The geophysical implications of minimal Tertiary motion along Nares Strait

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In the light of the geological evidence indicating less than 25 km of left-lateral offset along the Wegener Fault in Nares Strait, we examined three models for the formation of Baffin Bay which do not involve sea-floor spreading in that region. Our purpose was to investigate whether these models present realistic alternatives to sea-floor spreading and simultaneously remove the requirement for extensive lateral separation between Greenland and North America. These models are crustal extension, mantle upwelling and magmatic intrusion. Each model is constrained to match the observed subsidence and present width of the basin and, where possible, the observed crustal thickness. The crustal extension and magmatic intrusion models require extensive left-lateral motion between Greenland and North America, and thus they appear to be at odds with the geological observations. Furthermore, neither the mantle upwelling model nor the magmatic intrusion model can produce the required crustal thinning (85% of continental crust must be eliminated), and there are no analogous examples of such an extreme case of 'oceanization' elsewhere in the world. Thus none of the models can account for both the thin crust in central Baffin Bay and the apparent lack of offset along the Wegener Fault.

We suggest two possible solutions to the conflict between the available observations: 1) Tertiary left-lateral motion has reversed earlier right-lateral motion; or 2) left-lateral motion between Greenland and North America was accommodated elsewhere than along the Nares Strait waterway. The first is shown to be in conflict with geological evidence from the margins of Baffin Bay. There is at present no evidence to support the second, but we suggest that this possibility be critically evaluated in future studies of the geological history of the region. In this context, we suggest that minimal offset across the Nares Strait waterway need not be incompatible with major Tertiary left-lateral motion on the Wegener Fault if one accepts the concept of a fault zone rather than a single discrete offset. Future studies of the extent of horizontal deformation immediately north of Baffin Bay and within the Sverdrup Basin are also required.

A tectonic model, which includes elements of mantle upwelling and crustal extension at the margins and sea-floor spreading in central Baffin Bay, accounts for the observed subsidence and crustal thickness in the centre of the basin, and explains the uplift of eastern Baffin Island and western Greenland. It also satisfies the geometrical requirements of plate tectonic reconstructions for the North Atlantic and Arctic Oceans. However, it requires that an acceptable means of accommodating the opening of Baffin Bay be found before it can be considered valid.

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The concept of extensive left-lateral motion along the Wegener Fault in Nares Strait during the Tertiary has been revitalized in the last decade to satisfy the need for lateral separation between Greenland and North America in regional plate reconstructions (see Kerr 1980, for a review). Recent geological evidence presented at the symposium (Dawes & Kerr, Dawes et al., Frisch & Dawes, Higgins et al., Hurst & Kerr, Peel & Christie, Peel et al., this volume) strongly favours an interpretation with no more than 25 km of net left-lateral offset along the fault. This apparent impasse prompted us to re-examine the geophysical evidence in search of a new interpretation which is compatible with minimal offset on the fault.

Models for the formation of Baffin Bay

The formation of Baffin Bay and that of Nares Strait (Fig. 1) are intimately related; any tectonic model which explains one must at least not be in conflict with the evidence from the other. Although all recent papers agree that a rifting event is involved in the formation of

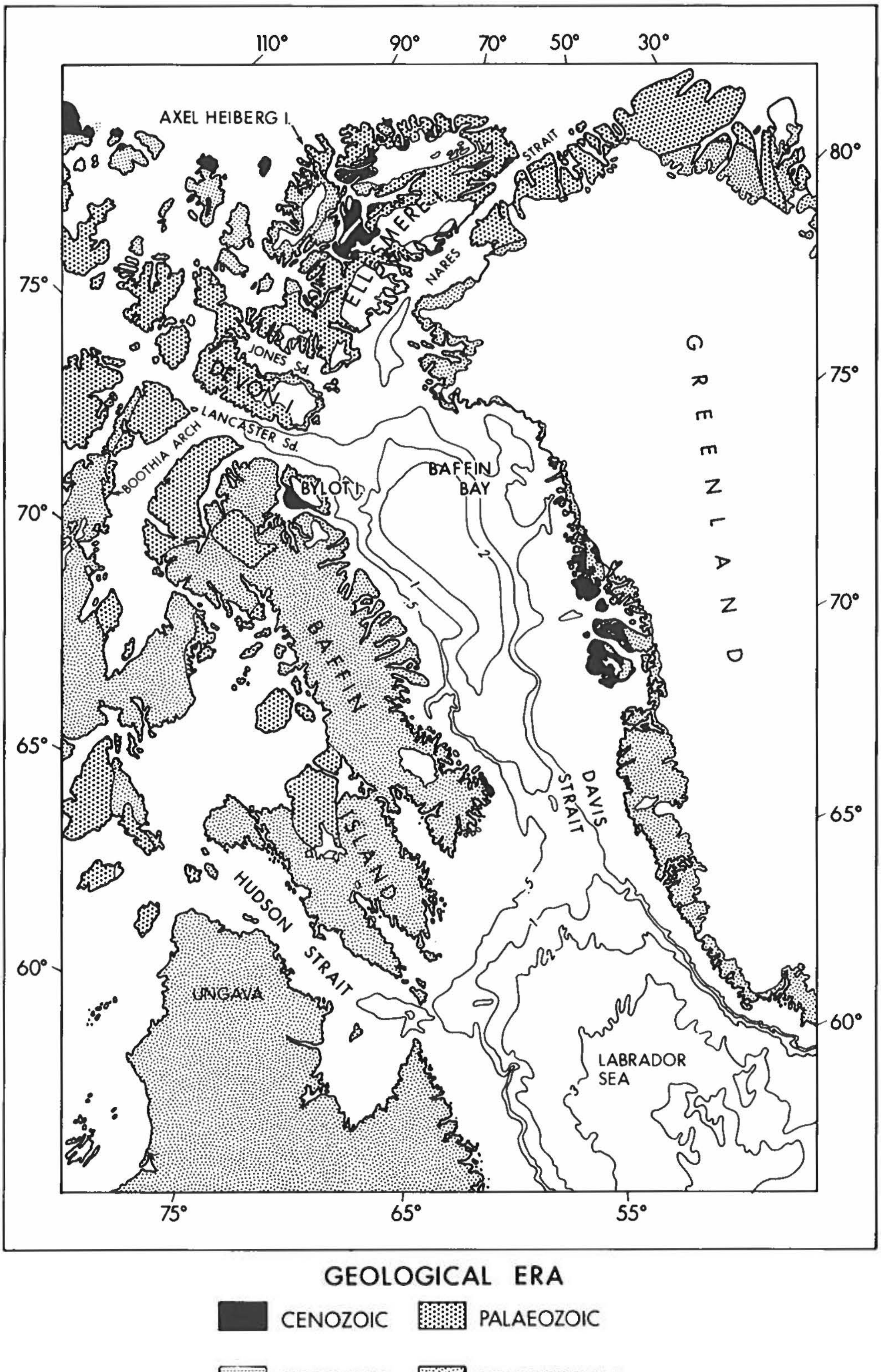

Fig. 1. Index map showing the generalized geology of the area around Baffin Bay and Nares Strait. Water depths are in kilometres.

Baffin Bay, they disagree on its importance. The conventional plate tectonic model is that central Baffin Bay is underlain by oceanic crust produced as Greenland moved away from North America (Keen et al. 1974), although a simple sea-floor spreading mechanism may not be adequate to explain the complex pattern of magnetic and gravity anomalies (Srivastava 1978, Jackson et al. 1979). On the other hand, Kerr (1981: 160) favours a model which combines a "small to moderate amount of lateral movement" with "subsidence or oceanization of a very large intervening segment of continental crust".

The crust in central Baffin Bay consists of two basic units: sediments about 4 km thick and the underlying crystalline crustal rocks not more than 5 km thick. The latter thickness is less than that of most oceanic crust except near spreading centres and in some back-arc basins (e.g. 4 km in parts of the West Philippine Basin (age 40 Ma), Louden 1980). Crustal and upper mantle velocities are 6.5–7.0 and about 8.0 km/sec respectively. Thus, the seismic characteristics of the crust in this region closely resemble those of oceanic crust (Keen & Barrett 1972).

By comparison, intra-cratonic and intra-arc sedimentary basins which are underlain by continental rocks exhibit a relatively thick crust. Some examples of crustal thickness from the best studied of these basins are given in Table 1. In all cases the crystalline crustal thickness is greater than 15 km, with the exception of the Black Sea. This latter region has been used by many workers as evidence of 'oceanization' of continental crust (e.g. Kosminskaya & Pavlenkova 1979). However, recent plate tectonic reconstructions in the Mediterranean–Alpine region suggest that the Black Sea may be the remnant of an ocean basin formed by sea-floor spreading in the Mesozoic, which has not yet been destroyed by the complex plate interactions occurring in that area (Biju-Duval et al. 1977). With this one possible exception, continental sedimentary basins appear to have crystalline crustal thicknesses which are much greater than that observed in Baffin Bay. The same is true of continental rift systems such as the Rhine Graben, the East African Rift System and the Baikal Rift (Table 1). Continental margin sedimentary basins of similar dimensions to the Baffin Bay basin also appear to have a much thicker crust (e.g. see Keen & Barrett 1981).

The total subsidence of the central region of the Bay is estimated to be the present total depth to crystalline basement, about 6 km. The total subsidence is corrected to remove the effect of sediment loading, assuming Airy isostatic compensation (Watts & Ryan 1976). The resulting subsidence of the basin is 3.7 km, or about 800 m less than the depth to 40 Ma old oceanic crust using the standard depth versus age curve for ocean basins (Sclater et al. 1971, Parsons & Sclater 1977). An age of 40 Ma has often been associated with the creation of the central part of Baffin Bay by sea-floor spreading (e.g. Keen et al. 1974, Srivastava 1978). The estimated subsidence will be in error if the crystalline crust was not initially near sea level. However, the arguments presented below will remain valid, unless the initial elevation differed by more than several hundred metres from present sea level.

We consider three numerical models, corresponding to three geological processes which can account for the observed subsidence in the basin. The three processes are: 1) uniform horizontal extension of the lithosphere (McKenzie 1978); 2) mantle upwelling or doming (non-uniform extension) (Sleep 1971, Royden & Keen 1980, Sclater et al. 1980) and 3) magmatic (dyke) intrusion of the lithosphere (Royden et al. 1980). The physical basis for the models and numerical analysis of basin subsidence are described in the above references. Each process produces heating and density changes in the

Table 1. Crystalline crustal thicknesses of several sedimentary basins and some rift systems.

Region	Age of formation	Crystalline crustal thickness-km	Reference
Pannonian	Mid-Tertiary	20	Sclater et al. (1980)
North Sea	Mesozoic	17	Sclater & Christie (1980)
Aegean	Young	20	Makris (1978)
Gulf of St. Lawrence	Palaeozoic	40	Ewing et al. (1966)
Hudson Bay	Palaeozoic	30	Ruffman & Keen (1967)
Black Sea	? Mesozoic	5–8	Neprochnov et al. (1970)
Sverdrup Basin	Palaeosoic–Mesozoic	20–30	Forsyth et al. (1979)
Afar region of Ethiopia	Young	20	Berckhemer et al. (1975)
Rhine Graben	Young	25	Edel et al. (1975)
E. African Rift (Gregory Rift)	Young	18	Long et al. (1973)
Baikal Rift	Young	30	Kosminskaya & Pavlenkova (1979)

Note: Ages are approximate. Many of these features have experienced several episodes of renewed subsidence, extension or volcanism. Crustal thicknesses obtained by removing best estimates of sediment thickness.

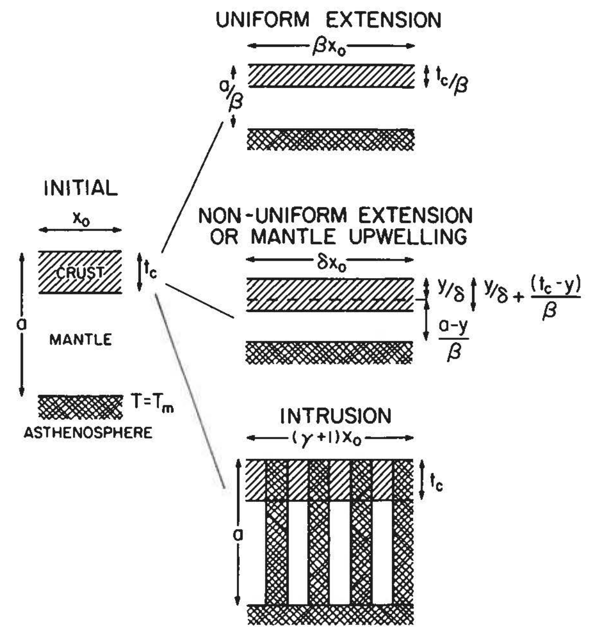

Fig. 2. Schematic representation of the three models considered to describe the formation of Baffin Bay. The initial configuration of the lithosphere is shown on the left. Initial crustal width is x_0, initial crustal thickness is t_c, initial thickness of the thermal lithosphere is as defined by the position of the melting temperature isotherm ($T = T_m$). For our models x_0 is unknown, $t_c = 35$ km, $a = 125$ km, $T_m = 1350°C$.

In the uniform extension model (top), the entire lithosphere is stretched by a factor of β and thinned by a factor of 1/β. As the lithosphere is thinned, hot asthenosphere upwells passively from below. After stretching, the crustal width is βx_0 and crustal thickness is t_c/β.

In the mantle upwelling model (middle), the shallow lithosphere above a depth y is stretched by a factor δ and thinned by 1/δ. The deeper lithosphere below y is thinned by a factor of 1/β. After stretching the horizontal extent of the region is δx_0. If $\delta = \beta$, this model is equivalent to uniform extension.

The intrusion model (bottom) involves the intrusion of dykes of asthenospheric material. The intrusion parameter, γ, is the fraction of dykes replacing original lithosphere. Assuming that the lithosphere extends to accommodate the additional material, no thinning occurs and the horizontal extent of the region is $(1 + \gamma)x_0$.

lithosphere which require uplift or subsidence to maintain isostatic equilibrium. When the tectonic processes become dormant, cooling and subsidence occur. Each numerical model is constrained to match the observed subsidence (3.7 km), the present basin width (220 km), and, where possible, the observed crustal thickness (5 km).

The models are shown schematically in Fig. 2. The β parameter describes the amount of extension in the uniform extension model. Its inverse is the crustal thinning factor. In the mantle upwelling model, δ describes the amount of extension and thinning down to depth y, and β defines the amount of thinning below depth y. The γ parameter in the intrusion model describes the volume fraction of dykes replacing crust (and therefore the amount of extension), but this model does not predict thinned crust. The limiting case in all three models is the total destruction of continental lithosphere, which is equivalent to sea-floor spreading. This extreme is represented numerically by β = infinity in the uniform extension model, δ = β = infinity in the upwelling model, and γ = 1 in the intrusion model.

The model parameters, observed and computed subsidence, and approximate amount of horizontal separation required by each model are listed in Table 2. It has been assumed that tectonic processes ceased and cooling began about 35 to 40 Ma ago in central Baffin Bay. All values of subsidence are given for a water-filled basin; the observed subsidence has been corrected for sediment loading assuming Airy, pointwise isostatic compensation (Watts & Ryan 1976). The original thickness of continental crust is assumed to be 35 km. The physical constants used in the calculations are the same as those used by Royden & Keen (1980).

The evolution of many rifted continental margins can be described by a combination of these three processes (Royden & Keen 1980, Royden et al. 1980). Extension and thinning of the lithosphere appear to be the primary processes during the rift phase of the development of continental margins (Montadert et al. 1979, Keen & Barrett 1981). The observational data can be satisfied by extension and mantle upwelling which increases towards the ocean–continent boundary, at which point total destruction of the continental lithosphere occurs and sea-floor spreading begins. Magmatic intrusion undoubtedly plays a role in the formation of rifted continental margins, but the importance of this is not well understood.

Uniform extension model

This model produces the Baffin Bay basin by extension and thinning of the lithosphere and the crust. It can satisfy the crustal thickness constraint and predict the observed subsidence of the basin if extension by a factor of 7 (crustal thinning to 5 km) occurred prior to 35 Ma (Table 2).

The model has been used very successfully in describing the geological history of intra-cratonic, intra-arc and continental margin sedimentary basins (Royden & Keen 1980, Sclater & Christie 1980, Sclater et al. 1980). However, these basins require much less extension and thinning (β ≤ 3) than Baffin Bay. The horizontal separation predicted for Baffin Bay by this model is about 200 km, almost as much as that required in conventional plate tectonic models. Also it may not be physically or chemically reasonable to postulate the large extension factor required for Baffin Bay without consideration of either significant volcanism (perhaps Davis Strait is an example) or the triggering of true sea-floor spreading.

Table 2. Results of model calculations.

Model	Parameters				Predicted present uplift[1] or subsidence (km)	Observed present uplift[1] or subsidence (km)	Predicted lateral motion (km)
						Central Basin (cooling starts 35 Ma ago)	
	δ	β	γ	y(km)			
Extension	7	7	0	–	3.51	3.74	214
Mantle upwelling	1	100	0	5.0	3.47	3.74	small
Dyke intrusion	1	1	0.8	–	3.45	3.74	111
						Continental Shelves (cooling starts 60 Ma ago)	
Extension and upwelling	2	7	0	35.0	1.99	1.74	112
						Baffin Island (cooling starts 60 Ma ago)	
Mantle upwelling	1	4	0	35.0	–0.49	~–0.8[2]	

1. Negative sign indicates uplift.
2. Observed uplift of eastern Baffin Island relative to 200 m elevation of western Baffin Island. Figures for West Greenland are not as representative due to the large ice sheet over most of the island.

Mantle upwelling or non-uniform extension model

In this model, upwelling occurs when light, fluid asthenosphere rises diapirically, replacing the denser lithosphere. The resulting thermal and subsidence histories will be the same as those for the non-uniform extension model of Royden & Keen (1980). In order to generate the thin crust, hot material must penetrate the upper crust, assimilating or replacing the original crustal material. Mantle upwelling can produce the correct basin subsidence and it may result in a relatively small amount of lateral separation. However, neither this model nor the intrusion model described below, account for the mechanism by which a large amount of the continental crust is destroyed, leaving the observed thin crustal layer. Possible 'oceanization' models are discussed later.

Magmatic intrusion model

This model requires that γ volume of dykes be intruded into the lithosphere in some randomly distributed manner which is not concentrated at a definable spreading axis. These dykes are assumed to be composed of basic and ultrabasic material from the asthenosphere. In its simplest form, this process does not include phase changes or the segregation of basaltic melt from the asthenosphere (but see petrological implications of such complications discussed below).

While intrusion can explain the observed subsidence of the basin, provided that a very large percentage (80%) of the original lithosphere is replaced by intrusive material, it does not predict the thin crust. Either extension of the lithosphere must occur to accommodate the volume of dykes intruded, giving 110 km of horizontal separation, or the lithosphere must thicken. In neither case is thin crust expected. Furthermore, such processes should lead to a rather heterogeneous crustal structure, perhaps without a well-defined crust–mantle boundary.

Crustal thinning by 'oceanization'

The above results suggest that upwelling might account for the formation of Baffin Bay and not require much lateral separation. However, a plausible means for destroying 85% of the continental crust must be found. There are various ways in which 'oceanization' or crustal thinning might occur apart from extension, many of which have been reviewed by van Bemmelen (1972). Unfortunately, there is little direct evidence supporting any of these hypotheses collectively known as 'oceanization' models. Modes of 'oceanization' can be broadly divided into two groups: those involving sub-crustal erosion and those requiring phase transformations. Both require the segregation of basaltic magma from hot mantle material and its intrusion into the crust. Sub-crustal erosion presumes that the intrusion causes melting of the crustal material followed by its eventual removal and assimilation into the mantle by downward convection. Alternatively, the gabbro-eclogite phase change has been postulated to transform the basalt saturated crustal rocks into eclogite upon cooling.

There are several difficulties with these 'oceanization' models. Both assume that large volumes of basalt are available to effect the necessary chemical and physical changes. As Jarvis & McKenzie (1980) have noted, it is, in general, unlikely that more basaltic magma will be available than that generated at mid-ocean ridges where about 5–6 km of basaltic crust is created (see also Ahern & Turcotte 1979). Modern examples of regions where sufficiently large quantities of basaltic magma are being generated, such as Iceland and the Afar region of Ethiopia, do not exhibit thin crust (Table 1), but appear to consist of about 20 km of basaltic crust overlying the mantle. The phase change hypothesis further suffers from the difficulties of generating a well-defined

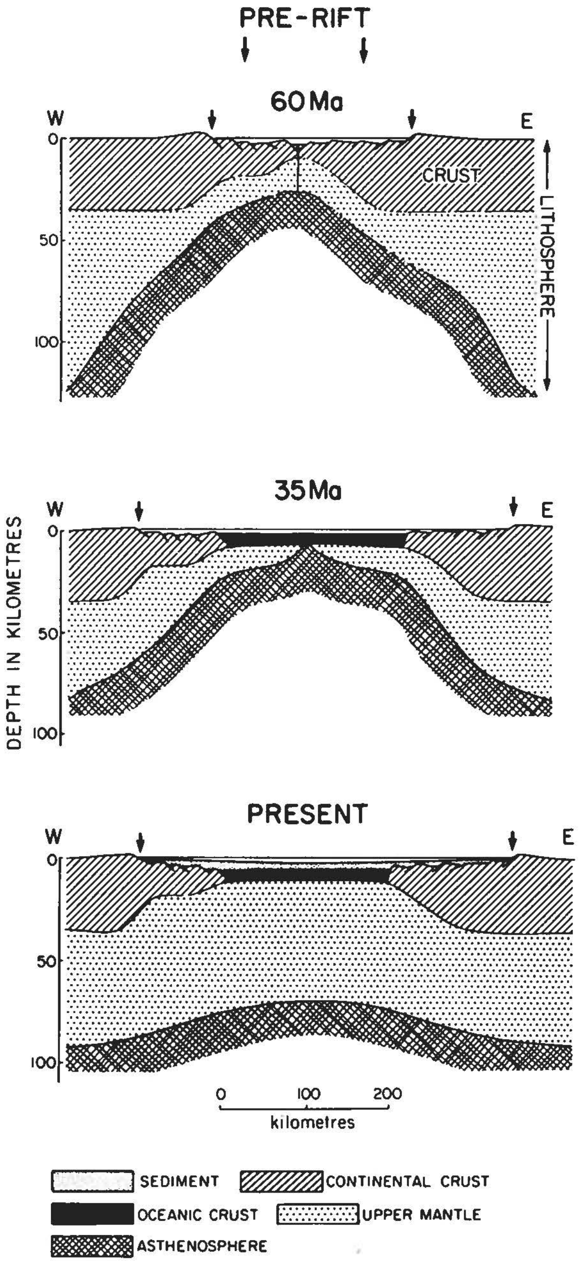

Fig. 3. Schematic representation of three stages in the evolution of Baffin Bay according to our preferred model. Prior to 60 Ma continental rifting between Greenland and Baffin Island occurs. This process may have begun in the Early Cretaceous. The thicknesses of the crust and lithosphere are based on the stretching and thinning parameters given for the continental shelves in Table 2. In particular, note the marginal uplift and initial subsidence of the continental shelves. Sea-floor spreading began about 60 Ma and ceased about 35 Ma ago when Greenland became part of the North American plate. The arrows indicate the amount of horizontal separation attributed to sea-floor spreading and rifting. Since 35 Ma the entire region has been cooling and subsiding, and the lithosphere has been thickening. The total extension of the region is obtained by comparing the separation of the pre-rift arrows with the arrows for 35 Ma.

crust–mantle boundary which is required by the Baffin Bay seismic data, and from the lack of experimental evidence for its occurrence at the temperatures and pressures (Wyllie 1971) which are likely to occur at the shallow mantle depths in Baffin Bay.

Discussion

While the controversy concerning the feasibility of 'oceanization' will undoubtedly continue, it appears to be an unsatisfactory solution to the mode of crustal thinning in central Baffin Bay, where the crust is thin compared to normal oceanic crust. While the three models discussed above can satisfy the basin subsidence, all but the mantle upwelling model require significant lateral motion between Greenland and North America, and therefore do not remove the dilemma created in attempting to reconcile the formation of Baffin Bay with the geological evidence for minimal lateral displacement in the Nares Strait region. The mantle upwelling model suffers from the absence of a realistic mechanism for thinning the crust by 85% from below. While the numerical models we have used are admittedly oversimplified, they do provide reasonable estimates of the subsidence history of the basin and they describe some of the possible alternatives to sea-floor spreading in Baffin Bay. In the absence of a satisfactory oceanization model, we feel compelled to reject these alternative means of forming Baffin Bay and to accept the fact that sea-floor spreading did occur beneath the deep, central basin.

Our preferred model for the formation of Baffin Bay is outlined in Fig. 3. We have assumed that plate tectonic motions and sea-floor spreading occurred between 60 and 35 Ma ago (e.g. Srivastava 1978) and that this was preceded by continental rifting. The rift phase may have begun in the Early Cretaceous as discussed by McWhae (1981) and Peirce (this volume), and probably ended in the Early Paleocene. During this time the present margins of the Bay underwent extension and mantle upwelling. The amount of extension and thinning was most intense near the present ocean–continent boundary and decreased landward. It produced the observed crustal thinning ($\delta = 2$) beneath the shelf of Baffin Island (Jackson et al. 1977, Keen & Hyndman 1979), but little or no crustal change occurred beneath the flanking mainland region. The latter, however, experienced uplift due to the greater lateral extent of mantle upwelling. This uplift is necessary to explain the present uplift of eastern Baffin Island and West Greenland. Sea-floor spreading began about 60 Ma ago, coincident with a major change in spreading direction in the Labrador Sea (Srivastava 1978). The thermal anomaly beneath the adjacent shelf and mainland regions probably began to decay at that time. Given the complicated pattern of the magnetic anomalies in Baffin Bay

(Srivastava 1978, Jackson et al. 1979), the sea-floor spreading mechanism may be somewhat diffuse and is perhaps more similar to that envisioned in back-arc basins (Karig 1971, Isezaki & Uyeda 1973, Isezaki 1975) than to that at most mid-ocean ridge spreading centres. Sea-floor spreading, diffuse or otherwise, formed the deep central part of Baffin Bay and ended about 35 Ma ago. From that time to the present, the entire region has been subsiding.

Geological evidence relating to the timing of the proposed uplift of the mainland regions is sparse and cannot be interpreted unambiguously. In the Davis Strait region, Early Paleocene subaqueous volcanics are now elevated 600 m above sea level, suggesting that uplift occurred after emplacement of these rocks about 57 Ma ago (Parrott & Reynolds 1975). In the Eclipse Trough on Bylot Island, Tertiary (Paleocene?) sediments were deposited in a near-shore marine environment and are now 600 m above sea level (Miall et al. 1980). However, it has proved difficult to establish a reliable age for these sediments. These observations perhaps suggest that the entire coastline of eastern Baffin Island experienced uplift during or since Early Paleocene time. MacLean & Falconer (1979) suggest that the uplift occurred since the Eocene; this would be difficult to reconcile with the timing of tectonic events as proposed here. However, uplift in the Early Paleocene is also consistent with the geological evidence and with the model presented above.

The present amounts of uplift and subsidence predicted for the mainland and shelf regions are given in Table 2. The mainland exhibits a residual amount of its initial uplift. The predicted (500 m) and observed (600 to 800 m) present uplift of eastern Baffin Island agree reasonably well, and this model provides an explanation of the observed topography in that region. Similar uplift is predicted and observed on the Greenland side. Isostatic effects due to glacial rebound are unlikely to exceed 100 m (G. Quinlan, pers. comm. 1980) and we have ignored this relatively short term effect on the subsidence history of the region. Unlike the mainland, the shelf has subsided, and the observed and predicted subsidence are in good agreement.

This composite model provides an excellent explanation of the observed features of the Baffin Bay region. However, the model requires that significant lateral motion (350 km) is produced by crustal extension of the shelves and sea-floor spreading. This must be accommodated to the north of Baffin Bay, primarily during the Tertiary. While some of this extension (perhaps 100 km) can be attributed to graben structures such as Lancaster and Jones Sounds and to the relative motion of Baffin Island and North America, about 250 km of lateral motion is suggested between the Greenland and North American plates.

Difficulties of present pre-drift reconstructions and suggestions for future studies

In a North Atlantic context a probable pre-drift position for Greenland relative to North America and Europe can be derived by closing up the Mesozoic and Cenozoic ocean basins. The geophysical evidence (Bullard et al. 1965, Kristoffersen & Talwani 1977, Sclater et al. 1977, Srivastava 1978, Srivastava & Falconer, this volume) clearly indicates that Greenland moved as a separate plate during the Late Cretaceous and Early Tertiary. We have assumed this to be true in the reconstructions shown in Fig. 4. There is, however, no direct constraint on the position of Ellesmere Island relative to Greenland from these pre-drift reconstructions because the amount of horizontal deformation within the Sverdrup Basin is not well understood. Among the many pre-drift positions for Ellesmere Island which have been proposed (reviewed by Kerr 1980), we have chosen to depict Ellesmere Island against Greenland. In contrast, Srivastava (1978) and others showed a significant gap between them and the implication is that the material in this gap must be destroyed during the opening of the Labrador Sea. As there is no geological evidence to support a subduction zone but there is some evidence for compression (but not enough) in the Sverdrup Basin at the correct time, Peirce (this volume) has argued that the Sverdrup Basin was much wider during the early Mesozoic. If Ellesmere Island and Greenland are juxtaposed, and furthermore if one assumes that significant left-lateral motion occurred on the Wegener Fault in the Tertiary, the pre-drift reconstructions shown in Figs 4a and 4b result. Fig. 4a was obtained using the Bullard et al. (1965) position for Greenland relative to North America, while 4b was derived using Srivastava's (1978) Labrador Sea data to define these positions. If one chooses to allow only minor left-lateral displacement on the Wegener Fault in the Tertiary, then one must choose the Bullard et al. (1965) position for Greenland to avoid overlap of Ellesmere and Devon Islands, as shown in Fig. 4c.

These reconstructions illustrate the difficulties in satisfying both the requirement for minimal offset across Nares Strait and the evidence for some form of sea-floor spreading in Baffin Bay. Fig. 4c demonstrates that it is possible to imagine an initial position of Ellesmere Island relative to Greenland which satisfies the requirement of minimal offset along Nares Strait without overlapping continental blocks. However, if we require that the deep central region of Baffin Bay be closed before sea-floor spreading began there about 60 Ma ago, pre-Tertiary right-lateral motion along Nares Strait is required. This motion could have been reversed by subsequent left-lateral Tertiary motion, resulting in little net offset along the Strait. We do not favour this argument. The closure of Baffin Bay should have

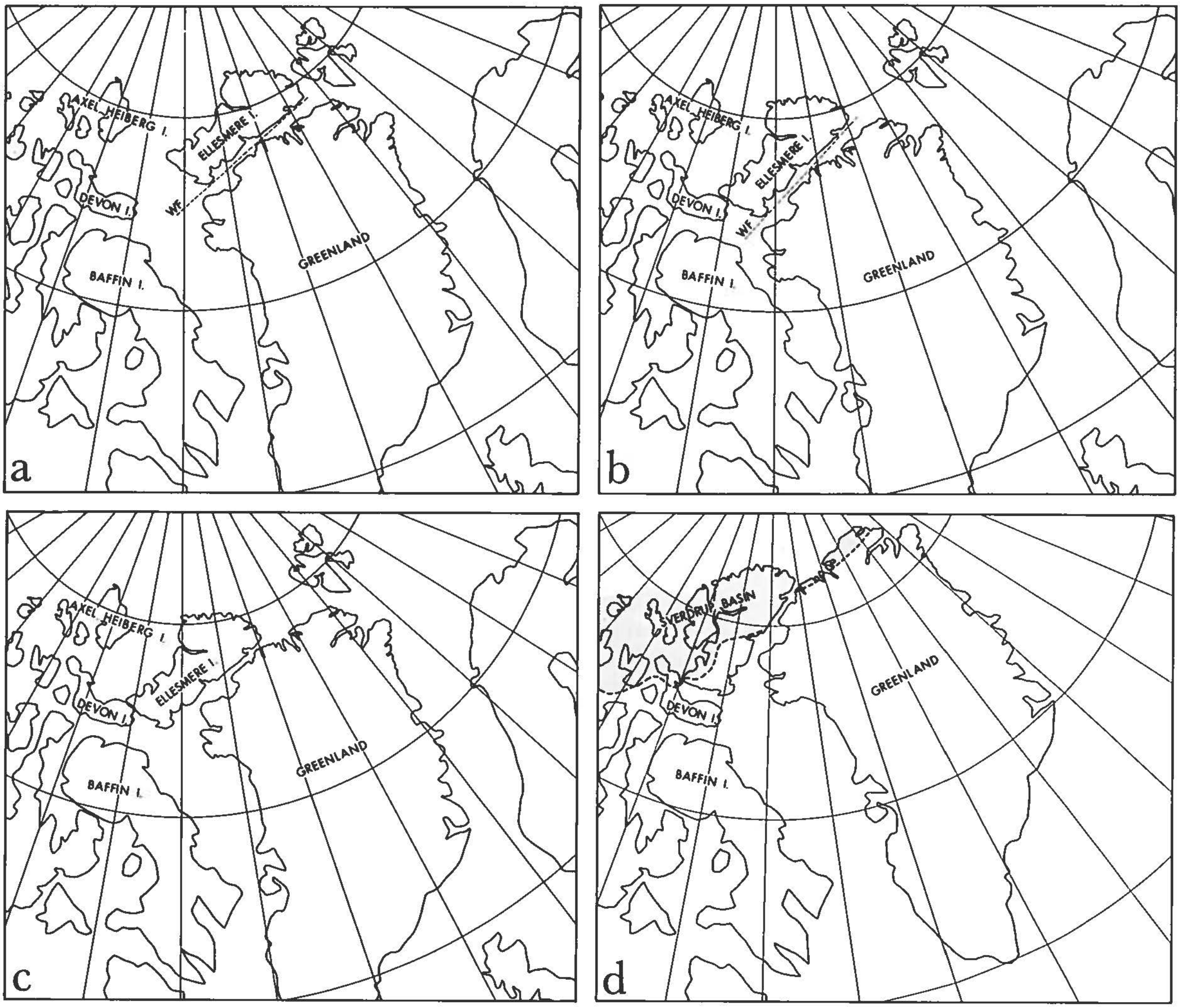

Fig. 4. a. Initial position of Ellesmere Island relative to Greenland assuming the fit of Bullard et al. (1965) for the North Atlantic with Ellesmere Island closely juxtaposed to Greenland. Greenland has been rotated first to the anomaly 25 position of Srivastava (1978), and then Ellesmere Island and Greenland were rotated together to the Bullard et al. (1965) position for Greenland relative to North America. Baffin Island has been rotated 3.8° towards North America about a pole at 70°N, 90°W (Peirce, this volume).

In Fig. 4a,b and c Axel Heiberg Island has been left in its original position and Ellesmere Island has been rotated in its present form to indicate the degree of compression in the Sverdrup Basin during the Eurekan orogeny. The maps are Lambert equal area projections centred at 80°N, 70°W. WF = Wegener Fault.

b. Initial position of Ellesmere Island relative to Greenland using the same rotations as in Fig. 4a except Greenland has been positioned relative to North America according to the anomaly 33 position of Srivastava (1978). Note the difference in the width of Baffin Bay as compared to 4a.

c. Initial position of Ellesmere Island relative to Greenland based on the geological correlations and allowing 25 km of left-lateral motion on the Wegener Fault. Ellesmere Island has been moved 25 km to the northeast and then positioned with Greenland according to the Bullard et al. (1965) fit. This initial fit appears to reconcile the geological evidence with the geophysical evidence, but carrying this picture forward in time requires major right-lateral motion on the Wegener Fault and compression in Baffin Bay. There is no evidence to support the former and some evidence in Baffin Bay indicates extension since the Early Cretaceous.

d. Present geography shown for reference. The present outline of the Palaeozoic and Tertiary fold belts, including the Sverdrup Basin of Canada, is indicated.

caused compression along its margins, and there is no evidence to support this. Indeed, the evidence for graben formation on Bylot Island in the Early Cretaceous (Miall et al. 1980, McWhae 1981) suggests that extension, not compression began at least that early in the region. Similar difficulties apply to the reconstruction of Fig. 4a; Fig. 4b shows Baffin Bay closed, but the 250 km offset along Nares Strait is at odds with most interpretations of the geological data in that region.

We are thus still left with an impasse. We have shown in this paper that alternative geological models which explain the geological and geophysical data in Baffin Bay without sea-floor spreading are either untenable or require almost as much lateral motion between Greenland and North America as the conventional plate tectonic models. Others have shown that the geological data and their correlation across the Nares Strait waterway require less than 25 km of offset across the Strait. Too often the 'solution' to this impasse has been to disregard either one or the other of these apparently conflicting, but well documented, studies. This is no longer acceptable and one must search elsewhere for solutions to this impasse in future studies. The main question which must be addressed concerns the nature and extent of deformation of the continental lithosphere north of Baffin Bay during rifting and spreading to the south.

One possibility is that the Wegener Fault is a fault zone which behaved in a complex manner, rather than a discrete feature as exemplified by the Nares Strait waterway. Several sub-parallel faults may have accommodated the motion at various times, and within this fault zone there may be several fault blocks, some of which may have been rotated. Such a multiplicity of faults occurs along parts of the San Andreas fault system and has been recently observed on the Queen Charlotte Fault (Riddihough 1980). At least one minor strike-slip fault has been observed in eastern Ellesmere Island (Mayr & de Vries, this volume) which could be interpreted as being part of a wide fault zone. Additionally there may be a zone of plastic deformation on either side of the major faults. This type of deformation has been documented near the Alpine Fault in New Zealand (Walcott 1979).

Furthermore, perhaps the amount and nature of the deformation of the continental lithosphere immediately north of Baffin Bay and within the Sverdrup Basin have been underestimated. Good measurements of crustal and sedimentary thicknesses on the shelf and in the sounds north of Baffin Bay would be helpful in estimating the amount of extension in these regions. Quantitative measures are also needed of the net amount of lateral motion in the Sverdrup Basin since the early Mesozoic. One must also ask if the deformation expressed in the surface rocks is a realistic estimate of the deformation at depth, involving the whole lithosphere.

While it is premature to speculate further on alternative interpretations until more evidence is available, we suggest that these and other alternative perspectives need further consideration.

Conclusions

We have considered three possible models to explain the observed subsidence, width, and crustal thickness in Baffin Bay without appealing to a sea-floor spreading origin. The uniform extension model requires nearly as much lateral motion between Greenland and North America as does a sea-floor spreading model, and there are no analogous basins elsewhere in the world which exhibit the high degree of extension required in Baffin Bay. Neither the magmatic intrusion model (which also requires lateral motion) nor the mantle upwelling model can adequately explain the thin crust observed in Baffin Bay. Therefore none of these three geological models offers a realistic alternative to sea-floor spreading as a means of forming the Baffin Bay basin.

Our preferred explanation of the geophysical evidence from Baffin Bay requires a sea-floor spreading origin for the central basin and moderate extension of each continental margin. Total extension of roughly 350 km must be accommodated by motion north of Baffin Bay. It is simplest to propose that most of this motion took place in Nares Strait but this is at odds with the geological data in that region. Geophysically it is possible that this phase of major left-lateral motion has reversed an earlier phase of right-lateral motion, but this seems unreasonable geologically. We suggest that future work might consider the possibility that the Wegener Fault is a fault zone with complex local tectonics rather than a localized, single offset. Also, estimates of the amount of lateral motion which could be accommodated by extension of the continental lithosphere immediately north of the Baffin Bay basin and by compression within the Sverdrup Basin are critical to solving the geological history of this region.

Thus we favour a tectonic history similar to that discussed by Peirce (this volume) for the eastern Arctic. Such a history requires a sea-floor spreading origin for Baffin Bay and the accommodation of significant lateral motion to the north of the basin. We cannot agree that Baffin Bay was formed by extension, subsidence and modification of continental crust. The Nares Strait dilemma cannot be solved in this manner because large, probably unrealistic amounts of crustal thinning are required. We recognize that an interpretation of the geology around Nares Strait which favours minimal Tertiary motion is compelling. We are not able to offer an alternative interpretation; we only suggest different perspectives which may be promising. The challenge remains to develop fully a unified model which is consistent both with the geophysical evidence in Baffin Bay and the North Atlantic *and* with the geological evidence in Nares Strait.

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References

Ahern, J. L. & Turcotte, D. L. 1979. Magma migration beneath an ocean ridge. – Earth planet. Sci. Lett. 45: 115–122.

Berckhemer, H., Baier, B., Bartelsen, H., Behle, A., Burkhardt, H., Gebrande, H., Makris, J., Menzel, H., Miller, H. & Vees, R. 1975. Deep seismic soundings in the Afar region and on the highland of Ethiopia. – In: Pilger, A. & Rösler, A. (eds), Afar Depression of Ethiopia: 89–107. – Schweizerbart, Stuttgart.

Biju-Duval, B., Dercourt, J. & Le Pichon, X. 1977. From the Tethys ocean to the Mediterranean seas: a plate tectonic model of the evolution of the western Alpine system. – In: Biju-Duval, B. & Montadert, L. (eds), Structural history of the Mediterranean basins: 143–164. – Éditions Technip, Paris.

Bullard, E., Everett, J. E. & Smith, A. G. 1965. The fit of the continents around the Atlantic. – In: Blackett, P. M. S., Bullard, E. & Runcorn, S. K., A symposium on continental drift. – Phil. Trans. Roy. Soc. Lond. 258A: 41–51.

Dawes, P. R. & Kerr, J. W. 1982. The case against major displacement along Nares Strait. – This volume.

Dawes, P. R., Frisch, T. & Christie, R. L. 1982. The Proterozoic Thule Basin of Greenland and Ellesmere Island: importance to the Nares Strait debate. – This volume.

Edel, J. B., Fuchs, K., Gelbke, C. & Prodehl, C. 1975. Deep structure of the southern Rhinegraben area from seismic refraction investigation. – J. Geophys. 41: 333–356.

Ewing, G. N., Dainty, A. M., Blanchard, J. E. & Keen, M. J. 1966. Seismic studies on the eastern seaboard of Canada: the Appalachian system. 1. – Can. J. Earth Sci. 3: 89–109.

Forsyth, D. A., Mair, J. A. & Fraser, I. 1979. Crustal structure of the central Sverdrup Basin. – Can. J. Earth Sci. 16: 1581–1598.

Frisch, T. & Dawes, P. R. 1982. The Precambrian Shield of northernmost Baffin Bay: correlation across Nares Strait. – This volume.

Higgins, A. K., Mayr, U. & Soper, N. J. 1982. Fold belts and metamorphic zones of northern Ellesmere Island and North Greenland. – This volume.

Hurst, J. M. & Kerr, J. W. 1982. Upper Ordovician to Silurian facies patterns in eastern Ellesmere Island and western North Greenland and their bearing on the Nares Strait lineament. – This volume.

Isezaki, N. 1975. Possible spreading centers in the Japan Sea. – J. Mar. geophys. Res. 2: 265–277.

Isezaki, N. & Uyeda, S. 1973. Geomagnetic anomaly of the Japan Sea. – J. Mar. geophys. Res. 2: 51–59.

Jackson, H. R., Keen, C. E. & Barrett, D. L. 1977. Geophysical studies on the eastern continental margin of Baffin Bay and in Lancaster Sound. – Can. J. Earth Sci. 14: 1991–2001.

Jackson, H. R., Keen, C. E., Falconer, R. K. H. & Appleton, K. P. 1979. New geophysical evidence for sea-floor spreading in central Baffin Bay. – Can. J. Earth Sci. 16: 2122–2135.

Jarvis, G. T. & McKenzie, D. P. 1980. Sedimentary basin formation with finite extension rates. – Earth planet. Sci. Lett. 48: 42–52.

Karig, D. E. 1971. Origin and development of marginal basins in the western Pacific. – J. geophys. Res. 76: 2542–2560.

Keen, C. E. & Barrett, D. L. 1972. Seismic refraction studies in Baffin Bay: an example of a developing ocean basin. – Geophys. J. Roy. astr. Soc. 30: 253–271.

Keen, C. E. & Barrett, D. L. 1981. Thinned and subsided continental crust on the rifted margin of eastern Canada: crustal structure, thermal evolution, and subsidence history. – Geophys. J. Roy. astr. Soc.: 65: 443–465.

Keen, C. E. & Hyndman, R. D. 1979. Geophysical review of the continental margins of eastern and western Canada. – Can. J. Earth Sci. 16: 712–747.

Keen, C. E., Keen, M. J., Ross, D. I. & Lack, M. 1974. Baffin Bay: small ocean basin formed by sea-floor spreading. – Bull. Am. Ass. Petrol. Geol. 58: 1089–1108.

Kerr, J. W. 1980. Did Greenland drift along Nares Strait? – Bull. Can. Petrol. Geol. 28: 279–283.

Kerr, J. W. 1981. Evolution of the Canadian Arctic Islands: a transition between the Atlantic and Arctic Oceans. – In: Nairn, A. E. M., Churkin, M. & Stehli, F. G. (eds), The ocean basins and margins 5, The Arctic Ocean: 105–199. – Plenum Press, New York & London.

Kosminskaya, I. P. & Pavlenkova, N. I. 1979. Seismic models of inner parts of the Euro-Asian continent and its margins. – Tectonophysics 59: 307–320.

Kristoffersen, Y. & Talwani, M. 1977. Extinct triple junction south of Greenland and the Tertiary motion of Greenland relative to North America. – Bull. geol. Soc. Am. 88: 1037–1049.

Long, R. E., Sundaralingam, K. & Maguire, P. K. H. 1973. Crustal structure of the East African rift zone. – Tectonophysics 20: 269–281.

Louden, K. E. 1980. The crustal and lithosphere thicknesses of the Philippine Sea as compared to the Pacific. – Earth planet. Sci. Lett. 50: 275–288.

MacLean, B. & Falconer, R. K. H. 1979. Geological/geophysical studies in Baffin Bay and Scott Inlet-Buchan Gulf and Cape Dyer-Cumberland Sound areas of the Baffin Island Shelf. – Pap. geol. Surv. Can. 79–1B: 231–244.

Makris, J. 1978. The crust and upper mantle of the Aegean region from deep seismic soundings. – Tectonophysics 46: 269–284.

Mayr, U. & de Vries, C. D. S. 1982. Reconnaissance of Tertiary structures along Nares Strait, Ellesmere Island, Canadian Arctic Archipelago. – This volume.

McKenzie, D. P. 1978. Some remarks on the development of sedimentary basins. – Earth planet. Sci. Lett. 40: 25–32.

McWhae, J. R. H. 1981. Structure and spreading history of the northwestern Atlantic region from the Scotian Shelf to Baffin Bay. – In: Kerr, J. W. & Fergusson, A. J. (eds), Geology of the North Atlantic borderlands. – Mem. Can. Soc. Petrol. Geol. 7: 299–332.

Miall, A. D., Balkwill, H. R. & Hopkins, W. S. 1980. Cretaceous and Tertiary sediments of Eclipse Trough, Bylot Island area, Arctic Canada, and their regional setting. – Pap. geol. Surv. Can. 79–23: 20 pp.

Montadert, L., de Charpal, O., Roberts, D., Guennoc, P. & Sibuet, J.-C. 1979. Northeast Atlantic passive continental margins: rifting and subsidence processes. – In: Talwani, M., Hay, W. & Ryan, W. B. F. (eds), Deep drilling results in the Atlantic Ocean: continental margins and paleoenvironment: 154–186. – Am. geophys. Un., Washington, D. C.

Neprochnov, Yu. P., Kosminskaya, I. P. & Malovitsky, Ya. P. 1970. Structure of the crust and upper mantle of the Black and Caspian Seas. – Tectonophysics 10: 517–538.

Parrott, R. J. E. & Reynolds, P. H. 1975. Argon-40/Argon-39 geochronology: age determinations of basalts from the Labrador Sea area. – Geol. Soc. Am. Abs. with Prog. 7: 835 only.

Parsons, B. & Sclater, J. G. 1977. An analysis of the variation of ocean floor bathymetry and heat flow with age. – J. geophys. Res. 82: 802–827.

Peel, J. S. & Christie, R. L. 1982. Cambrian–Ordovician platform stratigraphy: correlations around Kane Basin. – This volume.

Peel, J. S., Dawes, P. R., Collinson, J. D. & Christie, R. L. 1982. Proterozoic – basal Cambrian stratigraphy across Nares Strait: correlation between Inglefield Land and Bache Peninsula. – This volume.

Peirce, J. W. 1982. The evolution of the Nares Strait lineament and its relation to the Eurekan orogeny. – This volume.

Riddihough, R. P. 1980. Recent plate tectonics along Canada's west coast. – Geol. Ass. Can., Min. Ass. Can. Prog. with Abs. 5: 78 only.

Royden, L. & Keen, C. E. 1980. Rifting process and thermal evolution of the continental margin of eastern Canada determined from subsidence curves. – Earth planet. Sci. Lett. 51: 343–361.

Royden, L., Sclater, J. G. & von Herzen, R. P. 1980. Continental margin subsidence and heat flow: important parameters in formation of petroleum hydrocarbons. – Bull. Am. Ass. Petrol. Geol. 64: 173–187.

Ruffman, A. [S.] & Keen, M. J. 1967. A time-term analysis of the first arrival data from the seismic experiment in Hudson Bay, 1965. – Can. J. Earth Sci. 4: 901–928.

Sclater, J. G. & Christie, P. A. F. 1980. Continental stretching: an explanation of the post-mid-Cretaceous subsidence of the central North Sea Basin. – J. geophys. Res. 85: 3711–3739.

Sclater, J. G., Anderson, R. N. & Bell, M. L. 1971. The elevation of ridges and the evolution of the central eastern Pacific. – J. geophys. Res. 76: 7888–7915.

Sclater, J. G., Hellinger, S. & Tapscott, C. 1977. The paleobathymetry of the Atlantic Ocean from the Jurassic to the present. – J. Geol. 85: 509–552.

Sclater, J. G., Royden, L., Horvath, F., Burchfiel, B. C., Semken, S. & Stegena, L. 1980. Subsidence and thermal evolution of the intra-Carpathian Basins. – Earth planet. Sci. Lett. 51: 139–162.

Sleep, N. H. 1971. Thermal effects of the formation of Atlantic continental margins by continental break-up. – Geophys. J. Roy. astr. Soc. 24: 325–350.

Srivastava, S. P. 1978. Evolution of the Labrador Sea and its bearing on the early evolution of the North Atlantic. – Geophys. J. Roy. astr. Soc. 52: 313–357.

Srivastava, S. P. & Falconer, R. K. H. 1981. Nares Strait: a conflict between plate tectonic predictions and geological interpretation. – This volume.

van Bemmelen, R. W. 1972. Geodynamic models. An evaluation and synthesis. – Developments in geotectonics 2. – Elsevier Publ. Co., Amsterdam: 267 pp.

Walcott, R. I. 1979. Plate motion and shear strain rates in the vicinity of the southern Alps. – In: Walcott, R. I. & Cressell, M. M. (eds), The origin of the southern Alps. – Bull. Roy. Soc. N. Z. 18: 5–12.

Watts, A. B. & Ryan, W. B. F. 1976. Flexure of the lithosphere and continental margin basins. – Tectonophysics 36: 25–44.

Wyllie, P. J. 1971. The dynamic Earth. – J. Wiley & Sons, New York: 416 pp.