New aerogeophysical study of the Eurasia Basin and Lomonosov Ridge: Implications for basin development

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ABSTRACT

In 1998 and 1999, new aerogeophysical surveys of the Arctic Ocean's Eurasia Basin produced the first collocated gravity and magnetic measurements over the western half of the basin. These data increase the density and extend the coverage of the U.S. Navy aeromagnetic data from the 1970s. The new data reveal prominent bends in the isochrons that provide solid geometrical constraints for plate reconstructions. Tentative identification of anomaly 25 in the Eurasia Basin links early basin opening to spreading in the Labrador Sea before the locus of spreading in the North Atlantic shifted to the Norwegian-Greenland Sea. With the opening of the Labrador Sea, Greenland began ∼200 km of northward movement relative to North America and eventually collided with Svalbard, Ellesmere Island, and the nascent Eurasia ocean basin. Both gravity and magnetic data sets reconstructed to times prior to chron 13 show a prominent linear anomaly oriented orthogonal to the spreading center and immediately north of the Yermak Plateau and Morris Jesup Rise. This anomaly may mark the locus of shortening and possibly subduction as Greenland collided with the nascent Eurasia Basin and impinged upon the southern Gakkel Ridge. This collision may have contributed to volcanism on the Morris Jesup Rise. By chron 13, Greenland had ended its northward motion and had become fixed to North America, and the plateau north of Greenland had rifted apart to become the Morris Jesup Rise and the Yermak Plateau.

Keywords: Arctic Ocean, Eurasia Basin, aerogeophysics, Arctic plate motion, marine magnetic anomalies.

INTRODUCTION

The Eurasia Basin is bounded by northern Greenland, the Barents, Kara, and Laptev Sea margins of Eurasia, and the Lomonosov Ridge (Fig. 1). Persistent ice cover does not permit conventional data collection; thus the first-order structure and evolution of the Eurasia Basin have been deduced largely from aeromagnetic surveys flown during the 1960s and 1970s. Subsequent ice-breaker–based (Jokat et al., 1995a, 1995b) and recent submarine-based geophysical surveys (Coakley and Cochran, 1998) have been guided, to a considerable extent, by the earlier aeromagnetic results. Whereas the satellite altimetry-derived gravity field has provided significant information about much of the Arctic Ocean (Laxon and McAdoo, 1994), most of the Eurasia Basin is north of the satellite coverage.

In the 1990s, the Naval Research Laboratory (NRL) conducted seven aerogeophysical surveys over the Arctic Ocean, measuring gravity, magnetics, and sea-surface heights from P-3 aircraft. Five surveys (1992–1997) spanned much of the eastern Amerasia Basin, and the last two (1998–1999) covered the western half of the Eurasia Basin (Fig. 2). In 1998 and 1999, the Danish National Survey and Cadastre (KMS) measured gravity from a Twin Otter aircraft in the region north of the coast of Greenland in the Lincoln Sea and the western Eurasia Basin (Fig. 2). The resulting new maps of the gravity and magnetic fields better resolve the main structural features of the Eurasia Basin. The new magnetic measurements extend the U.S. Navy aeromagnetic data coverage eastward to encompass a prominent bend in the Gakkel Ridge and magnetic isochrons in the basin that provides significant constraint for plate tectonic reconstructions that further clarify the basin's evolution.

DATA COLLECTION AND MAP CONSTRUCTION

Following the early work of Karasik (1968), the U.S. Navy conducted a series of aeromagnetic surveys over the western Eurasia Basin, Lincoln Sea, and northern Norwegian-Greenland Sea (Fig. 2) that provided new information on the structure and evolution of the Eurasia Basin (Feden et al., 1979; Vogt et al., 1979). Lack of tie lines and navigation errors of as much as 10–15 km limited interpretation of the

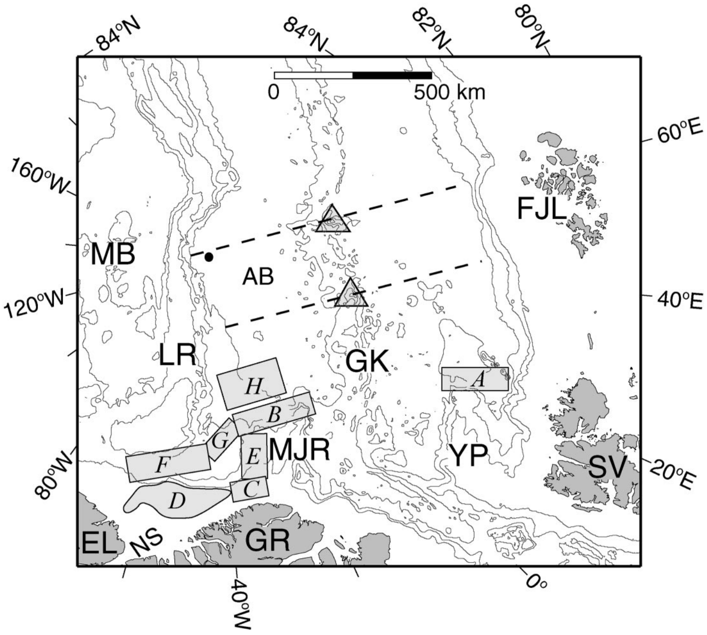

Figure 1. Main bathymetry and physiographic features of Eurasia Basin. *International Bathymetric Chart of the Arctic Ocean* bathymetry (Jakobsson et al., 2000) is displayed with contour interval of 1000 m. AB—Amundsen Basin; EL—Ellesmere Island; GR—Greenland; SV—Svalbard; FJL—Franz Josef Land; LR—Lomonosov Ridge; GK—Gakkel Ridge; MJR—Morris Jesup Rise; NS—Nares Strait; YP—Yermak Plateau; MB—Amerasia Basin. Outlined lighter shaded areas A–H denote features of interest in gravity (Fig. 3A) and magnetic (Fig. 3B) data (see text). Dashed lines locate bends in magnetic isochrons. Triangles mark inside-corner highs. Black circle denotes North Pole. Figure was generated using GMT software (Smith and Wessel, 1990).

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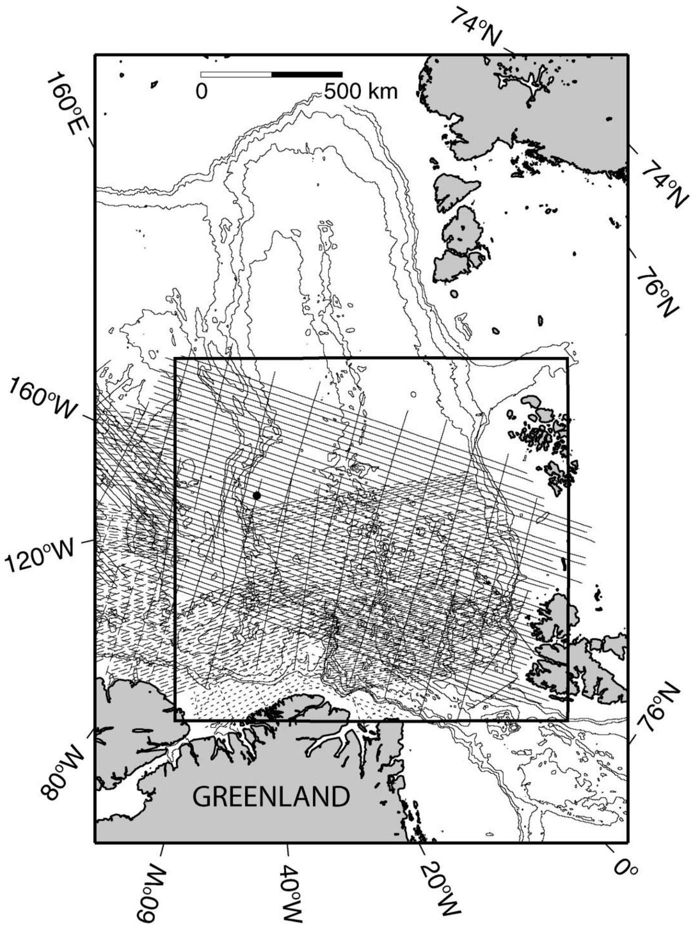

Figure 2. Track lines for new and historical aerogeophysical data in Eurasia Basin. Solid lines—1992–1999 Naval Research Laboratory surveys; dashed lines—older U.S. Navy aeromagnetic lines; dotted lines—Danish National Survey and Cadastre survey lines. Bold box—region shown in Figures 1 and 3. Black circle north of Greenland is North Pole.

data to along-track profiles. Subsequently, Verhoef et al. (1996) compiled available U.S., Russian, and Canadian Arctic aeromagnetic data. In the Eurasia Basin, however, the compilation quality is impaired by the limitations of the input data sets.

The 1998–1999 NRL surveys, based from Svalbard, were designed to overfly the historic Navy flights, to extend coverage eastward, and to connect with more recent NRL surveys in the Amerasia Basin (Childers et al., 2001). A P-3 Orion aircraft was equipped with two modified LaCoste and Romberg (LCR) marine gravimeters, a scalar proton precession magnetometer, and a radar altimeter. Differential-carrier-phase Global Positioning System (GPS) solutions precisely located the aircraft with estimated three-dimensional errors of <1 m. The survey grids (Fig. 2) have data lines 1200–1400 km long spaced ~18 km apart, with cross tracks every 75–100 km. The tracks were flown at a nominal 600 m altitude and 465 km/h. The new magnetic data were processed and leveled independently to provide a standard for adjustment of the older magnetic surveys; then the historical aeromagnetic data and the gridded data extracted from Verhoef et al. (1996) were leveled against the adjusted line data.

KMS conducted airborne gravity surveys along the northern coast of Greenland (Fig. 2) in 1998 and 1999 (Forsberg et al., 2001) using a Twin Otter equipped with a modified LCR gravimeter, dual-frequency GPS receivers, and a radar altimeter. Track lines were spaced ~18 km apart, and the survey was flown at 220 km/hr at a nominal 300 m altitude. These data were merged directly with the NRL gravity data.

Figure 3A[1] shows the gridded free-air gravity anomaly data, and Figure 3B shows the final adjusted magnetic data containing both the new NRL and older U.S. aeromagnetic data. The change in resolution from the leveled-line magnetic data to the older gridded data near the top of Figure 3B (i.e., above where the red crustal-age isochrons stop) should not be misinterpreted as a regional tectonic difference.

Our magnetic anomaly identifications, picked from the profile and contoured data, are generally similar to those of Vogt et al. (1979), but the denser sampling, improved navigation, and greater geographic coverage improve isochron resolution. Here we show the young and old edges of several diagnostic positive anomalies. (Note that we abbreviate ''chron'' as ''C'' as in C5 for chron 5 and append suffixes to indicate events or periods: ''y'' for the young side of the anomaly, ''o'' for the old side, ''n'' for the normal polarity period, and ''r'' for reversed.) The new surveys extend the data coverage to include the bend in Gakkel Ridge at 87°N, 62°E, previously outlined by bathymetric maps (Perry et al., 1985; Jakobsson et al., 2000).

MAIN FEATURES OF THE POTENTIAL FIELDS

Gakkel Ridge

The Gakkel Ridge (Fig. 1) is the northward continuation of the Mid-Atlantic Ridge (MAR) and is transformed into the Eurasia Basin via the Spitsbergen and Molloy Fracture Zones and the Lena Trough. It is the slowest seafloor-spreading ridge known (13 mm/yr full rate at 84°N, 2°W; 10 mm/yr at 86°N, 80°E). It is characterized by a lack of significant offsets, by abnormally deep axial valleys, and significant rift mountains with a peak to trough range of gravity values over the ridge axis greater than is typically found along the MAR (Coakley and Cochran, 1998).

Gakkel Ridge is expressed as a central prominent linear gravity low flanked by broken, elongated gravity highs. The gravity data reveal a ridge with long, straight segments, few offsets, and several prominent bends where the ridge abruptly changes trend near 30°E and 62°E. Prominent inside-corner highs (e.g., Karson and Dick, 1983) mark each bend (triangles, Fig. 1). These bends in the Gakkel Ridge are reflected in the morphology of the Lomonosov Ridge and the Barents margin (Fig. 3A) and in the magnetic isochrons (denoted by dashed lines, Fig. 1). The shape of the initial breakup evidently has been preserved in the plate-boundary configuration to the present day.

The magnetic data (Fig. 3B) show that the linear ridge segment between the Yermak Plateau and Morris Jesup Rise has an unusually high amplitude central anomaly, typically four times that of the flanking anomalies. Except for this ridge segment, the magnetic signature of the Gakkel Ridge is discontinuous and shows regions of missing or low-amplitude central anomalies punctuated by short, high-amplitude segments. This amplitude discontinuity is also seen in older anomalies, although there does not seem to be a correlation of amplitudes along flow lines, suggesting that the along-strike ridge variability is not caused by long-lived processes. Recent dredging operations on the Gakkel Ridge produced a good, but not perfect, correlation of basalt (vs. peridotite) recovery with the areas of high-amplitude central anomalies (P. Michael, 2002, personal commun.).

Lomonosov Ridge

The Lomonosov Ridge (Fig. 1) is characterized by linear gravity and bathymetric highs flanked by lows with a generally steeper gradient on the Amerasia Basin side. The gravity data (Fig. 3A) reveal a complex ridge structure. The southern end of the ridge (just north of the Greenland-Ellesmere margin) is a broad topographic high separated

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[1] Loose insert: Figure 3, gravity and magnetic data with bathymetry derived from IBCAO; Figure 4, plate configurations at 58 Ma and 52.4 Ma; Figure 5, reconstructed gravity and magnetic data; and Figure 6, anomaly 15 reconstructed gravity and magnetic data.

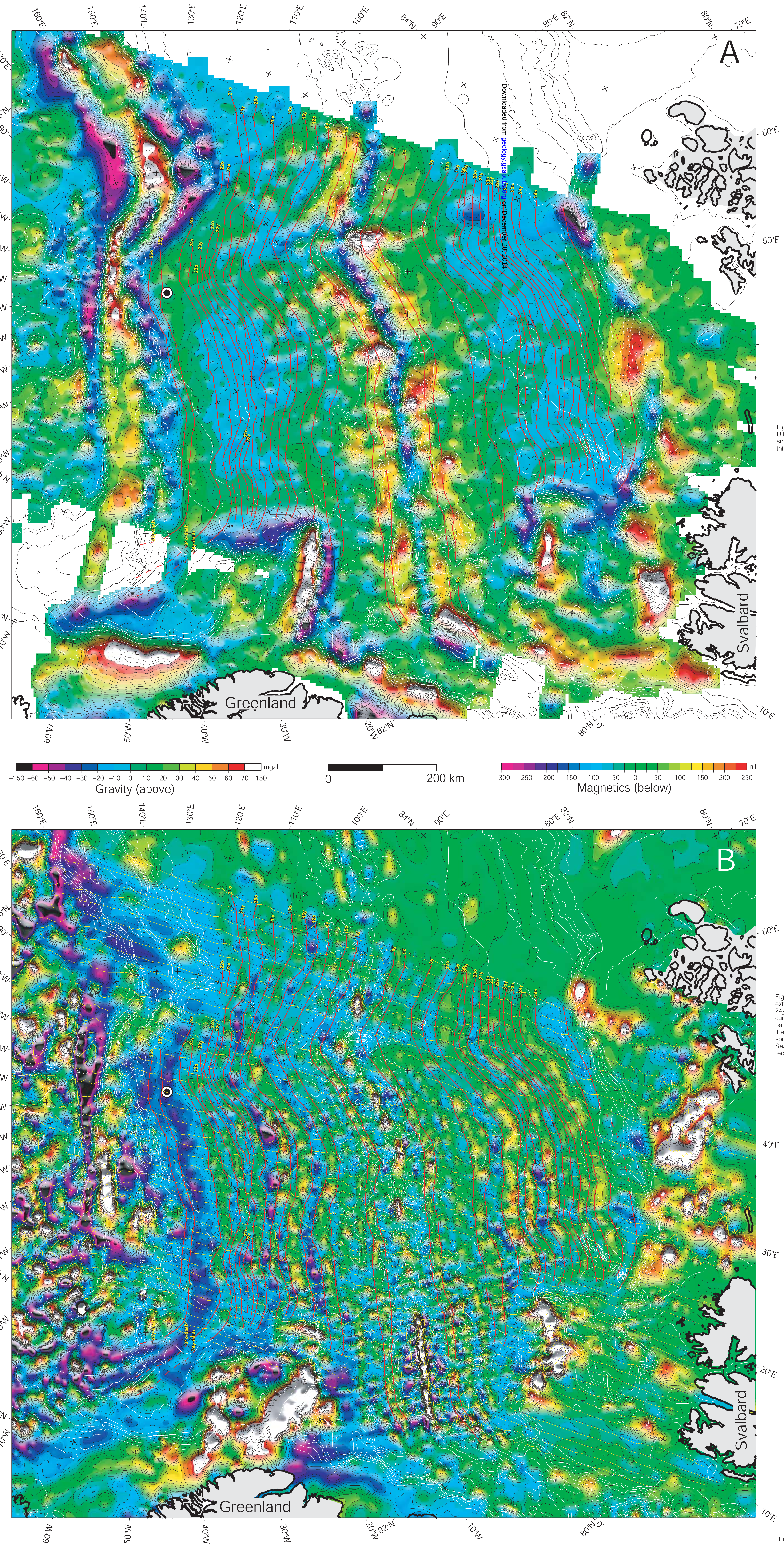

Figure 3. Gravity and magnetic data with bathymetry derived from IBCAO gridded bathymetric set contoured at 500 m intervals (shown by thin white lines [and by black lines at top of A]). Red lines denote crustal-age isochrons interpreted from magnetic anomalies. Black and white circle denotes the North Pole. A: Gridded and contoured gravity data from the NRL and KMS surveys. Contour interval is 5 mgal. B: Gridded and contoured magnetic data from the 1998-1999 NRL surveys merged with the historical U.S. Navy aeromagnetic data. Contour interval is 25 nT. Contours above 400 nT and below 200 nT have been eliminated for clarity. NW-SE-trending black lines show flight tracks, accompanying yellow lines show magnetic data.

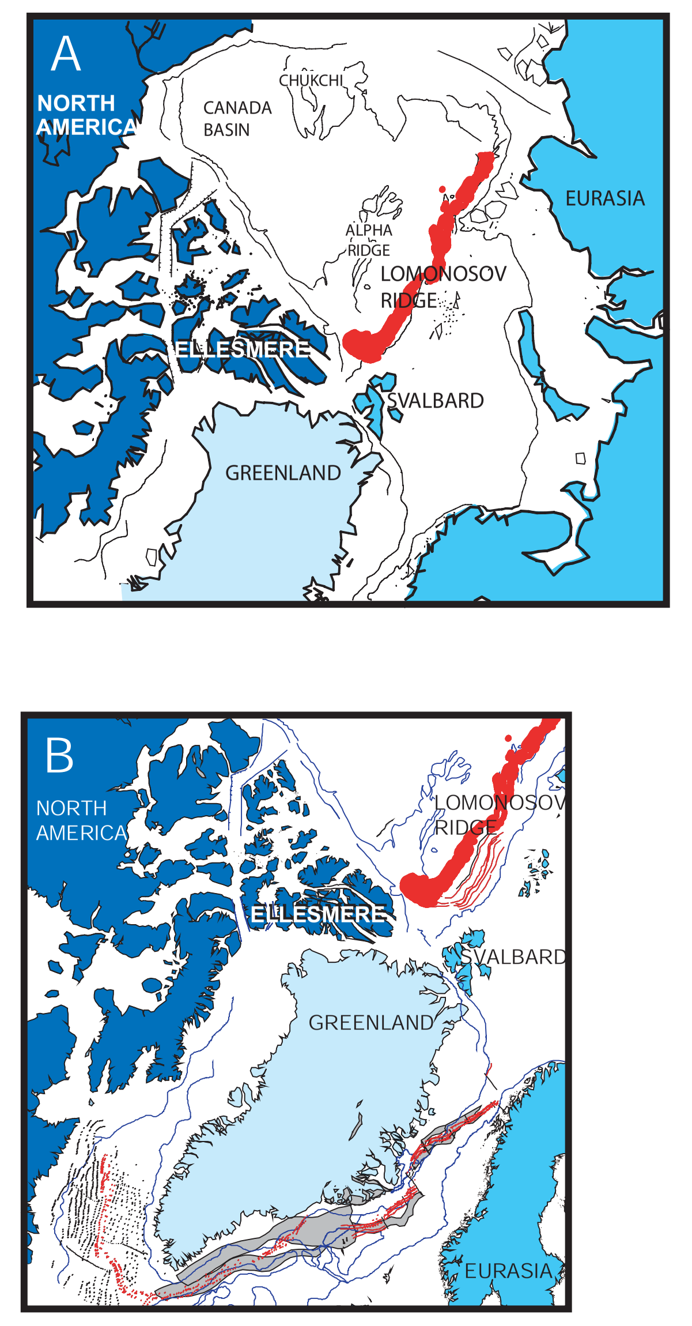

Figure 4. Plate configuration at A: 58 Ma (C26o) and B: 52.4 Ma (C24y) based upon the UTIG plate motion model. Thin red lines in B are magnetic isochrons on seafloor created since 58 Ma showing more opening in Eurasia Basin than in Norwegian-Greenland Sea at this time.

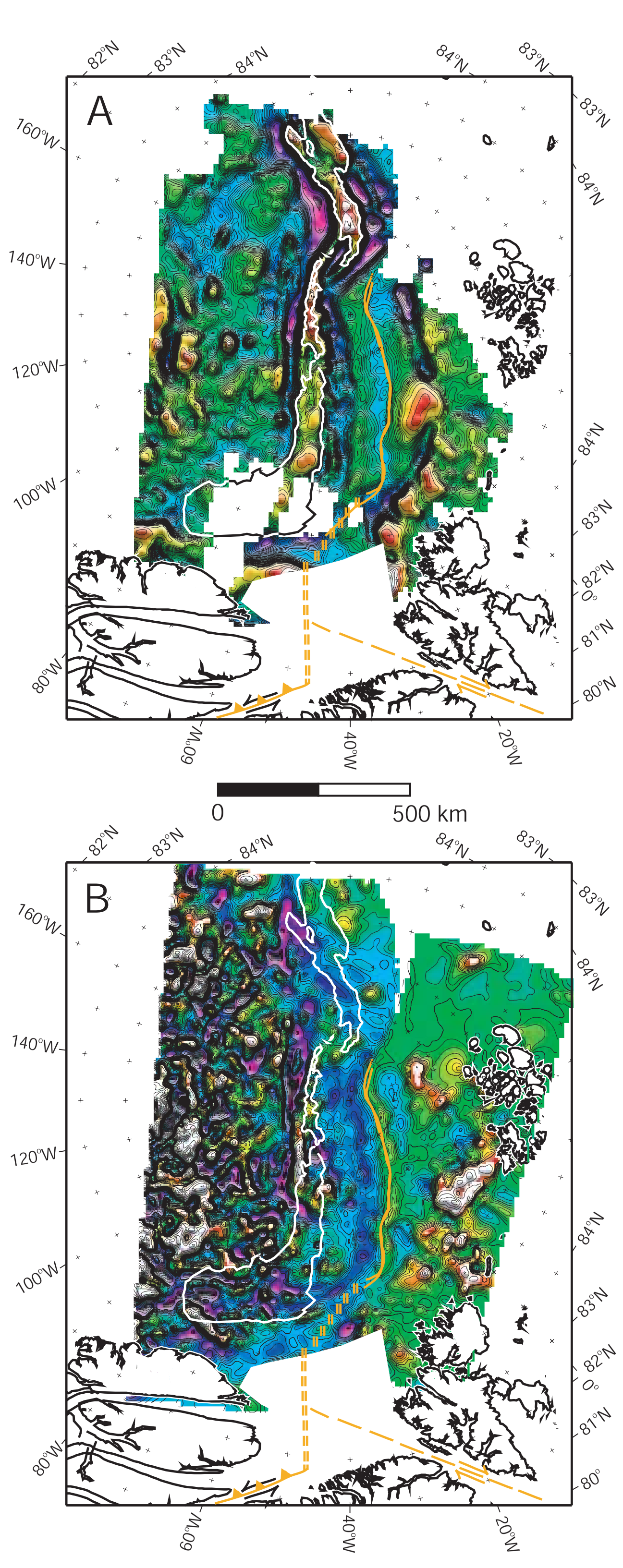

Figure 5. A: Reconstructed gravity data. B: Reconstructed magnetic data. Data have been extracted from the grids in polygons that contain crust thought to have existed at anomaly 24y time. Lomonosov Ridge data polygon and the map registration have been held fixed to current position and Eurasia data polygon rotated about the stage pole in Table DR1. Color bars and contour intervals are the same as in Figures 3A and 3B. White line approximates the present-day 1500 m isobath. Orange lines represent a hypothetical configuration of the spreading axis plus transpressional connections to the Labrador and Norwegian-Greenland Seas. Note the additional space north of Greenland as compared to the anomaly 15 reconstructions (Figs. 6A and 6B).

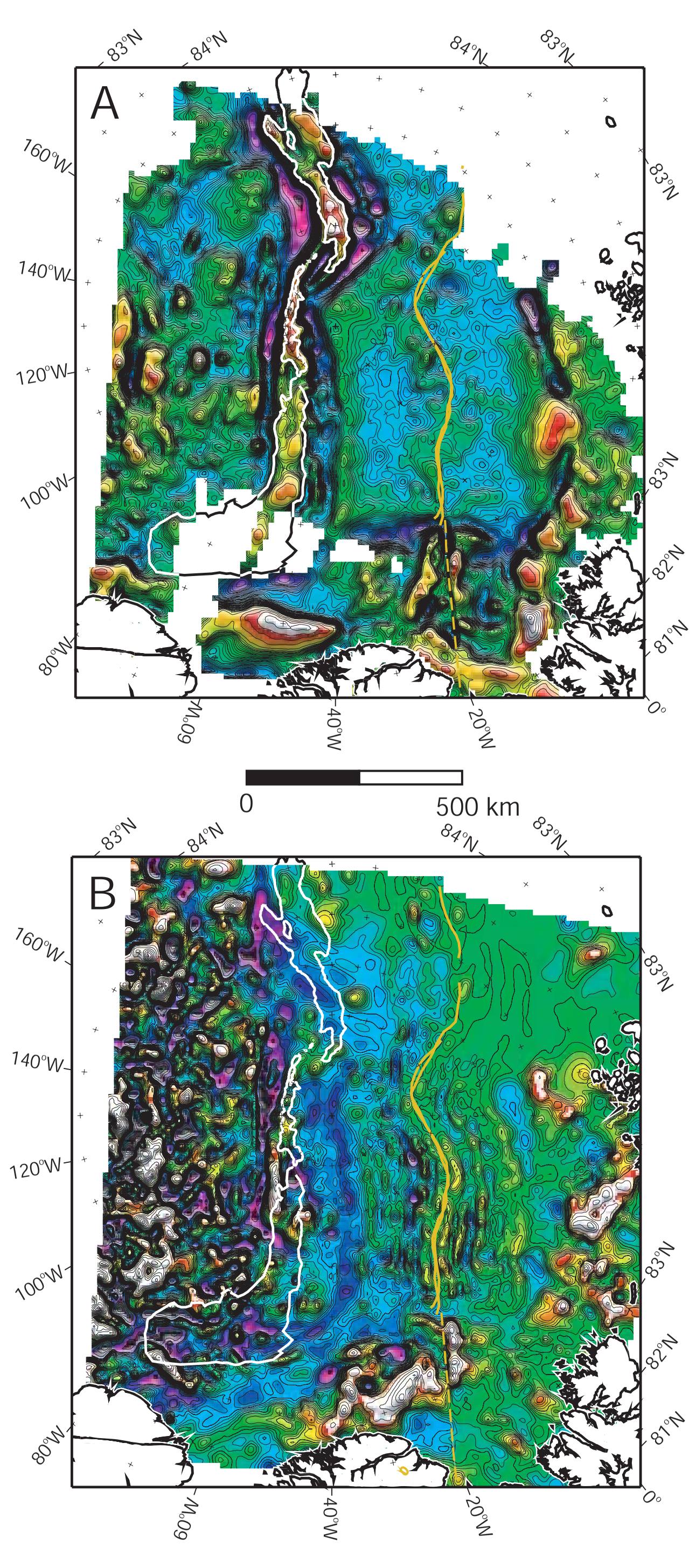

Figure 6. A: Anomaly 15 reconstructed gravity data. B: Anomaly 15 reconstructed magnetic data. Lomonosov Ridge data polygon and reference frame have been held fixed in its present-day location and the Eurasia margin data polygon has been rotated about the stage pole in Table DR1. Color bar and contour intervals are as in Figures 3A and 3B. White line approximates the present-day 1500 m isobath, solid yellow lines are C15y isochrons, dashed yellow line shows polygon boundary. Prominent, continuous trough in gravity north of the paired rises is proposed site of crustal shortening during the northward motion of Greenland.

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from the margin by an intervening deep that is also the site of gravity and magnetic lows. From the pole to the southern end, the ridge exhibits linear gravity highs and lows, suggesting horst and graben topography. Discontinuous gravity highs along its right side suggest extended continental crust (for clarity, we refer to some map directions as top, bottom, left, and right because of the difficulty with directions near the pole). At ~160°W the ridge bends sharply to the right, mirroring the bend in the Gakkel Ridge at 62°E, and bifurcates into slivers.

From the North Pole toward the top of Figure 3B, the Lomonosov Ridge is magnetically subdued with only a few anomaly highs. From the pole to the Greenland margin, the ridge may have a magmatic overprint.

Adjacent to the ridge (Fig. 3B), the broad C24r between isochrons C24o and C25y appears to bend around and into the topographic high at the southern end of the Lomonosov Ridge. C24n (between C24o and C24y) also follows this bend and may connect with a magnetic positive between Lomonosov Ridge and the Greenland-Ellesmere margin. Immediately to the right of the ridge, between its southern end and its rightward bend at 160°W, is a small-amplitude linear positive magnetic anomaly located between C24r and the ridge that we tentatively interpret as anomaly 25. Models cannot effectively define C25 for lack of a distinctive anomaly shape; however, its location is consistent with the 17.3 mm/yr presumed spreading rate for the first 6 m.y. of seafloor production (C25o–C23y). Both ends of this anomaly terminate into the margin of Lomonosov Ridge, which argues against it being a simple edge effect from the continent-ocean boundary. On the Barents Shelf side, a shoreward transition from the negative C24r to a positive anomaly is also seen. However, this may represent either a continental edge effect or the 25y transition. In any case, a complete conjugate anomaly 25 cannot be discerned on the Barents margin, perhaps owing to an early ridge jump. An alternative explanation is that the low-amplitude pattern adjacent to the ridge may reflect rift structures in extended continental crust. We consider this explanation less likely because the anomaly 25 sits on the abyssal plain (not on the shallowing slope of the ridge flank), and the gravity data show it as geographically distinct from the crustal slivers beside the ridge.

Yermak Plateau and Morris Jesup Rise

The Yermak Plateau and the Morris Jesup Rise once formed a contiguous plateau (Feden et al., 1979; Jackson et al., 1984) that was likely the site of considerable magmatism, as evidenced by the extensive, high-amplitude magnetic anomaly (Fig. 3B) that spans much of the Morris Jesup Rise and the conjugate margin of the Yermak Plateau. Seismic, gravity, and heat-flow data indicate that south of 82°N the Yermak Plateau is thinned continental crust (Jackson et al., 1984; Eldholm et al., 1987; Faleide et al., 1991). Recent seismic reflection and refraction measurements north of 82°N suggest extended continental crust that is heavily intruded (W. Jokat, 2003, personal commun.). Along the northeast margin of the plateau, prominent linear gravity and magnetic lows extend from the Barents shelf to the left edge of the plateau (box A, Fig. 1).

Little is known about the crustal composition of the Morris Jesup Rise. The rise has one large, continuous magnetic anomaly that covers the lower (southern) half of the escarpment and nearly one-third of the plateau; it also extends onto the nearby Greenland margin. The left and upper sides of the plateau have high-amplitude, dipole-like magnetic anomalies that may be unrelated to the primary anomaly. The strong linear gravity and magnetic anomaly lows located just above the Morris Jesup Rise (box B, Fig. 1) are similar to those found above the Yermak Plateau. Separating the Morris Jesup Rise from the Greenland margin is a northeast-trending gravity low (box C, Fig. 1) that truncates against a large positive gravity anomaly (box D, Fig. 1) most likely created by late Quaternary glacial deposition (e.g., Vogt et al., 1998). We interpret this gravity low as the eastward end of the Nares Strait transform that has been proposed as the site of transform motion during the opening of the Labrador Sea (e.g., Kerr, 1982).

DISCUSSION

Isochrons picked from the new and historic aeromagnetic data were incorporated into the University of Texas Institute for Geophysics ‘‘Plates’’ plate-motion model for the North Atlantic and Arctic regions. This plate model maps the motion of the three-plate circuit involved in the opening of the Eurasia Basin—North America (and the Amerasia Basin), Greenland, and Eurasia—and is constrained by magnetic anomaly picks in the Atlantic Ocean, the Labrador (Roest and Srivastava, 1989) and Norwegian-Greenland Seas (Talwani and Eldholm, 1977; Skogseid et al., 2000), and now in the Eurasia Basin. Although the model will be discussed more fully elsewhere, here we show the model at two stages to elucidate features in the potential field data.

At closure, the Lomonosov Ridge is placed along the Barents-Kara margin with the ridge's southern end just above (or northeastward) of the ancestral Yermak Plateau (Fig. 4A, see footnote one). This reconstruction aligns the ridge ~200 km farther eastward along the margin than has been supposed in previous models (Lawver et al., 1990) and provides space for an extension of the Svalbard continental margin that will later constitute part of the Yermak Plateau. In addition, the new data require that the Lomonosov Ridge be decoupled from Greenland from basin opening until C13 (34 Ma), unlike previous models that assumed that the ridge moved with Greenland (Lawver et al., 1990). This decoupling is consistent with Jackson and Gunnarsson (1990), who presented the need for an independent Lomonosov Ridge plate while the Labrador Sea opened, both before and after the initial opening of the Eurasia Basin. We show C24y and C15y reconstructions (Figs. 5 and 6, see footnote one) to illuminate various features found in the gravity and magnetic data.

Our identification of anomaly 25 in the Amundsen Basin implies that the Lomonosov Ridge began to rift from the Barents margin prior to that time. If so, the Eurasia Basin opening predates that of the Norwegian-Greenland Sea and must have been initially linked to the opening of the Labrador Sea via Baffin Bay and Nares Strait. This early connection is supported by the ~150 km of seafloor created between the Lomonosov Ridge and the Eurasian margin by C24y (Fig. 5A) as compared with only 90 km of seafloor created between the Vøring and Greenland margins during this same time period, as shown in Eldholm and Grue (1994). Our model's plate configuration at C24y (Fig. 4B) also shows the greater seafloor production in the Eurasia Basin. Were the Eurasia Basin spreading linked only to the opening of the Norwegian-Greenland Sea, less seafloor should have been produced in the Eurasia Basin than in the Norwegian-Greenland Sea, given its proximity to the rotation pole (62.5°N, 135.6°E; see Table DR 1[2]).

As the Lomonosov Ridge rifted from the Barents shelf, it left the Yermak Plateau continental segment attached to the Eurasian margin, with a transform-transtensional boundary between these two features (box A, Fig. 1) that also linked into the Nares Strait. Along the left edge of the Morris Jesup Rise are two lines of roughly circular, magnetic anomalies aligned north-south (Fig. 3B; box E, Fig. 1) that extend to the interpreted Nares Strait transform fault. These features may represent a young, highly volcanic spreading center that connected the Gakkel Ridge to the Nares Strait as long as seafloor spreading in Baffin Bay continued.

As the North Atlantic opening shifted from the Labrador Sea to the Norwegian-Greenland Sea, a new plate boundary (Fig. 5) was

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[2] GSA Data Repository item 2003118, Table DR 1, stage poles for C24y and C15y, is available online at www.geosociety.org/pubs/ft2003.htm or on request from editing@geosociety.org, or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.

formed between Eurasia and Greenland that quickly became primary as Labrador Sea opening slowed and then ceased. The evolution of this new boundary was likely complicated by the ∼200 km of northward motion of Greenland relative to North America shown by the plate motion model from C25 through C15.

The effects of Greenland's northward motion are well documented in the Eurekan orogeny on Ellesmere and Svalbard, but its impact on the basin seafloor has not been discussed. Greenland acted as a triangular indenter as it moved northward into the space created by the east-west extension of the Eurasia Basin. The amount of compression exerted on this region was a function of the rates of northward motion vs. the rates of east-west extension and the geometry of the plate boundaries. Greenland's convergence into the Eurasia Basin may have had two important consequences: (1) impingement on the southern Gakkel Ridge, which may have contributed to the proposed volcanism that formed the large magnetic anomaly on the present-day Morris Jesup and Yermak Plateaus, and (2) shortening of the Eurasia Basin seafloor. The reconstructions for C15y (Figs. 6A, 6B) show prominent, linear, east-west–trending gravity and magnetic anomaly lows just northward of the plateaus(s) (boxes F, G, B, and A in Fig. 1) against which the magnetic anomalies from the north terminate; shortening and possibly subduction may have occurred here as a result of the northward convergence of Greenland. The positive gravity anomaly of the basin floor north of Morris Jesup Rise (box H, Fig. 1) resembles a flexural bulge that increases in wavelength toward the Lomonosov Ridge, as would be expected with the underthrusting or subduction of lithosphere of increasing age. The northward motion of Greenland ended before C13, and seafloor spreading began to separate the Yermak and Morris Jesup Plateaus before C12 (Fig. 3B).

CONCLUSIONS

The new magnetic data extend farther eastward and reveal a prominent bend in the isochrons not covered by the previous U.S. Navy aeromagnetic data. This bend, along with the morphology of the structural features revealed by the gravity, magnetic, and bathymetric data, allows for a well-constrained reconstruction of this region.

At closure, the Lomonosov Ridge can be reconstructed tightly against the Eurasian margin, with the southern end of the ridge fitting just east of the continental Yermak Plateau crust. With the opening of the Labrador Sea, Greenland began ∼200 km of relative northward movement, producing compression in the West Spitsbergen fold and thrust belt and later the Eurekan orogeny on Ellesmere Island. Identification of anomaly 25 in the Amundsen Basin links the earliest extension in the Eurasia basin to spreading in the Labrador Sea. As the opening in the North Atlantic shifted from the Labrador Sea to the Norwegian-Greenland Sea, spreading in the Eurasia Basin connected to the latter opening. As Greenland collided with the opening Eurasia Basin, it caused shortening along the strike of the Gakkel Ridge and possibly subduction in the area north of the Morris Jesup Rise. By C13, Greenland was fixed to North America as the Labrador Sea spreading had ceased, and the plateau north of Greenland rifted apart to become the Morris Jesup Rise and the Yermak Plateau.

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