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Structure and plate tectonic evolution of the marine Arctic as revealed by aeromagnetics

Arctic
Magnetic anomalies
Plate tectonics
Sea floor spreading

Arctique
Anomalies magnétiques
Tectonique des plaques
Ouverture océanique

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ABSTRACT

Over 400,000 km of low level aeromagnetic data were collected by US Navy research organizations over the Arctic Basin and Greenland-Norwegian Sea during the years 1972 to 1978. These data provide new constraints on the crustal structure and tectonic evolution of this vast region.

Magnetic anomalies over continental fragments (Lomonosov Ridge and Chukchi Borderland) are irregular, with local short-wavelength features indicating relatively shallow basement. Long-wavelength anomalies indicate deep basement under most Arctic shelves except locally near coastlines. Conspicuously lineated anomalies are found only on the wide east Greenland Shelf and to a lesser extent along the Norwegian shelf and Barents Sea. Initial rifting between Greenland and Scandinavia followed a structural boundary separating the north-trending pre-rift anomalies on the Greenland side from more northeasterly trends on the Eurasian side. The northern part of the Greenland Sea began to open when the Hornsund transform fault became a rifted margin. However, from the Bear Island area south to the Greenland-Senja F.Z., an oblique rift began to open already in the early Tertiary.

Sea-floor spreading between Scandinavia and Greenland commenced about 58 m.y.b.p. during the reversed period preceding anomaly 24. Spreading between the Lomonosov Ridge and Eurasia also began at this time or possibly somewhat earlier. Anomalies in the Lofoten-Greenland Eurasia basins are relatively linear and well-defined despite the slow spreading rates (0.3 to 1 cm/yr half-rate). In the Greenland Sea oblique spreading, close-spaced transforms, and sediment input may explain the complex, generally undecipherable or non-existent anomalies there. A slight but persistent asymmetry has characterized crustal accretion in the Greenland-Norwegian Sea and Eurasia Basin : the Euranian flank of the plate boundary tends to exhibit faster spreading, greater depth, and reduced gravity and magnetic anomaly amplitudes.

An extinct spreading axis in the Canada Basin is indicated by gravity and magnetic data. A possible scenario is that during the early Cretaceous ('M' — magnetic reversal sequence) the Chukchi Borderland rifted away from the margin of Arctic Canada along a transform fault along the Alaskan North slope. Linear anomalies of possible spreading origin are found over some other parts of the Canada Basin, the Makarov Basin, and near the junction between the Lomonosov Ridge and the North American continental margin. Magnetic anomalies over the Alpha Ridge and parts of the adjacent basins are chaotic in trend and high in amplitude. Direct correlation between basement topography and magnetic anomaly is found over part of the Alpha Ridge crest. The detailed aeromagnetic data have not settled the controversy about the origin of the Alpha Ridge.

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RÉSUMÉ

Structure et évolution tectonique globale de l'Arctique d'après des études aéromagnétiques.

400 000 km de levés aéromagnétiques à basse altitude ont été effectués par les organismes de recherche de l'US Navy sur le bassin Arctique et les mers de Norvège et du Groënland, au

cours des années 1972 à 1978. Ces données restreignent les possibilités d'interprétation de la structure crustale et de l'évolution tectonique de cette vaste région.
Au-dessus des fragments continentaux (ride de Lomonosov et bordure de Chuckchi), les anomalies magnétiques sont irrégulières, avec des structures locales de courte longueur d'onde qui trahissent la relative proximité du socle.
Des anomalies de grande longueur d'onde indiquent la présence d'un socle profond sous la majeure partie de la plate-forme Arctique, sauf localement près des côtes. Des anomalies remarquablement linéaires ont été découvertes seulement sur la vaste plate-forme Est-Groënland et sur une moindre étendue le long de la plate-forme norvégienne et de la mer de Barentz.
La séparation initiale entre le Groënland et la Scandinavie a été guidée par une limite structurale séparant les anomalies pré-rift, alignées Nord-Sud, du côté du Groënland, de celles de l'Eurasie, dirigées plutôt Nord Est-Sud Ouest. La partie septentrionale de la mer du Groënland a commencé à s'ouvrir lorsqu'à la faille transformante de Homsund a succédé une véritable ouverture. Cependant, un rift oblique a commencé à fonctionner, dès le début du Tertiaire, du sud de la zone de Bear Island à la zone de fracture Groënland-Senja.
L'ouverture océanique entre la Scandinavie et le Groënland a commencé il y a environ 53 millions d'années, au cours de la période inverse précédant l'anomalie 24. L'ouverture entre la ride de Lomonosov et l'Eurasie a aussi commencé à cette époque, ou peut-être un peu plus tôt. Les anomalies dans les bassins des Lofoten-Groënland-Eurasie sont assez linéaires et bien définies bien que le demi-taux d'ouverture soit faible (0,3 à 1 cm/an). Dans la mer du Groënland, l'existence d'une ouverture oblique, de failles transformantes serrées et d'apports sédimentaires peut expliquer pourquoi les anomalies sont complexes, généralement indéchiffrables, voire inexistantes. Une asymétrie faible mais continue a caractérisé l'accrétion crustale en mer du Groënland et de Norvège et dans le bassin d'Eurasie : sur le côté eurasien de la limite de plaques, une ouverture tend à être plus rapide, la profondeur plus grande et les amplitudes des anomalies gravimétriques et magnétiques moindres. L'existence d'un axe d'ouverture abandonné dans le bassin du Canada est indiquée par les données gravimétriques et magnétiques. Il est probable que, durant le Crétacé inférieur (séquence magnétique inverse « M »), le bord continental de Chukchi s'est séparé de la marge de l'Arctique et du Canada le long d'une faille transformante longeant la pente Nord-Alaska. Des anomalies magnétiques pouvant être liées à une accrétion océanique ont été trouvées sur plusieurs autres parties du bassin du Canada, du bassin de Makarov et près de la jonction entre la dorsale de Lomonosov et la marge continentale nord-américaine. Les anomalies magnétiques sur la dorsale Alpha et des parties des bassins adjacents sont de directions irrégulières et d'amplitudes élevées. Une corrélation directe entre la topographie du socle et les anomalies magnétiques est mise en évidence sur une partie de la crête de la dorsale Alpha. Les données aéromagnétiques détaillées n'ont pas clarifié la controverse sur l'origine de la dorsale Alpha.

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INTRODUCTION

During the period 1972 through 1978 several US Navy research organizations [Naval Research Laboratory (NRL), Naval Oceanographic Office (Navoceano), and Naval Oceanographic Research and Development Activity (Norda)] collected a total of about 400,000 km of low level aeromagnetic data over the Arctic Basin and Greenland-Norwegian Sea. Typical track spacings ranged from 10 to 25 km ; the flight speed was about 440 km/hr and the altitude 150 m to 300 m above the sea surface. A number of research publications have been based on these aeromagnetic data (e.g. Vogt *et al.*, 1978 ; 1979 *a*, *b* ; 1981 ; Kovacs, 1981 ; Kovacs *et al.*, 1981 ; Phillips *et al.*, 1981 ; Phillips, Tapscott, 1981 ; Bernero, 1981 ; Taylor *et al.*, 1981). The present paper is a synthesis of the plate tectonic and other geophysical conclusions drawn from this data base. Although the data have been or are being published elsewhere in one form or another, all but Figures 1 and 4 are new to this paper. For a more detailed geophysical review of the Eurasia Basin and Greenland-Norwegian Sea the reader is referred to Vogt *et al.* (1979 *b*) and Vogt *et al.* (1981) respectively. Sweeney (1980) published the most recent review and synthesis of the entire Arctic Basin. Data compilations are also found in Grønlie and Talwani (1978) and Sweeney *et al.* (1978) ; the latter report is a subject-by-subject review.

The present paper begins with the Eurasia Basin and Greenland-Norwegian Sea, and emphasizes the post-mid-Paleocene plate tectonic development ; the Canada Basin is discussed next, since it now appears to have a spreading origin. Following comes the Alpha Ridge, whose nature is still unknown, and finally the magnetic characteristics of known or suspected continental crust overflown during the 1972-1978 studies.

THE GREENLAND-NORWEGIAN SEA AND EURASIA BASINS

The Tertiary opening of the Greenland-Norwegian Sea and Eurasia Basin can now be reconstructed with considerable precision (e.g., Phillips, Tapscott, 1981 ; Talwani, Eldholm, 1977 ; Kristoffersen, Talwani, 1977 ; Le Pichon *et al.*, 1977). As the geology and geophysics of this area have been reviewed in some detail (Vogt *et al.*, 1978 ; 1979 *b* ; 1981), the present treatment will be abbreviated.

Figure 1

Bathymetry (0.5, 1, 2, 3, and 4 km isobaths), sea ice limits, and names of major ocean-floor topographic features and seas. From Vogt et al. *(1979b).*

A lineated anomaly pattern is well-developed in most deep-water parts of this area and can be recognized easily even in the less detailed Soviet data (Fig. 2, 3). One exception is the Yermak and Morris Jesup plateaus ("M" and "Y" in Fig. 3) which appear to be Iceland-like aseismic ridges with probably thickened oceanic crusts and complex, high-amplitude magnetic anomalies (Fig. 8 and Feden *et al.*, 1979). Another magnetically complex area is the Greenland Sea from the Greenland-Senja fracture zone northward to the Eurasia Basin. Anomalies are continuous only over

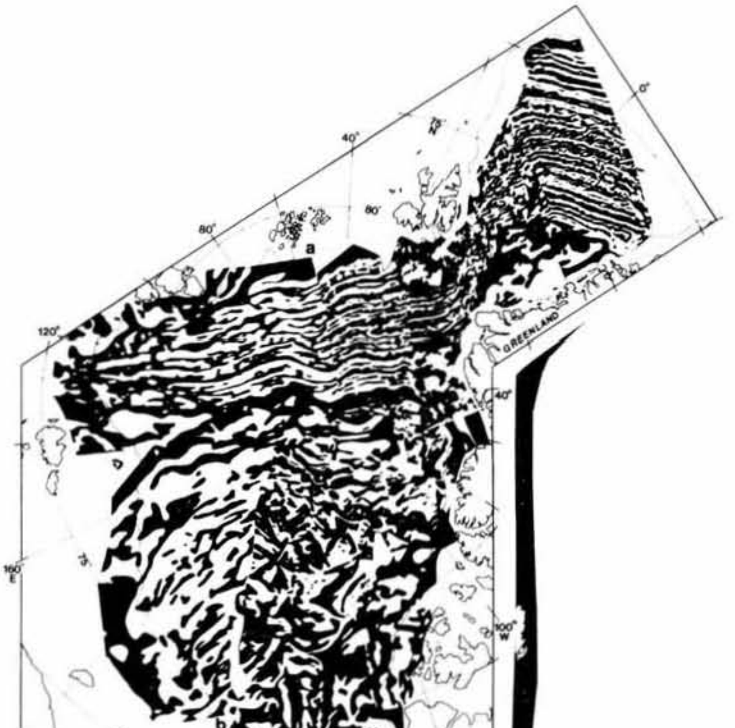

Figure 2

"Zebra-stripe" (zero-contour) chart of magnetic anomalies in the Arctic Basin and northern Greenland-Norwegian Sea. Black denotes negative anomalies. Based on US Navy, Soviet, and some Canadian aeromagnetic data. Soviet and Canadian contours were taken from Coles et al. *(1978); US data were high-pass filtered to remove regional IGRF residuals and diurnal effects (see Kovacs* et al. *1981). No attempt was made to adjust contours at survey boundaries, such as the "discontinuity" a – b which separates US-Canadian from Soviet aeromagnetic coverage. Where detailed data sets overlap older, less detailed data, the latter were eliminated.*

Figure 3

Magnetic lineations and linear offsets or disruptions of magnetic anomaly patterns. Based on Canadian ship-borne results in Baffin Bay (Jackson et al., *1979), Soviet "zebra-stripe" chart of eastern Eurasia Basin (Karasik, 1974 ; Karasik, Rozhdestvenskii, 1977 ; Phillips* et al., *1981) and US Navy aeromagnetic data (Vogt* et al., *1979*a, b *; Kovacs 1981 ; Feden* et al., *1979 ; and Taylor* et al., *1981). In Greenland-Norwegian Sea, Baffin Bay, and Eurasia Basin, dotted and numbered solid lines denote anomalies due to sea-floor spreading and magnetic reversals ; diagonally striped lines are fracture zones. Dotted lines labelled K, M, and N refer to age-distance plots for Kolbeinsey, Mohns, and Nansen Ridges (Fig. 4). Both positive (solid) and negative (dashed) lineations are shown in Amerasia Basin ; some may be due to early Tertiary and Mesozoic sea-floor spreading (e.g., Fig. 9). Possible "fracture zones" are shown by diagonally striped lines. Linear anomalies believed to be associated with continental crust are denoted by barred lines. Small "Y" and "M" show locations of Yermak and Morris Jesup aseismic plateaus (Feden* et al., *1979).*

short distances — suggesting a large number of transform faults — and in many parts of the area, including segments of the present spreading axis (Knipovich Ridge), are absent altogether. Such magnetic smooth zones may be due in part to thermal effects caused by the rapid sedimentation or to other processes related to the slow and oblique spreading geometry (Vogt *et al.*, 1978). It is also likely that Knipovich Ridge has changed its configuration and at least parts of it have migrated or jumped eastwards. In spite of the close-spaced aeromagnetic data and other information, the plate-tectonic details for the Greenland Sea have not been worked out.

By contrast the lineation pattern in the Greenland, Lofoten, and Eurasia basins is straightforward in interpretation. Sea-floor spreading began during the reversed period before anomaly 24, i.e. sometime during the time 57-58 m.y.b.p. on the time scale of La Brecque *et al.*, 1977 (anomaly 24 on the American flank of Nansen Ridge is shown by a "u" in Fig. 8 ; the same anomaly in the Greenland-Norwegian Sea is depicted in Fig. 6 and 7). Although some plate kinematic models predict modest pre-anomaly 25 movement of Greenland away from Eurasia (Srivastava, 1978 ; Phillips *et al.*, 1981), there is no magnetic or other direct evidence for such motion in the Greenland-Norwegian Sea. However, if the small positive lineation near the Lomonosov Ridge is a spreading anomaly (Fig. 4, 8), then the separation of Lomonosov Ridge from Eurasia occurred before 56 m.y.b.p. A cartographically careful reconstruction to the time of anomaly 24 — i.e. shortly after spreading had started — is shown in Figure 7. Figure 6 is a reconstruction to the time of anomaly 13 (36 m.y.b.p.). Regional and temporal variations in spreading rate are shown in Figure 4. Regional reconstructions and paleobathymetry are shown in Figure 5. Many interesting observations can be made by studying the reconstructions. Some major points are the following :

1) The line of initial rifting was segmented into incipient spreading centers and transform faults (for reference purposes these faults and several additional points have been marked by capital letters in Fig. 7). The length of the segments is typically 200 to 400 km, comparable to the spacing between major fracture zones in the equatorial Atlantic and elsewhere.

2) There is only weak evidence so far for pre-rift structures colinear with, and therefore perhaps helping to localize the incipient fracture zones. One example is what we here call the Scoresby fracture zone ("C" in Fig. 7) which when extended southeastwards forms the northern edge of the Shetland platform, and upon further extension, continues into a series of bends in the fault pattern west of the Viking Graben. Farther north, the Barents and Greenland-Senja fracture zones ("G" and "F" in Fig. 7) extrapolate "northwestwards" into minor breaks in the pre-rift magnetic anomaly pattern. Dikes and lines of volcanic centers in the Faeroes and the British Isles (Noe-Nygaard, 1974) are examples of Paleocene structures with the right transform trend, developed within continental crust. But does this volcano-tectonic trend reflect the Paleocene stress field or also deeper, older continental structures ? This question remains unanswered.

3) The incipient spreading axes in many cases parallel pre-rift structures (Fig. 7), and thus may have been controlled by them. One notable complication is the difference in structural trend between the Norwegian and Greenland sides of the rift. From C northwards to H (Fig. 7), and particularly from D to F, structures on Greenland and its shelf trend "north" whereas those on the Norwegian-

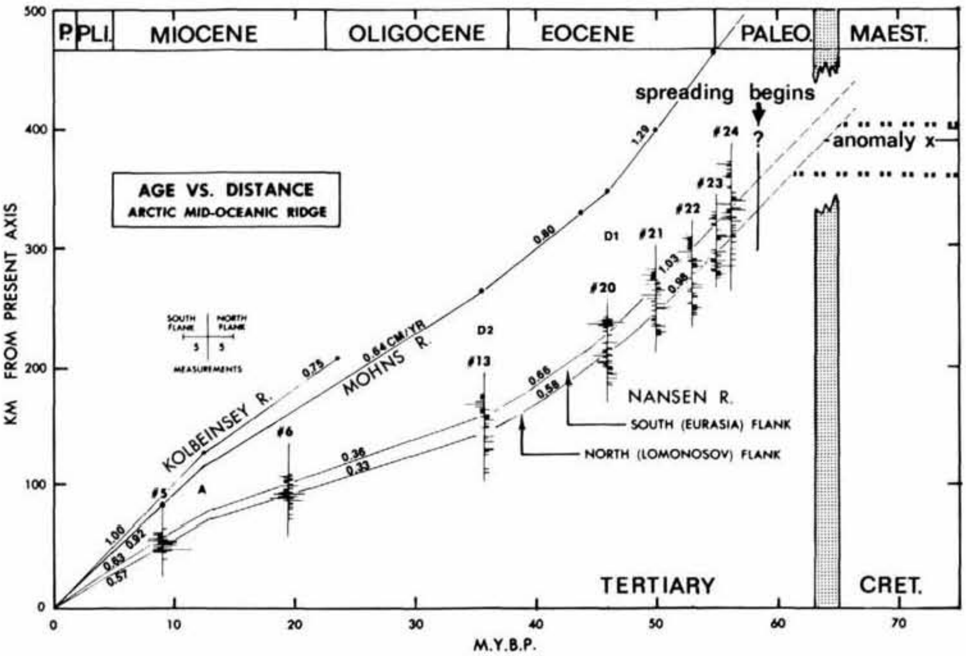

Figure 4

Age vs. distance plots for Kolbeinsey, Mohns, and Nansen ridges (see Fig. 3). Average spreading half-rates are entered along graph segments. Note that if linear anomaly "X" (Vogt et al., *1979*a, b*) is of sea-floor spreading type, the Eurasia Basin began to open near the Cretaceous-Tertiary Boundary (within stippled band). From Vogt,* et al. *(1981) and based on Vogt* et al. *(1979*a, b, *1980), and Talwani and Eldholm (1977).*

Figure 5

Paleobathymetry at 42, 33, 20, and 9 m.y.b.p. and present bathymetry in Greenland-Norwegian Sea and Eurasia basins. Contours in 100's of meters at 500 m interval. Oceanic crust above sea level, and Jan Mayen Ridge at 33 m.y.b.p. are stippled. Dotted line shows approximate location of plate boundary.

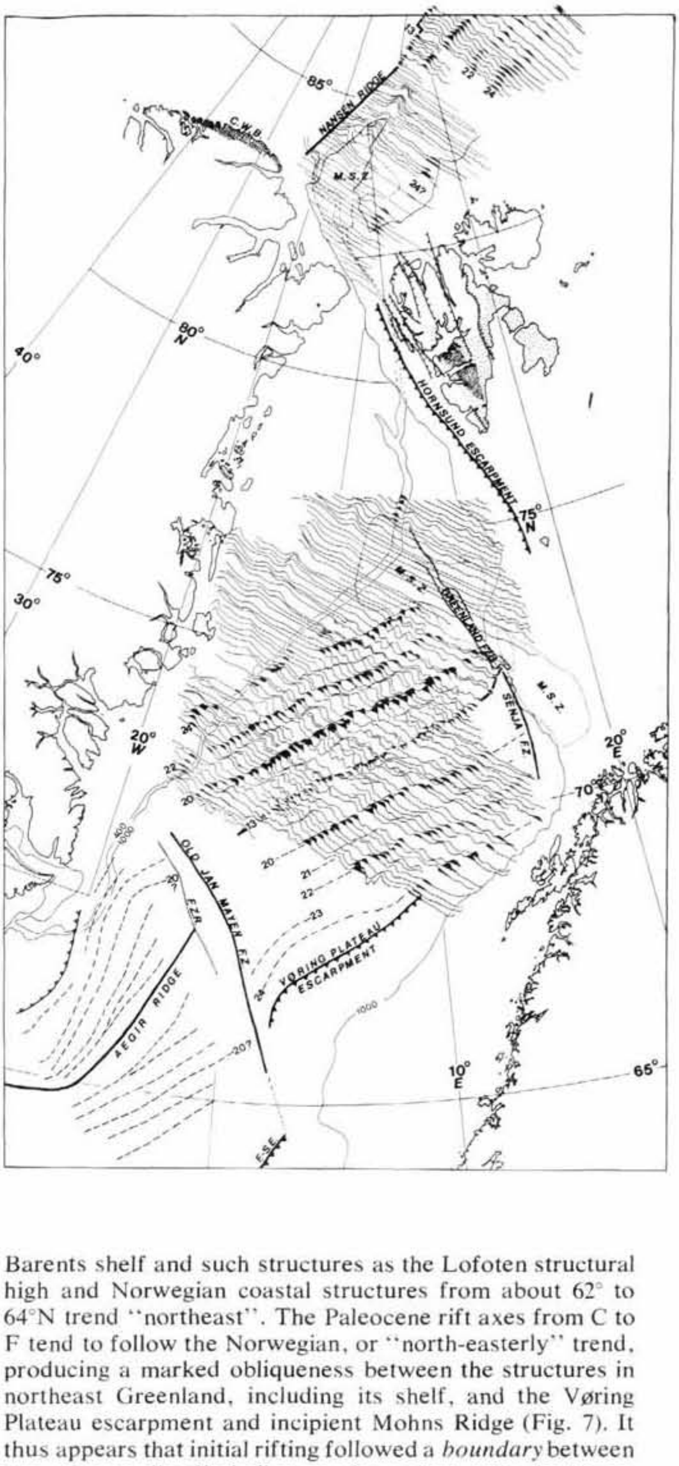

Figure 6

Reconstruction on polar stereographic projection to anomaly 13 time (36 m.y.b.p.), showing major tectonic features, magnetic lineations of 13 age and older, and magnetic smooth zones (M.S.Z.). Present isobaths in meters from Perry et al. *(1980). Sea-floor spreading-type positive magnetic anomalies are shown black (US Navy aeromagnetic profiles) and as dashed lines (Talwani, Eldholm, 1977). Post-anomaly 13 accretion at Aegir Ridge is assumed to be negligible. On Greenland, Cape Washington Basalts (C.W.B.) are stippled ; on Spitsbergen, dense stippling denotes Tertiary and light stippling, Mesozoic sediments. Reconstruction based on plate rotation parameters of Phillips* et al. *(1981).*

Barents shelf and such structures as the Lofoten structural high and Norwegian coastal structures from about 62° to 64°N trend "northeast". The Paleocene rift axes from C to F tend to follow the Norwegian, or "north-easterly" trend, producing a marked obliqueness between the structures in northeast Greenland, including its shelf, and the Vøring Plateau escarpment and incipient Mohns Ridge (Fig. 7). It thus appears that initial rifting followed a *boundary* between two structurally dissimilar provinces (we note, however, that "north" or Greenland trends are also represented to some degree on the Eurasian side of the rift — for example, the Viking Graben, the central coast of Norway, the central Caledonian front, the Tromsø Basin, and the southern part of the Troms-Finnmark fault zone).

4) Thulean volcanism (Noe-Nygaard, 1974), apparently slightly older than anomaly 24, occurred preferentially on the Greenland side of the line of initial rifting (Fig. 7). The present volcanic and plutonic exposures in most places lie 100 to 300 km west of the incipient accretion axis. It is not clear whether the volcanism shifted abruptly eastwards (as by a jump of the incipient spreading axis) or migrated eastwards more gradually. In the latter case the continental crust between the Thulean volcanics (KGH-K-S-B-SH) and the Paleocene rift (A-B-C-D-E) would have been intruded and partially covered by volcanic rocks slightly older than anomaly 24 but younger than the Thulean volcanics, which are themselves also not much older than anomaly 24. The gradual migration hypothesis is hard to prove since the volcanics in question would be found under generally thick Tertiary and Quaternary sediments. However, it is known that Faeroes volcanism did migrate in an eastward direction (Noe-Nygaard, 1974).

Interestingly most Thulean volcanic lineaments tend to parallel the NE or "Norwegian" structural trend. An example is the northern east-Greenland volcanics, from south of Bontekoe Is. (B) to Shannon Is. (SH). This volcanic lineament is closely parallel to the Vøring Plateau escarpment and structural trends to the east, but cuts the north-trending Jurassic (and older) fault-bounded basins (Surlyk, 1978) as well as other Greenland structures of

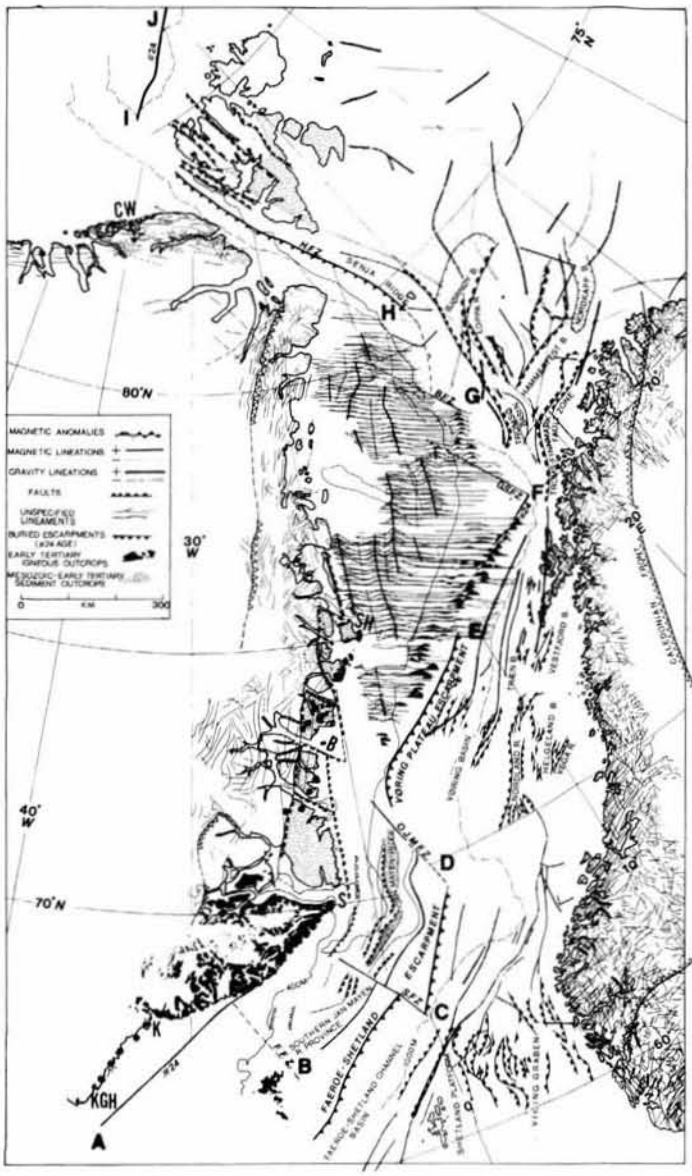

Figure 7

Polar-stereographic reconstruction to anomaly 24 time (56 m.y.b.p.) soon after sea-floor spreading began. Anomaly 24 and older spreading-type anomalies are black (positive) whereas pre-rift anomalies on east Greenland shelf are stippled. Other magnetic, gravity, and structural lineations, subaerial early Tertiary igneous and Mesozoic-early Tertiary outcrops plotted on reconstruction from publications including the following works : Eldholm and Ewing (1971), Eldholm and Sundvor (1980), Eldholm and Talwani (1977), Gabrielsen and Ramberg (1979), Gairaud et al. *(1978), Grønlie and Talwani (1978), Jørgensen and Navrestad (1979), Larsen (1978), Phillips* et al. *(1981), Rønnevik (1979), Sundvor* et al. *(1978 ; 1979), Surlyk (1977), Surlyk* et al. *(1980), Talwani and Eldholm (1972 ; 1977) and Talleraas (1979). Large capital letters A through J mark major offsets or irregularities in trace of initial break : F.F.Z., Faeroes Fracture Zone ; S.F.Z. Shetland F.Z., : O.J.M.F.Z., Old Jan Mayen F.Z. ; G.S.F.Z., Greenland-Senja F.Z. ; B.F.Z., Barents F.Z. ; and H.F.Z., Hornsund F.Z. Along east Greenland coast, small capital letters KGH denotes Kap Gustav Holm ; K, Kanderdlugssuaq ; S. Scoresby Sund ; B, Bontekoe Island ; and SH, Shannon Island.*

similar trend. There is also a crude correspondence between segments of the incipient spreading axis and segments of the onshore volcanic lineaments : the southern part of the Faeroe-Shetland Escarpment lies adjacent to the main body of plateau basalts south of Scoresby Sund (S, Fig. 7) and parallels the coastal dike swarm extending southwest from S. The northern part of the Faeroe-Shetland Escarpment, east of what would later become the separate Jan Mayen Ridge microcontinent, corresponds to the mostly non-volcanic segment B-S of the Greenland margin. The Vøring Plateau Escarpment parallels and corresponds to the volcanic lineament B-SH. SH and E mark the northern limits of east Greenland Thulean basalts and the outer Vøring Plateau, respectively.

Hot spots provide one possible explanation for the pattern of escarpments and Thulean volcanism. The Iceland hot spot, centered in the area around B, would have caused the volcanism from KGH to S on the Greenland coast, in the Faeroes, along the Faeroe-Shetland Escarpment, and in the British Tertiary province. The same hot spot subsequently produced the Greenland-Scotland aseismic ridge, including present-day Iceland (Vogt, 1974 ; see Vogt *et al.*, 1981 for review). A second, less potent Jan Mayen hot spot is invoked to explain the outer Vøring Plateau and its escarpment, the East Greenland volcanics from B to SH (Fig. 7) and, subsequently, such volcanoes as Vesteris and Eggvin banks (Vogt *et al.*, 1981). Two additional hot spots have been identified west and north of Greenland ; in both cases the earliest known activity is Paleocene as well. The Disko hot spot, now extinct, is credited with subaerial basalts of Baffin Island (Cape Dyer) and Disko Island-Svartenhuk (Keen, Clarke, 1974). Subsequently this hot spot produced the basement rise below the Davis Straits. A variant of the hot spot hypothesis is due to Talwani and Eldholm (1977) who envisage one extensive Iceland hot spot responsible for the Iceland, Jan Mayen, and Disko Island volcanic provinces. Both hypotheses would attribute the concentration of initial Faeroe-Vøring area volcanism on the Greenland plate to the hot spots' initial location under that plate.

Off northern Greenland the Yermak hot spot produced the

Kap Washington basalts, lower Tertiary tuffs on Spitsbergen, the Yermak and Morris Jesup aseismic ridges (plateaus), and a high magnetic-amplitude zone on the late Tertiary crust of the Nansen Ridge (Feden *et al.*, 1979). The Yermak hot spot would have been located in the area between point I and the Kap Washington basalts (CW in Fig. 7).

One difficulty for the hot spot hypothesis in its simplest form is that the Iceland, Jan Mayen, Disko and Yermak hot spots all developed within pre-existing non-oceanic sedimentary basins or along their margins. None developed within the nearby cratons. If this observation is not fortuitous, either *a*) magmas from a hot spot (plume) rising below a craton are generally unable to break through the thick cratonic lithosphere to the surface ; or *b*) plume convection occurs primarily in the asthenosphere — rather than the middle or deep mantle ; the lack of a well-developed asthenosphere under cratonic lithosphere would then preclude hot spots there ; or *c*) the process of plate separation itself alters the kind of convection possible in the upper mantle, and plume-like convection is stimulated by the onset of rifting, rather than the other way around.

5) According to Talwani and Eldholm (1977) the Svalbard-Barents continental margin (F to I in Fig. 7) was a shear margin from anomaly 24 to anomaly 13 time (36 m.y.b.p. ; Fig. 6). At that time Greenland became attached to the North America plate and the Svalbard-Barents margin became a rifted margin leading to the formation of the Greenland Sea. Our new aeromagnetic data, combined with the morphology of the Greenland and Barents continental margins (Perry *et al.*, 1980) indicate a somewhat more complicated geometry of opening : Only the *northern* part of the Greenland-Barents margin (from H to I in Fig. 7) was a shear margin which became a rifted margin. The plate boundary along this segment probably followed the Hornsund Escarpment (Sundvor *et al.*, 1979) a buried, west-dipping escarpment and probably a fault system — initially a zone of major dextral shear. We think the southern part of the Greenland-Barents margin (F-G-H) was never a simple shear margin, but consisted of at least two spreading centers and two transform faults, the Greenland-Senja fracture zone (Talwani, Eldholm, 1977) and another fracture zone we call the Barents F.Z. (G in Fig. 7). If, as we suggest, the spreading-type anomalies south of G were formed during the initial opening (anomaly 24), then the initial offset on the Greenland-Senja F.Z. was about 175 km. No sea-floor spreading anomalies associated with the early opening have yet been identified between G and H, perhaps because of thick sediments and oblique spreading. A small rhombus-shaped ocean basin already existed between the Greenland-Senja and Hornsund fracture zones at anomaly 13 time ; this basin was probably larger than shown in Fig. 6 because of substantial shelf-prograding after anomaly 13 time (Vogt, Perry, 1978).

6) New plate kinematic reconstructions have been made for the system of plates in the Atlantic north of the Azores, and in the Arctic (Phillips *et al.*, 1981 ; Phillips, Tapscott, 1981). These reconstructions have been based primarily on the detailed aeromagnetic data described in this paper. Combining the reconstructions with newly published bathymetry (Johnson *et al.*, 1979 ; Perry *et al.*, 1980) sediment isopach charts (Vogt *et al.*, 1979 *b*, Grønlie, Talwani, 1978), DSDP drill hole information (Talwani, Udintsev, 1976), and seismic reflection profiles (e.g., Vogt *et al.*, 1978 ; Grønlie, Talwani, 1978), Bernero (1981) constructed paleobathymetric charts for the Greenland-Norwegian Sea and Eurasia Basin (Fig. 5). This is the first paleobathymetric chart for the Eurasia Basin ; in the Greenland-Norwegian Sea we feel the charts in Figure 5 are somewhat more accurate than the rather similar ones published by Grønlie (1979), in part because crustal ages could be specified more accurately from the detailed magnetic data, but primarily because our model incorporates the effects of sedimentation. As a first approximation Bernero assumed that the relatively sediment-starved basins on the American side of the plate boundary accumulated sediments at a constant rate in time. At each site the excess sediment in the basins and margins on the Eurasian side was assumed to have been deposited in post-anomaly 5 time, primarily in the Plio-Pleistocene glacial ages (Vogt, Perry, 1978). In other words, the pre-9 m.y. sedimentation rates were assumed independent of the flank. As a consequence of stripping off large masses of presumably Plio-Pleistocene glacial sediments along the Eurasian margins and adjacent abyssal plains, the corresponding basins show up deeper in the middle Tertiary than at the present time, notwithstanding the effects of crustal subsidence ! Note also in Figure 5 the persistent shallow to subaerial sea floor in the Iceland area, and the emergence, before 33 m.y.b.p., of the Vøring outer ridge and the Yermak-Morris Jesup plateaus. The deep-water connection between Greenland and Svalbard (the Fram Straits) had begun to develop by 20 m.y.b.p. and was complete by 9 m.y.b.p. However, in detail the evolution of this sill area remains uncertain owing to the confused and low-amplitude character of the magnetic anomalies (Vogt *et al.*, 1978).

7) Minor but significant asymmetries have characterized the accretion of oceanic crust in the Greenland-Norwegian Sea and Eurasia Basin (Vogt *et al.*, in prep.). Spreading half-rates have been generally higher on the Eurasian side of Nansen Ridge since the time of opening (Vogt *et al.*, 1979 *a*), while magnetic anomalies tend to be of lower amplitude (Vogt *et al.*, 1979 *a*) and the basement depth, adjusted for age and sediment loading, greater (Karasik, Rozhdestvenskii, 1977). The same or similar asymmetry can be found in the Greenland-Norwegian Sea : Corrected basement depth is greater on the Eurasia side — except for the Vøring plateau area — and Free-Air gravity anomalies (Grønlie, Talwani, 1978) not surprisingly show a corresponding asymmetry (Vogt *et al.*, 1978, 1981). At least in the Mohns Ridge sector during the period 56 to about 36 m.y.b.p., spreading half-rates were higher and magnetic amplitudes lower on the Norwegian side of the accreting plate boundary (Fig. 6). The pervasive asymmetry in the crustal accretion process (Vogt *et al.*, in prep.) may relate to the difference in absolute plate motion, which at least over the last few m.y. has been higher for the North America plate than for the Eurasia plate (Minster, Jordan, 1978). We therefore postulate that at slow spreading rates the more nearly stationary plate accretes lithosphere more rapidly, so that the available basalt magma, if delivered in equal quantity to both plates, is smeared out into a thinner layer at higher spreading rates, resulting in a thinner, deeper crust, and lower gravity and magnetic anomalies.

THE AMERASIA BASIN

A very substantial aeromagnetic data base notwithstanding (Fig. 2, 3, 8), the crustal character and plate-tectonic history of the Amerasia Basin remains very uncertain. Using surface geology and borehole data from the surrounding continents, several authors have recently proposed that the

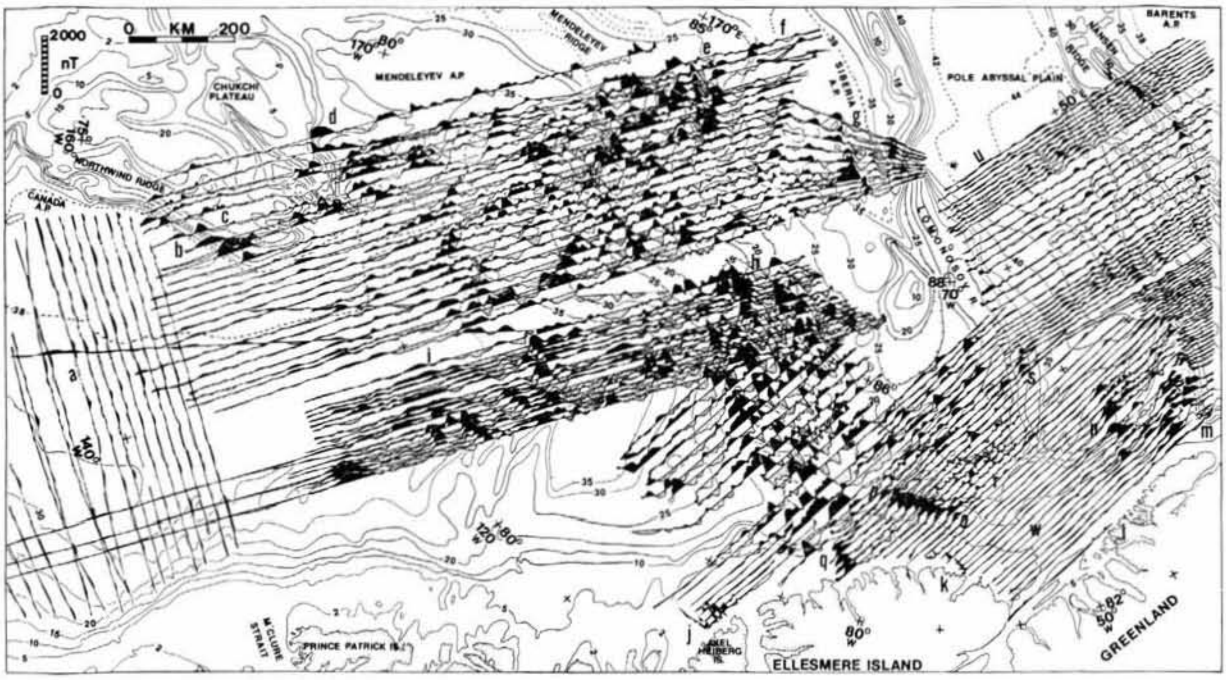

Figure 8

Residual magnetic anomalies (positive, black) plotted along flight tracks and superposed on GEBCO bathymetric chart (Johnson et al., *1979). Magnetic profiles were high-pass filtered to remove diurnal variations and other long-wavelength IGRF residuals (Kovacs* et al., *1981). Letters "a" through "w" refer to features discussed in text.*

crust under the Amerasia Basin formed by spreading some time in the Jurassic or early Cretaceous (Grantz *et al.*, 1979 ; Jones, 1980 ; Churkin, Trexler, 1980).

Despite an approximate consensus on the timing, there are large differences among kinematic models. We shall consider the three most recent ones [Grantz *et al.*, (1979), Jones (1980), and Churkin, Trexler (1980)] and then attempt to test these hypotheses against the aeromagnetic data (see also Taylor *et al.*, 1981 ; Vogt *et al.*, 1979 *a,b*).

The Amerasia Sphenochasm models

Grantz *et al.* (1979) favor an opening geometry similar to that originally proposed by Carey (1958). According to this model in its original form, the entire Amerasia Basin opened as a roughly triangular-shaped rifted basin with an apex in northwestern Canada. Grantz *et al.* (1979) infer a pole of opening at 69.1°N, 130°5 W. According to this "Amerasia sphenochasm model" both the Siberian-Alaskan and the Canadian continental margins would be of the rifted (Atlantic) type, and any magnetic anomalies due to sea-floor spreading should form a fan shaped pattern generally perpendicular to the Lomonosov Ridge/Eurasia Basin. An extinct spreading axis (fossil rift) should exist in the middle of this fan-shaped magnetic anomaly pattern. Using only gravity data, Grantz *et al.* (1979) were the first to identify an extinct axis in the Canada Basin. However, the geologic and paleomagnetic evidence advanced by them in support of the Amerasia sphenochasm model (e.g., Newman *et al.*, 1977) has been questioned by Churkin and Trexler (1980).

The North slope transform models

Several plate tectonic models have been proposed in which the Alaska-East Siberian continental margin acted as a major transform fault in the opening of the Amerasia Basin. Herron *et al.*, (1974) suggested that the Kolymski area, now part of eastern Siberia, rifted away from Arctic Canada and parallel to the Alaskan North Slope, which thus acted as a transform fault during the opening of the Amerasia Basin. The opening time was proposed to be Jurassic (180-150 m.y.b.p.). Herron *et al.* further speculated that the Alpha-Mendeleev Ridge system represents a fossil subduction zone of Laramide age (81-63 m.y.b.p.). A dextral transform along the Canadian Arctic margin was proposed to have connected this subduction zone to the Rocky Mountain Laramide Thrust.

Another North Slope transform model is that of Jones (1980), who views the North Slope margin ("Beaufort-Laptev fault") as originally a continuation of the Tintina fault. The Alpha-Mendeleev Ridge is proposed by Jones to have been an active spreading center connected to the Beaufort-Laptev transform during the Jurassic and Early Cretaceous. Subsequently, in the Late Cretaceous, right-lateral strike slip motion along the Kaltag fault displaced the Tintina from the postulated Beaufort-Laptev fault by 500 km. The Kaltag fault itself continued along the Arctic Canadian margin. In the Jones (1980) model, the Canada Basin crust was left unaffected by these events and is pictured as already existing in the Permo-Triassic. Jones does not adress the arguments against the Alpha Ridge having been a spreading center (e.g., de Laurier, 1978).

The Pacific microplate model

Churkin and Trexler (1980) propose that the Amerasia Basin represents a part (or parts) of the Kula (proto-Pacific) plate which was cut off and isolated by complex processes of plate convergence and microplate accretion. This hypothesis makes no specific predictions about the geometry of oceanic crustal structures in the Canada Basin. However, the authors' suggestion that the Alpha-Mendeleev ridges represent a fold belt caused by submarine collision between the Eurasia and Kula plates places some geometric constraints on the types of structures (and perhaps magnetic anomalies) in the area of these ridges. Furthermore, if oceanic crust now in the Amerasia Basin was formed in the Pacific substantially to the south, the magnetic anomalies would probably exhibit greater skewness and lower amplitude than would be expected if this crust had formed at high latitudes.

AEROMAGNETIC TESTS

Keeping in mind the hypotheses outlined above, consider now the aeromagnetic data as a possible test (Fig. 2, 3, and 8-10). As discussed by Taylor *et al.* (1981), there are in the Amerasia Basin at least two areas of linear magnetic anomalies, suggestive of sea-floor spreading and geomagnetic reversals : the southern Canada Basin and the central Makarov Basin (Siberia or Fletcher Abyssal Plain).

In the southern Canada Basin anomalies with amplitudes of a few hundred *n*T peak-to-trough, typical for Mesozoic oceanic crust formed in mid- or high-latitudes, strike north in the central parts of the basin but more northeasterly in the marginal zones (Fig. 9). The northerly trend is convincingly exhibited by a broad magnetic negative flanked by two narrower highs. The broad negative was suggested to represent a fossil axis of sea-floor spreading (Taylor *et al.*, 1981) ; limited gravity data from air-lifted ice-floe stations reveal a + 25 to + 50 mgal Free-Air high (Fig. 10) coinciding with the main, central segment of the extinct axis indicated in Figure 9. The existence of this gravity anomaly lends credence to the suggested extinct axis. Presumably the basement topography responsible for the gravity high lies entirely buried below thick sediments known to exist below the Canada Abyssal Plain (Grantz *et al.*, 1979).

Lineations on either side of the extinct central rift zone become more northeasterly in trend, paralleling the Northwind Ridge and the Canadian margin. The northeasterly anomaly trend is somewhat debatable, particularly on the Canadian side where the flight separation is comparable to anomaly wavelength (Fig. 9). The locations and trends of fracture zones offsetting these lineations are similarly somewhat conjectural. Although interpretations of the magnetic data of Figure 9 may vary in details (compare Fig. 9 of this paper with Fig. 2 of Taylor *et al.*, 1981), the first-order magnetic tectonic fabric of the southern Canada Basin nevertheless now appears delineated.

The age of the magnetic lineations is still uncertain although the probable Jurassic or Early Cretaceous age of the basin makes it very likely that the lineations represent part of the Keathley (M) series of geomagnetic reversals. The Keathley reversals (Vogt, Einwich, 1979) occurred in the period 110 to 155 m.y.b.p. (late Callovian to mid-Aptian), so the age of the Canada Basin crust probably lies somewhere within this interval. This would be consistent with ages independently deduced from borehole data and surface geology (e.g., Grantz *et al.*, 1979). Taylor *et al.* (1981) proposed an identification for the Canada Basin anomaly pattern. According to them the spreading lasted approximately from 153 m.y.b.p. (anomaly M-25) to 127 m.y.b.p. (anomaly M-12), or late Jurassic to early Cretaceous. Certainly other correlations with the Keathley Sequence are possible. For example, if the axial magnetic low (Fig. 9) represents the reversed interval M-3 the Canada Basin could have begun to form in the early Cretaceous, a time favored on geological grounds by Sweeney (1980). In any case, the existence of spreading-type lineations rules out the suggestion of Herron *et al.* (1974) who thought the basin was formed during a time of few or no reversals (180-150 m.y.b.p.). Whereas a Keathley (M-Series) age for the Canada Basin crust is probable, we cannot be certain that the observed lineations do not belong to a more ancient reversal sequence, as implied by the model of Jones (1980).

The somewhat fan-shaped anomaly pattern in the central Canada Basin (Figs 9, 10) and extinct axis is consistent with the Amerasia Sphenochasm Model (Carey, 1958 ; Grantz *et al.*, 1979 ; Taylor *et al.*, 1981). However, there is no magnetic or other evidence for a *continuation* of this pattern northward towards and across the Alpha-Mendeleev Ridge (Fig. 8). Admittedly the aeromagnetic flight tracks north of 76°N run parallel or sub-parallel to any such pattern and therefore are poorly suited to test the Amerasia sphenochasm model in its original form. Of course, if the Alpha

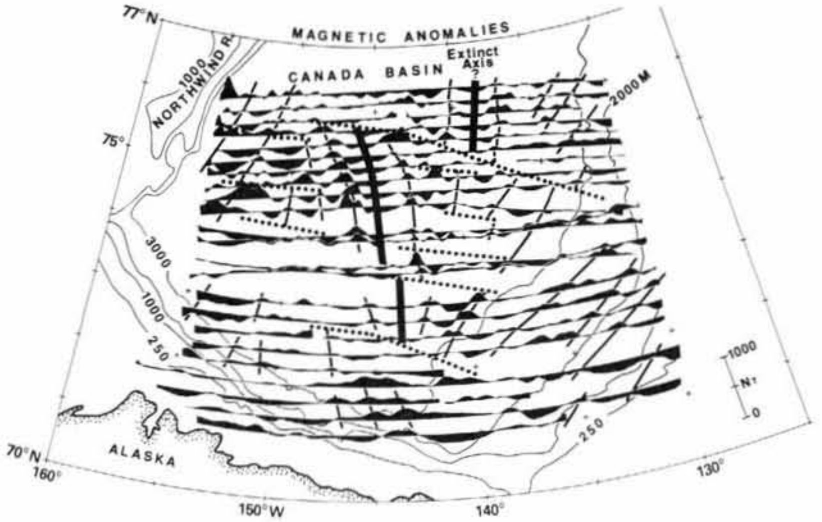

Figure 9

Residual magnetic lineations, suggested correlation lines and transverse fractures (dotted) and extinct speading axis (thick line) in Canada Basin. Bathymetric contours in meters. See also Taylor et al. *(1981).*

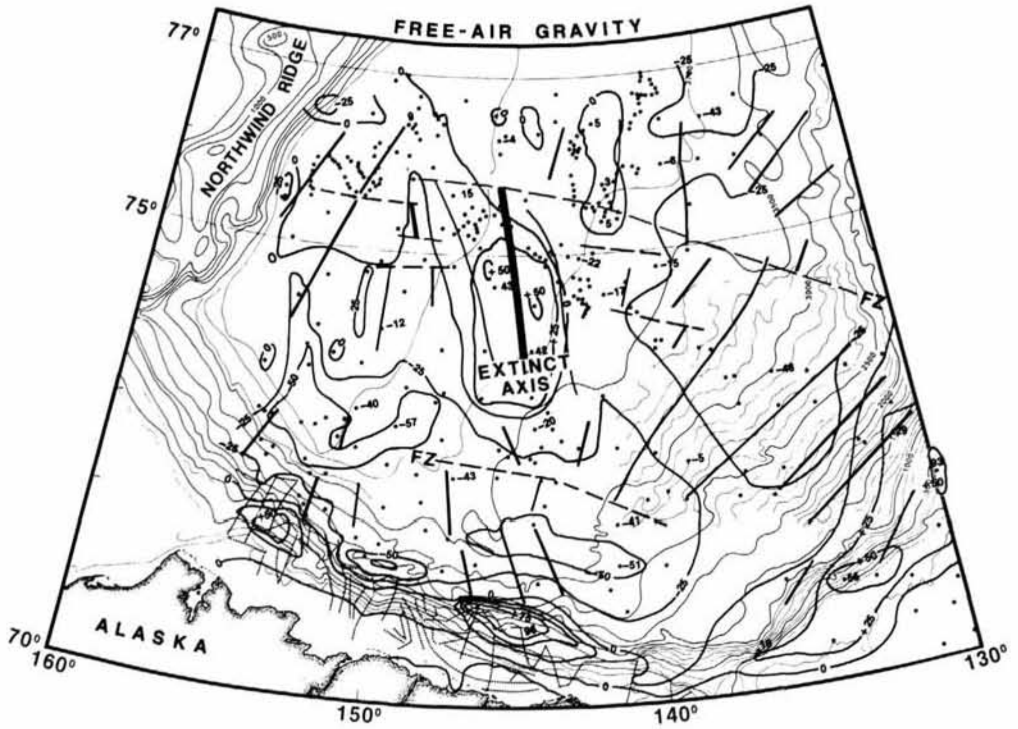

Figure 10

Gravity measurements (dots) and 25 mgal Free-Air anomaly contours. Solid and dashed lines are magnetic anomaly correlations and proposed fractures from Figure 9. Bathymetric contours in meters. See also Taylor et al. *(1981).*

Ridge is continental in nature, the fan-shaped pattern would be expected to continue only to the boundary between this ridge and the Canada Basin crust (e.g. Sweeney, 1980 ; Johnson *et al.*, 1978). It is also possible that such a continuation once existed but was subsequently overprinted or erased by the tectonic or volcanic processes that formed the Alpha-Mendeleev Ridge.

We have not yet critically examined the skewness and amplitudes of the Canada Basin magnetic lineations (Fig. 9) as a test for the Pacific microplate hypothesis. However, when allowance is made for 4 to 5 km sediments in the central Canada Basin (Grantz *et al.*, 1979), the low anomaly amplitudes observed there (150 to 250 nT peak-to-trough) resemble those of Keathley anomalies in the western North Atlantic, present latitude 30°-35° (Vogt, Einwich, 1979) and paleo-latitude 20°-25°N (Irving, 1979). While this observation is in qualitative agreement with a large-scale northward displacement of Canada Basin crust (Churkin, Trexler, 1980) there are many other factors that influence magnetic anomaly amplitudes (e.g., Vogt *et al.*, 1979 *a*, *b*). Furthermore, the existence of a fossil spreading center between the Chukchi borderland and the margin of Arctic Canada (Fig. 9 and 10) is not predicted by the Pacific microplate model, and would have to be fortuitous.

Although the extinct Canada Basin axis is oblique to the Alaska North slope, the flank anomalies appear more nearly parallel to the Northwind escarpment and to the Canadian margin. At the same time these marginal lineations are roughly perpendicular to the Alaska margin. These relationships are best explained by the North Slope transform model : The Chukchi Borderland was originally attached to Arctic Canada in the shelf-edge reentrant north of the McKenzie delta (Fig. 3). Some time after the Chukchi Borderland block had begun to move away, along a North Slope transform fault (e.g., Herron *et al.*, 1974), the plate kinematic pattern changed and the axis of spreading became reoriented to its present oblique configuration (Fig. 9, 10). Although we prefer this interpretation — implied by the lineations and fracture zones proposed in Figure 9 and 10 — more detailed aeromagnetic data are needed to establish beyond doubt the pattern of anomalies along the margins of the Canada Basin.

Anomaly amplitudes are not low throughout the Canada Basin but increase irregularly as the Alpha-Mendeleev Ridge is approached from the south. It is uncertain how the extinct spreading axis continues northward beyond the area of Figures 9 and 10. It was suggested that the lineations extending towards the lower right from point "i" (Fig. 8) may belong to the M-Series (Vogt *et al.*, 1979 *a*) and therefore form a continuation with the southern Canada Basin anomalies. Additional data are needed to establish the relation between these anomaly patterns.

THE MAKAROV BASIN

Aeromagnetic data reveal another region of lineated anomalies in the Makarov Basin (Siberia or Fletcher Abyssal Plain) between the Alpha-Mendeleev and Lomonosov ridges (fig. 3 and 8 ; Taylor *et al.*, 1981). The lineations are located within the area bounded by *h*, *e*, *f*, *g*, and the North Pole in Figure 8. The Makarov Basin anomalies are of much higher amplitude and somewhat more irregular than those in the Eurasia Basin or in the area of the extinct Canada Basin spreading axis (Fig. 9). Taylor *et al.* (1981) suggest that the Makarov Basin anomalies were formed by spreading from a now-extinct axis roughly bisecting this basin during the time period 80 to 47 m.y.b.p. (anomaly 19 to 34) at a half-rate of 0.85 cm/yr. The observed fan-shaped anomaly pattern (Fig. 8) would then mean that the amount of opening decreased from the Siberian side toward the North American side. If the Alpha-Mendeleev Ridge was some type of subduction zone (Herron *et al.*, 1974 ; Churkin, Trexler, 1980), the Makarov Basin may have been its corresponding back-arc basin. The proposed accreting plate boundary was connected to the Labrador-Baffin rift and the Greenland-Norwegian Sea rift in some way not yet understood.

One difficulty with the Taylor *et al.* (1981) hypothesis is that one of the most prominent positive lineations (just to the left of point "*g*" in Fig. 8) follows a line of seamounts (the Marvin Seamounts, previously referred to as the Marvin Spur ; see Sobczak, 1977). The magnetic lineation may therefore be a topographic or structural effect rather than a sea-floor spreading lineation. It could be that the Marvin Seamounts represent the summits of rift mountains associated with the extinct Makarov Basin axis, now largely buried under thick sediments (Ostenso, Wold, 1977 ; Blasco *et al.*, 1979). However, this is unattractive because the seamounts and associated anomaly do not correspond to an axis of symmetry either for the entire lineation pattern or for the Makarov Basin. Another difficulty with the interpretation of the Makarov Basin as a simple rifted basin is the great difference between the topography, magnetic anomalies, and crustal structure of the Alpha-Mendeleev and Lomonosov ridges. If these two features are fragments of a once continuous continental massif (Johnson *et al.*, 1978 ; Sweeney, 1980) one should expect some geophysical similarities between them.

THE ALPHA-MENDELEEV RIDGE

The Alpha-Mendeleev Ridge complex has been the object of much speculation over the last decade (e.g., Vogt, Ostenso, 1970 ; Vogt, Avery, 1974 ; Herron *et al.*, 1974 ; Sweeney, 1980). Since the US Navy aeromagnetic data extend only to the junction between the Alpha and Mendeleev ridges, we shall only discuss the Alpha Ridge here. However, it may well be that the two features are only one, in which case the following discussion also applies to the Mendeleev Ridge. The origin of even the Alpha Ridge still remains conjectural despite the large volume of new detailed aeromagnetic data (Fig. 8), which reveal irregular anomalies of high amplitude (500 to over 1,000 nT peak to trough and various irregular to sublinear patterns (Fig. 3). We summarize our inferences about the Alpha Ridge under the following ten points :

1) The thick cover of sediment (400-1,200 m), the recovery of Eocene and Maastrichtian sediment from the ridge crest, and the absence of seismicity all rule out the hypothesis that the Alpha Ridge is an active plate boundary of any type, or a Tertiary axis of sea-floor spreading (de Laurier, 1978).

2) The shallow present basement depth (2,900 ± 500 m after isostatic correction for sediment loading ; de Laurier, 1978) rules out the hypothesis that the Alpha Ridge is a typical accretion axis extinct since Mesozoic or earlier times, because subsequent thermal subsidence would have essentially reduced the initial "ridge" form to zero. This point has been made repeatedly in the literature (Vogt, Avery, 1974 ; Herron *et al.*, 1974 ; de Laurier, 1978).

3) The age and shallow basement depth do not rule out the hypothesis that the Alpha Ridge is an ancient hot spot generated oceanic plateau, like the Shatsky Rise and Ontong Java Plateau in the Pacific, or the Greenland-Iceland-Faeroe Ridge, Azores Plateau, or Rio Grande Rise in the Atlantic. All these features have dimensions of the same magnitude as that of the Alpha Ridge (400 km × 800 km, with a topographic anomaly of about 3.5 km with respect to average Cretaceous oceanic crust).

4) The Alpha Ridge could also have originated by plate convergence (Herron *et al.*, 1974), perhaps like Japan or the Lord Howe Rise (Taylor, 1978). The limited seismic refraction data (Hunkins, 1961 ; 1962) do not support this hypothesis, and no arc-like fossil trench or volcanic chains are apparent from existing data. The existence of a median rift-like valley (Vogt *et al.*, 1979 *a*) is also unexplained by this hypothesis, unless the valley is reinterpreted as a fossil trench or abortive inter-arc spreading center. The onlapping relationship between Makarov Basin sediments and the Alpha Ridge seems more in line with the "spreading center" than with the "subduction zone" hypothesis (Ostenso, Wold, 1977).

5) The Alpha Ridge could represent a region of plate compression and deformation not like either an Andean or an island-arc type convergence zone. This is a purely ad hoc hypothesis since no such convergence zone has elsewhere been identified in an oceanic area.

6) The Alpha Ridge could represent a subsided, perhaps thinned shield (King *et al.*, 1966). The long-wavelength magnetic anomaly over the Alpha Ridge is similar to what is observed over continental shields (Coles *et al.*, 1978). Again, the subsided shield hypothesis is inconsistent with sparse seismic refraction and surface wave studies (Hunkins, 1961 ; 1962) and it does not explain the existence of a crestal valley.

7) The aeromagnetic data do not reveal simple lineations of the sea-floor spreading type. In the best-known part of the Alpha Ridge crest the "central valley" and flanking ridges correlate with a magnetic low ("*h*" in Fig. 8) flanked by highs (Vogt *et al.*, 1979 *a*). These observations suggest that a highly magnetized (normal polarity) basement topography — rather than bands of alternating polarity — is responsible for the observed anomalies (the two sharp, *en echelon* magnetic lows below point "*e*" in Figure 8 may represent exceptional strips of reversed polarity). The magnetic anomaly pattern is not inconsistent with the hypothesis that the Alpha Ridge is an oceanic plateau — an ancient Iceland — formed during a long period of normal polarity such as the mid-Cretaceous. Magnetic anomalies on Iceland and the Iceland-Faeroe Ridge also exhibit great irregularity and high amplitudes.

8) However, neither is the magnetic pattern over the Alpha Ridge necessarily inconsistent with the "compression/subduction zone" (Herron *et al.*, 1974 ; Churkin, Trexler, 1980) and "subsided shield" (King *et al.*, 1966) hypotheses. One should expect anomalies even over a complex imbricate subduction zone to exhibit some regional lineations corresponding to volcanic arcs, trenches, back arc basins, and remnant arcs. No such regional banding is observed. If, on the other hand, the Alpha Ridge is a subsided shield, one should expect some magnetic similarity to adjacent, presumably once contiguous continental fragments such as the Chukchi Plateau, the Lomonosov Ridge, and Ellesmere Island. However, Figure 8 as well as Soviet (Karasik, 1974) and Canadian data (Coles *et al.*, 1978) show little or no similarity between magnetic anomalies of the Alpha Ridge and those over adjacent continental

fragments. Only at "*q*" (Fig. 8) is a magnetic anomaly found that carries the Alpha Ridge trend across the continental shelf toward the coast of Ellesmere Island.

9) Careful examination of the anomaly pattern (Fig. 8) suggests a set of parallel "fracture zones" disrupting the anomalies along a trend parallel to 170°W, roughly the same trend as the Mendeleev Ridge and Chukchi Borderland (Fig. 3). The fractures, if real, extend from the Makarov Basin across the Alpha Ridge and into the northern Canada Basin. The trend of the "fractures" is significantly oblique to the topographic fracture trend (parallel to 142°W) inferred by Hall (1973) from scattered ice-island and submarine soundings. It is uncertain whether the subtle trends in the magnetic data represent true transform faults. Several linear anomalies extending towards the lower right from point "*i*" (Fig. 8) parallel the "fracture" trend.

Apart from the suggested "fractures", the magnetic anomalies over the Alpha Ridge and adjacent parts of the Canada Basin are generally at least subparallel to the regional strike of that ridge. Overall the pattern is quite chaotic and lineations of diverse trends can be found (Fig. 3, 8). However, track spacing is in some areas too wide to permit reliable correlation of shorter-wavelength anomalies from one track to the next ; furthermore, lineations parallel to the tracks were filtered from the data set as displayed in Figure 8. This should be kept in mind when the lineation chart (Fig. 3) is evaluated.

10) Although the highest magnetic anomaly amplitudes occur near the crest of the Alpha Ridge, it is clear from Figure 8 that this ridge is merely part of a much more extensive province of chaotic to sublinear, high-amplitude anomalies (Vogt *et al.*, 1979 *a* ; Taylor *et al.*, 1981). This province extends over much of the northern Canada Basin — about to a line connecting the Chukchi Plateau with Prince Patrick Island. The anomalies in the Makarov Basin are more lineated than those over the Alpha Ridge (Taylor *et al.*, 1981). However, in terms of wavelength and amplitude the Makarov Basin may also belong to the Alpha Ridge province. The large extent of the Alpha Ridge magnetic anomaly province suggests that the crust under the ridge differs from that under adjacent parts of the basins only in its greater elevation.

In conclusion, despite a large increase in magnetic data, we still cannot decide among several mutually inconsistent hypotheses about the Alpha Ridge. It is hoped that the bottom sampling and deep seismic programs to be carried out by Canada in 1982 will break this impasse.

MAGNETIC ANOMALIES OVER CONTINENTAL FRAGMENTS AND MARGINS

US Navy aeromagnetic data extend across portions of the eastern (Fig. 7) and northern (Fig. 8) continental shelf of Greenland and the shelf north of Axel Heiberg and Ellesmere Islands (Fig. 8). A few profiles cross the continental margin of Alaska and adjacent Arctic Canada (Fig. 9). Parts of the Lomonosov Ridge and the northern tip of the Chukchi Plateau — Northwind Ridge complex were also overflown. Since these features are generally considered fragments of continental crust they are included in this section. The Alpha Ridge was discussed separately although some authors have suggested a continental nature (King *et al.*, 1966). In view of the wide variation in crustal age, composition and structure of continental crust, the variety in magnetic expression of shelves and continental fragments is not surprising (Fig. 6-9).

On the wide shelf east of northern Greenland, remarkably linear anomalies strike north to north-northeast, parallel to adjacent coastal topography and inland structures including the Caledonian Front (Fig. 7). The anomaly sources lie buried up to 10 km below sea level according to our magnetic source depth calculations. The east Greenland shelf is therefore underlain by a thick sediment-filled basin. The anomalies presumably reflect magnetization contrasts within rocks of Caledonian and/or Pre-Cambrian age. It is not known whether there are correlative seismic structures and gravity anomalies. The east Greenland shelf anomalies are notably oblique to the trend of Paleocene rifting except in a small area between the Barents fracture zone (BFZ ; point G in Fig. 7) and the Greenland-Senja F.Z.

Less regular patterns of magnetic lineations lie along the Norwegian margin and in the western Barents Sea (Fig. 7). Correlations with gravity anomalies and seismically determined structures are the exception rather than the rule. However, the magnetic anomalies do generally parallel the other geophysical trends and coastal structures, and probably reflect deeply buried, pre-Mesozoic structures.

There is no consistent anomaly associated either with the presumed continent-ocean crustal boundary or the present shelf edge (Fig. 6 and 7). An exception is the Vøring Plateau escarpment (Fig. 7) which is characterized by a distinctive short-wavelength negative anomaly (Talwani, Eldholm, 1977). The aeromagnetic data reveal a similar anomaly off the east Greenland margin, between E and F in Figure 7. This anomaly probably corresponds to the "Greenland Escarpment" of Talwani and Eldholm (1977) and marks an abrupt westward increase in the depth to magnetic basement (Kovacs, unpubl. data).

The continental shelves off northern Greenland and adjacent Arctic Canada are generally subdued in their magnetic expression (Fig. 8), an indication of thick sediment accumulations and at the same time lack of strong magnetization contrast. Exceptions are areas *j* (off Axel Heiberg Island), *k* (off northeast Ellesmere Island) and *l* (off central northern Greenland). Relatively highly magnetized crystalline basement and/or shallow depth volcanic/intrusive bodies within sediment sequences must occur at these sites. The anomaly trends (*j* and *k* only) are parallel to the fjords of northern Ellesmere Island and to the adjacent Alpha Ridge — a hint that these features are structurally related. The spike-like linear positive anomaly at *k* resembles that expected from a large dike. The zone of short-wavelength anomalies crossed by only one track (*l* in Fig. 8) may mark the seaward extent of the Kap Washington basalts of early Tertiary age.

A few longer-wavelength anomalies extend across the Ellesmere Island shelf east of *q* (Fig. 8) on the same strike as the adjacent Alpha Ridge. These are the only evidence that Alpha Ridge basement structures may extend into the continental crust. High-amplitude magnetic anomalies (between *m* and *n*) are associated with the Morris Jesup Rise, a presumed oceanic plateau (Feden *et al.*, 1979). These become subdued and essentially disappear as the Greenland shelf is approached. No magnetic anomaly is systematically associated with the continental margin. However, the east-west positive anomalies *p-o* and *m-n* may represent local examples of such edge anomalies (Kovacs, 1981). Kovacs further suggested that the anomalies *p-o* and *m-n* were once colinear, their present displacement (250 km) attesting to the cumulative sinistral displacement of Ellesmere Island with respect to Greenland. Three difficulties with this interpretation are : 1) a 150 km gap remains between *o* and *n* even after the lineations are brought into alignment ; 2) the lineation *m-n* may be an artifact of fortuitous arrangement of the irregular, high amplitude anomalies associated with the Morris Jesup Rise ; and 3) independent evidence for a displacement of this magnitude is inconclusive (Brook, 1980).

A magnetic smooth zone is found over much of the Lincoln Sea (*w* in Fig. 8) and appears to be associated with a seaward extension of the Nares Strait (Wegener) transform fault. Magnetic source depths are about 5 to 10 km (Kovacs, 1981), but the type of crust below this marginal smooth zone is unknown. If this smooth zone (*w*) describes the extent of transform motion at sea, then the zone of shear must be much wider (100-200 km) than the Nares Strait portion of the fault.

The Lomonosov Ridge was overflown along a short section near the North Pole and also over its widest part, where it approaches the Greenland-Ellesmere continental margin. Aeromagnetic data over other parts of the Lomonosov Ridge have been reported by Ostenso (1962), King *et al.* (1966), Vogt and Ostenso (1970), Ostenso and Wold (1971), Karasik *et al.* (1971), Karasik (1974), and Coles *et al.* (1978).

Taken together, these data indicate several irregular to sublinear anomalies of low to moderate amplitude. Source-depth calculations imply crystalline rocks at shallow subbottom depths, at least locally (Ostenso, Wold, 1971). A prominent positive anomaly is found over the Amerasia flank of the ridge near the north pole (Fig. 8). This and the anomaly "*s*" over a part of the Eurasian margin of the Lomonosov Ridge may mark the continental-oceanic crustal boundary.

Between the wide North American end of the Lomonosov Ridge and the Greenland-Ellesmere continental shelf there appears to be a sill of 1,500-2,000 m depth although this area is very sparsely sounded. The magnetic anomalies over this sill ("*r*" in Fig. 8) are remarkable for their short wavelength. Some are lineated, with a strike subparallel to "*p-o*" and perpendicular to the north Greenland coast. Magnetic source depths suggest outcropping crystalline rocks on the sea-floor, perhaps ancient continental crust but more probably oceanic crust of early Tertiary age (Kovacs, 1981). This region of disturbed magnetic field may reflect the zone of deformation associated with the relative movement between the Lomonosov Ridge and Greenland-Ellesmere. Kovacs (1981) suggests a sea-floor spreading origin for the anomalies. If this is so, they may correspond to part of the interval between anomalies 20 and 12, a time when, according to Phillips and Tapscott (1981), the Lomonosov Ridge moved *away* from Greenland-Ellesmere. During the preceding interval (anomaly 24 to 20) these two terrains had moved towards each other, creating the Eureka orogeny as one manifestation (Phillips, Tapscott, 1981).

Over the northern end of the Chukchi Plateau-Northwind Ridge complex (the "Chukchi Borderland" of Grantz *et al.* (1979)) the magnetic profiles show relatively irregular, short to moderate wavelength anomalies ("*c*" in Fig. 8) similar to those mapped over other continental borderlands and fragments, such as the Lomonosov Ridge. Higher amplitude anomalies of positive signs are found at several sites along the margins of the Chukchi Borderland (*b* and *d*). These anomalies may be associated with the boundary between continental and oceanic crust.

The Alaska continental margin and shelf was overflown on only a few flights, and the orientation of the tracks is unfavorable for detecting anomalies paralleling the margin (Fig. 9). The anomalies are low in amplitude and long in wavelength, consistent with seismic studies that indicate at least 4 to 8 km of sediments (Grantz *et al.*, 1979).

CONCLUSION

The large volume of new aeromagnetic data from high-latitude ocean basins has now been milked for the more straightforward conclusions. Even without additional geophysical data, the plate tectonic evolution of the Greenland-Norwegian Sea and Eurasia Basin is now reasonably well established. Frustrating complexities remain, for example the Greenland-Scotland transverse ridge, the Aegir Ridge (Norway Basin), and the Greenland Sea (Vogt *et al.*, 1978). It is not likely that the evolutionary details and crust/mantle character of these anomalous areas can be deduced if yet more detailed magnetic data are collected. Rather, detailed seismic reflection surveys, including multichannel profiles, are needed, in conjunction with deep drilling at critical sites. This is not to say that more cannot be extracted by careful processing of the large aeromagnetic data base, for example the calculation of the depth to magnetic basement (Kovacs, 1981).

Over the Amerasian Basin the only significant new plate-tectonic findings are an extinct Early Cretaceous (112-130 m.y.b.p.?) spreading axis in the Canada Basin (Fig. 9, 10 ; Taylor *et al.*, 1981) and the existence of magnetic lineations, also possibly of spreading origin, in the Lincoln Sea ("*r*" in Fig. 8 ; Kovacs, 1981) and in the Makarov Basin ("*g*" in Fig. 8 ; Taylor *et al.*, 1981). Additional magnetic data are needed to fill the gaps, but there is scant assurance that detailed coverage of the entire Arctic Basin would result in a unique plate kinematic scenario. The role of the Alpha Ridge remains conjectural, and is unlikely to be resolved without systematic sub-basement reflection-refraction profiling and sampling.

Acknowledgements

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