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Integrated crustal thickness mapping and plate reconstructions for the high Arctic

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ABSTRACT

The plate tectonic history of the Amerasia Basin (High Arctic) and its distribution of oceanic and continental lithosphere are 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 (ArcGP) data to predict crustal thickness and continental lithosphere thinning factors which are used 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. The two end member plate reconstruction models are consistent with the gravity inversion for their prediction of the location of oceanic lithosphere within the Canada Basin but fail in the Makarov and Western Podvodnikov Basins. The hybrid model is consistent with predictions of the location of the ocean–continent transition from continental lithosphere thinning factors obtained from gravity inversion. A crustal thickness of approximately 20 km is predicted for Late Cretaceous Makarov/Podvodnikov Basins which is similar to the value obtained from seismic refraction. We suggest that this method could be used for discriminating between various plate tectonic scenarios, especially in remote or poorly surveyed regions.

1. Introduction

The kinematic evolution of the Arctic region (Fig. 1a) is poorly understood. The crustal structure, age and origin of some of the main tectonic blocks (e.g. Alpha Ridge, Mendeleev Ridge and the Makarov and Podvodnikov Basins) are not well resolved. However, new data collection (ACEX expedition etc.) and compilations (the 'Arctic Gravity Project' (ArcGP (Forsberg and Kenyon, 2004)), new magnetic gridded data (Verhoef et al., 1996; Glebovsky et al., 1998; Kovacs et al., 2002) Fig. 1b and c) offer the opportunity to address the evolution of the Arctic region in greater detail. We have used the new geophysical potential field gridded data (Glebovsky et al., 1998; Forsberg and Kenyon, 2004) to construct plate tectonic models for the Arctic oceanic basins, and model their present day crustal thickness. The plate tectonic models are tested for consistency using continental lithosphere thinning factor, crustal thickness and ocean–continent transition (OCT) location predicted by gravity inversion. The gravity inversion, which incorporates a lithosphere thermal gravity anomaly correction (Greenhalgh and Kusznir, 2007; Chappell and Kusznir, 2008b), has been applied to the Arctic region to obtain the first regional estimate of crustal thickness and continental lithosphere thinning factor. The lithosphere thermal gravity anomaly is a large negative gravity signal within oceanic and rifted continental margin lithosphere for which a correction must be made in order to determine crustal thickness by gravity anomaly inversion. To calculate the lithosphere thermal gravity anomaly, the position of the OCT, the age of the oceanic lithosphere and the rift age of the continental margin lithosphere must be known. The age of the oceanic lithosphere in many cases may be inferred from magnetic anomaly data, however in the Amerasia Basin the magnetic signature has been overprinted by later volcanism or the orientation of the magnetic lineations leads to non-unique solutions (Fig. 1c). Therefore, plate tectonic rules and other geological and geophysical evidence have been used to model

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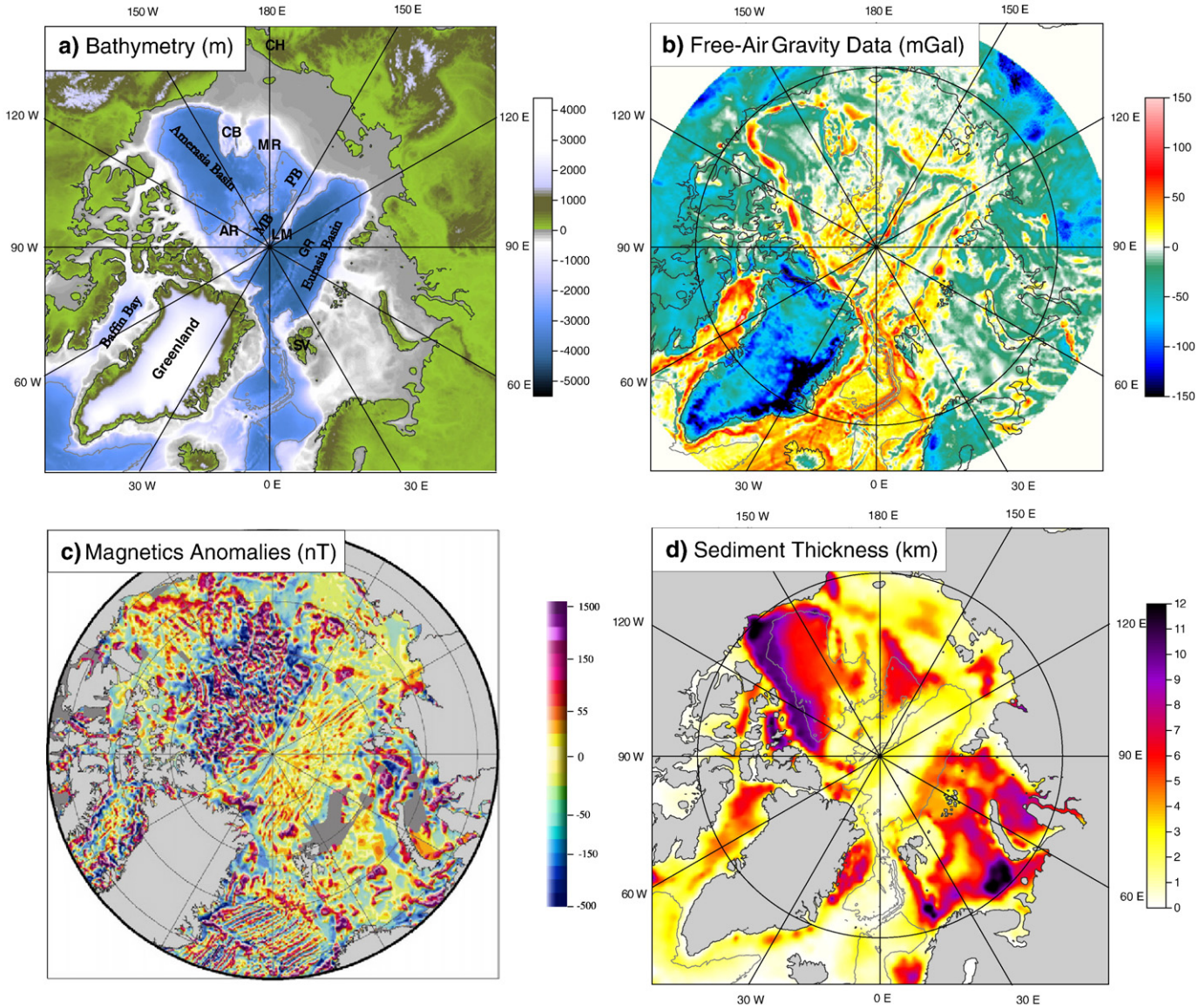


Fig. 1. (a) Bathymetry-topography (m) from IOC, IHO and BODC (2003), (b) free-air gravity anomalies (mGal) from ArcGP Project (free-air data for regions below sea-level and Bouguer including ice thickness correction for regions above sea-level) (Forsberg and Kenyon, 2004), (c) magnetic anomaly data (nT) (Verhoef et al., 1996; Glebovsky et al., 1998), d) sediment thickness data (km) (Laske et al., 1997). AR = Alpha Ridge, CB = Chukchi Borderlands, CH = Chukotka, GR = Gakkel Ridge, LM = Lomonosov Ridge, MR = Mendeleev Ridge, PB = Podvodnikov Basin, SV = Svalbard.

the tectonic evolution of the Arctic region. In this paper we present crustal thickness maps calculated by gravity anomaly inversion for two distinct plate reconstruction models for the Amerasia Basin and a model for the opening of the Eurasia Basin and North Atlantic by Gaina et al. (2002). The predicted crustal thickness maps shown within this paper are calculated for the Arctic region going down to 65°N with the inclusion of the southern tip of Greenland; however the results outside the Amerasia and Eurasia Basins are not discussed within this paper.

Prior to 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 with trapped Pacific ocean crust (Churkin and Trexler, 1981), has also been postulated. The rotational model is apparently supported by paleomagnetic data (Halgedahl and Jarrard, 1987), stratigraphic studies of the North Slope and Sverdrup basin margins, and a fan-shaped magnetic pattern observed in the southern Canada Basin. Recent paleomagnetic data by Lewchuk et al. (2004) also suggest that the North Alaska terrane may have been involved in rotation during the opening of the Canada Basin. However, in recent reviews of the age and geology of the rifted margins (i.e. North Slope of Alaska and Canadian northern margin), and 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 (Grantz et al., 1998) vs. Late Jurassic–Late Cretaceous (Lane, 1997)). Additional evidence for a strike-slip component associated with the opening of the Canada Basin has been presented by Miller et al. (2006); they showed that the Chukotka block has not traveled as far away from the northern Eurasian margin as implied by the rotational models.

Well-preserved magnetic isochrons that are relatively easy to identify have allowed a straightforward interpretation of the Eurasian Basin (Gaina et al., 2002; Gaina et al., 2005). Most authors have identified

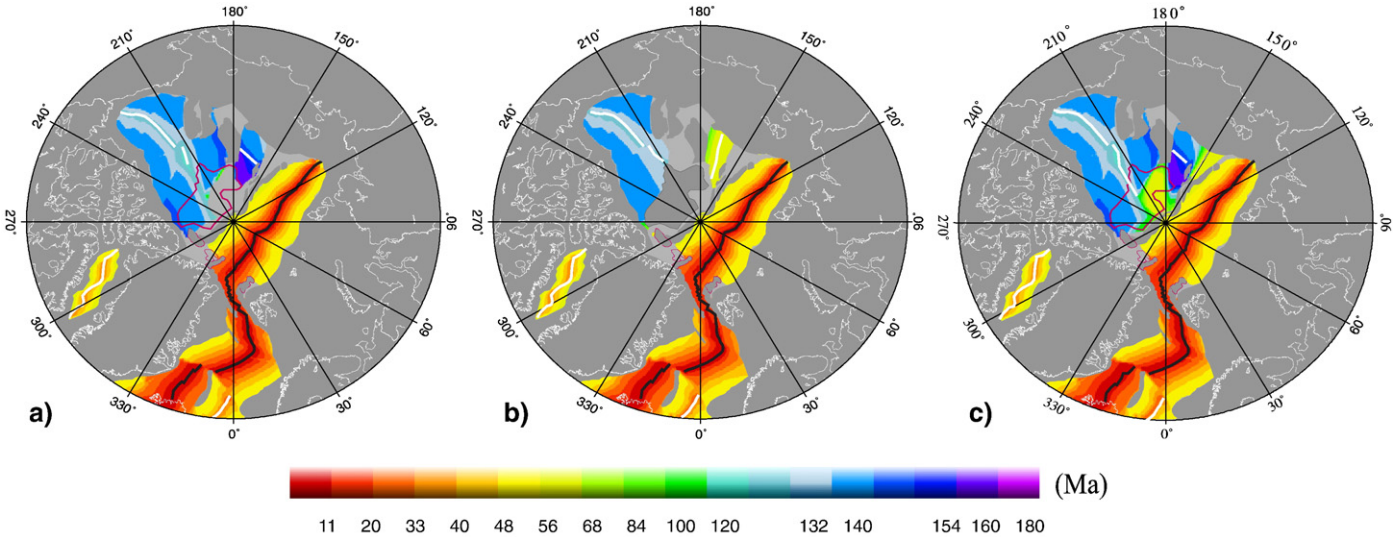


Fig. 2. Present day oceanic age grids and coastlines for the Arctic region. (a) Plate reconstruction model 1; Mendeleev Ridge is rifted from the Canadian continental margin at 150 Ma with a conventional rotational opening of the Amerasia Basin. (b) Plate reconstruction model 2; Mendeleev Ridge is rifted from Lomonosov Ridge/Barents Sea Margin at 71 Ma with the Amerasia Basin opening in a rotational fashion beginning at 140 Ma. (c) Plate reconstruction model 3; a hybrid model containing older trapped and younger oceanic floor within the Makarov Basin.

chron 24 (ca. 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 (ca. 55 Ma) in the proximity of Lomonosov Ridge. If correct, this structure implies that the opening of the Eurasian Basin may have been linked to the evolution of Baffin Bay and the Labrador Sea (Brozena et al., 2003).

In this study we examine three models (Fig. 2) for the opening of the Amerasia Basin taking into account that new seismic data (Kaminsky, 2005; Lebedeva-Ivanova et al., 2006) predict that part of the Mendeleev Ridge is continental in origin. The models have been created by varying the initial position of Mendeleev Ridge, with model 1 having the ridge rifting off the Canadian continental margin juxtaposed to the Chukchi Borderlands, model 2 having Mendeleev Ridge rifting from the Lomonosov Ridge (Eurasia) and model 3 being a hybrid of the first two models. The location of the ocean–continent transition (OCT) and the age of oceanic lithosphere are two of the most significant input parameters into the thermal model which is used within a 3D gravity inversion to obtain predicted crustal thickness for the region.

2. Crustal thickness mapping using gravity inversion with a lithosphere thermal gravity anomaly correction

The observed ArcGP free-air gravity anomaly Δg_{fag}, corrected for the negative gravity anomaly signal from bathymetry Δg_b, sediment thickness Δg_s (if no sediment thickness data are available then we set $\Delta g_s = 0$) and the lithosphere thermal gravity anomaly Δg_t to give the mantle residual gravity anomaly Δg_{mra}, has been used to calculate Moho topography.

$$\Delta g_{mra} = \Delta g_{fag} + \Delta g_b + \Delta g_s + \Delta g_t \quad (1)$$

Moho topography Δr has been calculated from the mantle residual gravity anomaly Δg_{mra} using the mathematical scheme derived by Parker (1973).

$$F[\Delta g_{mra}] = 2\pi G \Delta\rho e^{-|k|z_0} \sum_{n=1}^{\infty} \frac{(|k|)^{n-1}}{n!} F[\Delta r^n] \quad (2)$$

where z_o is the mean Moho depth, $G = 6.67 \times 10^{-11}$ (N m^2 kg^{-2}), $\Delta\rho = \rho_m - \rho_c$ and is the density contrast between mantle and crust, F denotes a Fourier transform and k is wavenumber. The assumption is made that the mantle residual gravity signal Δg_{mra} is caused solely by the variations in the depth to the Moho. Prior to the inversion of Δg_{mra} to determine Moho topography, the Δg_{mra} must be filtered to remove the high frequency components within the data. A Butterworth low-pass filter with a cut-off wavelength of 100 km has been used (Chappell and Kusznir, 2008b). Densities for sea-water ρ_w, crust ρ_c and mantle ρ_m used in the bathymetric correction and Moho gravity inversion are 1039 kg m^{-3}, 2850 kg m^{-3} and 3300 kg m^{-3} respectively.

Moho depth d and crustal thickness ct may be calculated from Moho topography Δr, the Moho reference depth d_{ref} and bathymetry b.

$$d = d_{ref} + \Delta r \quad (3)$$

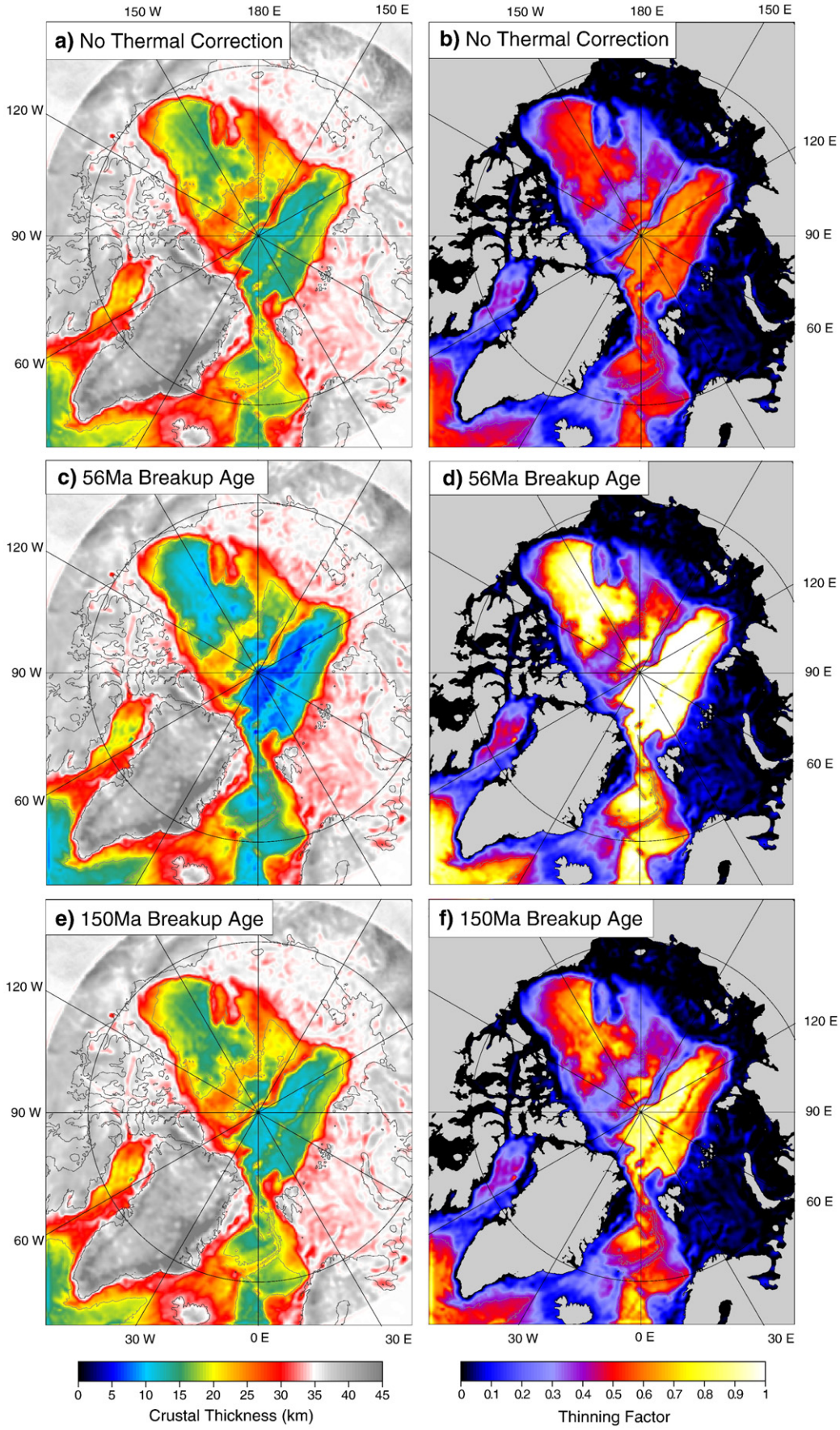
$$\mathrm{ct} = d - b. \quad (4)$$

The Moho reference depth d_{ref} may be determined by calibration using seismic refraction and corresponds to the thickness of crust that has zero bathymetry and zero long wavelength free-air gravity anomaly, and which has values in the range of 35–40 km (Mooney et al., 1998).

If sediment thickness data are available, a gravity anomaly correction for sediments may also be made (Chappell and Kusznir, 2008a). If no sediment thickness is used in the gravity inversion, the predicted crustal thickness and continental lithosphere thinning factors are upper and lower bounds respectively. Within the Arctic a 1° sediment thickness grid (Laske et al., 1997) is available; however no high resolution regional sediment thickness data exist. We compare crustal thickness and continental lithosphere thinning factors from gravity inversion predicted with and without a sediment thickness correction.

Fig. 3a shows the predicted crustal thickness values obtained when the gravity inversion is run without sediment correction and without any lithosphere thermal gravity anomaly correction (discussed later). This figure shows that crustal thicknesses approaching 20 km are

Fig. 3. (a) Predicted crustal thickness obtained from gravity inversion without using a lithosphere thermal gravity anomaly correction (TGC). (b) Corresponding continental lithosphere thinning factor. (c) Predicted crustal thickness obtained from gravity inversion with a TGC treating the entire region as continental with a uniform rift age of 56 Ma and volcanic addition prediction corresponding to a volcanic rifted margin. (d) Corresponding lithosphere thinning factor. (e) Predicted crustal thickness obtained from gravity inversion with a TGC treating the entire region as continental and volcanic addition prediction corresponding to a volcanic rifted margin. (f) Corresponding lithosphere thinning factor. A reference crustal thickness of 35 km is used in all cases.


a) No Thermal Correction
b) No Thermal Correction
c) 56Ma Breakup Age
d) 56Ma Breakup Age
e) 150Ma Breakup Age
f) 150Ma Breakup Age
150 W
180 E
150 E
120 W
90 W
60 W
120 E
90 E
60 E
30 W
0 E
30 E
0 5 10 15 20 25 30 35 40 45
Crustal Thickness (km)
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1
Thinning Factor

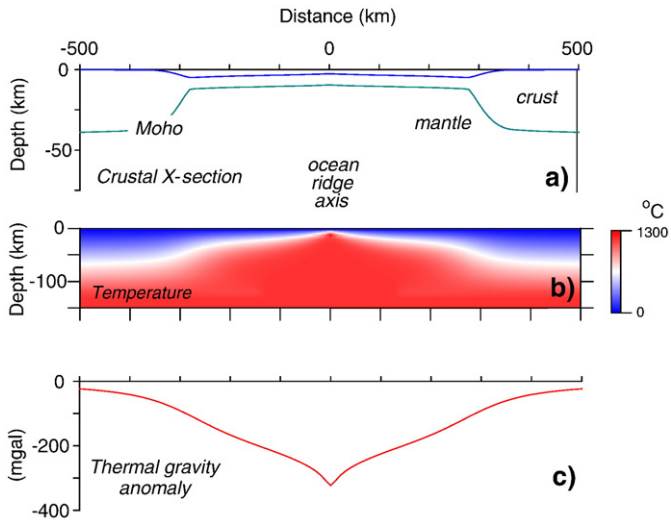


Fig. 4. (a) Lithosphere structure for a theoretical ocean basin and rifted continental margin after breakup and seafloor spreading for 25 Ma. (b) Cross-section showing lithosphere and asthenosphere temperature structure. (c) Corresponding lithosphere thermal gravity anomaly.

predicted under the Gakkel Ridge, and crustal thinning estimates (Fig. 3b) show continental lithosphere thinning values of ~0.5 (i.e. beta stretching values of ~2) for the oceanic regions which by definition should be 1.0 for oceanic lithosphere.

Seafloor spreading within oceanic lithosphere and stretching and thinning in the adjoining rifted continental margin lithosphere gives an elevated lithosphere geotherm. The lithosphere thermal gravity anomaly is caused by the lateral variation in temperature and therefore density between hot oceanic and rifted continental margin lithosphere and cool unstretched continental lithosphere. Fig. 4 shows calculated lithosphere thermal gravity anomaly across a schematic ocean basin and rifted continental margin. The thermal gravity anomaly, which at the ocean ridge may be as much as −380 mGal, decays away from the ocean ridge but may still be substantial within rifted continental margin lithosphere.

The calculation of the lithosphere thermal gravity anomaly correction requires the construction of a lithosphere thermal model for oceanic and rifted continental margin lithosphere. The initial perturbation of the geotherm within oceanic and rifted margin lithosphere is described by the lithosphere stretching factor β (McKenzie, 1978). Lithosphere temperature has been calculated using a three dimensional finite difference solution. A lithosphere thickness a of 125 km and base lithosphere temperature T_m of 1300 °C have been used (McKenzie, 1978). The density contrast $\Delta\rho_t$ arising from lateral variations in lithosphere temperature, which causes the lithosphere thermal gravity anomaly, has been calculated using:

$$\Delta\rho_t = \rho\alpha\Delta T. \tag{5}$$

The lithosphere thermal gravity anomaly at the lithosphere surface is then calculated from the three dimensional distribution of $\Delta\rho_t$.

The lithosphere thermal model requires, at each model location, the lithosphere β factor used to define the lithosphere temperature perturbation and lithosphere thermal re-equilibration time. For oceanic lithosphere $\beta=\infty$ and the thermal equilibration time is the age of the oceanic lithosphere at that location. For continental margin lithosphere, the lithosphere β factor is estimated from the thinning of the continental crust and is given by:

$$\beta = \mathrm{ct}_0/\mathrm{ct}_{\mathrm{now}} \tag{6}$$

where ct_0 is the initial thickness of the continental crust and $\mathrm{ct}_{\mathrm{now}}$ is the present continental crustal thickness derived from gravity anomaly inversion. Lithosphere thinning is assumed to be equivalent to crustal thinning.

For very thin rifted continental margin lithosphere adjacent to the oceanic–continent transition (and for oceanic lithosphere) volcanic addition from the seafloor spreading process results in crustal thickening. If va is the thickness of volcanic addition resulting from the seafloor spreading process then a correction may be made:

$$\beta = \mathrm{ct}_0/(\mathrm{ct}_{\mathrm{now}} - va). \tag{7}$$

The thickness of volcanic addition va may be estimated from the lithosphere thinning factor γ where $\gamma=1-1/\beta$ using the adiabatic decompression melt generation model predictions of White and McKenzie (1989) and Bown and White (1994). For this we must define a critical thinning factor for the initiation of oceanic crust production, and a maximum oceanic crustal thickness. A schematic diagram showing the variation of volcanic addition va with thinning factor γ is shown in Fig. 5. The relationship between va and γ depends on asthenosphere temperature and therefore the proximity of a mantle plume (White and McKenzie, 1989; Bown and White, 1994). Different relationships between va and γ are expected for volcanic and non-volcanic margins.

The β factor derived in Eq. (7) is used to define the continental lithosphere thermal perturbation of the three dimensional lithosphere thermal model used to calculate the lithosphere thermal gravity anomaly. The inclusion of the lithosphere thermal gravity anomaly correction modifies the estimate of crustal thickness determined for each location from the gravity inversion. This in turn modifies the β factor for the continental lithosphere and lithosphere thermal gravity anomaly correction. The cycle of gravity inversion to predict crustal and update of β stretching factor and lithosphere thermal gravity anomaly is carried out iteratively and rapidly converges.

In the absence of oceanic ages from isochrons or from plate reconstructions, an alternative strategy may be used to condition the lithosphere thermal model used to define the lithosphere thermal gravity anomaly correction. In this alternative approach, the whole region is treated as continental lithosphere with a thermal re-equilibration time equal to the continental breakup and seafloor spreading initiation age.

The effects of applying the lithosphere thermal gravity anomaly correction (using different continental rift ages of 56 Ma and 150 Ma) are shown in Fig. 3c, d, e and f for comparison with Fig. 3a and b which were calculated with no lithosphere thermal gravity anomaly correction. The 56 Ma continental rift age is more applicable to the Eurasia Basin and North Atlantic Margins whereas the 150 Ma continental rift age is more applicable to the Amerasia Basin margins.

Without the lithosphere thermal gravity anomaly correction we predict crustal thicknesses in excess of 20 km within the Eurasia and Amerasia Basins, but with the lithosphere thermal gravity anomaly correction this can be reduced to ~7 km which is a more realistic value for the thickness of the oceanic crust. As already noted these results contain no sediment correction and therefore give an upper bound to the maximum crustal thickness of the crust within the region.

3. Using plate reconstructions to refine the lithosphere thermal gravity anomaly correction

The lithosphere thermal gravity anomaly correction used in the gravity inversion to predict crustal thickness is highly dependent on the age of the oceanic lithosphere and the rift age of the continental

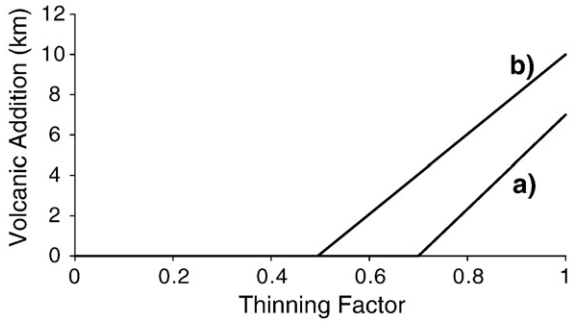


Fig. 5. Predicted volcanic addition as a function of continental lithosphere thinning factor for (a) a non-volcanic margin and (b) a volcanic rifted margin.

margin used. Therefore, crustal thicknesses predicted by the 3D gravity inversion are directly related to the age of the oceanic lithosphere and hence the plate reconstruction model used to obtain the oceanic lithospheric age.

3.1. Age and opening of the Eurasia Basin

The Eurasian Basin, is the youngest oceanic basin within the Arctic and its tectonic history is well constrained by well-preserved magnetic lineations. We have used Gaina et al. (2002) rotation parameters for 0 to 53.3 Ma, with an additional pole for chron 25 (55.9 Ma) for the southern Eurasian Basin.

3.2. Age and opening of the southern Amerasia Basin (Canada Basin)

The opening of the Amerasia Basin is poorly constrained and the uncertainty of the Amerasian Basin age increases for oceanic areas closer to the Alpha-Mendeleev Ridge due to poor data coverage and volcanism that hinders the magnetic signature interpretation.

We have based our models of the evolution of the Canada Basin on previous published models with a re-interpretation of the age of the oceanic crust based on gridded magnetic data (Glebovsky et al., 1998) and regional geology. It has been proposed that the present day configuration of the Canada Basin oceanic crust is due to the rotation and (some) relative strike-slip motion between the Northern Slope of Alaska (NS), Chukchi Borderland (CB) and Northwind Ridge (NR) (Grantz et al., 1998). Lawver et al. (1999) described a new set of aeromagnetic data acquired in the Canada Basin, and Brozena et al. (1999) suggested a three stage opening that would have formed a more complex pattern of magnetic lineations than the previously accepted fan-shaped evolution. Grantz (2006) has proposed that the Amerasian Basin is the product of two phases of anti-clockwise rotation: starting with the production of a 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 ((Glebovsky et al., 1998) Fig. 1c) and adjacent margins, and have modelled the following successions of events that led to the formation of the present day oceanic crust in the Canada Basin.

3.2.1. Pre-breakup extension before 145 Ma

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 seems 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, 1985). However, numerous stages of deformation of the Brooks Range from the Jurassic to Tertiary and their correlations with the North Pacific tectonics cannot be directly related to the inferred ages of breakup 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).

3.2.2. Seafloor spreading between 143 and 126 Ma by rifting the Alaskan Northern Slope from the Canadian margin (see Table 1 for finite rotation poles)

As the magnetic record in the Canada Basin shows a complex pattern one could infer at least 2 different stages of oceanic crust formation. 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 age of the magnetic lineations could be inferred only in conjunction with the geology of the margins and tectonic events succession. Considering that breakup 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 and Hart (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 ceased probably in Early Aptian as a result of the North Asian collision. 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 Chukotka peninsula (Toro et al., 2003) (Table 1).

3.2.3. Convergence between the Northwind Ridge and northern part of Canada

A prominent free-air gravity anomaly is visible parallel to the Northwind Ridge and the magnetic lineations in the north-western part of the basin are truncated. We suggest that an independent rotation of the Northwind Ridge/Chukchi Plateau caused deformation in that region probably toward the end of the seafloor spreading regime or shortly afterward.

3.3. Age and opening of North Amerasian Basin (including Makarov/Podvodnikov Basins)

Jakobsson et al. (2003) identify in the present day bathymetry of the Amerasian Basin several basins: the Stefansson and Nautilus Basins in the NE and NW of Canada Basin, the Fletcher Abyssal plain and the Wrangel Basin between the Alpha-Mendeleev Ridge and Lomonosov Ridge (also known as Makarov and Podvodnikov Basins in

Table 1
Rotation parameters for the opening of the Canada Basin (North Slope-Alaska relative to North America)

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

the Russian literature). Several authors have treated the Podvodnikov Basin as a continuation of the Makarov Basin.

Recent studies brought evidence for a continental crust underlying at least part of the Mendeleev Ridge (Kaminsky, 2005; Lebedeva-Ivanova et al., 2006). On the other hand, it has been suggested that the Chukotka tectonic unit has not been rifted from the northern North American margin (Miller et al., 2006); therefore, the Amerasian Basin must have been created by rifting the Northwind–Chukchi Borderland,

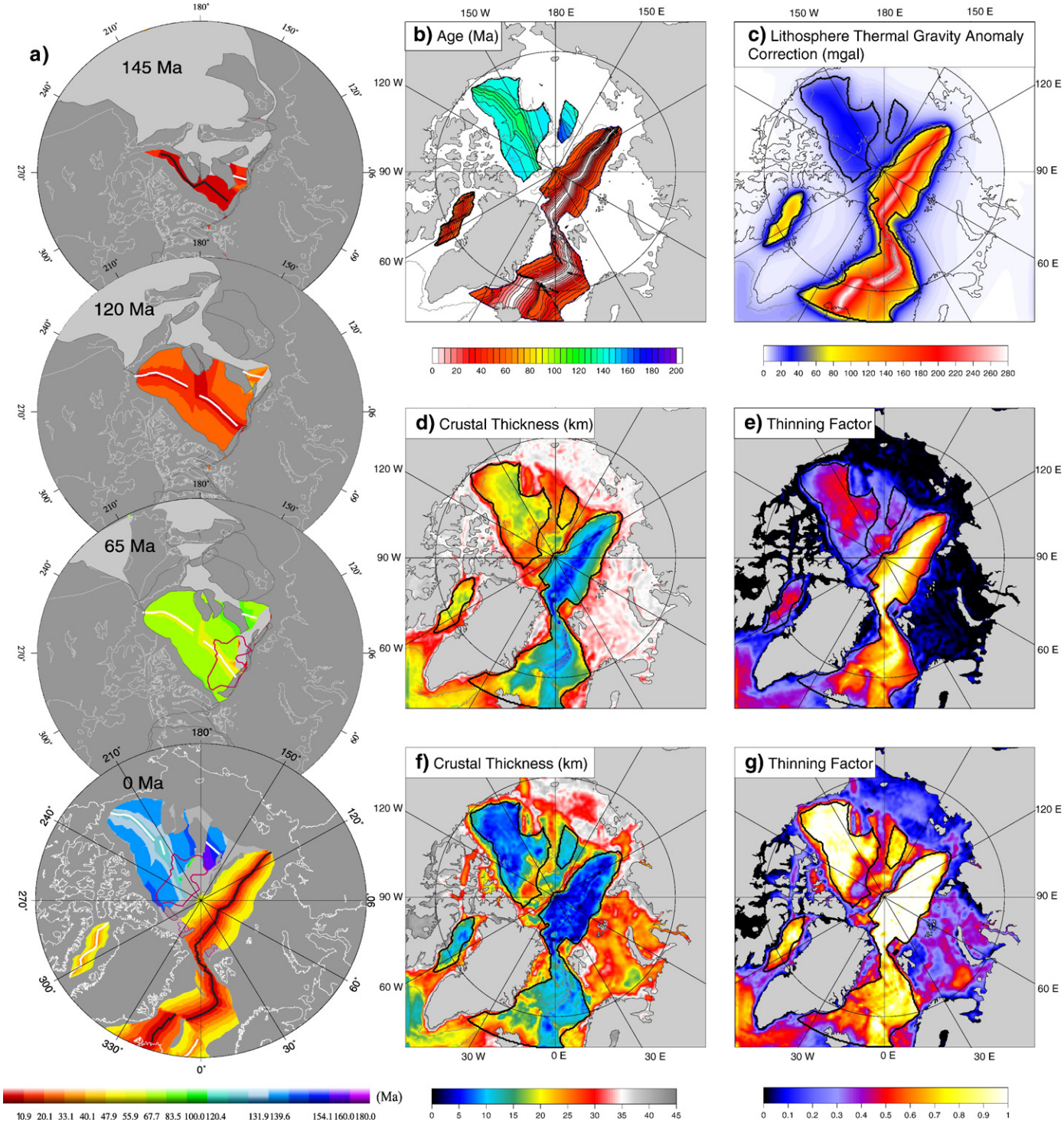


Fig. 6. (a) Set of plate tectonic reconstructions — model 1. Reconstructions are shown in a Eurasian plate fixed reference frame. 145 Ma — shows the initiation of the breakup of Mendeleev Ridge from the Canadian continental margin. The older ocean basin observed is the South Anyui ocean basin, which will be subducted during the opening of the Amerasia Basin. 120 Ma — the Amerasia Basin has opened fully, halted by the grounding of the Chukchi Borderlands against the Russian continental margin at this time. Mendeleev Ridge is now in its final position, with a block of the South Anyui Ocean still present. 65 Ma — after a period of compression between the North American Block and the Eurasian Block, a period of extension occurs, this results in a narrowing of the Makarov Basin. The opening of the Labrador Sea is initiated at this time (Chalmers and Laursen, 1995). 0 Ma — the present day oceanic age grid. (b) Predicted age (Ma) for the oceanic lithosphere within the Amerasia Basin with isochrons for the North Atlantic and Eurasia Basin as defined by Gaina et al. (2005, 2002). (c) Lithosphere thermal gravity anomaly correction (mGal) at surface. (d) Predicted crustal thickness (km) obtained from the gravity inversion without a sediment correction using the predicted age grid shown in b. (e) Continental lithosphere thinning factors corresponding to d. (f) Predicted crustal thickness (km) obtained from the gravity inversion using a sediment thickness correction and the predicted age grid shown in b. (g) Continental lithosphere thinning factors corresponding to f. OCTs used within the plate reconstruction model are indicated by a black line.

and the Mendeleev Ridge. Most of the Eastern Siberian Shelf, including the New Siberian Islands may 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 has experienced 100% stretching.

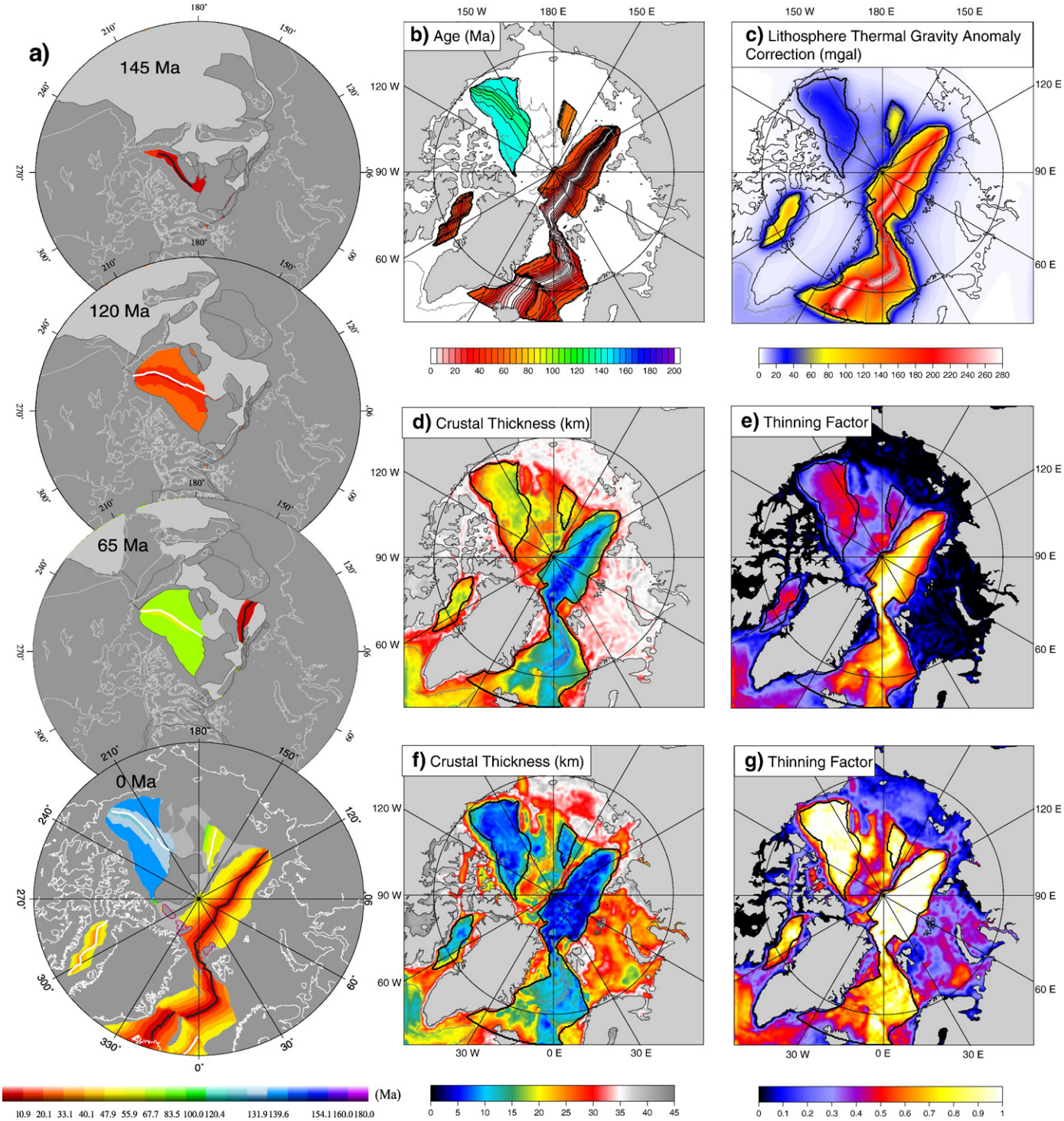


Fig. 7. (a) Set of plate tectonic reconstructions — model 2. Reconstructions are shown in a Eurasian plate fixed reference frame. 145 Ma — shows the pre-breakup geography of the Amerasia Basin. The ocean basin observed is the South Anyui ocean basin, which will be subducted during the opening of the Amerasia Basin. Mendeleev Ridge is juxtaposed to Lomonosov Ridge. 120 Ma — the Amerasia Basin has opened fully, halted by the grounding of the Chukchi Borderlands against the Russian continental margin at this time. Mendeleev Ridge is still in its original position. 65 Ma — after a period of compression between the North American Block and the Eurasian Block, a period of extension occurs resulting in the rifting of Mendeleev Ridge from the Lomonosov Ridge/Barents Sea Margin. This results in the subduction of part of the older Amerasia Basin. The opening of the Labrador Sea is initiated at this time (Chalmers and Laursen, 1995). 0 Ma — the present day oceanic age grid. (b) Predicted age (Ma) for the oceanic lithosphere within the Amerasia Basin with isochrons for the North Atlantic and Eurasia Basin as defined by Gaina et al. (2005, 2002). (c) Lithosphere thermal gravity anomaly correction (mGal) at surface. (d) Predicted crustal thickness (km) obtained from the gravity inversion without a sediment correction using the predicted age grid shown in b. (e) Continental lithosphere thinning factors corresponding to d. (f) Predicted crustal thickness (km) obtained from the gravity inversion using a sediment thickness correction and the predicted age grid shown in b. (g) Continental lithosphere thinning factors corresponding to f. OCTs used within the plate reconstruction model are indicated by a black line.

The age of the Makarov/Podvodnikov Basin is poorly constrained; most of the published models suggest a Mid or Late Cretaceous to Paleocene age (Weber and Sweeney, 1990; Grantz et al., 1998).

These uncertainties lead us to examine three new scenarios for the age and opening of the Makarov/Podvodnikov Basin, in which we assign an Early to Mid Cretaceous age to the Canada Basin and vary the

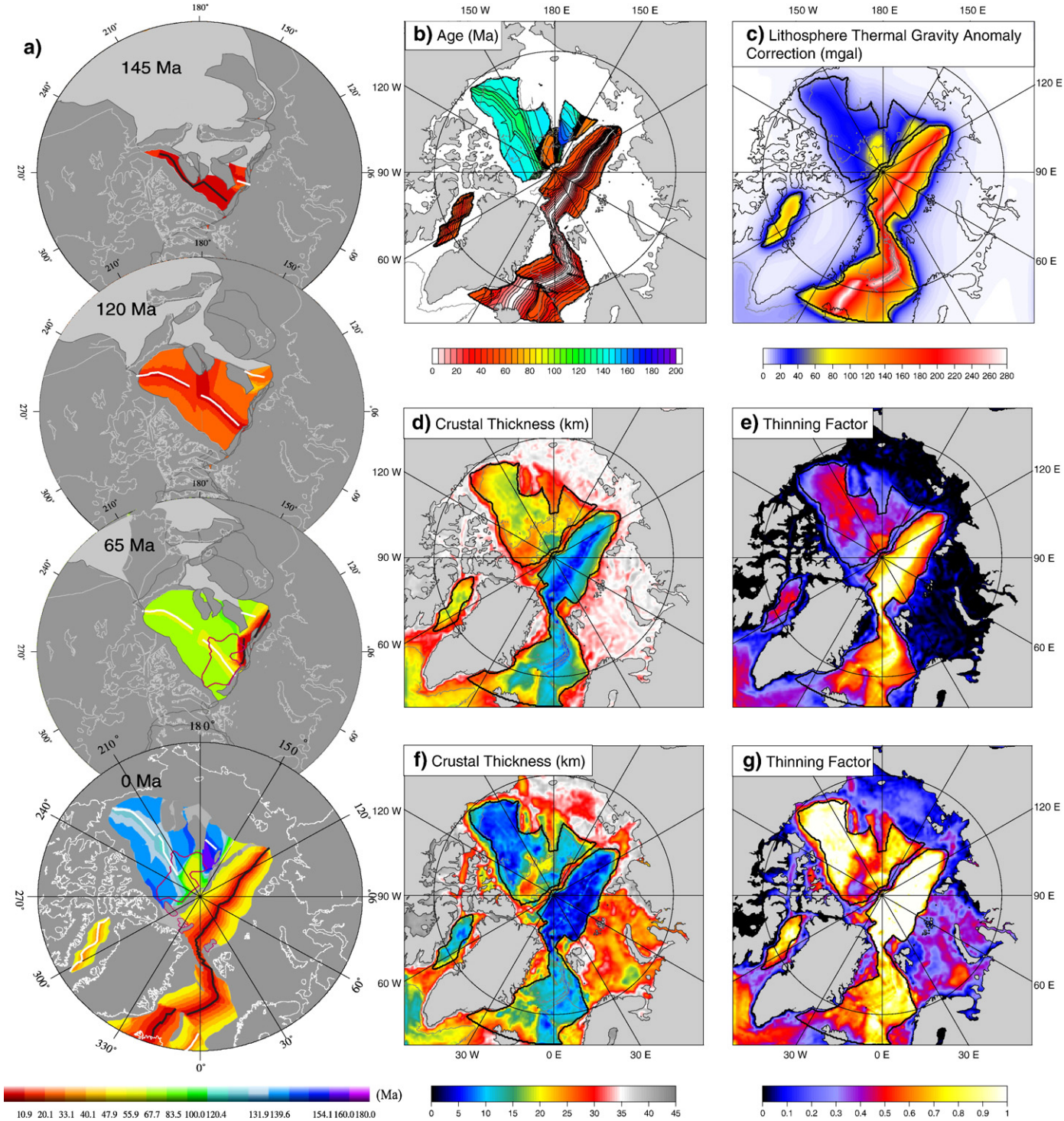


Fig. 8. (a) Set of plate tectonic reconstructions — model 3. Reconstructions are shown in a Eurasian plate fixed reference frame. 145 Ma — shows the initiation of the breakup of Mendeleev Ridge from the Canadian continental margin. The older ocean basin observed is the South Anyui ocean basin, which will be subducted during the opening of the Amerasia Basin. 120 Ma — the Amerasia Basin has opened fully, halted by the grounding of the Chukchi Borderlands against the Russian continental margin at this time. 65 Ma — after a period of compression between the North American Block and the Eurasian Block, a period of extension occurs resulting in the rifting of Mendeleev Ridge from the Lomonosov Ridge/Barents Sea Margin. This results in the subduction of part of the older Amerasia Basin. The opening of the Labrador Sea is initiated at this time (Chalmers and Laursen, 1995). 0 Ma — the present day situation with predicted ocean age. (b) Predicted age (Ma) for the oceanic lithosphere within the Amerasia Basin with isochrons for the North Atlantic and Eurasia Basin as defined by Gaina et al. (2005, 2002). (c) Lithosphere thermal gravity anomaly correction (mGal) at surface. (d) Predicted crustal thickness (km) obtained from the gravity inversion without a sediment correction using the predicted age grid shown in b. (e) Continental lithosphere thinning factors corresponding to d. (f) Predicted crustal thickness (km) obtained from the gravity inversion using a sediment thickness correction and the predicted age grid shown in b. (g) Continental lithosphere thinning factors corresponding to f. OCTs used within the plate reconstruction model are indicated by a black line.

age and nature of the crust between (and within) the Alpha Ridge and Mendeleev and Lomonosov Ridges. In all scenarios it is assumed that the Mendeleev Ridge and the Northwind/Chukchi borderland are continental (Grantz et al., 1998; Lebedeva-Ivanova et al., 2006).

3.4. Model 1 — trapped Jurassic crust from the South Anyui Basin

This plate reconstruction (Fig. 6a) proposes that an older piece of oceanic crust remained attached west of the continental Mendeleev Ridge when Amerasian Basin opened and is now flooring part of the Podvodnikov Basin. Most of the oceanic crust that was later (Mid Cretaceous) heavily intruded by volcanic material is interpreted to be Mid to Late Jurassic oceanic crust formed between the Northwind–Chukchi Borderland–Mendeleev Ridge and Sverdrup basin margin. The amount of seafloor spreading and its direction has been inferred from the overall architecture 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.

The modelled present day oceanic lithospheric age grid is displayed in Fig. 6b. The regions which contain no colour are designated to be continental crust with a rift age of 150 Ma in accordance with the breakup age of the Canada Basin within the model. This age grid was used within the gravity inversion to define the lithosphere thermal gravity anomaly correction (Fig. 6c) and hence obtain a prediction of crustal thickness (Fig. 6d and f).

By using continental lithosphere thinning factors (Fig. 6e and g) we can test the plate reconstruction model for consistency. By definition, areas with a continental lithosphere thinning factor of 1.0 are oceanic. The plate reconstruction model and gravity inversion predictions (when the sediment thickness correction is included) are consistent within the Canada and Eastern Podvodnikov Basins, however the plate reconstruction model predicts there to be continental crust within the Makarov and Western Podvodnikov Basins whereas the continental thinning factor map from gravity inversion indicates oceanic lithosphere (or highly attenuated continental lithosphere). For Alpha Ridge the gravity inversion predicts a crustal thickness greater than expected for normal oceanic crust; this may imply that the assumption of Alpha Ridge being oceanic is incorrect or alternatively that Alpha Ridge is anomalously thick oceanic crust. The lithosphere thermal gravity anomaly correction within the Podvodnikov Basin is ~15 mGal which modifies the Moho depth prediction very little with respect to the gravity inversion without a thermal gravity anomaly correction. Without a sediment thickness correction the crust is predicted to be 23–25 km thick within the basin however when sediment thickness is taken into account (Fig. 6f) the crustal thickness within the basin is predicted to be 10–12 km thick.

3.5. Model 2 — Late Cretaceous–Early Tertiary basin

In this model (Fig. 7a) we suggest that the Mendeleev Ridge rifted from the Lomonosov Ridge being transferred from the Eurasian plate to the North American plate. According to the regional plate tectonics, extension in this area was not possible before Late Cretaceous–Early Tertiary as North American plate was in convergence with the Eurasian plate. Assuming that the Northwind Ridge/Chukchi Borderland were part of the North American plate and the Mendeleev Ridge was attached to the Lomonosov Ridge (and therefore to the Eurasian plate), an extensional plate boundary might have developed between the two plates before propagating eastward into the Eurasian Basin. This extension could have created approximately 300 km of oceanic crust in the Podvodnikov Basin from 67 to 60 Ma, although, no major tectonic events have been recorded by the East Siberian Continental shelf basins whose subsidence history shows tectonic quiescence since the Late Cretaceous (Franke and Hinz, 2005). In this model Alpha Ridge corresponds to stretched continental lithosphere since the position of Mendeleev Ridge would hinder the formation of oceanic crust in the Alpha Ridge region. This hypothesis has been suggested by several authors in the past, and more recently by Coakley (2005).

This present day oceanic lithospheric age grid (Fig. 7b) was used to condition the lithosphere thermal gravity anomaly correction (Fig. 7c), and predicts a thermal gravity anomaly correction of ~70 mGal within the Podvodnikov Basin. The thermal gravity anomaly correction observed within the basin is due to the younger age of the lithosphere in this model, and has the effect of decreasing the Moho depth predicted.

The predicted continental lithosphere thinning factors from gravity inversion (Fig. 7e and g) and the plate reconstruction model are consistent within the Canada and Eastern Podvodnikov Basins. However the plate reconstruction model predicts there to be continental crust within the Makarov and Western Podvodnikov Basins whereas the continental thinning factor map from gravity inversion indicates oceanic lithosphere (or highly attenuated continental lithosphere). This plate reconstruction model also fails to predict oceanic lithosphere in the basin directly north of the Chukchi Borderlands (Nautilus Basin). A crustal thickness of ~18 km is predicted within the Podvodnikov Basin (Fig. 7d) but when a sediment correction is included (Fig. 7f) the crustal thickness predicted is reduced to ~7 km (a more typical value for the thickness of oceanic crust). Within this model, the Alpha Ridge is assumed to be stretched continental lithosphere and so has a lower lithospheric thermal gravity anomaly correction, and the crustal thickness predicted over this region is ~2 km thicker than the previous model.

3.6. Model 3 — combined–trapped Jurassic crust and Tertiary basins

This plate reconstruction model (Fig. 8a) combines the two previous hypotheses by suggesting a Jurassic–Early Cretaceous age for the Podvodnikov Basin and Tertiary age for the Makarov and South of Podvodnikov Basin crust.

The modelled oceanic age grid (Fig. 8b) has been used to condition the lithosphere thermal gravity anomaly correction (Fig. 8c). The resulting continental lithosphere thinning factors from gravity inversion (Fig. 8e and g) show consistency with the plate reconstruction for the entire Amerasia Basin. The only discrepancy is Alpha Ridge, which the plate reconstruction model assumes is entirely oceanic, however, the continental lithosphere thinning factor maps predict it to be thinned continental lithosphere. This result can be accounted for by volcanic addition if we assume that ~20 km of volcanic material has been added to oceanic crust to form Alpha Ridge.

Within the Makarov Basin (near the North Pole) a large lithosphere thermal gravity anomaly correction of ~100 mGal is predicted, and within the Western Podvodnikov Basin the lithosphere thermal gravity anomaly correction is ~70 mGal. However, within the Eastern Podvodnikov Basin the correction is much smaller at ~20 mGal. The effects of these different corrections can be seen in the predicted crustal thickness (Fig. 8d) where crustal thickness values of <15 km are predicted within the Makarov Basin, whereas in the Podvodnikov Basin values approaching 23 km are predicted. When a sediment correction is included (Fig. 8f) the predicted crustal thickness lowers to 7–10 km for both basins.

4. Discussion and summary

Existing plate reconstruction models proposed for the Amerasia Basin in the Arctic are inadequate to explain the tectonic feature observed within the basin, in particular, the origin of the of Alpha and Mendeleev Ridges. Among the Amerasian Basin abyssal plains, the Makarov Basin's tectonic history is the least constrained. We have used three plate tectonic scenarios (Fig. 2) for modelling the tectonic evolution of this basin and to predict its present day crustal thickness using gravity inversion (Figs. 6d, f, 7d, f and 8d, f).

The first plate reconstruction model places Mendeleev Ridge at the Canadian continental margin, and assumes that it rifts away during the Late Jurassic. The basin opens in a 'windscreen wiper' (Grantz et al., 1998) fashion, subducting the older South Anyui ocean basin,

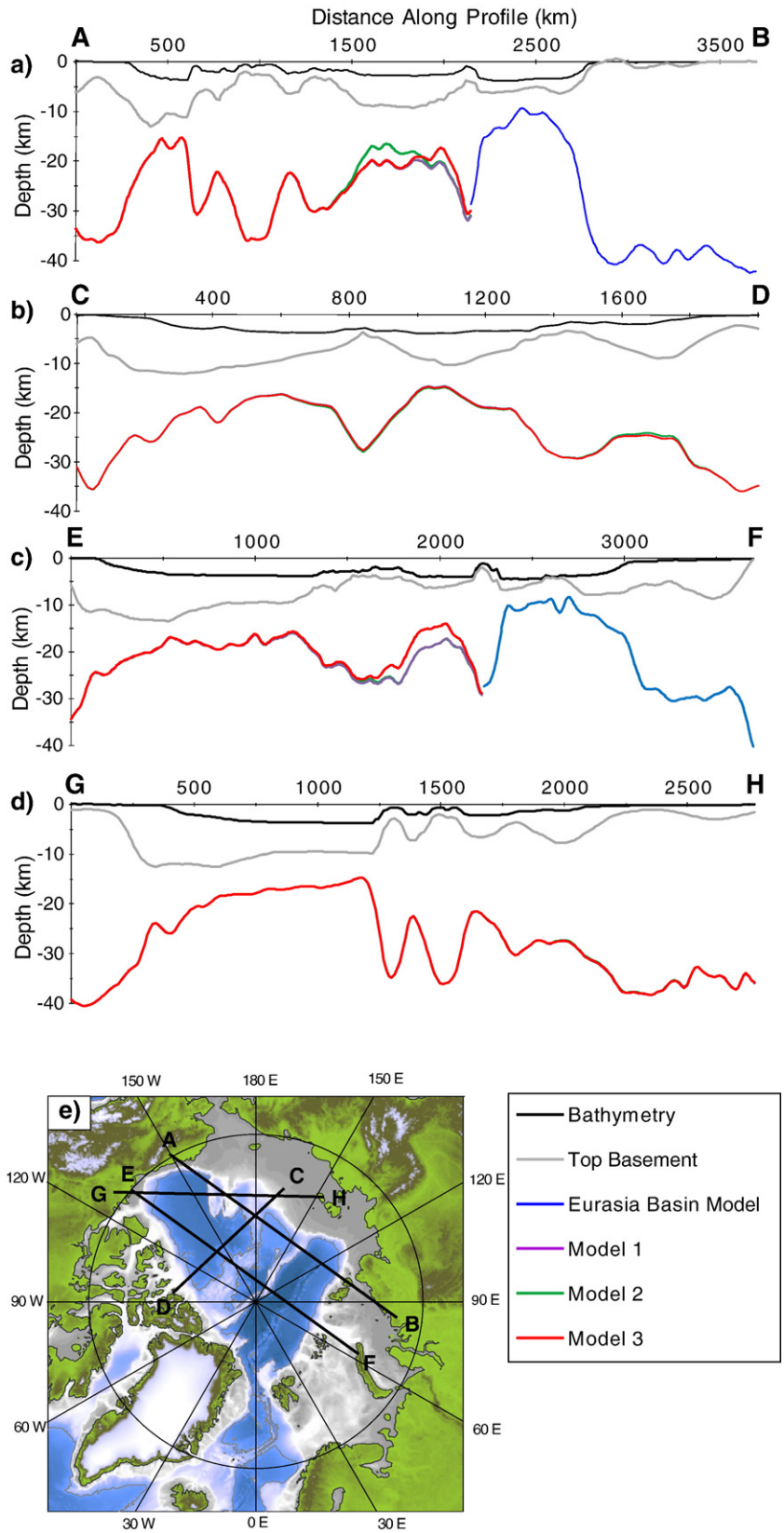


Fig. 9. Crustal cross-sections, A–B, C–D, E–F and G–H, across the Amerasia and Eurasia Basins comparing Moho depth determined from gravity inversions using lithosphere thermal gravity anomaly corrections for the 3 different plate reconstructions for the Amerasia Basin. (a) Cross-section A–B crossing the Chukchi Borderlands, Mendeleev Ridge, Podvodnikov and Eurasia Basins. (b) Cross-section C–D crossing the Mendeleev Ridge and Canada Basin. (c) Cross-section crossing the Alpha Ridge, Makarov and Eurasia Basins. (d) Cross-section crossing the Canada Basin and Chukchi Borderlands. (e) Location of cross-sections A–B, C–D, E–F and G–H. Predicted Moho depths in the Makarov and Podvodnikov Basins are dependent on the plate reconstruction model used.

resulting in a region of older crust being trapped within the Makarov/Podvodnikov Basin. The second plate reconstruction model places the Mendeleev Ridge at the Lomonosov Ridge/Barents Sea Margin, and rifts during the late Cretaceous. This causes extension within the Makarov Basin for approximately 10 Ma, ceasing when the Eurasia Basin begin spreading. The final plate reconstruction model examined is a hybrid between the first two models containing trapped Jurassic oceanic lithosphere, and younger oceanic lithosphere produced by later Tertiary rifting within the Makarov/Podvodnikov Basins.

The consistency of these different plate reconstruction models is tested using continental lithosphere thinning factors (Figs. 6e, g, 7e, g and 8e, g). It is shown that model 3 is most consistent with the gravity inversion for estimating the distribution of oceanic lithosphere, however, the gravity inversion is unable to distinguish between highly attenuated continental crust and anomalously thick oceanic crust so that it is impossible to say for certain if Alpha Ridge is continental or oceanic crust.

Fig. 9 shows cross-sections produced by the gravity inversion for four regional transects taken across the Arctic. Cross-section C–D is taken perpendicular to the spreading axis in the Canada Basin; sections A–B and E–F are taken perpendicular to the spreading axis of the Gakkel Ridge and section G–H is taken obliquely to the spreading axis of the Amerasia Basin crossing the Chukchi Borderlands and Mendeleev Ridge. The Moho shown in cross-sections A–B and E–F for the Eurasia Basin is produced using inversion parameters containing a continental rift age of 56 Ma, and volcanic addition parameters which are applicable to non-volcanic margins (i.e. γ_{crit}=0.7 and va=7 km). Cross-sections C–D and G–H show that within the Canada Basin a similar Moho depth is predicted by the gravity inversion in all three plate reconstruction models. However, cross-sections A–B and E–F predict a significant difference (~5 km) in the Moho depth predicted within the Makarov/Podvodnikov Basins for the different plate reconstruction models.

Seismic refraction studies by Lebedeva-Ivanova et al. (2006) provide a crustal thickness estimate within the Makarov/Podvodnikov Basin of ~18–20 km which is consistent with prediction from gravity inversion using a Late Cretaceous formation of the Makarov/Podvodnikov Basin.

The methodology reported in this paper of combining plate reconstruction modelling to predict oceanic lithospheric age, and gravity inversion incorporating a lithosphere thermal gravity anomaly correction to predict crustal thickness, provides a strategy for testing plate reconstruction models against seismic estimates of crustal thickness. However, to predict accurate crustal thicknesses and ocean basin formation ages a good knowledge of sediment thickness from seismic reflection data is required.

Acknowledgements

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