Mesozoic-Cenozoic Evolution of East Greenland: Implications of a Reinterpreted Continent-Ocean Boundary Location

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THEME 5: The Barents Shelf and the East Greenland Margin: A Comparison

Summary: Recent aeromagnetic syntheses of the North Atlantic region illustrate that on a key segment of the East Greenland margin immediately north of the Jan Mayen Fracture Zone, previous continent-ocean boundary locations are seriously in error. An area of crust 500 km long and 150 km wide at its widest, previously considered to be continental, is here reinterpreted as oceanic. Four important implications are recognised.

(1) Integration of different datasets in a geographic information system (GIS) has revealed an important onshore lineament compatible with the new interpretation of aeromagnetic data. Reconstructions of the East Greenland margin indicate that this lineament may have been a significant control on palaeogeography from at least Jurassic time.
(2) The East Greenland margin north of the Jan Mayen Fracture Zone is the conjugate margin to the Vøring Basin region of offshore Norway. Several authors have proposed the existence of a long-lived Mesozoic landmass in central parts of the North Atlantic rift system prior to spreading, located in the vicinity of the outer Vøring margin. The new reconstruction makes the existence of a significant landmass unlikely.
(3) Prior to the opening of the northern North Atlantic, the Vøring Basin lay much closer to the East Greenland coast than previously recognised, such that NE-SW trending structural highs along the outer margin of the Vøring Basin may have had original continuity to the southwest with the Liverpool Land/Jameson Land area of onshore East Greenland.
(4) The tighter fit between the Norwegian margin and the East Greenland coast enhances the significance of East Greenland as an analogue for hydrocarbon exploration in the Vøring Basin.

INTRODUCTION

Framework of the northern North Atlantic

Continental separation between Greenland and the NW European margin occurred around the Paleocene-Eocene boundary (Chron 24R), the last part of the Atlantic Ocean to open (TALWANI & ELDHOLM 1977). The line of original separation is now preserved by the two, approximately parallel, continent-ocean (C-O) boundaries on the conjugate margins. Using the orientation of these C-O boundaries, and the history of spreading, the northern North Atlantic can be subdivided into northern, central and southern segments, separated by fracture zones (Fig. 1). These subdivisions are used here as a basis for description, and in the subsequent discussion.

The northern segment has relatively linear C-O boundaries and the oceanic crust is symmetrically disposed around a central spreading axis (the Mohns Ridge). A similar symmetrical pattern around the Reykjanes Ridge is present in the southern segment. Both segments have comparable spreading histories. Furthermore, the C-O boundaries and the spreading axis in the southern segment are approximately on the same trend as the corresponding features in the northern segment (Fig. 1).

Although there are many similarities between the northern and southern segments, there is one important difference. In the northern segment, the general trend of the East Greenland coastline is approximately N-S, following the orientation of the principal Mesozoic (and earlier) faults. The Norwegian coastline also trends approximately parallel with the East Greenland coast for the same reasons. This coastline trend is significantly oblique to the NE-SW trend of final continental separation, such that the Northeast Greenland shelf widens markedly to the north as the Norwegian shelf correspondingly narrows (Fig. 1). In the southern segment, the East Greenland coastline is subparallel to the C-O boundary and presumably to the trend of earlier faults.

Between the northern and southern segments, there is a central segment which departs from the relatively simple spreading history of the adjacent segments. On the Greenland side, the C-O boundary curves out oceanward to form a significant promontory, and on the European side there is a corresponding embayment occupied by the Norway Basin (Fig. 1). The current spreading axis (the Kolbeinsey Ridge) is asymmetrically disposed, being much closer to the Greenland margin. On the Norwegian side lies the extinct Aegir Ridge, and between the two spreading centres lies the Jan Mayen Ridge, a possible microcontinent, which separated from the Greenland margin when spreading switched to the Kolbeinsey Ridge (NUNNS 1983, ELDHOLM et al. 1990). This central segment therefore had a much more complex spreading history, and it is probably not coincidence that this central area marks the location where two contrasting parts of the rift system meet.

Significance of East Greenland

Since the end of the Caledonian Orogeny in the northern North Atlantic region, a rift system has developed along the trend of the former orogen, characterised by a series of discrete rift pulses, with intervening thermal subsidence phases (e.g. ZIEGLER

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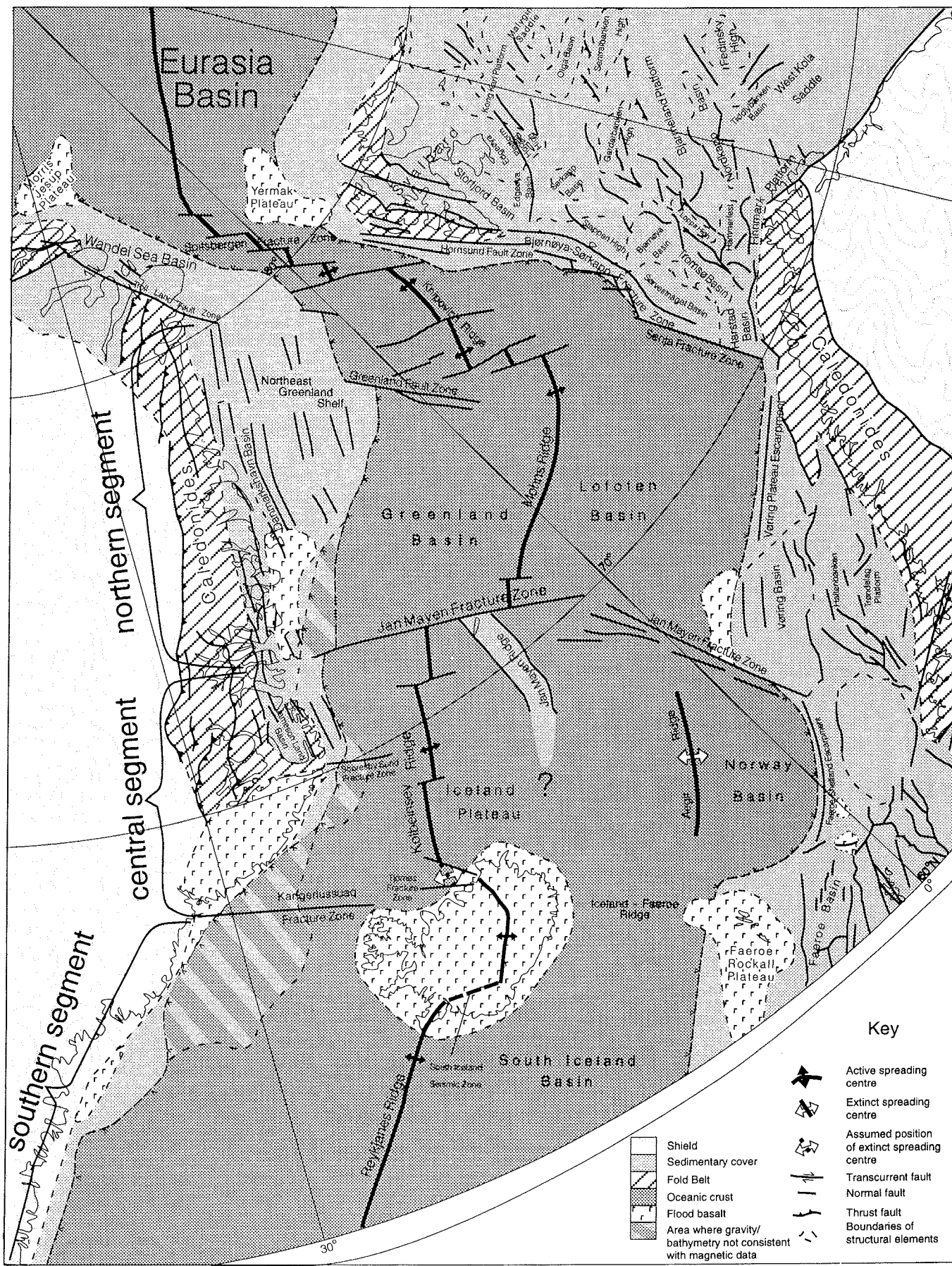
Fig. 1: Framework of the Northern Atlantic adapted from Scott et al. (1995). The areas indicated by the oblique shading on the East Greenland margin are those where the interpretation of the crust is open to dispute.

1988). When this prolonged period of intermittent rifting finally culminated in spreading, the line of continental separation did not always coincide with the axis of the former rift system, such that sediments sourced from one continental margin are now preserved on the other. This paper focuses on one such area of rift asymmetry north of the Jan Mayen Fracture Zone (JMFZ) (Fig. 1), where the East Greenland margin formerly supplied sediment to the Vøring Basin, which is now part of the Norwegian shelf. The outer Vøring Basin is also an area in which hydrocarbon exploration is actively in progress (e.g. BREKKE et al. 1999). East Greenland is therefore in a unique position to provide constraints for such exploration activity, a situation enhanced by the fact that it contains the only significant onshore Mesozoic-Cenozoic outcrop in the entire northern North Atlantic rift system.

If East Greenland is to be used most efficiently as an analogue, accurate pre-drift reconstructions are vital to understand palaeogeographic and tectonic evolution, to identify specific sediment transport paths, and to correlate formerly continuous structural features on the conjugate margin. Broad-scale plate motions during the opening of the northern North Atlantic are well constrained by the available magnetic anomaly, fracture zone and palaeomagnetic database (e.g. FREI & COX 1987, ROWLEY & LOTTES 1988). However, many existing reconstruction series contain significant simplifications arising from the large areas covered and the assumption that continental plates behave rigidly. When combined with any errors in defining plate boundaries, this can lead to serious misconceptions when attempting to reconstruct the detailed pre-drift configuration of specific areas.

In this paper, it is shown that on a key segment of the East Greenland margin north of the JMFZ, previous estimates of the C-O boundary location are seriously in error. This has led to overestimation of the width of this part of the northern North Atlantic rift system prior to the onset of spreading, which has important consequences both for the correlation of structural elements on the conjugate margins and for the palaeogeographic evolution of the rift system.

LOCATING THE CONTINENT-OCEAN (C-O) BOUNDARY

A number of crustal parameters (e.g. thickness, velocity structure, gravity and magnetic signature) are generally required to define the location of the C-O boundary. However, on continental margins characterised by large volumes of rift-related basaltic magmatism and highly attenuated continental crust, it is notoriously difficult to position the C-O boundary accurately. For example, WHITE & McKENZIE (1989) concluded that it "becomes a matter of semantics whether to call the isolated blocks of continental crust in a matrix of new igneous material a 'continental' or an 'oceanic' crust". However, as such transitional regions may be well in excess of 100 km across, arbitrarily deciding the location of the C-O boundary within this region can have fundamental consequences for reconstructions.

Owing to the adverse ice conditions on the East Greenland shelf, geophysical data for offshore areas are relatively sparse, and decrease northwards (LARSEN 1990). North of the JMFZ between 72 and 76 °N, the location of the C-O boundary has been based on the coincidence of a gravity high, bathymetric shelf margin and magnetic interpretation (see, for example, compilation of bathymetry and magnetic lineation data in ESCHER & PULVER-TAFT 1995). Multi-channel seismic profiles shot across the bathymetric shelf margin north of the JMFZ reveal seaward-dipping reflector wedges that have been interpreted to coincide approximately with the C-O boundary (HINZ et al. 1987), in agreement with these interpretations. It was, however, noted by HINZ et al (1987) that (1) thick sediment cover affects imaging, (2) the aeromagnetic pattern was not well defined owing to poor data coverage, and (3) by analogy with the conjugate part of the Vøring margin, distinguishing between rift-related volcanism and sub-aerial oceanic spreading is extremely difficult on this part of the margin. More recent compilations of aeromagnetic data (e.g. VERHOEF et al. 1996, OAKEY et al. 1998) quite clearly show that magnetic lineations can be traced across the previously assumed C-O boundary into areas that were interpreted to be continental crust (Fig. 2). Overall, this area of misinterpreted crust is 500 km long and 150 km wide at its widest, and includes large areas of seaward-dipping reflectors and crust interpreted by HINZ et al. (1987) to be greater than 20 km thick.

The pattern of magnetic lineations is here regarded as unequivocal evidence that this area should be considered oceanic crust, particularly for the purposes of plate reconstructions. However, this does not preclude the presence of highly attenuated continental fragments within it. It is assumed that the lineations are less clear because (1) the area is overlain by thick Cenozoic sediments which have built out onto oceanic crust (a feature noted further south on the East Greenland margin; LARSEN 1980, 1990), and (2) the 56 Ma oceanic crust was anomalously thick to begin with and/or has been thickened, and the magnetic signature confused, by 35 Ma intrusions associated with separation of the Jan Mayen block from the East Greenland margin. The fact that seaward-dipping reflectors are developed on oceanic crust is more compatible with the model for their origin proposed by MUTTER et al. (1982) than that of HINZ (1981), at least for this part of the margin. The new interpretation also extends anomalies 24 and 23 south towards the JMFZ on the East Greenland margin, improving the spreading symmetry with the conjugate Vøring margin.

IMPLICATIONS

East Greenland lineament

As noted above, the continental margin of East Greenland north of the JMFZ is approximately on the same trend as the margin south of the Kangerlussuaq Fracture Zone (Fig. 1). The new interpretation of the C-O location north of the JMFZ, makes this relationship even more apparent (Fig. 2). There is evidence that the onshore continuation of this trend across the intervening
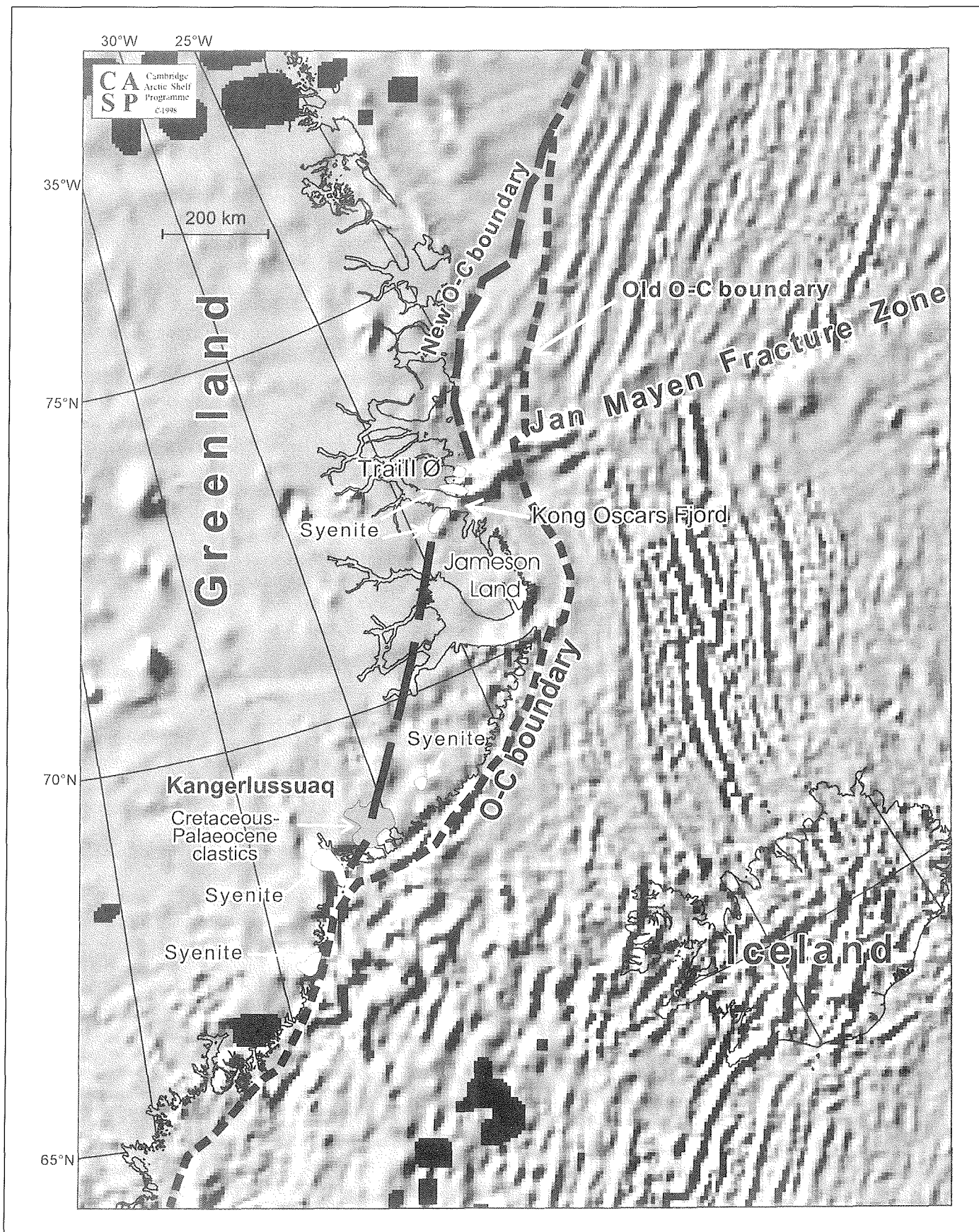
Fig. 2: Offshore and onshore aeromagnetic data (positive areas elevated, illumination from NW) combined with elements of onshore geology. Black patches signify gaps in the database. Note that north of Jan Mayen Fracture Zone, the aeromagnetic data clearly indicate that oceanic crust approaches much closer to the coastline than previously recognised. The long dashed line connects this new O-C boundary position to the O-C boundary south of Kangerlussuaq.

central segment (long dashed line on Fig. 2) is a lineament with geological significance. It is named here the Kap Syenit-Kangerlussuaq (KSK) lineament, after localities at each end (Kap Syenit is a small headland on the south coast of Kong Oscars Fjord). The potential significance of this lineament has already been recognised by LARSEN (1988), who pointed out that the lower part of the East Greenland plateau basalts were erupted along this line during anomaly 25/24R immediately prior to spreading. Evidence is documented here that the KSK lineament also had a later and an earlier significance.

Cenozoic significance

At the western end of the JMFZ, there are distinct magnetic anomalies which continue into continental crust, passing through the eastern end of Traill Ø and curving away southwestward to lie along the northern part of the KSK lineament (Fig. 2). These onshore anomalies are associated with syenite intrusions, which on Traill Ø are dated at 35 Ma (NOBLE et al. 1988, PRICE et al. 1997), and have been linked with the separation of the Jan Mayen block from the East Greenland margin.

Towards the southern end of the KSK lineament, an area of Cretaceous and Palaeocene sediment is exposed in the Kangerlussuaq area beneath thick Eocene basalt flows. A pronounced post-basaltic erosion dome has been identified here (GLEADOW & BROOKS 1979), which has been attributed to mid-Tertiary passage of the Iceland plume beneath the area (CLIFT et al. 1998). There are also several syenite intrusions in this region. These features at both ends of the KSK lineament are interpreted here to indicate that during the separation of the Jan Mayen block from the East Greenland margin, there was an attempt to separate a much larger continental fragment along the trend of the lineament. Somewhat to the east of the lineament, in the vicinity of the syenite intrusion northeast of Kangerlussuaq depicted on Figure 2, PEDERSEN et al. (1997) have described a fracture zone oriented N-S to NNE-SSW, which post-dates the basalt. This fracture zone may also relate to mid-Tertiary displacement on the lineament.

Pre-Cenozoic significance

It has long been recognised that areas north of Kong Oscars Fjord behaved differently to the Jameson Land area during Mesozoic rift events. Both areas were affected by Early Triassic rifting, whereas only areas north of Kong Oscars Fjord were significantly affected by subsequent Jurassic and Cretaceous rift events (e.g. PRICE & WHITHAM 1997). The lack of faulting of the Jurassic strata in Jameson Land was considered by SURLYK (1991) to reflect a structural discontinuity in the form of a "cross-fault" trending NW-SE along Kong Oscars Fjord (Fig. 2), which separated crustal blocks that responded differently to deformation. However, it seems probable from map evidence (e.g. BENGAARD & HENRIKSEN 1982) that faults on the south side of Kong Oscars Fjord are part of the same, largely Middle Jurassic to Early Cretaceous, fault system described from areas to the north. The fact that these faults largely occur to the northwest of the KSK lineament would

suggest it is the lineament itself that marks the fundamental divide between crustal blocks which had a distinct tectonic history, an argument strengthened by the fact that a distinct en echelon fault array runs along the lineament trend, part of which is depicted by BENGAARD & HENRIKSEN (1982). This right-stepping array is compatible with a sinistral element of displacement along the lineament; Jurassic sinistral displacement along similarly oriented structures has been proposed for areas west of Britain by KNOTT et al. (1993).

The reason for the different response to deformation northwest and southeast of the KSK lineament is not clear. Jurassic depositional histories northwest and southeast of the lineament suggest that it may have had some palaeogeographic significance during most of Jurassic time. Figure 3, for example, shows the apparent coincidence of the Oxfordian coastline with the northeastern part of the lineament (the southern part of the coastline towards Kangerlussuaq is extrapolated because no Oxfordian rocks are exposed in this region). Such a relationship can be inferred back to at least Bathonian time, when Jurassic strata began to be deposited in Milne Land (CALLOMON & BIRKE-LUND 1980). However, by latest Jurassic time there was a major contrast in depositional styles and assumed water depths between areas north of Kong Oscars Fjord and Jameson Land (e.g. SURLYK 1991). It is at this time that fault-controlled subsidence accelerated in areas to the northwest of the KSK lineament, as fault spacing reduced during hangingwall break-up (PRICE & WHITHAM 1997). This separated rapidly subsiding, fault-controlled turbidite basins to the north from stable and relatively shallow marine clastic deposition in Jameson Land (SURLYK & NOE-NYGAARD 1992, PRICE & WHITHAM 1997).

A mid-Atlantic landmass

Prior to the Cenozoic opening of the Atlantic, the nature of the Mesozoic rift system that occupied the area between East Greenland and northwest Europe is not entirely clear. There has been debate as to whether it was a simple, single rift, deepening towards the central area (e.g. ZIEGLER 1988), or whether a significant landmass (or at least a substantial area of erosion) effectively created two parallel depocentres for much of the time (e.g. DORÉ 1992, BREKKE et al. 1999). The fuel for this debate came initially from evidence of some westerly derived Jurassic sediments on Haltenbanken (for location, see Fig. 1). If such a landmass existed, it would have to be in the outer Vøring Basin region, currently the target of exploration. Seismic reflection profiles from this area reveal structural highs (e.g. LUNDIN & DORÉ 1997, BJØRNSETH et al. 1997, WALKER et al. 1997), but only Upper Cretaceous and Cenozoic strata can be interpreted with confidence; whether this area was elevated in earlier Mesozoic time is less clear.

On the basis of the new C-O boundary location north of the JMFZ, it is argued here that there can have been no significant landmass in the central part of the rift system during Mesozoic time. The Mesozoic reconstructions used by DORÉ (1992) and BREKKE et al. (1999) were constructed on the basis of the old C-
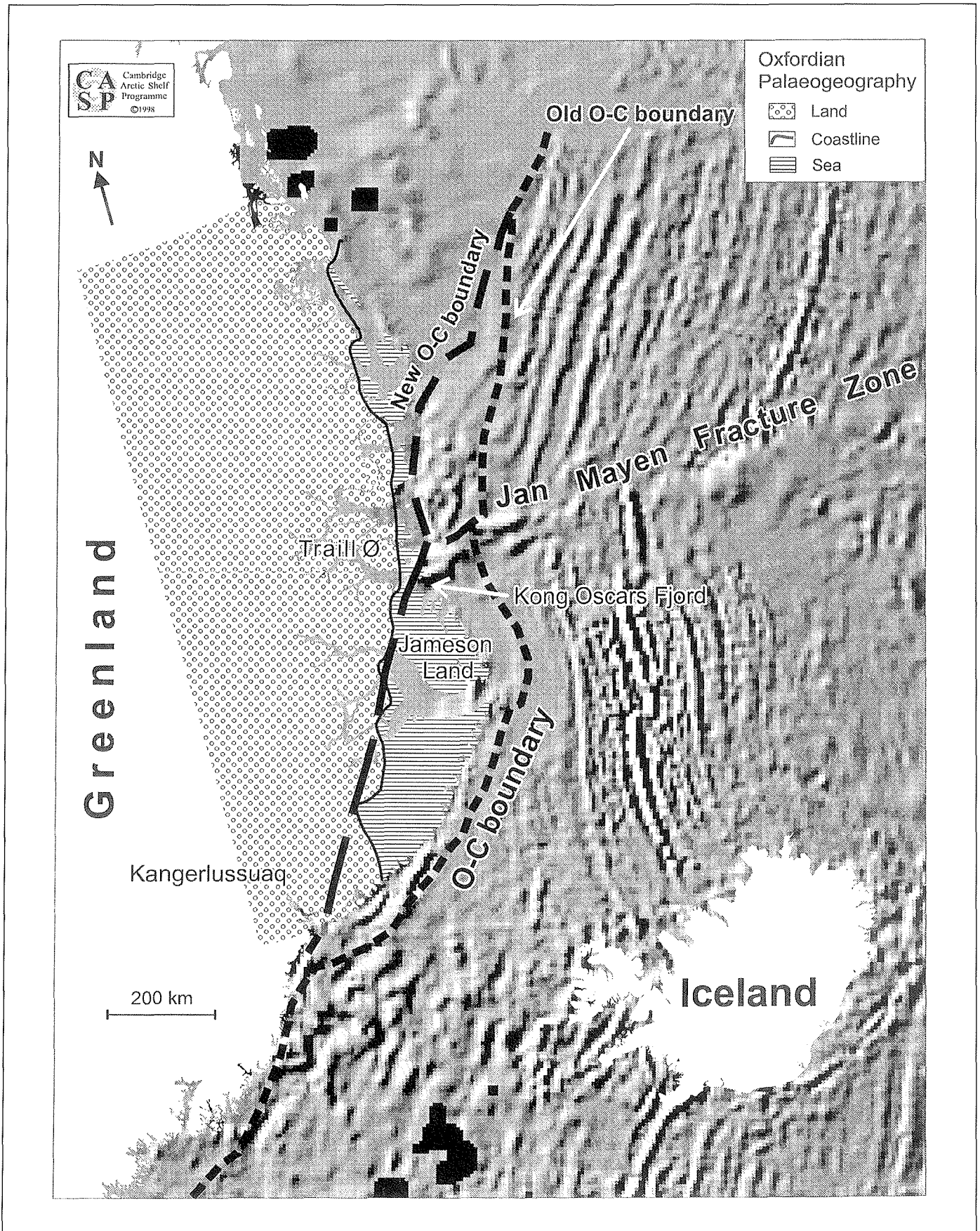
Fig. 3: Offshore aeromagnetic data (positive areas elevated, illuminated from NW) combined with Oxfordian palaeoceanography. The Oxfordian coastline is approximately coincident with the trend on the lineament connecting the O-C boundary north of the Jan Mayen Fracture Zone with the O-C boundary south of Kangerlussuaq.

O boundary location on the East Greenland margin, and without attempting to compensate for the effects of pre-drift lithospheric extension on the continental margins. This creates an unrealistically wide rift basin between Greenland and Norway. When the reconstruction is made using the new C-O boundary location, and the effects of extension are removed, there is simply insufficient space to accommodate a large landmass in the rift system (Fig. 4). This does not preclude the presence of some smaller areas of erosion within the rift, such as footwall scarps. For example, it is well established that the eastern margin of the Jameson Land Basin (the Liverpool Land high) was exposed and supplying clastic sediment during Triassic and part

of Jurassic time (e.g. BIRKENMAJER 1976). However, detailed sedimentological and stratigraphic studies comparing parts of the Mesozoic succession in the Jameson Land Basin with age-equivalent strata on the Norwegian margin indicate many similarities (e.g. DAM & SURLYK 1995, HELGESEN & KAAS 1997), which suggests that connectivity between the areas was unimpeded by an intervening landmass. Furthermore, there is no evidence from the well-studied Mesozoic successions of East Greenland north of the JMFZ to indicate a large land area immediately to the east. The implication is that the principal westerly source of sediment for rocks now on the Norwegian margin is Greenland itself (Fig. 4). This conclusion is
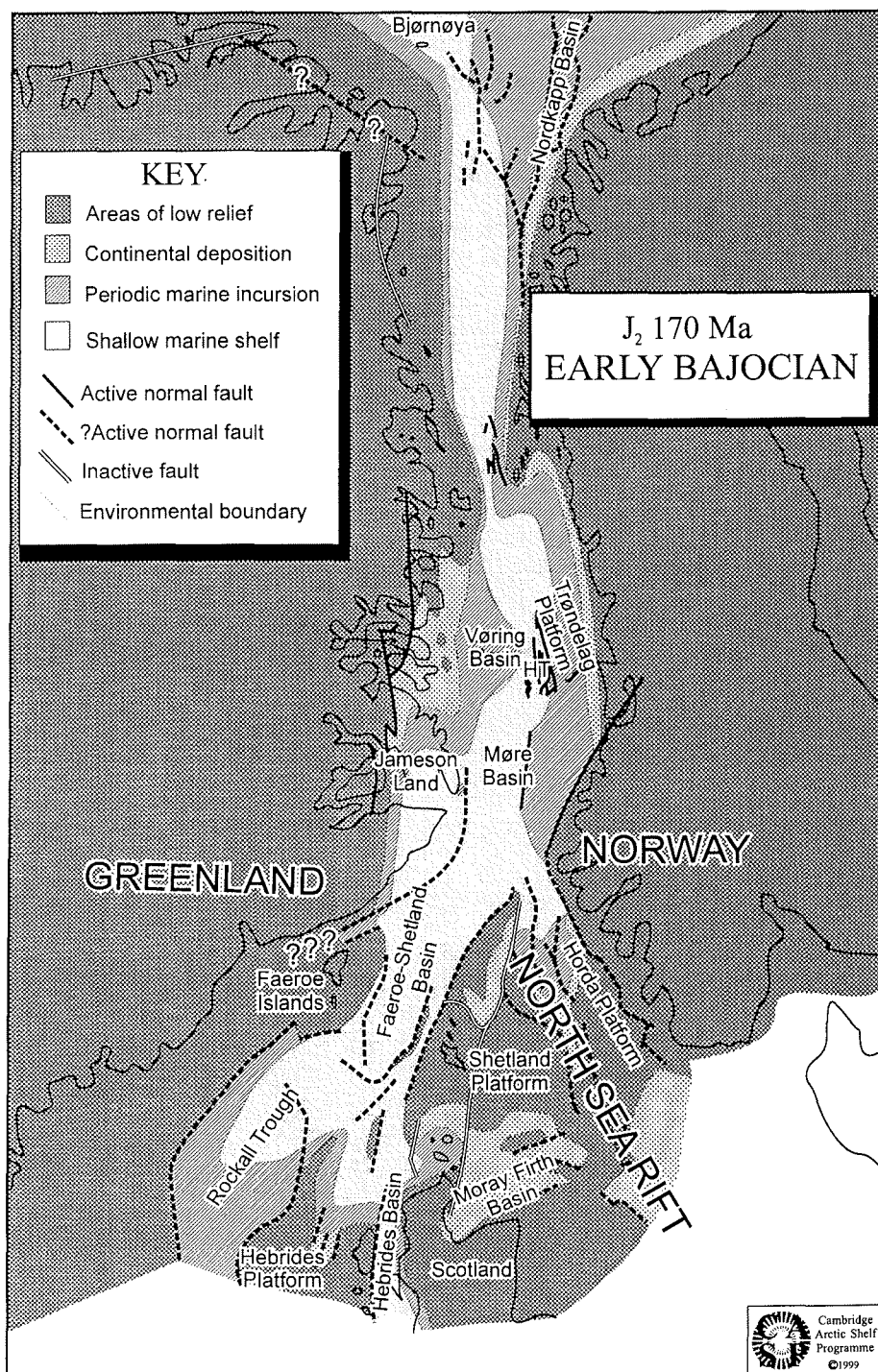

Fig. 4: Bajocian palaeoceanography based on new O-C boundary interpretation and removal of stretching on continental margins. In the reconstruction, East Greenland becomes the principal westerly source of sediment to the Norwegian margin. HT = Halten Terrace.

compatible with recent provenance studies based on heavy minerals (e.g. MORTON & GRANT 1998).

Structural correlation on the conjugate margins

A major implication of the new C-O boundary position is that the outer Vøring margin region must have originally been very close to the East Greenland coast, such that NE-SW trending structural elements of the outer Vøring margin probably had an original southward continuation into onshore areas of East Greenland south of the JMFZ (Jameson Land / Liverpool Land). It is outside the scope of this paper to discuss the nature of this connection in detail; however, it is clear that there are potential implications for hydrocarbon exploration in the Vøring Basin. Unfortunately, it is the Late Cretaceous and Cenozoic evolution of the outer Vøring Basin that is of most relevance to exploration, and it is this part of the history of the Jameson Land / Liverpool Land area for which there is least stratigraphic constraint. However, the uplift history of the Jameson Land / Liverpool Land during this time may provide important constraints for areas to the north. Furthermore, during Jurassic-Cretaceous extension the Jameson Land Basin area responded differently to deformation compared with areas to the northwest of the KSK lineament. If this lineament can be extrapolated to the northeast along the line of the new C-O boundary location north of the JMFZ, the outer Vøring Basin lies on its southeast side in the same relative position as Jameson Land; this may be significant in how the Vøring Basin's Mesozoic evolution is modelled.

WIDER SIGNIFICANCE

As noted in the introduction, this part of the northern North Atlantic marks the location where two contrasting parts of the rift system meet. In the northern segment (Fig. 1), the principal Mesozoic faults are oblique to the line of final continental separation, whereas in the southern segment they are apparently parallel. The intervening central segment represents an area of transition between the two domains. It is important in the southern segment to establish if N-S trending extensional faults were originally present, and at what point the NE-SW trend became dominant.

The different structural geometries of the northern and southern segments has been interpreted to reflect a change in the orientation of the main rift axis in the northern North Atlantic from N-S during Jurassic time (passing east of Britain) to NE-SW in Cretaceous time (passing west of Britain) (e.g. LUNDIN & DORÉ 1997). Supporting evidence comes from the fact that extension ceased in the N-S oriented rift basins of the northern North Sea around the Jurassic-Cretaceous boundary (RATTEY & HAYWARD 1993). Models invoking this change of rift orientation imply either that Jurassic and earlier rifting was absent to the west of Britain or oblique to the present NE-SW structural grain. Alternatively, NE-SW trending rift systems could already have been active during Jurassic and earlier time, suggesting a

network of variably oriented rifts (e.g. ROBERTS et al. 1990). The interpretation of the KSK lineament presented here suggests that elements of both models may be correct: the NE-SW trending lineament had a subtle but recognisable influence from at least Bathonian time, but only became a significant influence at the end of Jurassic time.

On a pre-drift reconstruction, the northern North Sea lies adjacent to the central segment, as defined above (Figs. 1, 4). It is therefore interesting to note that at the time the North Sea rifting ceased, the KSK lineament crossing the central segment in East Greenland began to have a significant influence on palaeogeography. Why the Jameson Land Basin to the southeast of the lineament should respond in such a different way to areas to the northwest is unclear. It could reflect a different basement composition or orientation of major structures within the basement. It may also be a mechanical consequence of extreme extension in Palaeozoic rifting episodes in Jameson Land compared with areas to the northwest (PRICE & WHITHAM 1997). Alternatively, the different response may simply reflect the location, at the point at which the rift system changed orientation. Whatever the reason, it is interesting to speculate whether the rigidity of the Jameson Land block may have played any part in the failure of the adjacent North Sea rift at the end of Jurassic time.

ACKNOWLEDGMENTS

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