Fold belts and metamorphic zones of northern Ellesmere Island and North Greenland

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The Innuitian tectonic province extends in its eastern part through northern Ellesmere Island and across North Greenland. The mid- to late Palaeozoic Ellesmerian orogeny produced NE–SW to E–W trending fold belts and metamorphic zones in the strata of the Franklinian geosyncline. The late Cretaceous–Tertiary Eurekan orogeny deformed the Carboniferous–Tertiary rocks of the Sverdrup and Wandel Sea Basins, and overprinted or accentuated the older structures of the Franklinian geosyncline. The locations of the south limit of Ellesmerian folding, and of fold belts of comparable style, deformation intensity and metamorphic grade on the two sides of the Nares Strait lineament are consistent with models of left-lateral displacement in the range 0–50 km. Models of displacement greater than 50 km introduce increasingly improbable mismatches of fold belts and metamorphic zones.

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The Innuitian tectonic province extends in its eastern part through northern Ellesmere Island and into North Greenland. Proterozoic, Lower Palaeozoic and Devonian rocks of the Franklinian geosyncline were deformed in the Ellesmerian orogeny, and Carboniferous–Palaeogene sediments overlying the folded rocks were themselves deformed in the mid-Cenozoic Eurekan orogeny. The Nares Strait lineament lies oblique to the trend of the Ellesmerian fold belts and metamorphic zones, allowing a possibility of determining the displacement, if any, on the lineament. The most recent summaries of the province in Ellesmere Island and North Greenland are respectively those of Trettin & Balkwill (1979) and Dawes & Peel (1981).

Thick Proterozoic and Cambrian to Devonian sedimentary sequences accumulated in the Franklinian geosyncline which extended through Ellesmere Island and across northern Greenland. Shallow marine to non-marine conditions prevailed throughout the earliest Cambrian in Ellesmere Island and in North Greenland, with subsequent development of a marine basin. From the middle Cambrian to early Devonian three major depositional belts are apparent: an unstable south-eastern shelf which received mainly carbonate sediments; the Hazen Trough in which starved-basin sediments (cherts, graptolitic shales and redeposited carbonates) and thick flysch deposits accumulated; and a complex north-western belt including volcanic rocks and clastic and carbonate sediments. The third belt is restricted to northern Ellesmere Island. Clastic sedimentation continued until the Middle and Late Devonian in northern Ellesmere Island, and into the Upper Silurian and locally Devonian in North Greenland, being brought to a close by the Ellesmerian orogeny.

The Ellesmerian orogeny produced the most extensive and intense deformation of the Innuitian tectonic province. The folds developed in the mainly Cambrian–Devonian rocks show a strong alignment with NE–SW to E–W trends dominant, the folds being most intense in the north, and in the south passing into unfolded platform terrain. Significant metamorphic grades were only reached in northern Ellesmere Island and in northern Peary Land in Greenland. Plate-tectonic models have been suggested for the origin of the folding in Ellesmere Island (Trettin et al. 1972, Trettin & Balkwill 1979) and North Greenland (Dawes & Soper 1973), in both regions being interpreted in terms of southward underthrusting of ocean floor against and beneath the continental block and Franklinian geosyncline.

Folded Cambrian–Devonian sediments are overlain by great thicknesses of early Carboniferous to late Cretaceous, locally Eocene, sediments in Ellesmere Island (Sverdrup Basin: Balkwill 1978), and by Carboniferous to early Tertiary sediments in eastern North Greenland (Wandel Sea Basin: Dawes & Soper 1973, Håkansson 1979). In both the Sverdrup Basin and Wandel Sea Ba-

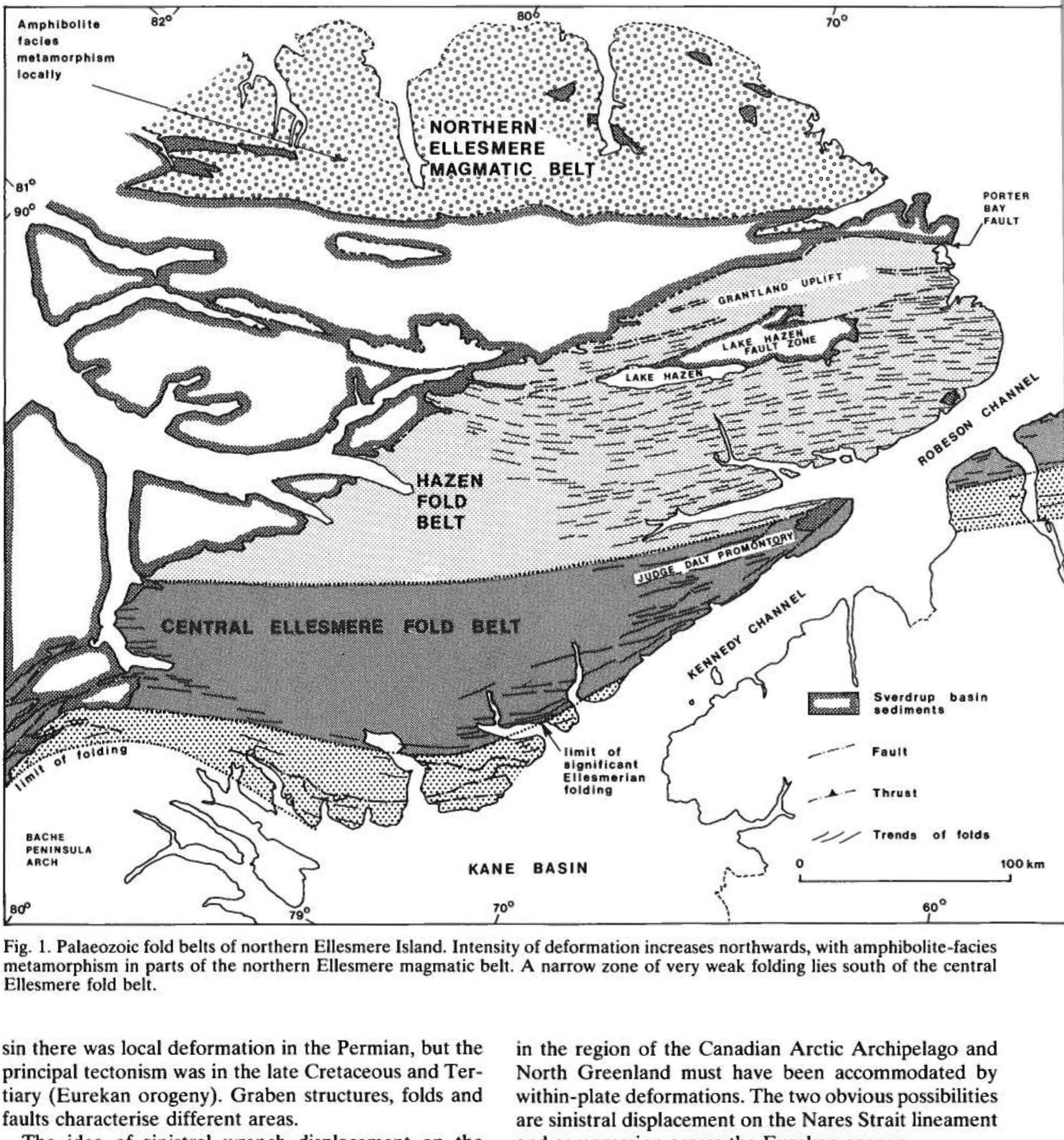

Fig. 1. Palaeozoic fold belts of northern Ellesmere Island. Intensity of deformation increases northwards, with amphibolite-facies metamorphism in parts of the northern Ellesmere magmatic belt. A narrow zone of very weak folding lies south of the central Ellesmere fold belt.

sin there was local deformation in the Permian, but the principal tectonism was in the late Cretaceous and Tertiary (Eurekan orogeny). Graben structures, folds and faults characterise different areas.

The idea of sinistral wrench displacement on the Nares Strait lineament has arisen from the necessity of accommodating the anti-clockwise rotation of Greenland relative to North America due to the spreading origin of the Labrador Sea. Spreading was confined to the period between anomalies 31 (68 m.y. late Cretaceous) and 13 (35 m.y. early Oligocene); note that the polarity time scale of Hailwood et al. (1979) is adopted. Since spreading as far north as Baffin Bay is debatable (Grant, this volume, Soper et al., this volume), motion in the region of the Canadian Arctic Archipelago and North Greenland must have been accommodated by within-plate deformations. The two obvious possibilities are sinistral displacement on the Nares Strait lineament and compression across the Eurekan orogen.

Any sinistral wrench movements along Nares Strait should be revealed by offset of trends and boundaries associated with the Ellesmerian (Palaeozoic) orogeny, whereas Eurekan structures should show little displacement. Such features have previously been used in arguments in support of little movement (Kerr 1967) or very extensive movement (Newman 1977, Newman & Falconer 1978). In this paper the deformation and metamorphic patterns due to the Ellesmerian orogeny

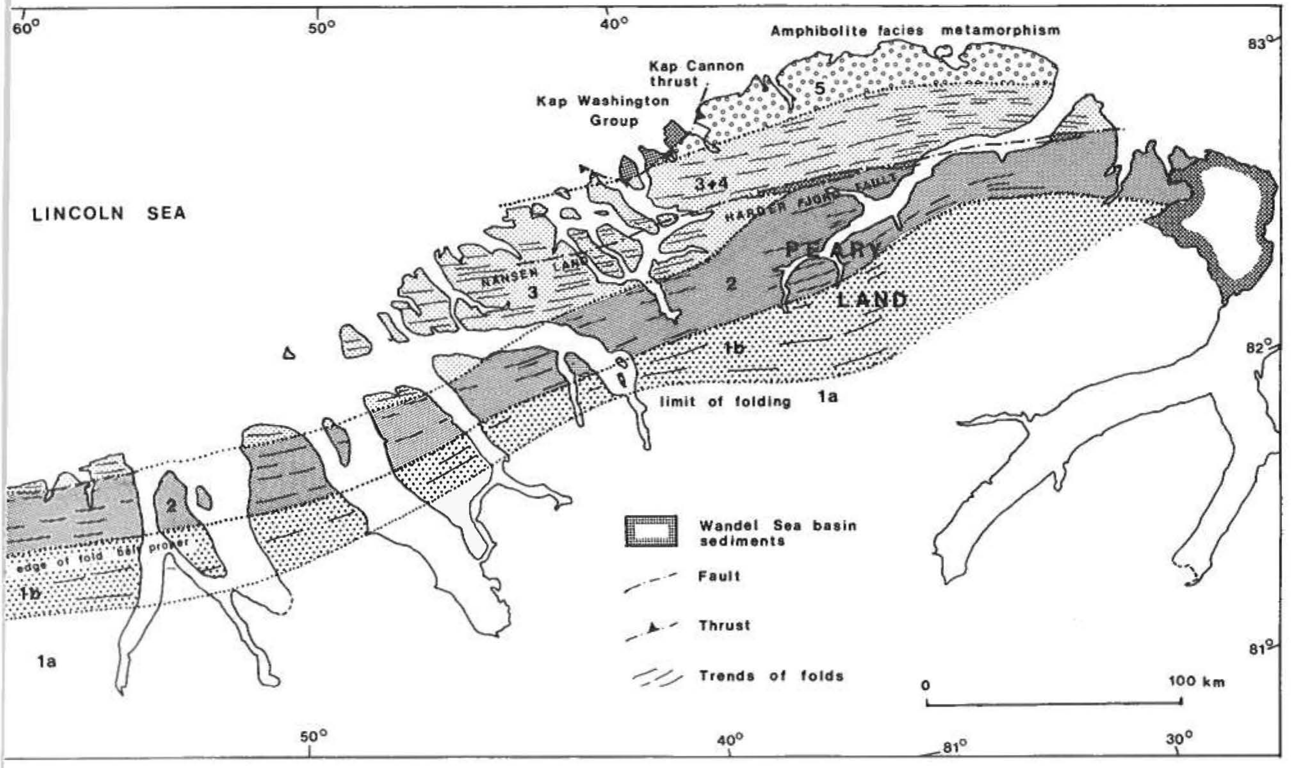

Fig. 2. Structural and metamorphic zones of the North Greenland fold belt (after Dawes 1976). Deformation intensity increases northwards, with amphibolite-facies metamorphism only in the northern part of zone 5. The ornament used for each zone indicates correlations with the equivalent fold belts of northern Ellesmere Island.

on the two sides of Nares Strait are reviewed, and the boundaries between comparable belts of deformation and zones of metamorphism are considered in a series of displacement models.

Ellesmere Island

The history of deformation within the Innuitian tectonic province of Ellesmere Island has most recently been reviewed by Trettin & Balkwill (1979). The Palaeozoic Ellesmerian orogeny progressed from north to south and produced three major fold belts with markedly different structural characteristics (Fig. 1): central Ellesmere fold belt, Hazen fold belt, northern Ellesmere magmatic belt (or fold belt). In the north deformation commenced not later than middle Devonian, and in the south probably began in latest Devonian or earliest Carboniferous time. The fold trends are generally ENE–WNW, but show locally pronounced variations, as for example in the south where structures swing around the Bache Peninsula arch. There is only a narrow zone of unfolded platform rocks at the present level of exposure.

The southernmost of the three fold belts, the *central Ellesmere fold belt,* is characterised by extensive concentric folds controlled by competent carbonate units. In the southern part of Judge Daly Promontory the folds have north-east trending, sub-horizontal fold axes, and individual folds can be traced for up to 50 km. Wide, open synclinoria alternate with tight, steep anticlines. A change in fold style occurs in the northern part of Judge Daly Promontory, where the Palaeozoic structures are strongly dissected by steep normal and reverse faults of probable Tertiary age. Typical recognisable Palaeozoic structures are monoclines and tight, steep anticlines. Some folds are overturned toward the north-west, indicating the beginning of a northerly vergence which is much more obvious in the folding in North Greenland. Southwards a zone of very weak folds separates the main central Ellesmere fold belt from unfolded platform carbonates.

The *Hazen fold belt* comprises the deformed strata of the north-east part of the Hazen Trough, and shows greater stratal shortening than the central Ellesmere fold belt (Trettin & Balkwill 1979). It is characterised by very numerous, closely-spaced tight and isoclinal major folds, of chevron type in the flysch, and concentric type where they deform thin chert units. Axial planes dip generally north-west at angles between 75° and vertical, but south-east dips are also recorded (Trettin 1971). The folds display well-developed axial-plane cleavage, and they are associated with numerous faults, including south-eastward directed minor thrusts. The Grantland uplift, bordered to the south by the Lake Hazen fault zone and crossed by the Porter Bay fault zone, is now regarded as the northernmost part of the Hazen fold belt (H. P. Trettin, pers. comm. 1980). Parts of the Hazen fold belt are characterised by sub-greenschist and greenschist-facies metamorphism. It has not been greatly modified by Tertiary deformation, as outliers of Carboniferous and Tertiary strata, except where directly involved in the faulting, are only weakly deformed.

The *northern Ellesmere magmatic belt* exhibits a number of unique features: the presence of Grenvillian basement, Ordovician and Silurian volcanics, Devonian plutons, and amphibolite-facies grade early Palaeozoic rocks (Frisch 1974). It also differs from the Hazen fold belt by the presence of Ordovician and lower Silurian shelf carbonates. Fold trends are mainly NE–SW, but arcuate trends are also recorded.

Late Cretaceous to Tertiary tectonism (Eurekan orogeny) overprinted the Ellesmerian fold belts to a varying degree, in some cases merely accentuating the older structures. One of the principal results was the uplift of the southern Grantland mountains by thrust faulting on the Lake Hazen fault zone. The Grant Land Formation was thrust over early Ordovician to Tertiary rocks. Strike-slip faulting probably took place along the Porter Bay fault zone. The Sverdrup Basin sediments in the vicinity of the faults were warped into open folds. The compressional folds and faults are commonly cited as supporting the rotation of Greenland as a result of early Tertiary sea-floor spreading, but this is only possible if the revised polarity time scale of Hailwood et al. (1979) is employed. If the Heirtzler et al. (1968) time scale is used, the structures, generated between middle Eocene and early Miocene, are too young (Trettin & Balkwill 1979).

Along the south-east margin of that part of the central Ellesmere fold belt adjacent to Kane Basin several low-angle thrusts formed; Lower Palaeozoic formations are thrust on Paleocene conglomerate and sandstone. Along the Kennedy Channel coast the thrusts are transformed into strike-slip faults as far north as the Judge Daly fault zone on northern Judge Daly Promontory. Stresses associated with the strike-slip movement disrupted and overprinted the Ellesmerian structures (Mayr & de Vries, this volume). The earliest possible local age for thrusting and strike-slip movement is late Paleocene, but from regional considerations the deformation is more likely to be post-middle Eocene in age.

North Greenland

The North Greenland fold belt has been divided into a series of approximately E–W trending zones (Dawes 1976, Dawes & Soper 1973, 1979) which show increasing northwards intensity of deformation and metamorphism.

The hinterland of the fold belt is a broad zone of unfolded, flat-lying to gently northward-dipping Lower Palaeozoic strata, mainly platform carbonates (zone 1a, Fig. 2). The first indications of deformation are large-scale open warps and very gentle structures (zone 1b). The margin of the fold belt proper is abrupt and without regional dislocations; it is an easily traceable line across entire North Greenland. Zone 2 is marked by the appearance of E–W trending generally steep-limbed symmetrical folds. The folds vary from open to tight, and in several areas along the length of the fold belt they have a box-fold style. In Peary Land the folds at the south margin of the zone are southward-facing monoclines (Dawes & Soper 1979, Pedersen 1979), but the structures are more often overturned northwards with steep south-dipping axial planes. Parts of zone 2 studied by Pedersen (1980) in eastern North Greenland are characterised by westward-directed imbricate thrusts.

Zones 3, 4 and 5 represent increasingly complex deformation, a sequence only fully developed in eastern North Greenland. In zones 3 and 4 first folds are still conspicuous as chains of tight to isoclinal folds, upright or with steep south-dipping axial planes. Second phase folds are common, developed on south-dipping axial planes with a congruous cleavage, and become progressively more intense and overturned northwards in zone 5, where they are joined by similarly oriented third folds. It is in particular the second and third phase folds which give the strong northerly vergence to the fold belt.

Zones 1 and 2 are essentially non-metamorphic. Metamorphic grade increases gradually northwards in zones 3, 4 and 5 with the appearance of chlorite, biotite, garnet, and locally staurolite, andalusite and cordierite. Amphibolite-facies rocks are found only in the northern part of zone 5.

The three main deformation phases so far recognised and the progressive metamorphism are considered to be of Devonian and/or early Carboniferous age. However, cross-cutting basic dyke swarms, of presumed Cretaceous age, are locally affected by post-intrusion deformation and greenschist-facies metamorphism in the vicinity of the Tertiary Kap Cannon thrust. Late Phanerozoic K-Ar mineral ages have been obtained from Palaeozoic metasediments as well as from cross-cutting basic dykes (Dawes & Soper 1971).

The Kap Cannon thrust is a south-dipping major structure of probably mid-Tertiary age separating volcanic rocks known as the Kap Washington Group from overlying highly-deformed metasediments of the fold belt. The Kap Washington Group is of late Cretaceous age and has given a Rb-Sr isochron age of 63 m.y. (Larsen et al. 1978, Batten et al. 1981). It overlies Carboniferous–Permian and Cretaceous sediments of the Wandel Sea Basin succession (Higgins et al. 1981, Håkansson et al. 1981).

Other Tertiary structures include a system of NW–SE trending faults and associated drag folds affecting the Wandel Sea Basin sediments (Håkansson 1979), and the Harder Fjord fault zone — a major E–W structure running through the centre of the fold belt. The Harder Fjord fault zone shows relative uplift of the northern block, while within graben-like structures in the fault zone there are preserved restricted sequences of Upper Permian, Cretaceous and Tertiary sediments (Croxton et al. 1980, Soper et al. 1980, Wagner et al. in press).

Discussion

It is evident that the mid-Palaeozoic fold belts of northern Ellesmere Island and North Greenland were formerly continuous. In both regions the effects of the Ellesmerian orogeny are seen in the northward increase in deformation intensity and metamorphic grade, and the 'fold belts' distinguished in northern Ellesmere Island can be closely compared and correlated with the 'structural-metamorphic zones' of North Greenland. The obvious correlations have been depicted in Figs 1 and 2 by use of the same ornamentation. However, the positioning of the boundary lines between the different 'belts' or 'zones' is subjective, and they cannot be used for other than generalised assessments of the displacement along the Nares Strait lineament. The northern Ellesmere magmatic belt is, for example, of different character from the northernmost parts of the North Greenland fold belt; their only common feature is the occurrence of amphibolite-facies Palaeozoic rocks.

A feature of interest is the general alignment of the Lake Hazen fault zone in Ellesmere Island and the Harder Fjord fault zone in North Greenland. Both structures show substantial uplift to the north and had their latest movements in the Tertiary; both structures may have had a long pre-Tertiary history, though the evidence for early movements is not well documented. The two faults are separated by about 200 km of the Arctic Ocean with the present configuration of Ellesmere Island and Greenland (Figs 1 and 2), but may represent a single fundamental fracture zone of potentially the same importance as the Nares Strait lineament. In addition, the important fault zones on Judge Daly Promontory and northern Nyeboe Land also show good alignment (see Dawes, this volume).

A striking feature of the Innuitian tectonic province in the region as a whole is its greater north–south width in Ellesmere Island compared to North Greenland (Figs 1 and 2). Complexly folded rocks in amphibolite facies are in the one case 350 km distant from the south limit of folding, and in the other 150 km. Another general difference between the folded rocks on the two sides of Nares Strait is the general southwards overturning of folds in Ellesmere Island compared to a general northwards sense of overturning in Greenland; there are exceptions in both regions. These features are no doubt original characteristics developed during the Ellesmerian orogeny, arising in part from the nature and distribution of the rocks undergoing deformation, and in part from the nature and location of the active deformation mechanism; discussion of their significance is beyond the scope of this paper.

In view of the above considerations, and since the Nares Strait lineament transects structural trends and boundaries at low angles, precise determination of wrench movements along the line of the lineament is not possible. Nevertheless there is sufficient information to place restraints on the likely range of displacement.

Constraints on displacement

A range of models ranging from 0 to 250 km left-lateral displacement are considered, with their consequences for correlation of structural and metamorphic features (Fig. 3).

No displacement (Fig. 3a). – The present-day configuration requires a pronounced swing of the south limit of folding parallel to the line of the Nares Strait lineament, but this swing in trend is clearly reflected by the trends of individual folds on the Canadian side of Kennedy Channel. There is a good line-up of the southern belts of more open folding, and also of the Hazen fold belt and the tightly folded rocks of Nansen Land. Fold trends show good alignment. The highest grade metamorphic areas lie on strike, but as they are 500 km apart this is not a conclusive line of argument.

50 km left-lateral displacement (Fig. 3b). – The swing of the south limit of folding is less pronounced in this model, but still reflects that of the folds on land. The two southern zones of more open folding line up well, the central Ellesmere fold belt showing a gradual, and realistic, attenuation eastwards into zone 2 on the Greenland side.

100 km left-lateral displacement (Fig. 3c). – The southern two fold belt boundaries can now be joined by sinuous curves, somewhat less pronounced than the swings of individual fold trends on the west side of Kennedy Channel. However, the south margin of the Hazen fold belt is now offset relative to the 2–3 zone boundary, such that open folds on Judge Daly Promontory lie on strike with tight folds in Greenland. Furthermore there is non-alignment of individual fold trends in this model from the central Ellesmere fold belt over to zone 2 on the Greenland side.

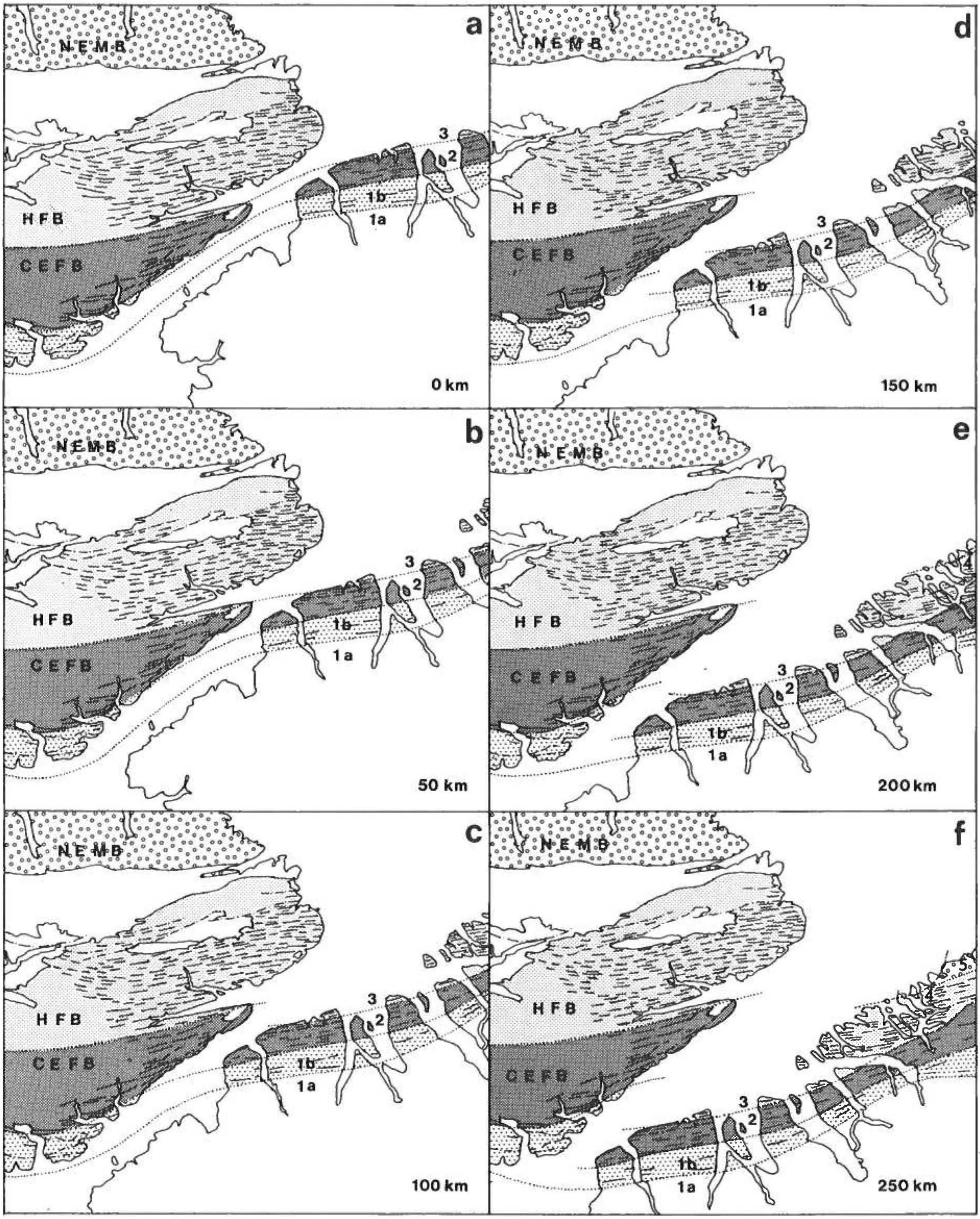

Fig. 3. Pre-displacement constructions of the relative positions of northern Ellesmere Island and North Greenland, assuming sinistral strike-slip displacements on Nares Strait of zero to 250 km. NEMB: northern Ellesmere magmatic belt. HFB: Hazen fold belt. CEFB: central Ellesmere fold belt. 1a, 1b, 2, 3, 4, 5: structural–metamorphic zones in North Greenland.

150, 200 and 250 km displacement (Fig. 3d, e, f). – With increasing displacement there is progressively greater mismatch of the fold belts, fold trends and metamorphic zones. In the worst case (250 km displacement), amphibolite-facies, intensely deformed metasediments in Greenland (zone 5) lie on strike with non-metamorphic gently folded terrain in Ellesmere Island.

Conclusions

The present distribution of fold belts and metamorphic zones in northern Ellesmere Island and North Greenland is consistent with no sinistral displacement on the Nares Strait lineament since mid-Palaeozoic time. However, we consider that displacements up to 50 km can be accommodated without causing unlikely geological relationships. In any case zero offset seems improbable in view of the scale and remarkable linearity of the structure. Displacement models greater than 50 km show increasing mismatch of structural and metamorphic elements and are considered most unlikely to have occurred.

The structural and metamorphic data thus favour those interpretations of Greenland – North America spreading geometry which require small wrench displacements on the Nares Strait line (see Soper et al., this volume).

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