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Significance of crustal-scale shear zones and synkinematic mafic dykes in the Nagssugtoqidian orogen, SW Greenland: a re-examination

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Abstract—The published accounts of the structural geology and tectonic evolution of the Early Proterozoic Nagssugtoqidian orogen, SW Greenland, require modification in several fundamental respects. The geometry of the orogen has been attributed to important displacements on major conjugate shear zones and thrust zones. From new field observations, we are unable to confirm that crustal-scale shear zones have played an important role in Nagssugtoqidian tectonics. The 'dextral' component of 'conjugate' shear zones is demonstrably sinistral and transpressive, strike-slip shear zones are incipient, and a major thrust zone within the orogen cannot be confirmed at its projected inland location. The sinistral strike-slip *Nordre Strømfjord shear zone* is an order of magnitude smaller than previously thought. It comprises an array of non-linked segments of annealed mylonite and cannot have accommodated large displacements. The dextral *'Itivdleq shear zone'* is characterised by heterogeneous, sinistral, noncoaxial flow, but compared with deformation elsewhere in the orogen, it is not a large-scale zone of strain localisation. *'Ikertôq thrust zone'* is not an orogen-scale shear zone, but appears to be part of a large-scale, rheological boundary. Application of an *èn relais* fracture array model to what is classically identified as the Kangâmiut mafic dyke swarm suggests that the sinistral vorticity determined throughout much of the Nagssugtoqidian orogen is detectable in the Archean foreland up to 150 km south of the orogenic front.

INTRODUCTION

In the Early Proterozoic (ca 2.0–1.8 Ga) Nagssugtoqidian mobile belt or orogen, SW Greenland (Fig. 1; Escher *et al.*, 1976a; Marker *et al.*, 1995), several deep-seated, crustal-scale shear zones have been defined on the basis of fabrics and strain gradients observed in the field (Bak *et al.*, 1975a,b; Escher *et al.*, 1975; Grocott, 1979a,b). They have been studied for their intrinsic structural and petrological interest (Grocott, 1979a,b, 1981; Grocott and Watterson, 1980; Sørensen, 1983; Hickman and Glassley, 1984; Sørensen and Winter, 1989), and interpreted as tectonically significant faults accommodating important conjugate strike-slip movements, as well as thrust displacements, during the Early Proterozoic evolution of the North Atlantic region (Bak *et al.*, 1975b; Watterson, 1978; Korstgård *et al.*, 1987; Van Kranendonk *et al.*, 1993; Park, 1994). Subsequently, they have been taken as type examples of crustal-scale, high temperature shear zones (Grocott, 1977; Sibson, 1977, 1983; Hanmer, 1988a). Moreover, they are of potential geological significance in the geophysical investigation of the nature of faults in the lower crust (Lemiszki and Brown, 1988; Gilbert *et al.*, 1994).

We have undertaken a comprehensive field examination of three of the documented crustal-scale shear zones in the Nagssugtoqidian orogen (Nordre Strømfjord, Itivdleq and Ikertôq, sinistral, dextral, and thrust zones respectively; Fig. 1), paying particular attention to criteria to justify their definition, morphology, sense of vorticity, and relationships to metamorphism and plutonism (see Figs 2, 3 and 4). We have also examined the relationships of the shear zones to the extensive Kangâmiut mafic dyke swarm. Our principal findings are: (i) we are unable to confirm the structures at Itivdleq and Ikertôq fjords as large-scale shear zones; (ii) the Nordre Strømfjord shear zone is an array of non-linked segments interpreted to represent the aborted growth of a crustal-scale, deep-crustal, transcurrent fault, and (iii) the overall sense of vorticity in most of the orogen and its adjacent foreland is sinistral. None of the structures examined during this study appears capable of accommodating tectonically significant displacements and influencing the gross geometry of the orogen.

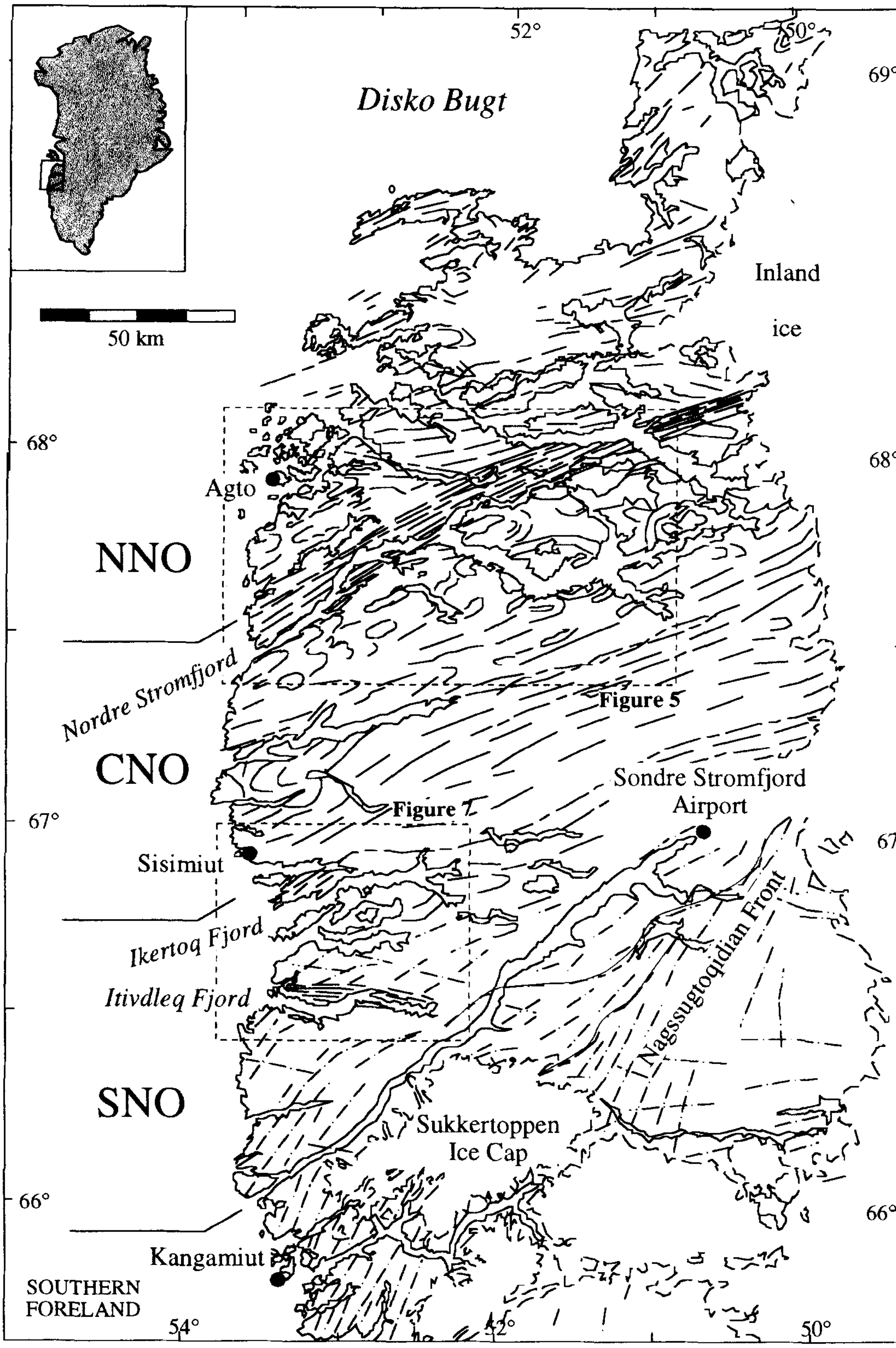

Fig. 1. Generalised structural map of the Nagssugtoqidian orogen and its southern foreland with Kangâmiut dyke swarm (dot–dash lines) and traces of foliation and lithological layering (solid lines) indicated. Inset shows the location in SW Greenland. NNO, CNO and SNO are northern, central and southern segments of the Nagssugtoqidian orogen, respectively. The boundary between the SNO and the Southern Foreland is only approximately indicated. Note that the orogen corresponds to the 'mobile belt' referred to in the text. Locations of Figs 5 and 7 are indicated by boxes.

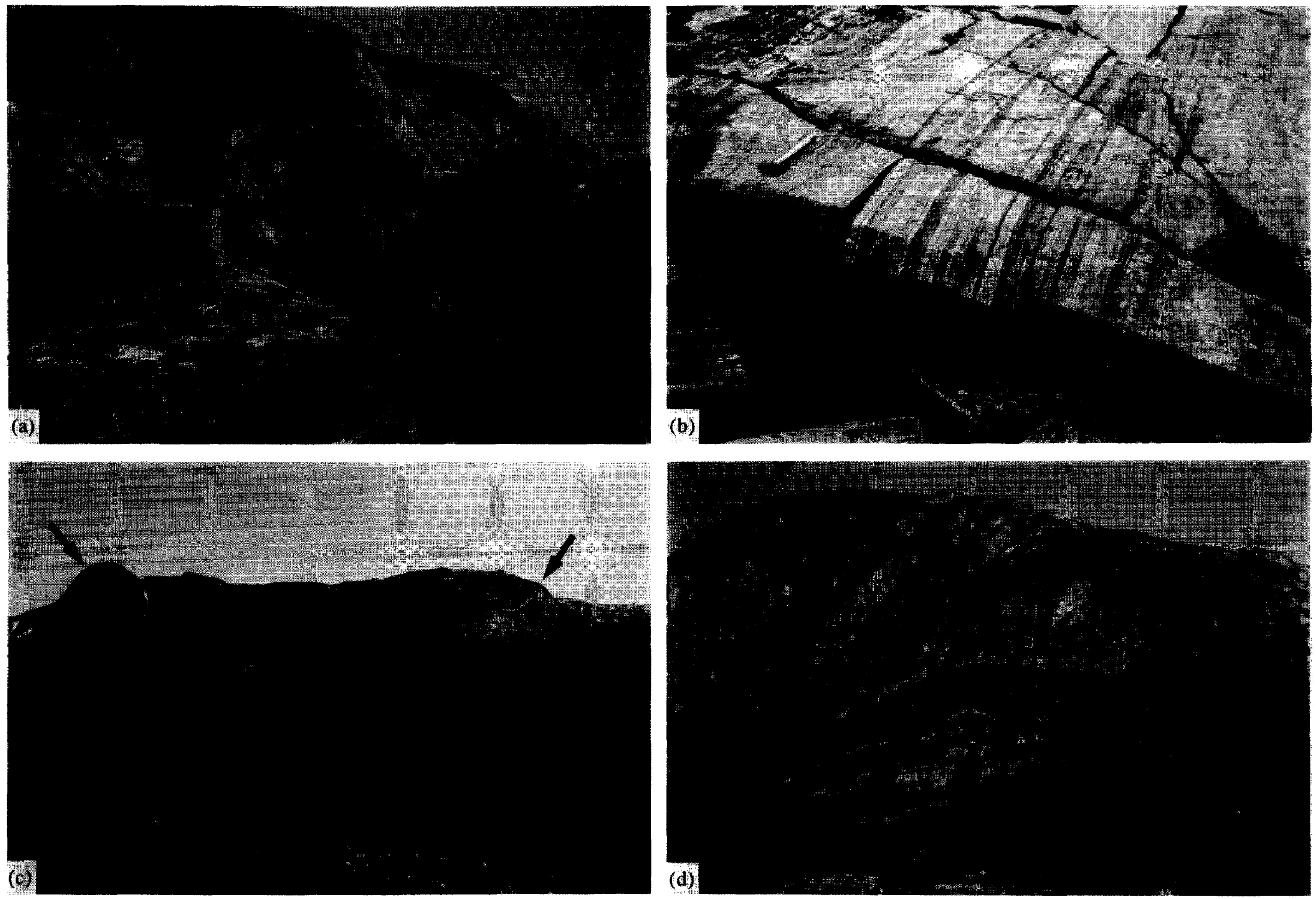

Fig. 2. Illustrations of the structural geology of Nordre Strømfjord. (a) Vertical foliation and horizontal lineation in slabby straight gneiss. Cliff 5 m high. (b) Typical outcrop-scale aspect of straight gneiss. Note the $S >> L$ fabric. Hammer for scale. (c) Panoramic view of flat-lying gneissic layering in the wallrock south of Tiggait, looking to the southeast. The geological history of the layering remains unknown, but could be related to thrust tectonics. The rounded knob to the left (arrow) includes a closure which may represent a recumbent fold nose. Another closure is indicated to the right. (d) Detail of the folded gneissic layering south of Tiggait, looking to the east. Exposure about 300 m high.

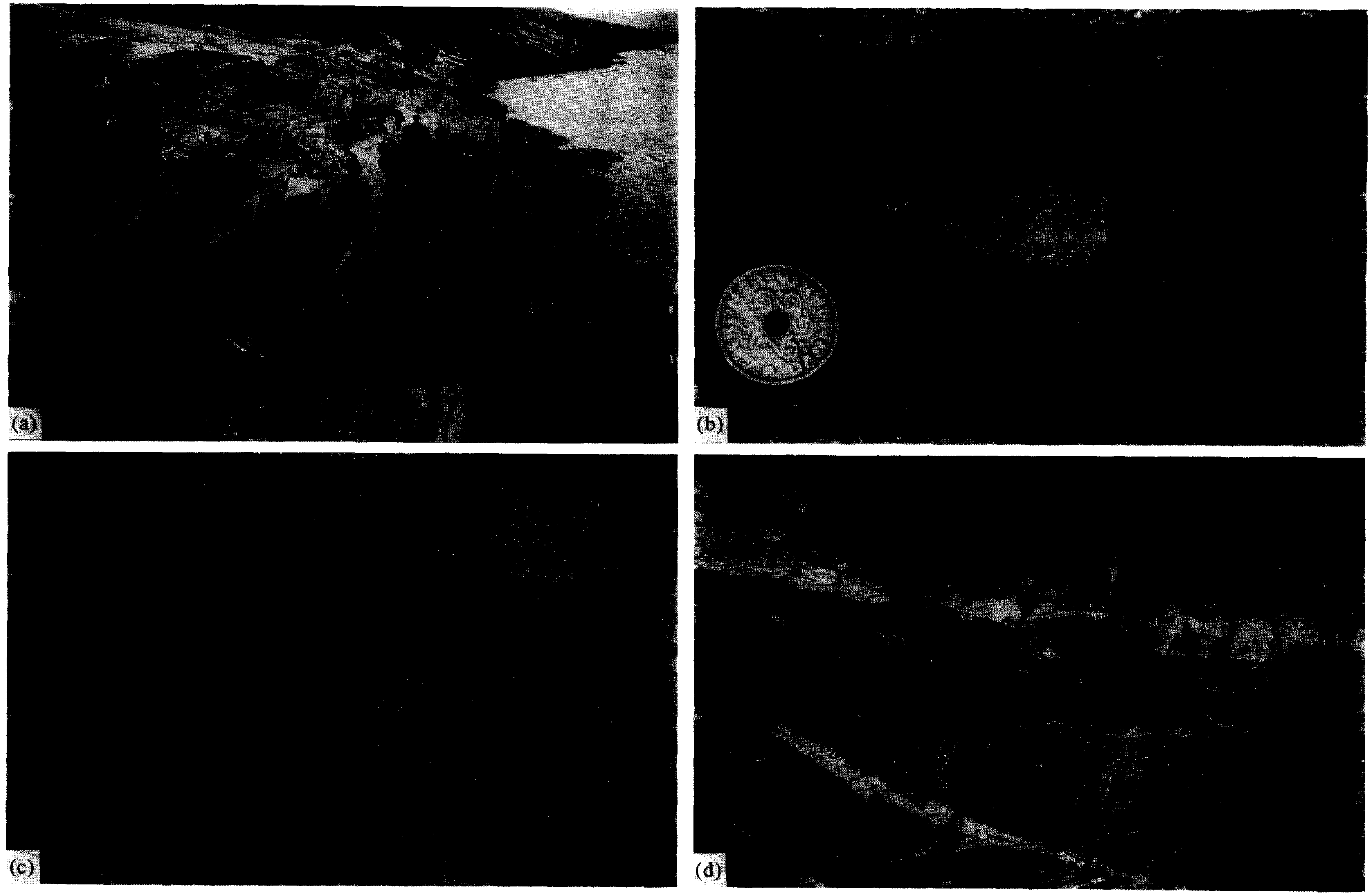

Fig. 3. Illustrations of the geology of Itivdleq Fjord. (a) Narrow strand of straight gneiss developed at the expense of tonalite host charged with mafic inclusions of irregular size and shape in which densely packed fragments separated from one another by pegmatitic granitoid material, concordant to gneissosity in host tonalite, represent a deformed dyke or sill. Note the strain gradient. FCM for scale. (b) Winged 'in-plane' δ porphyroclast indicative of transpressive sinistral shear in straight gneiss (see Hanmer, 1990; Hanmer and Passchier, 1991). Coin for scale. Observed on subhorizontal surface, perpendicular to extension lineation. (c) Mafic inclusions in irregularly banded amphibolite facies tonalitic gneiss. Note the thin filaments extending to the left, and the lobe-and-cusp morphology of the left end of each inclusion. The lobe-and-cusp structure indicates that the mafic rock was softer than its tonalite host during folding, as would be expected if the inclusions are mafic dyke material, deformed just after cooling through the solidus. If the inclusions represent dismembered, rather than heterogeneously dilated dykes, then the associated deformation has not been recorded in the tonalite host. Lens cap for scale. (d) A narrow mafic dyke cutting clockwise across tonalite gneiss. Note the narrow low-angle apophyses pointing away from the observer on the left margin of the dyke (arrows). The dyke represents a dilated array of right-stepping en relais fractures associated with dextral slip along the average trend of the array. Lens cap for scale. Discussed in text.

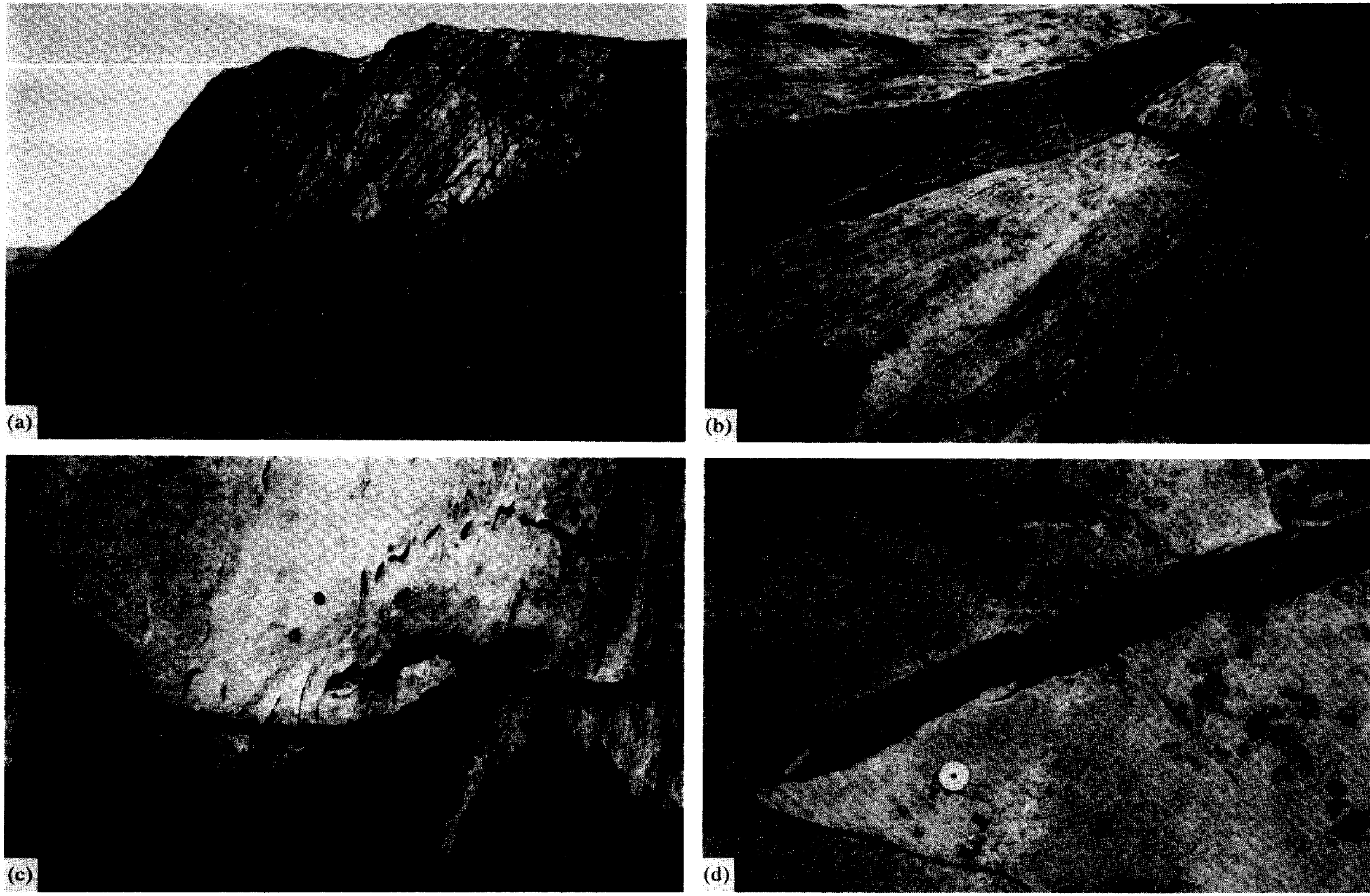

Fig. 4. (a)–(c) Illustrations of the geology of Maligiaq, eastern Ikertôq Fjord (Fig. 8b), to show that the regular and monotonous layering is a reflection of intrusional features, rather than strain and transposition. (a) Looking east at a cliff face (100 m high) of regularly dipping tonalite, tonalitic gneiss and mafic sills (dark bands). Low angle cross-cutting sills indicated by arrow. (b) Detail of outcrop showing cross-cutting relationships well preserved in mafic sills. Hammer for scale. (c) Isotropic, medium grained leucotonalite with irregularly shaped banded gneiss xenoliths, cut by mafic dykes. Note the extreme dismemberment of the older dyke (top left to bottom right), which is cut by the second, less disrupted mafic dyke. The lack of fabric in the leucotonalite suggests that it was unable to permanently record the strain involved in pulling apart the dykes, as might be expected if the mafic dykes were emplaced into a highly mobile, partially crystallised melt. Discussed in text. Lens cap for scale. (d) Example of a Kangâmiut dyke cutting isotropic tonalite on the south shore of Itivdleq Fjord, at the northern margin of the Archean foreland. Note the asymmetrical low-angle apophyses, the broken 'bridges' of wallrock floating in the dyke, and their equivalents still attached to the wallrock adjacent to the apophyses. All the elements are preserved to demonstrate that the dyke intruded along a right-stepping en relais fracture array.

REGIONAL STRUCTURE

The Early Proterozoic Nagssugtoqidian orogen was initially identified on the basis of a progressive change in strike of the Early Proterozoic Kangâmiut mafic dyke swarm from NNE in the Archean foreland to ENE within the 'mobile belt' (Fig. 1; Ramberg, 1948; Noe-Nygaard, 1952; Escher *et al.*, 1976a; Kalsbeek *et al.*, 1978; Myers, 1984; Bridgwater *et al.*, 1995). However, it is now well known that the change in orientation of the dyke swarm is primary, rather than the result of deformation (e.g. Bridgwater *et al.*, 1973; Korstgård, 1979a; Myers, 1984; Korstgård *et al.*, 1987). Syntheses of the geology of the Nagssugtoqidian orogen have been formulated, based on regional reconnaissance and air photo interpretation (Escher, 1971; Escher *et al.*, 1976a; Allaart, 1982), supplemented by detailed local observations (Korstgård, 1979a,b). Metamorphic grade in the orogen is everywhere at upper amphibolite to granulite facies, and its tectonic evolution is purportedly dominated by conjugate, strike-slip shear zones and crustal-scale thrusts of Early Proterozoic age (e.g. Escher *et al.*, 1976a; Watterson, 1978). It is generally considered in three parts (Fig. 1). On the basis of overall metamorphic grade, Ramberg (1948) identified the Isortôq, Ikertôq and Egedesminde Complexes, which approximate to the Southern (SNO), Central (CNO) and Northern Nagssugtoqidian Orogen (NNO) domains of more current usage (Marker *et al.*, 1995).

Historically (Escher *et al.*, 1975), the role and sequence of thrust and strike-slip shear zones in the Nagssugtoqidian orogen have been determined using the Kangâmiut dykes as an approximate time marker to separate earlier and later Nagssugtoqidian events (Myers, 1984, and references therein; see, however, Kalsbeek, 1979). The Kangâmiut dykes are described as cutting a variety of Nag.1 structures, including strike-slip shear zones. Subsequently, they were deformed during a Nag.2 deformation event, principally represented by SSE directed, crustal-scale thrust zones within the orogenic belt, i.e. Ikertôq, and at the Nagssugtoqidian front (Fig. 1; Escher *et al.*, 1975; Grocott, 1979a,b). A model of Early Proterozoic indentation has been proposed to account for the Nagssugtoqidian orogen (Watterson, 1978). However, it has also been suggested that the strike-slip shear zones could be Archean in age (Hickman, 1979; Kalsbeek *et al.*, 1978; Kalsbeek, 1979; Myers, 1984; Korstgård *et al.*, 1987; see also Mengel and Connelly, 1995).

NORDRE STRØMFJORD SHEAR ZONE

As defined by previous workers, the Nordre Strømfjord shear zone extends ENE from the coast, via Arfersiorfik Fjord, towards the inland ice (Bak *et al.*, 1975a; Olesen *et al.*, 1979) and marks a fundamental boundary between the Northern and Central Nagssugtoqidian orogen (NNO and CNO; Figs 1 & 5). Previous workers described the shear zone as an upright corridor of highly strained gneisses, 150 km long, whose anastomosing foliation encloses large augen of less strained rocks (Bak *et al.*, 1975a,b; Sørensen, 1983). At the coast, the shear zone was estimated to be 15 km wide and developed at granulite facies (garnet–clinopyroxene–orthopyroxene in mafic rocks, orthopyroxene in felsic gneisses, garnet–sillimanite–cordierite in metapelites). Inland, it purportedly narrows progressively to 7 km and formed at amphibolite facies (orthopyroxene-absent). The margins of the shear zone are described as dipping outward at about 70° to either side of the vertical. Accordingly, the shear zone widens with depth. The change in metamorphic grade along strike was taken to reflect an overall ENE plunge of the paleohorizontal, exposing the deeper levels of the shear zone in the west. From the mean orientations of foliation, extension lineations and the map-scale shear plane, in great part identified by air-photo interpretation, Bak *et al.* (1975b) calculated a sinistral shear strain (γ) of 6 and a displacement of at least 100 km.

We have made detailed observations at selected locations along the excellent shoreline exposures of Nordre Strømfjord and Arfersiorfik Fjord (Fig. 5). For reasons which will be apparent below, we follow the example of Escher (1970) and refer to the 'Nordre Strømfjord shear zone' (Olesen *et al.*, 1979) as the Nordre Strømfjord steep belt. It is a belt of steeply dipping gneisses and homogeneous, foliated orthopyroxene-bearing metagranitoids sharing a common moderately west plunging to horizontal extension lineation (Figs 2a & 5b). The latter may be marked by mineral aggregates (e.g. quartz or feldspar), aligned metamorphic minerals (e.g. sillimanite or orthopyroxene), or isoclinal fold axes. The gneisses are composed of compositionally and texturally homogeneous to subtly layered, foliated leucocratic tonalite and granodiorite, with laterally continuous screens of garnet–sillimanite–cordierite metapelite, marble and quartzite (Olesen *et al.*, 1979). Throughout the steep belt, orthopyroxene is common in the plutonic rocks in the west, but is absent in the east.

Sørensen (1983) suggested that strain gradients and zones of intense deformation were manifested as air-photo lineaments. There are no obvious criteria to evaluate qualitatively the strain represented by the layering in the paragneisses or the planar foliation in the homogeneous plutonic rocks. However, material heterogeneities present at all scales (e.g. variable grain size in general, feldspar porphyroblasts and megacrysts, irregular layer thicknesses, and cross-cutting pegmatites or mafic dykes), have clearly not been eliminated by dynamic recrystallisation and transposition (see Hanmer, 1988b). Our ground investigation of the air-photo lineaments revealed that they commonly corre-

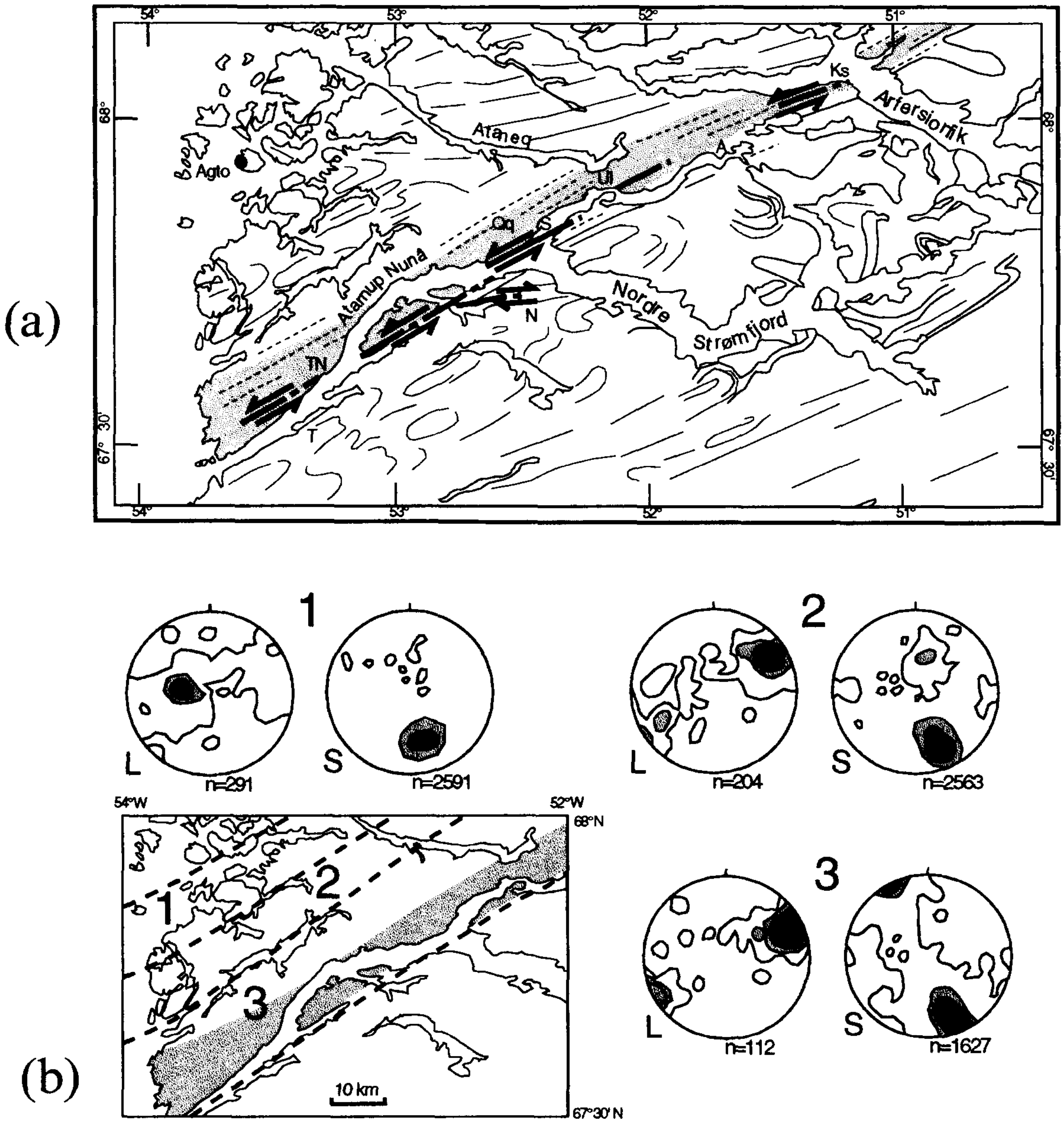

Fig. 5. (a) Map of Nordre Strømfjord and part of Afersiorfik Fjord to show the disposition of the principal straight gneiss strands in a left-stepping array, and locations referred to in the text (A, Amitsuarssuk; Ks, Kangimut sangmissup qaqa; N, Nagssugtûta; Qq, Qaersup qula; S, Sagdleq; T, Tiggait; TN Tungarnt Nuunat; UI, Ulorssuit). The limits of the Nordre Strømfjord steep belt are indicated by the shaded band. The traces of foliation and gneissic layering in the wallrocks (solid lines) are also indicated. (b) Equal-area stereoplots of poles to foliation and extension lineation in the Nordre Strømfjord steep belt (shaded) and its northern wallrocks. Number of measurements indicated by *n*.

spond to homogeneous plutonic rocks containing weakly folded xenoliths to which the pluton foliation is axial planar. We surmise that the lineament pattern is a reflection of the planarity of the foliation. Whereas a planar fabric may represent the product of intense deformation and transposition (see below), its morphology can also reflect the homogeneous response of a rheologically uniform medium to shortening, even at moderate strain magnitudes.

The principal high strain tectonites of the Nordre Strømfjord steep belt occur as straight gneisses (Fig. 2b; Davidson, 1984; Hanmer, 1988b; James *et al.*, 1989; Nadeau and Hanmer, 1992; Kroner *et al.*, 1994). The straight gneisses are composed of granoblastic quartzo-feldspathic to mafic layers, about 10–25 cm thick, and form vertical belts from 10–1000 m wide, some of which can be traced for several tens of kilometres along strike (Fig. 5). On the north shore, at Sagdleq, the termination of the largest of these belts splays into at least a half dozen separate strands of straight gneiss, each up to 100 m thick. Only one such strand crosses the fjord, but it too terminates within a few kilometres. On the margins of each strand, and locally within the thicker belts, strain gradients demonstrate that the straight gneisses are the product of intense progressive deformation. The material heterogeneities and irregularities of the precursor host rocks (see above) are progressively attenuated with strain. The resulting straight gneisses are granoblastic, with grain size of about 1 mm. Nevertheless, the grain size and grain size distribution are smaller and less variable than in the parent material. The end product is a very straight layered rock with few visible intrafolial isoclinal folds and occasional trains of feldspar porphyroclasts; in other words, a statically annealed mylonite in which transposition is complete (Davidson, 1984; Hanmer, 1988b). The $S >> L$ fabric symmetry indicates a strong component of layer-normal shortening (Fig. 2b). The presence of strain gradients, and feathering-out at the terminations of the straight gneiss belts, indicates that they are shear zones (Simpson, 1983; Ingles, 1986). This is confirmed by abundant examples of rotated δ porphyroclasts, asymmetrical extensional shear bands and asymmetrical back-rotated pull-aparts (Hanmer and Passchier, 1991). These indicate a transcurrent sinistral shear-sense in all the belts of straight gneiss, except for the dextral belt at Nagssugtûta, which splays off the main array (Fig. 5). Relict orthopyroxene is common in the straight gneisses in the western part of the fjord, but in general it appears that the shearing occurred at amphibolite facies.

From the foregoing, the spatial disposition of the straight gneisses reflects the distribution of strain localisation. In Nordre Strømfjord there are three principal left-lateral straight gneiss belts. They outcrop along the north shore of the fjord, opposite Tiggait (500 m wide), and southwest and northeast of Sagdleq (1000 m and 100 m wide, respectively; Fig. 5). In Arfersiorfik Fjord, a single 200 m wide belt outcrops just south of Kangimut sangmissup qaqa (Fig. 2). Although we cannot yet constrain the degree of possible overlap between the belts, they form a geometrical array of left-stepping segments that do not appear to link across the intervening step-over areas. In the absence of a master shear plane, the array could not have readily accommodated significant displacements of the wallrocks (Saucier *et al.*, 1992). In fact, it is unlikely that a non-linked array of shears could accommodate much displacement at all (Logan *et al.*, 1992). In other words, the straight gneiss belts represent the aborted early stages of development of a crustal-scale shear zone. Seen in this light, the sense of stepping of the sinistral segments is compatible with a model of shear zone initiation based upon initial brittle fracturing (Segall and Simpson, 1986), where the propagation of sinistral fractures is favoured in left-stepping arrays (Segall and Pollard, 1980; Burgmann and Pollard, 1992; see below). In contrast to the ENE-striking sinistral segments, the belt of dextral straight gneiss trends E–W, and lies to the south of the left-stepping array, and could thus be described as right-stepping and conjugate with respect to the sinistral array. The ubiquitous development of $S >> L$ fabrics in the straight gneisses suggest a bulk transpressive sinistral regime, within which subsidiary antithetic shears are to be expected (Harris and Cobbold, 1985). The generation of mylonite up to a kilometre thick in the absence of significant displacements would be enhanced by a high ratio of coaxial to noncoaxial flow (Hanmer *et al.*, 1995).

We have been able to compare the lithological and structural nature of the Nordre Strømfjord steep belt with its southern wallrock around Tiggait and in the branching arms of the fjord closer to the inland ice, and with its northern wallrock at the head of Ataneq Fjord (Fig. 5). In the southern wallrock, panels of metapelite, marble and quartzite, and homogeneous foliated tonalite alternate with pinkish grey granitic rocks, and appear to be rafts within and possibly between the tonalite plutons. The gneissic layering is subhorizontal (Fig. 5b), with rare fold closures which may represent large (100 m) rootless intrafolial folds (Fig. 2c & d). Closer to the inland ice, the layering is deformed about upright horizontal folds, several kilometres in wavelength (see Escher, 1971). In the northern wallrocks, the shallowly dipping gneissic layering is deformed by open, upright folds, cut by discordant granites, pegmatites and folded mafic dykes (Mengel and Connelly, 1995). Apparently, the fundamental difference between the wallrocks and the Nordre Strømfjord steep belt is the average attitude of the gneissic layering (Fig. 2a & c). At first glance, this suggestion would seem to contradict the regional geology because the map pattern (Escher, 1971; Olesen *et al.*, 1979) depicts subhorizontal gneissic layering, deformed by open, upright, horizontal dome-and-basin folds in the wallrocks, and hair-pin fold traces in the steep belt, interpreted by earlier workers as evidence of a strain gradient (Bak *et al.*, 1975a; Sørensen, 1983). However, the difference in apparent tightness is simply a reflection of oblique sections through highly cylindrical, south verging, upright, horizontal folds within the steep belt, compared with dome-and-basin folding in the wallrock (Escher, 1971; Olesen *et al.*, 1979).

The foregoing begs the question of the origin of the Nordre Strømfjord steep belt. Within the steep belt, on the north side of Nordre Strømfjord (Atarnup Nunâ; Fig. 5), we observed that the gneisses dip steeply to moderately toward the NNW (Fig. 6). The gneissic layering and foliation is folded about upright, horizontal folds. The folds are open to tight, with wavelengths of the order of 100–1000 m, with axes parallel to the extension lineation. In places, a new foliation is developed in homogeneous tonalite, parallel to the axial planes of these folds. Fold asymmetry consistently indicates antiformal closure to the south, in contrast to the southern wallrock, where fold asymmetry consistently indicates antiformal closure to the north (Figs 2d & 6). As a result of these folds, the gneissic layering throughout the belt dips steeply to the NNW (Fig. 6). Nowhere have we observed extensive SSE dipping panels (Bak *et al.*, 1975a; Sørensen, 1983). Rather, both the present northern and southern boundaries of the steep belt appear to be relatively late, discrete, vertical faults (Fig. 6; Mengel and Connelly, 1995). Although Bak *et al.* (1975a) project the steep belt through Nordre Strømfjord to the inland ice, we have followed it

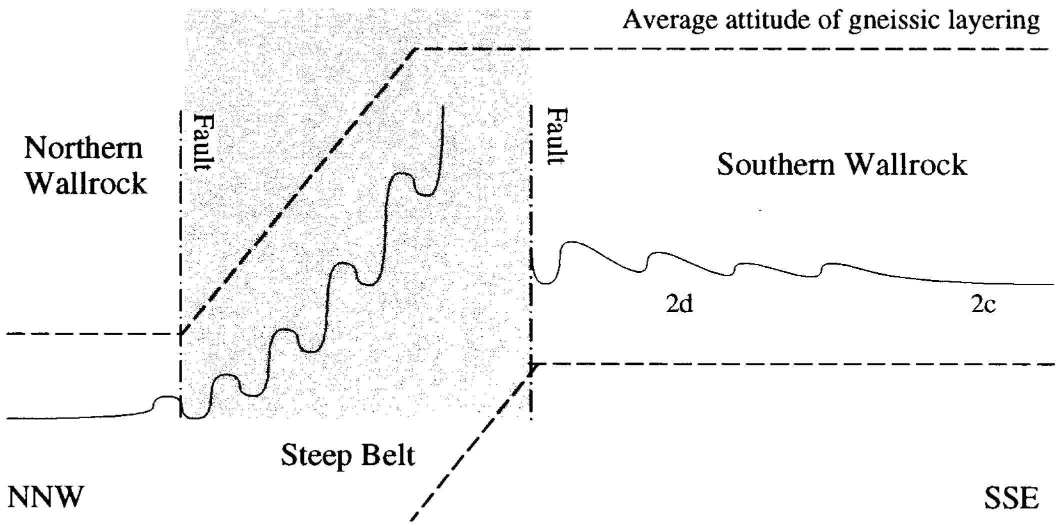

Fig. 6. Highly schematic cartoon section of the Nordre Strømfjord steep belt, at the longitude of Tiggait (Fig. 2), to illustrate the relationship between dip variation of foliation and gneissic layering, as well as fold asymmetry in the flanking wallrocks. Locations of Fig. 2(c & d), corresponding to the flat and folded segments of the southern wallrock, respectively, are indicated. One possible interpretation is that the steep belt is the short limb of a regional-scale NNW verging monoclinal fold.

along strike to Amitsuarssuk, where it dies out (Fig. 5). The steep northward dip of the gneissic layering decreases and passes ENE into a set of symmetrical upright, horizontal folds. One possible interpretation of these geometrical variations is that the steep belt represents the steep limb of a NNW-verging, regional-scale, noncylindrical, monoclinal fold, whose amplitude decreases toward the ENE (Fig. 6). If correct, the transpressive sinistral straight gneiss array may have initiated within the steep belt because the latter was suitably oriented for strike-slip displacement. This suggestion is supported by the absence of folding of the straight gneisses which appear to represent the last ductile deformation structures in the steep belt. Finally, the straight gneiss belt in Afersiorfik Fjord suggests that the array propagated eastward beyond the termination of the monocline.

ITIVDLEQ SHEAR AND IKERTÔQ THRUST ZONES

A 40 km wide corridor of ENE to E–W trending amphibolite facies deformation fabrics between Ikertôq and Itivdleq fjords (Fig. 7), has been identified as the Ikertôq shear belt (Bak *et al.*, 1975b; Grocott, 1977, 1979a,b; Grocott and Watterson, 1980). As defined, it occupies most of the Southern Nagssugtoqidian orogen (SNO; Fig. 1). For reasons which will become apparent below, we shall refer to this feature by the non-genetic term Ikertôq belt. The Ikertôq belt is invaded by the Kangâmiut mafic dyke swarm (Escher *et al.*, 1975, 1976b). On the basis of cross-cutting and deformational relationships with respect to the Kangâmiut dykes, previous workers have postulated two principal phases of deformation within the belt. According to them, the first phase is preserved in the southern part of the Ikertôq belt and is best manifested as the Itivdleq shear zone of Korstgård (Fig. 7; Korstgård, 1979a; Korstgård *et al.*, 1987) and Nash (1979a,b). The second phase is represented at the northern margin of the belt by a major thrust (Grocott, 1977, 1979a,b), referred to as the Ikertôq thrust zone (Fig. 7; Escher *et al.*, 1976a; Korstgård *et al.*, 1987). We have made detailed observations along the length of Itivdleq Fjord, and at the head of Ikertôq Fjord. In the latter location, the fjord presents a complete transect through the Ikertôq thrust zone into the interior of the Ikertôq belt. Observations in Qeqertalik, Kangerdluarssuk, and at Kingaq, complete the cross-section of the Ikertôq belt (Fig. 7).

Itivdleq shear zone

As presented in the literature, the Itivdleq shear zone is a 6 km wide corridor of upright E–W trending fabrics, principally outcropping along the north shore of Itivdleq Fjord (Fig. 8a; Korstgård, 1979b). Although acknowledging that extension lineations may plunge moderately to steeply westward, previous workers placed much emphasis on the presence of shallow plunges and lineation-parallel, strike-slip displacements (Korstgård, 1979b; Nash, 1979a). One of the diagnostic features of the Itivdleq shear zone is the intimate spatial association of deformed and metamorphosed Kangâmiut dykes with their nearly pristine equivalents (Korstgård, 1979b). The traces of the 1–25 m thick dykes are symmetrically disposed at about 25° on either side of the trace of the regional foliation, such that the latter bisects the acute angle between the dyke sets (Bak *et al.*, 1975b; Nash, 1979a; Korstgård, 1979b). These authors interpreted the Itivdleq structure as a dextral shear zone.

Our observations suggest that the structural history of

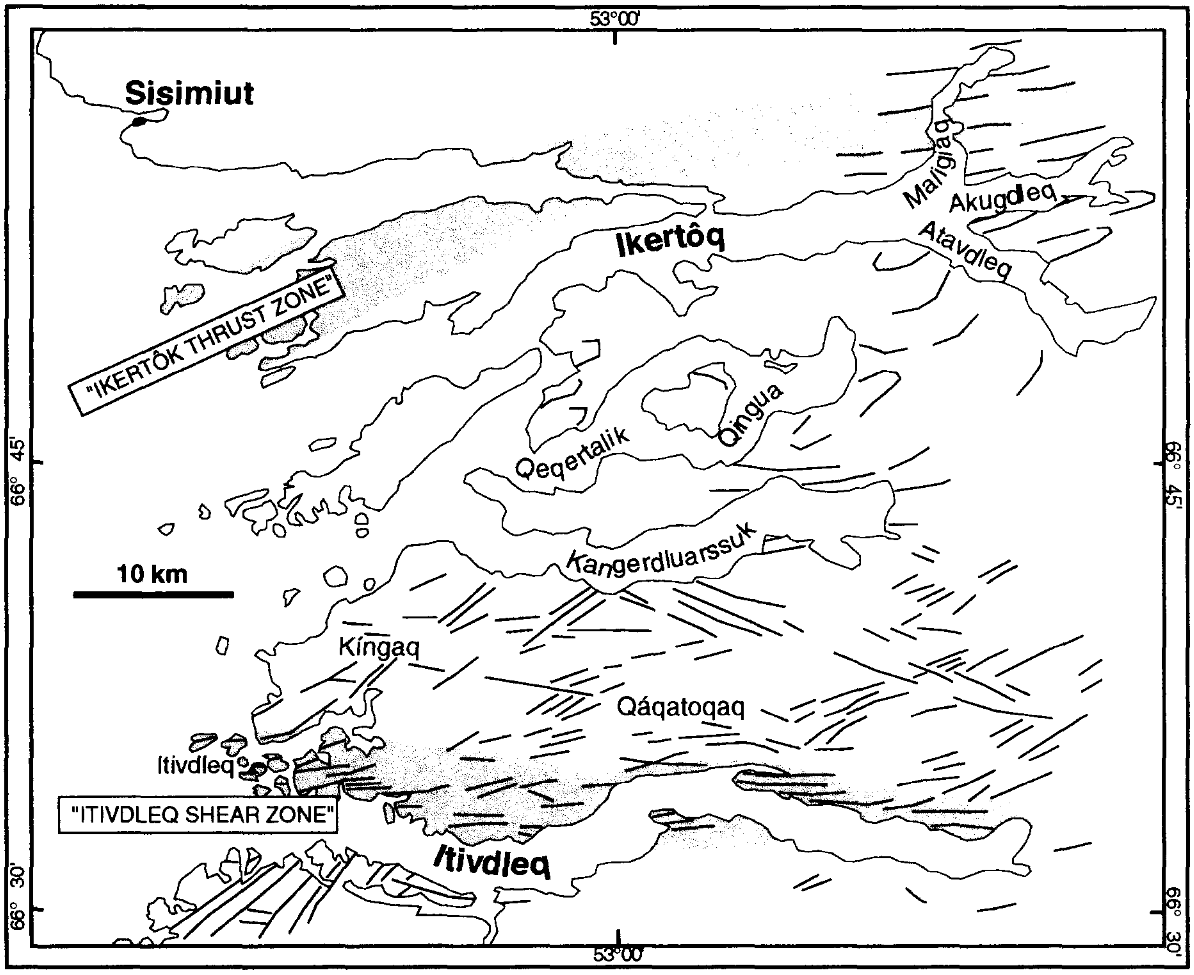

Fig. 7. Sketch map of 'Itivdleq shear zone' and 'Ikertôq thrust zone' (shaded), and locations referred to in the text. Traces of foliation and gneissic layering are indicated as solid lines.

the southern margin of the Ikertôq belt is more complex than that described above. Even within Itivdleq Fjord, complex cross-cutting relationships of pre-Kangâmiut dyke age are very well preserved. Such observations are described here in some detail because they are central to the evaluation of the published large-scale shear zone model. Laterally discontinuous, E–W striking strands of straight gneiss occur all along the northern shore of Itivdleq Fjord. However, they are generally less than 10 m thick, up to a maximum of about 40 m. Except for their dimensions, the straight gneisses and their associated strain gradients (Fig. 3a) are very similar to those already described from Nordre Strømfjord. None of the strands could be traced from one outcrop to the next, and there is no indication that they are part of a linked network. Although the extension lineation may plunge shallowly to the west in some of the outcrops near the mouth of the fjord, lineations are mostly steeply westward plunging to dip-parallel. The straight gneiss strands are upright and concordant to the regional strike. They contain excellent examples of unequivocal sinistral shear-sense indicators, such as δ porphyroclasts (Fig. 3b). These are observed on planar outcrop surfaces which are perpendicular to the steeply plunging extension lineation, and clearly indicate a strongly transpressive flow regime (see Hanmer, 1990), where in the vorticity vector is lineation-parallel and flow is perpendicular to the lineation (Sanderson and Marchini, 1984; Robin and Cruden, 1994).

The straight gneisses, flanked by very obvious strain gradients, are derived from inclusion-charged, leucocratic, hornblende tonalite. The tonalite between the straight gneiss strands is deformed and may commonly be layered. However, the following observations show that it is not highly strained, and that much of its deformed aspect is the result of synplutonic flow. More particularly, it does not represent a zone of strongly localised strain. The included material within the tonalite comprises several components. Panels of folded quartzo-feldspathic gneisses, tens of metres long and enclosed by poorly foliated tonalite, are clearly xenoliths. Similar panels and blocks of banded amphibolite gneiss are probably also xenolithic. The long dimensions of such inclusions are generally concordant to the fabric in the moderately foliated and banded host tonalite. Other mafic inclusions are internally homogeneous and dis-

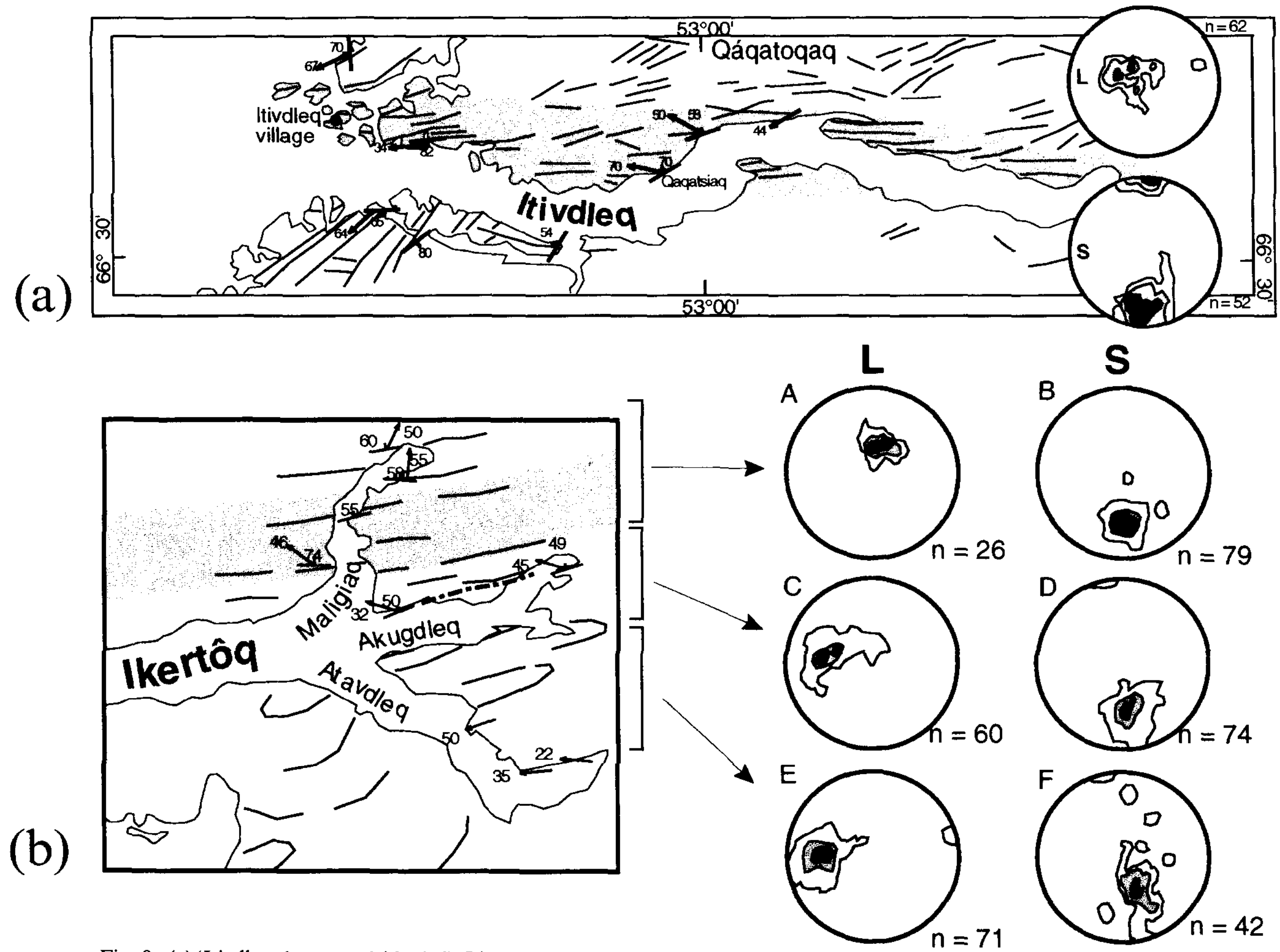

Fig. 8. (a) 'Itivdleq shear zone' (shaded). Lines are traces of Kangâmiut dykes. (b) The projected location of 'Ikertôq thrust zone' at the eastern end of Ikertôq Fjord (shaded). Both (a) and (b) are shown with equal-area stereoplots of extension lineations and poles to foliation, and locations referred to in the text. The bold dashed line in (b) is the trace of the Akugdleq fault. Standard symbols used for strike and dip of foliation and trend and plunge of lineation.

posed either as (i) isolated fragments of centimetre to metre size (Fig. 3c), (ii) concordant, 10–50 m long trains of densely packed fragments separated from one another by pegmatitic leucocratic granitoid material (Fig. 3a), or (iii) discrete, parallel sided, concordant sheets of similar length. The latter resemble concordant dykes or sills. Morphologically, the inclusion trains appear to be fractured and dilated equivalents of the concordant sheets, hence they could be deformed dykes or sills (Hanmer and Connelly, 1986). If this suggestion is valid, then the isolated inclusions may represent extreme dismemberment of once continuous mafic sheets intruded into the tonalite host. Foliation and tectonic banding are heterogeneously developed throughout the tonalite host material. In widespread low strain windows, the high degree of dismemberment of the homogeneous mafic inclusions is apparently at odds with the observed poor foliation development in the tonalite, and the high degree of shape variability and orientation variance of the inclusions themselves. It is possible that the homogeneous mafic material may represent dykes intruded into the tonalite while the latter was in a magmatic state (Bottinga, 1994), and therefore capable of flowing and dismembering the dykes without permanently registering the strains involved (Hanmer and Scott, 1990; McLelland *et al.*, 1992). This suggestion is strongly supported by the common occurrence of lobe-and-cusp folding of suitably oriented sections of the boundaries of some of the inclusions (Fig. 3c; Talbot and Sokoutis, 1992). The tonalite host and the inclusions are visibly deformed in the strands of straight gneiss, and the planar and linear components of the deformation fabric within and between the strands of straight gneiss are coplanar and colinear.

All of the aforementioned features are cross-cut by an array of homogeneous mafic dykes. By convention, these have been designated as Kangâmiut dykes by previous authors (Escher *et al.*, 1975; Korstgård, 1979b; Nash, 1979a,b), and they occur in several structural settings. In the simplest case, medium to fine grained ophitic diabase dykes, up to 10+ m thick, are disposed along an octahedral network of fractures whose enveloping surface dips steeply to the north (Fig. 9a). Although some of the dykes are isotropic, at least in their centres, many carry a wall-parallel foliation with a steeply pitching extension lineation, parallel to that in the adjacent host rocks.

In some cases, the dyke margins are simple and cross-cutting with respect to the wallrock structure. They may also be decorated by asymmetrical bayonet-like apophyses projecting at a low angle into the wallrock (Fig. 3d; see also Fig. 5 of Escher *et al.*, 1975). These are particularly well preserved in pristine or weakly deformed examples. For a given dyke, the apophyses on both margins show the same asymmetry (Fig. 9b). Looking outward from the dyke centres, apophyses on dykes making an anticlockwise angle with the regional foliation in the host rocks point to the left, while those on clockwise dykes point right (Fig. 3d). Such structures are consistent with the geometry of the stepped brittle fracture array into which the dykes were emplaced (Nicholson and Pollard, 1985). In some cases, isotropic and foliated dykes have planar margins and are flanked by narrow mylonitic or finely brecciated selvages of sheared wallrock. In pristine examples, the dyke apophyses intrude already sheared wallrock, and it is clear that the principal activity on the shear zone pre-dates the final emplacement of the dyke. Identical asymmetrical apophyses and sheared selvages have been described and illustrated from individual dykes by Escher *et al.*, 1975, 1976b (see Fig. 9b). Steeply plunging extension lineations in the sheared selvages are parallel to those in the rest of the wallrock, and in the dykes themselves when the latter are foliated. From the deflection of the wallrock layering and foliation, anticlockwise dykes are associated with lineation-normal sinistral shear, and clockwise dykes with lineation-normal dextral shear. In other words, the dykes were emplaced along an array of narrow, plastic to brittle shear zones which accommodated approximately N–S, subhorizontal shortening, and steeply west-plunging extension. A numerical predominance of anti-clockwise dykes is suggestive of a sinistral strike-slip shear component (see also Escher *et al.*, 1975), and indicates that the principal direction of shortening must have been oriented somewhat to the east of north. In brief, emplacement of the Kangâmiut dykes appears to be associated with sinistral transpression, similar to that deduced for the straight gneisses which they cut.

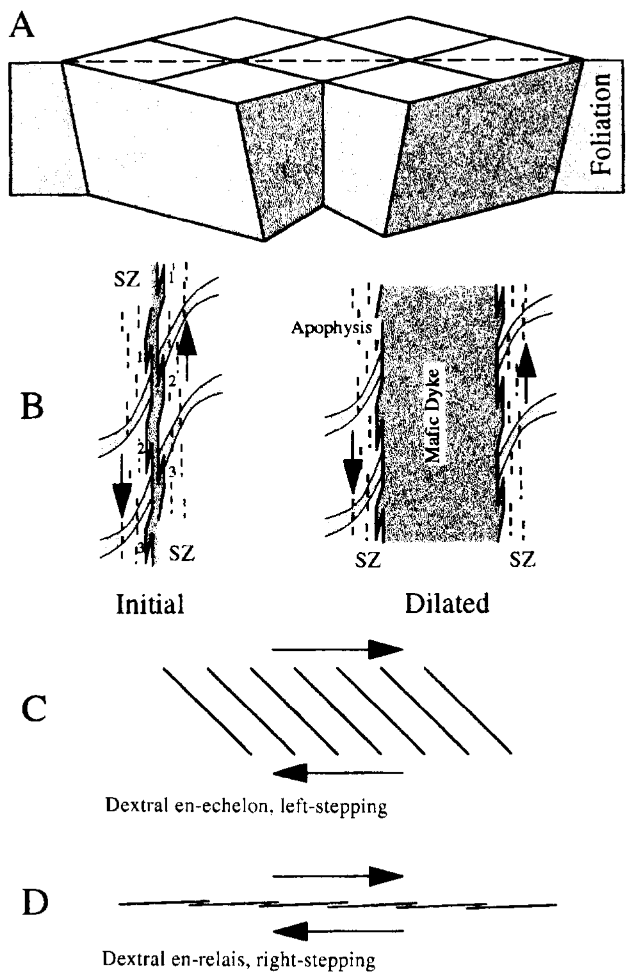

Fig. 9. Schematic illustrations of the configuration of the Kangâmiut dykes, and the discrimination of en échelon and en relais fracture arrays. (a) Three-dimensional representation of Kangâmiut dykes disposed along an octahedral network of fractures whose acute angle is bisected by the regional foliation and gneissic layering. (b) The relationship between shearing, initial fractures (1–3) in an array, mafic dyke emplacement and dilation, and the geometry of low-angle apophyses at the dyke margins. The dilated example is taken from Escher *et al.* (1975). (c) In dextral shear, left-stepping en échelon fracture arrays are readily distinguished from (d) right-stepping en relais fracture arrays. The opposite applies in sinistral shear. Discussed in text.

Ikertôq thrust zone

We have examined the Ikertôq thrust zone and its footwall in the superb shore-line and cliff exposures of Maligiaq, Akugdleq and Avatdleq (Fig. 8b), at the eastern end of Ikertôq Fjord (Korstgård, 1979b; Grocott, 1979a,b). The striking feature of these exposures is the regular nature of the gneissic layering throughout the section (Fig. 4a). Panels of tonalite, 10's to 100's of metres thick, alternate with laterally extensive panels of garnet–sillimanite–kyanite bearing metapelite and quartzite with minor carbonate. The gneissic layering dips shallowly to moderately to the NNW. Extension lineations pitch moderately to the west in Avatdleq, but are dip-parallel in Maligiaq (Fig. 8b). Locally, the extension lineation has a very shallow westward pitch in Akugdleq.

The panels of tonalite are intruded by a dense swarm of concordant metadiabase dykes, generally 1–3 m thick (Fig. 4a), which have been identified as part of the Kangâmiut dyke swarm by Korstgård (1979b) and Grocott (1979b). By comparing the concordant disposition, narrower average width, and more thoroughly metamorphosed state of the Kangâmiut dykes in Ikertôq Fjord with their equivalents further south, these workers have identified a 7 km wide ductile shear zone, whose entire outcrop width projects though Maligiaq (Fig. 8b;

Grocott, 1977, 1979b). This shear zone was interpreted as a thrust, transposing the Kangâmiut dykes and emplacing hot granulite facies rocks over cooler amphibolite facies rocks (Grocott, 1979a).

Our observations do not support the concept of a ductile thrust zone in Maligiaq. Although they are internally foliated and broadly concordant to the host rock layering (Fig. 4a), the mafic dykes preserve local cross-cutting relationships and primary intrusion-related irregularities at their margins (Fig. 4a & b). In places, mafic dykes are disposed in an octahedral configuration, exactly as observed in Itivdleq Fjord. Superb examples of mafic dykes disrupted by magmatic flow in isotropic tonalite, as discussed above, are preserved in the mid-reaches of Maligiaq (Fig. 4c). Locally, the dyke margins are deformed into lobe-and-cusp folds. As at Itivdleq Fjord, these features are collectively suggestive of synplutonic emplacement of the dykes into host rocks which were still in a magmatic state (McLelland *et al.*, 1992 and references therein). The important point here is that the dykes have not been transposed by further deformation. In the northern part of Maligiaq, banded gneisses of uncertain protolith are heterogeneously folded. Their 10 cm scale banding is remarkably regular and was probably straight prior to folding. However, in the absence of strain gradients, the origin of the banding is unconstrained, although it could be related to deformation and transposition. However, the gneisses are cut and included as xenoliths by 100+ m thick concordant sheets of moderately foliated tonalite, themselves cut by the synplutonic mafic dykes just described. The salient point here is that, whatever its origin, the once straight banding is older than the mafic dykes. Isolated folds of layering are present in Avatdleq, but there is no indication that their absence in Maligiaq is the result of progressive strain and transposition. Rather, we suggest that the concordant disposition and width of the dykes is simply a reflection of their mode of emplacement and degree of magmatic inflation; in other words the 'dykes' are really narrow sills. Indeed, there is no fundamental change in the banded aspect of the host gneisses and their sills from Avatdleq to Maligiaq, i.e. there is no evidence of a strain gradient.

Except for Akugdleq (Fig. 8b), few shear-sense indicators are preserved in these rocks. However, at one place near the mouth of Maligiaq, penetratively developed asymmetrical extensional shear bands indicate sinistral shear with the vorticity vector parallel with the down-dip extension lineation. In Akugdleq, scattered, laterally discontinuous strands of concordant, granoblastic straight gneiss, up to 10 m thick, contain extension lineations plunging gently to the west, with shear bands and winged feldspar porphyroclasts indicating lineation-parallel dextral shear. The base of the cliffs all along the north shore are riddled with spectacular pseudotachylite veins, similar to those described to the west by Grocott (1981). These are associated with narrow (50 m) chlorite-bearing greenschist mylonites and cataclasites, all containing asymmetrical shear bands indicative of dextral strike-slip movements (Grocott, 1981). These observations suggest that Akugdleq may be the site of a dextral strike-slip shear which began to localise at high metamorphic grade, but which only propagated successfully at greenschist facies.

'Ikertôq belt'

Our observations in Qeqertalik and Kangerdluarssuk (Fig. 7) indicate that the state of deformation there is very similar to that described above for Itivdleq Fjord. The principal difference is that the attitude of the planar structures and lithological layering passes rapidly from vertical to shallowly northward dipping at Qingua, in the NE corner of Qeqertalik (Fig. 7). Combining our structural observations across the width of the Ikertôq belt, we conclude that the area between Ikertôq and Itivdleq fjords is characterised by a diffuse noncoaxial flow regime. Sinistral transpression can be demonstrated in the south (Itivdleq Fjord), and there is some suggestion that it may also apply across the entire belt. We see no indication of the localisation of major high grade shear zones. The strain gradient identified by Grocott and Watterson (1980) in the vicinity of Itivdleq village (Fig. 7) is perhaps a local feature, rather than diagnostic evidence for a major shear zone in Itivdleq Fjord. Nonetheless, we agree with the above cited previous workers who were impressed by the homogeneous nature of the concordant layering along the northern margin of the Ikertôq belt, compared with the heterogeneous nature of the fabrics to the south. However, in the absence of regional-scale strain gradients, we suggest that homogeneous flow in Ikertôq Fjord was a function of large-scale anisotropic rheology, induced by the presence of the laterally extensive alternating panels of metasediment and orthogneiss. Furthermore, we speculate that by providing pre-existing planes of weakness, such an anisotropy could have favoured the emplacement of mafic sills, rather than dykes. The only mappable shear zone we have found is the low grade dextral precursor to brittle deformation and pseudotachylite generation along what we would call the Akugdleq fault, which probably underlies the length of Ikertôq Fjord (Fig. 8b). Larsen and Rex (1992) note that pseudotachylite associated with the fault cuts lamprophyre dykes of probable Late Proterozoic age.

DISCUSSION

In a preliminary description of the geometry of the Nagssugtoqidian orogen, Escher (1970) referred to laterally continuous 'steep belts', which he distinguished from the intervening terrains. As documented above, subsequent workers interpreted some of the steep belts as crustal-scale shear zones, and presented criteria for their identification, shear-sense and tectonic significance, both at the scale of the orogen and that of the North Atlantic craton as a whole (Bak *et al.*, 1975b; Watterson, 1978; Korstgård *et al.*, 1987). Of the three putative shear zones we have examined, we were only able to confirm one, Nordre Strømfjord, as a potential crustal-scale feature. Even there, the shear zone component of the steep belt was found to be volumetrically minor, and of little account in terms of orogen-scale tectonic displacements. However, it offers an unrivaled opportunity to directly study the processes operating in a large, deep-seated shear zone during the early stages of its development (Segall and Simpson, 1986).

We suggest that the Ikertôq thrust zone may represent the boundary between crustal-scale homogeneous flow, canalised by a large-scale anisotropy (Lister and Williams, 1983) due to extensive alternating panels of paragneiss and tonalite to the north, and heterogeneous crustal-scale flow in the less anisotropic tonalites to the south. The thrust zone identified in the westernmost part of this boundary (Grocott, 1979a,b) does not appear to project as far inland as was originally proposed (Bak *et al.*, 1975b; Korstgård, 1979b). The spatial association between this rheological boundary and the southern limit of granulite facies metamorphism is either coincidental, or related to an as yet undetected cryptic structure. Itivdleq shear zone is not a zone of localised deformation. Rather, it appears to be a spectacularly accessible example of the diffuse, heterogeneous noncoaxial flow which characterises the entire southern part of the orogen.

With the exception of the precursor shear zone to the Akugdleq fault, all of our shear-sense determinations indicate sinistral transcurrent shear across the orogen, from Nordre Strømfjord to Itivdleq. We have shown that the disposition and bayonet-like apophyses on mafic dykes intruded within the orogen also suggest an overall sinistral shear-sense, albeit associated with transpression. It has long been recognised that the Kangâmiut dykes in the Archean foreland also carry systematically asymmetrical apophyses (Escher *et al.*, 1976b), and that the change in their orientation is primary (Fig. 1; Bridgwater *et al.*, 1973). Nevertheless, these observations have never been explicitly integrated with those from within the Nagssugtoqidian orogen. As we shall now show, despite the large gaps in our knowledge of the structural history of the orogen as a whole, the results of such an exercise allow us to attempt a comparison between the deformation within the orogen and that of the foreland.

Dykes as vorticity indicators

Dykes are emplaced into fracture arrays which subsequently dilate in response to magmatic pressure (Delaney *et al.*, 1986). Examination of the field data presented by Escher *et al.*, 1975, 1976b, as well as our own, demonstrates that the pre-dilation fracture arrays stepped left in sinistral shear and stepped right in dextral shear (Figs 4d & 9). In bulk pure shear, stepping fracture sets can result from the interaction between the first two overlapping fractures generated in the array and the local stress field (Olson and Pollard, 1991). However, where the sense of stepping is systematically related to the orientation of the fracture array, it is a function of the sense of shear along the array (Segall and Pollard, 1980; Baer and Beyth, 1990; Burgmann and Pollard, 1994).

Two kinds of fracture array associated with the emplacement of dykes have been documented in the literature, and each has a diagnostic stepping relationship with respect to sense of shear along the array (Fig. 9). En échelon fractures form normal to the direction of principal instantaneous extension (Fig. 9c; Nicholson and Pollard, 1985; Olson and Pollard, 1991). Where they form during noncoaxial flow, right-stepping arrays are associated with sinistral shear, and left-stepping arrays with dextral shear (Ramsay, 1980). In either case, the fractures initiate at a significant angle to the flow plane, at an orientation which depends upon the kinematical vorticity number (W_k) of the flow (Means *et al.*, 1980). Overlap between neighbouring fractures in the array is commonly well in excess of 50 %. In the second kind of array, the fractures make a very low angle ($<5°$) with the flow plane and only overlap their neighbours at the tips (Fig. 9d; Delaney *et al.*, 1986). Although often referred to in the literature as en échelon, such arrays are clearly distinct from the first kind. We suggest referring to such arrays as en relais (Berthelsen and Bridgwater, 1960). When they form during noncoaxial flow, right-stepping arrays are associated with dextral shear, and left-stepping arrays with sinistral shear (Segall and Pollard, 1980; Burgmann and Pollard, 1992). Although arrays of low angle, barely overlapping fractures can result from the dilation of internally over-pressured en échelon fractures (Nicholson and Ejiofor, 1987), the relationship between stepping and shear-sense would still be diagnostic of the array type. The salient point here is that the relationships we describe from Itivdleq Fjord, and those described from elsewhere in the southern part of the Nagssugtoqidian orogen (Escher *et al.*, 1975, 1976b), correspond to the emplacement of the Kangâmiut dykes into en relais fracture arrays.

From the dykes in Itivdleq Fjord, we derive the same approximately north–south, subhorizontal direction of principal shortening as indicated by the ductile shear zones into which many of them were emplaced (see also Nash, 1979a). Escher *et al.* (1976b) have examined the Kangâmiut dykes in the Archean foreland immediately south of Itivdleq Fjord (Fig. 1). The dykes are described as conjugate, with one set striking NE and the other ESE. Morphologically the dykes are very similar to those within the Nagssugtoqidian orogen, with a systematic relationship between apophysis asymmetry and dyke orientation (Figs 4d & 10). By treating the initial fractures as contemporaneous en échelon arrays in their kinematic analysis, Escher *et al.* (1976b) predicted that the direction of principal instantaneous shortening bisected the obtuse angle between the dyke sets. Although they noted that this was a significant departure from fracture theory, these authors interpreted oblique internal fabrics and local offsets across the dykes as supporting evidence for the shear-sense determined from the fracture arrays. Furthermore, they considered that the NNW oriented principal shortening was consistent with the pattern of major conjugate shear zones within the Nagssugtoqidian orogen, i.e. Nordre Strømfjord (sinistral) and Itivdleq (dextral), and subsequent SSE directed thrusting at Ikertôq and the Nagssugtoqidian front. However, in light of our observations, this direction of instantaneous shortening is at odds with the observed sinistral sense of vorticity throughout the orogen.

We suggest that the Kangâmiut dykes in the Archean foreland were emplaced into en relais fracture arrays, similar to the dykes within the orogen (compare Fig. 3e with Fig. 4d). Accordingly, the direction of principal instantaneous shortening bisects the acute angle between the dyke sets, as predicted by failure theory for isotropic Coulomb materials (see Fig. 10; Reches, 1983). We suggest that the local internal foliations and offsets described by Escher *et al.* (1976b) might reflect minor antithetic slip along the dykes in response to post- or syn-emplacement rotation of the dykes. If it is valid to extend the observations on dykes south of Itivdleq Fjord (Escher *et al.*, 1976b) deep into the Southern Foreland, the bisector or direction of principal instantaneous shortening at the latitude of Kangâmiut village (Fig. 1) trends NE and is compatible with the observed sinistral vorticity resolved onto E–W to ENE striking shear planes within the orogen. At first glance, the approximately N–S trending direction of principal shortening, bisecting the obtuse angle between the Kangâmiut dyke sets in Itivdleq Fjord might appear to contradict this analysis. However, it has been established that the change of the Kangâmiut dyke trend is primary, and that the dykes in Itivdleq Fjord cut foliated rocks with a well developed E–W grain. The effect of a rheological anisotropy on the development of discrete conjugate shear zones is two-fold. First, it results in rotation (refraction or spin; see Lister and Williams, 1983) of the instantaneous principal stretches towards the anisotropy and its normal (Treagus, 1983, 1988). Second, it results in an opening of the inter-shear zone angle bisected by the direction of principal shortening (Cobbold *et al.*, 1971). Accordingly, we suggest that the boundary conditions compatible with the sinistral vorticity observed throughout the Nagssugtoqidian orogen south of and including Nordre Strømfjord are detectable in the Archean foreland up to 150 km south of Itivdleq Fjord. Rather than being dominated by crustal-scale localised shear zones, the Nagssugtqidian orogen and its southern foreland appear to represent a vast domain of diffuse sinistral transpression.

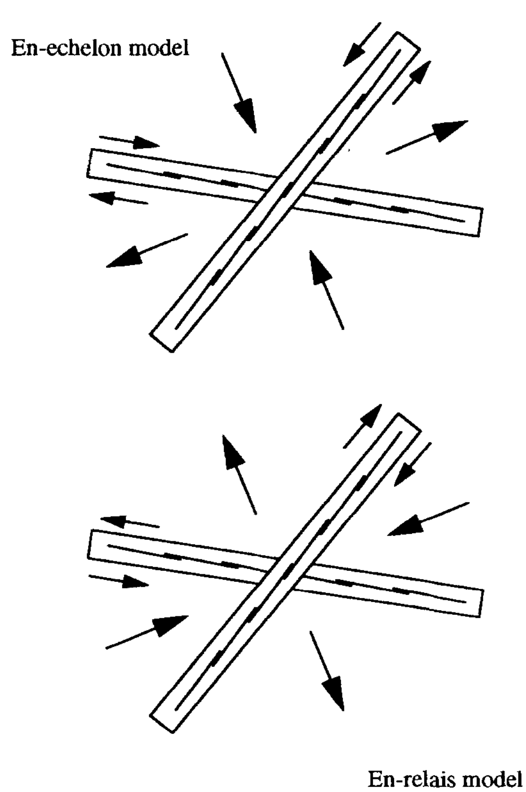

Fig. 10. Schematic comparison of the bulk kinematic interpretation derived by Escher *et al.* (1976b) from mutually cross-cutting Kangâmiut dykes in the southern foreland assuming an en échelon fracture model, compared with the interpretation determined from an en relais model for the fracture arrays (see Fig. 9c & d). Discussed in text.

CONCLUSIONS

We are unable to confirm that crustal-scale shear zones have played a major role in the tectonic history of the Nagssugtoqidian orogen.

(1) Nordre Strømfjord shear zone is a sinistral strike-slip structure, but the shear zone is an order of magnitude smaller than previously thought. It comprises an array of non-linked segments and cannot have accommodated tectonically significant orogen-scale displacements.

(2) 'Itivdleq shear zone' is characterised by heterogeneous sinistral transpressive flow, but compared with deformation elsewhere in the orogen, it is not a large-scale zone of strain localisation.

(3) 'Ikertôq thrust zone' appears to correspond to an orogen-scale rheological boundary between homogeneous and heterogeneous noncoaxial flow, rather than a crustal-scale, contractional shear zone.

(4) Application of an en relais fracture array model to the Kangâmiut mafic dyke swarm suggests that the sinistral vorticity observed throughout much of the Nagssugtoqidian orogen is detectable in the Archean foreland up to 150 km south of the orogenic front.

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