The evolution of the Nares Strait lineament and its relation to the Eurekan orogeny

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If one accepts that the Labrador Sea was closed in Early Cretaceous time, then this assumption creates extra space northwest of Greenland. Where Ellesmere Island lay within it relative to Greenland and also to North America becomes a major problem in geological interpretation. Whatever solution is chosen creates conflicts with the current interpretations of the geology of the eastern Sverdrup Basin and/or the geology of Nares Strait.

The main elements of the tectonic model presented herein are: 1) Early to Middle Cretaceous: incipient rifting in the Labrador Sea terminated in an RRR triple junction north of Bylot Island and established the Nares Strait and Lancaster Sound lineaments; 2) Late Cretaceous to Early Paleocene: Greenland and Ellesmere Island rotated together counter-clockwise relative to North America, causing crustal shortening in the Sverdrup Basin (the first phase of the Eurekan orogeny); 3) Late Paleocene to Early Oligocene: responding to a new pole of rotation, Greenland moved left-laterally relative to Ellesmere Island along the Wegener Transform Fault; 4) Middle Oligocene: Greenland and Ellesmere Island moved northwestwards some 40–50 km (the main phase of the Eurekan orogeny); 5) Middle Oligocene to Present: compressive stresses relaxed followed by rapid subsidence of all basins.

This model requires that the Early Cretaceous Sverdrup Basin was much wider than today. An analogy is drawn with the thin-skinned tectonic model for the southern Appalachians as a possible mechanism to reconcile this requirement with the known geology. As major lateral Tertiary motion on the Wegener Fault is at odds with the geological interpretations across Nares Strait, this model suggests that either an alternative geological interpretation of Nares Strait (perhaps in the context of a fault zone) be found, alternative locations to accommodate the motion be found, or else the currently accepted tectonic history of the North Atlantic is seriously in error.

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Nares Strait is the long linear waterway which separates Ellesmere Island and Greenland (Fig. 1). Parts of it are commonly referred to as Robeson Channel, Hall Basin, Kennedy Channel, Kane Basin and Smith Sound (see Fig. 3).

The debate (see Kerr 1980a for a review) about the amount of left-lateral displacement along this lineament began with early papers by Taylor (1910) and Wegener (1924). It has remained unresolved since then, largely because correlations of geological and structural features on either side of the Strait require considerable interpretation. Those favouring little or no significant motion along Nares Strait include most of the geologists who have worked in the area. Kerr (1967: 483) claimed that correlation of the stratigraphy across the Strait "conclusively disproves the suggestion that Greenland has drifted hundreds of kilometers to the northeast by strike-slip movement". Dawes (1973) felt that the geological arguments against major motion were inconclusive, but after several seasons of field work in the area, he (pers. comm. 1980) strongly supports the consensus that the geological correlations between Ellesmere Island and Greenland are consistent with little or no net lateral offset.

Those favouring major left-lateral offset (200 km or more) along the Wegener Fault in Nares Strait approach the problem from a regional perspective using plate tectonic theory but lack first-hand knowledge of the geology on either side of Nares Strait. Kristoffersen & Talwani (1977) and Srivastava (1978) demonstrated that an extinct triple junction south of Greenland and the magnetic anomalies in the Labrador Sea require major left-lateral motion along Nares Strait if all the plates have behaved rigidly to a first order approximation. Sclater et al. (1977) demonstrated that a comprehensive reconstruction of the North Atlantic plates predicts a similar motion along Nares Strait.

Recent work by the Greenland Geological Survey reported in this volume (Dawes & Kerr, Dawes et al., Frisch & Dawes, Higgins et al., Hurst & Kerr, Peel & Christie, Peel et al.) has strengthened the geological arguments supporting no major offset. Newman (1977, this volume) has suggested alternative interpretations, but clearly the most convincing geological interpreta-

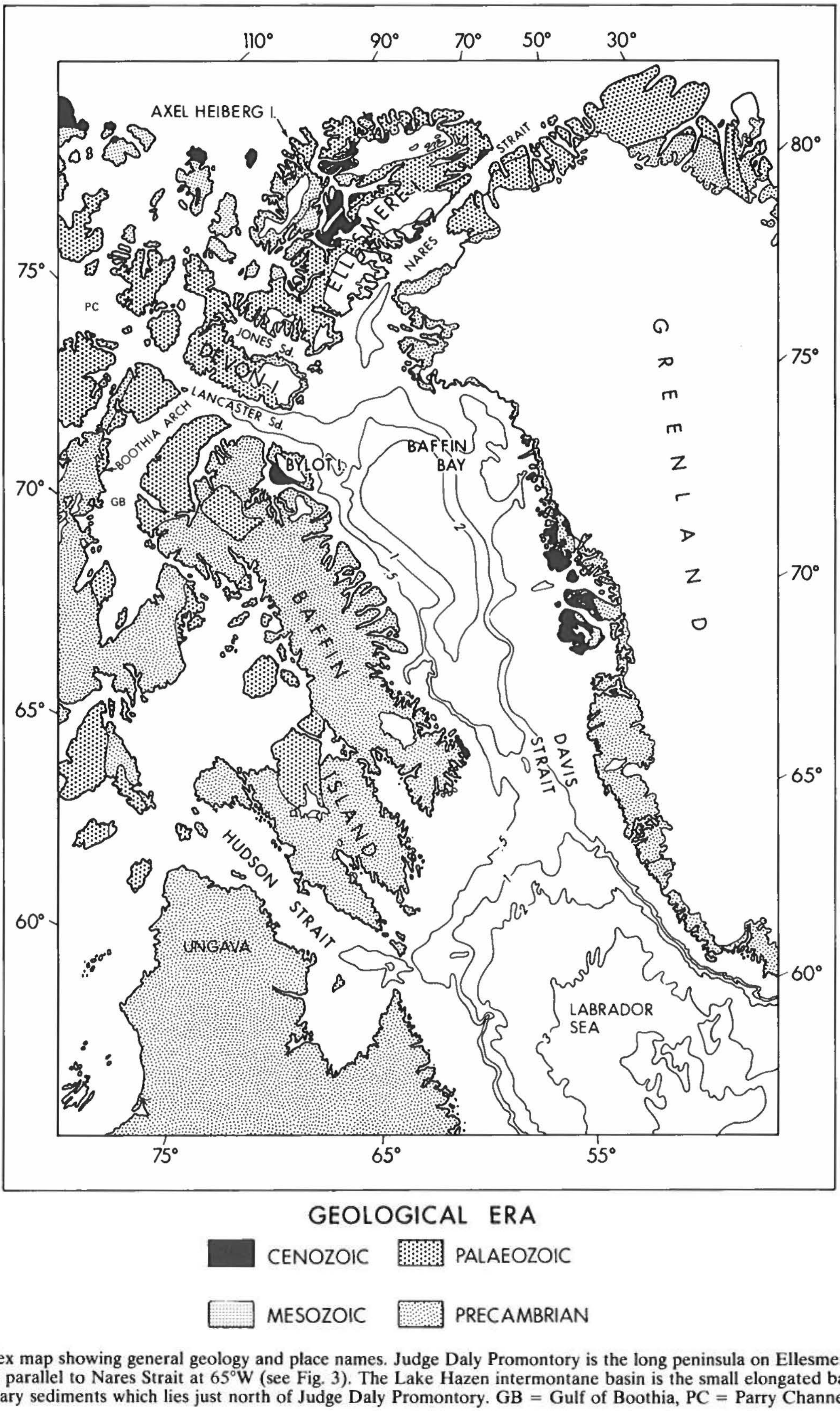


Fig. 1. Index map showing general geology and place names. Judge Daly Promontory is the long peninsula on Ellesmere Island which runs parallel to Nares Strait at 65°W (see Fig. 3). The Lake Hazen intermontane basin is the small elongated basin with some Tertiary sediments which lies just north of Judge Daly Promontory. GB = Gulf of Boothia, PC = Parry Channel.

tions are at odds with any regional model requiring major offset on the Wegener Fault.

There is little geophysical evidence which bears directly on the correlations across Nares Strait. There is a magnetic anomaly near the edge of the Palaeozoic folding on Ellesmere Island which appears to intersect the coast at a higher angle than the thrust faults. Riddihough et al. (1973) cited this as evidence against extensive left-lateral displacement along the Wegener Fault. However, a careful look at their published map reveals that this anomaly ends at the coast of Greenland and does not continue into the craton. Furthermore, 250 km to the northeast there is an anomaly which does continue into the craton at the same angle proposed by their correlation. In my opinion, there is a better correlation with displacement of 250 km than without, but neither correlation is particularly convincing.

The contours of the regional gravity field in the Lincoln Sea just northwest of Greenland run roughly parallel to the strike of the Palaeozoic folds. Sobczak (this volume) has argued that the lack of a major break in the gravity gradient is evidence against significant offset. However, the lack of seismicity in Nares Strait (Wetmiller & Forsyth, this volume) and the isostatic rebound pattern in the area (England, this volume) strongly suggest that Nares Strait is not tectonically active today. Therefore, it is likely that the gravity field reflects more recent events than the Wegener Fault, primarily the lithospheric flexure associated with the Ellesmerian and Greenland ice caps.

Keen & Peirce (this volume) have tested three models for the formation of Baffin Bay which are alternatives to sea-floor spreading there. As none of these models could explain the subsidence and crustal thickness of Baffin Bay and simultaneously remove the requirement for significant Tertiary motion on the Wegener Fault, they suggest that the geology in Nares Strait be reinterpreted in the context of a fault zone rather than a discrete offset.

The Nares Strait debate is not about the observations; it is a debate about what those observations mean. The geophysicists espouse a regional explanation which is an extension of their view of North Atlantic plate motions. The geologists argue for a different regional explanation which is an extension of their correlations made on a more local scale. My initial assumptions in this paper are on a North Atlantic scale, and therefore my model is inherently prejudiced toward the 'major offset' perspective. Many aspects of the regional geology have been considered in this overall tectonic model which have not been discussed previously in this particular debate. However, some of the regional geology — notably the amount of observed compression in the eastern Sverdrup Basin and the geology around Nares Strait — are undeniably at odds with this model as they are presently understood. My model offers a different perspective for these important problems along with testable implications.

With this preamble, there are several pieces to the Nares Strait puzzle which I consider key to understanding the larger tectonic picture. These are:

1) It is probable that the cratonic cores of Ellesmere Island and Greenland were once joined to that of Baffin Island as part of the North American craton.
2) The stratigraphy of the Eclipse Trough on Bylot Island indicates that an initial graben had opened by the Middle Cretaceous. Sedimentation was interrupted by the Bylot unconformity in the Early Paleocene (McWhae 1981, Miall et al. 1980).
3) The Alexis volcanics (Umpleby 1979) of offshore Labrador are Early Cretaceous in age (McWhae & Michel 1975, McWhae et al. 1981).
4) The first phase of the Eurekan orogeny (Balkwill 1978) is synchronous with the initial opening of the Labrador Sea (Srivastava 1978). Compressive motion north of the pole of rotation can explain the orientation and timing of the early Eurekan structures such as the Princess Margaret Arch (see Fig. 3).
5) The Nares Strait lineament does not form a small circle about the last pole of opening of the Labrador Sea (Srivastava 1978), apparently contradicting the idea that the Wegener Fault was a transform fault.
6) The separation of Greenland from Norway (Kristoffersen & Talwani 1977, Sclater et al. 1977, Talwani & Eldholm 1977) was synchronous with the late phase of opening of the Labrador Sea. Therefore active plate margins must have existed northeast and northwest of Greenland during this time (Srivastava & Falconer, this volume).
7) The second phase of the Eurekan orogeny produced about 40–50 km of crustal shortening in a NW–SE orientation (Balkwill 1978, McWhae 1981). This compression post-dated the last phase of opening of the Labrador Sea.
8) The major marine unconformities are the Early Cretaceous Labrador unconformity, the Middle Cretaceous Avalon unconformity (only well developed south of Baffin Island), the Late Cretaceous to Paleocene Bylot unconformity, the Oligocene Baffin Bay unconformity (best developed in northern Baffin Bay), and the Miocene Beaufort unconformity. These names were informally adopted by McWhae (1981) to aid discussion in the context of this area. Although they occur on a world-wide basis (Vail et al. 1977), all but the Avalon and Beaufort unconformities appear to have a major tectonic component in their formation in eastern Canada.

These points will be discussed in chronological order below.

Initial plate positions

One premise for determining the initial positioning of plates is to close up the Mesozoic and Cenozoic ocean basins. This puts Greenland up against Baffin Island near the position originally proposed by Bullard et al. (1965) (Fig. 2). The problem which this premise creates is that an extra wedge of space appears northwest of Greenland which no longer exists today. What was the spatial relationship between Greenland and the Arctic Islands? If one leaves Ellesmere Island in its present position relative to North America, then how can one explain the geological correlations across Nares Strait or remove the intervening wedge of material? Likewise if Ellesmere Island is put up against Greenland to avoid these arguments, how can one account for some 200 km of compression at the northern rim of the Sverdrup Basin? Thus one critical assumption for any tectonic model of the eastern Canadian Arctic is how close Greenland was to Labrador in Early Cretaceous time.

Kerr (1981) took a middle course between the conflicting choices presented above by minimizing the closure of the Labrador Sea. This interpretation was indirectly supported by Grant (1980) who argued that the oceanic crust in the Labrador Sea is much narrower than Srivastava (1978) proposed. Grant's interpretation makes assumptions about the formation of unconformities with which I cannot agree. However, one of his main points was that the existence of the Labrador unconformity implied continental crust underneath. That conclusion is no longer necessarily valid if an Early Cretaceous rifting phase occurred.

For this paper, I have assumed that Srivastava's (1978) model for the Labrador Sea is essentially correct, although I disagree with some critical details, particularly the time of initial rifting. Kristoffersen & Talwani (1977) and Sclater et al. (1977) arrived at nearly the same answer as Srivastava using different data sets. Also Tapscott (1979) has done a detailed statistical analysis of the Greenland/Rockall/North America plate

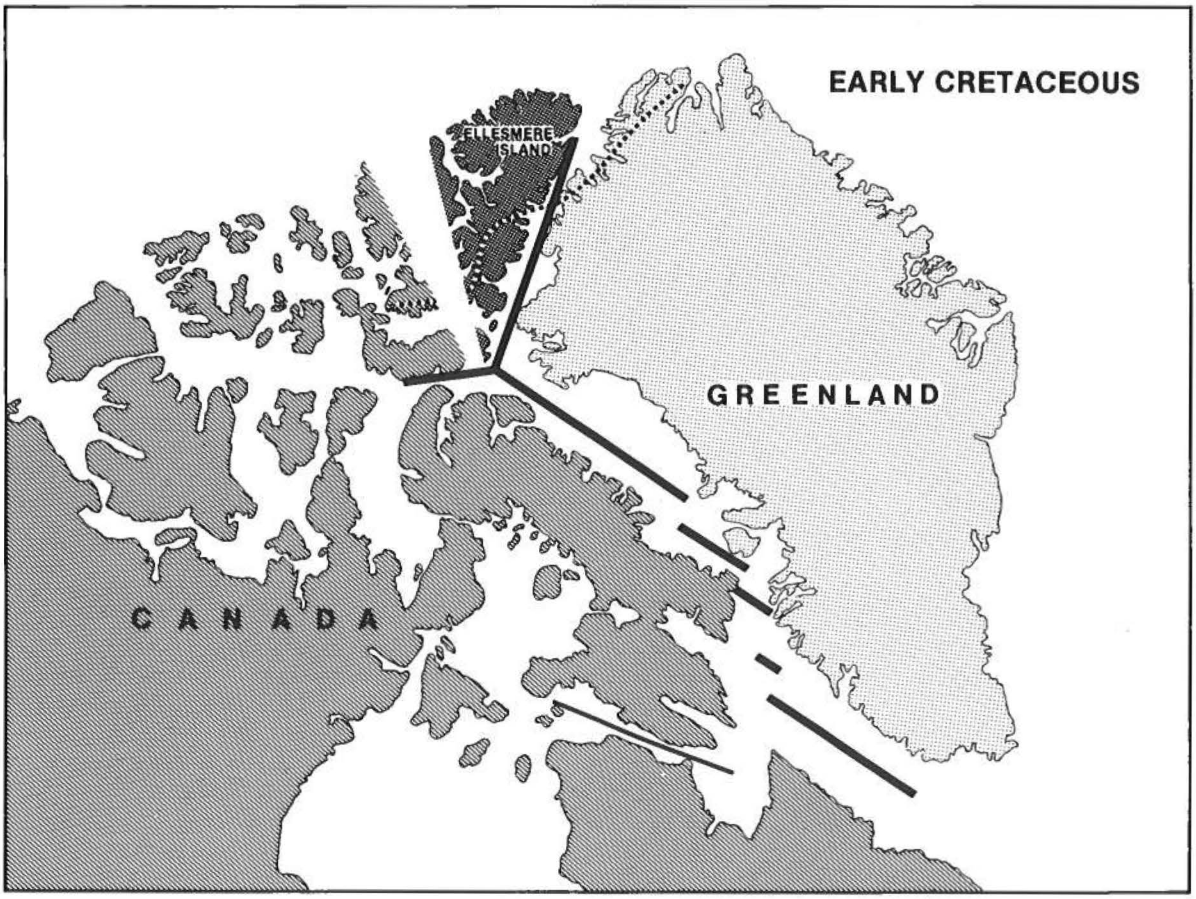


Fig. 2. Initial positioning of the plates around the Labrador Sea. Greenland's position is that given by Srivastava (1978). Ellesmere Island is assumed to be part of Greenland. Baffin Island has been closed up against Ungava. The heavy lines indicate the incipient rifting pattern which developed in the Early Cretaceous; thin line indicates extension in Hudson Strait; dotted line indicates the southern edge of the Palaeozoic fold belt. The open wedge west of Ellesmere Island shows diagrammatically the amount of extra space in the Sverdrup Basin predicted for this time.

system which supports some of Srivastava's poles. To my mind, these independently similar solutions give considerable credence to the validity of the sea-floor spreading model in this area.

Having assumed an initial position for Greenland closely juxtaposed to Labrador, the next critical assumption is where Ellesmere Island lay initially. In the absence of unambiguously definitive criteria, I have chosen to reassemble the Precambrian cratonic pieces. This puts Greenland against Baffin Island with Ellesmere Island rotated clockwise up against northern Greenland. This position eliminates the need to destroy material between Ellesmere and Greenland in some subsequent event, but it does imply that the Sverdrup Basin was much wider in the early Mesozoic. This is contrary to present interpretations of the geology of the eastern Sverdrup Basin, and will be discussed further below.

The position chosen (Fig. 2) for Ellesmere Island requires about 200 km of left-lateral offset along the Wegener Fault since the end of the Jurassic. An initial position with only 25 km offset could have been chosen if the Bullard et al. (1965) initial fit position for Greenland had been used, but Keen & Peirce (this volume) have shown that such a choice cannot be carried forward in time without creating serious overlaps of Devon and Ellesmere Islands and creating apparently unacceptable compression in Baffin Bay. Thus this reconstruction (Fig. 2) appears to be at odds with the geological correlations across Nares Strait summarized by Dawes & Kerr (this volume). The implication is that either an acceptable alternative model be found for the Labrador Sea or an alternative explanation be found for the geology of Nares Strait. The concept of a fault zone rather than a discrete offset in Nares Strait (Keen & Peirce, this volume) is a promising perspective. Another alternative is that the motion has been accommodated elsewhere, but no satisfactory interpretation has yet been offered.

A further, more minor assumption has been made in the initial position shown in Fig. 2. The overlap between Baffin Island and Greenland can be largely eliminated by closing Hudson Strait about a pole in the Gulf of Boothia. Although no direct evidence supports this ad hoc rotation, there exists a narrow channel striking ENE–WSW between Baffin Island and the islands off the northern end of the Ungava Peninsula which limits any possible motion of Baffin Island and makes this hypothesis quite plausible. If allowance is made for stretching and thinning of the continental margins as well, then the overlap problem in Davis Strait can be completely eliminated even if no oceanic crust exists there as Menzies (this volume) has suggested.

Incipient rifting phase

The principal clues for the timing of the incipient rifting phase are: 1) the stratigraphy of the Eclipse Trough, Bylot Island; 2) the age of the Alexis volcanics off the coast of Labrador; and 3) the Labrador unconformity. All of these indicate that incipient rifting began in the Early Cretaceous, although significant extension did not occur until much later.

In the Eclipse Trough, the base of the visible section rests on the Labrador unconformity. It is not known if a significant sedimentary section lies below the Labrador unconformity within the trough. These sediments are tentatively correlated with the Bjarni Formation (Umpleby 1979) further south (which lies on the Alexis volcanics) by McWhae (1981) and Miall et al. (1980). This evidence suggests that sufficient extension must have occurred by Middle Cretaceous time to allow graben formation.

The Alexis volcanics have been drilled at several locations off Labrador. Their petrological and magnetic characteristics are intermediate between continental and oceanic affinities and are consistent with an early rift phase tectonic setting (Srivastava et al. 1977, McWhae et al. 1981). The most reliable K/Ar ages for these volcanics are between 118 and 122 m.y. (McWhae et al. 1981).

Although the causal relationship between marine unconformities and tectonic activity is far from clear, the presence of the Labrador unconformity in a non-marine section as far north as Baffin Bay strongly suggests a tectonic component in its formation (Miall et al. 1980). The same unconformity is closely associated with the Alexis volcanics in Labrador where the overlying Bjarni Formation becomes at times more marine in character. McWhae (1981) estimated the time interval represented by the Labrador unconformity as 133–120 m.y.

Burke & Dewey (1973) speculated that a triple junction once existed in northern Baffin Bay. I suggest that this three ridge (RRR) triple junction was part of the incipient rifting phase. Lineaments were established through Lancaster Sound (perhaps as far as the Parry Channel) and through Nares Strait. Graben structures developed along these lineaments. The Paleocene volcanic sands at Judge Daly Promontory (Miall 1981) suggest that some Cretaceous volcanism may have occurred in Nares Strait and, by analogy, in Lancaster Sound as well. However volcanism in both these areas must have been limited in volume or there would be more evidence of it present today. This suggests that very limited extension occurred, consistent with the concept of an unsuccessful rifting phase. It is interesting to note that the present orientations of the three limbs of the triple junction are not symmetrical. However, rotation of Greenland and Ellesmere Island back against North America puts the three limbs of the triple junction nearly 120 degrees apart (compare Figs 2 and 4).

The concept of a long period of incipient rifting has parallels in the early opening history of the North Atlantic (e.g. the Triassic volcanics of New England and the Maritimes) and in the present-day tectonic style of the East African rift valley. It has been recognized in this area by both McWhae (1981) and Kerr (1981). Furthermore Sclater et al. (1977) treat Greenland as a separate plate as early as 95 m.y. ago in their analysis of North Atlantic plate motions, although its early motion was minor.

The incipient rifting phase persisted until the end of the Cretaceous. The presence of the Avalon unconformity (Jansa & Wade 1975) as a minor marker in the northern Labrador Sea during this time seems to be related to events farther south and east such as the opening of the Bay of Biscay and the development of Rockall Trough and does not appear to have a local tectonic component. At the end of the Cretaceous the incipient rifting phase was superseded by a more successful pattern of rifting, dubbed the Eurekan rifting episode by Kerr (1967, 1981).

Early phase of the Eurekan orogeny

The Eurekan rifting episode began in the Maastrichtian about 70 m.y. ago (anomaly 32 time, Srivastava 1978,

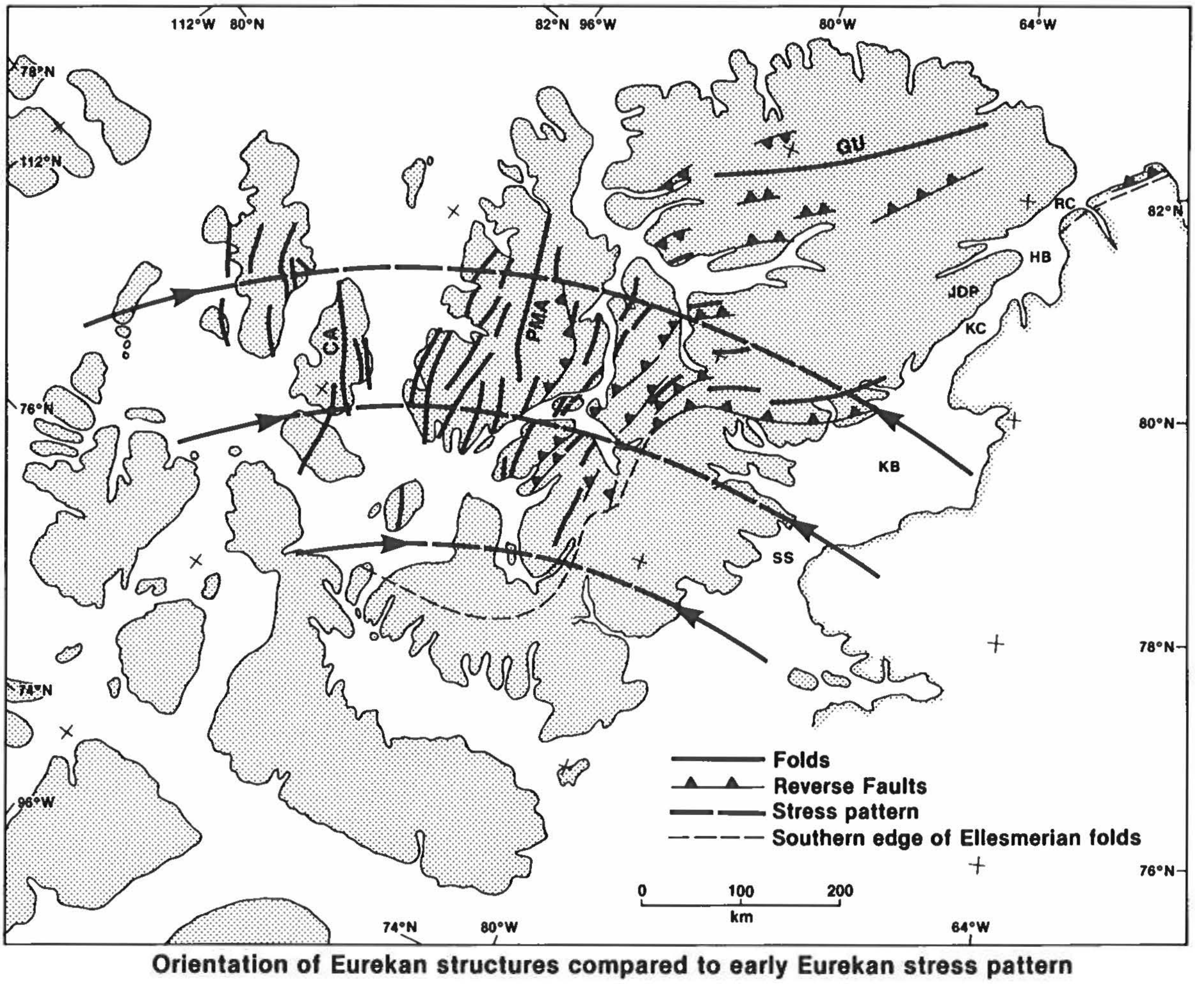


Fig. 3. Predicted stress pattern in the eastern Sverdrup Basin during the initial opening of the Labrador Sea. Eurekan folds and thrust faults are shown. No attempt has been made to sort out early Eurekan structures from those formed during the main phase of the orogeny as most structures probably moved at both times. The NE–SW structures on northern Ellesmere Island appear to be Palaeozoic lineaments reactivated during the main phase of the Eurekan orogeny. The structural data are from King (1969), Balkwill (1978) and McWhae (1981); base map is from King (1969). CA = Cornwall Arch, PMA = Princess Margaret Arch, GU = Grantland Uplift, JDP = Judge Daly Promontory, RC = Robeson Channel, HB = Hall Basin, KC = Kennedy Channel, KB = Kane Basin, SS = Smith Sound.

modified using the time scale of LaBrecque et al. 1977). Greenland and Ellesmere (and the Nares Strait lineament) rotated in a counter-clockwise sense away from the North American coast. As the pole of rotation was near northern Baffin Island (Sclater et al. 1977, Srivastava 1978), compression and uplift occurred north of the pole of rotation. The compressive stress pattern followed small circles about the pole of rotation. As folds were produced normal to this stress pattern, the fold pattern produced was a fan converging towards the pole of rotation. Fig. 3 shows the predicted stress pattern and the orientation of the Eurekan folds in the Sverdrup Basin. The folds were restricted to the less competent rocks of the Sverdrup Basin and did not extend into the Precambrian terrain. Some strike-slip faulting parallel to the predicted stress pattern is shown in McWhae's (1981) map near the southern margin of the basin.

Using the rotation poles given by Srivastava (1978), the amount of compressive strain predicted for the centre of the Sverdrup Basin (approximately 900 km north of the pole of rotation) is 200 km. This amounts to crustal shortening of nearly 25 per cent. During the early phase of the Eurekan orogeny, major arches such as the Cornwall Arch and Princess Margaret Arch did develop. Balkwill (1978) argued that these early Eurekan structures were caused by uplift with little compression. In contrast, this interpretation suggests that compression was the primary cause of the early phase of the Eurekan orogeny. Also a strong unconformity below the Eureka Sound Formation on the northern rim of the basin indicates a major pulse of tectonic activity in the Sverdrup Basin at this time (see fig. 8 in Meneley et al. 1975). There is also some evidence from deep seismic refraction work that a wave-like pattern with a 10 km amplitude and a N–S orientation has developed on the Mohorovicíc discontinuity underneath the Sverdrup Basin (Forsyth et al. 1979).

Taken together, the known features which may represent crustal compression can only account for 5–10 per cent shortening. Accounting for the remainder is a major unsolved problem. There is an interesting analogy to be drawn between this problem and a similar one regarding compression in the southern Appalachians of the United States. Were the basement rocks underlying the sediments involved in the deformation (thick-skinned deformation) or were the sediments decoupled from basement rocks as they deformed (thin-skinned deformation) (Rodgers 1970)? Geological interpretations of the southern Appalachians have indirectly suggested thrusting of less than 100 km (e.g. map of Williams 1978), but recent geophysical evidence from the COCORP program suggests thin-skinned deformation with at least 260 km of thrusting (Cook et al. 1979). If similar processes operated in the Sverdrup Basin, attaining compression of up to 25 per cent in the sedimentary section would not be a problem. Such a hypothesis provides a possible answer to arguments against major compression which are based on surface geology, but how and if the deeper crust was shortened remains unanswered.

During this time the Baffin Bay area was very close to the pole of rotation. The stress pattern was compressive in the north and mildly tensional in the south. In the north, the Bylot unconformity can be explained by uplift and erosion. In the south, and particularly further south in Labrador, there is no tectonic explanation for it. As a similiar unconformity has been noted in the North Sea (Kent 1981) and observed on a world-wide basis (Vail et al. 1977), it appears that the primary cause of the Bylot unconformity was a eustatic lowering of sea level and its effect was amplified by tectonic events in northern Baffin Bay and the Sverdrup Basin.

Opening of Baffin Bay

Between the time of anomalies 25 and 21 (59–50 m.y.), the pole of rotation for Greenland with respect to North America moved from Baffin Island to equatorial Africa (13°N, 2°E, Srivastava 1978). Although the magnetic anomalies in Baffin Bay are difficult to correlate at best (Jackson et al. 1979), the history of these changes is clearly recorded in the Labrador Sea (Srivastava 1978). At the same time spreading in the Atlantic migrated northwards between Greenland and Europe (Kristoffersen & Talwani 1977, Talwani & Eldholm 1977) and into the Arctic Ocean (Vogt et al. 1979). By anomaly 24 time the Wegener Transform Fault and its equivalent on the northeast side of Greenland, the Nansen Transform Fault, were established (Peirce 1980), and Greenland was separated from the surrounding plates.

The volcanics near Davis Strait are clearly related in age (dated at 58–60 m.y. by Parrott & Reynolds 1975) to the early opening of Baffin Bay. There is debate about whether or not they are related to a hot spot or mantle plume (Morgan 1972). Hall (1981) includes them in the Thulean volcanic line and relates them to the Icelandic hot spot. However, either such a hot spot must have been 1000 km in diameter, more than five times the commonly accepted scale of hot spots, or there must have been considerable lateral transport similar to that suggested by Morgan (1978) for some other hot spots. Moreover, Clarke (1977) argues convincingly that the Davis Strait volcanics are geochemically distinct from the others in the Thulean line. If they are not part of the Thulean volcanics, then the period of eruption was too short to qualify as a hot spot. I agree with Clarke (1977) that there was no Davis Strait hot spot and that these volcanics were erupted in response to the changing stress pattern as spreading migrated north into Baffin Bay.

At anomaly 25 time (Fig. 4), Ellesmere Island became part of the North American plate and was separated from Greenland by the Wegener Transform Fault.

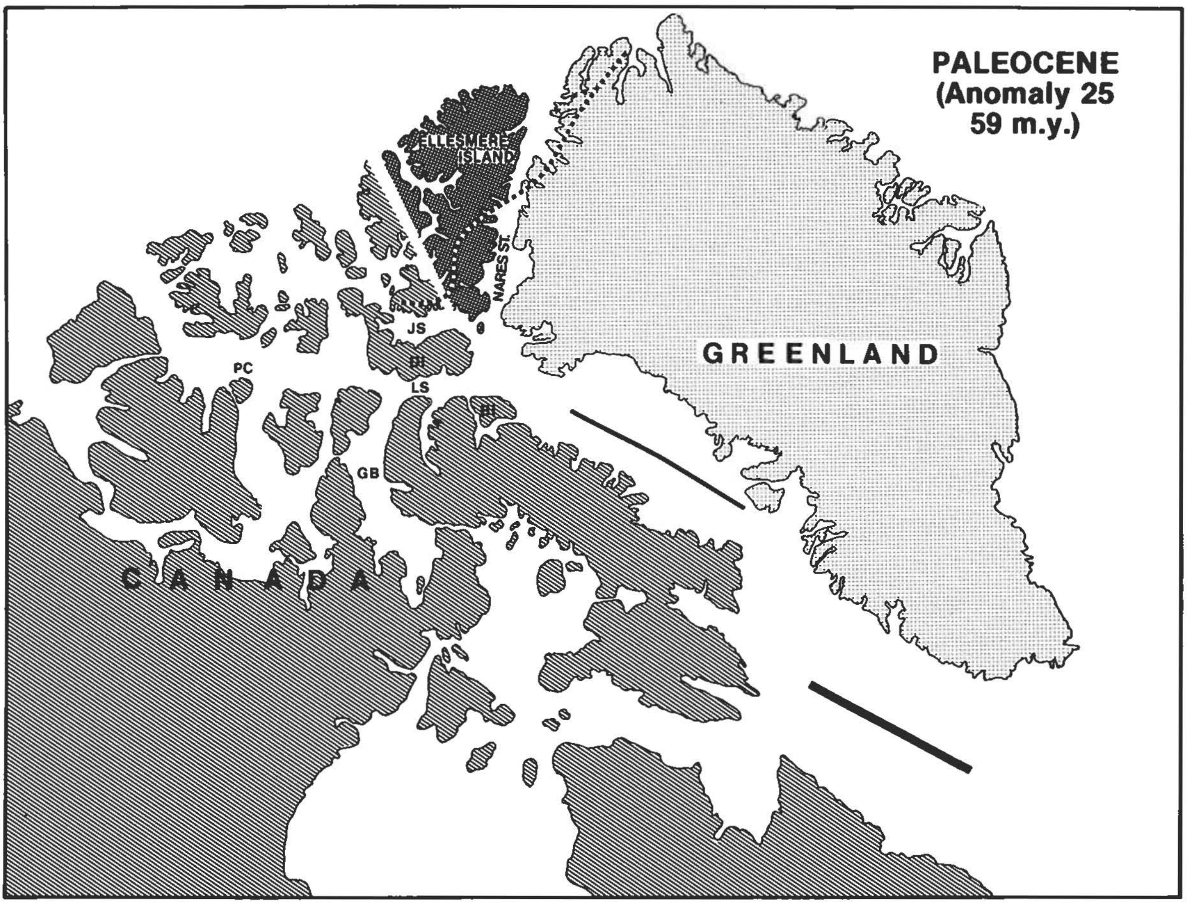


Fig. 4. Positioning of the Labrador Sea plates at anomaly 25 time (Paleocene). Note closure in the Sverdrup Basin since the Early Cretaceous. The heavy line indicates the Labrador Sea spreading centre; thin line indicates extension in Baffin Bay at this time. PC = Parry Channel, DI = Devon Island, LS = Lancaster Sound, JS = Jones Sound, BI = Bylot Island, GB = Gulf of Boothia.

According to the poles derived by Srivastava (1978), about 200 km of left-lateral offset occurred during the Late Paleocene and Early Eocene (anomalies 25–21) and 120 km of offset occurred during the Middle Eocene to Early Oligocene (anomalies 21–13, Fig. 5). The total offset is 320 km, not 250 km as Srivastava says in the text. About a third of this distance was accommodated in Baffin Bay by stretching and attenuation of the continental margins (Keen & Peirce, this volume). A similar amount of stretching may have occurred between North America and Ellesmere Island and contributed to the widening of grabens such as Lancaster and Jones Sounds.

Lancaster Sound was by now a failed arm rift. The other two limbs of the original RRR triple junction had become active plate boundaries while Lancaster Sound subsided and received a huge influx of Tertiary sediments.

Main phase of Eurekan compression

McWhae (1981) has suggested that a triple junction existed at the mouth of Jones Sound during the Eocene. This triple junction is required to explain his hypothesis that Greenland moved northwestwards during the Eocene causing the main phase of the Eurekan orogeny.

The Eocene triple junction is rejected on two counts. First, the timing is wrong. Balkwill (1978) showed that the Eurekan orogeny extended into post mid-Eocene time because rocks of that age were deformed by it. Secondly, the geometry is impossible. Had such a triple junction existed, it must have been a ridge-fault-fault (RFF) junction with the Baffin Bay spreading centre, the Wegener Transform Fault, and a Jones Sound Transform Fault as its limbs. The vector and stability diagrams (Fig. 6) demonstrate that such a triple junction could not have maintained itself unless the spreading was either very asymmetric or very oblique to the strike of the spreading centre.

Kerr (1980b, 1981) has suggested that a quadruple

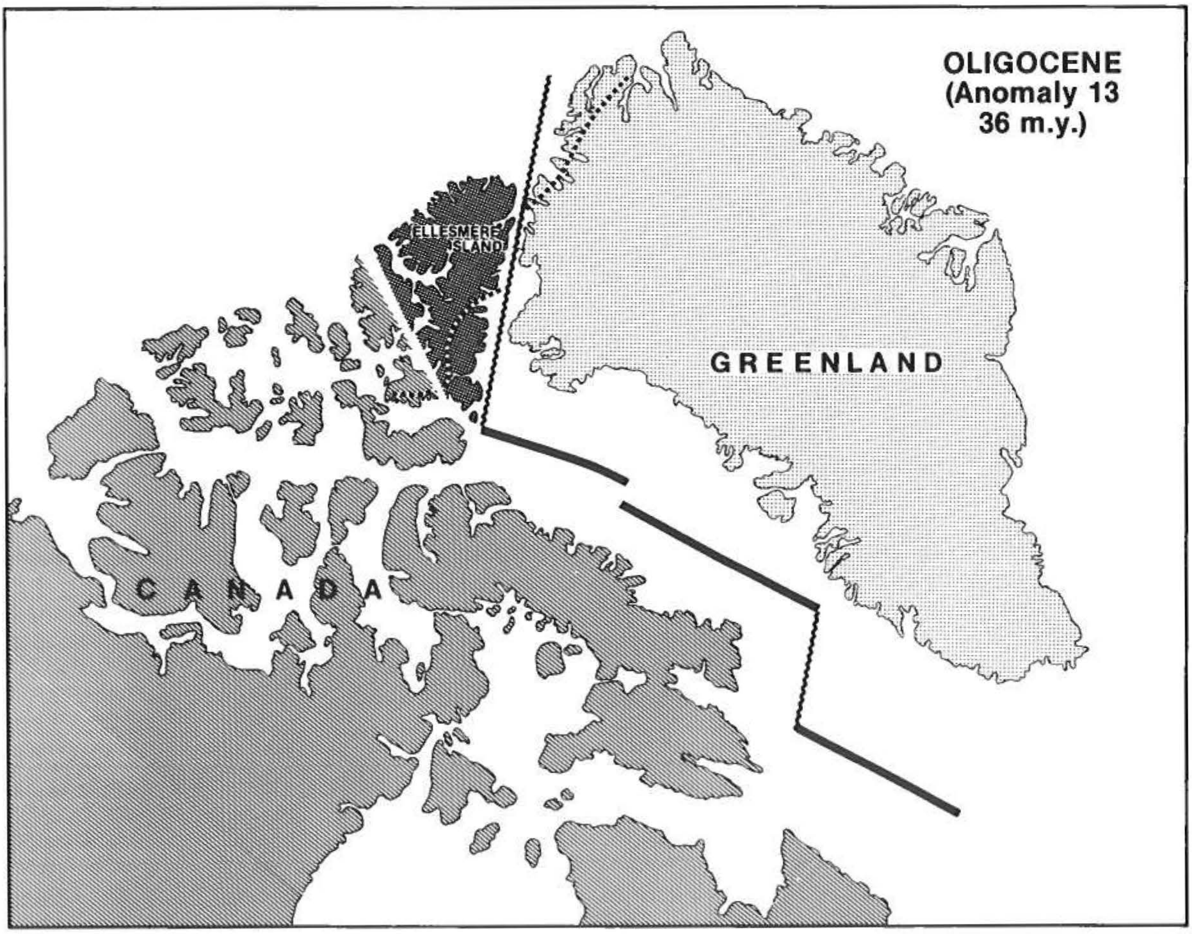


Fig. 5. Positioning of the Labrador Sea plates at anomaly 13 time (Oligocene). The heavy lines indicate the spreading centres which ceased to be active at this time. There probably was no discrete spreading centre which extended through Davis Strait. The wavy lines indicate transform faults. Note how the southern edge of the Palaeozoic fold belt has been apparently offset.

junction existed at this location during the opening of Baffin Bay. As a quadruple junction is inherently unstable (it will degenerate into two triple junctions, McKenzie & Morgan 1969), this hypothesis is also rejected.

However, McWhae's (1981) hypothesis can be modified to fit the constraints if the northwesterly motion of Greenland is delayed until Early Oligocene time (anomaly 13, 36 m.y.) when spreading had ceased in the Labrador Sea (Kristoffersen & Talwani 1977, Sclater et al. 1977, Srivastava 1978). I hypothesize that as the Wegener Transform Fault locked, Greenland moved northwestwards, relative to North America, about 50 km. There is some evidence for motion in this sense in Davis Strait in the form of possible fault offsets and folds with keystone structures associated with faulting (fig. 13 in McWhae 1981). Ellesmere Island was pushed ahead of Greenland producing the main phase of the Eurekan orogeny. Presumably the folding did not occur at Nares Strait because the crust on either side was relatively competent. Instead the stress was transmitted across eastern Ellesmere Island to the less competent rocks of the Sverdrup Basin where the strain could be accommodated. This stress reactivated early Eurekan structures in the Sverdrup Basin and Palaeozoic structures in northern Ellesmere Island. Similar variations in the style of deformation have been observed in the Himalayan collision and have been interpreted to be related to crustal age and strength (Molnar & Tapponnier 1981).

Srivastava (1978) breaks the motion of Greenland relative to North America between anomaly 24 and the Present into two stages of motion (see arrows on his fig. 21d) which ended at anomaly 13 time. Although the generally accepted strike of the Wegener Transform Fault is parallel to Nares Strait, the last pole of rotation postulated by Srivastava (1978) predicts a strike 25° different from this (see his fig. 21d). A careful examination of the data (particularly his fig. 2) shows that there is good control on the amount of rotation during this time, but there is poor control on the azimuth to the

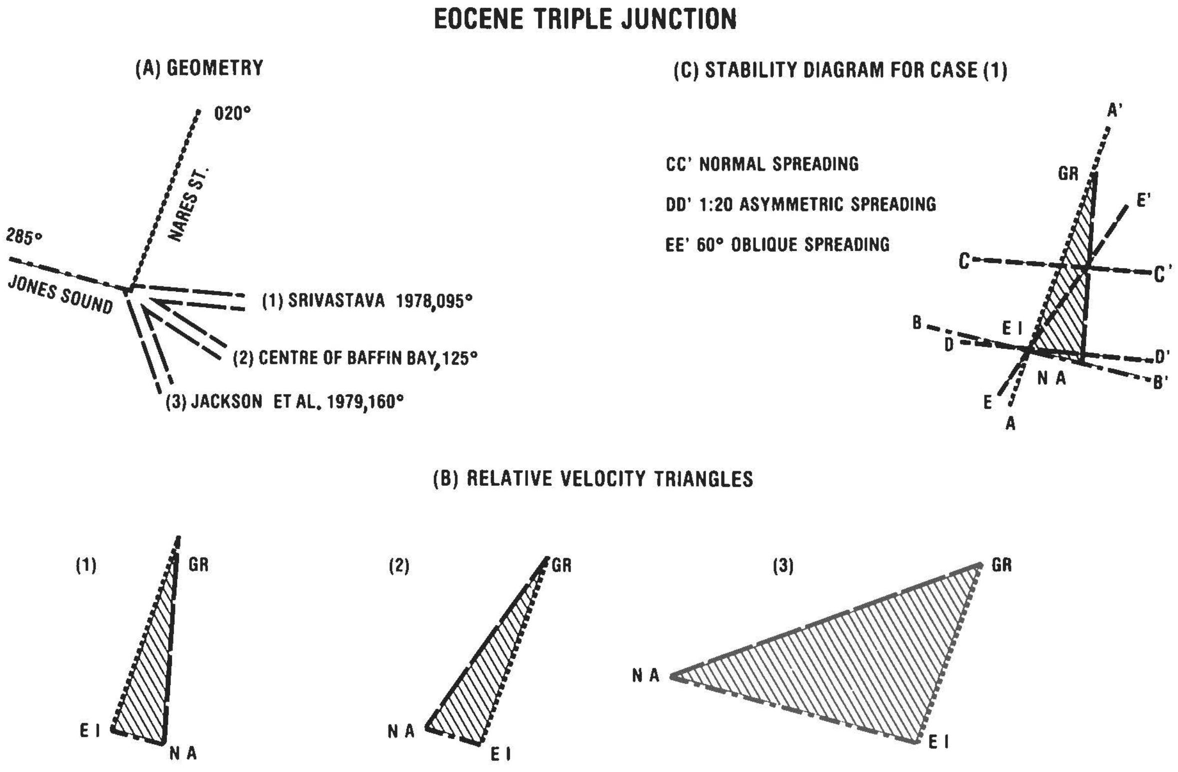


Fig. 6. Vector and stability diagram (McKenzie & Morgan 1969) for the Eocene triple junction in Baffin Bay hypothesized by McWhae (1981). NA = North America, EI = Ellesmere Island, GR = Greenland. Orientations of EI/NA and GR/EI vectors based on strikes of Jones Sound and Nares Strait. GR/NA spreading assumed perpendicular to Baffin Bay spreading axis. Relative velocities unknown. The lines of no motion in the stability diagram are AA', BB' and CC'. For the triple junction geometry to be stable these must intersect in a point. This junction has an unstable geometry unless the spreading is 60° oblique to the spreading axis which would be oriented along line EE', or spreading was asymmetric in a 1:20 ratio, being faster on the eastern side (DD').

pole of rotation because the fracture zones are poorly defined. The first well-defined pole is the total pole of rotation for anomaly 25 to the present. This pole does predict the strike of Nares Strait (Fig. 7). There remains, however, a discrepancy between that pole and that estimated from the data in the North Atlantic by Sclater et al. (1977) for the same motion. If we accept Srivastava's total pole as the best estimate of motion between Greenland and North America between anomaly 25 and anomaly 13, when spreading ceased in the Labrador Sea, then the combination of that pole with a rotation of +1.5° about a pole at 15°N, 130°W produces the overall pole computed by Sclater et al. (1977). This new combination of poles predicts the strike of Nares Strait, moves Greenland to the northwest relative to North America, and explains the 50 km of compression in Ellesmere and Axel Heiberg Islands during the main phase of the Eurekan orogeny.

Kristoffersen & Talwani (1977) did suggest northwesterly motion of Greenland, but they were basing their conclusions only on magnetic anomalies near the triple junction and they had no Labrador Sea anomalies to work with. Sclater et al. (1977) considered the fit of all the North Atlantic pieces of the puzzle without the benefit of Srivastava's (1978) correlations in the Labrador Sea. Their poles of opening are in excellent agreement with those of Srivastava (1978), except that their pole for the opening of the Labrador Sea between anomalies 13 and 21 is significantly further east than Srivastava's pole for the same period. The addition of a small amount of northwesterly motion of Greenland as suggested above reconciles the three results very well.

This model predicts some left-lateral motion in the vicinity of Jones Sound, as indicated on McWhae's (1981) maps, but the timing is later. The amount of motion is based primarily on Balkwill's (1978) and McWhae's estimates of crustal shortening during the main phase of the Eurekan orogeny. There is no direct evidence in the magnetic anomaly correlations for the 50 km move of Greenland. However, as the motion would have been nearly parallel to the Labrador Sea anomalies, and as there are no sharply-defined fracture zones to be offset, such motion could have been easily overlooked. On the other hand, it is unlikely that more than about 50 km of translation would go undetected.

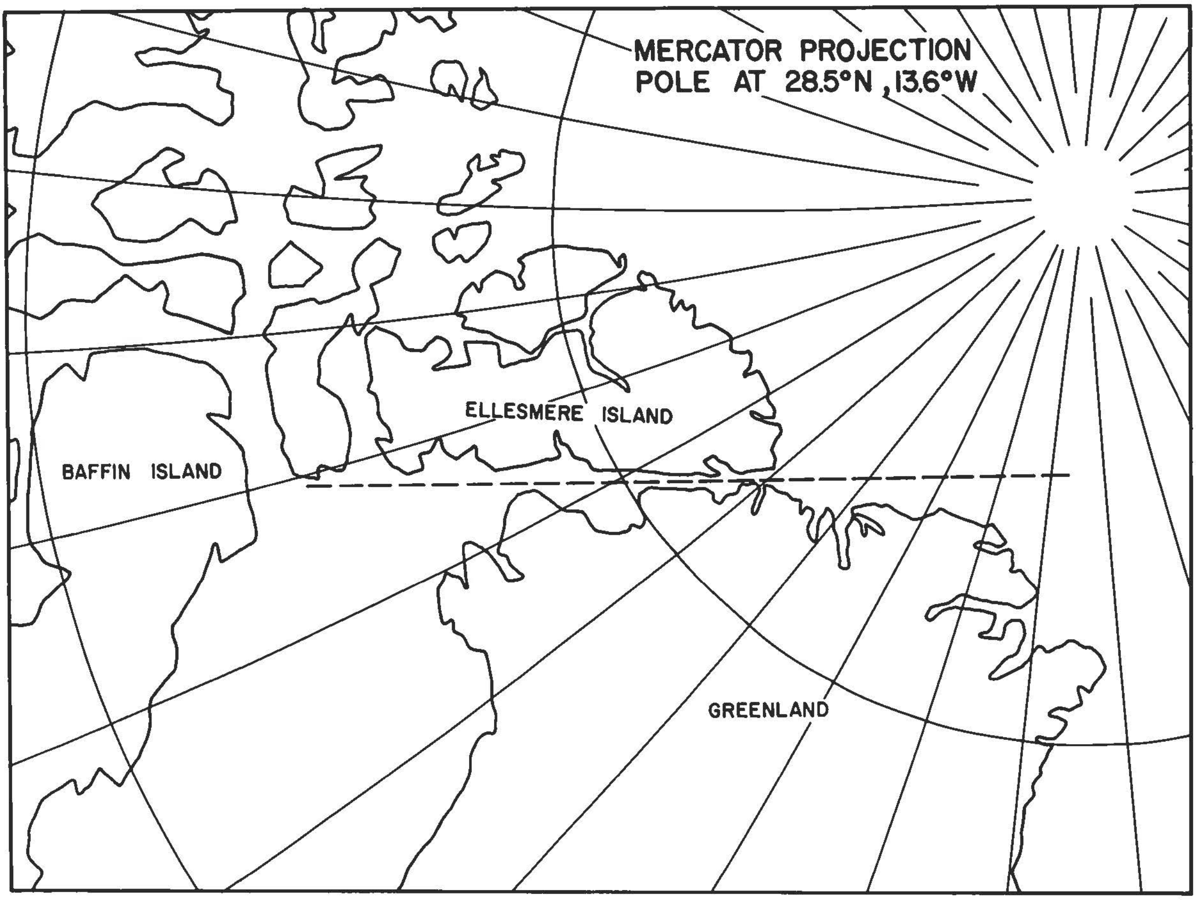


Fig. 7. Mercator projection of Nares Strait area about pole of rotation at 28.5°N, 13.6°W, which is Srivastava's (1978) total pole of rotation for anomaly 25 to the present. Note that Nares Strait appears as a parallel of 'latitude' relative to this pole and is therefore a small circle about this pole. Major transform faults form small circles about their poles of rotation. The strike predicted by Srivastava's (1978) pole for his last direction of spreading (anomaly 21 to 13) is about 25° more northeasterly than the strike of Nares Strait (see case (1), Fig. 6).

Sedimentary section in Lancaster Sound and Nares Strait

The tectonic time diagram in Fig. 8 outlines the changing tectonic styles of each area and schematically shows the extent of the major unconformities.

The incipient rifting probably migrated northwards up the Labrador coast. Therefore, I expect the Labrador unconformity to be diachronous, being younger to the north. When the triple junction was established in northern Baffin Bay in the Early–Middle Cretaceous, the structural lineaments in Nares Strait and Lancaster Sound were established. These features resembled the East African Rift Valley of today — extensional grabens without any oceanic crust developed in the centre and surrounded by uplifted highlands. The oldest sedimentary rocks in both areas are likely to be Palaeozoic blocks preserved within the grabens (Daae & Rutgers 1975, Kerr 1980b). Above these there should be continental equivalents of the Bjarni Formation similiar to those found in the Eclipse Trough. If the highlands were dipping away from the central grabens, the sediment supply may have been limited. On the other hand, the grabens may have acted as the major line of drainage for the area concentrating sedimentation within it. The palaeocurrent evidence cited by Miall et al. (1980) suggests that the Eclipse Trough was a tributary feeding north into the more major lineament of Lancaster Sound. There is also the possibility of volcanics associated with the rifting occurring anywhere in the Early–Middle Cretaceous section. The volcanic sands at Judge Daly Promontory (Miall 1981, see Fig. 1) might be derived from such Cretaceous volcanics.

The incipient rifting phase probably persisted until Late Cretaceous, although it is unlikely that any large amount of subsidence occurred to allow accumulation of a thick section. With the onset of sea-floor spreading in the Labrador Sea, both Lancaster Sound and Nares

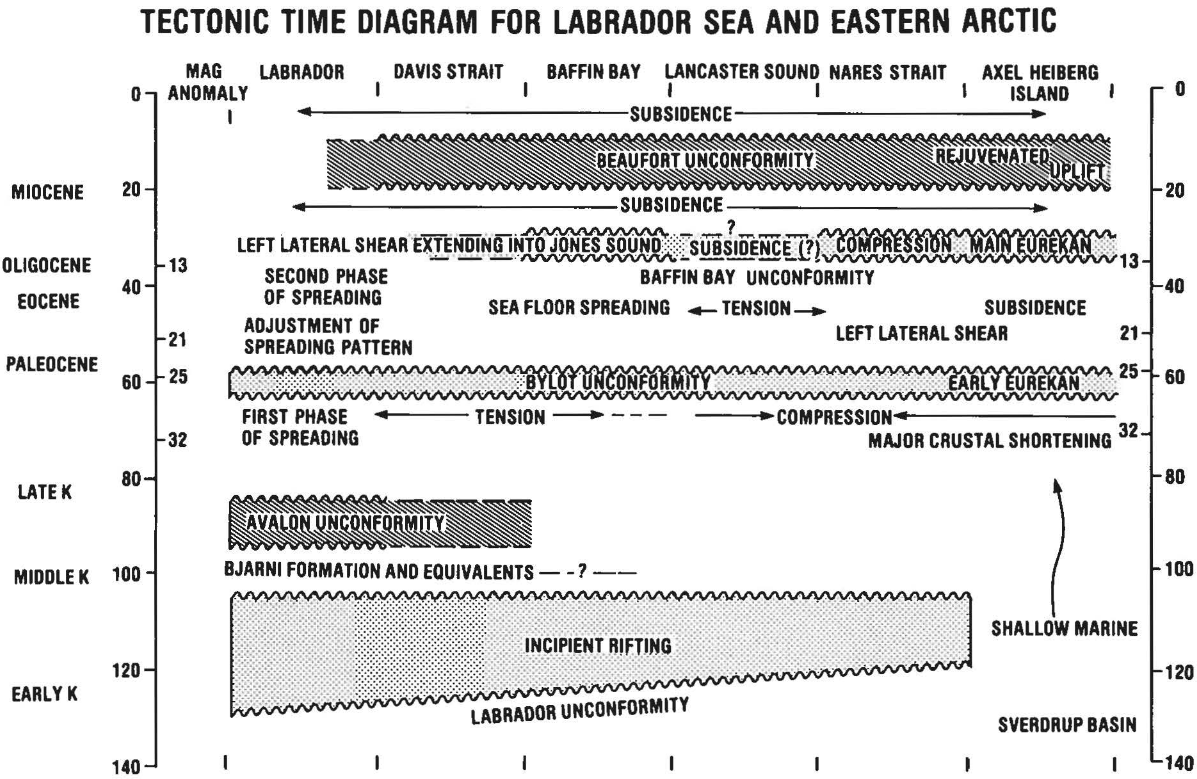


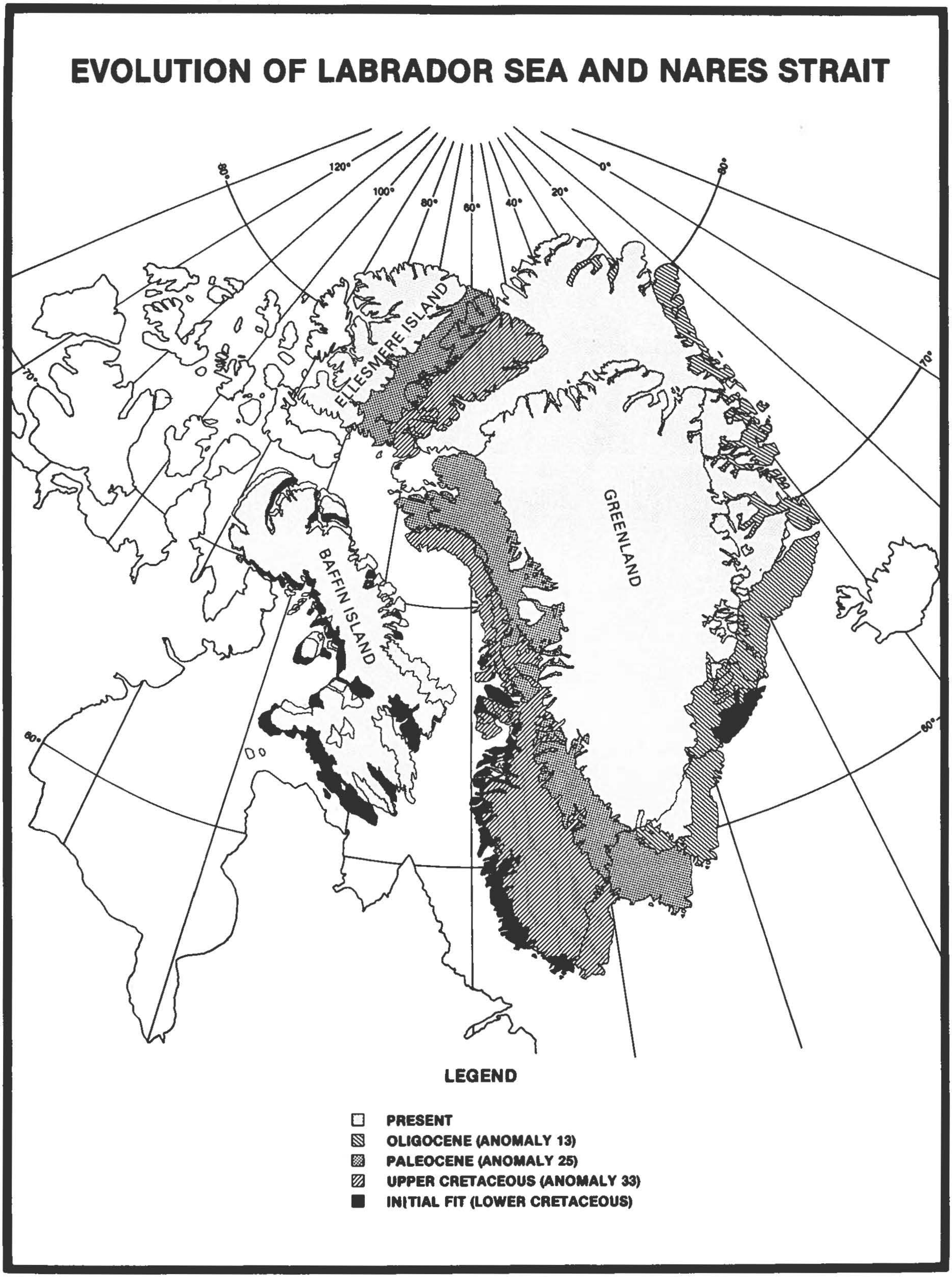
Fig. 8. Tectonic time diagram for the eastern Canadian Arctic and Labrador Sea. The major unconformities are informally named after McWhae (1981). The three unconformities where local tectonics may have enhanced their development are shaded with dots. The two unconformities without a local tectonic component are shaded with diagonal lines. All five unconformities occur in many parts of the world, indicating that eustatic changes of sea level may have contributed to their formation (Vail et al. 1977). The validity of these eustatic sea level changes is a matter of lively debate. The ages of the magnetic anomalies are based on the time scale of LaBrecque et al. (1977). K indicates Cretaceous.

Strait were placed in a compressive stress regime where the amount of compression was proportional to the distance from the pole of rotation. Therefore both these lineaments should have experienced more compression, and probably more erosion, during the time represented by the Bylot unconformity than did the Eclipse Trough. Lancaster Sound was close enough to the pole of rotation that the amount of compression was probably minimal — perhaps an absence of subsidence would be a more accurate description.

When the spreading pattern changed in the Labrador Sea and Baffin Bay began to open, Ellesmere Island became detached from the Greenland plate. Compression in Lancaster Sound relaxed and there was tensional stress to widen the structure and accelerate subsidence. As the other two limbs of the original triple junction were still active plate margins, Lancaster Sound became a failed rift. Subsidence and sedimentation have been rapid since then, except for a brief hiatus during the Baffin Bay unconformity and a possible hiatus during the Miocene Beaufort unconformity.

Lancaster Sound has at least six kilometres of sedimentary section in it (Daae & Rutgers 1975, Kerr 1980b). McWhae (1981) has argued that the bulk of the section in Lancaster Sound is Cretaceous in age based on an attempt to correlate the Bylot unconformity into Lancaster Sound on seismic sections and by analogy with the Eclipse Trough. However, the structural his-

Fig. 9. Summary diagram showing the major stages in the evolution of the Labrador Sea and Nares Strait. The complete outlines of Greenland and Baffin Island are shown in their initial and present-day positions. Intermediate positions shown where they are not covered by a later position. The initial fit position from Bullard et al. (1965) is shown for reference, but Keen & Peirce (this volume) have suggested that Srivastava's Upper Cretaceous position is a more likely initial fit geologically. The motion of Greenland is generally to the northeast and then to the northwest. The Oligocene position of Greenland is explained in the text. The Upper Cretaceous and Paleocene positions are from Srivastava (1978). The initial position of Ellesmere Island is not known but the model predicts that it was near the Upper Cretaceous position shown. The Upper Cretaceous position assumes that Ellesmere Island and Greenland moved as one until the Paleocene. The Oligocene and Paleocene positions of Ellesmere Island are the same and are explained in the text. The motion of Ellesmere Island is generally to the northwest.


EVOLUTION OF LABRADOR SEA AND NARES STRAIT
80°
120°
100°
80°
60°
40°
20°
0°
80°
70°
70°
60°
60°
ELLESMERE ISLAND
BAFFIN ISLAND
GREENLAND
LEGEND
☐ PRESENT
▧ OLIGOCENE (ANOMALY 13)
▩ PALEOCENE (ANOMALY 25)
▨ UPPER CRETACEOUS (ANOMALY 33)
■ INITIAL FIT (LOWER CRETACEOUS)

tory outlined above suggests that it is unlikely that rapid subsidence and sedimentation could have begun before the Paleocene. Therefore, an alternative interpretation is that the majority of the Lancaster Sound section is Tertiary in age. In short, I suggest that the Bylot unconformity may be considerably deeper than McWhae (1981) has suggested. Kerr (1980b) arrives at the same conclusion, although his interpretation of the tectonic history is different.

Nares Strait has had a more complicated history than Lancaster Sound. Until the Paleocene their histories were quite similar and continental equivalents of the Bjarni Formation should be expected at the bottom of the Nares section as well. However, during opening of Baffin Bay, while Lancaster Sound was beginning to subside rapidly, the extensive left-lateral motion on the Wegener Transform Fault must have sheared and deformed these early sediments extensively. Furthermore, it is unlikely that there was an overall subsidence of Nares Strait while it was an active transform fault, although local deeps may have been developed in the fault zone.

During the main phase of the Eurekan orogeny, Nares Strait was under compressive stress while Lancaster Sound was relatively unaffected. It is likely that the Baffin Bay unconformity cut quite deeply into whatever section had accumulated in Nares Strait. As there were continued pulses of uplift in the eastern Sverdrup Basin into the Miocene (Balkwill 1978), it is unlikely that the compressive stresses there relaxed before then. Miall (1979) cites the absence of Paleocene sediments in the Lake Hazen intermontane basin on Ellesmere Island as evidence that subsidence in the area did not begin until the Eocene or Oligocene. Nares Strait probably did not begin to subside rapidly until the Neogene, well after Lancaster Sound began to subside. However, as the rate of subsidence decreases exponentially (under similar conditions of sediment loading), during the Miocene and Pliocene Nares Strait may have been subsiding more rapidly then than Lancaster Sound.

Conclusion

Both Nares Strait and Lancaster Sound are features which were localized along older lineaments established during an Early to Middle Cretaceous incipient rifting phase. Because northern Baffin Bay was in a compressive stress regime through the Late Cretaceous and especially in the Paleocene (early phase of Eurekan orogeny) it is unlikely that major subsidence could have occurred until the Late Paleocene. At this time Lancaster Sound became a true failed rift while Nares Strait became a major transform fault. Given the post mid-Eocene age of the main phase of the Eurekan orogeny, I have hypothesized that Greenland moved northwestwards about fifty kilometres after spreading ceased in the Labrador Sea. This additional motion of Greenland appears to make some of the key geological and geophysical pieces of the Nares Strait puzzle fit together, although the arguments about the correlation of geological trends across Nares Strait will undoubtedly continue. Fig. 9 shows these motions superimposed on one diagram summarizing the evolution of the Labrador Sea and Nares Strait.

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