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Thrust transport directions and thrust sheet restoration in the Caledonides of Finnmark, North Norway

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Abstract—Thrust sheets of the Late Cambrian to Early Ordovician Finnmarkian phase of the Caledonian Orogeny of Finnmark, northern Norway, have been displaced, firstly to the SE, under ductile conditions and later, under more brittle conditions, towards the ESE/E. These thrust sheets have been sequentially restored with the aid of branch-lines and balanced cross-sections. The minimum displacement for each thrust sheet is: Gaissa Nappe, 165 km; Laksefjord Nappe Complex, 105 km; Komagfjord Antiformal Stack, 30 km; and Kalak Nappe Complex, 75 km. This restoration has three significant implications: (1) the total displacement across the Finnmark Caledonides is over 375 km; (2) the Raipas Supergroup exposed within the Komagfjord Window, the allochthonous origin of which has previously been contentious, has been displaced as a basement horse, firstly to the SE and later to the ESE/E by at least 375 km; and (3) in a palinspastic reconstruction the Raipas Supergroup basement did not form the Finnmark Ridge, the source area for the sediments of the Laksefjord Nappe Complex. This restoration does not include the deformation within the Kalak Nappe Complex or the imbricates of the Gaissa Nappe in East Finnmark.

INTRODUCTION

THE THRUST belt of Finnmark, North Norway (Fig. 1), evolved during the Late Cambrian to Early Ordovician, Finnmarkian phase of the Caledonian orogeny (Sturt *et al.* 1978). The belt is divided into three Finnmarkian nappe units (see Fig. 1); the Kalak Nappe Complex (Roberts 1974), Laksefjord Nappe Complex (Chapman 1980) and the Gaissa Nappe (Rosendahl 1945), which have been thrust southeastwards and east–southeastwards on to the Baltic Shield and its autochthonous cover sediments. In recent reviews of the Scandinavian Caledonides of northern Norway these nappe units constitute part of the Lower and Middle Allochthons (Ramsay *et al.* 1985, Roberts 1985). Chapman *et al.* (1985) have shown that these Finnmarkian nappes evolved in a piggy-back fashion in which the metamorphic grade decreases to the southeast and east. The upper greenschist to amphibolite facies Kalak Nappe Complex now rests on the greenschist facies Laksefjord Nappe Complex and on the Gaissa Nappe where the Laksefjord Nappe Complex is absent (Fig. 1). On Varangerhalvøya, east Finnmark, and to the north of the WNW–ESE trending, dextral Trollfjord–Komagelv Fault, lies a fourth tectonic unit, the Barents Sea Group (Fig. 1). The rocks in the northwest corner of the Varangerhalvøya peninsula have been correlated with those of the Kalak Nappe Complex (Levell & Roberts 1977; see Fig. 1), and they are separated from the Barents Sea Group by a steeply dipping fault, which Levell & Roberts (1977) believed to be an extension of the Kalak Thrust.

Within the Kalak Nappe Complex there are three tectonic windows (Fig. 1); the Alta–Kvaenangen, Altenes and Komagfjord Windows, which expose rocks of the Svecokarelian Raipas Supergroup (Pharaoh *et al.* 1983) and are unconformably overlain by a thin sequence of post-Riphean sediments. Based on a simple restoration of the Gaissa Thrust, Rhodes (1976) suggested that the Komagfjord Window was allochthonous, having been transported over 30 km. However, more recently, the origin of the rocks within this window has become contentious. Pharaoh *et al.* (1983) believed the window to be autochthonous, Gee *et al.* (1985) suggested it was parautochthonous, whilst for the thin-skinned models for the Finnmark Caledonides of Chapman *et al.* (1985) and Townsend *et al.* (1986) to be valid it must be allochthonous. Other arguments in favour of the allochthonous model for the Komagfjord Window include the greenschist facies metamorphism of the post-Riphean sediments (Rhodes 1976, Bevins *et al.* 1986), the orientation of Caledonian structures within the window (see Pharaoh *et al.* 1983) and the doming of the Kalak Nappe Complex meta-sediments around the window. Boyer & Elliott (1982) suggested that this type of doming around windows could be produced by the formation of an antiformal stack, although in this case it could be produced by later, possibly post-Finnmarkian folding. Townsend (1986) has constructed a balanced cross-section through the window, demonstrating that the structure forms an antiformal stack (Boyer & Elliott 1982) whose trailing edge has been displaced a minimum of 30 km to the southeast. It is, therefore, suggested that the structure which domes the Kalak Nappe Complex, forming the Komagfjord Window, be named the Komagfjord Antiformal Stack.

The first attempt at restoring the Caledonian nappes of Finnmark was made by Gayer & Roberts (1973), estimating displacements for the Kalak, Laksefjord and Gaissa Nappes, of 12, 18 and 40 km, respectively; this

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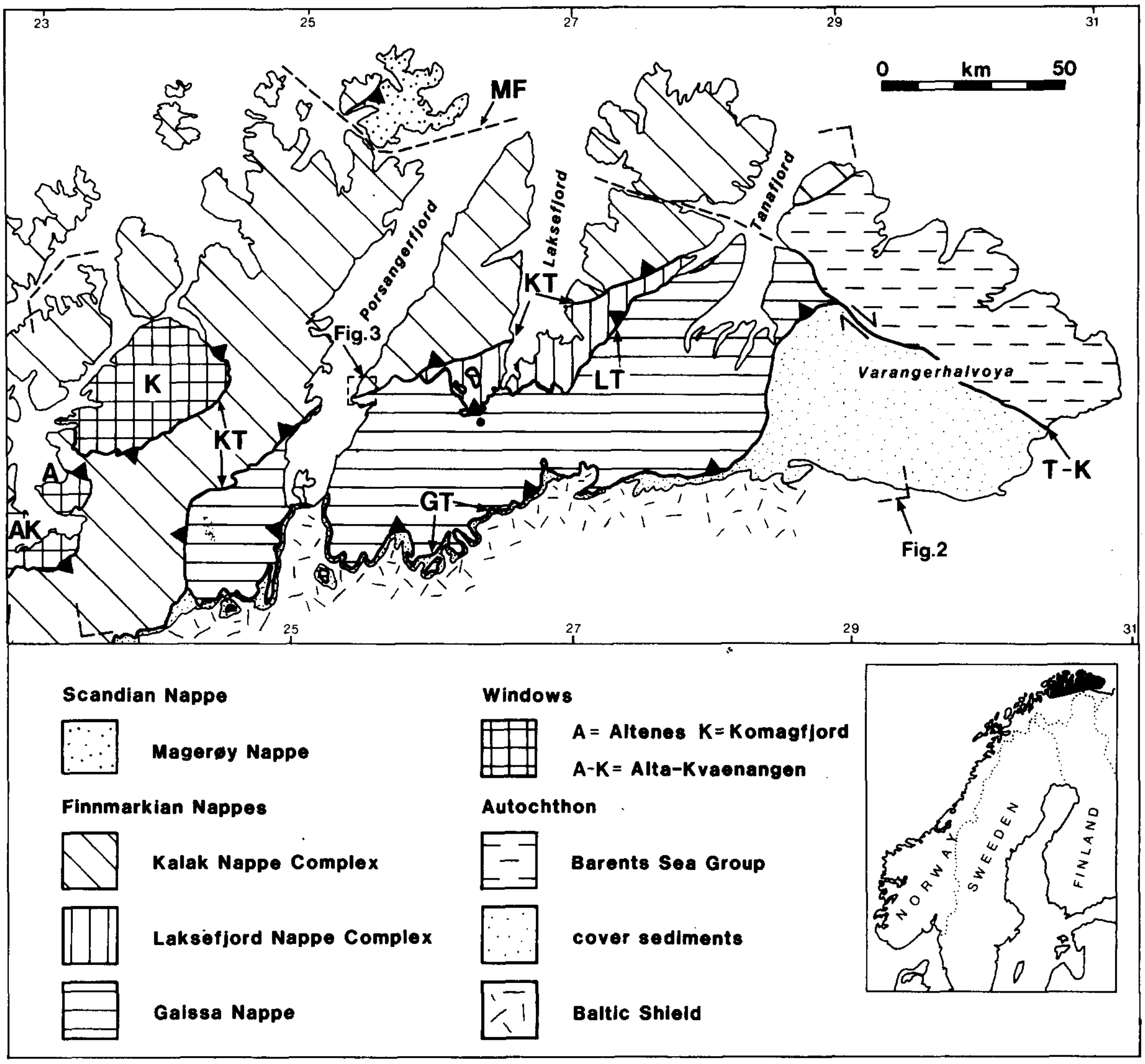

Fig. 1. Tectonostratigraphic map of the Finnmark Caledonides; GT = Gaissa Thrust, KT = Kalak Thrust, LT = Laksefjord Thrust, MF = Magerøysundet Fault and T–K = Trollfjord–Komagelv Fault. Position of the thrust front in East Finnmark is after Chapman *et al.* (1985) and Townsend *et al.* (1986).

to a cumulative displacement of 70 km for the Kalak Nappe Complex. This restoration did not take account of internal shortening within the nappes and assumed a constant SE/SSE thrusting direction. Chapman *et al.* (1985) have balanced and restored cross-sections through the Laksefjord Nappe Complex resulting in approximately 30% shortening, after a similar amount of extension. As the later contraction cancels this earlier phase of extension (Chapman *et al.* 1985) there is no need to restore the thrusts within the Laksefjord Nappe Complex due to no net shortening. Townsend *et al.* (1986) have constructed a balanced cross-section through part of the Gaissa Nappe in east Porsangerfjord (see Fig. 2) and, on restoration, this cross-section yields over 104 km of displacement. Townsend (1986) has calculated a further 16 km of displacement from a balanced cross-section in south Porsangerfjord, from which it was suggested that the total displacement in the Porsangerfjord region, when taking west Porsangerfjord into account, could well be in excess of 165 km.

The geometric patterns produced by the lines along which fault surfaces join are pertinent to the restoration of the Finnmark nappe sequence. Boyer & Elliott (1982) defined the line along which two fault planes join as a branch-line, which must contain all outcrops and subcrops of a particular thrust sheet, as a thrust sheet will only lie between the two fault surfaces joining along that particular branch-line. On a map it should be possible to distinguish between the eroded and buried parts of a branch-line as has been done by Elliott & Johnson (1980).

The aim of this paper is to cast further light on the evolution of the Caledonian thrust belt of Finnmark, by sequentially restoring the nappe pile in the true transport direction as determined by thrust displacement vectors. Branch-lines and balanced cross-sections are used to determine the amount of displacement of each nappe, leading to a palinspastic reconstruction for the Finnmark Caledonides.

THRUSTING DIRECTIONS

Thrust displacement vectors in the Finnmark Caledonides vary across the thrust belt, indicating a

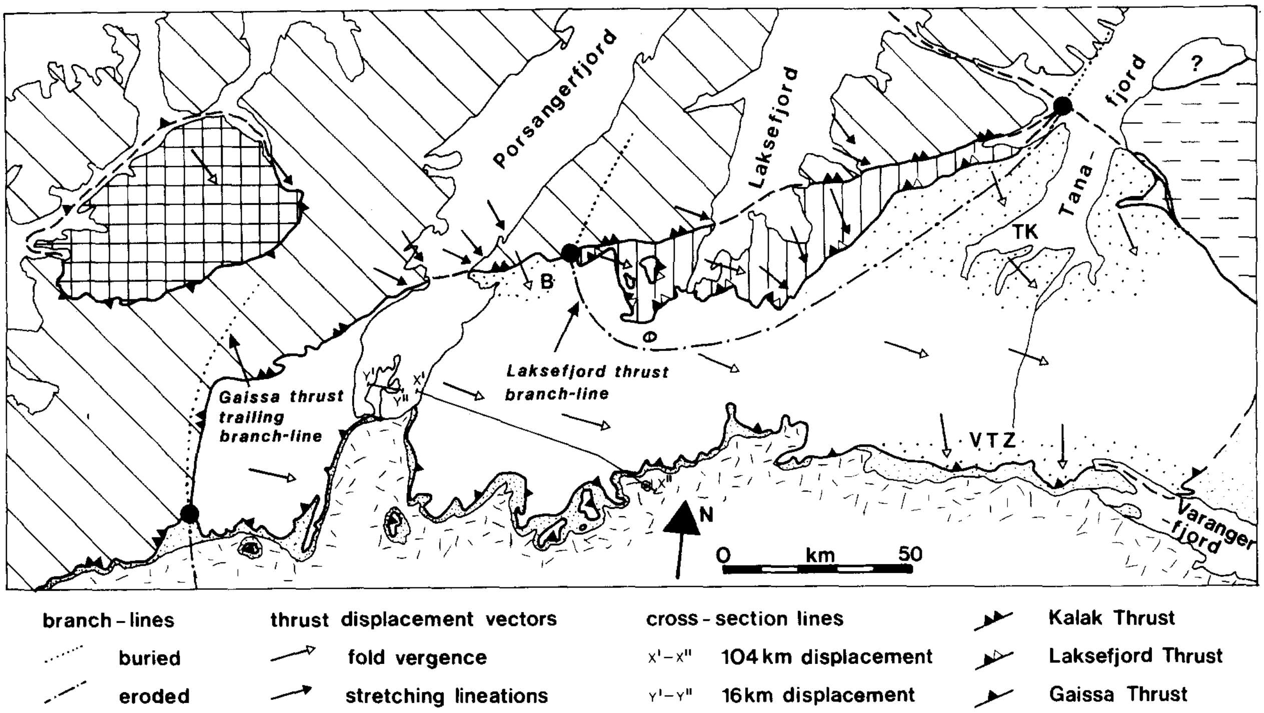

Fig. 2. Map of Central and East Finnmark showing the various thrust displacement vectors, constructed branch-lines and lines of balanced cross-sections. Shading same as Fig. 1, except for Gaissa Nappe which has been left blank with the exception of areas of oblique trending structures (coarse stipple); B = Borselv Duplex, VTZ = Varangerfjord Transpression Zone and TK is related to the Trollfjord–Komagelv Fault. Thrust front lies further east than on Fig. 1 where it is actually exposed, after Townsend (1986). See Fig. 1 for location.

change in transport direction as the belt evolved. This change, and its timing, is important for the restoration of each nappe unit and in determining the evolution of the nappe pile as a whole. The evidence for the thrust displacement vectors in the four nappe units is as follows.

(1) In the Gaissa Nappe, thrust sheet displacement was towards a direction between ESE and E (Townsend *et al.* 1986), as determined by the NNE–SSW to N–S trending fold axes. These folds generally verge eastwards (Fig. 2), with a westerly dipping cleavage. However, within the Gaissa Nappe there are three areas of oblique trending structures: (1) the Børselv Duplex (Fig. 2), a small area to the east of Porsangerfjord in the immediate footwall to the Kalak Thrust (Townsend *et al.* 1986); (2) the Varangerfjord transpression zone (Fig. 2), formed by the partial sticking of the Gaissa Thrust (Townsend 1986); and (3) adjacent to the Trollfjord–Komagelv Fault, where thrust related structures interact with this strike–slip fault (Williams 1979). These oblique trending structures cover only a small area of the Gaissa Nappe and previously have overshadowed the evidence for eastward directed thrusting (e.g. Gayer & Roberts 1973, Chapman *et al.* 1985).

(2) In the Laksefjord Nappe Complex there is evidence for two phases of thrusting (Williams *et al.* 1984); ductile thrusting along a broad shear zone at the base of the complex and a later phase of brittle thrusting, along discrete thrust planes. The ductile thrusting is thought to have been directed towards the SSE, as indicated by the 335° mean plunge of stretching lineations (Chapman *et al.* 1979, see Fig. 2). However, Chapman *et al.* (1979) noted an anomalous area in the southwest of the Laksefjord Nappe Complex where stretching lineations plunge towards 303° (Fig. 2). The direction of brittle thrusting appears to be similar to that in the Gaissa Nappe. In the central part of the Laksefjord Nappe Complex folds, thrust planes and their branch-lines generally have a N–S/NNE–SSW trend (Føyn *et al.* 1983, Føyn 1984), and in the western part of the nappe late N–S trending and eastward verging folds are present (Noake 1975; Fig. 2). These late folds may be associated with the brittle phase of thrusting, and if so indicate a transport direction towards the ESE/E, similar to that in the Gaissa Nappe.

(3) The Kalak Thrust in Porsangerfjord also carries evidence of two phases of thrusting, with the earlier ductile thrusting occurring along the Kalak Thrust Zone and the later brittle thrusting along the Kalak Thrust Plane which is a discrete surface lying at the base of this thrust zone. The thrusting direction within the Kalak Thrust Zone is indicated by stretching lineations and fold axes (Figs. 2 and 3). At the top of the thrust zone the linear structures plunge towards the NW, but with increasing proximity to the Kalak Thrust Plane the plunge gradually changes towards the WNW (Figs. 2 and 3). This indicates that the direction of thrusting changed from SE to ESE as the Kalak Thrust Zone evolved (assuming the direction of maximum extension is parallel to the movement direction). In east Laksefjord a similar change in the plunge of linear structures has been mapped in the Kalak Thrust Zone (Williams 1976, map 2; see Fig. 2). Føyn *et al.* (1983) show linear structures to be plunging to the W or WNW on the same thrust zone

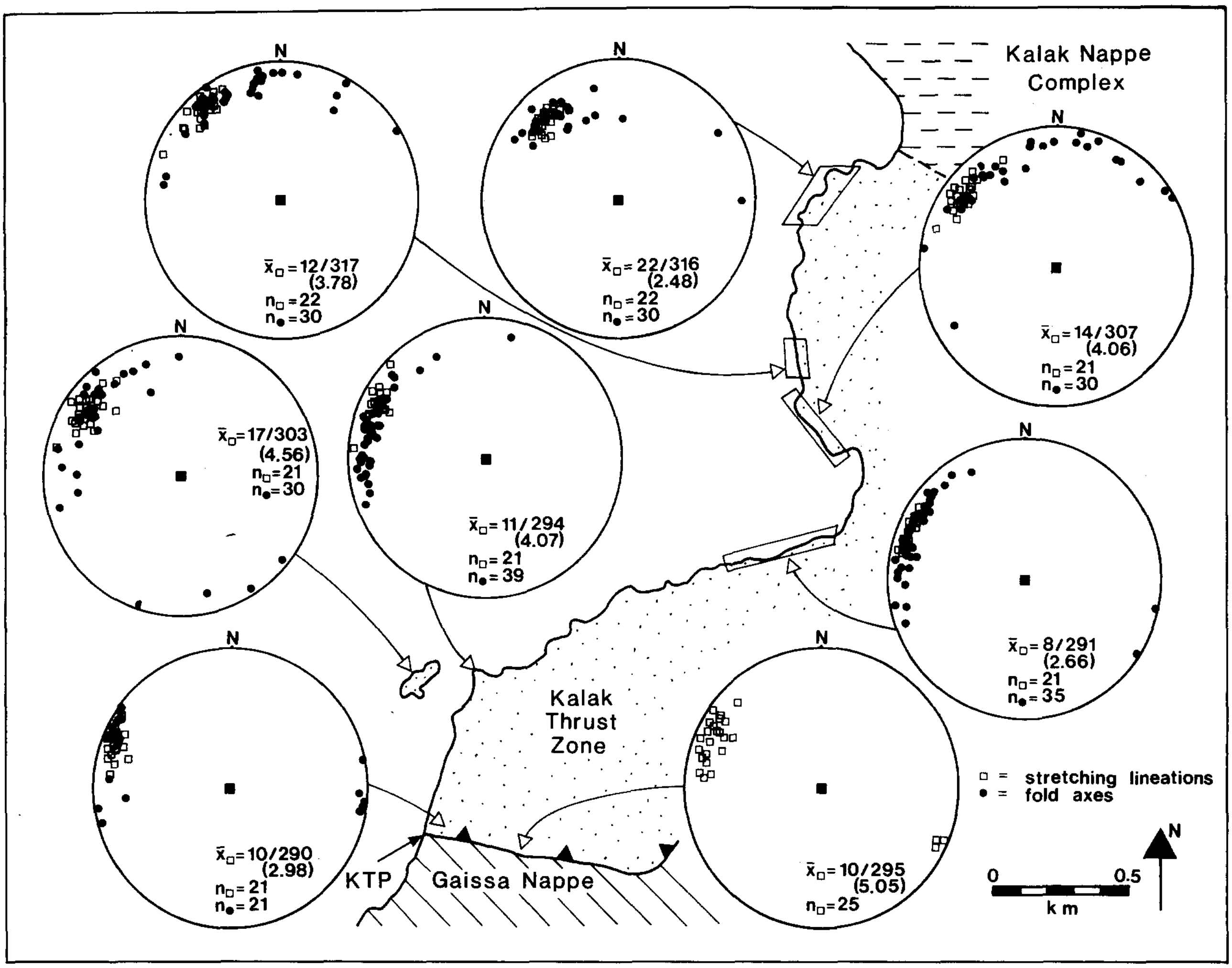

Fig. 3. Map of the Kalak Thrust Zone in east Porsangerfjord showing stretching lineations and fold axis orientations from specific localities across the zone. All stereograms are equal area and location is outlined in Fig. 1. Note: at the top of the thrust zone these structures generally plunge to the NW, whereas at the base they plunge towards the WNW, demonstrating a change in thrusting direction as the zone evolved. KTP = Kalak Thrust Plane.

in west Laksefjord (Fig. 2). The Kalak Thrust Zone in Laksefjord is also cut by a brittle thrust plane as in Porsangerfjord (Williams 1976). The thrusting direction along the Kalak Thrust Plane cannot be determined directly by the orientation of related structures. However, it has been assumed that the movement was towards the ESE or ESE/E, because the displacement occurred after the thrusting direction had changed towards the ESE. The change in thrusting direction may have continued during the displacement along the Kalak Thrust Plane with displacement towards the ESE/E, parallel to the imbricate thrusts in the Laksefjord and Gaissa Nappes.

(4) The Komagfjord Antiformal Stack contains discrete thrust planes striking NE–SW (Pharaoh *et al.* 1983) with associated folds which have a NW dipping axial-planar cleavage and NE–SW trending axes, indicating a thrusting direction towards the SE (Fig. 2). The Kalak Thrust around the Komagfjord Antiformal Stack contains stretching lineations and fold axes plunging towards the SE or NW (Rhodes 1976; see Fig. 2), with no evidence of the change in thrusting direction observed in Porsangerfjord and Laksefjord.

In conclusion, the higher, more ductile and earlier formed nappes in the piggy-back sequence of thrusting (Chapman *et al.* 1985), were initially displaced towards the SE/SSE. As the thrust belt evolved this thrust displacement vector changed in an anticlockwise manner, to an ESE/E orientation. Evidence for this progressive anticlockwise rotation has been found within the Kalak Thrust Zone (see Fig. 3).

The recognition of the change in thrusting direction as the thrust belt evolved has important consequences for the Komagfjord Antiformal Stack. As the thrusting direction within the antiformal stack is towards the SE, it must have developed prior to the change in thrusting direction. Further displacement would have been transferred onto a lower thrust, which at a later time would have accommodated the change in thrusting direction. Consequently the Komagfjord Antiformal Stack would have been transported piggy-back, as a basement horse, first to the SE and later to the ESE. This supports the thin-skinned model for the evolution of the structures within the window, forming a culmination beneath the Kalak Nappe Complex (Chapman *et al.* 1985).

RESTORATION OF THE FINNMARKIAN THRUST SHEETS

The Gaissa Thrust trailing branch-line

The trailing branch-line to the Gaissa Thrust, where it joins the Kalak Thrust, crops out as a branch-point in Stabbursdalen (Fig. 2); west of this branch-point the Kalak Thrust becomes the regional sole thrust (Holtedahl & Dons 1960). This trailing branch-line is buried to the north of the branch-point (Fig. 2) and its orientation is unknown, but it may have a NNE–SSW orientation, as shown in Fig. 2, which would result in a minimum restoration of the Laksefjord Thrust (see later).

Thrust sheets within a portion of the Gaissa Nappe near the head and to the east of Porsangerfjord have been restored; Townsend *et al.* (1986) have estimated 104 km of displacement (X′–X″, Fig. 2) east of Porsangerfjord, Townsend (1986) calculated a further 16 km near the head of the fjord (Y′–Y″, Fig. 2) and Townsend *et al.* (1986) stated that a similar amount of shortening existed to the west of the fjord, increasing the displacement by a further 45–50 km. Thus the total displacement is probably in excess of 165 km in the Porsangerfjord region. Therefore, the restored position of the trailing branch-line to the Gaissa Thrust must lie at least 165 km back in the ESE/E transport direction, placing the exposed branch-point in Stabbursdalen to the west of the island of Arnøya (GT1, Fig. 4). In restoring the internal deformation in the Gassa Nappe, the Kalak and Laksefjord Nappe Complexes must also move 165 km towards the WNW/W (Fig. 4).

The Laksefjord Thrust branch-line

The Laksefjord Thrust joins the Kalak Thrust along the Laksefjord Thrust branch-line, the trailing portion of which intersects the ground surface between Porsangerfjord and Laksefjord (Fig. 2). It has been assumed that the Laksefjord and Kalak Thrusts rejoin and form a leading branch-point in Tanafjord, where the two thrusts are converging (Figs. 1 and 2), as this will result in a minimum restoration. However, the leading branch-line may have been offset along the Trollfjord–Komagelv Fault, in which case the leading branch-point would lie further to the NE, although there is no evidence for this.

The Laksefjord Thrust branch-line is eroded to the south and buried northwards (Fig. 2). A possible position of the eroded part of the branch-line has been constructed (Fig. 2), so as to give the minimum restoration possible for the Laksefjord Thrust, although it is likely that it extended further to the south. The buried position has not been constructed as it is uncertain and does not affect the restoration.

Since the exhumed footwall to the Laksefjord Thrust is unexposed and does not underlie the Laksefjord Nappe Complex (Figs 1 and 2), it must, therefore, be buried beneath the Kalak Nappe Complex. Hence, the minimum restored position for the Laksefjord Thrust branch-line must lie back in the ESE/E transport direction (Fig. 4), beneath the position of the Kalak Nappe Complex; this is a displacement of at least 42 km to the WNW/W. If the eroded branch-line had been constructed further to the south the minimum position would lie further to the west.

The minimum restored position of the Laksefjord Thrust is unsatisfactory, because the greenschist facies Laksefjord Nappe Complex would be juxtaposed along strike to the anchizone grade Gaissa Nappe (Bevins *et al.* 1986; LT2a against GT1 on Fig. 4). There would, therefore, have been a tectonic boundary between the Gaissa and Laksefjord Nappes, prior to thrusting. A more realistic restored position, in view of the metamorphic grade, is to take the Laksefjord Thrust branch-line back even further, to just behind the restored position of the Gaissa Thrust trailing branch-line (LT2b, Fig. 4). This more realistic restoration of the Laksefjord Thrust branch-line suggests that the displacement along the Laksefjord Thrust may be as much as 105 km, with a total displacement of 270 km for the Laksefjord Nappe Complex. However, the displacement along the Laksefjord Thrust would be greater if the Gaissa Thrust trailing branch-line had not been constructed in its minimum position.

Restoration of the Kalak Thrust and the Komagfjord Antiformal Stack

The Kalak Thrust can be restored fairly easily. Its easternmost outcrop must be restored back along its transport direction, to the west of the trailing edge of the Laksefjord Nappe Complex. However, the position of the easternmost outcrop of the Kalak Nappe Complex is uncertain. Levell & Roberts (1977) believed it to be the NW corner of Varangerhalvøya (see Fig. 1), separated from the Barents Sea Group by a steeply dipping fault, which they regarded as an extension of the Kalak Thrust. No evidence has been published to determine that this fault has a contractional geometry and, in addition, no mylonitic metasediments have been recorded immediately to the northwest of this fault, as there are for the entire outcrop length of the Kalak Thrust. As the extension of the Kalak Thrust onto Varangerhalvøya is still in some doubt, the easternmost outcrop of the Kalak Thrust will be taken as that in west Tanafjord (Fig. 1). This outcrop in Tanafjord must be restored, back in the ESE/E transport direction, along the Kalak Thrust, to the west of the restored position of the Laksefjord Thrust trailing branch-line (KT3, Fig. 4). This is a reasonable restoration because the metamorphic grade of the Kalak Nappe Complex is higher than that of the Laksefjord Nappe Complex and higher grade thrust sheets are generally derived from further into the hinterland. This restoration suggests that the displacement along the Kalak Thrust Plane is a minimum of 75 km, a total displacement of 345 km brittle, ESE/E displacement for the Kalak Nappe Complex.

The Kalak Thrust Zone is more difficult to restore, for two reasons; the displacement accommodated by it is unknown and it must be restored in several steps, each

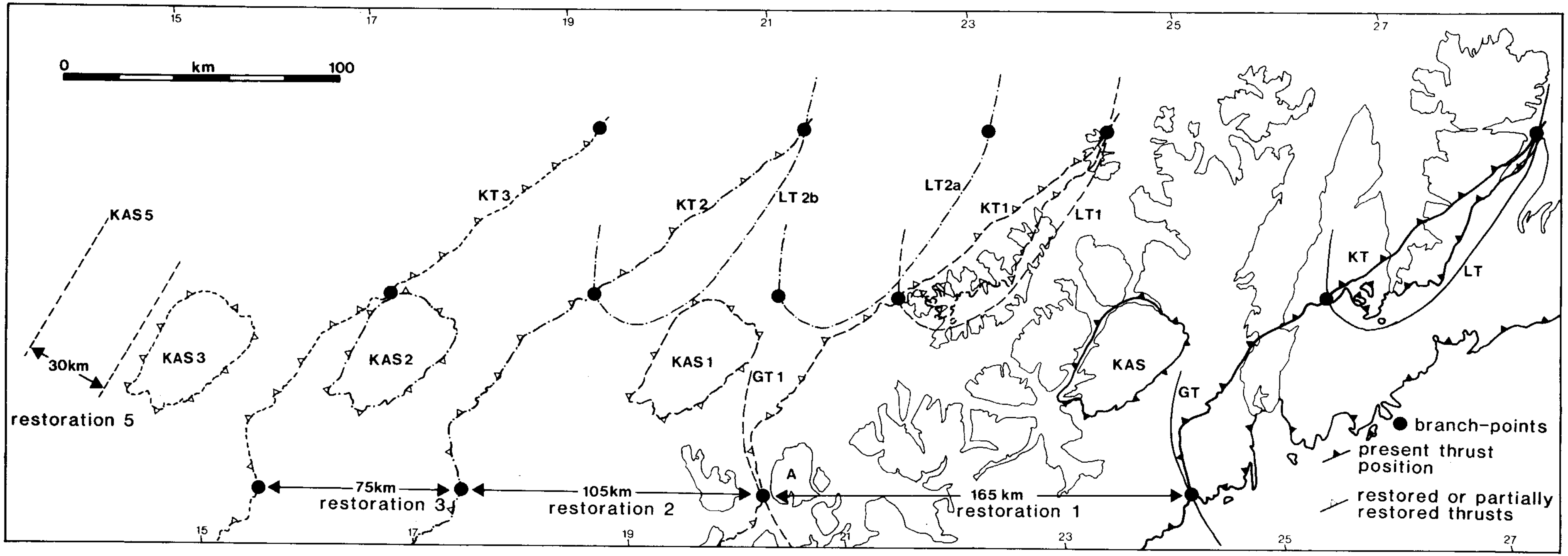

Fig. 4. Restoration of the Finnmarkian thrust sheets: restoration 1, the trailing branch-line to the Gaissa Nappe (this does not include the imbricates of East Finnmark); restoration 2a, minimum restoration of the Laksefjord Thrust branch-line, which is metamorphically incompatible; restoration 2b, a metamorphically feasible restoration of the Laksefjord Thrust branch-line; restoration 3, the Kalak Thrust; restoration 4, the Kalak Thrust Zone, which has been omitted because it is incalculable; and restoration 5, the trailing edge of the Komagfjord Antiformal Stack to the NW. A total cumulative displacement for the trailing edge of the Komagfjord Antiformal Stack of 375 km. A = Arnøya and S = Stabbursdalen. GT = Gaissa Thrust trailing branch-line, KAS = Komagfjord Antiformal Stack, KT = Kalak Thrust and LT = Laksefjord Thrust branch-line; numbers refer to sequentially restored positions.

time changing the transport direction. Thus any point in the Kalak Nappe Complex must have been displaced along an arc-shaped path, during this earlier ductile displacement. As a consequence of these two indeterminable factors, no attempt has been made to restore the Kalak Thrust Zone (therefore KT4 is omitted in Fig. 4).

The final restoration is that of the Komagfjord Antiformal Stack and the Kalak Thrust around it. The imbricate thrusts within the Komagfjord Window have been restored by balancing and restoring a cross-section (Townsend 1986) and this yields a displacement of the trailing edge of the duplex structure of 30 km to the southeast (KAS 5, Fig. 4). The Kalak Thrust around the window must finally be restored, but it is possible that there was no significant displacement, because cover sediments have been thrust over Caledonian basement without any proven stratigraphic inversion and no restorable stratigraphic boundary has been offset. However, a considerable displacement is thought more likely. The restoration of the Caledonian structures in the Komagfjord Window suggests a further displacement of at least 30 km, but in a southeasterly direction; a total displacement of over 375 km.

EVOLUTION OF THE CALEDONIAN THRUST SHEETS OF FINNMARK

Based on the above considerations, a sequence of events for the evolution of the thrust sheets in the Finnmark Caledonides can be proposed.

(1) Kalak Nappe Complex cover metasediments were thrust southeastwards onto or along the autochthonous Raipas Supergroup which is now exposed within the Komagfjord Window. This displacement cannot be estimated.

(2) These Caledonian basement rocks of the Komagfjord Window were imbricated, forming an antiformal stack, doming the Kalak Nappe Complex around it and displacing the trailing edge of the duplex by 30 km to the southeast (Townsend 1986).

(3) An unknown amount of displacement occurred along the Kalak Thrust Zone, displacing the Kalak Nappe Complex and the Komagfjord Antiformal Stack along an arc-shaped path, firstly to the southeast and later to the east-southeast.

(4) The Kalak Nappe Complex was then displaced along the Kalak Thrust to the east-southeast by at least 75 km. The Laksefjord Nappe Complex was then picked up as a horse, shortened internally and transported a further 105 km, in the same direction. This resulted in a cumulative displacement for the trailing edge of the Komagfjord Antiformal Stack of at least 210 km.

(5) Finally, the Gaissa Nappe formed, as the external thrust belt, with an estimated displacement for its trailing branch-line of 165 km, a cumulative displacement of 375 km.

It should be stressed that this total cumulative displacement for the Finnmark Caledonides of over 375 km does not take into account either the imbricates in the Gaissa Nappe in east Finnmark, which have yet to be restored, or any displacement within the Kalak Nappe Complex above the Kalak Thrust Zone.

PALINSPASTIC RESTORATION

Previous palinspastic restorations of the Finnmark Caledonides (e.g. Gayer & Roberts 1973, Chapman 1980, Føyn *et al.* 1983, Rice 1986) have involved the presence of a basement ridge, the Finnmark Ridge, between the restored Gaissa and Laksefjord Nappes. The Finnmark Ridge separated two distinct sedimentary basins, with the Tanafjord and Vestertana Groups of the Gaissa Nappe deposited to the southeast and the Laksefjord and Kalak Group sediments to the northwest (Gayer & Roberts 1973, Chapman 1980).

Detailed sedimentological studies of the Laksefjord Nappe Complex by Chapman (1980) show the source area to be from the southeast, in agreement with the Finnmark ridge model of Gayer & Roberts (1973). However, the suggestion that this ridge was formed by the basement highs now exposed as the Alta-Kvaenangen, Altenes and Komagfjord windows within the Kalak Nappe Complex (Gayer & Roberts 1973) is inconsistent with the restoration outlined above.

The present restoration of the Finnmark sediments (Fig. 5) suggests that the Raipas Supergroup, now

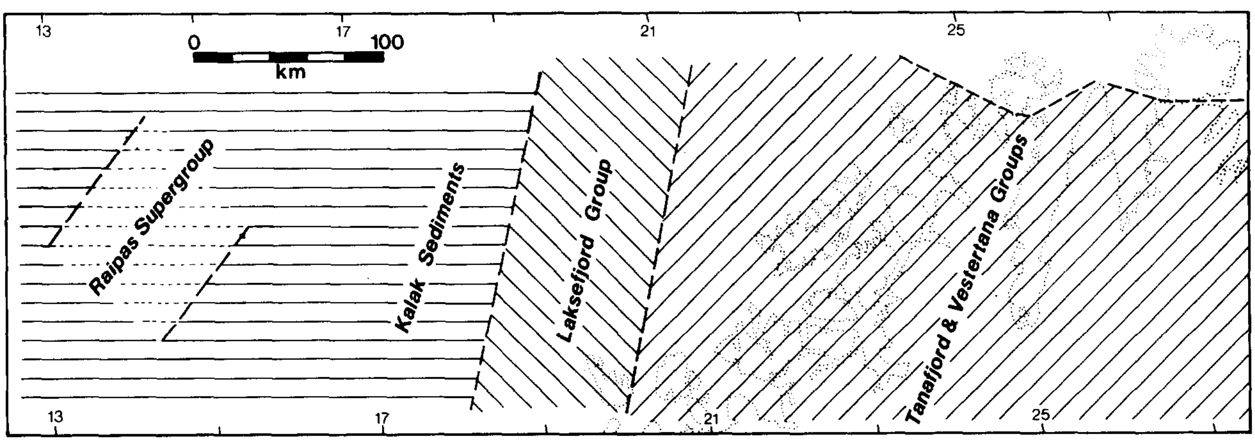

Fig. 5. Palinspastic reconstruction of the Finnmark Caledonides based on the restoration outlined in this paper. This reconstruction suggests that the Raipas Supergroup could not have formed the Finnmark ridge, as it originally lay to the northwest of the Laksefjord Group whose sediment source was from the southeast.

exposed in the Komagfjord Window, originally lay a considerable distance to the northwest of the Laksefjord Group and possibly formed part of the basement to the Kalak Group sediments. It is more likely that the source for the Laksefjord Group sediments was the basement of the lower Laksefjord Nappe Complex (see Føyn *et al.* 1983), as suggested on sedimentological grounds by Chapman (1980), and that these basement rocks may have once formed the Finnmark ridge.

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