcanic Alpha Ridge (AR). NSI is New Siberian Islands, NS is the North Slope (N Alaska) and NAM

is the north American plate. A prominent low in the gravity data is interpreted as the extinct ridge in the Canada Basin, the magnetic lineations in the Canada Basin show 2 distinct trends (light pink and orange lines). Between the Northwind/Chucki Plateau and the oceanic crust in the Canada Basin a deformed zone (DF) was probably formed after (or shortly before) the extinction of the spreading ridge in this basin.

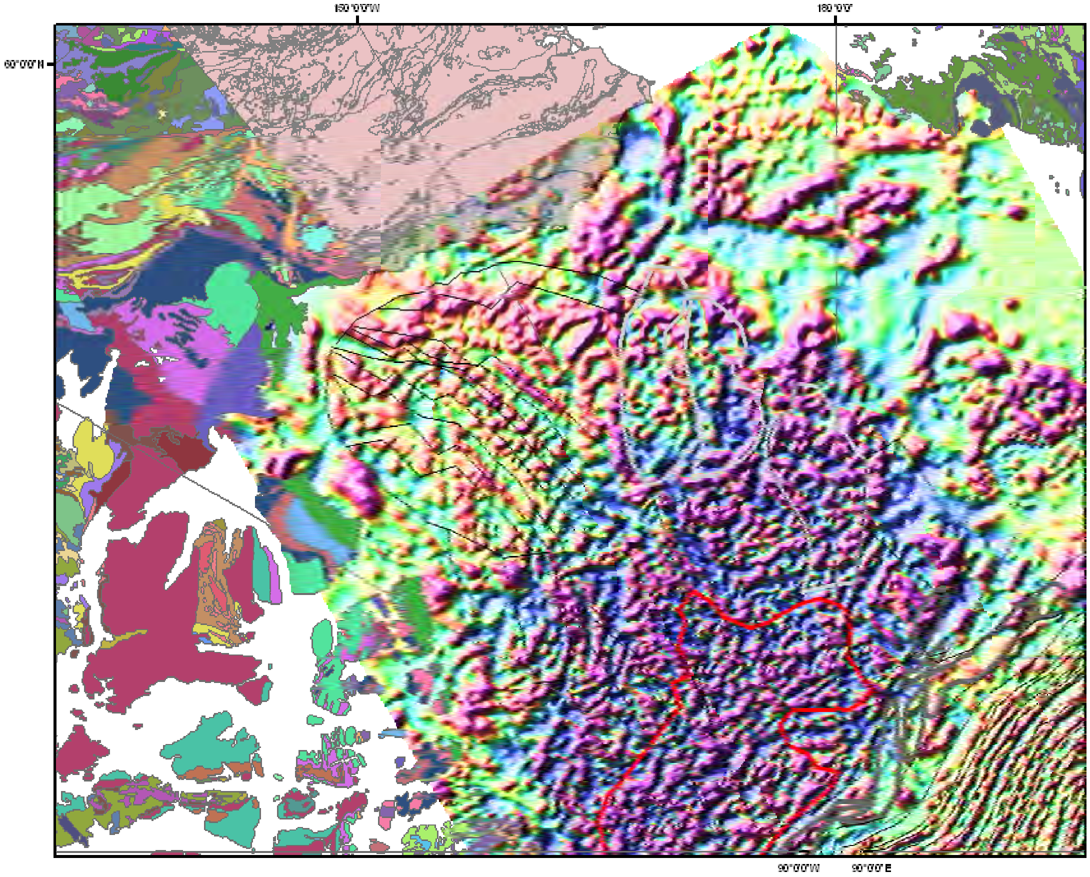


Fig. 1.3.2.4. Amerasian Basin – Gridded magnetic data and interpreted isochrons (thin black lines).

Table 1. Rotation parameters for the opening of the Canada Basin

Age[Ma]	***Lat***	***Lon***	***Angle***
145.0	65.0	-130.2	-34
142.5	65.0	-130.2	-30
139.6	65.0	-126.0	-10
136.5	60.0	-126.0	-6.5
132.0	60.0	-126.0	-3.0
126.0	0.0	0.0	0.0

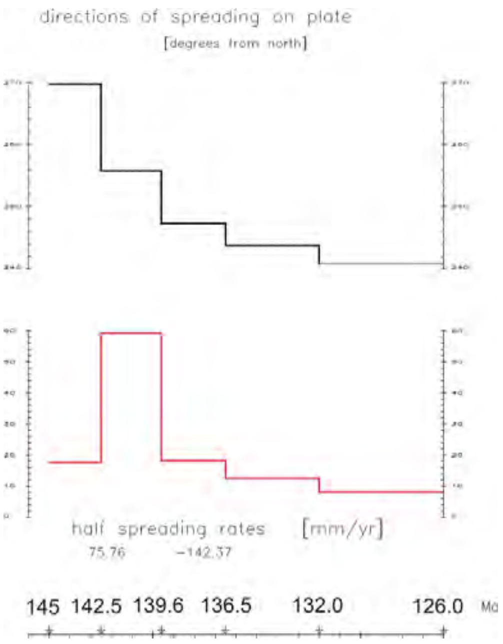


Fig. 1.3.2.5. Direction and rates of seafloor spreading in the Canada Basin. Note the high rates between 142.5 and 139.6 Ma that coincide with a change in the spreading direction as observed in the magnetic lineations. This period seems to be characterised by asymmetrical seafloor spreading. Alternatively, a ridge jump might have taken place, but the resolution of magnetic data is insufficient for a detailed analysis.

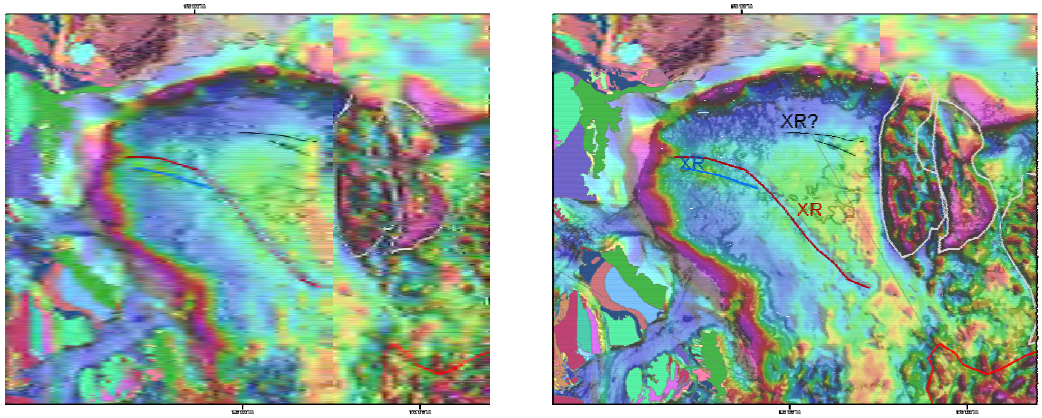


*Fig. 1.3.2.6.*Canada Basin: Free air gravity grid (ArcGP) draped on bathymetry grid (Jakobssons et al., 2003). Dark red line indicates a gravity low that could indicate the presence of an exinct ridge, the blue line is a bathymetric low offset from the gravity low, and the thin black lines show a feature visible in the bathymetric data located between isochrons dated 142.5 and 139.6 (possible extinct ridge?).

North Amerasian Basin (including Makarov/Podvodnikov basins)

Jakobsson (2003) identifies in the present day bathymetry of the Amerasian Basin several basins: Stefansson and Nautilus basins in the NE and NW of Canada Basin, the Fletcher Abyssal plain and Wrangel Basin between the Alpha-Mendeleev Ridge and Lomonosov Ridge (known as Makarov and Podvodnikov in the Russian literature). Several authors treated the Podvodnikov basin as a contiunuation of the Makarov basin.

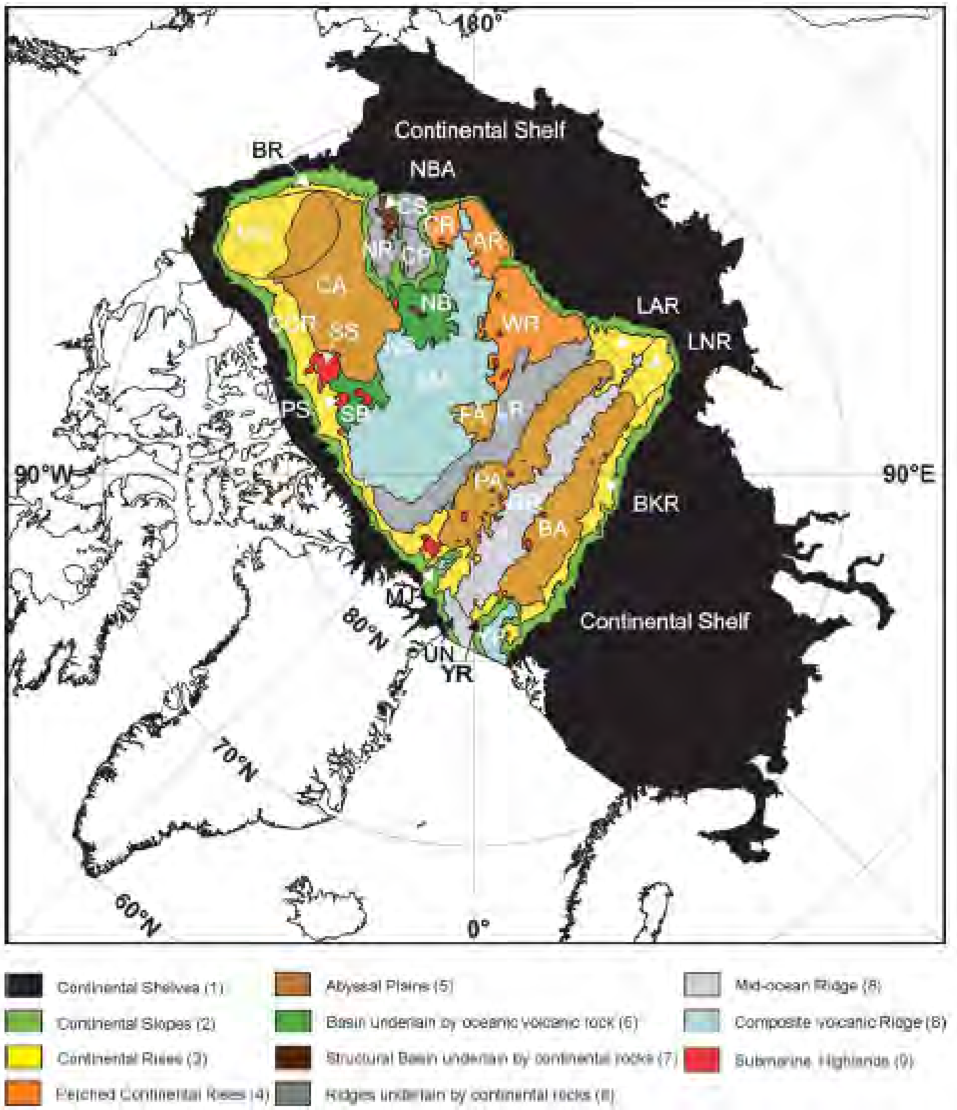


Fig. 1.3.2.7. Bathymetric provinces in the Arctic Ocean (from Jakobssons et al., 2003).

Since recent studies show evidences for a continental crust underlying at least part of the Mendeleev Ridge (Lebedeva-Ivanova et al., 2006), and it has been suggested that the Chukotka tectonic unit has not been rifted from the northern North American margin, then most probably the Amerasian Basin has been created by rifting the Northwind-Chucki Borderland and Mendeleev Ridge. Most of the Eastern Siberian Shelf, including the New Siberian Islands could also be a terrane with North American origins, but the lack of detailed information (except the fact that it collided with the Siberian Craton probably in the Aptian) makes it difficult to include it in the plate tectonic reconstruction. Miller et al., (2006) suggest that this unit experienced 100% stretching.

Our model proposes that an older piece of oceanic crust remained attached west of the continental Mendeleev Ridge and is now flooring part of the Podvodnikov basin. Most of the crust that was latter (Mid Cretaceous ?) heavily intruded by volcanic material is interpreted to be Early Cretaceous oceanic crust formed between the Northwind-Chucki

Borderland-Mendeleev Ridge and Sverdrup basin margin. The amount of seafloor spreading and its direction has been inferred from the overall arhitecture of the Amerasian Basin and some lineations in the magnetic gridded data that could be followed parallel to the Mendeleev Ridge and Sverdrup basin margin. A period of Tertiary extension that precluded the opening of the Eurasian Basin might have formed small basins between the northern Lomonosov Ridge and the older oceanic crust.

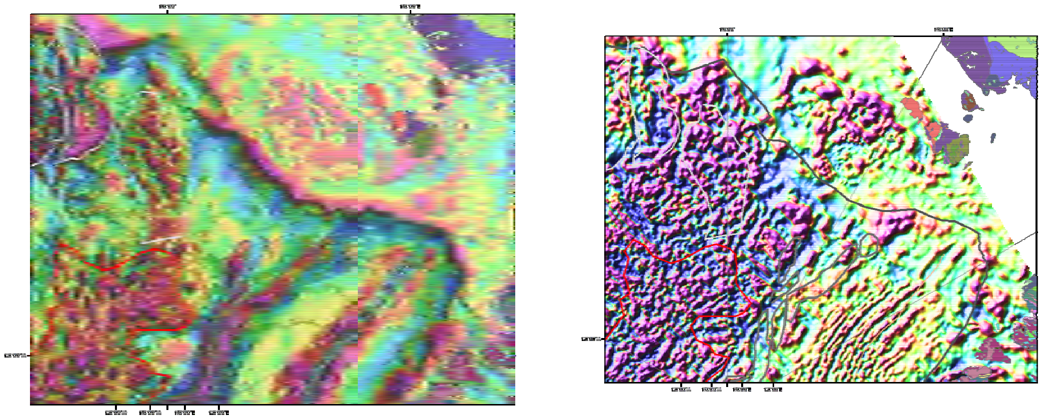


*Fig. 1.3.2.8.*Podvodnikov Basin: Free air gravity draped on bathymetry (left) and magnetic anomaly grid (right).

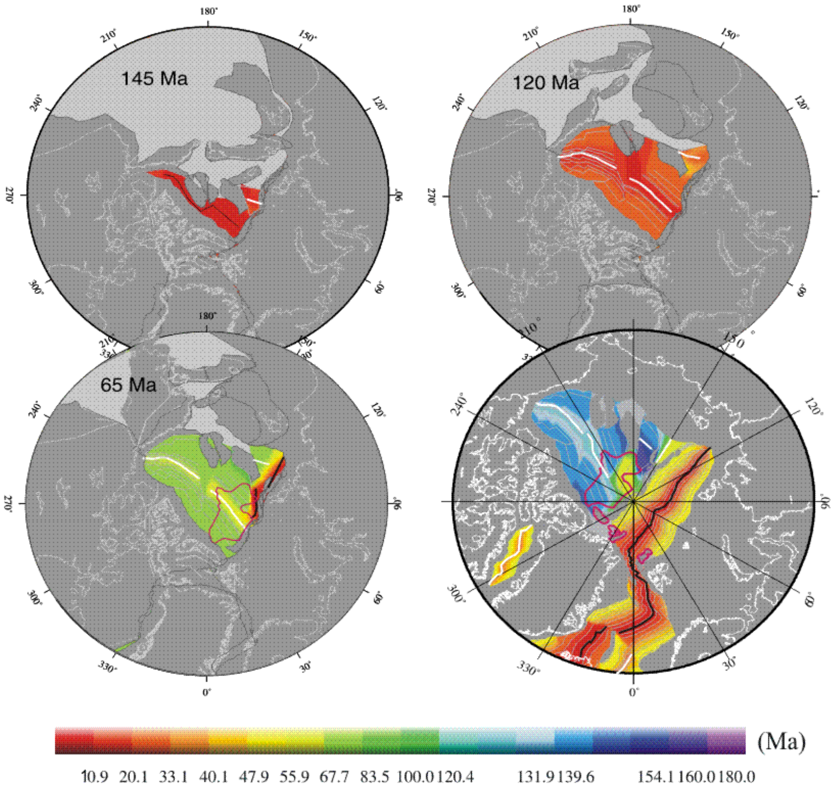


Fig. 1.3.2.8.. Palaeo-age grids for the oceanic Arctic region. Black lines are active mid-ocean ridges (MOR), white lines are extinct MOR, magenta outlines the volcanic features (shape and size are digitized from the present day free air gravity and bathymetry gridded data).

1.3.3. *Integrated Crustal Thickness Mapping & Plate Reconstructions for the High Arctic*, Alvey et al. (in prep) – abstract

The plate tectonic history of the Amerasia Basin (High Arctic) and its distribution of oceanic and continental lithosphere is poorly known. A new method of gravity inversion with an embedded lithosphere thermal gravity anomaly correction has been applied to the NGA (U) Arctic Gravity Project data to predict crustal thickness and to test different plate reconstructions within the Arctic region. The inversion of gravity data to map crustal thickness variation within oceanic and rifted continental margin lithosphere requires the incorporation of a lithosphere thermal gravity anomaly correction for both oceanic and continental lithosphere. Oceanic lithosphere and stretched continental margin lithosphere produce a large negative residual thermal gravity anomaly (up to -380 mGal), for which a correction must be made in order to determine realistic Moho depth by gravity anomaly inversion. The lithosphere thermal model used to predict the lithosphere thermal gravity anomaly correction may be conditioned using plate reconstruction models to provide the age and location of oceanic lithosphere. Three plate reconstruction models have been examined for the opening of the Amerasia Basin, two end member models and a hybrid model: in one end member model the Mendeleev Ridge is rifted from the Canadian margin while in the other it is rifted from the Lomonosov Ridge (Eurasia Basin), the hybrid model contains elements of both end member models. A crustal thickness of about 20 km is predicted for an Early to Mid-Cretaceous Makarov Basin which is similar to the value obtained from seismic refraction data (Lebedeva-Ivanova et al., 2006). We suggest that this method could be used for discriminating between various plate tectonic scenarios, especially in remote or poorly surveyed regions.

1.3.4. Bering Sea

1.3.4.1. *Plate tectonic reconstructions predict part of Hawaiian hotspot track to be preserved in Bering Sea*, Steinberger and Gaina (submitted to Geology) - abstract

We use plate reconstructions to show that parts of the Hawaiian hotspot track of about 80–90 Ma age could be preserved in the Bering Sea. Based on these reconstructions, the Hawaiian hotspot was beneath the Izanagi plate before about 83 Ma. Around that time, the part of the plate carrying the hotspot track was transferred to the Kula plate. By 75–80 Ma, the Hawaiian hotspot was overridden by the spreading ridge between Pacific and Kula plate and subsequently underlay the Pacific plate. Around 40-55 Ma, subduction initiated in the Aleutian trench. Part of the Kula plate was attached to the North American plate and is preserved as the oceanic part of the Bering Sea. We show that for a number of different plate reconstructions and a variety of assumptions covering hotspot motion, part of the hotspot track should be preserved in the Bering Sea. The predicted age of the track depends on the age of Aleutian subduction initiation. We speculate that Bowers and Shirshov Ridge may be the present–day expression of the Hawaiian hotspot track, which may have acted as a weak zone in the oceanic lithosphere that was subsequently re–activated as a shear zone.

1.4. Tectonic models for selected continental areas

1.4.1. Barents Sea

1.4.1.1. *Basin inversion in the eastern Barents Sea constrained by numerical models and plate reconstructions* (Buiter and Torsvik, in prep) – abstract

The eastern Barents Sea basins, west of Novaya Zemlya, were formed by multiple phases of extension, which occurred between the Ordovician and the Early Triassic. Mild folds in the basin sediments and large thrusts at the eastern margin of the basin (Novaya Zemlya) indicate that the region underwent shortening at a not-well constrained time between the Late Permian and Early Jurassic. It is assumed that Novaya Zemlya was thrust westward, but the magnitude of this compressive movement is not well known. Our aim is to provide an order-of-magnitude constraint on the amount of shortening associated with the displacement of Novaya Zemlya and the inversion of the eastern Barents Sea basins by combining numerical models and plate reconstructions in an iterative process. We use a 2D thermo-mechanical finite-element method to model inversion of a pre-defined basin. The total amount of shortening imposed on the models is first constrained by plate reconstructions for the Barents Sea region for the late Palaeozoic to early Mesozoic. The magnitude of the westward movement of Novaya Zemlya in these reconstructions is, however, highly uncertain due to the allochthonous nature of the rocks of the island and the scarcity of palaeomagnetic data in the region. By comparing the inversion obtained in the numerical models to the inferred inversion structures in the eastern Barents Sea basin we further constrain the amount of shortening that caused the inversion and therewith improve the plate reconstructions for the region. Our models indicate that the westward movement of Novaya Zemlya occurred in the Late Triassic-Early Jurassic (220-190 Ma) and was limited in magnitude (100-200 km), which is considerably less than previous (loose) estimates (500-700 km).

1.4.2. Alaska

1.4.2.1. *The Extrusion of Alaska: Past, Present, and Future,* Redfield and Scholl (in prep) - abstract

The north Pacific rim sector of western North America is constructed of a series of tectonostratigraphic terranes entrained within the continental crust of the north-central Canadian Cordillera, southern and central Alaska, and the Beringian shelf. Similar to other plate boundary zones (in particular those that involve crustal extrusion kinematics), the length and width of the Pacific rim crustal expanse is characterized by block rotations, structural complexity, and non-rigid internal and boundary-zone deformation. We suggest that the Pacific rim mobile belt has long behaved as a tectonically active plate boundary zone that can be characterized as a laterally mobilized crustal 'orogenic stream' (e.g. Oldow et al., 1990; Mazzotti & Hyndman, 2002) moving northward along maritime Canada, CCW through the "oroclinal" nexus of curving strike slip faults of central Alaska, and westward and southwestward toward the Aleutian-Bering Sea region. Throughout the Cenozoic, and possibly earlier, at and west of the nexus the North Pacific Rim orogenic stream (NPRS) has in Anatolian fashion been moving kinematically as a tectonically escaping crustal body. Since the early Eocene (i.e., past 50-55 Myr) its extrusive motion accounts for (1) the observed 800+ km combined dextral offset across the great curved fault systems of Alaska and British Columbia and (2) the absence of *massive mountain building in central Alaska summing up the measured offsets. Tectonic escape of the NPRS to the west and southwest has since the early Eocene been largely accommodated by the free tectonic face of the offshore Aleutian subduction zone, but for some of this time also by the now-extinct, tectonically kindred Bowers and Shirshov subduction zones. The 'orogenic stream' model implies that the present-day terrane framework of western North America is more a product of differential flow lines within the 'stream' than of individual accretionary events at the margin. Relatively rigid crustal blocks acquired paleomagnetic rotations and fault-juxtaposed boundaries while flowing through the system from their point of entrainment to their point of extrusion.*

2. NE ATLANTIC
2.1. Introduction

The break-up and evolution of the Greenland Sea, Norwegian Sea and oceanic basin south of Iceland were influenced by a special thermal regime that affected the configuration of margins and architecture of the oceanic basins. Despite numerous studies, the volcanic margins are not yet well understood, controversies arising from the cause of volcanism, location of seaward dipping reflectors (SDR) and continent ocean boundaries (or transition zones) and age and style of seafloor spreading. In the following chapter we will address some of these issues, with a particular emphasis on the location of the COB and early seafloor spreading.

2.2 Regional Setting

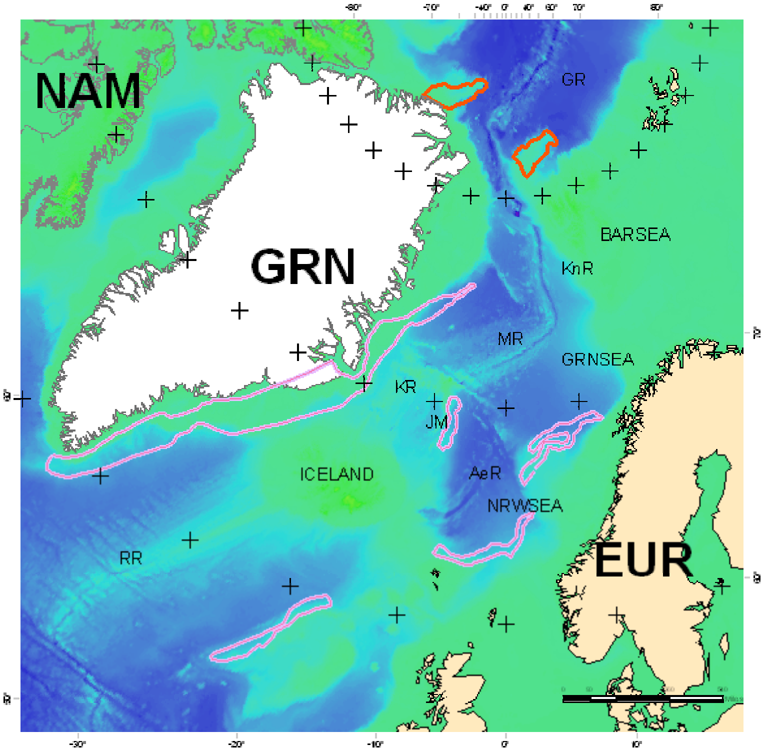


Fig. 2.2.1. Bathymetry of the NE Atlantic region (Smith and Sandwell, 1994). Abbreviations are: BARSEA-Barents Sea, GRNSEA-Greenland Sea, NRWSEAQ-Norwegian Sea, RR-Reykjanes Ridge, AeR-Aegir Ridge, KR-Kolbeinski Ridge, MR-Mohns Ridge, KnR-Knipovich Ridge, GR-Gakkel Ridge. Magenta lines indicate Sea Dipping Reflectors outlines, red lines are outlines of volcanic plateaus in the Eurasian Basin.

2.3. Early history of the North Atlantic

2.3.1. *North Atlantic fits with implications for the Barents Sea* Torsvik et al., (in prep) – abstract

Permo-Triassic reconstructions for the Northeast Atlantic differ considerably and thus predict different geological scenarios for the ensuing development of the Norwegian-Greenland passive margins. Bullard et al. (1965) developed the first computer-generated fit by matching 500-fathom contours of conjugate margins in the Atlantic realm. Their fit for the North Atlantic matches North American and European palaeomagnetic poles reasonably well from Mid-Palaeozoic to Early Mesozoic times (Van der Voo 1993; Torsvik et al. 1996, 2001). For that reason, many North Atlantic reconstructions use the Bullard et al. (1965) fit despite the somewhat problematic geological implications this reconstruction creates, notably in the Norway-Greenland Sea. This is illustrated in Figure 1a where we reconstruct the location of the continent-ocean boundary (COB) established from published seismic interpretations and re-processed and interpreted potential field data (satellite derived gravity anomaly and magnetic anomalies). The COB, in reality described as a continent-ocean transition zone between true continental and true oceanic crust, defines the Early Tertiary (~ 54 Ma) break-up line or zone between Europe and Greenland. In pre-breakup reconstructions COB overlap signifies pre-drift extension whilst a gap point to compression prior to break-up. The Bullard fit generates a tight fit (COB overlap) in the Rockall region and SE Greenland (i.e. more than 400 km of younger extension) but a troublesome COB gap in the Norwegian–Greenland Sea (Fig. 1a) is suggestive of compression prior to Early Tertiary seafloor spreading. Pure post-Pangea Mesozoic compression on the Mid/North-Norwegian margin is geologically unacceptable and this prompted Torsvik et al. (2001) to consider other alternatives.

2.4. Continent-ocean boundaries, break-up and seafloor spreading North and South of Iceland

Continent Ocean Transition versus Continent Ocean Boundary

Margins are often classified as amagmatic, weakly volcanic, or volcanic (e.g. Menzies et al. 2002). According to current classifications about ~70% of identified passive margins around the world are volcanic (e.g. Mahoney & Coffin, 1997). Figure 2.4.1. summarises the main characteristics observed within volcanic and weakly magmatic margins. The major differences between the two types are that volcanic margins are typically associated with: (i) narrow continent ocean transitions (COT); (ii) large post-rift subsidence; (iii) inner and outer sea-ward-dipping reflector (SDR); (iv) central intrusive complexes associated with dyke swarms parallel to the coast (v) voluminous flood basalts emplaced within a short period of time (vi) high seismic velocity bodies (underplating) at the base of the crust; and (vii) abnormally thick early oceanic crust (Fig. 2.4.1a). In comparison, our understanding of weakly magmatic margins tends to be dominated by the North Atlantic margins for example the Iberia-Newfoundland and Greenland-Labrador conjugate margins (e.g. Louden & Chian, 1999; Whitmarsh et al. 2001) (Fig. 2.4.1.b,c). Characteristics of Atlantic-type weakly magmatic margins may include: (i) a lack of voluminous magmatic activity; (ii) wide attenuated continental crust characterised by rotated fault blocks; (iii) wide (100-200 km) highly attenuated, and subdued COT's with elevated highs or ridges; (iv) unroofed upper mantle peridotites, serpentinite and horizontal reflectors (e.g. Iberian 'S-type') within the COT (e.g. Fig. 4. 2.3b) (v) large syn-rift subsidence (vi) asymmetric late stage continental break-up; (vii) anomalously thin early oceanic crust.

The following definitions for the complex zone between continental and oceanic crust are adopted (e.g. Wilson et al. 2001):
-Ocean-Continent Transition (COT) is defined as "*that region of uncertain affinity lying between fault blocks of thinned continental crust and crust that has the unequivocally normal geophysical characteristics of oceanic crust.*"
-Continent Ocean Boundary (COB) is defined as "*the basinward boundary of the COT; the first unequivocal oceanic crust exhibiting normal geophysical characteristics.*"

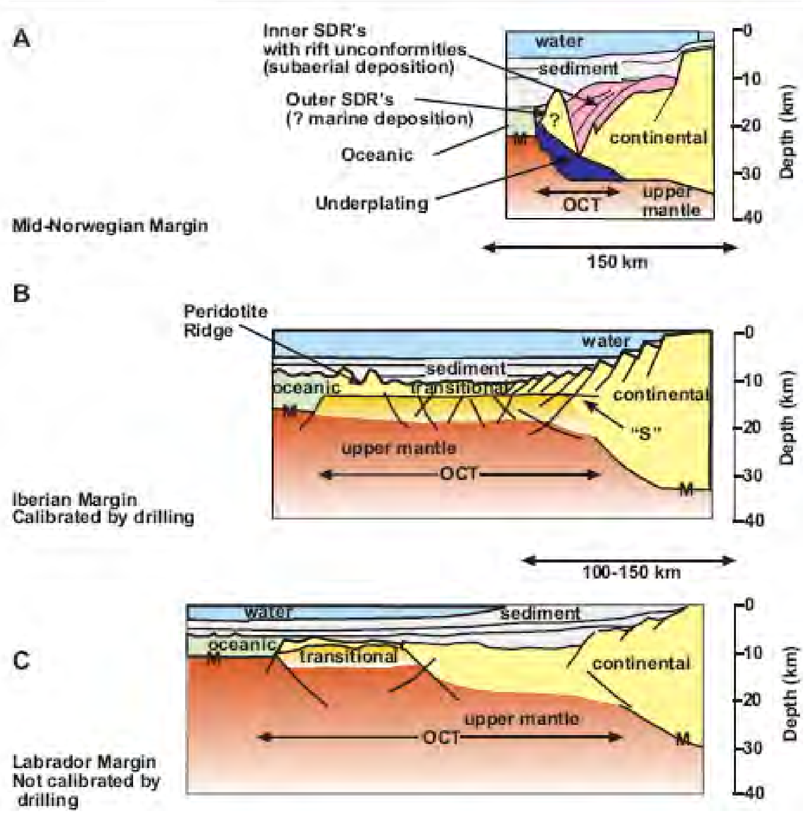


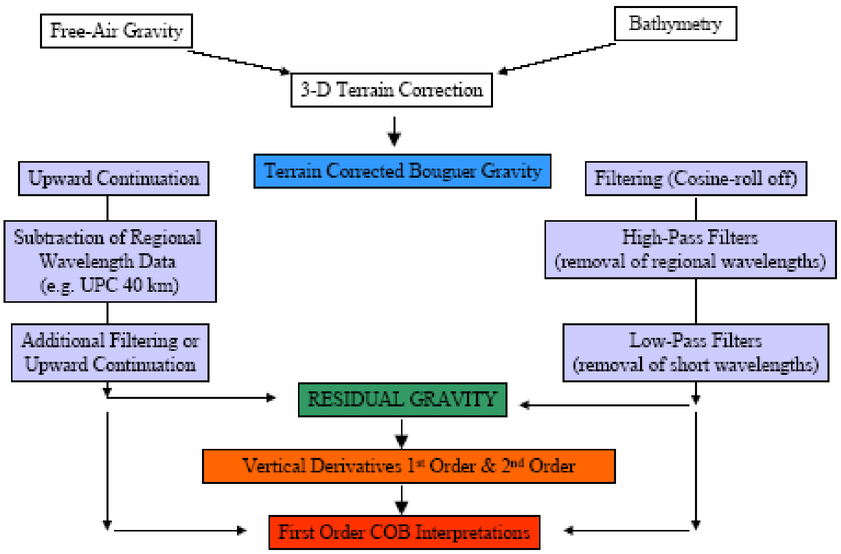
Fig. 2.4.1. Simplified sketches of volcanic and weakly magmatic passive margins highlighting the key geometrical differences between the two types of margins. A. Volcanic margin (modified after *Planke et al., 2000* and *Callot et al., 2002*) B. and C. Weakly magmatic margin two end members (after *Louden and Chian, 1999*) (figure from *Ball, 2005*)

COB identification in the North Atlantic

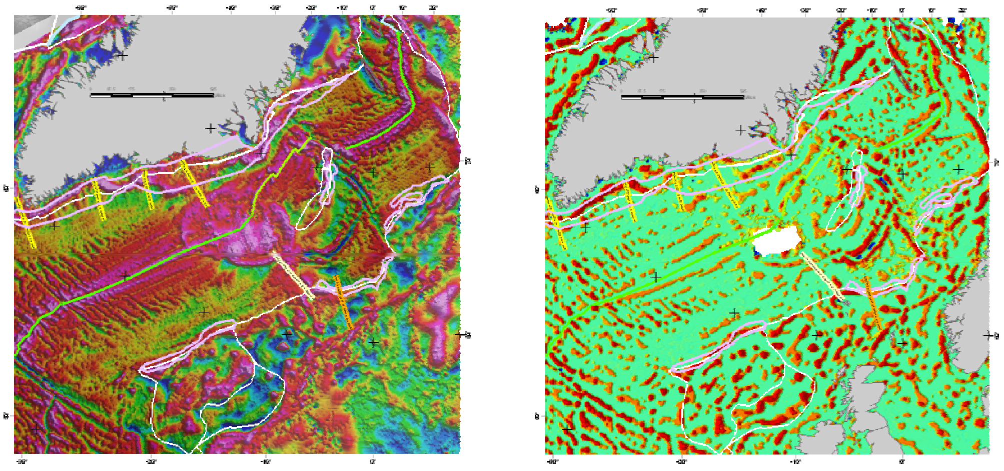
Gravity data

Free air gravity anomaly (Sandwell and Smith, 1997) and global topography/bathymetry (GEBCO) have been used to compute residuals of the North Atlantic area. Few edge enhancing methods have been applied to these residuals in order to help identifying changes in the basement characteristics (and therefore helping to identify first order boundaries between the oceanic and continental areas).

Gravity Processing Flow Diagram



In the case of volcanic margins, the double vertical derivative of upward continued (20 km) gravity anomaly residuals meant to enhance the edge effect show sometimes a stronger signal mainly due to SDR's (Fig. 2.4.2.a). Published seismic data interpretation has been used to refine the COB/COT interpretation.



a) b)

Fig. 2.4.2. Free air gravity anomaly (Sandwell and Smith, 1997) and gravity anomaly residuals (double vertical derivative of 20 km upward continued free air gravity) of North Atlantic area.

Published seismic data

1. iSIMM (orange line)
2. FIRE (pale yellow line)
3. SIGMASEIS (yellow lines)

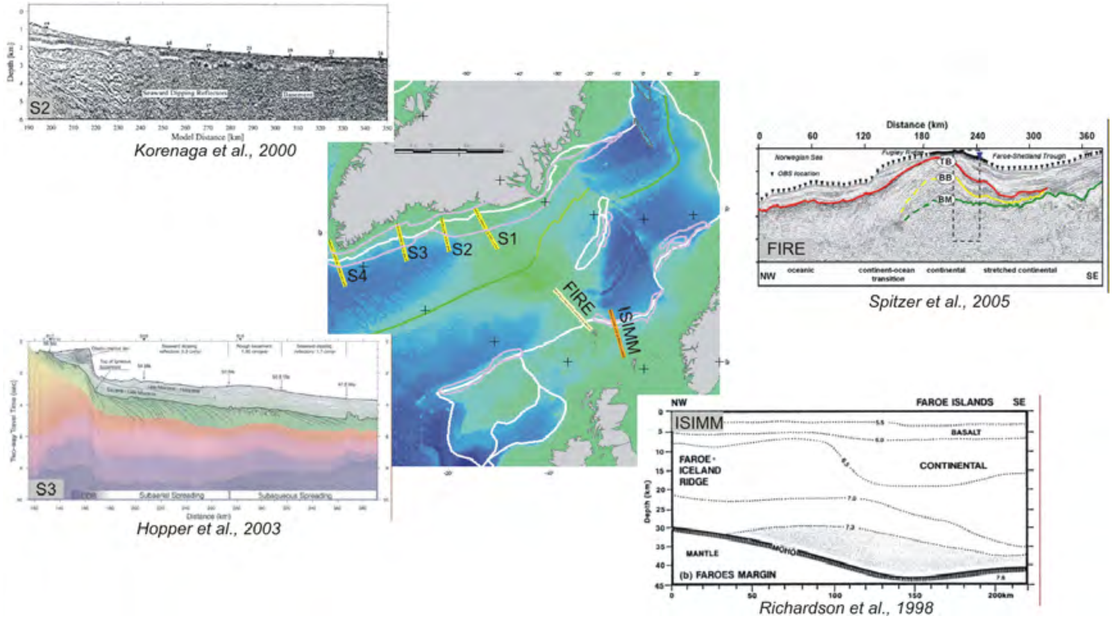


Fig. 2.4.3. Examples of COB/COT location based on reflection and refraction data along the East Greenland and Eurasian margins.

In the Faroe area the interpretation of the COB or COT proves to be a very difficult task due to the thick layer of volcanics that hinders imaging the structure beneath it. A study done in 1998 (FIRE project) running a seismic survey from Fareoe to Iceland could not precisely locate the COB (Richardson, 1998). Recently, more advanced technique (ISIMM project) allowed a better interpretation of the continent ocean transition (Spitzer et al., 2005).

2.4.1. Greenland Sea

Magnetic anomaly identifications

In order to define the postbreak-up evolution of the NE Atlantic, we have identified the oldest magnetic anomalies in the Greenland Sea, Norwegian Sea and in the oceanic basin south of Iceland.

A. Chron 24B (53.3 Ma)

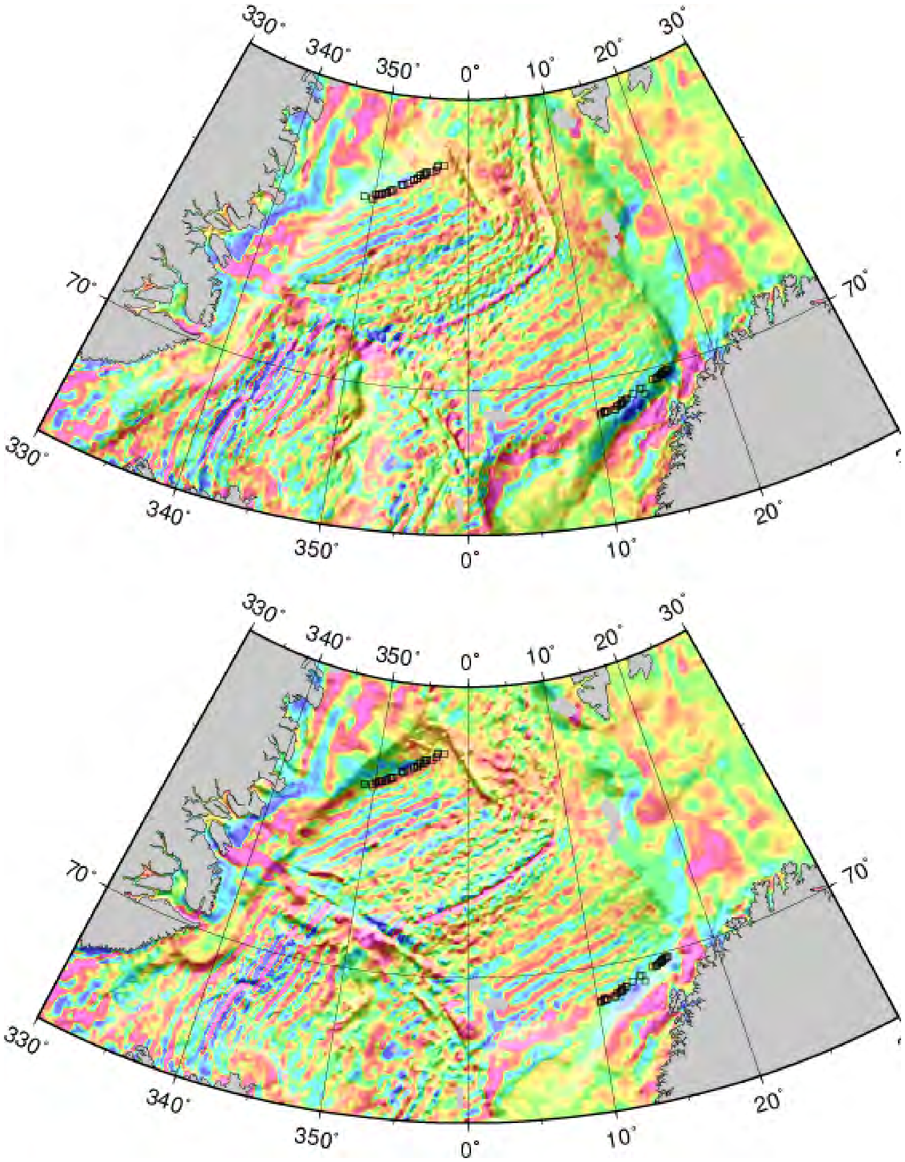


Fig. 2.4.1.2. Magnetic anomaly grid (Verhoef et al., 1996) of the Greenland Sea region overlayed on bathymetry grid (GEBCO) (illumination 100 deg for upper image, 345 deg for lower image). Square symbols for oldest magnetic anomaly (24o, 53.3 Ma, Cande and Kent (1995) timescale) locations.

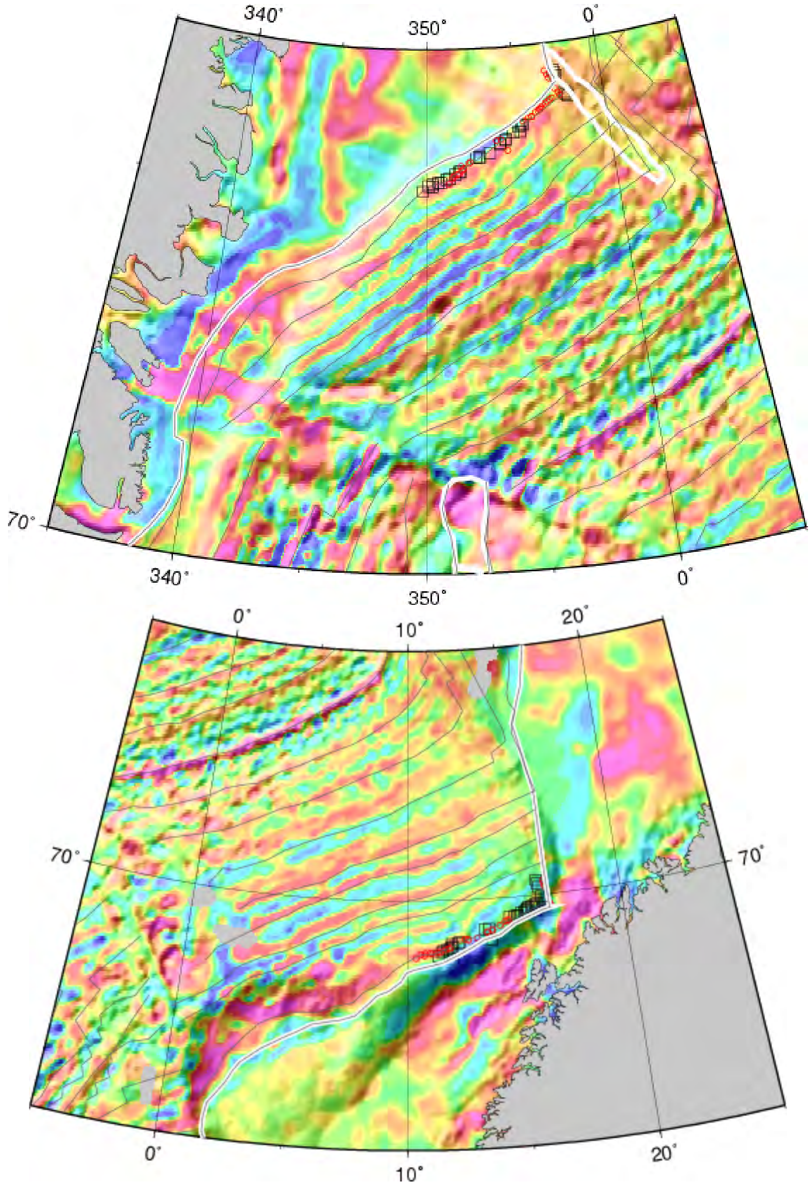


Fig. 2.4.1.3. Magnetic anomaly grid (Verhoef et al., 1996) of the Greenland Sea region draped on bathymetry grid (GEBCO) (illumination 100 deg for upper image, 345 deg for lower image). Square symbols for oldest magnetic anomaly, light graylines are the present study COB and isochrons.

The identification of the oldest magnetic anomaly in the Greenland Sea proves to be difficult, especially in the southern part where younger volcanic activity hinders the magnetic signature of chron 24. Previous interpretations identified an extinct spreading center (Skogseid et al., 2000) and a series of fracture zones in the southern Greenland Sea (Tsikalas, 2002). More recently, Olesen et al., (2004) used an improved magnetic dataset and proposed a continuous chron 24 (A and B) on both margins of the Greenland Sea. They have also interpreted the wide magnetic anomaly signature that intersects chron 24 as an igneous complex that affected the area around chron 22 time (approx. 48 Ma).

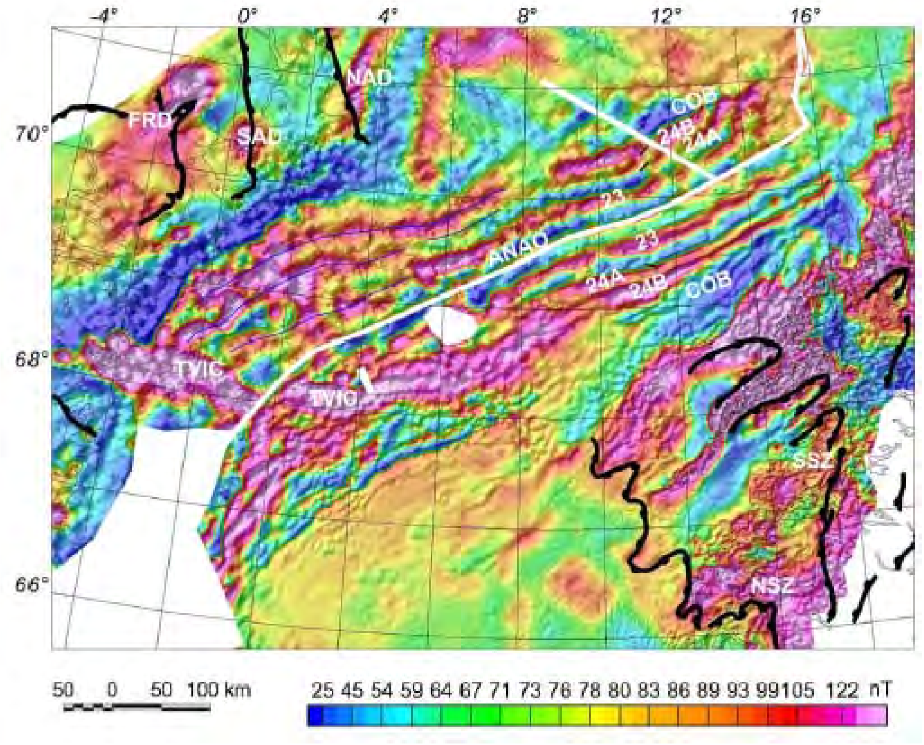


Fig. 2.4.1.4. Interpretation of oldest magnetic isochron in the Greenland Sea (Olesen et al,2004)

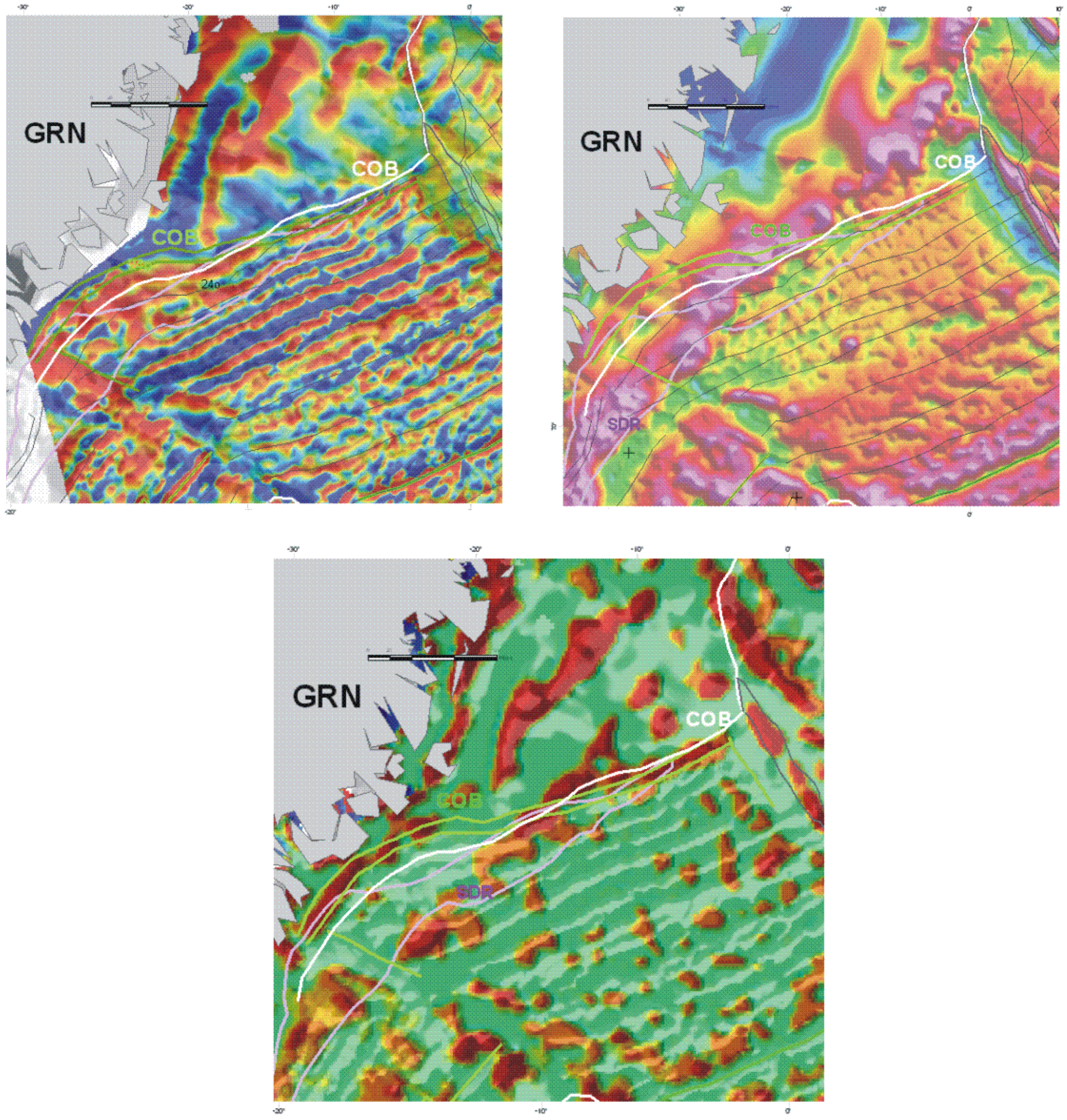


*Fig. 2.4.1.5.*A. Magnetic anomaly grid (left), free air gravity anomaly (right) and second vertical derivative of gravity anomaly overlaid on magnetic anomaly grid (below) for west Grennland Sea margin. Superimposed are two different interpretation of the COB and oldest magnetic anomaly (green-Olesen et al, 2004 and white - present study). Light magenta contour shows the extent of seaward dipping reflectors (SDR). Pale gray lines are the magnetic isochrons identified in this study.

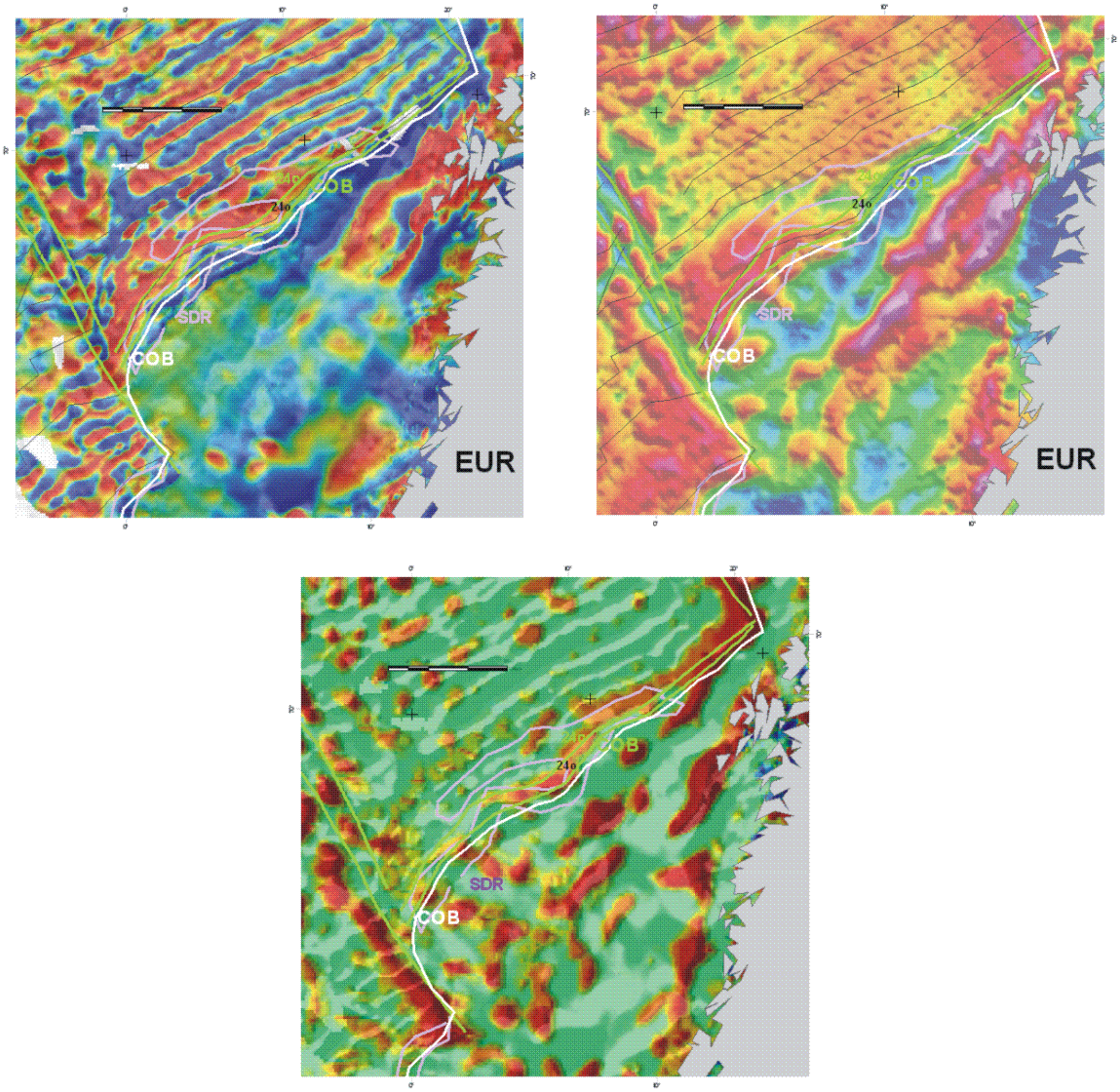


Fig. 2.4.1.5. Magnetic anomaly grid (left), free air gravity anomaly (right) and second vertical derivative of gravity anomaly overlaid on magnetic anomaly grid (below) for east Greenland Sea margin. Superimposed are two different interpretation of the COB and oldest magnetic anomaly (green-Olesen et al, 2004 and white - present study). Light magenta contour shows the extent of seaward dipping reflectors (SDR). Pale gray lines are the magnetic isochrons identified in this study.

Due to the complication introduced in the identification of the oldest magnetic chron by the subsequent volcanism, we have used plate reconstructions of individual sub-basins of the NE Atlantic area to constrain the location of chron 24 in the southern Greenland Sea. The kinematic models are described in a separate section.

2.4.2. Norwegian Sea

Magnetic anomaly identifications

A. Chron 24

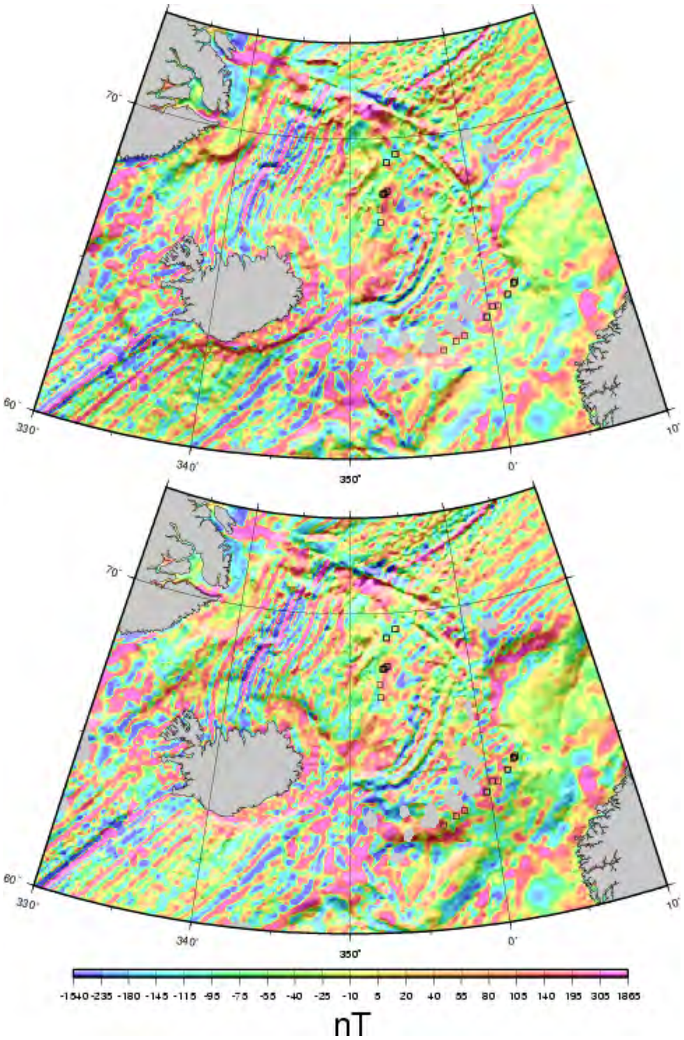


Fig. 2.4.2.1. Magnetic anomaly grid (Verhoef et al., 1996) of the Norwegian Sea region overlayed on bathymetry grid (GEBCO) (illumination 345 deg for upper image, 160 deg for lower image). Square symbols for oldest magnetic anomaly locations.

The magnetic anomaly data along the eastern part of the Jan Mayen microcontinent is rather sparse. In addition, the extent of this continental fragment is still disputed. Here we have identified the "core" of the Jan Mayen continental area whose extent can be better defined using additional geophysical data.

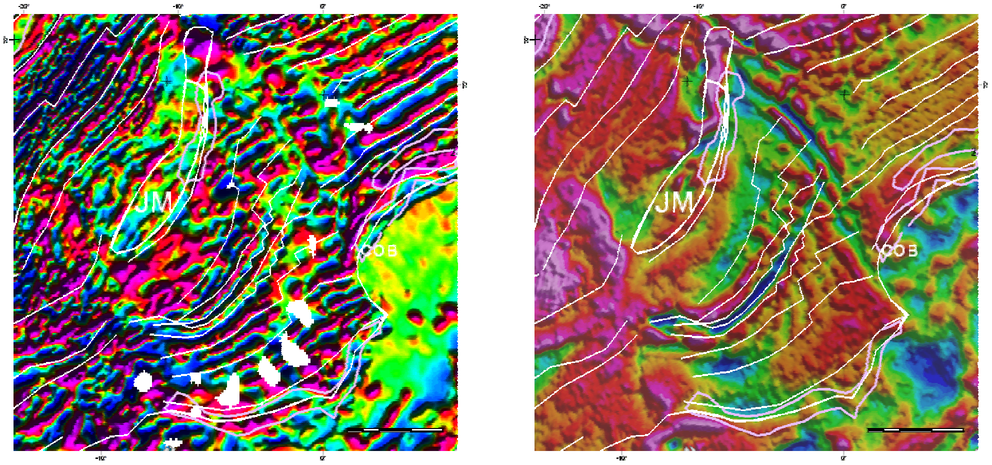


Fig. 2.4.2.2. Norwegian Sea – magnetic anomaly grid (left) and free air gravity (right). White lines are magnetic isochrons (thin) and interpreted COB (thick). SDR in light magenta.

2.4.3. South of Iceland

Magnetic anomaly identifications

A. Chron 24

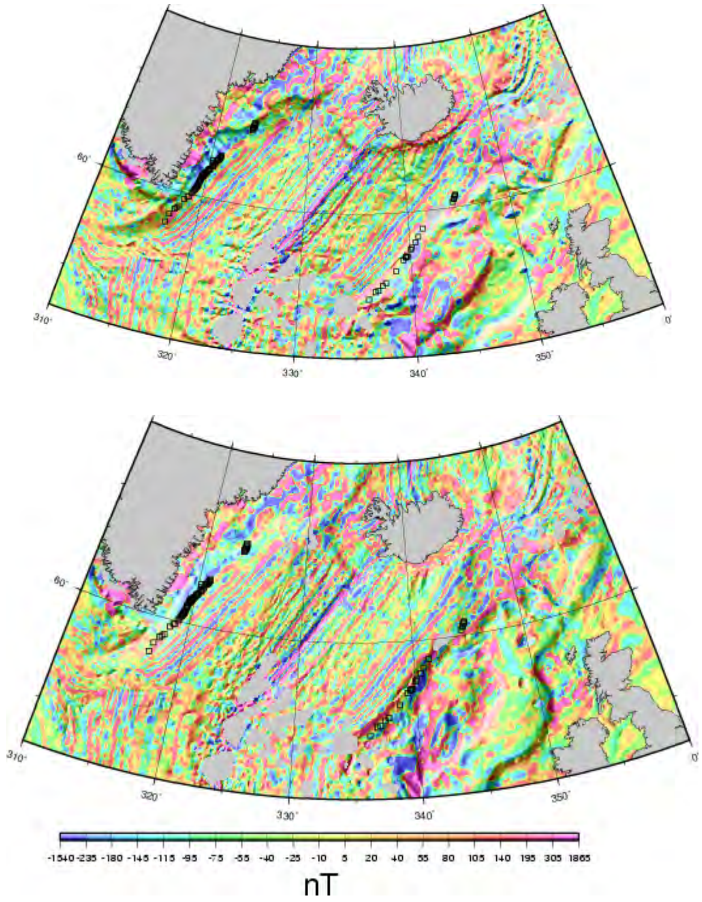


Fig. 2.4.3.1. Magnetic anomaly grid (Verhoef et al., 1996) of the area South of Iceland overlayed on bathymetry grid (GEBCO) (illumination 345 deg for upper image, 160 deg for lower image). Square symbols for oldest magnetic anomaly locations.

2.4.4. Early seafloor spreading in the NE Atlantic and plate kinematic implications

We have used the COB and magnetic anomaly identifications to derive rotation parameters for the early opening of the NE Atlantic. The magnetic pick identifications have been assigned an error of 5 km due to navigational and picking uncertainties. They have been inverted using the Hellinger (1981) criteria of fit as described in Gaina et al (2002). We have also inverted the magnetic picks from individual basins (Greenland Sea and South of Iceland basin) in order to test possible inconsistencies in the rotation parameters of the Greenland-Eurasia opening. The results of these inversions show that using magnetic data from north of Iceland or south of Iceland *only*, the opening of the NE Atlantic might require an additional plate boundary between these two domains (see reconstructions and location of rotation poles below). This hypothesis will be further tested using a statistical F test.

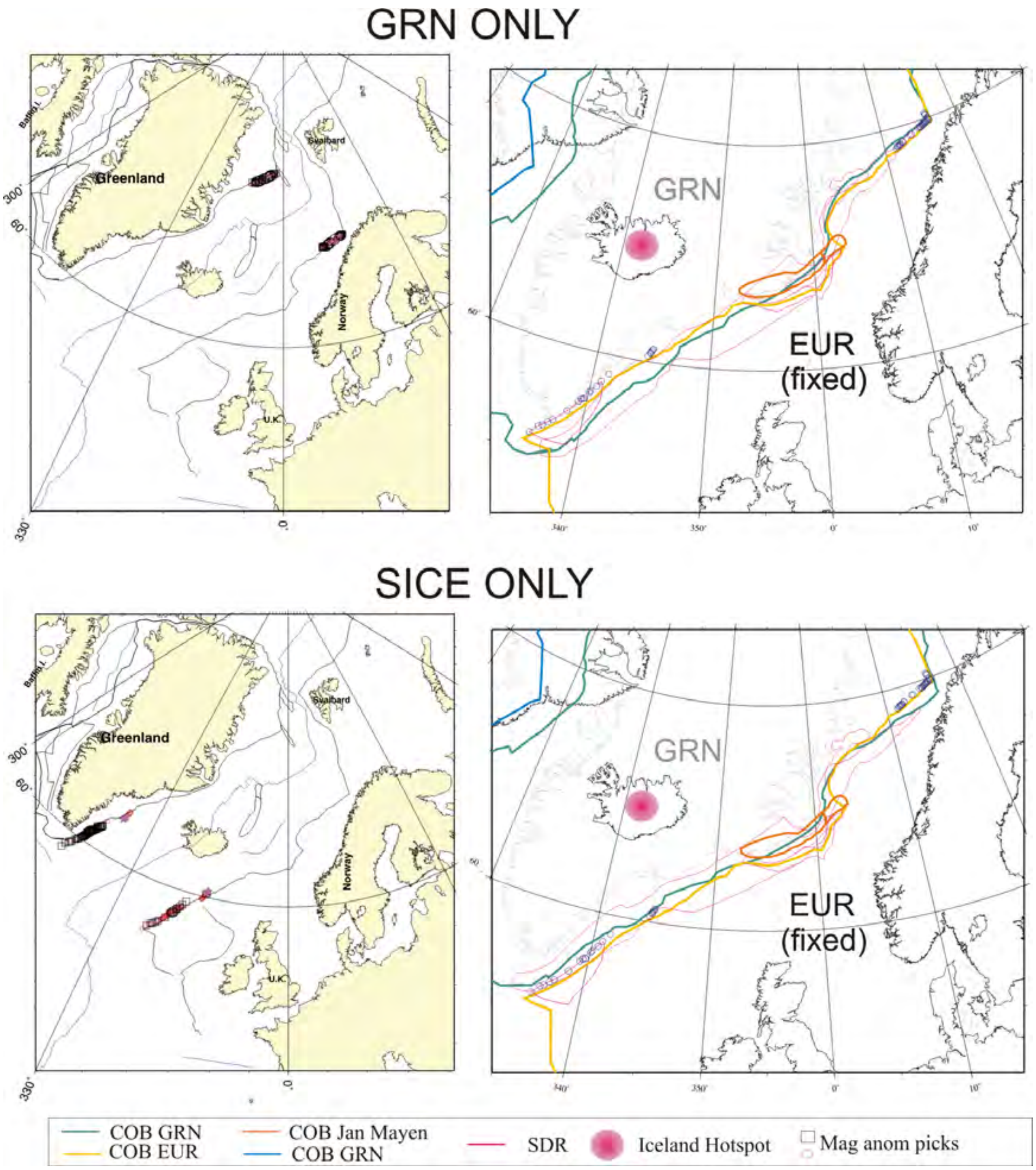
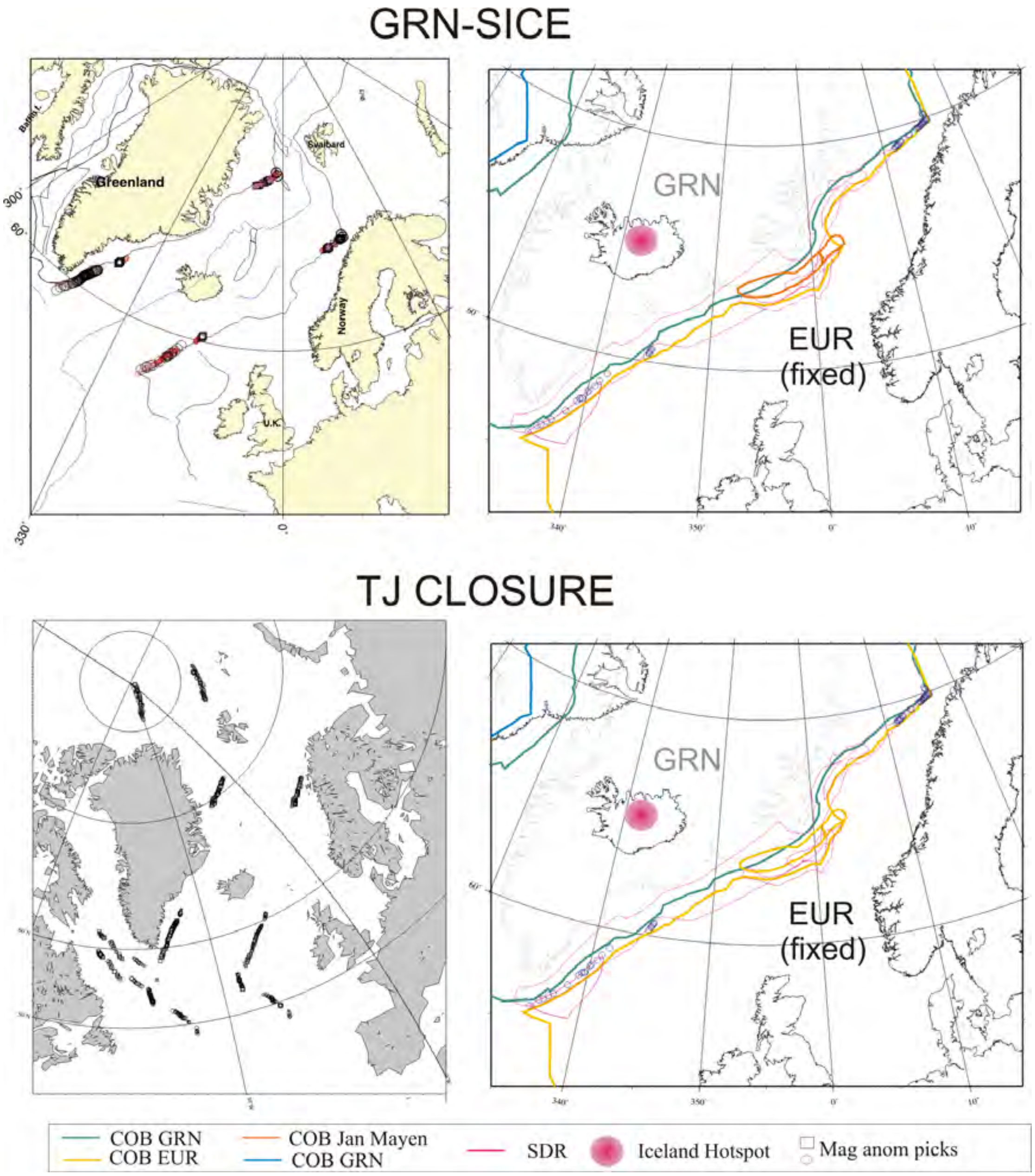


Fig. 2.4.4.1. Magnetic anomaly location in the present day and reconstructions at chron 24 (53.3 Ma) of the NE Atlantic using Greenland Sea magnetic identifications (upper maps) or South of Iceland (lower maps). COB are shown in yellow for Eurasia, green for Greenland and orange for Jan Mayen. Note the overlap in the Southern NE Atlantic if using the Greenland magnetics only, and in the northern Greenland Sea if using magnetics from the southern part only.


GRN-SICE

TJ CLOSURE

Fig. 2.4.4.2.. Reconstruction at 53.3 Ma using the magnetic anomaly identifications of both south and north of Iceland basins (upper maps) and using the entire North Atlantic magnetic data (after Gaina et al., 2002).

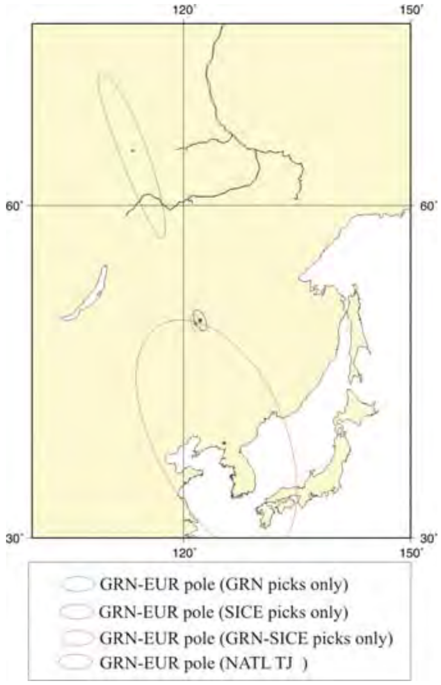


Fig. 2.4.4.3. Positions of finite rotation poles and 95% uncertainty ellipses for different magnetic pick inversion scenarios (see text).

Table 2. Rotation parameters for the early opening (53.3 Ma) of NE Atlantic (GRN-EUR, GRN fixed)

Location of magnetic data	**Lat**	**Lon**	**Angle**
Greenland Sea (GRN)	63.41	113.33	-14.61
South of Iceland (SICE)	40.25	125.38	-10.63
GRN and SICE	51.23	121.59	-11.31
All NE Atlantic and Arctic	-51.5	-57.8	11.37

2.4.3. North Atlantic Reconstructions

Quantitative tectonic reconstructions – a new tool to estimate COB uncertainties?

The Hellinger (1981) criterion of fit has been used mainly for deriving best-fit rotations from conjugate magnetic anomalies and fracture zone data. For fitting COB segments, a visual fit is usually preferred because the geometry of COB's is extremely sinuous and hard to break into great circle segments, as required by Hellinger's (1981) methodology. Therefore, pre-drift rotations mostly do not have uncertainties attached to them. However, plate circuits can be used to derive the amount of displacement (and uncertainties) for a pair of plates for which geophysical constraints are scarce or missing. As an example we used the rotations between North America and Greenland and between North America and Eurasia (see map of magnetic data location in Fig. 2.4.3.1.) to determine the relative motion and its uncertainties between Greenland and Eurasia before break-up (Fig. 2.4.3.2). According to our kinematic model, the position of the COB could be found within an area of 45 to 77 km wide (from south to north) – uncertainty given by the stage pole uncertainty ellipse calculated for stage pole 31 to 25 (67 to 55 million years). A rotated Eurasian COB at 55 and 57 million years fist the end limits of the oldest uncertainty ellipse, indicating the time of breakup slightly earlier than 55 million years.

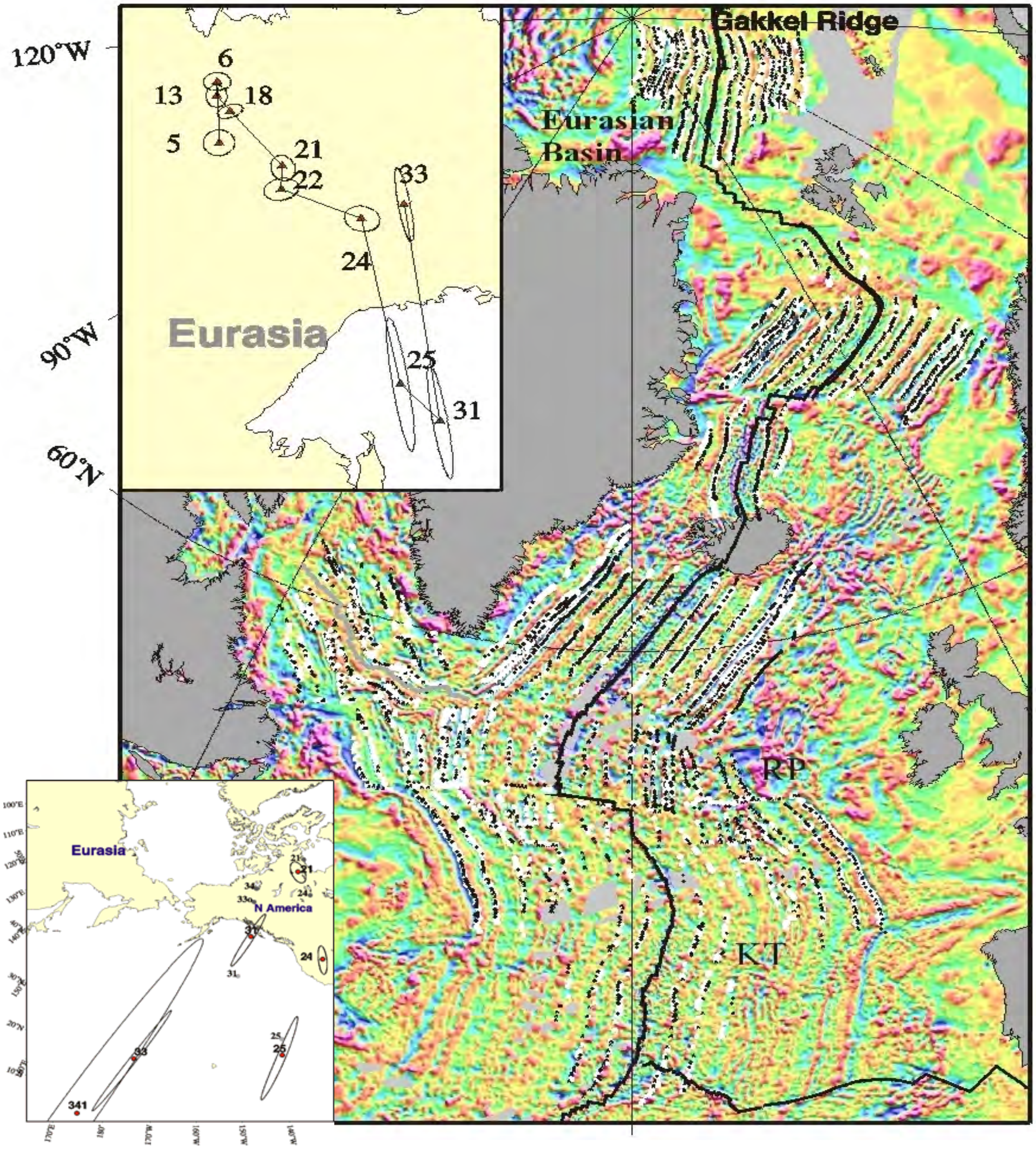


Fig. 2.4.3.1. Magnetic anomaly identifications in present day locations (black symbols) and rotated (white symbols) and rotation poles and their uncertainties for Eurasia – North America (upper inset) and Greenland-North America – lower inset). Modified after *Gaina, (2002).*

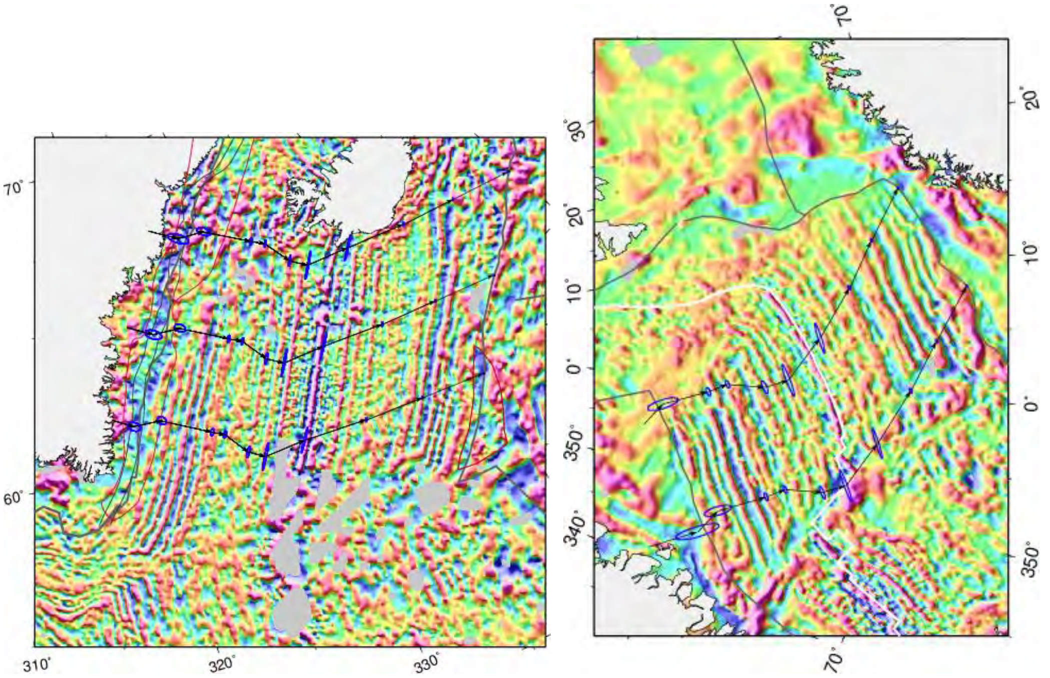


Fig. 2.4.3.2. Magnetic anomaly grid for the South of Iceland area (left) and Greenland Sea (right). Thick gray lines are COB. Motion vectors and their uncertainty elipses are calculated for 9 stage poles. In the case of South of Iceland area we have plotted the reconstructed positions of Eurasian margin at 55 and 57 million years (thin lines). Note that they outline an area that indicates the uncertainties in the position of the breakup as suggested by the 95% confidence errors. Light red areas show the mapped sea dipping reflectors (SDR): Greenland side - modified after Hopper et al., 2003; Eurasian side Gernigon, L. (pers comm.).

2.5. Iceland plume – new models

2.5.1. *The effect of the large-scale mantle flow field on the Iceland hotspot track* Mihalffy et al., (in press) – abstract

Fluid dynamical simulations were carried out in order to investigate the effect of the large-scale mantle flow field and the depth of the plume source on the structure of the Iceland plume through time. The time-dependent location and shape of the plume in the Earth's mantle was calculated in a global model and it was refined in the upper mantle using a 3D Cartesian model box. Global flow was computed based on density heterogeneities derived from seismic tomography. Plate motion history served as a velocity boundary condition in both models. Hotspot tracks of the plume conduits and the plume head were calculated and compared to actual bathymetry of the North Atlantic. If a plume source in the lowermost mantle is assumed, the calculated surface position of the plume conduit has a southward component of motion due to southward flow in the lower mantle. Depending on tomography model, assumed plume age and buoyancy the southward component is more or less dominating. Plume models having a source at the 660 km discontinuity are only influenced by flow in the upper mantle and transition zone and hence rather yield westward hotspot motion. Many whole-mantle plume models result in a V-shaped track, which does not match the straight Greenland-Iceland-Faroe ridge. Models without strong southward motion, such as for a plume source at 660 km depth, match actual bathymetry better. Plume tracks were calculated from both plume *conduits and plume heads. A plume head of 120 K anomalous temperature gives the best match between plume head track and bathymetry.*

3. LABRADOR/BAFFIN BAY

Labrador Sea is an ocean basin situated between North America and Western Greenland. Published models postulate an age of opening between 90 and 30 million years (with the oldest identified magnetic anomaly 33, i.e. 79 *Ma* Roest and Srivastava, 1989) or between 65 and 30 million years (oldest magnetic anomaly 27, i.e. 61 Ma, Chalmers and Lauresen, 1995) (Fig. 3.1.).

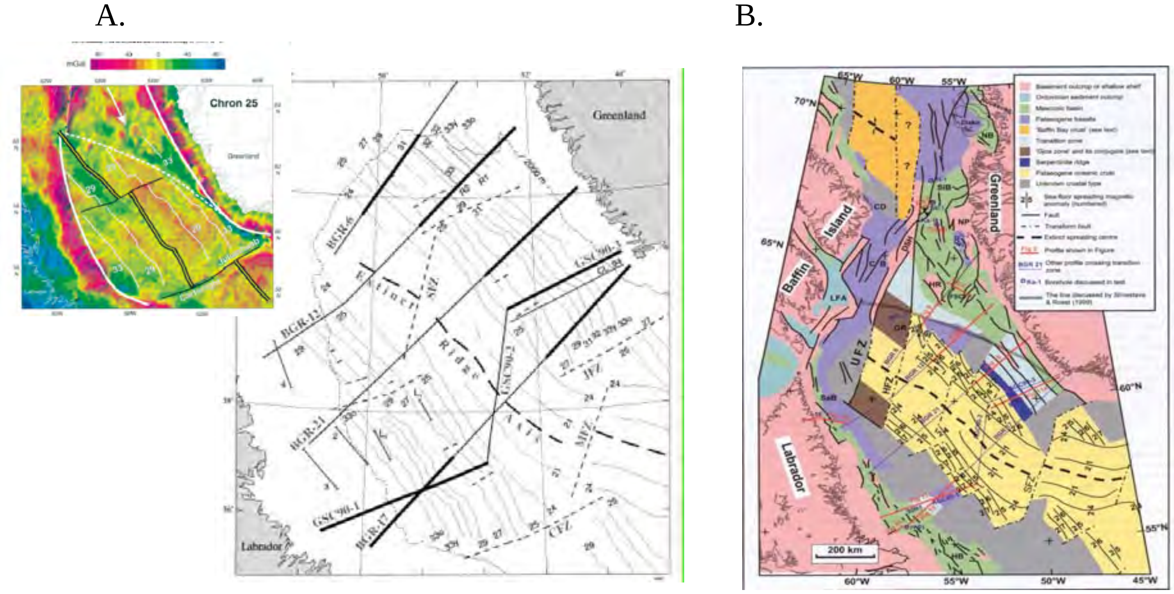
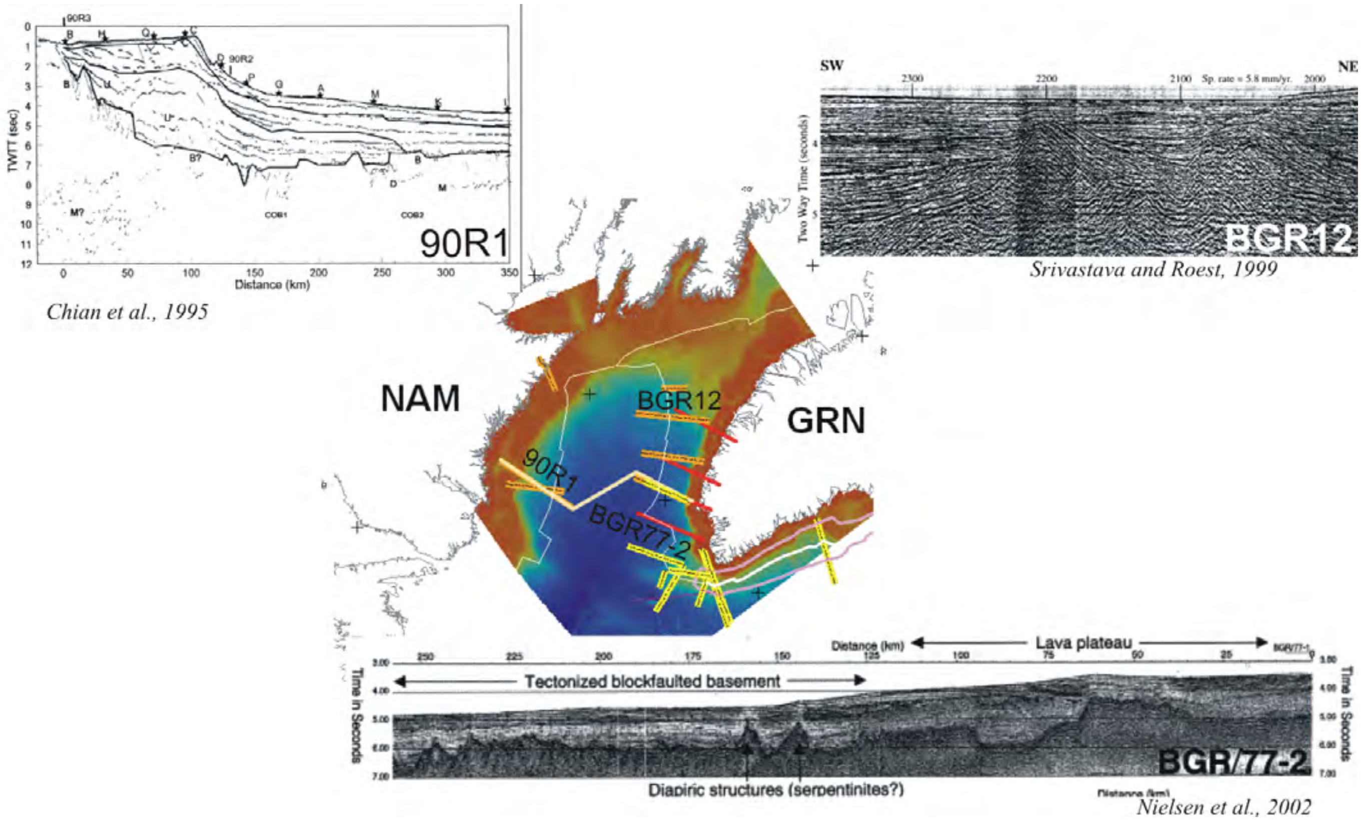


Fig. 3.1. Two competing models for the opening of the Labrador Sea: A *Roest and Srivastava, 1989* and *Srivastava and Roest, (1999)* and B. *Chalmers and Laursen, (1995); Chalmers and Pulvertaft, (2001).*

Numerous seismic reflection and refraction studies brought evidences of a wide area of transitional crust on both margin of the Labrador Sea (Fig. 3.2).



Chian et al., 1995

Srivastava and Roest, 1999

Nielsen et al., 2002

Fig. 3.2. Selected locations of published seismic lines in the Labrador Sea and examples of interpreted seismic data across the continent ocean transition.

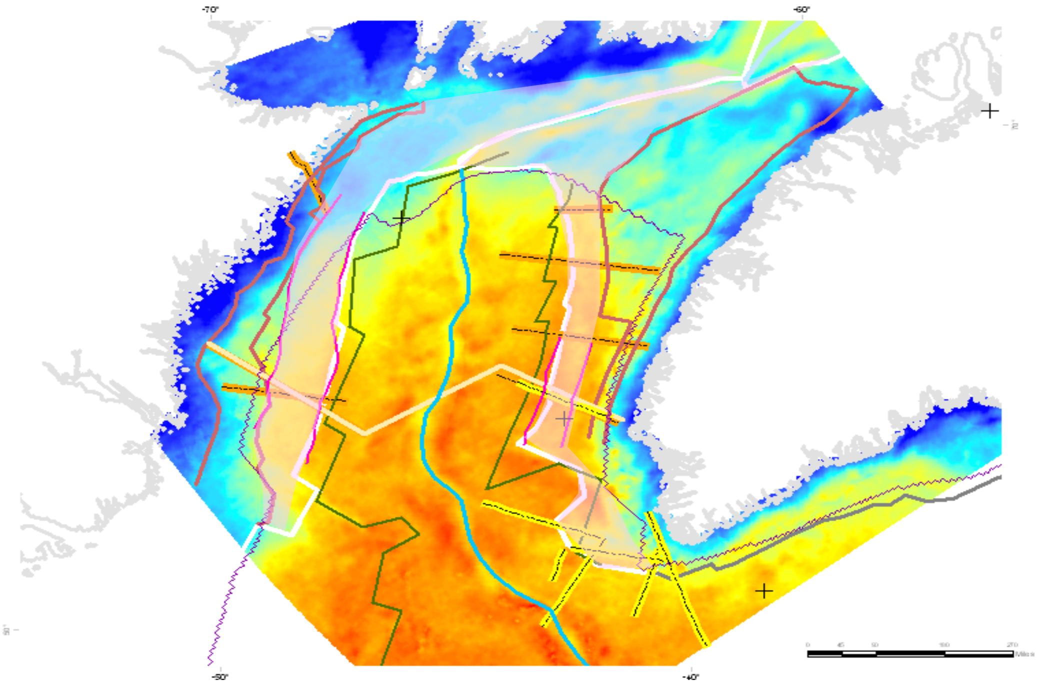


Fig. 3.3. Outline of COB and COT according to various seismic studies –seismic lines in yellow and orange (green – Chalmers and Pulvertaft, 2001; magenta - Chian and Louden, 1995; zigzagged magenta -

Roest and Srivastava, 1989; dark red –outline of Mesozoic basins by Chalmers and Pulvertaft, 2001), extinct spreading ridge in blue and this study re-interpretation of COT (white area).

In addition to published interpretation based on seismic data, potential field data (satellite derived gravity anomaly and magnetic anomalies) has been re-processed and interpreted.

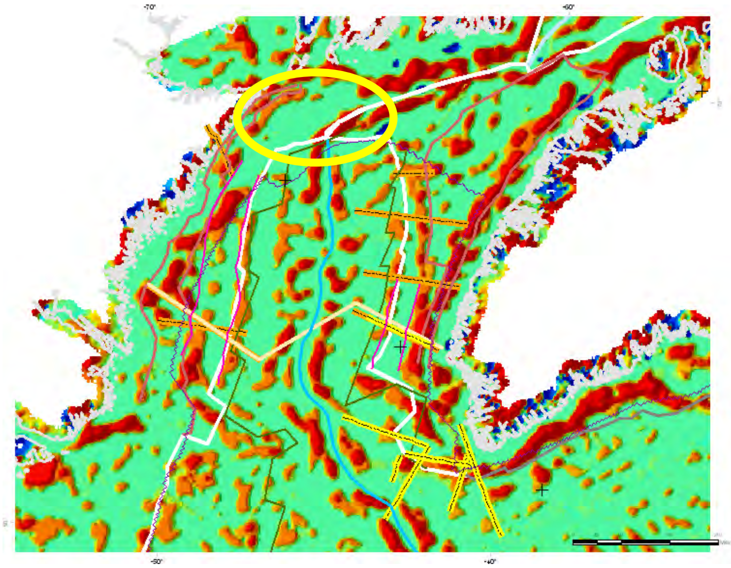


Fig. 3.4. Second vertical derivative of upward continued (20 km) gravity anomaly residuals. Note strong signal that outline the COT (COB and COT outlines the same as in previous figure). Area highlighted in yellow represent unknown crust and a potential target for future studies.

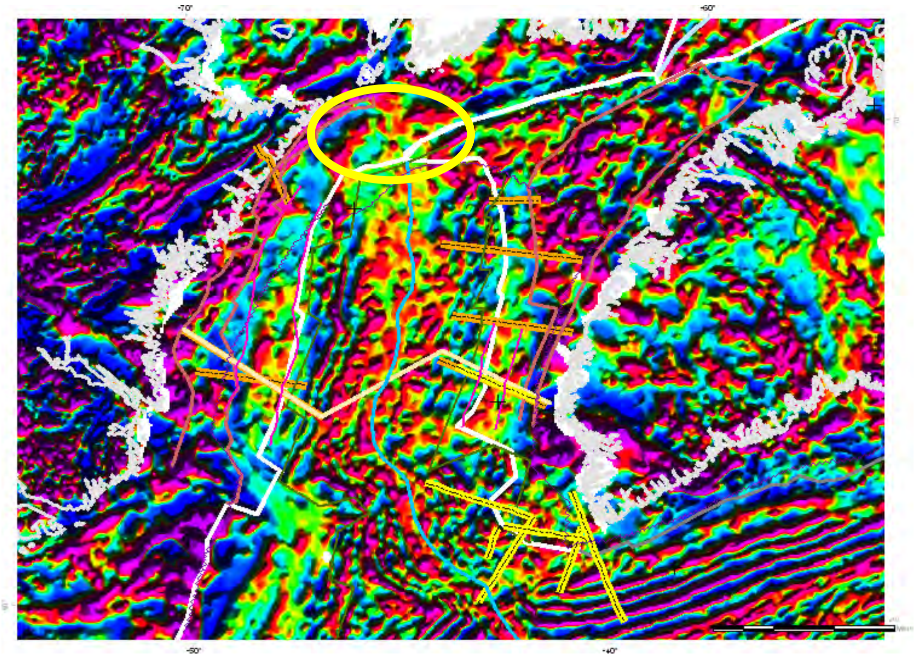


Fig. 3.5. Magnetic anomaly grid (*Verhoef et al., 1996*). Note the difference in the magnetic signal within the transitional area which is weaker and less linear than in the "true" oceanic area.

We have used North Atlantic quantitative tectonic reconstructions based on potential field data (Fig. 2.4.3.1., *Gaina et al., 2002*), to estimate motion vectors and their uncertainties for several stages in the Labrador Sea. Although "true" seafloor spreading seems to have started only before chron 27 (61 Ma), the linear magnetic signature of the peridotite ridges that might be present in the transitional could be used as isochrones, therefore indicating the timing of continental crust stretching as suggested in the Iberian margin (*Sibuet, personal communication*). Therefore we suggest that the oldest rotation stage and its uncertainties could be used to estimate the location and uncertainties of COB/COT (Fig. 3.6.).

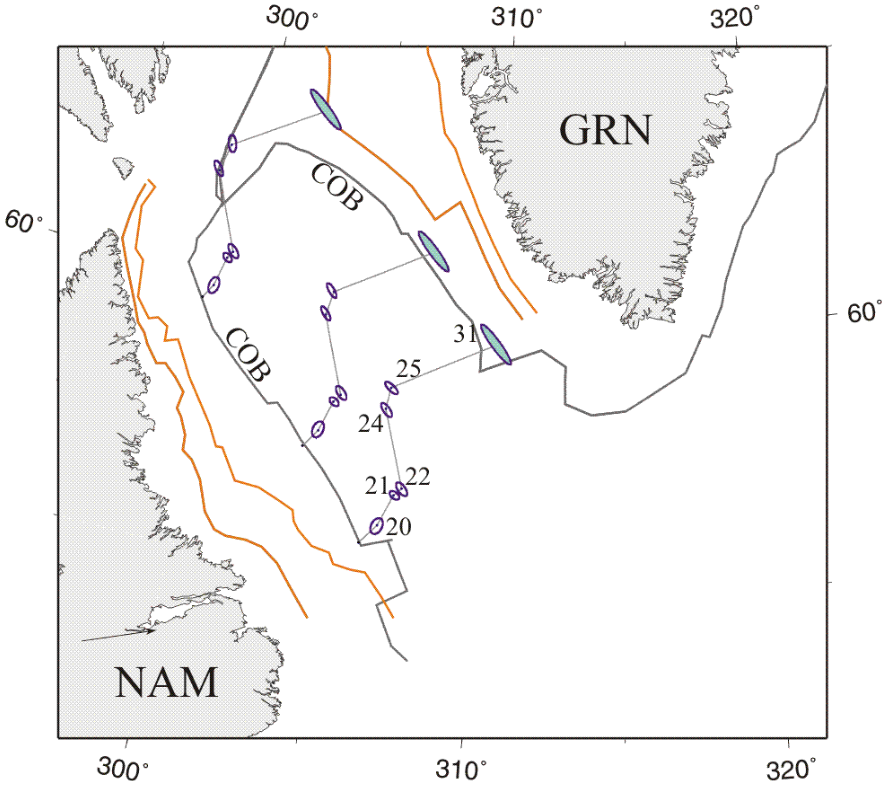


Fig. 3.6. Vectors of motion and 95% confidence ellipses for 6 stages of relative motion between Greenland (GRN) and North America (NAM). Orange lines show limit of Mesozoic (pre-breakup) exensional basins. Chron 31 indicates the position of pre-breakup (COB is interpreted oceanward from this position). The 95% ellipses show a narrow zone of uncertainties in location of this chron.

4. Palaeo-agegrids of North Atlantic – Arctic oceanic area

The newly interpreted continent ocean boundaries and magnetic isochrons together with a new derived set of rotation parameters allowed us to construct a series of digital palaeo-age grids for the North Atlantic oceanic areas. The digital grids serve to visualise the kinematic evolution of the entire North-Atlantic-Arctic realm and can be used to derive first order palaeo dept to the basement and heatflow.

4.1. North Atlantic gateway – Fram Strait

4.1.1. *Middle Miocene Ice Sheet Expansion in the Arctic – Views from the Barents Sea*, Knies and Gaina (submitted to Geology) – abstract

We present a revised model on the onset of glaciation in the North Atlantic-Arctic gateway region. From a perspective incorporating revised core data from Ocean Drilling Program (ODP) Leg 151, Hole 909C, pre-glacial paleorelief and bathymetric reconstructions in the Barents Sea and the gateway region, we propose that large-scale glaciations were already developed in the northern Barents Sea during the Middle Miocene climate transition (MMCT), ~14 million years ago. Our findings indicate that subsequently to an ice-free period during the Miocene Climate Optimum (MCO) glacially eroded material from the emerged northern Barents Sea were transported by iceberg flotillas towards the Fram Strait. The simultaneous opening of the North Atlantic – Arctic gateway provide the pathways of the icebergs from the North. The expansive ice growth is probably induced by both large-scale changes in ocean circulation due to enhanced flow of Atlantic water into the Arctic Ocean during opening of the gateway and concurrent global cooling during the MMCT. This new cryospheric model for the Barents Sea is in huge contrast to existing models. It has potentially large impact not only for the assessment of Northern Hemisphere climate feedback processes during this major step in Cenozoic climate evolution but also for the characterization of prolific petroleum systems in the Barents Sea regarding timing and duration of glacial erosion, deposition and ice load.

4.2. Palaeo-age grids of the North Atlantic-Arctic

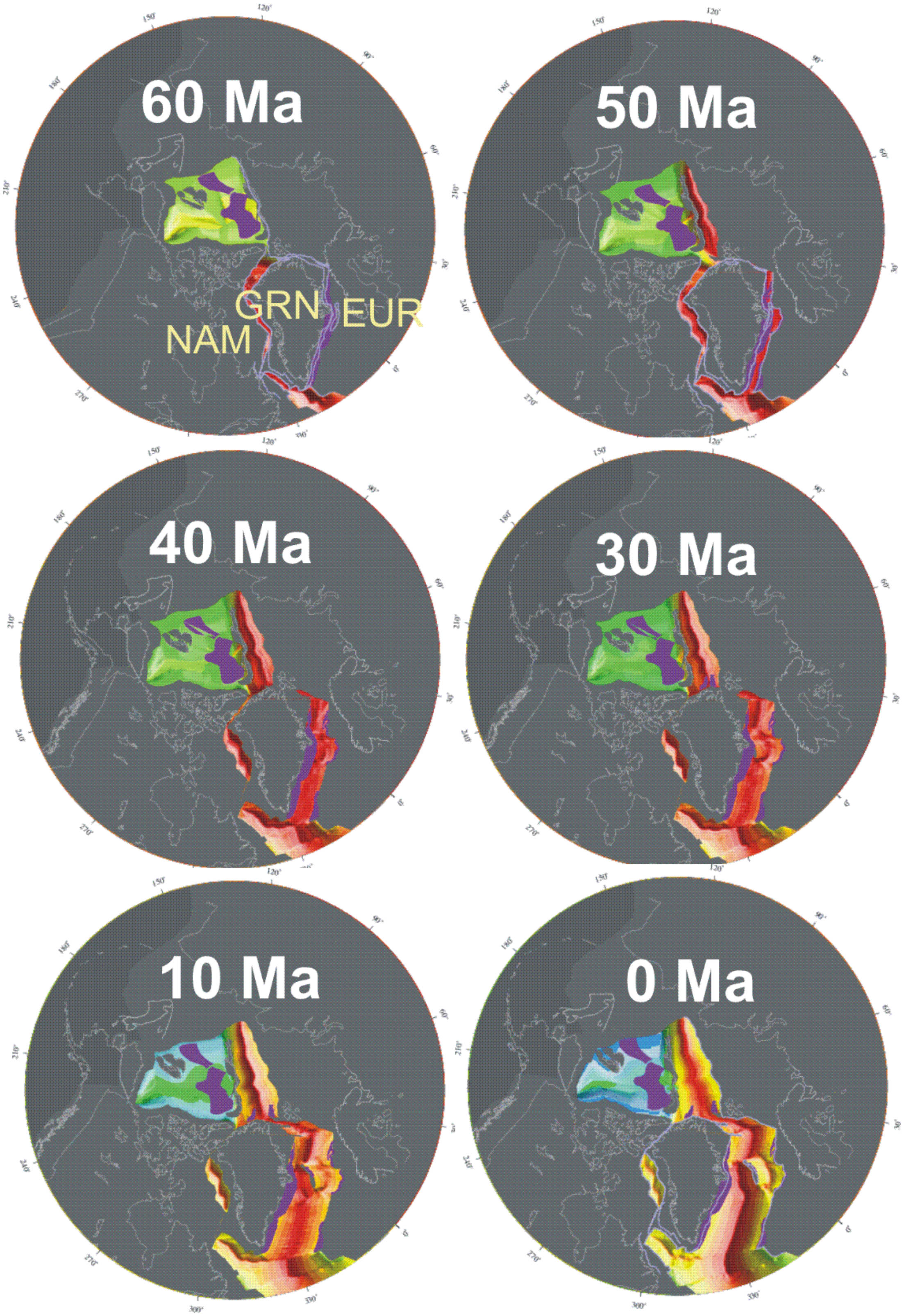


Fig. 4.2.1. Palaeo-age grids of the North-Atlantic-Arctic

5. INDIAN OCEAN

4.1. Early evolution of the Indian Ocean

4.1.1. *Breakup and early seafloor spreading between India and Antarctica in the light of new data: a Mesozoic magnetic anomaly sequence and an extinct spreading center in the Enderby Basin, Antarctica,* Brown et al., (JGI, in review) – abstract

We present a tectonic interpretation of the breakup and early seafloor spreading between India and Antarctica based on improved coverage of potential field and seismic data off the East Antarctic margin between Gunnerus Ridge and the Bruce Rise. We have identified a series of ENE trending Mesozoic magnetic anomalies from chron M9o (~130.2 Ma) to M2o (~124.1 Ma) in the Enderby Basin, and M9o to M4o (~126.7 Ma) in the Princess Elizabeth Trough and Davis Sea Basin, indicating that India-Antarctica and India-Australia breakup were roughly contemporaneous. We present evidence for an abandoned spreading center south of the Elan Bank micro-continent; the estimated timing of its extinction corresponds to the early surface expression of the Kerguelen Plume at the Southern Kerguelen Plateau around 120 Ma. We observe an increase in spreading rate from west to east, between chron M9 and M4 (38-54 mm/yr), along the Antarctic margin and suggest the tectono-magmatic segmentation of oceanic crust has been influenced by inherited crustal structure, the kinematics of Gondwanaland breakup and the proximity to the Kerguelen hotspot. A large, E-W oriented magnetic lineation named the Mac.Robertson Coast Anomaly (MCA), coinciding with a landwards step-down in basement observed in the seismic data, could be the boundary between continental and oceanic crust and a zone of excess melt production. The exposure of lower crustal rocks along the coast suggests that this margin formed in a metamorphic core complex extension mode with a high strength ratio between upper and lower crust, which typically occurs above anomalously hot mantle. Together with the existence of the MCA zone this suggests that a mantle temperature anomaly predated the early surface outpouring/steady state magmatic production of the Kerguelen LIP. An alternative model suggests that the northward ridge jump was limited to the Ellan Bank region, whereas seafloor spreading continued in the West Enderby Basin and its Sri Lankan conjugate margin. In this case, the MCA magnetic anomaly could be interpreted as the southern arm of a propagator that stopped around 120 million years when this crust has been transferred to the Antarctic plate.

4.2. New present day age grid of the Indian ocean

The present day agegrid of Mueller et al (1997) has been updated by adding the newly identified Enderby Basin seafloor age (Gaina et al., in review) and a new model of the development of the western Australian margin (Heine et al, 2004) (Fig. 4.2.1). We plan to add new reconstructions for the Tethys evolution and for the opening of Somali and Mozambique basins and to compute a series of palaeo-age grids for the Indian Ocean in the last year of this project.

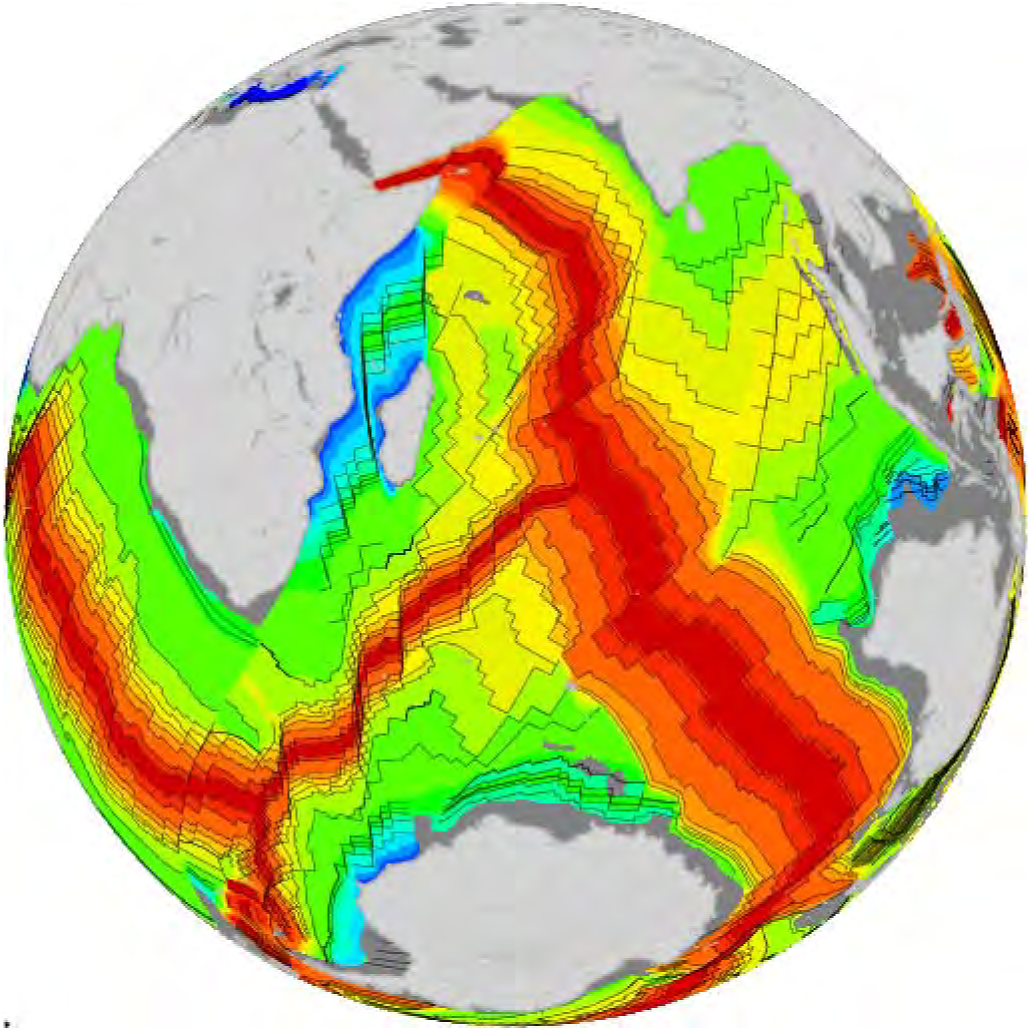


Fig. 4.2.1. Present day agegrid of the Indian Ocean.

5. LARGE IGNEOUS PROVINCES (LIPS)

5.1. *Large Igneous Provinces generated from the margins of the large low velocity provinces in the deep mantle*, Torsvik et al (GJI, 2006) – abstract

There is a clear correlation between downward projected Large Igneous Province (LIP) eruption sites of the past 200 My and the margins of the Large Low Velocity Provinces (LLVPs) at the base of the mantle. We established this correlation by using paleomagnetic as well as fixed and moving hotspot reference frames. Our finding indicates that the majority of the LIPs have been generated by plumes that rose from the D'' zone at the edges of the LLVPs. Most LIP eruption sites project radially downward to the Core Mantle Boundary (CMB) within ± 10º of the 1% slow shear wave velocity contour in the SMEAN tomographic model. Steep shear wave velocity gradients have been mapped near the CMB along much of the lengths of the LLVP margins close to that contour which marks a faster/slower boundary (FSB) within the D" zone. The observation that eruption sites of LIPs as old as 200 My can be linked to this prominent present day seismic structure shows that the FSBs of the two LLVPs have occupied their current positions for at least as long and that the process that leads to the generation of *deep-seated plumes has been localized on the FSBs at the margins of the African and Pacific LLVPs for the same interval. The persistence of the LLVPs over 200 My is consistent with independent evidence that they are compositionally distinct and are not just simply hotter than the material making up the rest of the D" zone.*

5.2. *Global plate motion frames: Toward a unified model* Torsvik et al., (ESR, in review) – abstract

Using improved plate-circuit closures we have developed and compared four different reference frames (paleomagnetic, Africa fixed hotspot, Africa moving hotspot and global moving hotspot). Concerning the paleomagnetic frame we regard zero longitudinal average motion of Africa as the best possible approximation and have developed a global 'absolute' apparent polar wander (APW) path back to the assembly of Pangea (~320 Ma). The Africa moving hotspot reference frame is exclusively based on Atlantic and Indian Ocean hotspots and is modelled back to 130 Ma; this provides the framework that best matches the paleomagnetic reference frame. The global moving hotspot frame also incorporates the Pacific realm back to 83.5 Ma. For the first time we compare Hellinger uncertainty ellipses, as derived from the Africa moving hotspot frame, with errors in mean paleomagnetic poles. From this analysis, it becomes evident that for most of the Tertiary one cannot argue for statistical significance (the average difference is only 3.7o), taking errors in both frames into account. Before 100 Ma we can demonstrate statistical differences at the 95% confidence level, but compared with fixed hotspot frames, the African moving hotspot frame significantly reduces the earlier noted mid-Cretaceous differences from about 18o to 10o, with important implications for debates concerning Cretaceous TPW, which remains a possibility (albeit of reduced magnitude) for the interval 110-130 Ma. The moving hotspot frame has added uncertainties for Early Cretaceous times because simple backward advection will be increasingly inappropriate for reconstructing past mantle density anomalies.

We have constructed the first hybrid 'absolute' reference frame model since the Carboniferous: we use a moving hotspot reference frame based on Atlantic and Indian Ocean hotspots for the last 100 Ma and for earlier times, we use the global paleomagnetic frame adjusted 5 degrees in longitude to smooth the frame transition. We also examine possible causes for kinks and cusps in the apparent polar wander paths, as extrapolated from the global frame to the individual continents, and find that we can successfully link many of them to plate tectonic reorganizations.

5.3. *Long term stability in deep mantle structure: Evidence from the ~300 Ma Skagerrak-centered Large Igneous Province (the SCLIP)* Torsvik et al., (in review) - abstract

Igneous rocks of intra-continental rifts are generated by decompression melting in response to extension but magmas generated by deep-seated mantle plumes may also find their way into intra-continental rifts by 'upside down drainage'. Consequently it can be hard to be confident that a particular set of igneous rocks in a rift is plume related. Uncertainty of this kind has long plagued research on the Oslo graben in SE Norway. We have addressed that problem within the broader framework of Permo-Carboniferous *magmatism and rifting in NW Europe, and show on the basis of (i) huge volume (>0.5 * 10^6 km^3), (ii) large areal extent and (iii) brevity of eruption interval (± 4 My), that the flare-up of igneous activity at 297 Ma in NW Europe which generated a Skagerrak-Centered Large Igneous Province (SCLIP) is the product of a deep-seated mantle plume: the Skagerrak Mantle plume. We confirm our location for the Skagerrak plume and show its derivation from the core-mantle-boundary (CMB) by restoring it, using a new reference frame, to its ca. 300 Ma position. That position (ca. 11°N, 16°E, south of Lake Chad, Central Africa) lies vertically above the edge of the African Large Low Velocity Province (LLVP). We have previously shown that eruption locations vertically above the edge of one or other of the Earth's two LLVPs at the CMB characterize nearly all the LIPs erupted since 200 Ma. Recognition of the SCLIP plume source enables us to show that the edge of the African LLVP at the CMB has not moved significantly with respect to the spin axis of the Earth during the past 300 My which is a 30% longer duration for the stability of a deep mantle structure than we have previously been able to demonstrate.*

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