Crustal history and basin development of Baffin Bay

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Menzies, A. W. 1982. Crustal history and basin development of Baffin Bay. – In: Dawes, P. R. & Kerr, J. W. (eds), Nares Strait and the drift of Greenland: a conflict in plate tectonics. – Meddr Grønland, Geosci. 8: 295–312.

Lack of definitive magnetic anomaly stripe data in Baffin Bay and Davis Strait imposes severe limitations on the extension of the Labrador Sea sea-floor spreading model into these areas. Using refraction and earthquake seismicity data to examine crustal and mantle structure, a case is presented for the existence of oceanic crust in Baffin Bay, and a bridge of continental crust connecting Greenland and Baffin Island across Davis Strait. Reconstruction or closure of Greenland with Labrador and Baffin Island is made by first defining their respective continental–oceanic crust boundaries, and then by juxtaposing these boundaries. The two sets of motion implied by Srivastava's (1978) interpretation of the magnetic anomaly pattern in the Labrador Sea are used to develop an opening motion for Labrador Sea and Baffin Bay. The Baffin Bay opening began in Paleocene time (anomaly 24) and ceased about Eocene time (anomaly 20). This motion is along a strike-slip fault crossing through Davis Strait which resulted in Baffin Bay opening as a rhombochasm with a bridge of continental crust being maintained in Davis Strait.

The suggested origin of Baffin Bay requires appreciable movement to have occurred either along Nares Strait or in the Canadian Arctic Archipelago.

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Studies of the formation of the Atlantic Ocean have provided an excellent model for the understanding of the origin of oceanic basins generally. The generalized model of sea-floor spreading as applied to the Atlantic Ocean has remained the primary operating hypothesis for the initial studies of all oceanic basins within the Atlantic area. Thus the widely held view pertaining to the area of this study is that the Labrador Sea was created by the separation of a Greenland 'plate' from the North Atlantic plate. The action was a northerly extension of the spreading evolution of the North Atlantic Ocean that began in early Jurassic time and by late Cretaceous (Senonian) time had extended into the region of the Labrador Sea. A two-stage opening has been postulated (Srivastava 1978) with, in the first stage, Greenland rotating in an anti-clockwise direction throughout Senonian time and then, in the second stage, continuing opening through the Paleocene to at least Eocene time and this included the opening of Baffin Bay with strike-slip movement along Nares Strait. The nature of the transformation of the spreading centre through Davis Strait has been the subject of considerable conjecture and speculation.

The timing of these events is derived from the interpretation of magnetic 'stripes' in the Labrador Sea. Although there is not complete agreement about the interpretation of the data amongst all investigators (see e.g. van der Linden 1975, Hinz et al. 1979), it appears to be generally agreed that anomaly 33 (Santonian) and anomaly 20 (Eocene) are the oldest and youngest probable in the Labrador Sea. Sometime subsequent to anomaly 20 the spreading centre aborted the Baffin Bay–Labrador Sea area and spreading at the present-day site to the east of Greenland took over the dominant role. Greenland has since moved with the North American plate as the North Atlantic opening progressed through the Norwegian–Greenland Sea.

This scenario provides a good first working hypothesis, but leaves some problems. Broadly speaking the major problems are:

1) Davis Strait is a morphological high in an apparently purely extensional regime. Is this a post-extensional, or syn-extensional feature such as Iceland, or is it more fundamental, a geomorphological high of some antiquity?
2) There are no basin-wide, good quality, magnetic stripes in Baffin Bay with which to interpret the evolution of this area, such as are present in the Labrador Sea (Jackson et al. 1979). Magnetic profiles are indeed available, but it appears that the ability to provide dependable correlations of anomalies is lacking.
3) In Baffin Bay there is an apparent lack of good morphological fit of either the coastlines or of any bathymetric contours with which to conjecture or

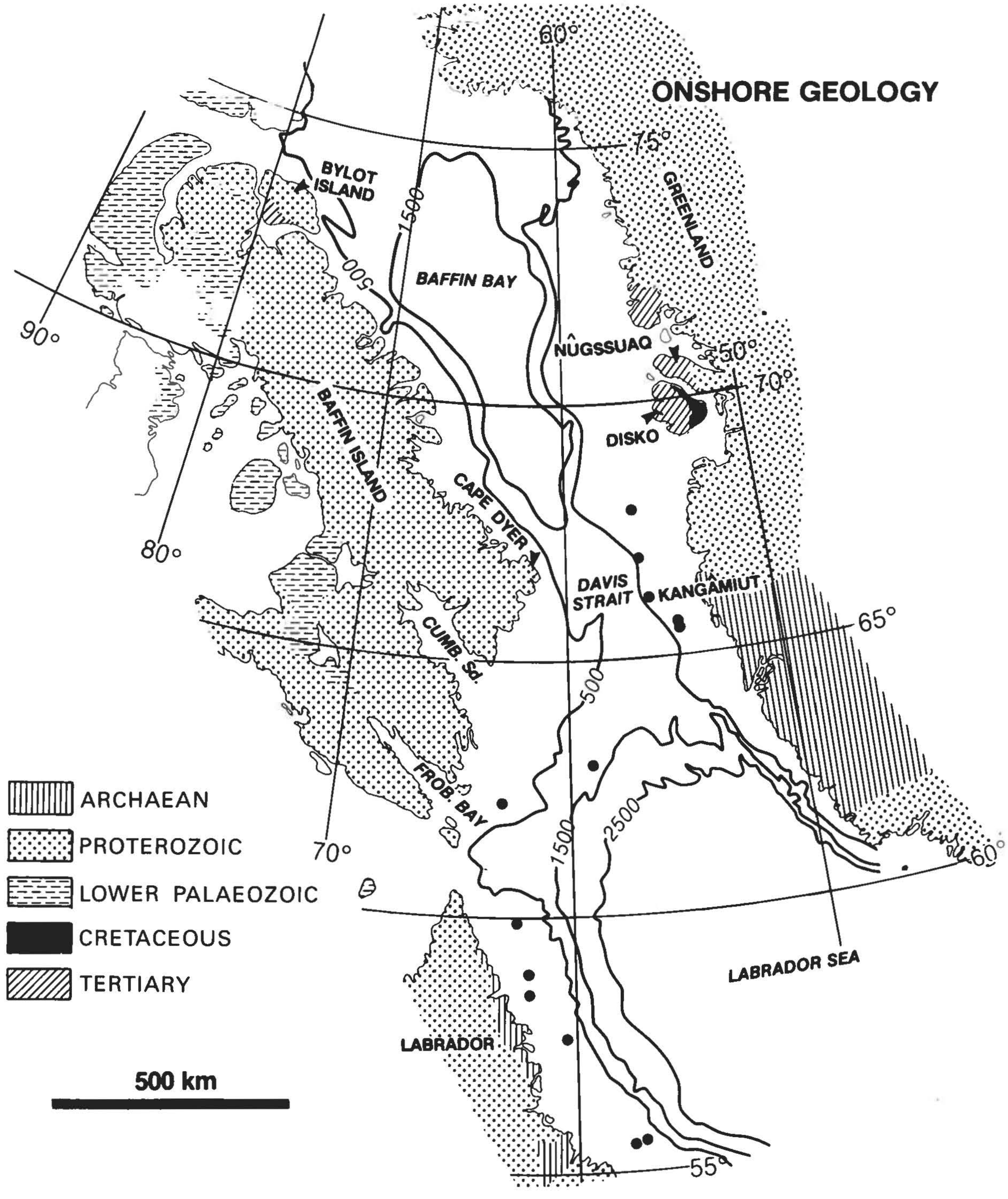

Fig. 1. General geological map of the study area compiled from published sources of the Geological Surveys of Canada (GSC) and Greenland (GGU). Black dots indicate sites of industry boreholes with one, Kangâmiut, named; bathymetry is in metres.

postulate a pre-spreading closure of the Bay. This is quite different from the Labrador Sea where there is a good morphological fit of the coastlines.

4) Whereas the Labrador Sea shows a general symmetry about a central bathymetric ridge and graben system, Baffin Bay shows an asymmetric bathymetric basin and no morphologic or crustal evidence of a ridge or graben.

It seems that the resolution of the problems rests on two parameters, viz. defining the nature of the crust in Baffin Bay and Davis Strait and the accurate definition of the continental–oceanic crust boundary.

Surface geology considerations

The oldest rocks in the study area are of Archaean age and these form a stable block flanked on the north by successively younger rocks (Fig. 1). The oldest of these are metamorphosed early Proterozoic rocks, mainly Aphebian that in places are intimately associated with reworked Archaean material (Douglas 1967, Escher et al. 1970, Jackson & Taylor 1972, Bridgwater et al. 1973, Escher & Watt 1976, Douglas et al. 1979). The late Proterozoic is represented by relatively unmetamorphosed sediments and volcanics that occur on northern Baffin Island and in North-West Greenland. Overlying the Proterozoic rocks on the north end of Baffin Island and occurring as outliers preserved in gra-

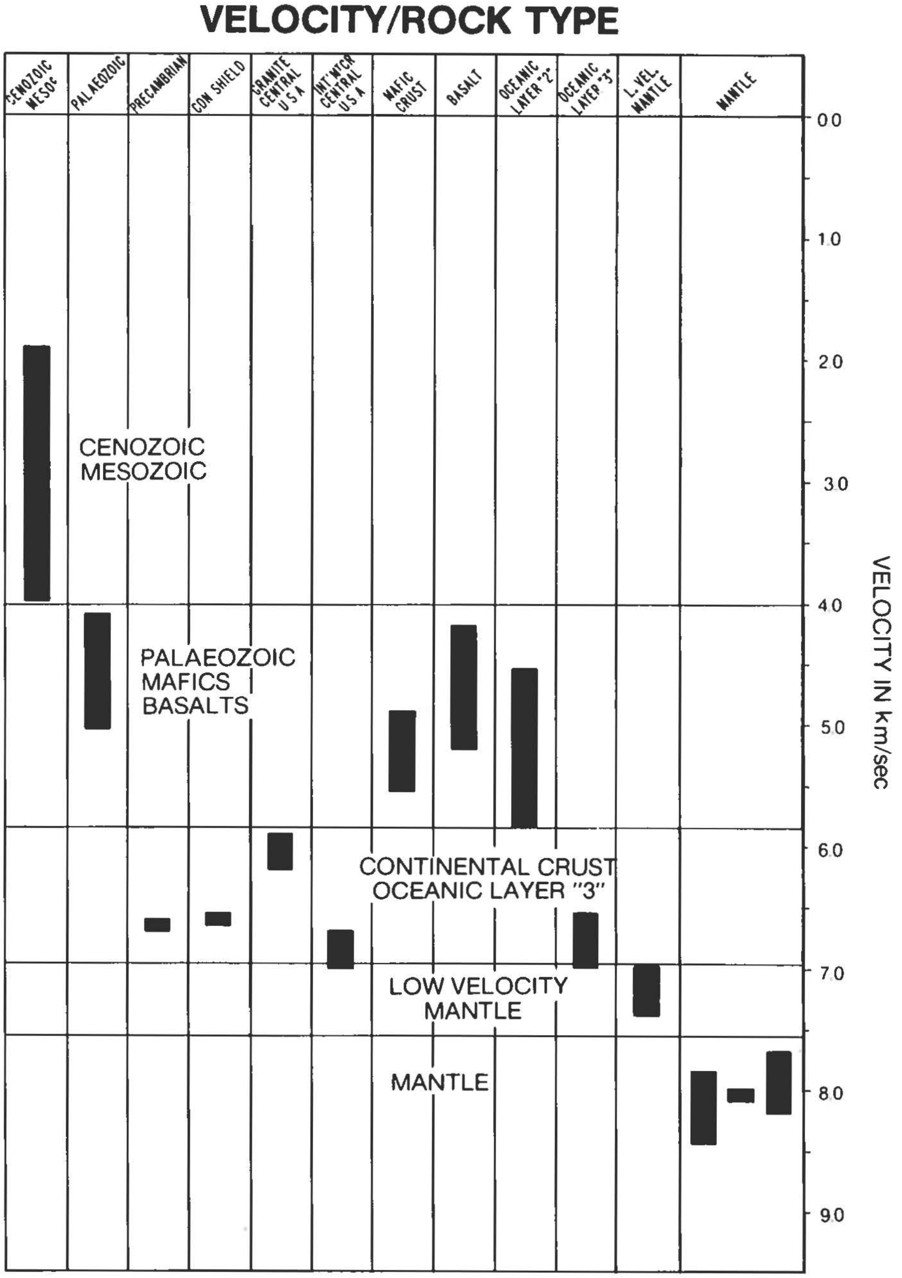

Fig. 2. Compilation diagram of seismic velocities versus rock type. Sources: Healy & Warren 1969, Keen & Barrett 1972, Berry & Fuchs 1973, van der Linden 1975 and Esso Resources Canada Ltd.

bens throughout the map area in Canada are early Palaeozoic carbonates of Cambrian through Silurian age (Beh 1975, Grant 1975). Isolated remnants of this once extensive Palaeozoic cover are also preserved in West Greenland (Escher & Watt 1976). Jurassic basic dykes (Watt 1969) and a small outcrop of possible Jurassic age (King & McMillan 1975) occur in the west coast of Greenland and Labrador, respectively. The next sequence of rocks within the study area are Lower and Upper Cretaceous strata that occur in the Disko region of West Greenland; the Upper Cretaceous is also represented on Bylot Island. Tertiary rocks, both sediments and volcanics, are known from West Greenland and from Cape Dyer and Bylot Island (Clarke & Upton 1971, Andrews et al. 1972, Henderson et al. 1976).

Detailed lithologic and stratigraphic descriptions and interpretations of the region have been published and bedrock summaries of the Canadian and Greenland sides of the study area are found in Douglas (1970) and Escher & Watt (1976). Only some brief comments on the historical significance of some surface outcrops are given here.

The major hiatus that exists between the Lower Palaeozoic carbonates and the late Mesozoic strata indicates that the study area was essentially a high standing craton for the majority of its history. Any sedimentation that took place during this period was most probably of thin continental rocks that were easily removed. This area was most probably a main provenance of the Late Palaeozoic, Mesozoic and Cenozoic strata of the Sverdrup Basin, where a thick and near-complete geologic sequence is present (Balkwill 1978).

The Cretaceous deltaic deposits of the Disko region, West Greenland, prograde from south-east toward north-west (Henderson et al. 1976), although it is postulated that the opening of Baffin Bay is supposed to have progressed from south to north. Additionally the uppermost Cretaceous of this delta is a marine sequence, thickening to the north. Thus the history of this delta indicates the development of a Baffin basin coincident, at least in part (Barremian–Turonian), with the opening of the Labrador Sea, but with the distinction that the marine invasions were from the north. It thus appears that the Baffin Bay sea and the Labrador Sea were converging upon each other, possibly joining at or in the vicinity of Davis Strait (B. MacLean, pers. comm.). This suggests some connection between the geological history of the Arctic Basin and that of the North Atlantic at least as early as early Cretaceous (Barremian) time. In other words, it may be that the

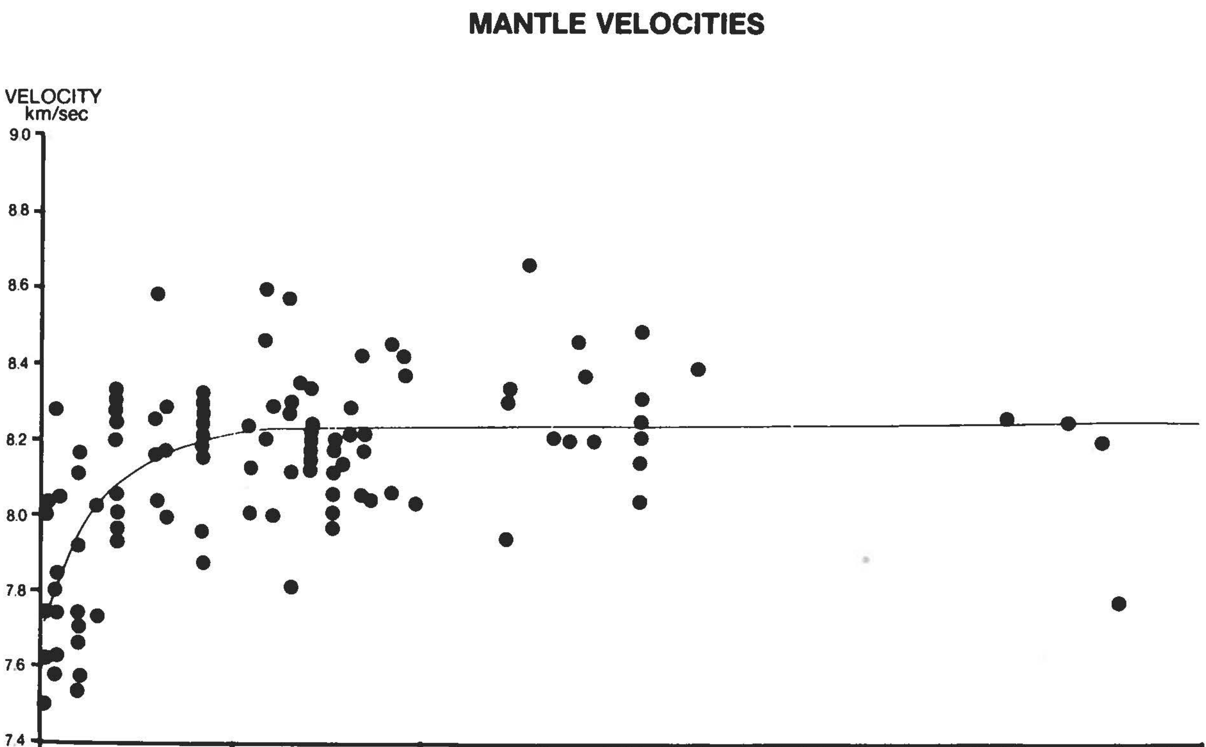

Fig. 3. Diagram showing relationship of mantle velocities and crustal age. From Lewis (1978).

history of Baffin Bay is connected with the Arctic Basin, at least as much, if not more, as with the Labrador Sea – North Atlantic.

The Tertiary volcanics of central West Greenland and Cape Dyer on Baffin Island as well as offshore outcrops indicate a major episode of volcanism beginning in Paleocene time (Clarke & Upton 1971, Clarke 1975, Clarke & Pedersen 1976, MacLean et al. 1978). Cross-bedding and overlap of flows indicate an easterly to north-easterly source for the Cape Dyer sequence and a south-westerly source for the Greenland volcanics. This points to the Davis Strait as a source area for the Tertiary volcanics. From the interpretation of the magnetics of the area it would appear that the volcanic province extends 1000 km from the Nûgssuaq–Disko region to at least Frobisher Bay, and is at least as wide as Davis Strait, i.e. about 200 km. Is Davis Strait an extinct Iceland and/or Faeroe Ridge situation?

Crustal definition

Until recently the interpretation of refraction data was concentrated on trying to relate velocities with rock type and in this way interpret the geology of the crust. It is now accepted that there is nothing sufficiently characteristic about oceanic or continental velocities to distinguish them from each other (Fig. 2). However, mantle velocities are distinguishable from each other. The mantle invariably seems to come in at 7.5 km/sec. or greater (Fig. 3). Parsons & Sclater (1977) indicate that for a crust 46 m.y. or younger the crustal velocity values would range from 7.85 to 8.35 km/sec. Fig. 4 indicates that oceanic crustal velocities range from 6.5 to 7.1 km/sec. Therefore the ability to distinguish mantle velocities makes it possible to attack the problem of oceanic versus continental crust on the basis of depth to mantle and mantle profiles.

Cross-sections A–A′, B–B′ and C–C′ (Figs 6, 7 and 8) show the profile of the mantle and interpreted crustal and sediment thicknesses across Baffin Bay, the Labrador Sea and from Baffin Bay to Labrador Sea (see Fig. 5 for locations). These cross-sections have been compiled from a variety of data both published and unpublished, the main published sources being Hyndman et al. (1971), Keen & Barrett (1972), Keen et al. (1972), Hyndman (1973), McMillan (1973), Pelletier et al. (1974), van der Linden (1975), Jackson et al. (1977, 1979), MacLean (1978), Srivastava (1978), Hinz et al. (1979), Keen & Hyndman (1979) and MacLean & Falconer (1979).

Essential points shown by the cross-sections are given below.

A–A′ (Fig. 6)

1. The velocities in central Baffin Bay ranging from 7.68 to 8.53 km/sec. are clearly mantle.

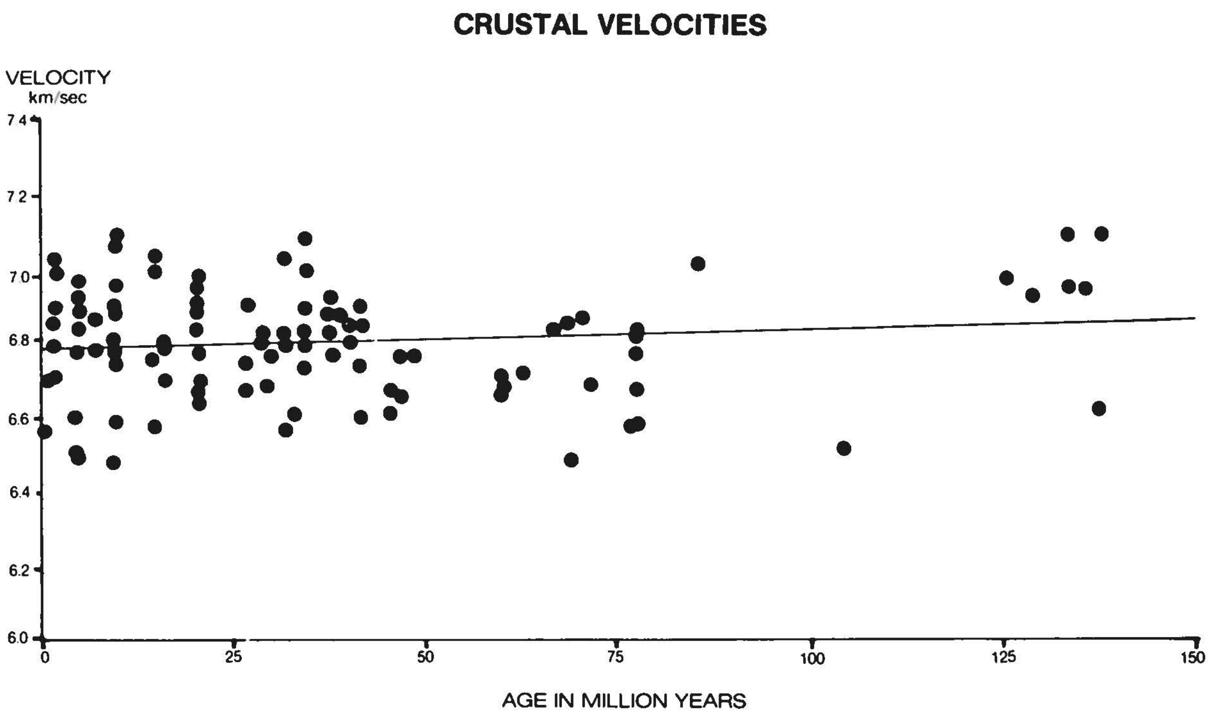

Fig. 4. Diagram showing relationship of crustal velocities and age of oceanic crust. From Lewis (1978).

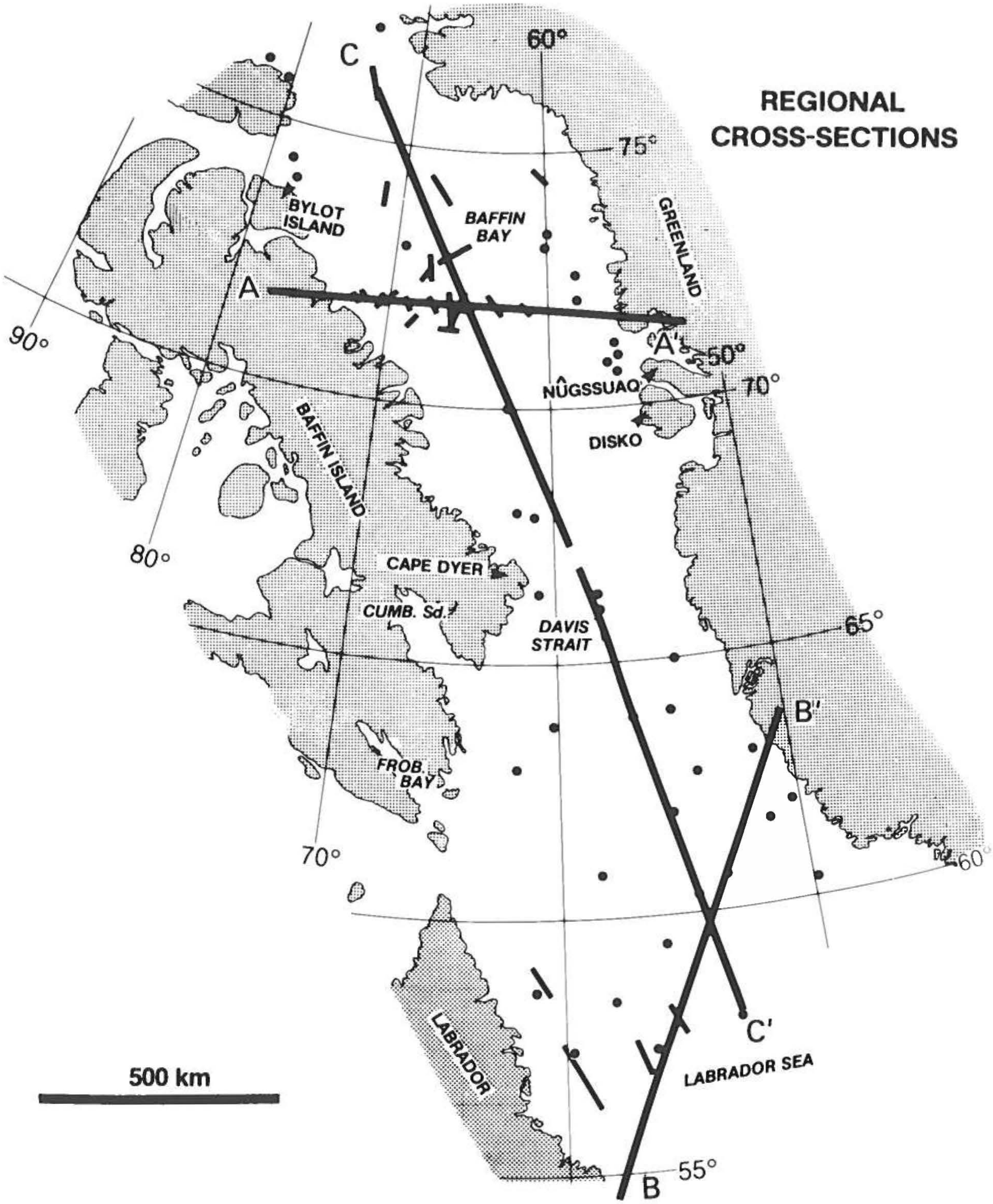

Fig. 5. Map showing location of refraction sonobuoy stations (dots), and seismic refraction profiles (bars). Heavy lines AA′, BB′ and CC′ are the locations of the regional cross-sections shown in Figs 6, 7 and 8.

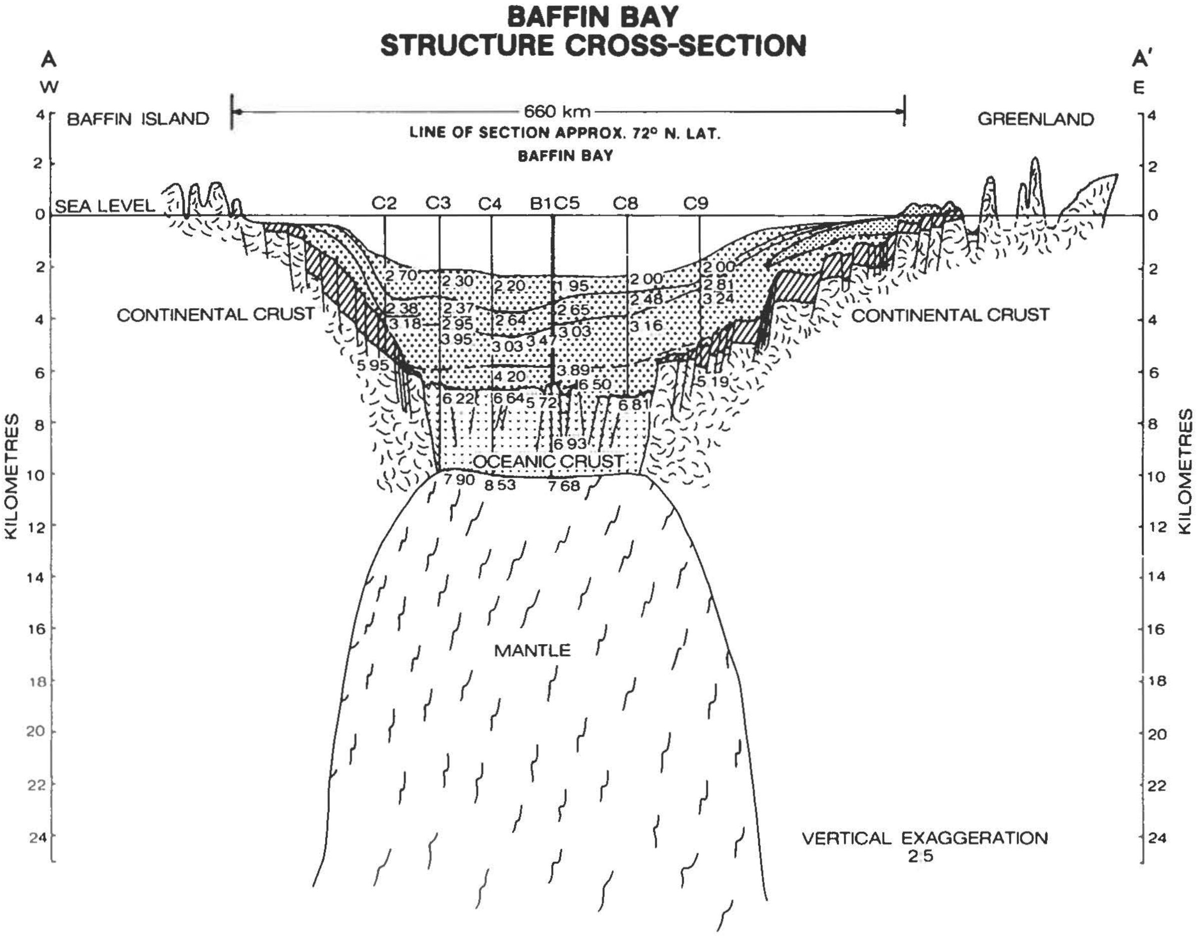

Fig. 6. Regional E–W cross-section of Baffin Bay as located in Fig. 5. Line shading = Mesozoic sediment; heavy dot symbol = Tertiary strata; light dot symbol = Tertiary volcanics. C2, B1, etc. refer to seismic refraction profiles taken from Keen & Barrett (1972). Numbers 2.70, 3.18, etc. are refraction velocities in km/sec.

2. The mantle profile is typical of the change from continental to oceanic crust. Although no depth to mantle is available below Baffin Island and Greenland, these are clearly continental blocks and the depth to mantle must be in excess of 30 km.
3. Depth to mantle of ±10 km is about what one would expect beneath oceanic crust.
4. Thickness of the crust in central Baffin Bay is compatible with the statistical range of values for oceanic crust, i.e. 3–5 km.
5. The submergence versus age relationship demonstrated by Parsons & Sclater (1977) indicates a mid-late Eocene age for this crust, which is compatible with the age postulated for this crust assuming Baffin Bay opened coincidentally with the Labrador Sea, i.e. spreading ceased at about anomaly 20 time.
6. Using crustal velocities and the mantle profile to place the continental–oceanic boundary as shown in Fig. 6, the resulting width of oceanic crust closely approximates the distance between anomalies 24 in the Labrador Sea.

B–B' (Fig. 7)

1. The mantle profile is typical of the change from continental to oceanic crust.
2. The depth to mantle in central Labrador Sea is again typical of depths beneath oceanic crust.
3. Flanking continental crust velocities are acceptable, but at 6.65 to 7.28 km/sec. they are high for simple continental crust. Because these velocities are in the range of both oceanic crust and low velocity mantle it is proposed that they reflect the alteration of velocities that would occur along a margin where there was significant dyke injection of mantle material.

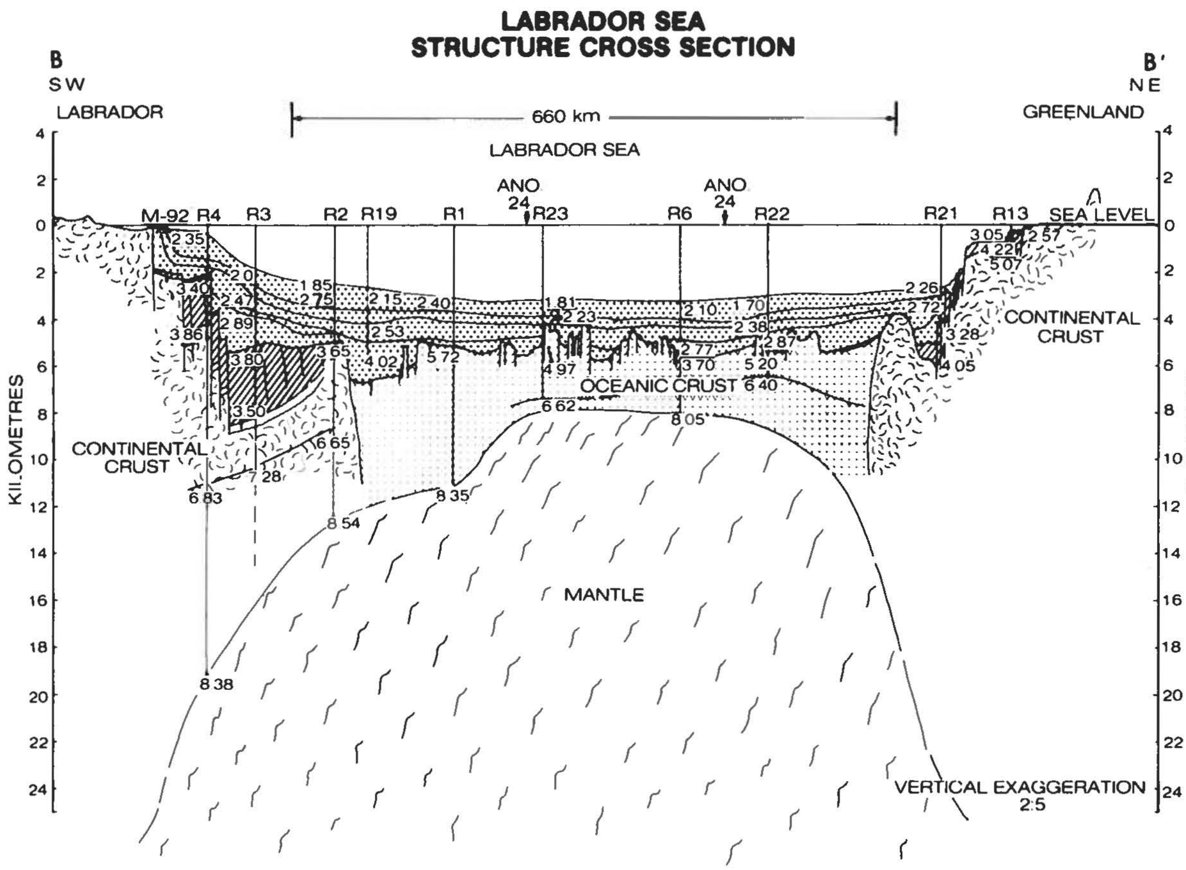

Fig. 7. Regional NE–SW cross-section of Labrador Sea as located in Fig. 5. Line shading = Mesozoic strata, dot symbol = Tertiary strata. The seismic refraction data are M–92, Herjolf eastcan well, Nov. 22, 1978; R1, R2, R3 and R4 from van der Linden (1975), and R6, R13, R19, R21, R22 and R23 from Hinz et al. (1979). Numbers 1.85, 2.35, etc. are refraction velocities in km/sec. Ano. 24 refers to the position of magnetic anomaly 24 of Srivastava (1978).

C–C′ (Fig. 8)

This section shows the tie between A–A′ and B–B′ and highlights the problem of Davis Strait. The single refraction profile D1, a reversed profile, brings forth the following points:

1. The thickness of the post-mantle layers is far too thick for a 'normal' oceanic crust.
2. The depth to mantle is too great for normal oceanic crust.
3. The relatively thin layer of 4 km/sec. material resting on the thick crustal layers is interpreted as Tertiary volcanics.
4. Possible analogous features to this Davis Strait phenomenon are:
   a) The Icelandic volcanic cone
   b) The Faeroe volcanic ridge
   c) Erratic or remnant continental blocks such as the Faeroe Islands, Flemish Cap and Orphan Knoll.

Comparison of Baffin Bay and Labrador Sea geology

The following points are considered significant.

1. Tertiary sediments are twice as thick in central Baffin Bay as in central Labrador Sea.
2. Tertiary sedimentation in the Labrador Sea is typically of coastal prism profile type as seen along open coastal margin sag basins, whereas Baffin Bay sedimentation is basically uniform across the basin. There is no evidence of progradation of sequences from the flanks into the centre of Baffin Bay and it appears to have been filled uniformly across the Bay. This difference in sedimentary style, as interpreted by seismic facies and sequence wedge geometry indicates a possible fundamental difference in the structural genesis of each basin during the Tertiary, even though both were responding to extensional forces

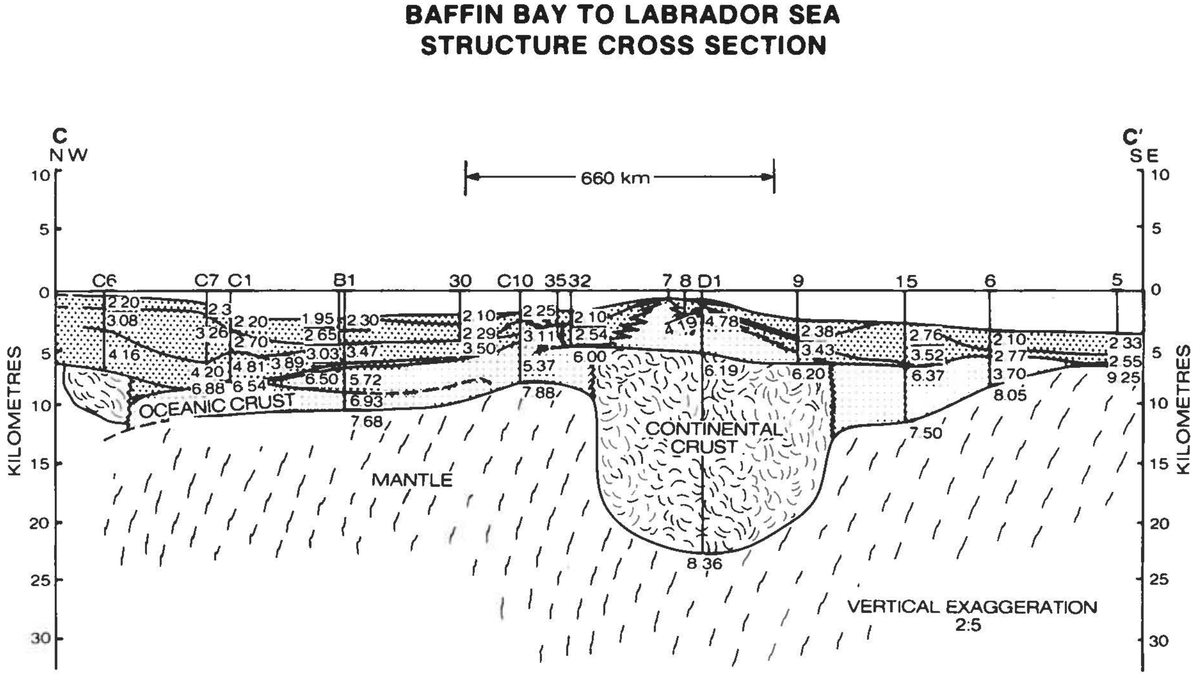

Fig. 8. Regional NW–SE cross-section of Baffin Bay and Labrador Sea illustrating the continental crust under Davis Strait. Dot symbol represents Tertiary strata. The seismic refraction data 7, 8, 30, 32, 35, B1, C1, C6, C7, C10 and D1 are taken from Keen & Barrett (1972); 5, 6, 9 and 15 are from Hinz et al. (1979).

related to plate separation and new crustal formation.

3. There is a good rationale available to reasonably conclude that Baffin Bay, like the Labrador Sea, is floored by oceanic crust.
4. Crustal definition within Davis Strait remains enigmatic. Although the mantle velocity is quite clearly defined, the crustal layer velocity remains ambiguous. Two interpretations are equally valid at this point. Davis Strait is a remnant, or thinned continental bridge between Greenland and Baffin Island; or it is a ridge of volcanics such as the Faeroe Ridge.

Seismicity

In Baffin Bay and Davis Strait interpretations of earthquake short and long period waves by Qamar (1974), Wetmiller (1974), Basham et al. (1977) and others have been made that throw some light on the problem.

Two short period and two long period waves crossing Davis Strait have given apparently conflicting results (Fig. 9). The short period waves as recorded at the Frobisher Observatory are without a long phase, thus indicating probable oceanic crust. The two long period waves indicate transmission through a continental crust. The solution to this conflict must be in the structural genesis of Baffin Bay and the translation of the apparent spreading centre from Labrador Sea through Davis Strait.

Structural trend analysis

For this analysis we are concerned only with major regional features, such as regional foliation in crystalline rocks, and most particularly with anomalous changes in trends and patterns. Major structural trends have been compiled in Fig. 10.

Onshore in coastal Greenland there is a change in the orientation of major lineations at about the contact of the Proterozoic and Archaean blocks. The Proterozoic lineations are generally parallel to the contact, in a sense wrapping around the Archaean block. This trend seems to continue into the more recent structure pattern described by seismic work off the southern end of Baffin Island, suggesting that the recent structures may follow the trend of the fabric of the deeper crustal rocks. A second change of trend occurs off southern Baffin Island where the NW–SE trends of onshore southern Baffin Island do not persist offshore. A third anomaly onshore is the Foxe fold belt which crosses central Baffin Island. This belt runs in an E–W arcuate pattern across the general NW–SE fabric of the island. In the east the belt curves to the south-east, so that when ex-

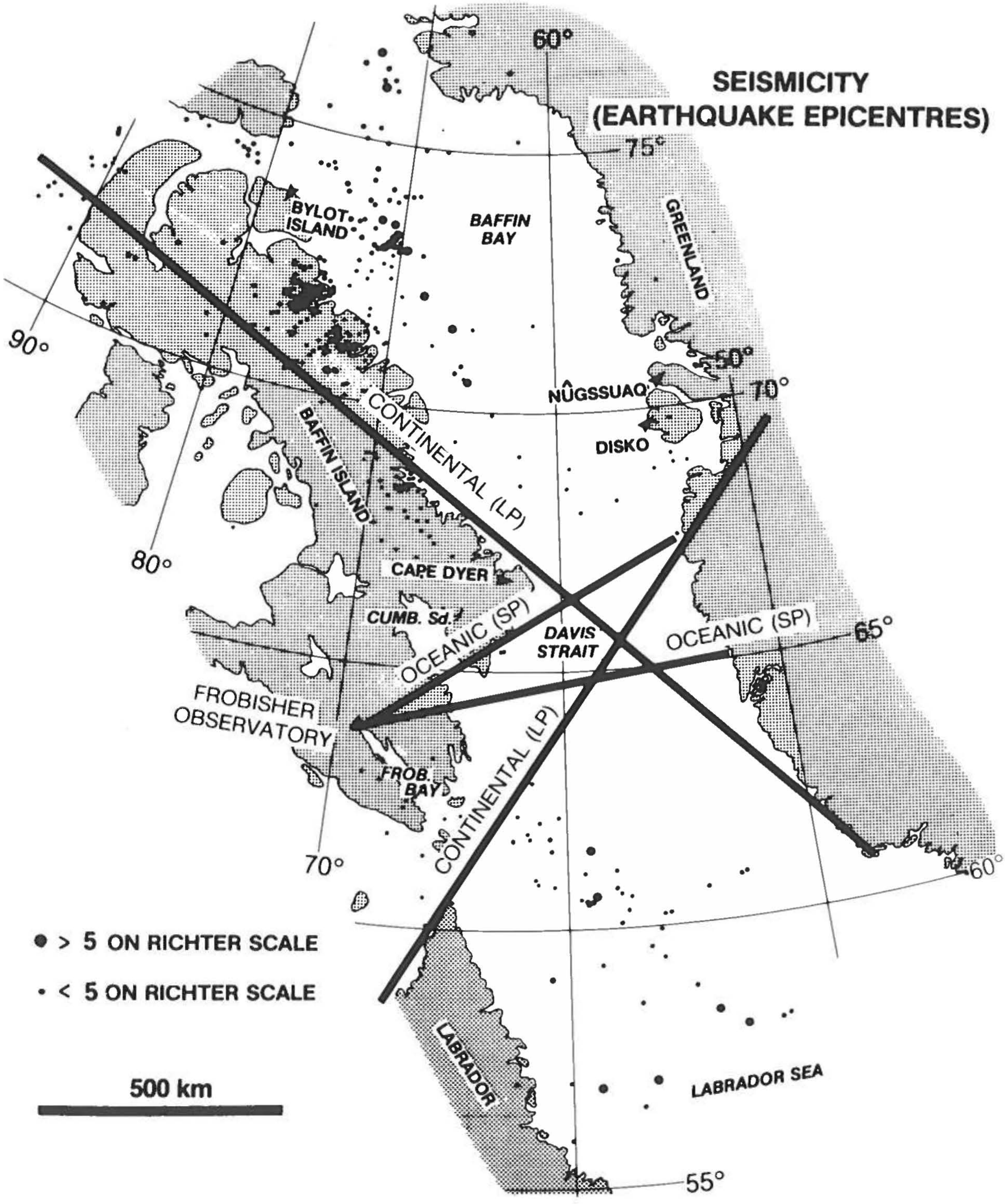

Fig. 9. Seismicity map of the study area. Black dots indicate earthquake epicentres; heavy black lines represent the location of earthquake travel paths across Davis Strait, whose Lg wave presence or absence has an important bearing on the interpretation of continental versus oceanic crust. Data supplied by Earth Physics Branch, Department of Energy, Mines and Resources, Ottawa.

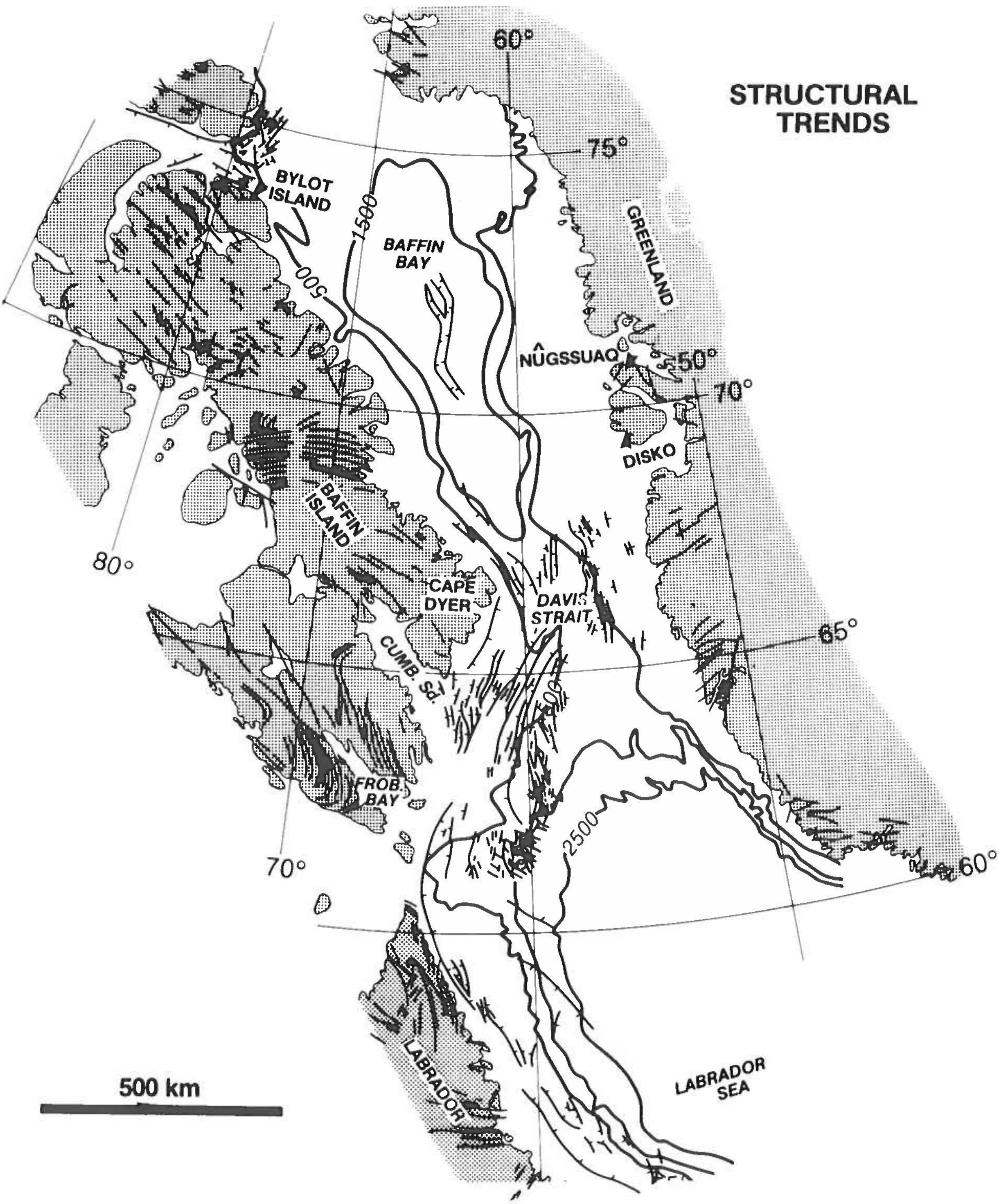

Fig. 10. Map compilation of faults, lineations and foliations to illustrate major onshore and offshore structural trends. Barbs on faults on downthrow side. Onshore interpretation from GSC and GGU maps; offshore interpretation from unpublished data (Esso Resources Canada Ltd.). Bathymetry is in metres.

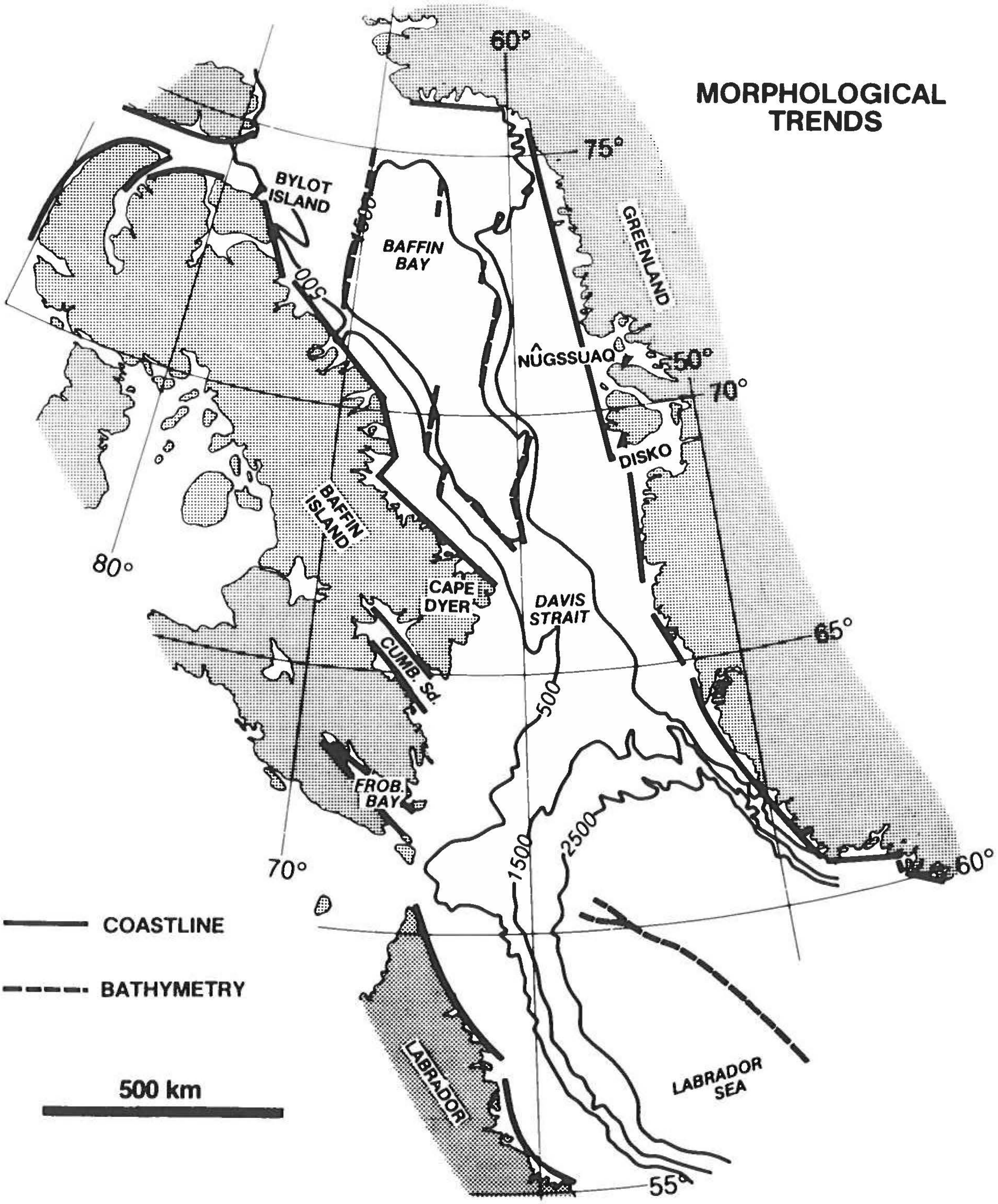

Fig. 11. Morphological trend map based on coastline and bathymetry (in metres).

tended offshore it trends parallel to the east coast of the southern half of the island. In addition, the general coastal orientation of Baffin Island changes south of the fold belt from the dominant NW–SE trend to a more N–S trend, as if skewed relative to the northern half of the island. It would be interesting to know if there is any evidence of Cretaceous tectonism within this ancient fold belt that has affected the regional structure of southern Baffin Island.

A morphological analysis of the bathymetry from various sources (e.g. Loken & Hodgson 1971) shows several anomalous trends and changes in direction of trends (Fig. 11). The most obvious is the Davis Strait high, which provides the morphological distinction between the Labrador Sea and Baffin Bay. In Baffin Bay there are some really striking changes in direction of the bathymetric gradients. It is possible that these have a structural genesis because there is no indication that they are caused by sedimentary constructional patterns (e.g. delta lakes) or destructional erosional patterns (e.g. palaeoslopes). The pattern exhibited is a series of coast-parallel lineations that are offset by N to NNE trends. The most obvious of these trends is the one at the north end of the Bay along the 70°W longitude, followed by the trend in the middle of the Bay which is coincident with the marked offset of the Baffin Island coast south of the Foxe fold belt.

Interpretation of a continental–oceanic crust boundary

From the crustal definition analysis presented it is concluded that Baffin Bay is floored by oceanic crust as is the Labrador Sea. Davis Strait remains ambiguous because of the conflict of the seismicity data. However, because the Kangâmiut well off West Greenland (Fig. 1) bottoms in granitic rocks, thus indicating continental crust at this point, it was decided as a first premise to assume continental crust as most likely for Davis Strait and see what constraint, if any, this would place on our reconstruction.

The continental–oceanic crust boundary shown in Fig. 14 was drawn on the basis of the following:

1) Refraction interpretations as given in cross-sections A–A′, B–B′, C–C′
2) Multichannel, reflection, seismic criteria
3) Structural trend analysis
4) Bathymetric morphological analysis
5) Earthquake seismicity analysis of long waves
6) Magnetic trends
7) Kangâmiut well results

Reconstruction of Baffin Bay and the Labrador Sea

Three reconstruction of the Baffin Bay – Labrador Sea region are presented in Figs 12, 13 and 14. The constraints we placed upon these reconstructions are given below.

1) Closure of Greenland with Labrador must be compatible with major plate motions in the Euro-American plate from 120 m.y. ago to present.
2) Rotation must closely approximate the motion expressed by the magnetic stripes in Labrador Sea.
3) Strike-slip motion along Nares Strait should be kept to a minimum to meet onshore geological data that suggest geological continuity between Ellesmere Island and Greenland (Kerr 1967).
4) Seismicity results in Davis Strait need an explanation.
5) Motions should be compatible with the observed structural and sedimentary styles.

Fig. 12 shows the position at full closure which is achieved by moving back to the approximate position of anomaly 33 (C. Tapscott, pers. comm.). Fig. 13 shows the position at anomaly 24 time (i.e. 57 m.y. on time scale of LaBrecque et al. 1977). The motion requires rotation about a relative pole of rotation located in northern Baffin Island. During this opening the following events are considered to have occurred:

1. As the Labrador rift valley gradually opened there was a marine invasion from the south such that by the end of the Cretaceous we have Atlantic marine conditions in the Frobisher Bay – Cumberland Sound area. Coincidentally there was a marine invasion from the high arctic entering the intracratonic Baffin Bay basin. This northern marine invasion progressed at a rate that permitted the linking up of the Arctic and Atlantic Oceans in late Cretaceous time across the Davis Strait structural high.
2. The Frobisher Bay region, and the Baffin Bay intracratonic basin were essentially extensional regimes. With these two areas under extension the Davis Strait area was placed under mild compression and remained relatively positive while the Cretaceous Labrador oceanic basin and the Cretaceous Baffin intracratonic basin were developing.

In the Tertiary the motion changed and the relative pole of rotation shifted to approximately the position of present-day Algeria. The translation of the opening through Davis Strait was along a NE–SW-trending

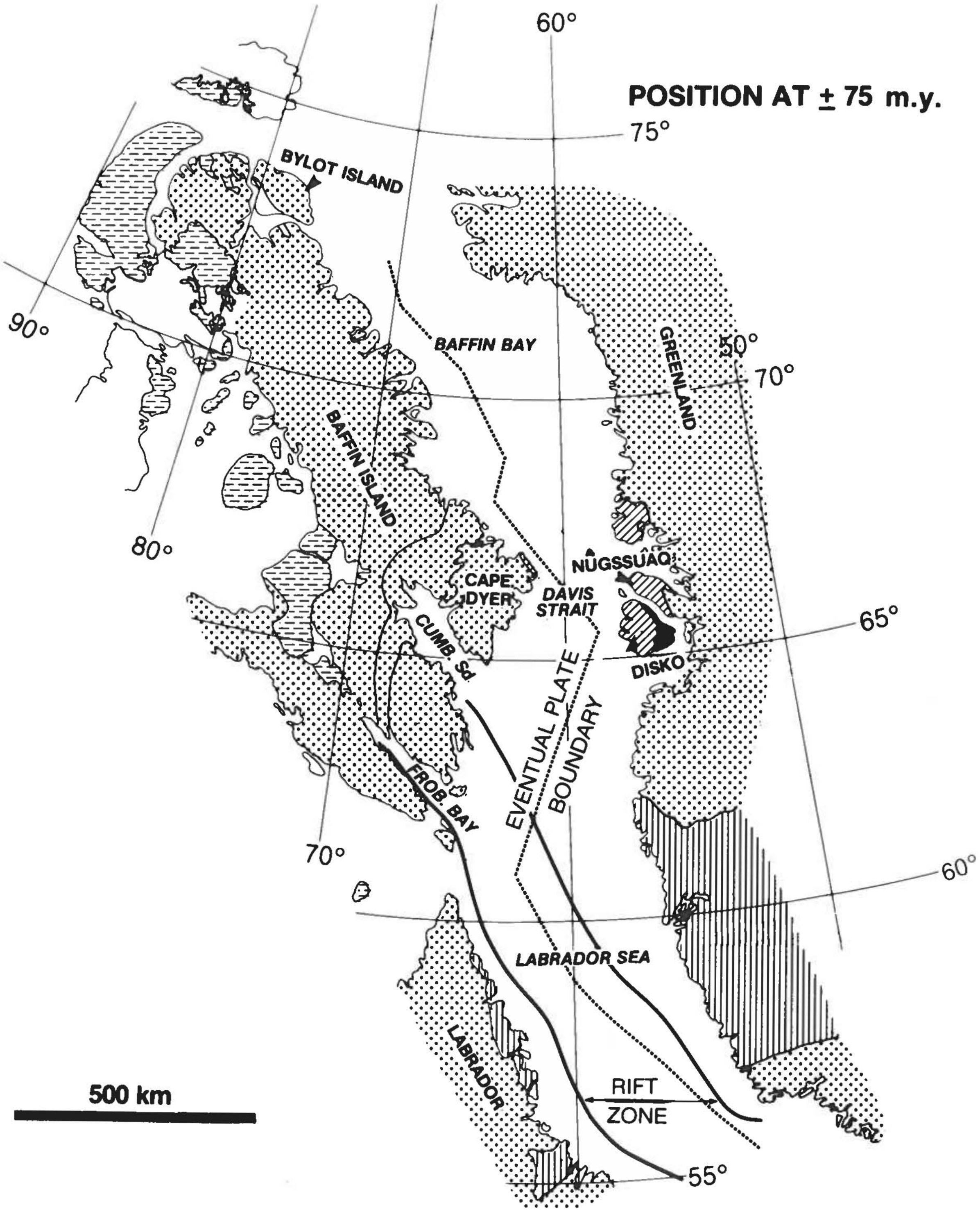

Fig. 12. Interpreted pre-drift position of Greenland and North America at about 75 m.y. (Late Cretaceous). Geology as in Fig. 1.

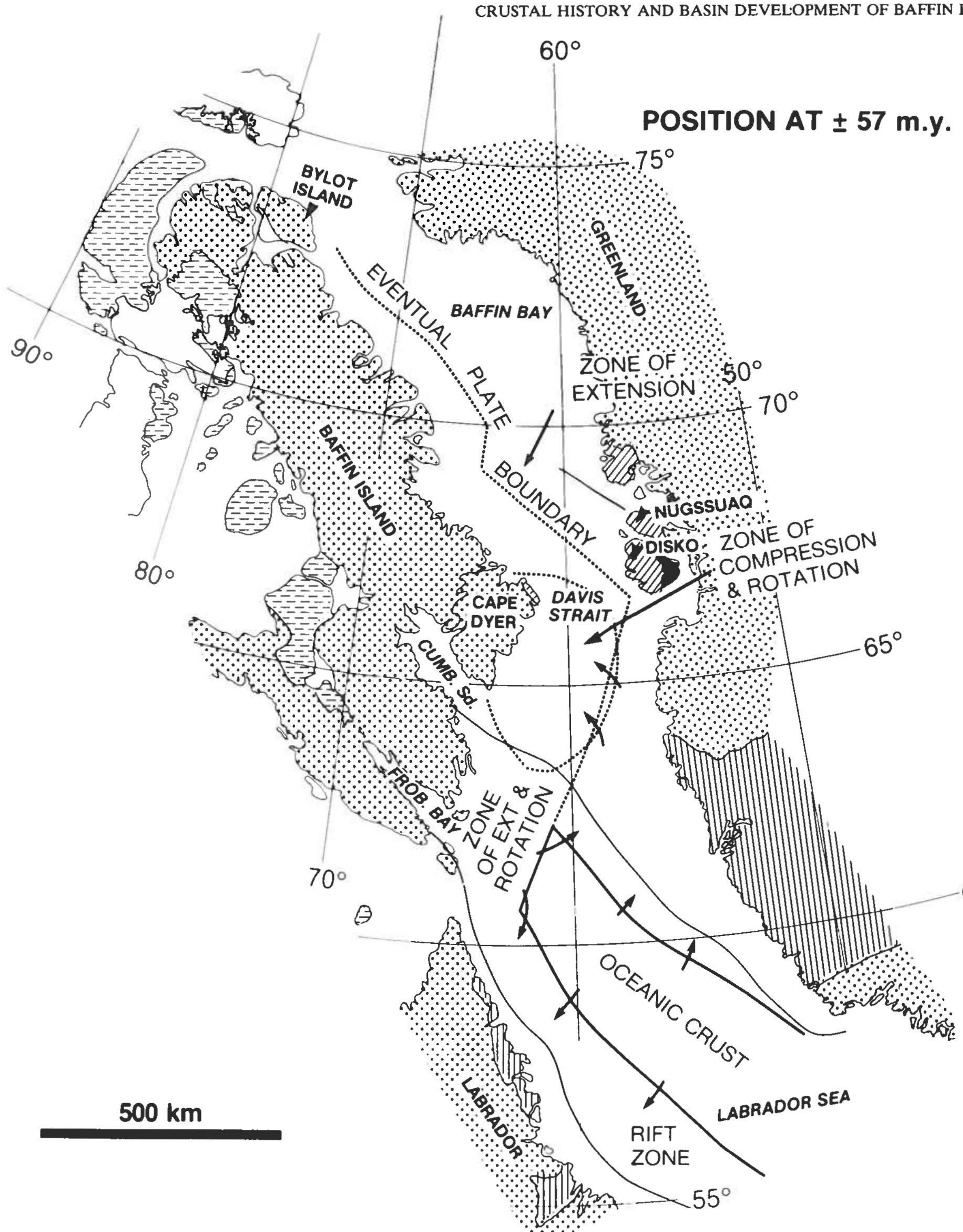

Fig. 13. Interpreted position of Greenland and North America at about 57 m.y. (Paleocene). Geology as in Fig. 1.

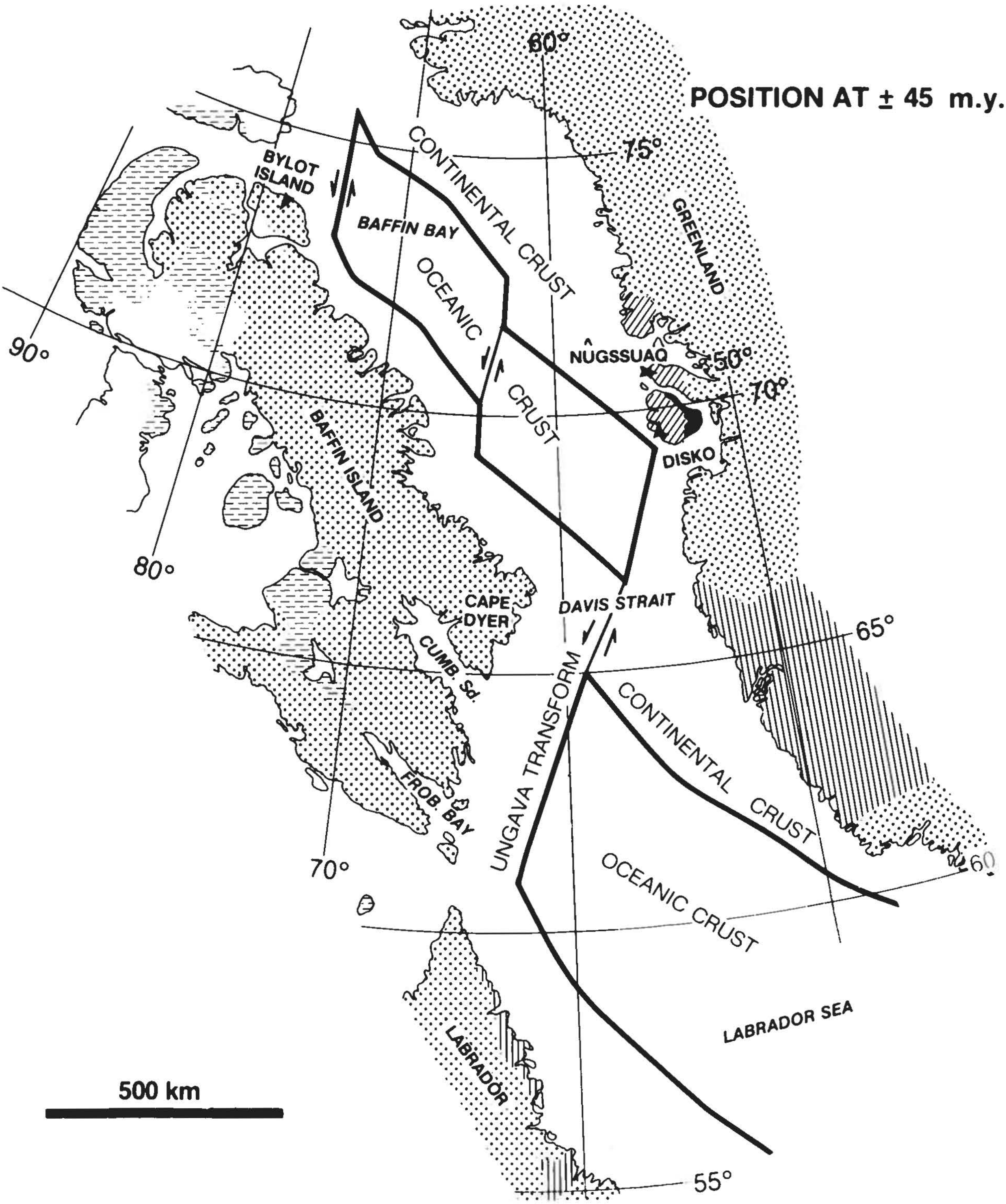

Fig. 14. Interpreted position of Greenland and North America at about 45 m.y. (Eocene) showing interpreted continental–oceanic crust boundary and the position of the Ungava transform. Geology as in Fig. 1.

transform fault. Consequently the Tertiary opening of Baffin Bay and the Labrador Sea was coincident and not progressive from south to north. Baffin Bay opened as a rhombochasm. It is probable that the extension occurred along lineations developed at a much earlier stage. For example the translation through Davis Strait may have followed the zone of weakness at the Proterozoic–Archaean contact, while the opening in southern Baffin Bay occurred along the zone of weakness created by the offshore extension of the Foxe fold belt.

As a result of this motion the Davis Strait continental block was subjected to wrenching and strike-slip motion. However, the motion was not great enough to cause the oceanic crusts of Baffin Bay and the Labrador Sea to link up and a bridge of continental crust was maintained between Greenland and Baffin Island (Fig. 14). During this wrench motion along the Ungava transform (Fig. 14), copeous quantities of basalts were erupted over the area. One might expect that in addition to the location of vents along the main faults there were also volcanic cones along the trend of this transform fault.

Conclusion

The reconstruction described here satisfies all the constraints imposed except for the small motion along Nares Strait. There appears at this stage no acceptable reconciliation between the onshore evidence along Nares Strait that suggests geological continuity between Ellesmere Island and Greenland and the interpretation of crustal history. However, throughout this study several lines of evidence indicate that from Cretaceous through to the present day, the histories of the Arctic Ocean basin and the North Atlantic basin (including Baffin Bay and Labrador Sea) are intimately related. Furthermore, the Nares Strait problem only exists if the Arctic Islands are held to be a separate plate from Greenland. Consequently it is suggested that further resolution of the problem rests with the pursuit of the reconstruction of the Arctic Ocean.

Acknowledgements

I am grateful to Esso Resources Canada Ltd. for permission to use company data and for permission to publish this paper. I thank Richard R. Boudreau and Peter N. Byers of Esso Resources Canada Ltd. for their help and guidance in the analysis of Baffin Bay. I am particularly grateful to Peter R. Dawes for his editorial help and for his untiring efforts in preparing this contribution for publication.

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