Streching lineations and structural evolution of the Kalak Nappe Complex (Middle Allochthon) in the Repparfjord-Fægfjord area, Finnmark, northern Norway

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Two small klippen of the Kalak Nappe Complex (Middle Allochthon) overlie the Komagfjord Antiformal Stack (Lower Allochthon) in the Repparfjord-Fægfjord area of the Caledonides in Finnmark. The Gargia Nappe, the lowest imbricate of the Kalak Nappe Complex, forms the base of both klippen; this nappe comprises pelitic to semi-pelitic schists and mylonites. In the western klippe, the Gargia Nappe is overlain by strongly sheared psammites of the Billefjord Member (Klubben Fm., Olderfjord Nappe). Generally, the mylonites have clustered stretching lineations reflecting SSE- or SE-directed movement. In the lowest part of the mylonites, however, the lineations have a great circle distribution, with SE- to E-directed movement. Subsequent deformation, related to out-of-sequence brittle oblique thrusting cutting both the mylonites and the underlying Komagfjord Antiformal Stack, folded the mylonites. The rotation in the stretching direction of the mylonites allows a restored length of the Lower Allochthon to be modelled at 296 km, a shortening of 54% and a time averaged thrusting rate of ca. 0.87 cm yr⁻¹.

Introduction

The present article concerns stretching lineations at the base of two small klippen of the Kalak Nappe Complex (Middle Allochthon) in the Fægfjord area of Repparfjord, and their significance in the restoration of the Caledonides in Finnmark (Fig. 1). Although the area was mentioned previously by Reitan (1963), Rhodes (1976) and Pharaoh et al., all these authors were primarily concerned with the basement rocks of the Komagfjord Window and their unconformably overlying Caledonian cover, the Lomvatn Formation, and hence do not discuss minor variations in the stretching lineation directions at the base of the klippe. These variations, detailed below, are comparable to those described elsewhere at the base of the Kalak Nappe Complex (Williams 1976; Townsend 1987). They allow a significant reduction in length to be made in the restoration of the cross-section through the Caledonian orogen presented by Gayer et al. (1987). The IUGS-recommended Precambrian chronostratigraphic terminology has been used (Plumb 1991).

Regional setting

Middle Allochthon. — The Kalak Nappe Complex (Fig. 1) is a greenschist to upper amphibolite facies sequence of nappes which, in the Kvaløy to Porsangerfjord area of Finnmark, northern Norway, was imbricated during essentially SE-directed syn-metamorphic thrusting (Gayer et al. 1985; Rice 1987). Within the complex, a variety of lithological successions have been identified, including basement and cover. Of these, the Sørøy Group is generally regarded as being a cover succession (but cf. Daly et al. 1991; Rice 1990), and it is to this group that the rocks discussed below belong. The stratigraphic terminology used for the Sørøy Group is that of Townsend et al. (1989).

Gayer et al. (1985) recognized five deformation events within the Kalak Nappe Complex: D1 was recognized solely from the central planar inclusion fabric within garnets, D2 as tight to isoclinal recumbent folds associated with a regional schistosity (S2) lying parallel to the axial surfaces, D3 by open to closed moderately inclined folds with an axial planar crenulation fabric, D4 by upright gentle to open folds with an axial planar crenulation cleavage, and D5 as kink bands. The regional orientation of D2–D4 folds is NE-SW. They represent a continuum of fold generation over time, and a decrease in syn- to post-folding finite strain, although many early folds have been more or less rotated into the X-direction. Kink bands have a clustered WSW–ENE to W–E orientation; in the Gargia Nappe to the north of Repparfjord, the mean axis plunges 03° towards 078° (Rice 1982).
The structural evolution of the base of the Kalak Nappe Complex in the Porsangerfjord region (Fig. 1) was studied by Townsend (1986, 1987), who reported ca. 800 m of initially garnet grade mylonites forming the ductile Kalak Thrust Zone and an inferred underlying brittle Kalak Thrust Plane. Within the mylonites, an anticlockwise rotation of the movement direction was recorded from the top (SE-directed) to the base (E- to ESE-directed; Fig. 2A). The same rotation was described by Williams (1976) in the Bekkarfjord area (Fig. 2A). This will be elaborated further in the discussion. The movement direction along the Kalak Thrust Plane was inferred by Townsend (1987) to be ESE- to E-directed.

In the Skaidi area, Rhodes (1976) mapped a large-scale 02 fold, in which the Gargia Nappe was inverted, together with psammites of the Billefjord Member at the base of the overlying Olderfjord Nappe. This structure was mapped north and northwestwards along the north coast of Repparfjord by Rice (1982), where a thin sliver of pale brown weathering bluish psammites of the Billefjord Member is exposed (Fig. 1, inset).

$^{40}$Ar/$^{39}$Ar dating of amphiboles from the internal parts of the Kalak Nappe Complex indicated a medium metamorphic grade tectonothermal event (Finnmarkian?) cooling through ca. 500°C at around 490 Ma, whilst muscovites indicated a Scandian age for cooling through the muscovite blocking temperature, at ca. 425–415 Ma (Dallmeyer 1988). Rb-Sr whole-rock dating of the basal part of the mylonites forming the Kalak Thrust Zone on the east side of Porsangerfjord yielded an age of 479 ± 15 Ma, with an uncertain significance (Roberts & Sundvoll 1990). Rb-Sr thin-slab dating of samples from the same locality with abundant late extensional crenulations, yielded late Scandian dates of 385 ± 26 and 380 ± 22 Ma, interpreted to reflect the age of the late E- to ESE-directed thrust movements (Roberts & Sundvoll 1990).

Lower Allochthon. – In the Kvaløy-Porsangerfjord area, the Lower Allochthon is represented by three major units, only briefly described here. The Komagfjord Antiformal Stack (Fig. 1) consists of Palaeoproterozoic Karelian basement rocks, exposed in three tectonic windows and unconformably overlain by a thin veneer of Neoproterozoic to inferred lower Palaeozoic sediments, which, in the north, are termed the Lomvatn Formation (Pharaoh et al. 1983; Pharaoh 1985; Føyn 1985). Structural considerations, outlined below, demonstrate that the basement is allochthonous. The northwestern margin of the basement is cut by a series of steeply dipping NE-SW trending thrusts (Pharaoh et al. 1983), forming the Forsa Duplex within the Komagfjord Antiformal Stack (Gayer et al. 1987). This SE thrusting direction, which is also recorded in structures in the Lomvatn Formation at the northeastern margin of the
Komagfjord Antiformal Stack (Fig. 2B) and in the overlying mylonites of the Kalak Nappe Complex, was used in the restoration of Gayer et al. (1987).

The Laksefjord Nappe Complex (Fig. 1) comprises three imbricates, the lowest of which consists almost entirely of pre-Caledonian basement with a thin cover succession of unknown age. The overlying imbricates have up to an 8 km-thick sedimentary succession, the Laksefjord Group (Føyen et al. 1983), locally resting on basement. The age of the cover succession is again unknown, but is thought to be broadly comparable to that of the Lomvatn Formation (Pharaoh 1985). The nappe was initially emplaced during SE-directed ductile deformation (Milton & Williams 1981), with later ESE-directed brittle out-of-sequence thrusting (Williams et al. 1984; Townsend 1987).

The Neoproterozoic rocks in the Gaissa Thrust Belt in the Porsangerfjord region (Fig. 1) have been intensively deformed by E- to ESE-directed thrusting (Townsend 1987; Gayer et al. 1987). Restoration, using balanced cross-sections, places the trailing branch line of the Gaissa Thrust Belt west of the present-day position of the Komagfjord Antiformal Stack (Townsend et al. 1986), and thus places the Tonian and Cryogenian rocks of the Gaissa Thrust Belt over the Neoproterozoic rocks in the Komagfjord Antiformal Stack.

K-Ar and 40Ar/39Ar dating of the epizone grade Lomvatn Formation indicate a 410–430 Ma Caledonian tectono-thermal event; no evidence of an older Caledonian event was recorded (Dallmeyer et al. 1988; Rice et al. 1989). Ultracataclasites at the base of the Gaissa Thrust Belt in Porsangerfjord have been dated to 391 ± 9 Ma (unpublished preliminary data of J. G. Mitchell, in Roberts & Sundvoll 1990). K-Ar analysis of the <0.5 μm fraction in the Gaissa Thrust Belt demonstrated that cleavage formation occurred after 440 ± 9 Ma, but the precise age could not be better constrained (Dallmeyer et al. 1989).

The Fægfjord region

At Fægfjord, on the northern margin of the Komagfjord Antiformal Stack, two small klippen of the Kalak Nappe Complex have been mapped overlying the Lomvatn Formation, which in turn lies on the basement rocks (Raipas Supergroup; Pharaoh et al. 1983) of the Komagfjord Antiformal Stack (Fig. 1; inset Fig. 3A). Under the eastern klippe (Fig. 3B), the contact between the Lomvatn Formation and the underlying basement rocks has been inferred to be a thrust (Reitan 1963; Rhodes 1976; Pharaoh et al. 1983), although these authors indicated on maps that they had not actually seen the presumed thrust contact. However, an unconformable contact was found at the southern end of the eastern klippe, putting the existence of the Markopp Nappe in some doubt.

Lithologies

The northeastern part of the western klippe (Væigus-vuonjarga; Fig. 3A) comprises flaggy, white-weathering, bluish psammitic rocks, locally biotitic, within which no sedimentary structures have been observed. Quartz and felspar porphyroclasts up to a few millimetres across suggest an initially coarser protolith. At the western end of this peninsula several dark brown to black heavy mineral bands up to 6 cm thick crop out. These may persist along strike for up to 30 m before gradually
wedging out. Similar, but thinner heavy mineral bands have been described from the Billefjord Member (Klubben Formation) of the Olderfjord Nappe in the Porsangerfjord area (Williams et al. 1976). The base of this unit is not exposed, but the lowest parts are mylonitic. This small outcrop is here tentatively correlated with the Billefjord Member, and is thought to be part of the inverted limb of the large-scale fold mapped in the Skaidi–north Repparfjord area (Fig. 1 inset; Rhodes 1976; Rice 1982), but in the absence of sedimentary structures, this cannot be conclusively demonstrated.

The remaining parts of the two klippen (Figs. 3A, 3B) comprise mixed blue-green to dark semi-pelitic, locally psammitic, schists and mylonitic schists. In thin-section they contain abundant epidote, clinozoisite and graphite, as well as muscovite, biotite and quartzofelspathic minerals. These lithologies are the same as those of the Nilpavatn Member (Kokelv Formation) within the Gargia Nappe (cf. Williams et al. 1976; Rice 1982). Rarely, garnets have been observed, up to 2 mm in diameter, sub-idioblastic and black-coloured. In thin-section these are heavily fractured and variably chloritized, both at the rims and along the fractures. Unaltered porphyroblasts contain a poorly-developed spiral inclusion fabric consisting of quartz, clinozoisite and opaques, again typical of the Gargia Nappe and which, where better developed, show a planar core inclusion fabric (S1; Rice 1984; Herrgö & Rice 1995). The lower part of the succession is clearly mylonitic, with very fine compositional banding and locally abundant shear bands, which indicate a top towards the southeast quadrant movement. Quartz veins are abundant; some were formed early, and are now thinned and elongate within the mylonitic foliation, whilst others are of a later age and are thicker, with a more obvious pinch-and-swell structure, and may be markedly discordant. In thin-section the mylonitic textures were found to be largely, but not wholly, recrystallized, with equilibrium grain boundary shapes developed against micas, although late and markedly discordant quartz veins also show evidence of pervasive ductile deformation. Felspar ε-porphyroclasts and associated muscovite quarter-mats (Hammer & Passchier 1991) have an asymmetry consistent with a top-to-southeast quadrant movement.

**Structure**

All the structural data have been processed using the computer program ‘Stereo’ (© D. B. McEachran), which
incorporates the shape fabric description method of Woodcock (1977). This provides two parameters quantifying the distribution of linear data on a stereonet. The K-parameter is a measure of the fabric shape (clustered vs. great circle); for perfect clustered distributions $K = \infty$, and for perfect great circle girdled distributions $K = 0$. $K = 1$ is the cluster–girdle boundary. The C-parameter is a measure of how good the distribution is; high C values ($>4.5$) indicate that the data lies in a tightly-grouped cluster or close to the best fit great circle, whilst low values ($<2$) indicate the opposite.

**Western klippe.** – Within the Billefjord Member of the Olderfjord Nappe, a penetrative foliation has developed, lying sub-parallel to a poorly preserved and strongly sheared compositional banding, giving the rock a markedly flaggy texture. In the absence of any sedimentary structures, it is not clear if this banding has a relic sedimentary origin, although the margins of the heavy mineral bands, which lie parallel to the flaggy layering, must be of sedimentary origin. Isoclinal to close, S- to SE-verging folds are common in the central and western parts of the outcrop. These fold the flaggy texture and have a variably developed axial planar fabric which is more penetrative in the tighter structures, forming an intersection lineation. The folds and intersection lineations have a mean trend plunging $14^\circ$ towards $074^\circ$ (Fig. 4A). Note, however, that the low K parameter (Table 2) indicates a girdled cluster, with $C = 5.2$. A contoured plot shows that the fold axis maxima (the mode) plunges at $10^\circ$ towards $057^\circ$ (36% of data). Stretching lineations have a mean (and mode) orientation at $17^\circ$ towards $145^\circ$; since this is at $90^\circ$ to the fold axis mode, it is inferred that the initial fold axis direction was $057^\circ$, or more northeasterly, and that minor fold rotation has occurred on the plane $029/20^\circ$E, the best fit great circle through the fold axis/intersection lineation data.

The underlying rocks of the Gargia Nappe (Nilpavatn Member) are predominantly mylonitic, with the intensity of strain qualitatively appearing to decrease away from the base of the klippe. In the southwestern part of the klippe the mylonitic foliation has been folded into a large-scale S-verging late open anticline, with the southern limb dipping at ca. $038/45^\circ$ SE (Fig. 3A). The fold axis, determined from foliation readings around the fold, plunges at $16^\circ$ towards $059^\circ$ (Fig. 4B) and dies away to the east. The Kalak Thrust Plane cuts across the fold axial surface and is not folded by this late structure.

Quartz stretching lineations are abundant within the mylonites, particularly in quartz veins lying parallel to the mylonitic foliation. A large number were measured between the south-dipping limb of the antiform and the coast (Fig. 3A). In this area, the contact between the mylonites and the underlying Lomvatn Fm. is generally not exposed, and only in the neighbourhood of the hinge and the immediately adjacent south-dipping limb of the large-scale fold can stretching lineations near the contact be recorded. The mean direction of all lineations plunges at $02^\circ$ towards $129^\circ$ (Table 3) and although the data fall on a great circle, the K- and C-parameters indicate a
reasonably distinct clustered distribution. This is reflected in the close parallelism of the mean and the mode, with $>23\%$ of the data lying in a group plunging at $00^\circ$ towards $136^\circ$. However, breaking the data down into sub-areas (shown in Fig. 3A) reveals a more complex pattern. In the southward-dipping limb of the late anticline (sub-area B, not far from the Lomvatn Fm.) and on the northern coast (sub-area C, well away from the Lomvatn Fm.) the mean trends are $136^\circ$ and $318^\circ$ respectively (Fig. 5A). The high K and C parameters (Table 1) indicate tight clusters and the mode and mean directions are parallel. In contrast, in the hinge region of the fold (sub-area A, close to the Lomvatn Fm.) and northwards (sub-area B, not far from the Lomvatn Fm.) the data is spread out along a girdle, although the K parameters still indicate clustered distributions (Fig. 5A). In these areas the mode encompasses orientations between $09^\circ$ towards $098^\circ$ and the reciprocal of $10^\circ$ towards $343^\circ$. 

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Fig. 4. A. Lower hemisphere equal-area net of structural data from the Billefjord Member, western klippe. B. Lower hemisphere equal-area net of structural data from the Nilpavatn Member in the western and eastern klippe. C. Lower hemisphere equal-area net of kink band axes and axial surfaces from the Fægfjord area. D. Lower hemisphere equal-area net of normal and reverse faults associated with kinks, western klippe. Open circles = mean orientations.
Kink bands are abundant in the Billefjord Member and the northern part of the Nilpavatn Member. Typically, kink bands are as narrow as <0.5 cm wide, and may be regularly spaced at <1 cm intervals. They are predominantly asymmetric to the south in the Billefjord Fm. and more often conjugate in the mylonites. In the Billefjord Member, the mean kink band axis plunges 12° towards 065° and in the Nilpavatn Member the mean kink band axis plunges 14° towards 071°, an essentially parallel direction (Fig. 4C; Table 2) and similar to that recorded in the rocks to the north of Repparfjord (see above).

In the southward-dipping steep limb of the late antiform described above, a number of very minor narrow brittle faults cut the rock at a high angle to the mylonitic foliation; frequently these faults pass into kink bands. Both normal and reversed faults/kinks were observed, with both sets dipping to the north, the former at a relatively low angle and the latter at a high angle. The faults form conjugate sets, with $a_1$ normal to the steepened mylonitic foliation and $a_2$ parallel to the foliation. These structures have a geometry similar to kink bands developed in anisotropic rocks dipping at a high angle to $a_1$ (Cosgrove 1976). The observed mean orientations of the two fault sets for three combined closely adjacent data sets are shown in Fig. 4D. The intersections of the normal and reversed planes ($a_2$) for the three data sets have a range of orientations similar to that of the kink bands seen in the sub-horizontal foliation, and the mean kink direction (taken as the mean $a_2$) plunges at 23° towards 060°, subparallel to the axes of the kink bands seen elsewhere in the western klippe and also to the large-scale fold axis.

**Eastern klippe.** The structure of the eastern klippe is simpler than that of the western, in that no large-scale folds have been found. Early minor folds, however, are somewhat more common, although often the smooth nature of the outcrop made it hard to measure the axial direction. Folds are close to isoclinal, reveal an early foliation (mylonitic) and have developed a weak axial planar fabric. The mean orientation of the axes and intersection lineations plunges 00° towards 155° (Fig. 4B), subparallel to the quartz-stretching direction (see below). Small-scale crenulations were also seen in pelitic lithologies, with a mean orientation plunging at 21° towards 058° (Fig. 4B). This direction is parallel to the axis of the late large-scale fold in the western klippe.

Stretching lineations are common in quartz veins lying parallel to the mylonitic foliation. The mean for all stretching lineations from this klippe plunges 03° towards 030° (Table 3) with a $K$ parameter which lies only just within the cluster field. The slightly girdled nature of the data is indicated also by the deviation between the mean and mode lineation directions. As in the western klippe, division of the data into sub-areas reveals marked differences. Away from the basal part of the mylonites the stretching directions show a strongly clustered distribution lying between 150° and 160°, with a mean plunging 00° towards 157°, with high K and C parameter values indicating a tight cluster (Fig. 5B, Table 3). Closer to the Kalak Thrust Plane the mean plunges 08° towards 144°, and immediately above the thrust it plunges 05° towards 128° (Fig. 5B). The overall range in the latter set, however, lies between 12° towards 159° and 11° towards 100°. This gradual change in mean (and mode) direction is accompanied by a reduction in the $K$
The ca. 800 m of mylonites at the base of the Kalak Nappe Complex in the Porsangerfjord area (Fig. 1) have a mean direction plunging at 19° towards 141° (Fig. 4B); this southeastern direction, typical of the main part of the Middle Allochthon in the mainland west of Porsangerfjord, reflects ductile imbrication and shearing within the Kalak Nappe Complex (Gayer et al. 1985).

Comparison with stretching lineations elsewhere in the Kalak Thrust Zone

The ca. 800 m of mylonites at the base of the Kalak Nappe Complex in the Porsangerfjord area (Fig. 1) were described by Townsend (1986, 1987), whose detailed measurements showed a marked, but very gradual, rotation of the stretching direction, from plunging at 12° towards 318° in the northern (upper) part of the mylonites to plunging at 10° towards 290° in the south, adjacent to the Kalak Thrust Plane (Fig. 2A; Table 1). Data sets in the northern part of the mylonite zone show little or no overlap with those from the southern part, and since the K parameters are typically >3, the data sets show little tendency towards girdle shapes. Individual data sets, which come from <ca. 80 m-thickness of mylonites (estimated from map in Townsend 1987), show a range of between 23° and 46° in the stretching directions, and in all cases the mean is the same as, or lies extremely close to, the mode. This variation, from SE-directed to ESE- to E-directed lineations, was interpreted by Townsend (1987) to reflect a gradual change in the direction of ductile thrusting during waning metamorphism, with strain gradually concentrating near the major dislocation at the base of the nappe as the rocks cooled and hardened. A similar anticlockwise rotation has been found in the <900 m-thick mylonites at the base of the Kalak Nappe Complex from Bekkarfjord (Laksefjord region; Figs. 1 & 2A; Table 1).

Stretching directions from the mylonites overlying the Komagfjord Antiformal Stack have been obtained from three other areas. Close to Fægfjord, stretching lineations were measured in the Lomvatn area (Fig. 1). Within this region only a very slight anticlockwise rotation was recorded when passing down into the lower 2–3 m of the >60 m of exposed mylonites (Fig. 6A; Table 1), with the mean direction changing from SE- to ESE-directed to ESE- to E-directed. Note, however, that the basal contact was not exposed and thus the lower ca. 5 m of mylonites were not sampled.

Stretching lineations in the basal mylonites at Komsa (Fig. 1) also show a slight anticlockwise rotation in the lower 20 m of the ca. 150 m-thick mylonites (Fig. 6B; Table 1), with the mean direction changing from E- to ESE-directed to E-directed. Lineations in the Raipas area on the southern side of the window (Fig. 1), however, revealed a marked clockwise rotation passing down through the >200 m-thick mylonites (Fig. 6B; Table 1). The significance of this is unknown, and further work is needed to delimit the variations in stretching lineation directions in the mylonites around the windows. A possible reason for the variation in sense of rotation may lie in the differing relative orientations of ramps in the footwall of the Kalak Nappe Complex in different areas when it was emplaced, deflecting the movement directions in different senses (cf. Apotria et al. 1992 for a brittle deformation model).

The mylonites in Fægfjord show both similarities and differences when compared to those elsewhere (see Table 4 for summary). In the western klippe the mean stretching direction along the coastal section, which is well above the Kalak Thrust Plane, is 315°, whilst in the

### Table 1. Stretching lineation orientations at the base of the Kalak Nappe Complex.

<table>
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<tr>
<th>Fig.</th>
<th>Data set</th>
<th>N</th>
<th>MEAN</th>
<th>PBFGC</th>
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<th>C</th>
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All data collected by the author except where stated.
Table 2. Other structural data.

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<td>4A</td>
<td>penetrative foliation (S2)</td>
<td>8</td>
<td>73–262</td>
<td>16–061</td>
<td>4.72</td>
<td>3.62</td>
</tr>
<tr>
<td>4A</td>
<td>F2 axial planes</td>
<td>17</td>
<td>74–278</td>
<td>15–083</td>
<td>3.39</td>
<td>4.57</td>
</tr>
<tr>
<td>4A</td>
<td>F2 axes &amp; intersection lineations</td>
<td>28</td>
<td>14–074</td>
<td>70–299</td>
<td>0.55</td>
<td>5.15</td>
</tr>
<tr>
<td>4C</td>
<td>stretching lineations</td>
<td>8</td>
<td>19–141</td>
<td>71–310</td>
<td>1.08</td>
<td>6.18</td>
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<tr>
<td></td>
<td>kink band axes</td>
<td>29</td>
<td>12–065</td>
<td>70–300</td>
<td>0.90</td>
<td>5.45</td>
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<td>Nilpavatn Formation, Gargia Nappe, E &amp; E klippe</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4B</td>
<td>fold axes/intersection lineations, EK</td>
<td>11</td>
<td>00–155</td>
<td>85–247</td>
<td>0.95</td>
<td>5.03</td>
</tr>
<tr>
<td>4B</td>
<td>crenulation axes, EK</td>
<td>4</td>
<td>21–058</td>
<td>21–156</td>
<td>3.44</td>
<td>5.80</td>
</tr>
<tr>
<td>4B</td>
<td>foliation, WK</td>
<td>60</td>
<td>69–285</td>
<td>15–059</td>
<td>0.91</td>
<td>4.49</td>
</tr>
<tr>
<td>4C</td>
<td>kink axes, WK</td>
<td>26</td>
<td>14–071</td>
<td>64–309</td>
<td>4.77</td>
<td>3.61</td>
</tr>
<tr>
<td></td>
<td>kink band axial surfaces, WK</td>
<td>7</td>
<td>37–158</td>
<td>09–062</td>
<td>0.59</td>
<td>4.80</td>
</tr>
<tr>
<td>4D</td>
<td>all Normal faults, WK</td>
<td>15</td>
<td>53–196</td>
<td>23–073</td>
<td>1.53</td>
<td>2.12</td>
</tr>
<tr>
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<td>all Reverse faults, WK</td>
<td>20</td>
<td>46–172</td>
<td>20–061</td>
<td>2.12</td>
<td>3.24</td>
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<tr>
<td>4D</td>
<td>mean of sigma-2 intersections, WK</td>
<td>3</td>
<td>23–060</td>
<td>57–190</td>
<td>0.45</td>
<td>6.79</td>
</tr>
</tbody>
</table>

All data collected by the author except where stated.

Structural evolution of the Fægfjord mylonites (Gargia Nappe)

The structural history of the Fægfjord mylonites, which form the Gargia Nappe at the base of the Kalak Nappe Complex, can be summarized into five events:

D1 – formation of early foliation, now preserved within spiral garnets, and associated shearing during garnet porphyroblastesis at peak metamorphic conditions (Gayer et al. 1985). This would have developed as a displacement over the autochthonous rocks underlying the Gargia Nappe root zone. This deformation was almost certainly Finnmarkian, related to the pre-to syn-490 Ma event defined from 40Ar/39Ar amphibole data (Dallmeyer 1988), since the second phase of garnet growth, both in the Gargia Nappe and the structurally identical overlying imbricates of the Kalak Nappe Complex (Rice 1984), occurred at temperatures greater than or essentially equivalent to the 40Ar/39Ar amphibole closing temperature. Further, no evidence of a Finnmarkian event has been found within amphiboles in the Komagfjord Antiformal Stack (Dallmeyer et al. 1988).

D2 – ductile thrusting of the Kalak Nappe Complex over the rocks later imbricated as the Komagfjord Antiformal Stack. Evidence from the Kvalsund area suggests that this was a SE-directed movement (Pharaoh et al. 1983), essentially parallel to the 141° stretching direction in the Billefjord Member of the western klippe. In the mylonites, this is represented by the SE- to SSE-directed (135° and 156°) movement directions, which overlap with the direction determined from the Billefjord Member. Since the peak metamorphism in the Lomvatn Fm. was epizone grade (Rice et al. 1989), and this is the same temperature as the 40Ar/39Ar muscovite blocking temperature, it seems probable that this deformation was Scandian, since no evidence of a Finnmarkian deformation has been recorded in the Komagfjord Antiformal Stack (Dallmeyer et al. 1988 – see above).

D3 – a change in thrusting direction towards the E to ESE, with the rotation of D2 lineations as well as the
eastern klippe, again well above the thrust, the direction is 156°, a difference of 21°. Adjacent to the Kalak Thrust Plane, however, the mean stretching direction is essentially the same in both klippen, with 125° in the west and 127° in the east. Both data sets show a wide distribution of orientations around E–W, particularly the data from the western klippe.

Thus, although most areas show a swing from a southerly to a more easterly stretching direction, in the Fægfjord mylonites the two directions are mixed in the lower zone, whilst in the other regions, such as Porsangerfjord and Bekkarfjord, they occur in different parts of the mylonites, with little overlap. This distributional variation may simply reflect the obvious difference in thickness of the mylonites in the various areas, with the rotational event condensed into a 10 m-thick zone at the base of only ca. 50 m of mylonites in Fægfjord rather than being spread throughout a thicker sequence, such as the 800 m of mylonites in Porsangerfjord. A similar broad range of directions was observed in the basal part of the exposed mylonites at Lomvatn (Fig. 6A), which are also thin. There is, therefore, the possibility that the true late stretching direction in the Fægfjord area (and Lomvatn) is more towards the east than the mean directions suggest, but that in the field the data are not readily distinguishable from the other directions and so a mixed mean is obtained.
development of new lineations in reworked mylonites, with mean stretching directions of $125^\circ$ and $127^\circ$. Since the mean directions and general distribution of the mixed D2 and D3 stretching lineations in the lower part of the Kalak Thrust Zone are so similar in the two klippen, it seems unlikely that the relative rotation of the D2 lineations in the two klippen could have occurred after D3.

D4 – development of a large-scale south-verging fold, with ENE-oriented axis and subsequent brittle-ductile to brittle thrusting, cutting out the lower part of the mylonites in the western klippe, so that the early thrusting direction now lies close to the Kalak Thrust. In the eastern klippe this deformation has been seen only as crenulations of the mylonites, with axes parallel to the large-scale fold in the western klippe (Fig. 4B). The folding is interpreted as a hanging wall anticline (both since it is directly underlain by a planar thrust fault and because it is asymmetric) and must therefore represent an out-of-sequence reactivation. The obliquity of the fold axis to both the inferred thrusting direction in D3 and the E- to ESE-directed deformation in the Gaissa Thrust Belt (Townsend et al. 1986), suggests that the fold is related to a lateral or oblique ramp, possibly at the margin of the Komagfjord Antiformal Stack. The lack of rotation of the stretching directions into parallelism with this oblique direction implies that deformation was a (predominantly) brittle event, possibly equivalent to the brittle movement along the Kalak Thrust Plane in the Porsangerfjord (Townsend 1987).

D5 – kinking, predominantly along an $070^\circ$ axis but locally $060^\circ$, clearly post-dates the D3 folding since it affects both limbs of the large-scale D4 fold, but with different geometrical relationships. This direction is similar to the kinking direction observed from the Gargia Nappe in the area north of Repparfjord (Rice 1982). The deformation associated with the subsequent brittle faults, which in some instances have breccias several centimetres wide, has not been studied, although it is locally common within the mylonites.

Pharaoh et al. (1983) argued that the first deformation in the Lomvatn Formation occurred prior to the emplacement of the Kalak Nappe Complex, because the Kalak Thrust Plane cuts these structures. However, since the thrust plane also cuts the folded mylonites, it is clear that the brittle Kalak Thrust Plane developed later than the early ductile deformation. A simpler model, therefore, is to infer in-sequence SE-directed ductile emplacement of the Kalak Nappe Complex over the Lomvatn Formation, which was essentially contemporaneously deformed in the footwall, followed by E- to ESE-directed out-of-sequence re-activation of the base of the Kalak Thrust Zone, and the somewhat later development of the brittle Kalak Thrust Plane, which cut down section, across the structures in the Lomvatn Formation.

**Significance for restoration models**

Gayer et al. (1987) published a balanced and restored cross-section through the Caledonides in Finnmark. The section line (Fig. 1) crosses the Gaissa Thrust Belt and all three basement horses which form the internal part of the Lower Allochthon. Although the section line does not cross the Laksefjord Nappe Complex, Gayer et al. (1987) incorporated it into the section as a schematic up-plunge projection, arguing that it was an integral part of the orogen, although of only local extent.

The early, SE-directed stretching direction was used to restore the Kalak Nappe Complex, Laksefjord Nappe Complex and Komagfjord Antiformal Stack (Gayer et al. 1987). Since no evidence of ESE- to E-directed deformation had been found within the Komagfjord Antiformal Stack, or in the mylonites of the immediately overlying Kalak Thrust Zone, it was inferred that during ESE- to E-directed shortening in the Gaissa Thrust Belt and Laksefjord Nappe Complex (late stage) the relative positions of the Kalak Nappe Complex and the three basement horses were fixed. As a consequence, a 143
Structural evolution, Kalak Nappe, Finnmark

Fig. 6. A. Lower hemisphere equal-area net of stretching lineations in the mylonites in the Lomvatn area. B. Lower hemisphere equal-area net of stretching lineations in the mylonites in the Komsa and Raipas areas. See Fig. 1 for localities. Open circles = mean orientations.

km-wide gap formed in the restored cross-section, between the trailing branch line of the Gaissa Thrust Belt and the leading branch line of the basement horses (cf. Gayer et al. 1987).

The stretching lineation data presented above allow a different restoration sequence to be envisaged; this is shown in a simplified revision of the section presented by Gayer et al. (1987), to which reference should be made for details outside the scope of this article. The deformation is described in a forwards time sense from the uppermost cross-section, in which the Scandian deformation in the Lower Allochthon has been fully restored and the Middle Allochthon restored relative to the Lower Allochthon (Fig. 7-I). In the first stage (Fig. 7-II) ductile SE-directed D2 imbrication of the Kalak and Laksefjord Nappe Complexes has been shown. The amount of movement of the Kalak Nappe Complex over the Laksefjord Nappe Complex at this stage is unconstrained, but must be less than the total inferred displacement, since some ESE-directed thrust movement also occurred along this fault zone. During this deformation, the Kalak Nappe Complex was emplaced over the basement horses, including the Lomvatn Formation at the top of the Komagfjord Antiformal Stack; this is D2 in the Fægfjord klippen. In the second stage (Fig. 7-IIIa), SE-directed ductile deformation cuts down into the basement, as a series of large-scale footwall shortcut thrust faults. Minor continuation of the D2 deformation in the klippen accompanied this, as the displacement associated with successive phases of basement shortening was transferred to the more foreland-ward parts of the base of the Kalak Nappe Complex.

In the succeeding phase, ESE- to E-directed out-of-sequence movement occurred at the base of the Kalak Nappe Complex and developed the three imbricates of the Lakekfjord Nappe Complex (Føyn et al. 1983). The first part of this is shown as the final movement of the Kalak Nappe Complex over the Lakekfjord Nappe Complex (Fig. 7-IIIb). During this deformation, out-of-sequence ESE- to E-directed deformation occurred at the base of the mylonites around the Komagfjord Antiformal Stack (D3). In the final phase (Fig. 7-IV), the ESE-to E-directed imbrication in the Gaissa Thrust Belt, and the emplacement of this unit over the autochthonous

Table 4. Summary of stretching lineation rotations.

<table>
<thead>
<tr>
<th>Area</th>
<th>Rotation</th>
<th>Direction</th>
<th>Early</th>
<th>Late</th>
<th>Mylonite thickness</th>
<th>Underlying unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bekkarfjord, Laksefjord</td>
<td>21</td>
<td>anticlockwise</td>
<td>ESE</td>
<td>E</td>
<td>ca. 900 m</td>
<td>Laksefjord N C</td>
</tr>
<tr>
<td>Borselv, Porsangerfjord</td>
<td>28</td>
<td>anticlockwise</td>
<td>SE</td>
<td>ESE</td>
<td>800 m</td>
<td>Gaissa T B</td>
</tr>
<tr>
<td>Føgfjord W, Repparfjord</td>
<td>17</td>
<td>anticlockwise</td>
<td>SE</td>
<td>SE-ESE</td>
<td>30-50 m</td>
<td>Komagfjord A S</td>
</tr>
<tr>
<td>Føgfjord E, Repparfjord</td>
<td>29</td>
<td>anticlockwise</td>
<td>SSEE</td>
<td>SE-ESE</td>
<td>30-50 m</td>
<td>Komagfjord A S</td>
</tr>
<tr>
<td>Lomvatn, Repparfjord</td>
<td>15</td>
<td>anticlockwise</td>
<td>SE</td>
<td>SE-ESE</td>
<td>&gt;20 m</td>
<td>Komagfjord A S</td>
</tr>
<tr>
<td>Komsa, Alta</td>
<td>15</td>
<td>anticlockwise</td>
<td>E-ESE</td>
<td>E</td>
<td>150 m</td>
<td>Komagfjord A S</td>
</tr>
<tr>
<td>Raipas, Alta</td>
<td>22</td>
<td>clockwise</td>
<td>E</td>
<td>ESE</td>
<td>&gt;200 m</td>
<td>Komagfjord A S</td>
</tr>
</tbody>
</table>
Dividal Group, occurred. At some stage between the D3 deformation and the imbrication of the Gaissa Thrust Belt, D4 deformation occurred within the Fægfjord mylonites, causing localized brittle deformation and intermediate-scale folding, with transport concentrated in a narrow brittle zone. This suggests that the ESE- to E-directed deformation cut through the basement horses, re-activating old thrust planes between the basement horses, as metamorphic conditions waned.

In the modified section the trailing branch line of the Lower Allochthon (Revsbotn Basement Horse) is restored to 316 km. The cross-section, including the 336 km of the restored Kalak Nappe Complex (cf. Gayer et al. 1987), not shown in Fig. 7, has an overall length of 652 km, compared to the 795 km deduced by Gayer et al. (1987). The reduced length places an upper limit on the extent of the Baltoscandian margin prior to deformation, and marginally affects models which used the restoration of Gayer et al. (1987) as a template (cf. Rice et al. 1989; Gayer & Rice 1989; Andréasson 1994).

Conclusions

The two klippen of the Kalak Nappe Complex in the Fægfjord area contain fragments of the Gargia and Olderfjord Nappes. The latter is represented by psammites thought to be correlatives of the inverted Billefjord Member rocks exposed to the north of Repparfjord. These rocks have a stretching direction plunging towards 141°. The <50 m-thick mylonites of the Kalak Thrust Zone at the base of the Kalak Nappe Complex overlying the Komagfjord Antiformal Stack in the Fægfjord area are part of the Gargia Nappe.

Ductile stretching directions in the upper part of the mylonites are tightly clustered, plunging towards 138° and 157° in the western and eastern klippe respectively. These represent the early emplacement of the mylonites over the underlying Lower Allochthon (D2).

Ductile stretching directions in the lower few metres of the mylonites are more girdled in distribution, with orientations between SSE and E, and mean orientations of 121° and 128°. These directions represent maxima of combined new lineations and rotated old lineations, rather than the actual direction of movement in this late phase of movement, which is inferred to have been ESE- to E-directed (D3).

Later deformation in the mylonites resulted in large-scale folding of the mylonites about an 060° trending axis, and then truncation of the fold (D4); this out-of-sequence movement is presumed to have been on a lateral branch line, accounting for the anomalous fold axis orientation.

Modification of the balanced cross-section of Gayer et al. (1987), with E- to ESE-directed out-of-sequence movement in the Kalak Thrust Zone overlying the Komagfjord Antiformal Stack, allows a section to be drawn
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in which there is no gap in the restored section. This has an overall length of 652 km, with deformation propagating across the Lower Allochthon at a time-averaged rate of ca. 0.87 cm yr⁻¹.

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