

Structural analysis of the northern Nagssugtoqidian orogen, West Greenland: an example of complex tectonic patterns in reworked high-grade metamorphic terrains

Stanislaw Mazur, Sandra Piazzolo and G. Ian Alsop

Structural analysis of the deeply eroded northern flank of the Palaeoproterozoic Nagssugtoqidian orogen shows marked regional variations in both the orientation and type of fabrics, as is characteristic of Precambrian high-grade terrains subjected to polyphase deformation. Here we investigate the relationship between strain, metamorphic grade, and the resulting structural patterns. The study area south of Aasiaat in West Greenland consists of amphibolite- to granulite-grade Archaean orthogneisses and relatively thin supracrustal units. The regional foliation displays a WSW–ENE to SW–NE strike associated with steep to moderate dips towards the WNW or SSE. Lineation trends are WSW–ENE and generally plunge gently towards the WSW. Mesoscopic fold hinges are usually colinear with the regional lineation. A systematic change in the plunge of lineations occurs across the south-western part of the study area. Towards the south, the lineation plunge progressively increases, despite the generally uniform strike of foliation. This southward increase of lineation pitch is typically associated with the transition from $L > S$ or $L = S$ shape fabrics in rocks characterised by a low pitch, to $S > L$ or S fabrics in the zone of moderate to high pitch. The structural patterns point to subdivision of the study area into a southern domain mostly characterised by S or $S > L$ shape fabrics and a moderate to high angle of lineation pitch, and a northern domain showing $L > S$ or $L = S$ fabrics and low angles of lineation pitch. This subdivision corresponds well with the map scale boundary between granulite facies rocks in the south and amphibolite facies rocks farther north. The observed structural pattern may be explained by two alternative tectonic models: (1) northward indentation of the previously cooled granulite block into the rheologically weaker amphibolite domain, and (2) strain partitioning within a mid-crustal transpression zone. In model 2 the northern domain represents a localised zone dominated by strike-slip kinematics, whereas the southern domain shows evidence of mostly coaxial shortening. Recent geochronology supports the indentator model in spite of limited available data. Despite the details and structural complexities of the two tectonic models, the granulite and amphibolite facies domains seem to form autochthonous segments of a crustal section linked by a transitional zone that was only reactivated and reworked during indentation or transpression. The Nagssugtoqidian compression was effectively transferred across this zone towards the northern amphibolite domain that suffered penetrative deformation during the Palaeoproterozoic event. The N–S shortening was accommodated through folding, indentation and/or strike-slip displacements, rather than by thrusting and folding as seen south of the study area.

Keywords: deformation, GIS, Nagssugtoqidian orogen, transpression, indentation tectonics, West Greenland

S.M., *Institute of Geological Sciences, University of Wrocław, Maxa Bornia 9, 50-204 Wrocław, Poland.*

E-mail: smazur@ing.uni.wroc.pl

S.P., *Geological Survey of Denmark and Greenland, Øster Voldgade 10, DK-1350 Copenhagen K, Denmark.* Present address: *Department of Geology and Geochemistry, Stockholm University, 10691 Stockholm, Sweden.*

G.I.A., *School of Geography and Geosciences, University of St. Andrews, Fife KY16 9AL, UK.*

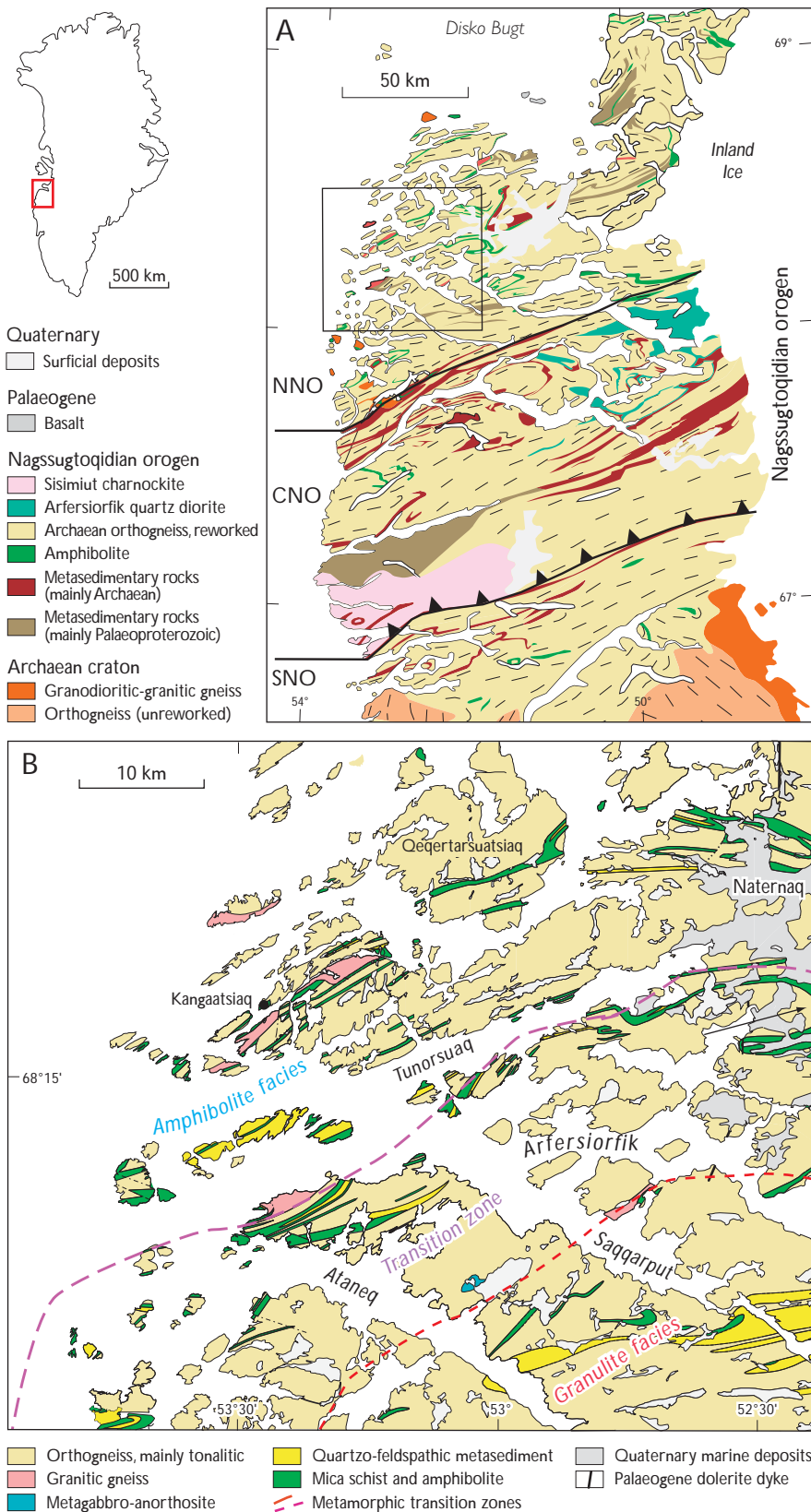


Fig. 1. A: Schematic geological map of the Nagssugtoqidian orogen and adjacent foreland (modified from van Gool *et al.* 2002b). **Outlined box** shows location of the study area. SNO, southern Nagssugtoqidian orogen; CNO, central Nagssugtoqidian orogen; NNO, northern Nagssugtoqidian orogen. B: Simplified geological map of most of the study area (modified from van Gool *et al.* 2002a).

The deeply eroded northern flank of the Palaeoproterozoic Nagsugtoqidian orogen is exposed south of Aasiaat in central West Greenland (Fig. 1). These rocks bear record of tectono-thermal processes that operated at mid-crustal levels in a collisional setting and controlled the distribution of strain and metamorphic facies. The area shows a complex structural pattern that varies significantly from south to north. The aim of this work is to describe the regional variation of structural elements and to investigate the relationship between strain, metamorphic grade and the orientation of deformational structures. This then leads to the consideration of two different tectonic models, which have been developed to account for the observed structural pattern: (1) an indenter model proposed originally by Piazzolo *et al.* (2004), and (2) a transpression zone model.

The study area covers the Kangaatsiaq geological map sheet at scale 1:100 000 (Garde 2004), mapped in 2001–2002 by the Geological Survey of Denmark and Greenland (GEUS; van Gool *et al.* 2002b). The directional and fabric type structural data sets were analysed using Geographic Information Systems (GIS) based techniques that proved to be a powerful tool in the investigation of complex structural patterns. Some of the structural data collected during this field campaign were presented by Piazzolo *et al.* (2004) to illustrate the application of GIS in a multidisciplinary approach to survey high-grade terrains. Our present study focuses on a more detailed analysis and interpretation of the structural relationships of the investigated area, a high-grade Precambrian terrain affected by more than one deformation phase, and whose interpretation is not unequivocal.

Geological setting

The study area covers over 3000 km², and extends from 68°N–68°30' N and 52°W–53°15' W, between the fjord of Ataneq in the south and the island of Qeqertarsuatsiaq in the north (Fig. 1). The area comprises the northern, *c.* 300 km wide exposure of the roughly E–W-trending Nagsugtoqidian orogen (Fig. 1). In the broadest sense, this tectonic belt resulted from a continent–continent collision between the Archaean North Atlantic Craton to the south and an Archaean continental mass to the north (e.g. Kalsbeek *et al.* 1987; Connelly *et al.* 2000; van Gool *et al.* 2002a). The orogen is generally characterised by E–W-trending kilometre-scale folds and ENE–WSW-trending linear belts which overprint an Archaean fabric. On the basis of the grade of metamorphic reworking, Ramberg (1949) and later Marker *et al.* (1995) distinguished south-

ern, central and northern segments of the Nagsugtoqidian orogen (SNO, CNO and NNO respectively; Fig. 1). Detailed structural investigations within the CNO show that deformation in this area is dominated by thrust tectonics (Manatschal *et al.* 1998; van Gool *et al.* 1999).

The investigated area lies within the NNO and is composed of amphibolite- to granulite-grade Archaean orthogneisses interlayered with relatively thin metasedimentary units (Fig. 1). This region is transected by major fjord systems that allow data collection along well-exposed coastal sections. Reconnaissance studies (Noe-Nygaard & Ramberg 1961; Henderson 1969; Marker *et al.* 1995; Kalsbeek & Nutman 1996; Mengel *et al.* 1998; Connelly *et al.* 2000) provided initial information on the structural style of the study area. A comprehensive description of the structural pattern was recently presented by Piazzolo *et al.* (2004) and interpreted in terms of indenter tectonics with a rigid granulite-grade domain moving northwards into a rheologically weaker amphibolite facies domain.

Although quartzofeldspathic orthogneiss dominates in the investigated area, the overall map pattern is governed by discontinuous NE–SW-trending supracrustal belts (Fig. 1). These 2–3 km thick sequences comprise several distinct lithological types: (a) monotonous, garnet-bearing quartzofeldspathic paragneiss locally containing subordinate mafic volcanic and metapelitic intercalations; (b) pelitic to semipelitic schist with or without garnet and sillimanite, including thin quartzofeldspathic layers and rarely quartzite; and (c) layered mafic to intermediate meta-volcanic successions with calc-silicate bands and/or pods.

Previous studies have demonstrated that the metamorphic grade of the NNO decreases northwards and is predominantly amphibolite facies, with granulite facies rocks preserved only in the south-western corner of the study area near the boundary with the CNO (e.g. Marker *et al.* 1995). The contact between these two facies is transitional over a distance of 10–12 km and forms a zone nearly parallel to the strike of the regional foliation (Fig. 1). The granulite facies gneisses are typically pyroxene-bearing and enclose frequent melt pockets and cross-cutting veins. Thermobarometric analyses point to a peak temperature of $800 \pm 30^\circ\text{C}$ at medium pressures of 6–7.5 kbar (Piazzolo *et al.* 2004). The amphibolite facies gneisses are lighter coloured and contain fewer biotite-bearing melt veins. They reveal peak metamorphism conditions of $650 \pm 30^\circ\text{C}$ at 4–5 kbar (Piazzolo *et al.* 2004). Within the supracrustal amphibolites, crystallisation of amphibole, usually developed along foliation planes, indicates a syntectonic fluid flux and associated metamorphism. No relics of earlier granulite facies assemblages are preserved in these rocks. Thrane & Connelly (2006, this volume) carried out seve-

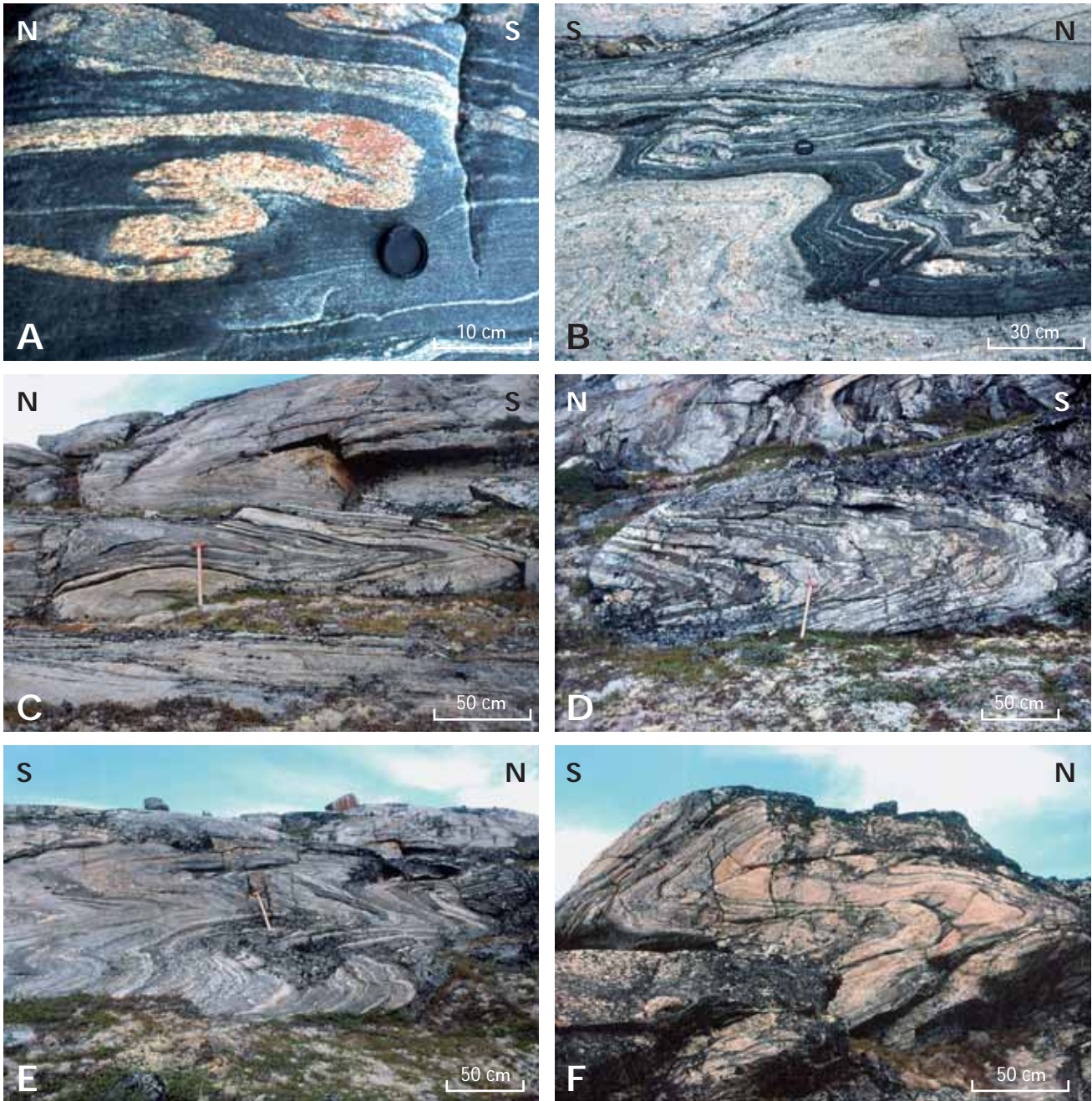


Fig. 2. Examples of mesoscopic folds in the orthogneisses and metasediments of the study area. **A:** Main foliation S_1 of orthogneiss developed parallel to the axial plane of isoclinal F_1 fold. **B:** Lithological boundaries and originally cross-cutting basic dykes folded by F_1 isoclinal fold and showing extensive migmatization. **C:** S_1 foliation folded into isoclinal folds during the same progressive D_1 event. **D:** S_1 foliation and its subsequent folding accompanied by pervasive migmatization. **E:** S_1 foliation locally folded by F_3 folds of variable geometry with fold axes developed subparallel to the lineation. **F:** S_1 foliation of the orthogneiss folded by the F_3 fold with fold axes parallel to the lineation and S-directed asymmetry. N, north; S, south.

ral laser ablation and ion probe age determinations of zircon from within and adjacent to the present study area. Deformation in the south-western part of the area is constrained by the emplacement age of 2748 ± 19 Ma for a synkinematic granite which intrudes the orthogneiss. A Palaeoproterozoic deposition age of *c.* 1950 Ma was obtained from a metasediment within the Naternaq supra-crustal belt (Fig. 1), and broad rims of zircons from an Archaean sediment from Kangarsuneq yielded a metamorphic age of *c.* 1850 Ma, suggesting that major Nagssugtoqidian deformation and metamorphism occurred at around this time. Thrane & Connelly (2006, this volume) also obtained an age of 1837 ± 12 Ma for a vertical, straight pegmatite north-east of Kangaatsiaq trending 020° and displaying sinistral shear along its margins, that is thought to date a late phase of overall N–S-directed Palaeoproterozoic shortening.

Characteristics of directional structures

The main foliation (S_1) is axial planar to rare isoclinal F_1 folds that fold lithological boundaries as well as cross-cutting basic dykes (Fig. 2A). These dykes have been rotated into parallelism with the foliation on the fold limbs (Fig. 2B). The S_1 foliation was itself later folded into isoclinal folds, although this refolding may reflect the same progressive D_1 deformation event since no overprinting fabric is associated with it (Fig. 2C). A characteristic feature of these folds is the broad parallelism of their axial planes to the regional foliation S_1 . A L_1 mineral lineation is developed on the foliation planes and is usually defined by a parallel alignment of amphibole crystals and/or elongated quartz-feldspar and biotite aggregates. The lineation is well developed in the amphibolite facies rocks but rather weak in the granulite facies gneisses. In the transition zone between the amphibolite and granulite domains (Fig. 1B), no mutually cross-cutting mineral lineations were detected and no evidence for fabric superimposition was observed. The L_1 lineation is only rarely associated with kinematic indicators that are commonly symmetric and must have resulted from coaxial strain and/or a finite strain combining the effects of several strain increments. Asymmetric fabrics have been observed only in zones of steeply dipping foliation, and typically indicate a sinistral rotational shear component in the present-day coordinates (Fig. 3). Restoration of the steep foliation attitude to more gentle regional dips would result in the same indicators implying a top-to-the-west or WSW sense of shear.

The S_1 foliation and its subsequent folding during the presumed progressive D_1 event, were accompanied by a

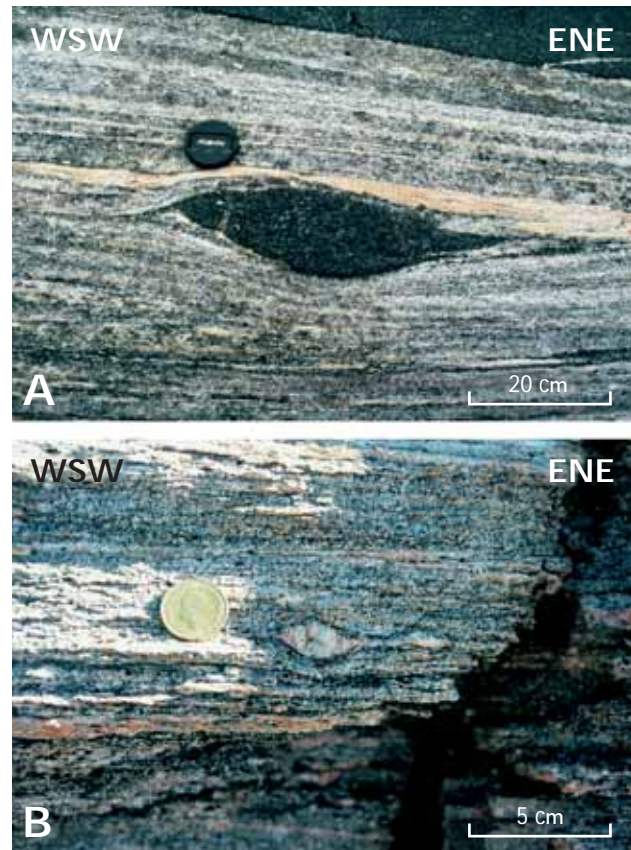


Fig. 3. Examples of sinistral (top-to-the WSW) kinematic indicators in the orthogneisses of the study area. The lineation is plunging towards WSW on north-dipping foliation planes. A: Sheared, asymmetric amphibolite enclave. B: Sigmoidal K-feldspar porphyroclast.

long-lasting pervasive migmatitisation. This is demonstrated by the common occurrence of migmatite layers or patches that are variably deformed and show mutually cross-cutting relationships. Some of them are parallel to the main foliation S_1 (Fig. 2D) whereas others define discordant veins or dykes oblique to the regional fabric. Between these two end members are a range of cross-cutting veins that are deformed and reoriented to varying degrees. In the metasedimentary rocks of the Naternaq (Lersletten) area, the S_1 regional foliation is refolded by F_2 folds characterised by steep to subvertical fold hinges. These folds are developed at kilometre- to centimetre-scale and, in a few cases, map scale F_2 folds can be seen refolding F_1 (A.A. Garde & J.A. Hollis, personal communication 2003). F_2 folds are found exclusively within the metasedimentary belts and at their contacts with the adjacent gneisses. At a mesoscopic scale, they are represented by folds plunging steeply towards the SE and in few cases towards the north. A moderate to strong, SE-plunging mineral lineation is associated with the hinges of F_2 folds, locally deviating

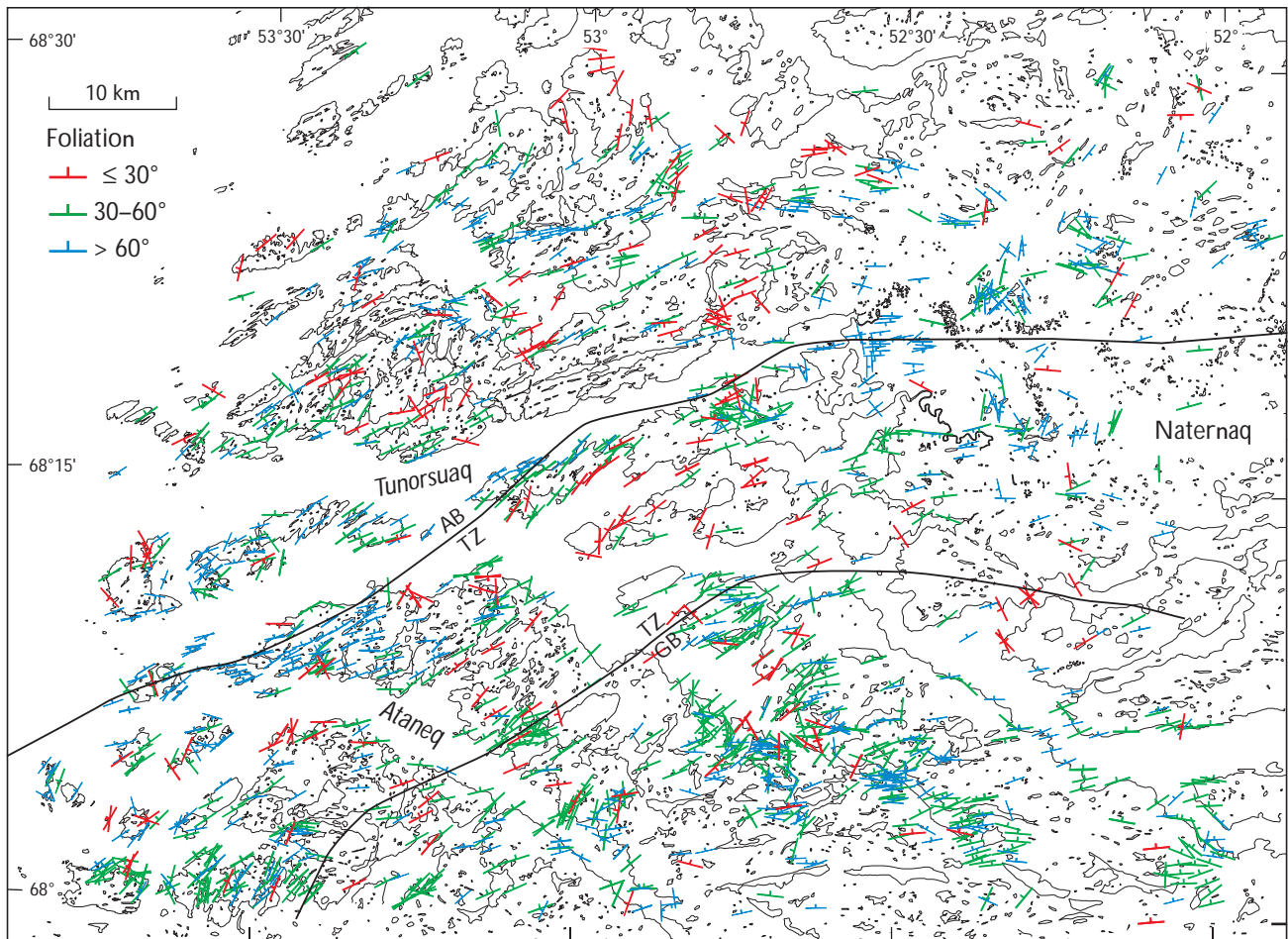


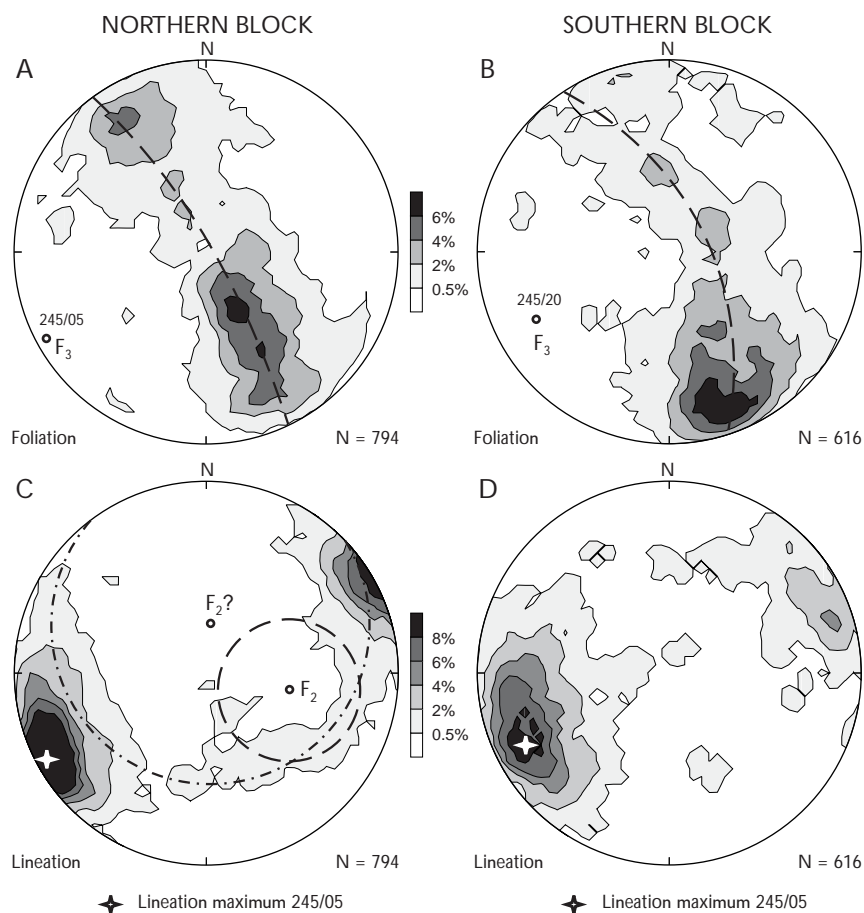
Fig. 4. Representation of foliation trends and dip directions in the study area. GB, granulite block; TZ, transition zone; AB, amphibolite block.

from its regional trend although it remains the only lineation present. An S_2 cleavage axial planar to F_2 is rarely, and only weakly, developed. Beyond Naternaq, the S_1 foliation is refolded by F_3 folds of variable, often complex geometry with gently plunging fold axes developed subparallel to the L_1 lineation (Fig. 2E). The frequency of such folds increases northwards within the amphibolite-grade rocks. Associated F_3 axial planes are locally marked by a subtle S_3 cleavage, accentuated by local mica aggregates and discrete joints which cut the main S_1 foliation. The distinction between F_2 and F_3 folds is primarily based on their different geometries since they both fold the regional fabric S_1 and are not associated with penetrative axial cleavages or intersection lineations. The hinges of F_2 folds are relatively steep and oblique to the regional lineation, whereas F_3 axes are gently inclined and run parallel to the lineation L_1 . The F_3 mesoscopic folds are frequently asymmetric with fairly uniform SSE vergence in the area south and west of Kangaatsiaq (Fig. 2F).

Orientation of directional structures

On the map scale, the regional foliation displays a WSW–ENE to SW–NE strike associated with steep to moderate dips towards the NNW or SSE (Fig. 4). Shallow-dipping foliations ($< 30^\circ$) are rare and randomly distributed throughout the study area. Their variable directions suggest that they are associated with the hinge zones of F_3 folds developed at different scales (Fig. 4). Moderately and steeply dipping foliations show a distinctly discrete grouping within the investigated area. The former predominate in the south-eastern corner of the area, corresponding with the granulite-grade block, whereas the steeply dipping foliations are developed in its central part, forming a wide belt along Tunorsuaq (Fig. 4). This belt coincides with a transition zone between the granulite and amphibolite facies domains and partly with the south-eastern margin of the latter (see Figs 1, 4). The strike of foliation dipping steeper than 30° remains fairly consistent throughout the area, while the dip direction varies only in the case of sub-

Fig. 5. Attitudes of foliation S_1 and stretching lineation L_1 in the northern amphibolite facies block (A, C), and southern granulite facies block (B, D). The positions of the poles to the foliation girdles and maximum of lineation measurements are indicated in stereoplots A, B and C, D, respectively.



vertical planes ($> 60^\circ$). On stereoplots, the poles to foliation are scattered along a regular girdle produced by the F_3 folds (Fig. 5).

In the southern granulite facies block the vast majority of foliation measurements cluster in one maximum, suggesting that late folding is insignificant or absent in this area (Fig. 5). This maximum corresponds to the foliation dipping moderately to steeply towards the NNW, while the axis of the foliation girdle plunges gently to the WSW at 20° . In the northern, amphibolite facies block measurements are more evenly distributed along the foliation girdle, providing evidence for the regional importance of F_3 folding (Fig. 5). In contrast to the southern block, the stereographic girdle axis is almost subhorizontal. Although the foliation patterns in the southern and northern blocks are fairly similar, a striking difference occurs within the latter between the rheologically competent orthogneisses and relatively incompetent supracrustal formations (Fig. 6). The orthogneisses reveal a regular girdle perfectly controlled by a cylindrical geometry of the F_3 folds. In contrast, the less competent supracrustal rocks display a pronounced foliation scatter, reflecting a complex interfer-

ence between the effects of the (possibly noncylindrical) F_2 and F_3 folding.

The lineation trends WSW–ENE over the whole study area, and frequently plunges gently towards the WSW (Fig. 7). Shallow lineations ($< 15^\circ$) are concentrated in the northern and central parts of the investigated area (Fig. 7), and commonly coincide with the subvertical foliation within the amphibolite facies block and the associated transition zone towards the granulite facies block. Conversely, lineations plunging steeper than 15° group largely in the south-eastern corner of the area, corresponding with the granulite block, and show mostly WSW-directed plunges. Mesoscopic F_3 fold hinges are usually colinear with the regional lineation, and this is also the case at the larger scale since the lineation maxima are located near the pole of the foliation girdle on stereoplots (cf. Fig. 5). In the amphibolite facies block, the lineation is shallow and relatively well grouped in the maximum representing the subhorizontal WSW–ENE trend. A significant scatter occurs only in the Naternaq area, which is displayed on the map by relatively steeply plunging lineations (Fig. 7) and on stereoplots by data distribution along a small cir-

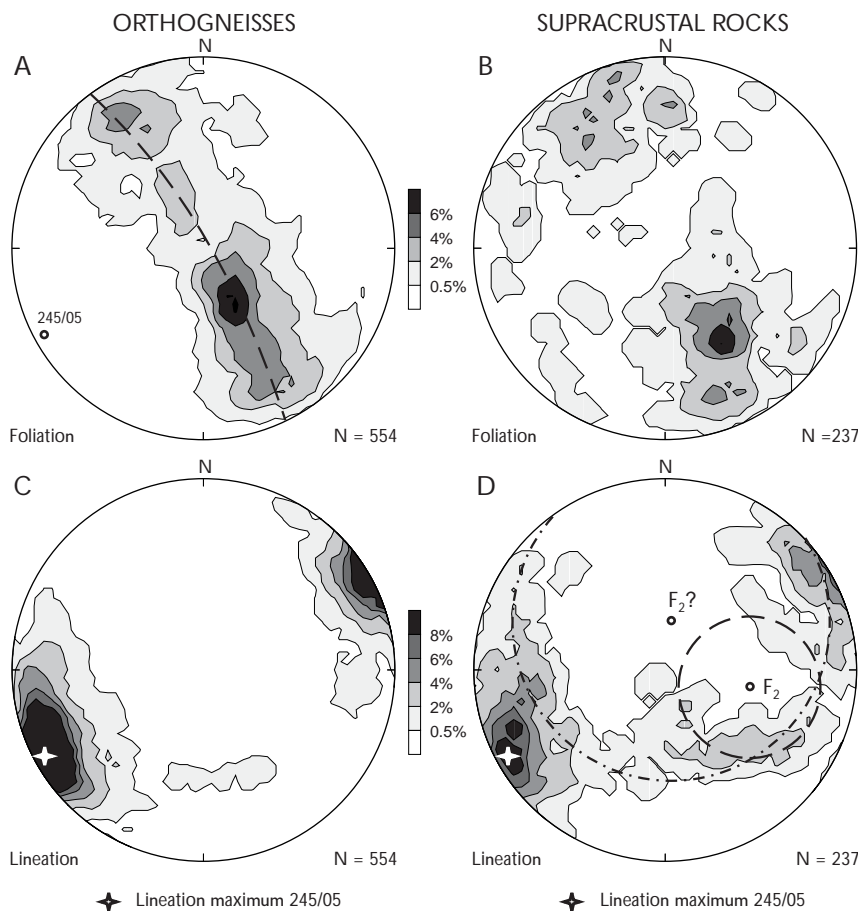


Fig. 6. Attitudes of foliation (S_1) and stretching lineation (L_1) in the orthogneisses (A, C) and supracrustal rocks (B, D) of the northern amphibolite facies block. The position of the pole to the foliation girdle and maximum of lineation measurements are indicated in stereoplots A and C, D, respectively.

cle (Fig. 5). A dispersal of lineation measurements is produced in that area by steeply plunging F_2 fold hinges whose orientation corresponds to the centre of a small circle defined by the scatter of the lineation (Fig. 5). Two different small circles can be delineated on the stereoplot (Fig. 5) based on the lineation scatter. One is centred at the orientation of F_2 hinges steeply inclined to the SE that are relatively frequent as mesoscopic structures. The second is developed around the nearly vertical north-plunging F_2 hinges rarely found in the outcrops but probably important at the map scale. The lineation scatter induced by the F_2 folding is very clear in the supracrustal rocks, whereas it is almost absent in the orthogneisses (Fig. 6). This relationship is consistent with the field observation that the F_2 folds are developed almost exclusively in the meta-sediments. In the southern block the lineation is slightly steeper than in the north and shows a mean plunge of $c. 20^\circ$. Its maximum is more diffuse than in the amphibolite-grade block and more lineations are relatively steep ($> 15^\circ$). Nevertheless, the average lineation trend defined by the position of maxima on stereoplots is exactly the same for the amphibolite and granulite facies domains (Fig. 5).

In order to better understand the geometric relation-

ships between planar and linear fabric elements during deformation, they may be directly compared on fabric topology plots in terms of fabric trends and lineation pitch (see Alsop & Holdsworth 2004 for a review). The angle of pitch may be defined as the angle that a line makes with the strike of a surface, when measured within that plane (Fig. 8A). A significant variation in the angle of lineation pitch on the regional foliation surface is observed (Fig. 8B); this may be caused by two independent factors: (1) variable plunge of the lineation, and (2) variable dip direction of the foliation. The latter feature seems to be a consequence of local folding, since a high pitch angle ($> 45^\circ$) is most characteristic for SW-dipping foliations (Fig. 9) that represent the hinges of F_3 folds (Fig. 5). On the other hand, a majority of measurements correspond to foliation dipping to the NW or SE that reveals a low or moderate pitch angle (Fig. 9). Such a foliation pattern is consistent with the regional attitude of foliation inclined towards the NW and only locally reoriented on limbs of the F_3 folds. Since the F_3 folds are only of minor significance in the southern part of the study area characterised by higher pitch values (Fig. 8), and the majority of lineations were measured on steep to subvertical foliation sur-

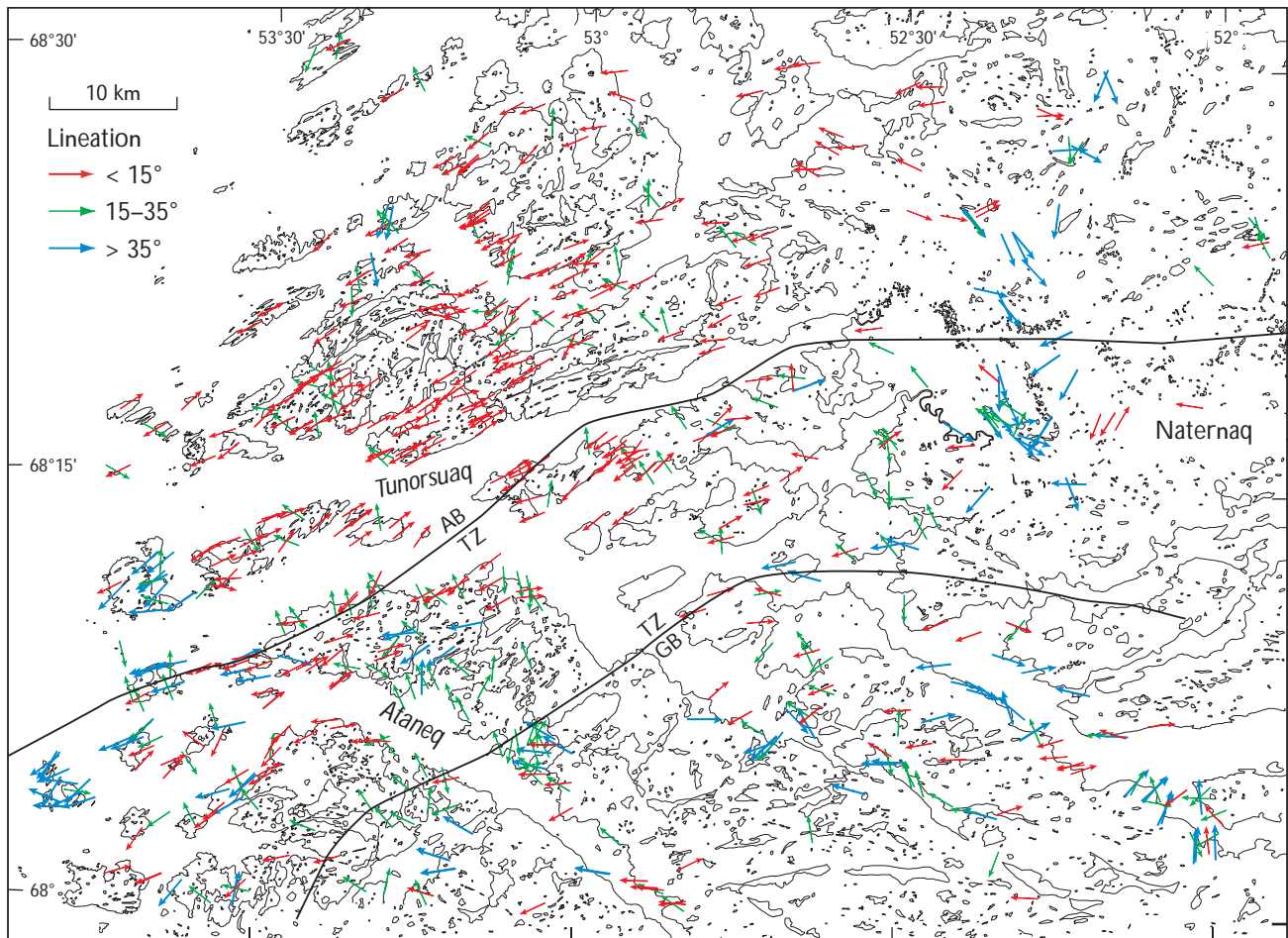


Fig. 7. Representation of lineation trends and plunge directions of the study area. GB, granulite block; TZ, transition zone; AB, amphibolite block.

faces, the broad scatter of the pitch angles can be attributed to variations in the lineation plunge (Fig. 10). Only a minority of measurements plot away from the line that indicates the similarity of pitch and plunge angles (Fig. 10). Thus, the change of foliation strike plays a less important role in the distribution of pitch angles. The low pitch angle ($< 15^\circ$) is characteristic of the central and northern parts of the study area (Fig. 8), corresponding to the amphibolite facies block and the transition zone to the granulite facies block. This is the area that is additionally characterised by the steep foliations and shallow lineation plunge. The higher pitch angles (exceeding 15°) are more common in the south-east corner of the study area within the granulite facies gneisses, where they are related to relatively steep lineations occurring on the moderately to steeply inclined foliation.

A systematic change in the plunge of lineations can be observed across the south-western part of the study area (Fig. 7). The steep SW–NE-striking foliation around Tunorsuaq is associated with the gently plunging lineation

that defines a low angle of pitch on the foliation. Towards the south, however, the plunge of lineation becomes progressively steeper despite the generally uniform strike of foliation (Fig. 4). A pitch versus lineation trend diagram (Fig. 11) demonstrates that the increase in pitch is unrelated to the change of lineation trend. This means that lineations are typically not reoriented on fold limbs, and that folds, if present, are mostly colinear with lineation. Furthermore, in the north-western part of the area the lineations plunge gently to the SW and NE to define a series of culminations and depressions, that are clearly illustrated by the opposing plunges on the south side of Tunorsuaq and the outer islands to the west-south-west (Fig. 7). This sinuosity of lineations and associated fold hinges defines a large-scale whaleback pattern consistent with a dominantly subhorizontal and approximately N–S contractional strain (cf. Piazzolo *et al.* 2004).

The finite planar (S) and linear (L) shape fabrics within a high-strain rock may be qualitatively described (Flinn 1978). Consequently, the relative dominance of these re-

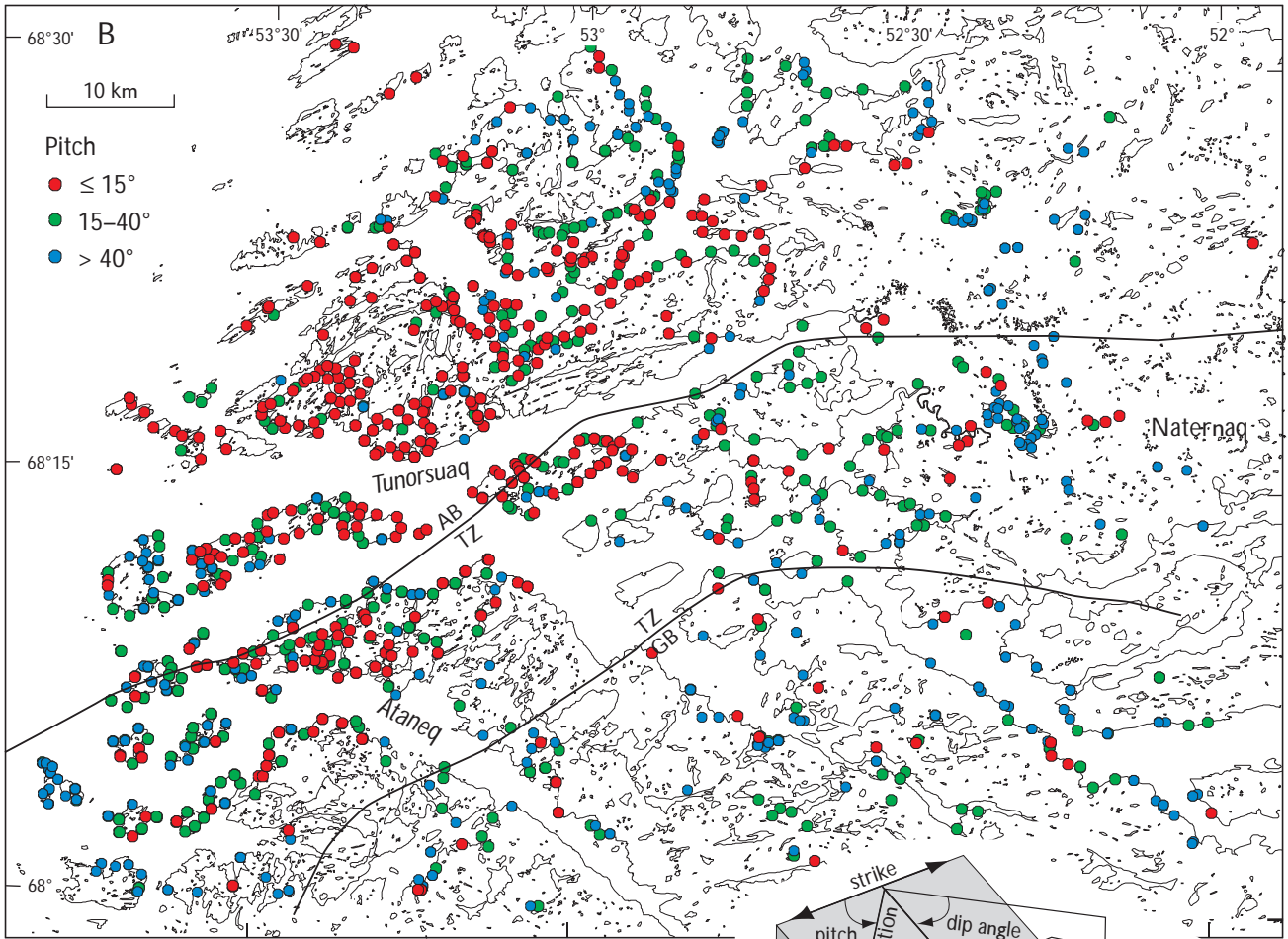


Fig. 8. Pitch data. A: schematic diagram illustrating the pitch of a lineation. B: representation of lineation pitch angles of the study area. GB, granulite block; TZ, transition zone; AB, amphibolite block.

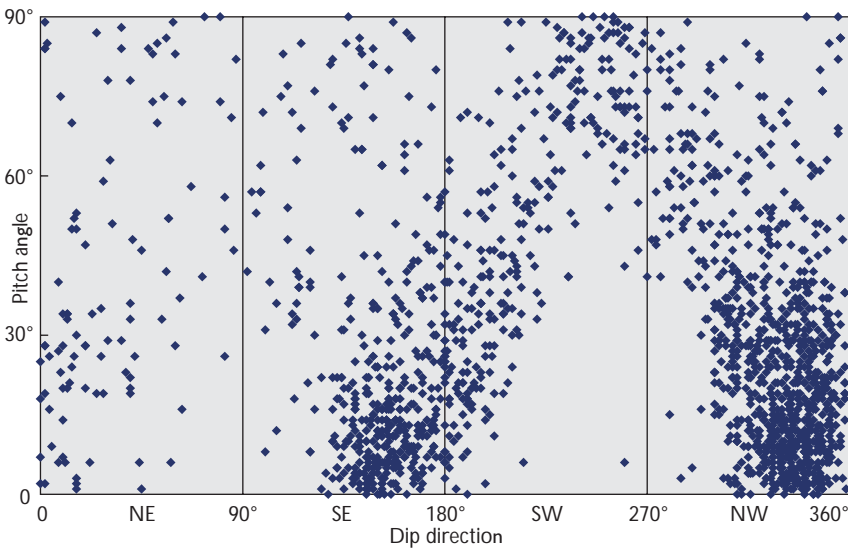
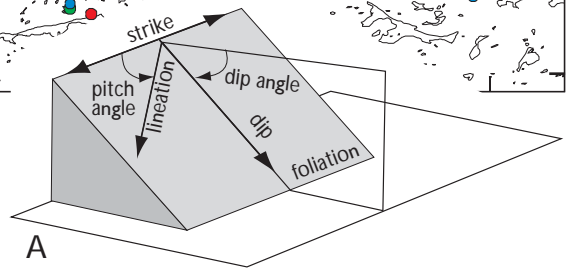
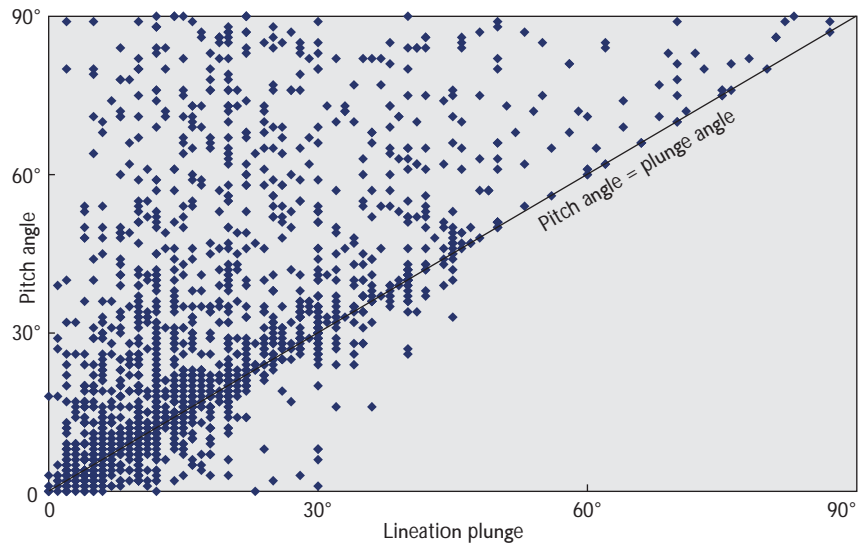


Fig. 9. Plot of lineation pitch angle vs. dip direction of foliation, showing the change of pitch as a consequence of local folding.

Fig. 10. Plot of lineation pitch angle vs. lineation plunge, showing the contribution of changing lineation plunge to the total variation of pitch. Measurements located on the straight line connecting the lower left and upper right corners of the plot have been taken on vertical foliation planes.



spective components enables a distinction to be made between fabrics that are foliation dominated (S tectonite), lineation dominated (L tectonite) or contain a combination of foliation and lineation (SL tectonite). The pattern shown by the spatial distribution of fabric types in the study area is clearly differentiated. The north-western part of the area is dominated by LS and $L > S$ fabric types whereas the south-eastern part reveals a vast preponderance of S or $S > L$ types (Fig. 12). The southward increase of lineation pitch is typically associated with the transition from $L > S$ or LS shape fabrics in rocks characterised by a low pitch, to $S > L$ or S fabrics in the zone of moderate to high pitch. Constrictional fabrics, i.e. L and $L > S$ fabrics, are typical of rocks with shallowly plunging lineations on the steep foliation belonging to the amphibolite facies block and the transition zone to the granulite facies

block. The latter is dominated by the flattening fabric types, i.e. S and $S > L$ fabrics, which are common in rocks containing steeply plunging lineations.

Discussion

Three main observations can be made concerning the data presented above: (1) structural elements, i.e. lineations, foliations, folding and fabric type, vary with lithology, (2) two broad domains with different structural patterns can be distinguished, and (3) the structural style in the NNO is markedly different to that previously described from the CNO, e.g. by Manatschal *et al.* (1998) and van Gool *et al.* (1999).

The observed scarcity of mineral lineations in the gran-

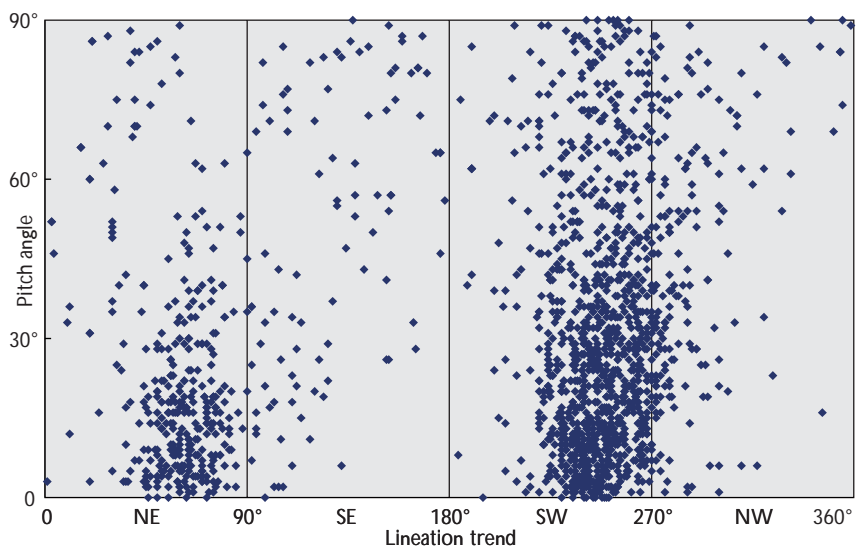


Fig. 11. Plot of lineation pitch angle vs. lineation trend, showing the variation of pitch despite the uniform trend of lineation.

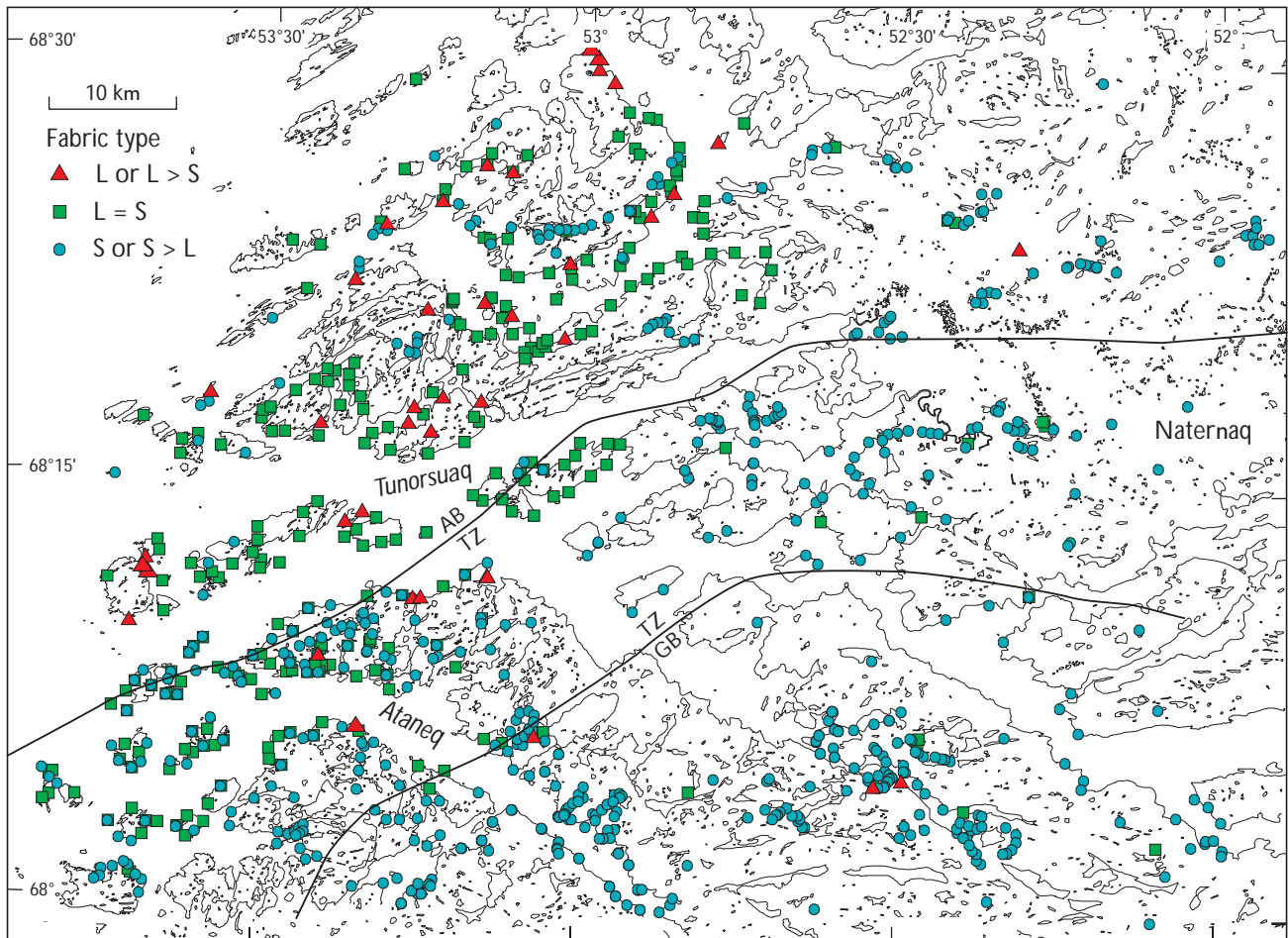


Fig. 12. Spatial distribution of fabric types (terminology of Flinn 1978). GB, granulite block; TZ, transition zone; AB, amphibolite block.

ulite facies gneisses could be attributed to the absence of minerals with a high shape aspect ratio. If such minerals are lacking, lineations of the type that forms by rigid rotation or due to growth parallel to the maximum extension direction or transport direction can hardly develop. Nevertheless, aggregate lineations that form by dynamic recrystallisation and material transfer should be expected in the granulite facies gneisses. Since even these lineations are lacking in the southern block, it seems that the scarcity of linear structures in this area is not only a function of lithology but also reflects specific features of deformation history. In the northern block, a significant strain partitioning between orthogneisses and supracrustal formations is indicated by the effects of F_2 folding in metasedimentary rocks and the resultant scatter of foliation and lineations in these rocks (Fig. 6). This points to the concentration of deformation in rheologically weak metasedimentary belts that accommodate the bulk of strain induced during F_2 folding. The competent orthogneisses experienced only subsequent F_3 folding, when they were de-

formed together with associated less competent supracrustal rocks.

At the western limb of the Naternaq supracrustal belt, there is a structural discordance with another E–W-trending supracrustal unit farther to the west. This structural discordance may suggest the presence of some kind of ‘stockwerke tectonics’ (Wegmann 1935), in addition to the inferred strain partitioning between the orthogneisses and metasedimentary rocks. The application of the ‘stockwerke’ model to the Naternaq belt itself remains an intriguing problem that cannot be resolved at present, due to the lack of sufficient information on the time relationship between the structural discordance and the main phase(s) of folding and metamorphism.

Disregarding the local complexity at Naternaq, the general structural pattern described in this paper allows subdivision of the study area into two main domains: (1) a southern domain mostly characterised by S or S > L shape fabrics and a moderate to high angle of pitch, and (2) a northern domain showing L > S or LS fabrics and low

angles of lineation pitch. This subdivision compares well with the map scale variation of the metamorphic grade from granulite facies in the south to amphibolite facies further north. The contact between these two facies is transitional and forms a gently curved boundary that is sub-parallel to the strike of the regional foliation (Piazolo *et al.* 2004). This division of the study area into two contrasting blocks, indicated by the structural data and variation of metamorphic grade, can be explained by two models, namely (1) an indenter model, and (2) a transpressive deformation model, the relevance of which is briefly discussed below.

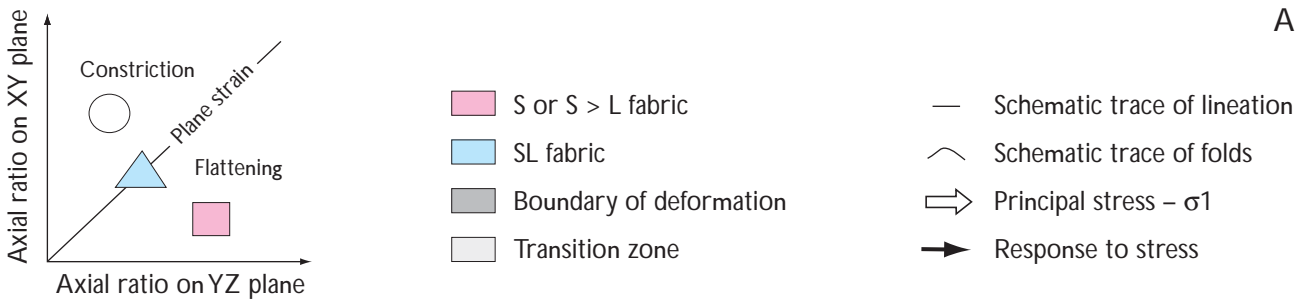
The indenter model, originally developed by Piazolo *et al.* (2004), invokes a twofold deformation history. During the first event the southern block was subjected to a coaxial flattening under granulite facies conditions (Fig. 13B – time A). A fairly uniform strain developed at that time and is manifested by prevailing S or S > L shape fabrics. During the second event (Fig. 13B – time B) the previously cooled granulite grade block acted as an indenter, with the amphibolite facies domain being plastered and moulded around the rigid block. The structural pattern and mineral assemblages of the southern domain were only modified in a transition zone that experienced retrogression to the amphibolite facies. At the same time, the amphibolite grade northern domain was subjected to mostly coaxial strain, including an important constrictional component. The resultant structural grain in the amphibolite facies rocks mimics the geometry shown by the boundaries of the southern block.

The alternative model (Fig. 13C) explains the observed structural relationships in terms of strain partitioning within a transpression zone (for a review of transpression see Holdsworth *et al.* 2002, and references therein). In this model, the different structural patterns documented in the northern and southern domains were produced during a single deformation event. Consequently, the model implies a continuity of the structural grain across the transitional zone as well as a gradual change in the orientation of directional structures, fabric type and kinematics of strain. The southern domain was mostly subjected to coaxial flattening, resulting in S or S > L shape fabrics with a moderately plunging lineation. The northern domain was deformed in a wrench-dominated regime, characterised by a constrictional or plane strain with a significant rotational strike-slip component. Hence, the northern block reveals L > S and LS shape fabrics and shallowly plunging lineations. A sinistral sense of displacement assumed in the model is consistent with rare observations in the field of kinematic indicators with the appropriate asymmetry.

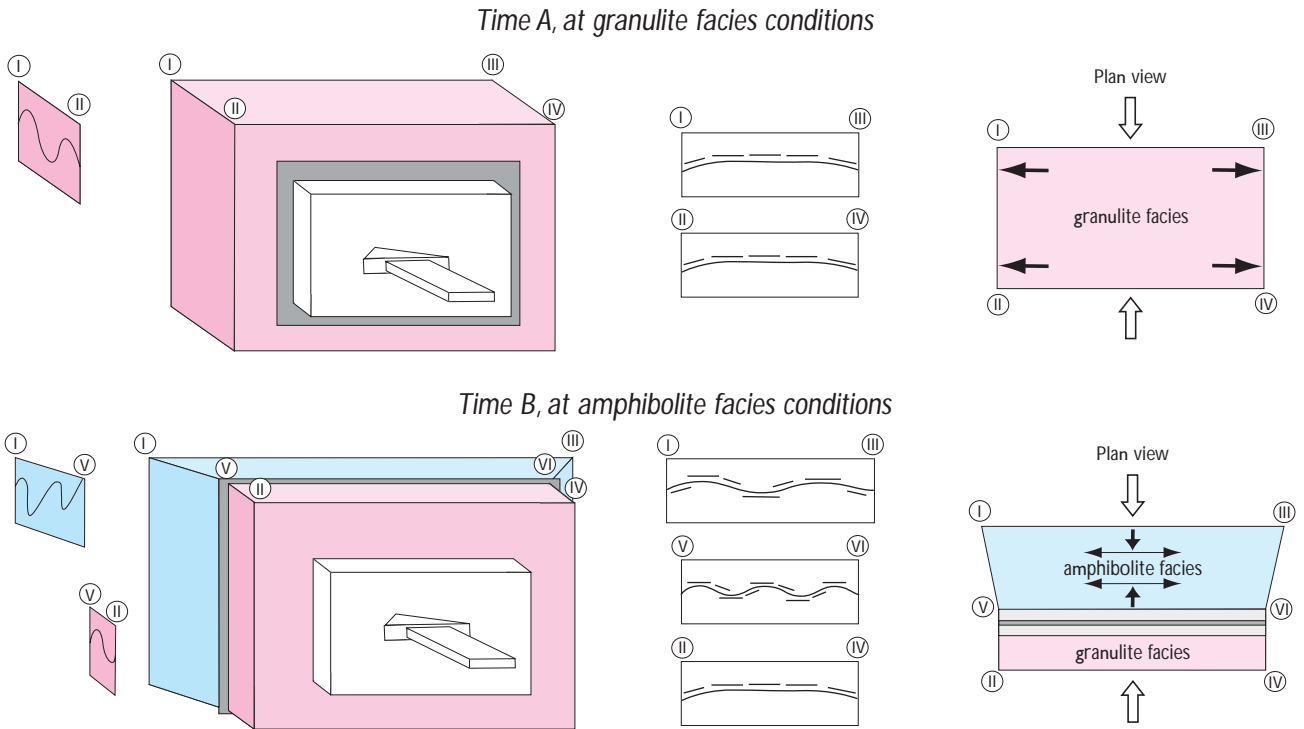
The indenter model explains the arcuate swing of the

structural grain around the granulite facies block, the map scale geometry of which may appear to control the foliation and lineation patterns within the amphibolite facies block further north. A serious weakness of the indenter model is the lack of evidence for fabric overprinting in the boundary zone between the two domains despite the assumed twofold deformation. However, high strain in the transitional zone could account for the obliteration of interference patterns and the apparent continuity of structural grain. The transpression zone model accounts for the presence of steep (F_2) fold hinges in the Naternaq supracrustal belt that are expected to develop within the wrench-dominated part of the transpressive system. The model also explains the contrast of structural style between the northern and southern domain without a detectable tectonic boundary or an overlap of structural patterns. Consequently, it is consistent with an apparent continuous transition linking the structural patterns within the granulite and amphibolite blocks. The somewhat steeper plunge of lineations within the granulite facies domain may indicate a greater component of coaxial strain in that area. However, the potential strain partitioning, as revealed by the lineation pattern, is relatively weak for a transpression zone. The partitioning of strain that takes place between the orthogneisses and supracrustal rocks within the northern amphibolite facies block is consistent with both of the discussed models. In addition, both models are consistent with a dominantly subhorizontal and approximately N–S contractional strain in the northern block causing the small-scale porpoising and large-scale whale-backing of lineations and associated fold hinges.

Thus, even a detailed structural analysis does not allow us to determine unequivocally which of the two models is the more appropriate. Nevertheless, the presented structural models can be indirectly verified by geochronological data, which constrain the age of peak metamorphism and associated deformation in the northern amphibolite facies block as Palaeoproterozoic (Thrane & Connelly 2006, this volume). Furthermore, the late Archaean crystallisation age of syndeformational granites emplaced at Saqqarput (Fig. 1) and at the southern margin of the NNO (Connelly & Mengel 2000; Thrane & Connelly *op. cit.*), points to a lack of significant deformation in the southern block from the late Archaean onwards. This is in conflict with the coincidence of deformation between the northern and southern blocks required by the transpression model and, thus, supports the indenter model. This is corroborated by the occurrence of undeformed but metamorphosed mafic dykes of likely Palaeoproterozoic origin emplaced at the southern margin of the investigated area (Glassley & Sørensen 1980; Ártung 2004).



Model I (Piazolo *et al.* 2004). Observed fabrics developed during two deformational events **B**



Model II (discussed in this paper). Fabrics developed during a single transpressional event **C**

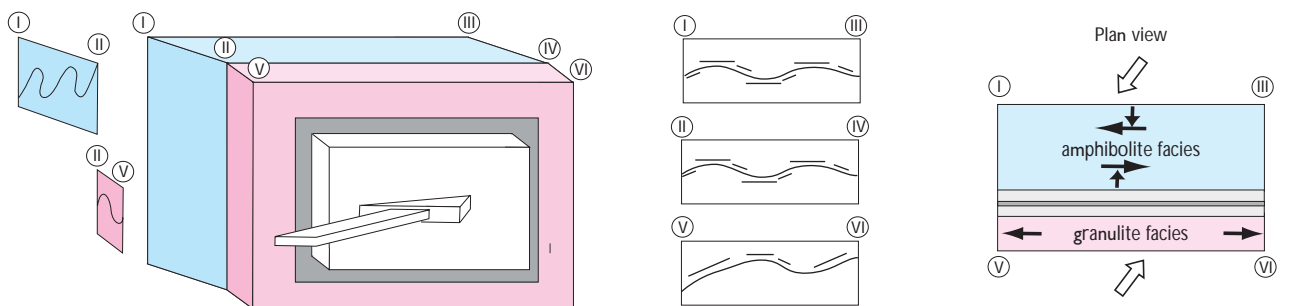


Fig. 13. Schematic indenter and transpression zone models with expected fabric types and fold patterns. **A:** Flinn graph with schematic qualitative descriptions of the finite planar (S) and linear (L) shape fabrics. **B:** Indenter model. **C:** Transpression zone model.

The F_3 folding apparently postdates the juxtaposition of the granulite and amphibolite blocks and had a relatively minor influence on their contact zone. The northward increase in intensity of F_3 folding is readily explained by the rheological weakness of the amphibolite facies domain during cooling. The origin of F_3 folds provides evidence for prolonged, approximately N–S-directed compression, the age of which is roughly constrained by the previously mentioned 1837 ± 12 Ma pegmatite (Thrane & Connelly 2006, this volume).

Our structural data also show that compressional stress related to the growth of the Nagssugtoqidian orogen was effectively transferred across the lower crust, and that the amphibolite facies domain south of Aasiaat was subjected to the penetrative Palaeoproterozoic deformation. Therefore, this area represents an integral part of the Nagssugtoqidian orogen despite the obvious paucity of Palaeoproterozoic crustal components. In contrast to the southern part of the orogen, the overall N–S shortening induced by the Nagssugtoqidian collision was accommodated in the study area through indentation and folding, in contrast to the central part of the orogen that displays significant thrust tectonics.

Concluding remarks

The indentor and transpression-driven tectonic models discussed in this paper share a number of features which shed a new light on the evolution of the northernmost Nagssugtoqidian orogen. The granulite and amphibolite facies blocks distinguished in the study area appear to be (par)autochthonous, and their boundary is only reactivated and reworked during indentation or transpression.

The area studied shows excellent examples of Precambrian deformation that are characterised by significant strain partitioning into less competent metasedimentary rocks. The presence or absence of lineations may be influenced significantly by lithology and metamorphic grade. Complex structural patterns may not always conclusively reveal the structural history on their own, hence geochronological data are essential in distinguishing between different deformation models such as transpression or indentation. In addition, it is apparent that the tectonic styles of the lower to middle crust can be highly variable within the same orogen. Deformation may vary from thrust-dominated in the central portion to folding associated with indentation or transpression on its flanks.

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