Fragmentation of the Canadian Arctic Archipelago, Greenland, and surrounding oceans

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Fragmentation of the Canadian Arctic Archipelago, Greenland and surrounding ocean basins is indicated mainly by a pattern of northeast-trending fractures and northwest-trending arches and rifts. Based on a comparison of this structural pattern with experimentally produced fracture patterns, a new evolutionary concept for the Cenozoic era is proposed for the region. The Eurasia Basin and North Atlantic sea-floors developed as rift-generated tensional zones separated by a later developed dextral transform shear zone, here named the Nansen Shear Zone. Sub-parallel to and some 2000 km southwest of this shear couple is another less well-developed system comprised of M'Clure Strait and Baffin Bay which were initiated by rifting and later connected by a dextral transform shear zone, here named the Parry Channel Shear Zone. The landmass between these two transform couples (Greenland and the Queen Elizabeth Islands) probably was and is acted upon by a sinistral force couple as a result of spreading between these couples and is probably partially responsible for generating internal deviatoric tensional and compressional stresses noted from earthquake data. Fractures and arch axes within the Queen Elizabeth Islands have similar directions to respective features within the North Atlantic sea-floor; stresses may have similar orientations in both regions.

Nares Strait may be a poorly-developed sinistral transform shear zone that joins rift-generated ocean basins: the Eurasia Basin to the north and Baffin Bay to the south.

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A fragmentation model for the region of the Canadian Arctic Archipelago, Greenland, and adjacent ocean areas is proposed on the basis of analogy with experimental results from Brown (1928) and Riedel (1929) summarized by De Sitter (1956); this fragmentation has occurred during and since the time of the Eurekan Deformation in the Cenozoic. In particular the azimuths of arches, fractures and rifts are utilized to interpret palaeostress fields that in turn may provide constraints on the evolution of the region. As well, the variation in thicknesses of the crystalline crust below sedimentary basins such as the Sverdrup Basin is considered to indicate possible stress directions and behaviour of crustal development. Theoretical calculation of the stress field from earthquake data for the Beaufort Sea region and Byam Martin Channel area in the Queen Elizabeth Islands (Hasegawa 1977, Hasegawa et al. 1979) also provides additional support for the model.

The fragmentation concept, here applied to the last 60 Ma or so, advocates that a northeastern piece of the North American plate (about 2000 km wide) split along two boundaries — one in the North Atlantic Ocean – eastern Arctic Ocean and the other in Baffin Bay – Parry Channel – M'Clure Strait (Fig. 1). These boundaries are considered to consist of early developed tensional rift zones at either end of a later developed dextral transform shear zone as described in this paper. The landmass between these boundaries (Queen Elizabeth Islands and Greenland) was fractured primarily by northeast-trending faults, grabens and troughs and was affected by northwest-trending uplifts, ridges, arches and folds.

Locations of fractures, arches and rifts are shown on a polar stereographic projection for a portion of the Arctic region in order to compare general trends and similarities. Azimuths of these features are taken from an arbitrary rectangular coordinate system superimposed on the polar stereographic projection. This paper does not utilize spherical geometry. It is considered unnecessary because the error in azimuths is about one degree using the rectangular coordinate system laid over the polar stereographic projection. Thus this method does not jeopardize the azimuths and arguments used throughout this paper.

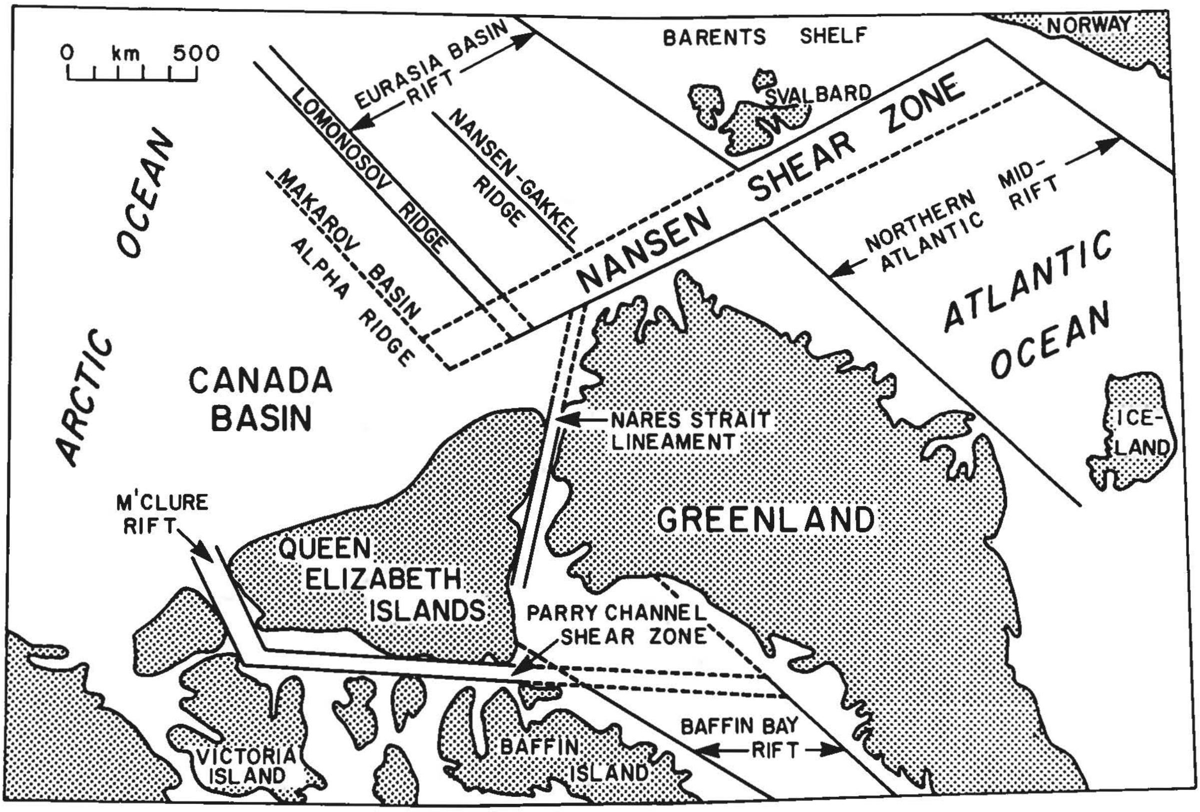

Fig. 1. Location map of major rift and shear zones of the Arctic region. Eurasia Basin Rift – Nansen Shear Zone – Northern mid-Atlantic Rift form one well-developed dextral transform couple, and M'Clure Rift – Parry Channel Shear Zone – Baffin Bay Rift form a poorly-developed dextral transform couple. The Nares Strait Lineament joins these two transform couples in two triple junctions, perhaps as a sinistral transform couple.

Geological and tectonic setting

The study region (Fig. 1) includes the Canadian Arctic Archipelago, Greenland and the neighbouring parts of the Atlantic and Arctic Oceans and Baffin Bay. The archipelago (Figs 2 and 3, Kerr 1981) formed from several major depositional subsiding basins laid in an overlapping fashion more or less one above the other on a Precambrian continental crystalline basement; the basins are progressively younger toward the north. Before and during the major period of deposition of the Franklinian Geosyncline and the Sverdrup Basin two prominent structural highs persisted. The Boothia Uplift has a north–south strike normal to the axis of the future Sverdrup Basin and a northward plunge. The Pearya Geanticline has a northeast strike, sub-parallel to the axis and was a magmatically quiet zone during the formation of the Sverdrup Basin. The Cornwallis Fold Belt (Kerr 1977), which developed prior to and during the Ellesmerian Orogeny in four pulses of uplift that together constitute the Cornwallis Disturbance, lies sub-parallel to and over the northern end of the Boothia Uplift. The Ellesmerian Orogeny also produced structural features normal (Rens Fiord Uplift, Fig. 2) and sub-parallel (Minto Arch, Parry Islands Fold Belt, Ellesmere–Greenland Fold Belt, and the northern Ellesmere Fold Belt, Fig. 2) to the future axis of the Sverdrup Basin.

The Sverdrup Basin developed in various phases after the Ellesmerian Orogeny as a subsiding basin (Sweeney 1977) commencing in Early Mississippian time (Balkwill 1978); basin development ended with the Eurekan Orogeny in the mid-Tertiary. Sweeney (op. cit.) proposed that initial subsidence was partly due to lithospheric cooling but later subsidence episodes were initiated by extensional forces operating in the Triassic and in late Early Cretaceous time. These forces resulted in the downdropping of graben blocks beneath the basin. Balkwill (1978) suggested that crustal foundering accompanied by fracturing and tapping of upper mantle fluids prompted primary subsidence and enlargement of basin space. Basalt flows and mafic dykes and sills are systematically intercalated with and transect all but the Cenozoic sediments of the Sverdrup Basin. Many of these dykes are coextensive with faults or are sub-parallel to local faults, folds, uplifts and arches, de-

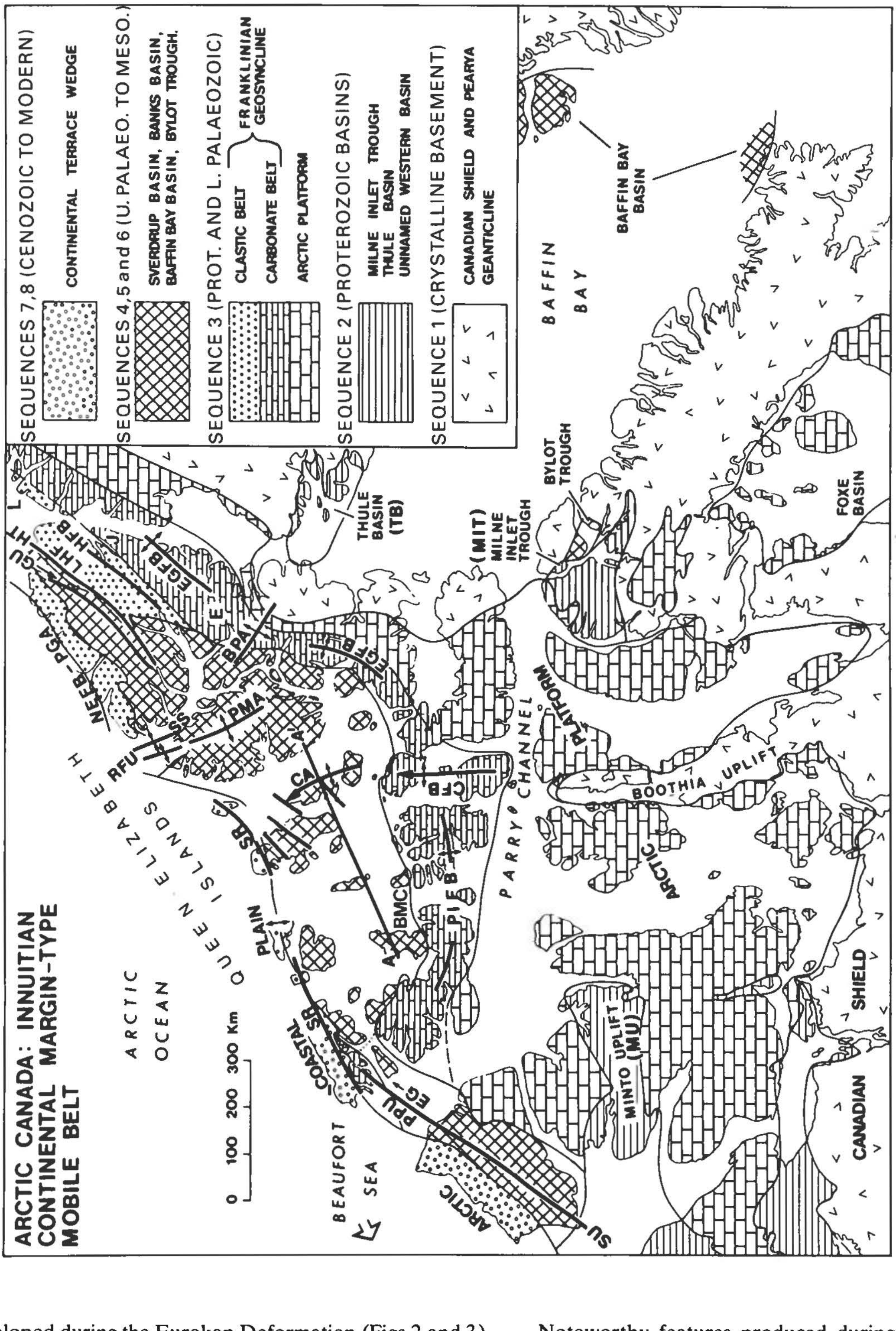

Fig. 2. Structures and structural provinces of the Canadian Arctic Archipelago (after Kerr 1981). A–A′ is location of profile shown in Fig. 4. BMC = Byam Martin Channel, BPA = Bache Peninsula Arch, CA = Cornwall Arch, CFB = Cornwallis Fold Belt, E = Ellesmere Island, EG = Eglinton Graben, EGFB = Ellesmere–Greenland Fold Belt, GU = Grantland Uplift, HFB = Hazen Fold Belt, HT = Hazen Trough, J = Judge Daly Promontory, L = Lincoln Sea, LHF = Lake Hazen Fault, NEFB–PGA = Northern Ellesmere Fold Belt–Pearya Geanticline, PIFB = Parry Islands Fold Belt, PMA = Princess Margaret Arch, PPU = Prince Patrick Uplift, RFU = Rens Fiord Uplift, SR = Sverdrup Rim, SS = Svartevaeg Syncline, SU = Storkerson Uplift.

veloped during the Eurekan Deformation (Figs 2 and 3) (Balkwill & Bustin 1980) and in places these overlie similar tectonic features produced by the older Ellesmerian Orogeny.

Noteworthy features produced during the development of the Queen Elizabeth Islands include variations in crustal thickness and an inverse relationship between thicknesses of sediments and crystalline crustal rocks.

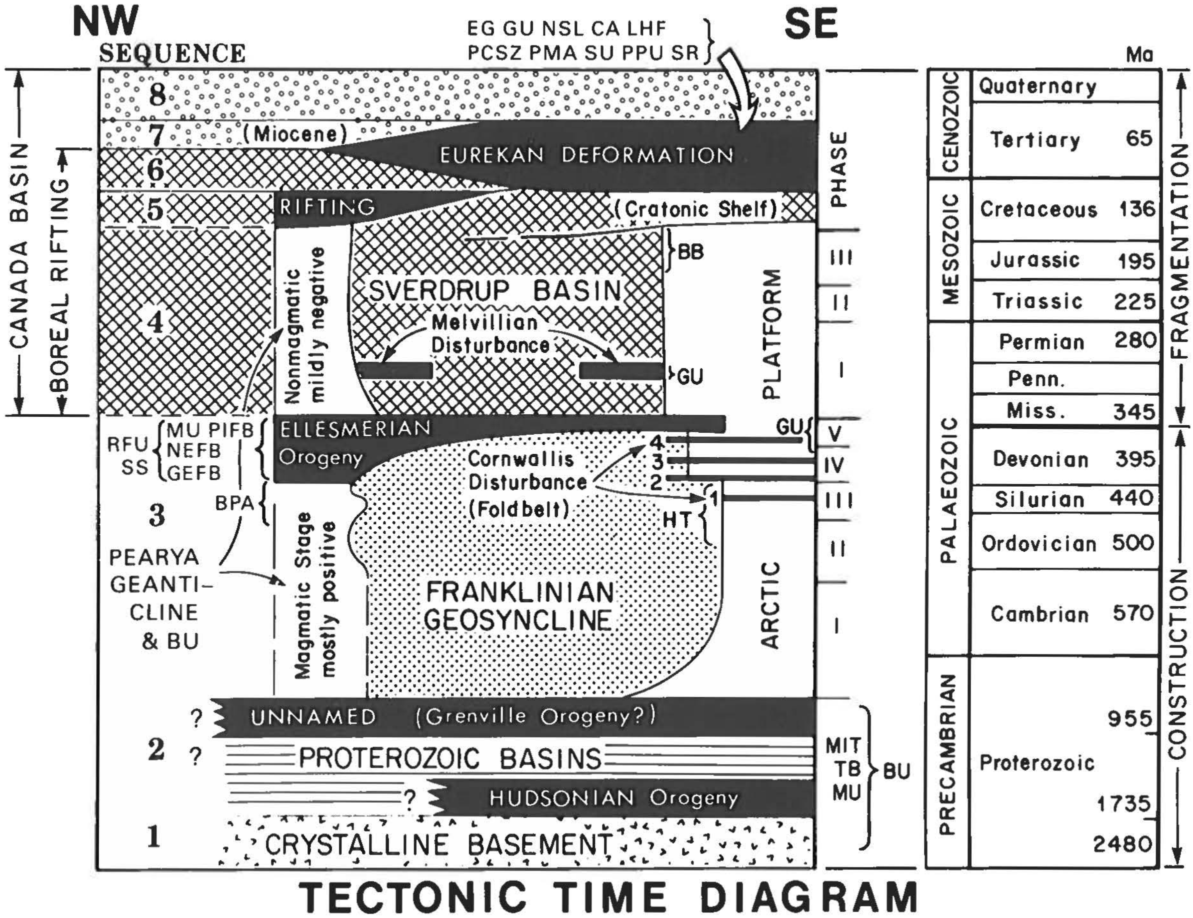

Fig. 3. Tectonic time diagram for the Canadian Arctic Islands (after Kerr 1980a) which resembles a cross-section. The stippled, cross-hatched and circled ornaments show regions where there was continuous or nearly continuous sedimentation. The solid black pattern indicates tectonic events with widespread unconformities. See Figs 2 and 7 for explanation of abbreviations.

The latter feature is a product of isostatic compensation. Oceanward crustal thinning below passive continental margin basins has also been advocated (Sobczak & Weber 1973, Sobczak 1975a, b) with the mass deficiency of the water and sediments being isostatically compensated by a mantle anti-root according to the Airy hypothesis. Analysis of gravity and seismic data for the Sverdrup Basin area (Sobczak & Overton in prep.) suggests that the sediments and water are compensated regionally by a mantle anti-root, and that the crystalline crust thins below the thickest sedimentary section and thickens towards the thinner sections in the axial region of the basin (Fig. 4). The seismic results also suggest that folds (long wavelength undulations) are prominent at the crust–mantle boundary along the axis of the basin. These features can be explained by a crust which was stretched by tensional forces perpendicular to the continental margin and folded, probably simultaneously, by compressional forces along the axis of the basin. Tensional forces caused necking of the crystalline crust whereby the top sagged (tectonic subsidence) and became a repository for sediments (loading subsidence) and the bottom arched upward to be replaced by mantle material in accordance with isostasy.

During and after the Eurekan Deformation, fragmentation was active in the oceanic areas of the North Atlantic Ocean and Baffin Bay. The evolution of the North Atlantic Ocean has been described by Grønlie et al. (1979) who have summarized the work of several authors including, in particular, that of Talwani & Eldholm (1977). The principal structural elements involved are numbered in Fig. 5 and listed with Fig. 7. Sea-floor spreading along the Mohns Ridge (#16, #13) has been more complex. In the latter area at least two spreading centres, now extinct, are believed to have been active before the establishment, about 10 Ma ago, of the presently spreading Iceland – Jan Mayen Ridge (# 18). One of the extinct axes (#14) located in the Norway Basin was active between 55 and 26 Ma ago after which period a new spreading axis developed to the west be-

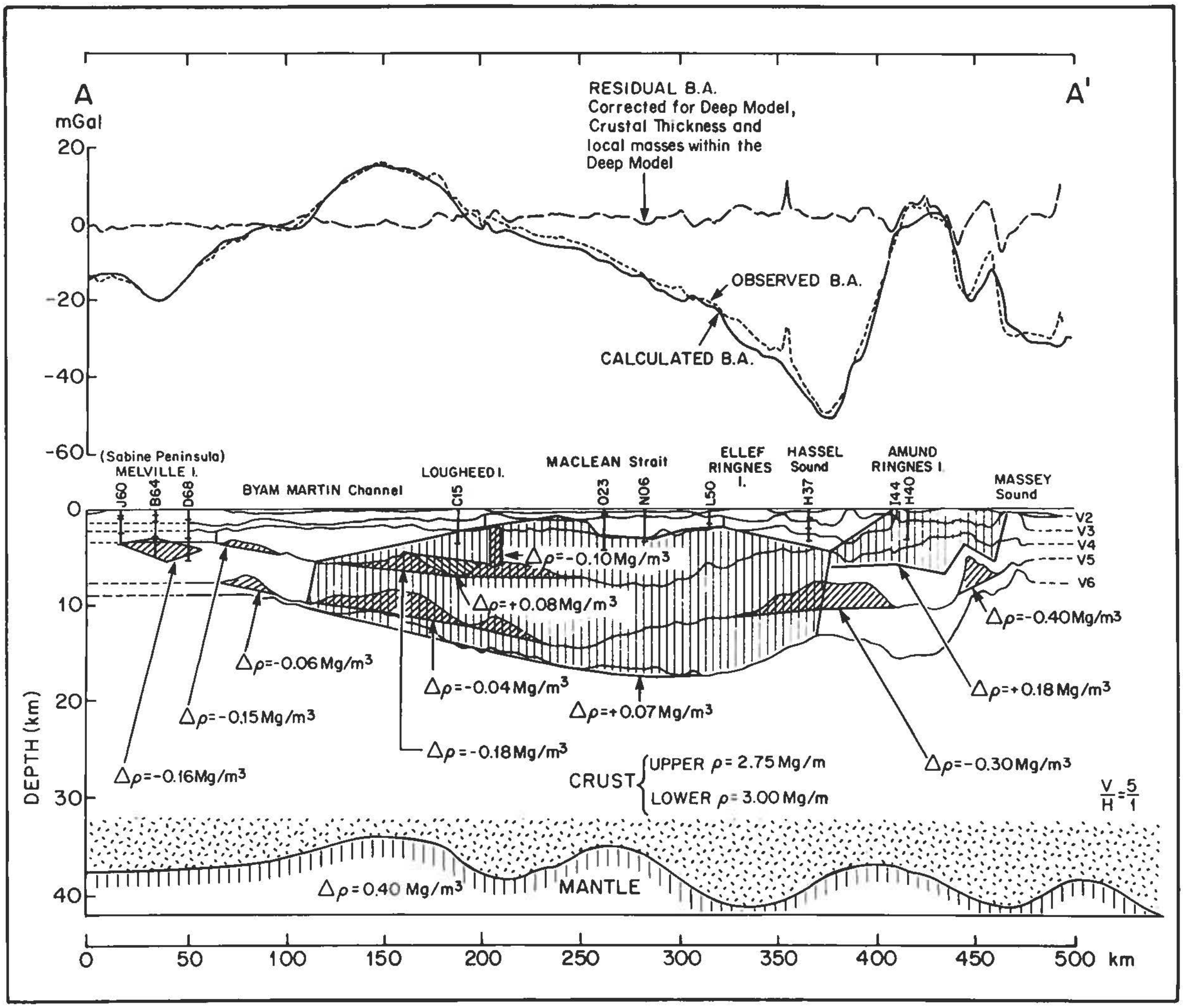

Fig. 4. Profile A–A′ shows observed modified Bouguer anomaly, calculated anomaly and corrected anomaly for all masses combined: Sobczak & Overton's (in prep.) deep model for Sverdrup Basin (layers 1 to 3) and Franklinian Geosyncline (layers 4 and 5), Forsyth et al.'s (1979) crust–mantle model, and local masses indicated by seismic and gravity data. The sedimentary thickness varies from 9 to 17.4 km, the crystalline continental thickness varies from 18 to 33 km and the total crustal thickness varies from 34 to 42 km (Sobczak & Overton in prep.). For location of profile see Fig. 2.

tween 23 and 17 Ma ago, forming the Jan Mayen Ridge (#17) which is considered to include a piece of Greenland (Grønlie et al. 1979). North of the Greenland Fracture Zone sea-floor spreading along the Knipovich Ridge (#9) has been active since about 36 Ma ago. No major opening existed before that time and motion between Greenland and Svalbard was primarily one of shear along the Greenland (#8) and Senja (#11) Fracture Zones.

For the Baffin Bay area, Jackson et al. (1977, 1979) have presented geophysical evidence which supports the existence of oceanic crust formed by sea-floor spreading in the central part of the bay. Preliminary magnetic evidence suggests that sea-floor spreading occurred between approximately 38 to 60 Ma ago along an extinct axis (#22) along the centre of the bay that is probably related to a negative gravity anomaly.

Since the end of the Eurekan Deformation (about 20 Ma ago) the Queen Elizabeth Islands area has been relatively stable (Kerr 1981). Recent crustal activity is indicated by earthquakes recorded during the period 1908 to 1975 (Basham et al. 1977, Wetmiller & Forsyth 1978). The epicentres appear to be concentrated over the northwestern continental margin where thick sedimentary basins are developing (Sobczak 1975a, b) over older structures such as the Sverdrup Rim (#48) and Boothia Uplift (#26) and over basin areas such as Baffin Bay and Sverdrup Basin (Byam Martin Channel area). For the Byam Martin Channel area Forsyth et al. (1979) have described various geophysical features

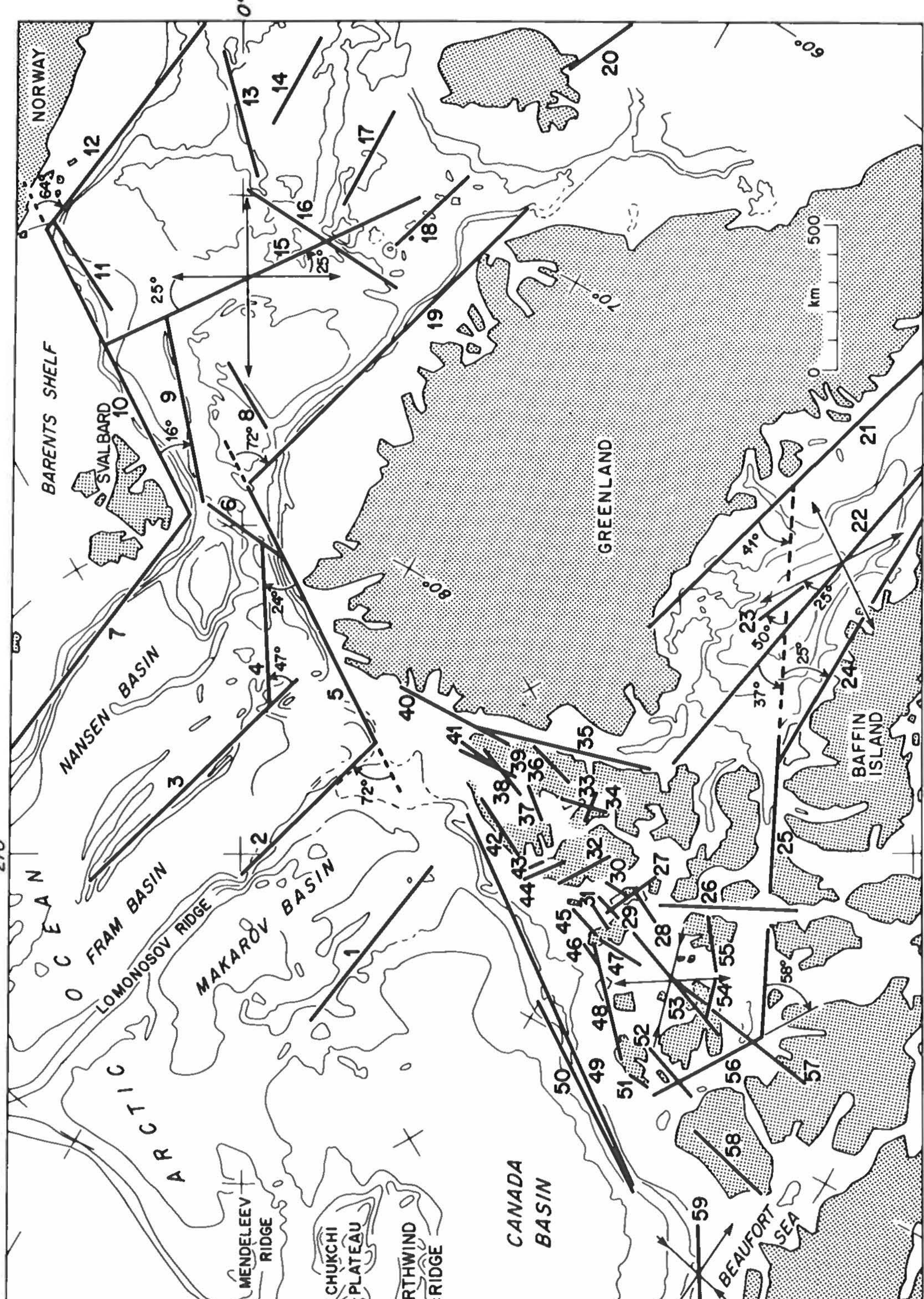

Fig. 5. Location of features on the northeastern part of the North American plate and surrounding oceans. In the text and Fig. 7 the azimuths of numbered structural features are taken relative to a local rectangular co-ordinate system in which 0° is towards the top of the figure, 180° towards the bottom, 90° towards the right side and 270° towards the left side. Bathymetric contours are 500, 1000, 2000 m, etc. See Fig. 7 for key to numbered features.

trending northeast such as the Byam Martin Channel earthquake swarm (#57, Hasegawa 1977) and magnetic linears (#46, 47, 53, Reford 1967) which are coextensive with mafic dykes and faults.

Terminology

Structural features discussed in this paper have been grouped into two broad categories, viz. fractures and arches. *Fractures* include all types of breaks at the surface of the crust such as 1) faults (all types with minor displacements), 2) rifts (zones of breaks) where adjacent crustal blocks have been displaced from an initial fault in a direction normal to the fault(s), usually over considerable distances (>100 km); these include rift-generated ocean basins bounded by continental margins which were the original zones of rifts, 3) shear zones, in which adjacent crustal blocks have been translated relative to one another in a direction parallel to an initial fault or fault zone between them and may be separated by faults with accompanying grabens > 50 km wide. *Arches* is applied here very generally as a term to include 1) mid-oceanic ridges (upwelling of mantle material), 2) uplifted areas (e.g. Boothia Uplift), and 3) antiformal structures.

Large-scale structural features are shown in Fig. 1 and are named as follows: 1) Eurasia Basin Rift, a rift-generated ocean basin, extends in width from the Lomonosov Ridge to the Barents Shelf and includes the Fram Basin, Nansen Basin and Nansen–Gakkel Ridge, 2) Northern mid-Atlantic Rift, another rift-generated ocean basin, extends in width from Greenland to Norway and includes most of the region of the northern Atlantic Ocean, 3) Nansen Shear Zone extends between Svalbard and Greenland, 4) Baffin Bay Rift, a proposed rift-generated bay, is the deeper portion of the Baffin Bay between Greenland and Baffin Island, 5) M'Clure Rift, which occurs along M'Clure Strait, forms the western portion of the Parry Submarine Rift Valley (Kerr 1981) and is here divided into a rift zone (M'Clure Rift) and a shear zone, Parry Channel Shear Zone. The M'Clure Rift is considered an incipient rift zone because probably little normal separation has taken place and no oceanic crust occurs in the middle of the strait, 6) Parry Channel Shear Zone is considered to extend along Parry Channel from M'Clure Strait to Baffin Bay and includes both the eastern portion of Parry Submarine Rift Valley and the Lancaster Aulacogen (Kerr 1981). The geological data used by Kerr (1981) to define the Parry Submarine Rift Valley and the Lancaster Aulacogen may also apply to a shear zone. For example, in the Lancaster Aulacogen faulted sediments are overlain by undeformed sediments and the uppermost 2 km of the sedimentary section are not cut by major faults. Some of the faults die out upwards, so there are folds rather than faults near surface but the uppermost part of the column is not folded. Thus the faults originated at depth and were propagated upwards and could be interpreted in terms of Brown's and Riedel's shear zone model discussed below.

Rifts and shear zone models

Experiments on shear zones have revealed some interesting facts which appear to apply to the regions of the Eurasia Basin, northern Atlantic Ocean, Baffin Bay, Parry Channel and M'Clure Strait. Brown (1928) and Riedel (1929), as discussed in De Sitter (1956), showed in their experiments with wet clay or paraffin-petroleum jelly mixture on two wooden blocks (Fig. 6a) that a shearing motion originating at the bottom of the mixture propagated upward in a wedge-shaped zone widening towards the surface. The first cracks observed on the surface were obviously tension cracks making a 45° to 47° angle with the shear plane (Fig. 6a). These cracks rotated during movement, increasing the angle to 50° or 60°. The tension cracks were parallel to the principal normal stress produced by the applied shearing stress. After the development of the tension cracks a zone of shear developed at the surface in which a second set of cracks developed at angles of 10° to 15° to the direction of shear.

These experimental structures appear to be analogous to observed, well-developed features in the North Atlantic region and to similar less clearly developed features in the Canadian Arctic Archipelago. Thus, in spite of the great differences in the elastic parameters of the crust and those of the experimental media there appears to be justification for drawing an analogy between the patterns and nature of faults produced in models and observed in the crust.

Eurasia Basin – Northern mid-Atlantic Rift system

The Eurasia Basin – Northern mid-Atlantic Rift system is well developed and about 57 Ma old (Grønlie et al. 1979). The edges of these rifts and the transform shear zone that joins them are approximated by straight lines drawn along the shelf breaks (Figs 1 and 5). These rift edges are taken to be analogous to the tension cracks in Brown's and Riedel's experiments. If their history followed this model the Eurasia Basin Rift and Northern mid-Atlantic Rift developed 57 Ma ago, initially at an angle of about 45° to the shear zone (Fig. 6b) and rotated during spreading to their present positions which make angles of 64° to 72° with respect to the Nansen Shear Zone (Fig. 6c) which developed later on the surface around 36 Ma ago (Fig. 5). In addition, two frac-

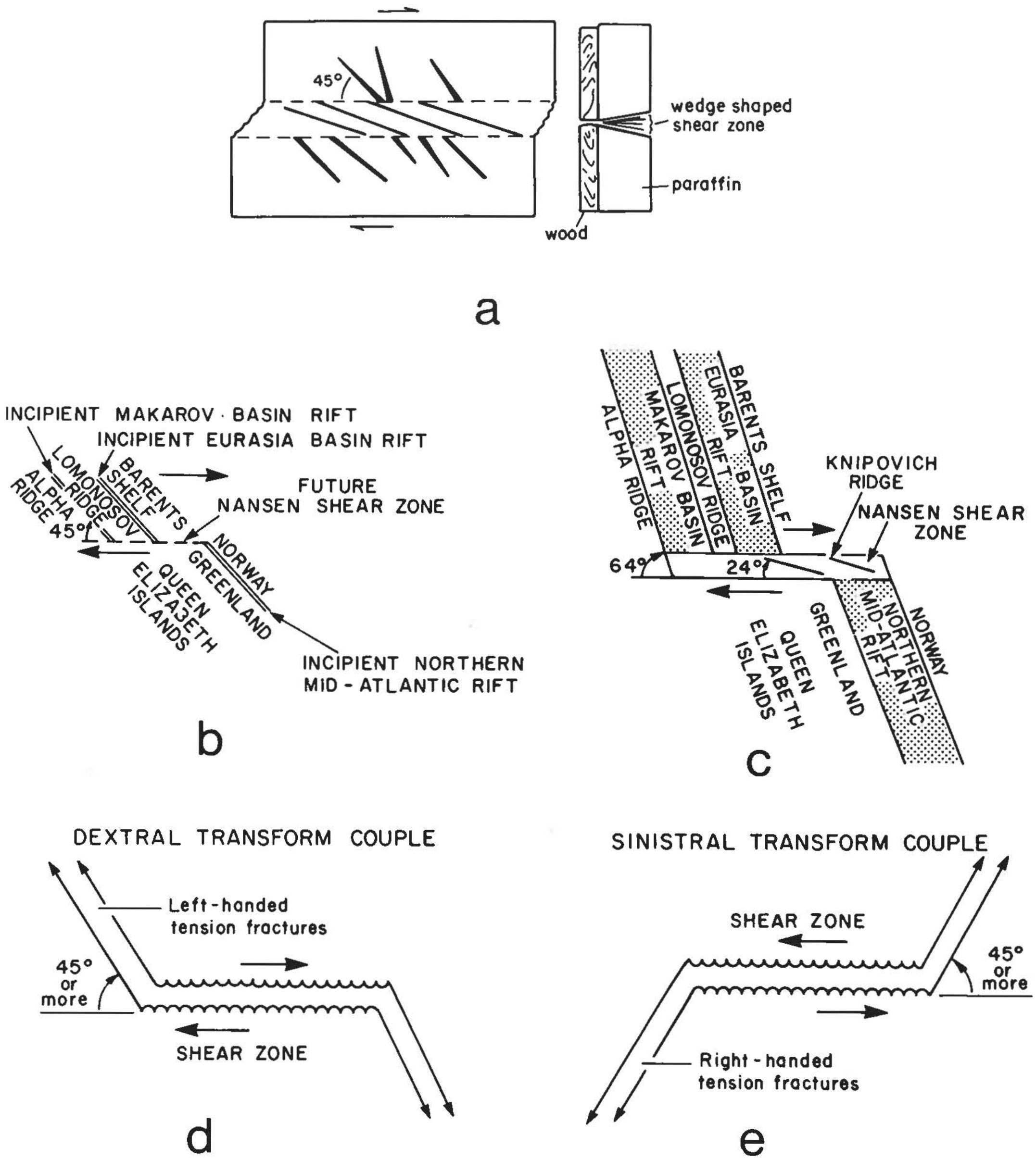

Fig. 6. (a) Fracture diagram explaining Brown's (1928) and Riedel's (1929) experiments. 45° tension cracks (rifts) appear first, then the shear zone develops and finally cracks develop at 10° to 15° in the shear zones, (b) schematic early development of the Eurasia Basin – Northern mid-Atlantic Rifts, (c) schematic early development of the Nansen Shear Zone (dextral) and later development of the Eurasia Basin – Northern mid-Atlantic Rifts, (d) generalized dextral transform couple, (e) generalized sinistral transform couple.

tures (Knipovich Ridge, north and south) identified as two narrow central deeps with flanking ridges developed about 36 Ma ago in the Nansen Shear Zone with angles of 16° to 24° to the shear zone (Fig. 5), again similar to the experimental results (Fig. 6c). Thus the Eurasia Basin – Northern mid-Atlantic Rift system appears to comprise tensional fractures radiating from a probable dextral transform shear zone (Fig. 6d) and is called here a dextral transform couple. The rifts may be described as left-handed as they trend to the left from a position facing the shear zone. The Makarov Basin may be another left-handed tensional rift zone lying subparallel to the Eurasia Basin Rift (Figs 6b, c) if the Nansen Shear Zone extends that far west.

M'Clure – Baffin Bay Rift system

This is a weakly-developed system (Figs 1 and 5) and is discussed in part by Jackson et al. (1979) and Kerr (1981). It lies some 2000 km southwest of, and more or less sub-parallel to, the Eurasia Basin – Northern mid-Atlantic Rift system. The M'Clure and Baffin Bay Rifts developed initially about 60 Ma ago, approximately at the same time as the Eurasia Basin and Northern mid-Atlantic Rift system. Then, about 38 to 25 Ma ago, the proposed Parry Channel Shear Zone developed and jointed the M'Clure – Baffin Bay Rift system as a weakly-developed, probably dextral, transform shear zone. In this paper Parry Channel is considered a shear zone even though geological evidence (Kerr 1981, pers. comm.) indicates extensional features across the channel. Parry Channel exhibits features analogous to the shear zone in Brown's (1928) and Riedel's (1929) experiments. In the experiments the shear zone (Fig. 6a), consisting of inward, steeply-dipping faults, progressively widens from depth towards the surface as the faults propagate upwards. Graben structures could develop within the shear zone if adjacent landmasses drifted apart while being translated parallel to the shear zone. Generally the inward-dipping faults are shown by Kerr (1981: fig. 17) for Lancaster Aulacogen which in this paper is considered to be part of the Parry Channel Shear Zone. The channel is about 100 km wide and if Kerr's geological section is extrapolated downwards assuming the dips of the faults to be constant (45°) then the shear zone could extend to a depth of about 50 km into the upper mantle. The faults in Parry Channel apparently die out within the sediments of sequences 6 and 7 (Fig. 3) and do not reach the surface (Kerr 1981). Sequence 3 is depicted as having different thicknesses on either side of the faults (Kerr 1981, fig. 17) and this might be interpreted to result from horizontal (shear) displacements along Parry Channel. The geological evidence, therefore, is not inconsistent with a shear zone developed as a wedge-shaped system of upward propagating faults, although evidence for shear movement may not be apparent at the surface until much later than the attendant rift zones, and may have very little indication of translational movement on the surface.

Determination of the azimuths of the rift zones is sometimes problematical. For example, the azimuth of the centre line of the Baffin Bay Rift may be taken as approximately 308° from bathymetry or 324° as indicated by the central negative gravity anomaly (Jackson et al. 1979). Using the latter value the M'Clure and Baffin Bay Rifts form angles of 58° and 50° respectively to the later developed proposed Parry Channel Shear Zone. Brown's and Riedel's models predict that rifts initially form at angles of 45°. These larger angles suggest that small angular rotations of 13° and 5° of the M'Clure and Baffin Bay Rifts and adjacent crustal blocks have taken place. If the magnitude of the angular rotation is any measure of the expected separation across the rifts then the width of Baffin Bay would be expected to be less than the 100 km width of the M'Clure Rift. However, it is 500 km in places! This paradox may result from either considerably greater crustal stretching during the initial development of the Baffin Bay Rift or because the Baffin Bay Rift is also a complementary rift of the Nares Strait lineament. Some support of the idea of crustal stretching is provided by Umpleby (1979) who has proposed that the margin of the Labrador Shelf is formed on downdropped, stretched continental crust, and by Le Pichon & Sibuet (1981) who have presented a simple stretching model for the continental margin in the northeast Atlantic. Their model explains the relationship between initial subsidence, thermal subsidence, continental crust thinning and gives the reason for the transition from continental stretching to oceanic accretion.

Nares Strait lineament

The Nares Strait lineament between Greenland and Ellesmere Island has been a focus of discussion for years (Kerr 1980b); some people advocate no movement along it, others favour a considerable amount of sinistral movement (up to 400 km). The present study tends to support the case for little or no movement, more or less in accord with Dawes' & Kerr's summary in this volume, who indicate that the boundaries between the various facies in Proterozoic and Palaeozoic rocks on either side of Nares Strait are in alignment. Riddihough et al. (1973) noted that magnetic anomalies are continuous across Nares Strait with no apparent offset along the Strait. A strong gravity gradient with a change in the gravity field of more than 100 mgal from relatively high values over Lincoln Sea and Ellesmere Island to lower values over Greenland (Sobczak & Stephens 1974), lies sub-parallel to the structural grain of the Palaeozoic strata and the north coast of Greenland. If this gradient is related to structures formed prior to 60 Ma ago then, because it is not offset along Nares Strait (35, azimuth of 14°, Fig. 5), very little movement along the Strait is indicated. On the other hand movement parallel to the gradient (40, azimuth 28°, Fig. 5) might not have disturbed the gradient significantly. For example, Nares Strait, about 50 km wide, could have been created by a sinistral movement of about 200 km along the gradient.

However, if this movement did occur along the gradient in the last 60 Ma then the Greenland side of the Nansen Shear Zone would be offset about 115 km. As there is no such apparent offset, then also very little movement is likely to have taken place along the gradient. Preliminary analysis of this gradient by the author suggests that the crust below Greenland, most of Nares Strait and Judge Daly Promontory of Ellesmere Island is either thicker by 6 to 8 km than the crust below Lincoln Sea and northern Ellesmere Island areas, or lower in mean crustal density by 0.07 Mg/m^3. Regardless of the cause of the gradient and providing the gradient has not occurred recently as a result of glacial loading, a major transition must take place along a line which crosses Nares Strait at an oblique angle and along which there has been no significant transcurrent movement.

Nares Strait is considered in Fig. 1 to be a shear zone as produced in Riedel's (1929) experiment; that is, there may be many inward and steeply-dipping faults that propagate upwards in a wedge-shaped shear zone that has undergone very little surface shear movement. In the latter respect it would be similar to Parry Channel. Initially, development of a shear zone would not require strike-slip movement at the surface and the shear movement would be manifested initially in the development of rift zones at either end. In this case the Baffin Bay Rift would form one rift zone at the south end of the shear making an angle of 50° with the shear zone, and the Eurasia Basin Rift would form the complementary rift making an angle of 61°; this system would be a sinistral transform couple according to the definition (Fig. 6e). As well, a northward extension of the Nares Strait lineament intersects the Nansen–Gakkel Ridge near the northward extension of the northeastern edge of the Nansen Shear Zone. Also the combined width of the Eurasia Basin and Makarov Basin Rifts is more than 100 km wider than the Northern mid-Atlantic Rift along the Nansen Shear Zone; this excess width on the Eurasian side of the shear zone may suggest that additional rifting sub-parallel to the Northern mid-Atlantic Rift may have taken place in Baffin Bay. The pattern that emerges across the entire region is that of three separate transform couples interlinked at two triple junctions (Parry Channel, Baffin Bay, Nares Strait junction and Eurasia Basin, Nares Strait, northern Atlantic Ocean junction).

Orientations of structures and tectonic forces with time

An examination of the orientations of structures formed during various time intervals and of recent principal forces (Figs 5 and 7) may provide a further insight into the fragmentation of the Arctic region. All the structural features are plotted on a polar stereographic projection (Fig. 5), but for convenience in measuring azimuths and making comparisons between the trends of various features an arbitrary rectangular coordinate system has been superimposed on this polar stereographic projection; the top and bottom of the map (Fig. 5) parallel to the 0°–180° azimuth of the polar stereographic projection are taken as 0° and 180° respectively and the left and right sides 270° and 90° in the rectangular system used here. Such a planar representation for the real surface produces only minor distortions as was discussed for a comparable projection, a polar azimuthal equidistant projection by Sweeney & Haines (1978). Distortions of distance between parallels of latitude increase southwards by a factor $(90°–\lambda)$rad./sin $(90°–\lambda)$ where λ is latitude. For example, a change of 30° of latitude represents a distortion of 47 km for a surface distance of 1000 km. As most of the azimuths were determined between 70° to 85° latitude a distortion of 39.4 km in a distance of 1675 km would represent an error in azimuth of 1.3 degrees which is considered insignificant in this study.

Azimuths of structures and forces have been grouped into broad time categories (Recent, Sverdrup Basin, and Franklinian Geosyncline intervals, Fig. 7). Azimuths of recent tectonic events are shown at the hub of Fig. 7, and include azimuths of deviatoric forces and faults and focal depths calculated in Byam Martin Channel and Beaufort Sea by Hasegawa (1977) and Hasegawa et al. (1979). In Byam Martin Channel four large (magnitude 5.1 to 5.7) earthquakes in 1972 with focal depths between 10 and 30 km yielded average deviatoric tension (T_1) and compression (P_1) azimuths of 340° and 90° respectively and a strike of the preferred, nearly normal (85°), fault plane (F_1) of 35°. These azimuths in the rectangular coordinate system used here are 357°, 106° and 50° respectively (Figs 5 and 7). In the Beaufort Sea a large (magnitude 4.2) earthquake in 1975 with a focal depth of 40 km gave azimuths in the rectangular coordinate system of (T_2) 204°, (P_2) 42°, and (F_2) 90°.

The azimuths of the folds and fractures that formed during development of the Sverdrup Basin interval (mainly Eurekan Deformation) are shown radiating from the hub of Fig. 7. Fractures (including shear zones) trend between 14° and 94° with a mean value close to the present fault direction of 50° in Byam Martin Channel (Hasegawa 1977), that is between the deviatoric tension (T_1) and compression (P_1) forces of the Byam Martin Channel earthquakes, while arches and rifts trend between 297° and 335° between T_1 and P_1 forces. The force diagram for the Beaufort Sea earthquake appears to be unrelated to the fractures and arches of the Sverdrup Basin interval as these fall in different quadrants of the force diagram of the Beaufort Sea (Fig. 7). Some of these azimuths were approximated from the general trend of many individual fractures, while some are more reliable such as those determined for the Cornwall Island faults over the Cornwall Arch by Balkwill (1974); the average azimuth of 54 faults is 35° and the average fold axis azimuth is 323°. Azimuths of fold axes is about half the variation in direction of the fractures. Apparently azimuths of folds and fractures in the Queen Elizabeth Islands are similar to those within the North Atlantic Ocean (Fig. 7). This suggests that both regions probably have been subjected to similar stresses regardless of the fact that two different types of crusts (oceanic and continental) are present. Ages of most oceanic structural features are indicated in Figs 5 and 7.

During the formation of the Franklinian Geosyncline (i.e. mainly during the Ellesmerian Orogeny, Fig. 3) azimuths of arches (237° to 333°) have a much larger variation (96°) than those produced in the Sverdrup Basin interval. The Cornwallis Fold Belt, which was uplifted as much as 7700 m (Kerr 1977), was probably influenced by the underlying Boothia Uplift, a northward-trending, Precambrian salient which plunges to the north below the Sverdrup Basin. This uplift existed during Precambrian time, persisted during the Phanerozoic and influenced the tectonics within the region. It is parallel to the alignment of the deviatoric tension force T_1 and normal to the deviatoric compression force P_1 (Hasegawa 1977). With the exception of the Boothia Uplift, no significant fractures dating from the Franklinian Geosyncline interval have been found.

Fractures and folds

It is difficult from simple fracture-fold theory to determine the exact nature of external forces from the pattern of fractures and arches (De Sitter 1956, Billings 1958). During the Sverdrup Basin interval, fractures generally occur in the first quadrant (0° to 90°) in both old, continental crust (Queen Elizabeth Islands) and new, oceanic crust (northern Atlantic Ocean). However, obvious fractures did not also occur in the fourth quadrant (270° to 360°), but, instead, arches predominate in this quadrant. Part of the explanation of this distribution may lie in the fact that most of the northwest-trending features are mid-oceanic ridges along which magma has intruded along zones of weakness or fractures. The two continental arch features, the Cornwall Arch and Princess Margaret Arch (Fig. 2), may also be zones of weakness that are largely intruded by igneous rocks. Along the Cornwall Arch evidence from drill holes and gravity data (Sobczak & Overton in prep.) suggest that a significant amount of mafic igneous rock is intruded along and may have largely caused the Cornwall Arch. On the other hand folds can develop at right angles to a principal compressive force (Billings 1958). Perhaps prior to and during the opening of the Eurasia Basin – Northern mid-Atlantic Rifts and the M'Clure – Baffin Bay Rifts compressive forces acted along the axis of the Sverdrup Basin (azimuth 50°) and may have been partially responsible for structures such as the Cornwall Arch and Princess Margaret Arch.

Discussion

Structures, earthquakes analysis and experimental models may indicate the tectonic forces that fragmented the Arctic region. Tectonic forces that affected the North American continent and adjacent oceans during the Sverdrup Basin interval produced arches and rifts whose azimuths trend northwest and fractures whose azimuths trend generally to the northeast (Fig. 7). However, during the Franklinian Geosyncline interval there were, apparently, no fractures, and azimuths of arches have a much greater range varying from the southwest to the northwest, making interpretation of the force field more difficult. The Boothia Uplift, a north-trending crystalline structure, persisted as a positive element throughout the Sverdrup Basin and Franklinian Geosyncline intervals with an azimuth that was consistent and intermediate to those of the arches and fractures (Fig. 7). With the exception of large rifts, structures produced in the Sverdrup Basin interval have similar azimuths, so it appears that they may have been produced by similar tectonic forces. Tertiary and early Mesozoic forces which caused these structures probably had azimuths similar to the present-day deviatoric forces (Fig. 7) as determined from four large earthquakes in Byam Martin Channel by Hasegawa (1977). Fault plane solutions for these earthquakes indicated dextral strike-slip motion in a northeasterly direction which is more or less the mean azimuth of the fractures for the Sverdrup Basin interval. Azimuths of tensional and compressional deviatoric forces for the Beaufort Sea earthquake lie 53° and 64° respectively counterclockwise from those determined in Byam Martin Channel (Fig. 7) (Hasegawa et al. 1979) and may be representative of the present-day force field in the Canada Basin.

Azimuths of fractures and arches produced during the Sverdrup Basin interval vary by as much as 80° and 38° respectively; these variations may relate to a rotation of up to ± 40° of a deviatoric force system having an initial orientation similar to that shown for recent forces in Byam Martin Channel (Fig. 5). Alternatively the magnitude of forces along the tensional and compressional directions may have varied with time. Older underlying structures and the structural grain may have also diverted or influenced the fracture–arch directions.

Arches and rifts produced during the Sverdrup Basin interval have similar azimuths which is paradoxical because arches are usually compressive features whereas rifts are tensional. This suggests that fragmentation within the Arctic region may be the result of two types of interacting deviatoric tectonic forces such as a regional tension-tension force couple acting longitudinally and latitudinally as proposed for the North Atlantic Ocean and Baffin Bay areas (Fig. 5) and a local (Queen Elizabeth Islands) tension-compression force couple as indicated for the Byam Martin Channel (Fig. 5) (Hasegawa 1977). The tension-tension forces may be a result of a mantle convection current or a revolving ellipsoidal earth with centrifugal forces that act radially from the North Pole. Probably one or both of these gradually forced the continents to move southward as

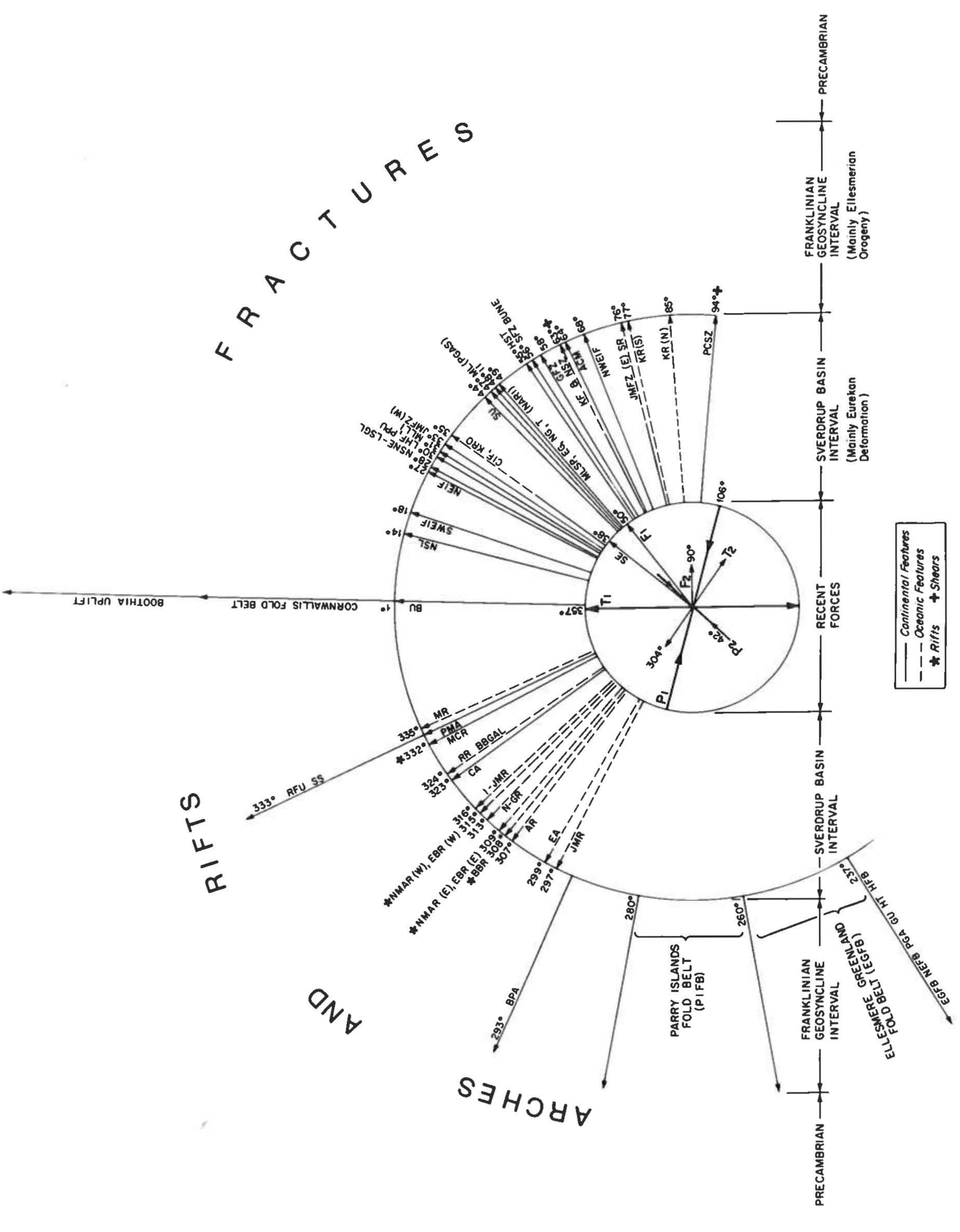

Fig. 7. Azimuth plot of structural features and forces relative to a rectangular coordinate system. For the Byam Martin Channel earthquake with focal depths between 10 and 30 km (Hasegawa 1977), deviatoric tensional and compressional forces shown as T_1 and P_1 and fault direction as F_1. Similarly for the Beaufort Sea with a focal depth of 40 km (Hasegawa et al. 1979) these quantities are shown as T_2, P_2, and F_2.

Explanation of abbreviations from Figs 3 and 7; numbers are from Fig. 5.

Arches

36	EGFB:	Ellesmere–Greenland Fold Belt (237° to 260°, Kerr 1981)
42	NEFB–PGA:	Northern Ellesmere Fold Belt – Pearya Geanticline (237°, Kerr 1981)
38	HFB:	Hazen Fold Belt (237°, Kerr 1981)
38	HT:	Hazen Trough (237°, Kerr 1981)
38	GU:	Grantland Uplift (237°, Kerr 1981)
54, 55	PIFB:	Parry Islands Fold Belt (260°–280°, Tozer & Thorsteinsson 1964)
33	BPA:	Bache Peninsula Arch (293°, Kerr 1981)
17	JMR:	Jan Mayen Ridge (297°, 17–23 Ma, Grønlie et al. 1979)
14	EA:	Extinct axis (299°, 26–55 Ma, Grønlie et al. 1979)
1	AR:	Alpha Ridge (307°, Fig. 5)
2	LR:	Lomonosov Ridge (315°, Fig. 5)
3	N–GR:	Nansen–Gakkel Ridge (313°, Fig. 6)
18	I–JMR:	Iceland – Jan Mayen Ridge (316°, 10 Ma, Grønlie et al. 1979)
27	CA:	Cornwall Arch (323°, Balkwill 1974)
20	RR:	Reykjanes Ridge (324°, 10 Ma, Grønlie et al. 1979)
23	BBGAL:	Baffin Bay gravity anomaly low (324°, Jackson et al. 1979)
44	RFU:	Rens Fiord Uplift (333°, Trettin 1969)
43	SS:	Svartevaeg Syncline (333°, Trettin 1969)
32	PMA:	Princess Margaret Arch (333°, Thorsteinsson 1974)
15	MR:	Mohns Ridge (335°, Sobczak & Sweeney 1978, 57 Ma, Grønlie et al. 1979)
26	CFB:	Cornwallis Fold Belt (1°, Fortier et al. 1963, Kerr 1977)
26	BU:	Boothia Uplift (1°, Fortier et al. 1963, Kerr 1977)

Rifts

21, 22, 24	BBR:	Baffin Bay Rift (308°, 38–60 Ma, Jackson et al. 1977, 1979, Fig. 5)
12	NMAR(E):	Northern mid-Atlantic Rift (East), (309°, 57 Ma, Fig. 5)
7	EBR(E):	Eurasia Basin Rift (East), (309°, Fig. 5)
19	NMAR(W):	Northern mid-Atlantic Rift (West), (315°, 57 Ma, Fig. 5)
2	EBR(W):	Eurasia Basin Rift (West), (315°, Fig. 5)
56	MCR:	M'Clure Rift (332°, Fig. 5)

Fractures and other linear features

35	NSL:	Nares Strait Lineament (14°, Kerr 1981)
34	SWEIF:	Southern Ellesmere Island faults (18°, Thorsteinsson 1974)
39	NEIF:	Northern Ellesmere Island faults (27°, Thorsteinsson 1974)
40	NSNE–LSGL:	Nares Strait north end – Lincoln Sea gravity linear (28°, Sobczak & Stephens 1974)
41	LHF:	Lake Hazen Fault (30°, Christie 1964)
51	PPU:	Prince Patrick Uplift (30°, Thorsteinsson & Tozer 1960)
47	MLLI:	Magnetic linears Lougheed Island area (31°, Forsyth et al. 1979)
16	JMFZ(W):	Jan Mayen Fracture Zone (West) (33°, 26–36 Ma, Grønlie et al. 1979)
30	CIF:	Cornwall Island Faults (35°, Balkwill 1974)
6	KRO:	Knipovich Ridge offset (35°, Sobczak & Haines 1978)
57	SE:	Seismic epicentres (38°, Byam Martin Channel, Hasegawa 1977)
58	SU:	Storkerson Uplift (44°, Kerr 1981)
46	ML(PGAS):	Magnetic linears (Prince Gustaf Adolf Sea) (47°, Forsyth et al. 1979)
45	II:	Igneous intrusions (strike of gravity anomaly) (48°, Sobczak & Overton in prep.)
53	MLSP:	Magnetic linears Sabine Peninsula (49°, Forsyth et al. 1979)
53	NG:	Narrow grabens (reflection seismic), (49°, Forsyth et al. 1979)
29	T(NARI):	Trough (northwest of Amund Ringnes Island), (49°, Sobczak & Overton in prep.)
52	EG:	Eglinton Graben (49°, Tozer & Thorsteinsson 1964)
53	BMCSF:	Byam Martin Channel Seismic Fault (50°, Hasegawa 1977)
31	HST:	Hassel Sound Trough (55°, Sobczak & Overton in prep.)
28	BUNE:	Boothia Uplift north end (56°, Sobczak & Overton in prep.)
11	SFZ:	Senja Fracture Zone (56°, 36 Ma, Grønlie et al. 1979)
8	GFZ:	Greenland Fracture Zone (58°, 36 Ma, Grønlie et al. 1979)
50	KF:	Kaltag Fault (63°, Kerr 1981)
5, 10	NSZ:	Nansen Shear Zone (63°, Fig. 5)
49	ACM:	Arctic Continental Margin (64°, Fig. 5)
37	NWEIF:	Northwestern Ellesmere Island faults (68°, Thorsteinsson 1974)
48	SR:	Sverdrup Rim (76°, Meneley et al. 1975)
13	JMFZ(E):	Jan Mayen Fracture Zone (East), (76°, 26–36 Ma, Grønlie et al. 1979)
9	KR(S):	Knipovich Ridge (South), (77°, 36 Ma, Fig. 5)
4	KR(N):	Knipovich Ridge (North), (85°, Fig. 5)
59	BSSF:	Beaufort Sea Seismic Fault (90°; Hasegawa et al. 1979, Fig. 5)
25	PCSZ:	Parry Channel Shear Zone (94°, 25–38 Ma, Jackson et al. 1979, Fig. 5).

indicated by the opening of the Eurasia Basin along meridians of longitude from the North Pole. The continents were forced to either fracture, stretch, or both in order to occupy a larger southward circumference than when the continents were closer to the pole. Thus tensional forces would be experienced by the continents both radially and tangentially as indicated for the North Atlantic Ocean and Baffin Bay (Fig. 5). Analogous to Brown & Riedel's experiments (Fig. 6a) the crust first rifted in the North Atlantic – Eurasia Basin at a 45° angle to the direction of tensional forces which were probably of similar strength and then sheared dextrally along the Nansen Shear Zone. At the same time a sub-parallel poorly-developed, rift-transform shear zone was probably formed some 2000 km to the southwest (M'Clure Strait, Parry Channel and Baffin Bay). The plate between these dextral transform couples (Fig. 6d) continued to be affected by more or less longitudinal tensional forces but the latitudinal forces became compressional due to a sinistral force couple resulting from the formation of two transform couples. Under this stress regime, in the rectangular frame of reference, fractures developed in the northeast quadrant at some acute angle to the principal force and arch features developed in the northwest quadrant. However, most of these arch features are mid-oceanic ridges produced by upwelling mantle material probably along zones of weaknesses which may be new fractures. In the Queen Elizabeth Islands the Cornwall Arch and Princess Margaret Arch may result from intruded mafic material along zones of weaknesses and the effects of an underlying crystalline crust that compressed along and stretched perpendicular to the axis of the Sverdrup Basin (Sobczak & Overton in prep.).

A crystalline crust that can stretch, and over a period of time behave more as a plastic than a rigid body, is another important tectonic feature to consider in the fragmentation and evolution of the region. It can best explain the undulating Moho and the thickness variation of the crystalline crust below the Sverdrup Basin (6 to 10 km thinner below the thickest sedimentary column, Fig. 4, Sobczak & Overton in prep.), the observed subsidence (Sweeney 1977), isostatic equilibrium and crustal thinning in the continental margin areas (Sobczak 1975a, b). As well it can offer an additional mechanism for the somewhat erratic fragmentation of the region. If the lower crystalline crust can be considered to behave like a balloon with strong and weak spots in it, then the weaker, more flexible spots could experience more stretching, fragmentation and subsidence. Perhaps this plastic variation can partly explain differences in widths between sub-parallel rift zones such as the Baffin Bay and M'Clure Rifts. Further, a plastic crust can explain arch features such as the Cornwall Arch and Princess Margaret Arch. If, in the past, the compressional force was rotated from present-day directions counter-clockwise more along the axis of the Sverdrup Basin, with the tensional force perpendicular to the Arctic continental margin, then as the crystalline crust stretched below in line with the tensional force the sediments and crystalline crust would subside and fold perpendicular to the compressive force. This picture is consistent with folding noted at the crust–mantle boundary more or less along the axis of the Sverdrup Basin (Fig. 4).

Perhaps similar circumstances may also apply to the Alpha Ridge. The Alpha Ridge, an accordian-like feature whose origin is unknown, is sub-parallel to the ridges of the North Atlantic Ocean and Queen Elizabeth Islands and nearly normal to the compressive force determined by Hasegawa et al. (1979) in the Beaufort Sea (Fig. 5). It lies mid-way in the Arctic Ocean between the coast of Alaska and Barents Shelf. The crests of the Alpha Ridge and Lomonosov Ridge and the upper part of the Barents Shelf, fall on a straight line which has a decreasing gradient from the Barents Shelf of 2000 m per 15° of latitude (Sobczak & Sweeney 1978). The crests of the ridges may thus be considered to have subsided at the rate of about 1.2 metres per kilometre of distance from the Barents Shelf, a subsidence which may be a function of time of separation. The Lomonosov Ridge and the Barents Shelf probably separated about 55 Ma ago (Vogt et al. 1979). If subsidence in the Sverdrup Basin can be considered typical for subsiding areas in the Arctic region, Sweeney (1977) showed a mean subsidence rate for the central region of the Sverdrup Basin of about 2.4 km/55 Ma and of about 1 km/55 Ma for the northwest margin area. The submerged ridge heights of 2.0 km depth for the Alpha Ridge and 1.5 km for the Lomonosov Ridge may correspond to a similar rate of subsidence with time as these features rifted away from the Barents Shelf. If ridge heights can be used as an indicator of separation, then the Alpha Ridge may have separated before the separation of the Lomonosov Ridge and Barents Shelf because of its greater depth. Also, high amplitude magnetic linears, which probably relate to mafic intrusions, lie parallel to the ridge axis and trend southeastward over the continental margin to the coast of Ellesmere Island (Riddihough et al. 1973). DeLaurier (1978) concluded that the Alpha Ridge did not fit the spreading hypothesis because cooling models would predict very little present relief. As well, spreading ridges are more or less parallel to rift edges (Fig. 7) but no obvious sub-parallel rift edge occurs on the North American side of the Alpha Ridge. Instead the central axis of the Canada Basin lies more or less sub-parallel to the direction of major fracturing.

A speculative concept that appears to emerge is that rift zones developed on the Eurasian side of the Alpha Ridge and more complicated stretched zones (the Canada Basin and Sverdrup Basin) on the North American side. Thus the Alpha Ridge is probably a former continental margin which rifted away from the Lomonosov Ridge and Barents Shelf. Initially, the Alpha Ridge and Canada Basin may have stretched more or less perpendicular to the ridge axis (radially from the pole) while rifting was taking place on the Eurasian side of the ridge, but as rifting terminated and landmasses on either side started to drift apart the Alpha Ridge was then probably compressed more or less perpendicular to the ridge and stretched latitudinally. Effects of stretching in and around the Canada Basin may take the form of down-faulted, inward-dipping blocks around the continental margins and Alpha Ridge similar to structures proposed by Umpleby (1979) for the Labrador Shelf, and by Le Pichon & Sibuet (1981) for passive margins; oceanic crust or heavily oceanized continental crust may be present in the centre of the basin. The greatest amount of separation is postulated to have taken place about the north-trending axis of the basin which may coincide with a buried, low-relief ridge.

Another feature that appears to emerge from this study is the variation of forces for the general region between 70° and 80° latitude (Fig. 5). From east to west, areas are alternatively under the influence of either latitudinal tension (North Atlantic Ocean and Beaufort Sea) or latitudinal compression (Queen Elizabeth Islands). If this pattern continues to the west to the region of Mendeleev Ridge, Chukchi Plateau and Northwind Ridge on the other side of the Canada Basin then it may also be under compression. This compression may have produced these more or less longitudinal trending features. In the Queen Elizabeth Islands the Boothia Uplift is more or less normal to the existing compressive force in Byam Martin Channel (Hasegawa 1977). A large number of seismic epicentres along the uplift (Basham et al. 1977, Wetmiller & Forsyth 1978) may indicate a response to this force.

Concluding remarks

The model for Cenozoic fragmentation of the Canadian Arctic Archipelago and surrounding region proposed in this paper is based on a pattern of northeast-trending fractures and faults and northwest-trending folds and rifts. In the context of this symposium Nares Strait is considered to represent a prominent example of one of the northeast-trending faults of this fracture system. It may represent a poorly-developed sinistral transform shear zone composed of many inward steeply-dipping faults, although very little surface shear movement is envisaged. This conclusion is supported by the strong gravity gradient that can be traced without apparent offset from northeastern Ellesmere Island across northern Nares Strait to Greenland. The fragmentation model in which Nares Strait links the rift-generated oceans of Baffin Bay to the south with the Eurasia Basin to the north supports the case against major strike-slip motion between Ellesmere Island and Greenland along Nares Strait.

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