# Field evidence for thrusting of the basement rocks coring tectonic windows in the Scandinavian Caledonides; an insight from the Kunes Nappe, Finnmark, Norway

A. H. N. Rice

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The Kunes Nappe is a basement unit (Storfjord Basement Complex) which is separated here from the Laksefjord Nappe in central Finnmark.It has features that are typical of basement rocks coring tectonic windows in the Scandinavian Caledonides (here called `Window Basement´). These are: A thin unconformable cover succession (Adamsfjord Formation); abundant imbrication; early SE-directed deformation overprinted by E- to ESE-vergent folding; a metamorphic grade that is slightly higher than in the underlying Lower Allochthon (lower greenschist facies *v.* u. anchizone); a domal form; a restored position immediately internal to the Lower Allochthon. In addition, the Kunes Nappe has its basal thrust exposed, providing *field* evidence to support the hypothesis that the Window Basement is allochthonous throughout the orogen.

*A. H. N. Rice, Institute for Geology, University of Vienna, Althanstrasse 14, 1090 Vienna, Austria.*

## Introduction

Basement rocks, often with a thin cover succession, are well documented from the centres of tectonic windows in the Scandinavian Caledonides (Fig. 1C; Gee et al. 1985a). Hereafter, both the basement and cover have been called the *XX* Window Basement, where *XX* is the name of the window; this includes both the Parautochthon and the directly overlying basement dominated internal parts of the Lower Allochthon (Gee et al. 1985a).

A problem in all palinspastic models is the restoration of the Window Basement. Two solutions have been proposed. One suggests an autochthonous to parautochthonous restoration, between/under the Lower Allochthon and the Autochthon (Gee 1975, Gee et al. 1985b, Stephens et al. 1985, Dallmeyer & Gee 1986, Lindqvist 1990, Andersen et al. 1991, Fossen 1992, Krabbendam & Dewey 1998). The other proposes an allochthonous position, internal to the restored Lower Allochthon sediments (Chapman et al. 1985, Gayer et al. 1987, Gayer & Greiling 1989, Anderson 1989, Andresen & Rykkelid 1989, Bax 1989, Rice 1998, 1999). This uncertainty results from the buried margins of the Window Basement concealing unequivocal evidence for its tectonic status. Whether the Window Basement tectonically underlies or overlies the basal thrust of the Lower Allochthon is the critical distinction. The former geometry implies a parautochthonous model and the latter an allochthonous model.

The Kunes Nappe is a small basement slice which is here taken out of the Laksefjord Nappe Complex, in which it was the lowest of three imbricates (Føyn et al. 1983; Fig. 1); the complex is downgraded to the Laksefjord Nappe. The Kunes Nappe not only displays features that are typical of Window Basement but also has its basal thrust exposed, overlying sediments of the Gaissa Thrust Belt (Lower Allochthon; Findlay & Elverson 1977, Føyn et al. 1983), providing an important insight into the Caledonian basement tectonics. Thus the aim of this article is to establish the Kunes Nappe as Window Basement, atypical only in having its floor thrust exposed.

## Window Basement – distinguishing criteria

Window Basement occurs in two sub-parallel zones; one along the Norwegian coast, the other along the Norway-Sweden border (Fig 1C). In the south, the eastern zone swings to the SW, along the Snødøla-Steinfjellet Antiform (Nystuen 1982; the very small Snødøla Window Basement lies immediately southwest of the Atnsjøen Window Basement), whilst in the north it swings ENE, along the Alta-Kvænangen, Altenes and Komagfjord Window Basement. Throughout this length, several features are common to Window Basement units;

(1) Window Basement is overlain by a thin, unconformable cover succession. In some cases this consists of Neoproterozoic III diamictites and younger sediments and in others of mid-Cambrian Alum Shales and younger rocks (Roberts & Fareth 1974, Gee 1980, Krill 1980, Thelander et al. 1980, Nystuen & Ilebekk 1981, Siedlecka & Ilebekk 1982, Føyn 1985, Pharoah 1985, Anderson 1989, Gayer & Greiling

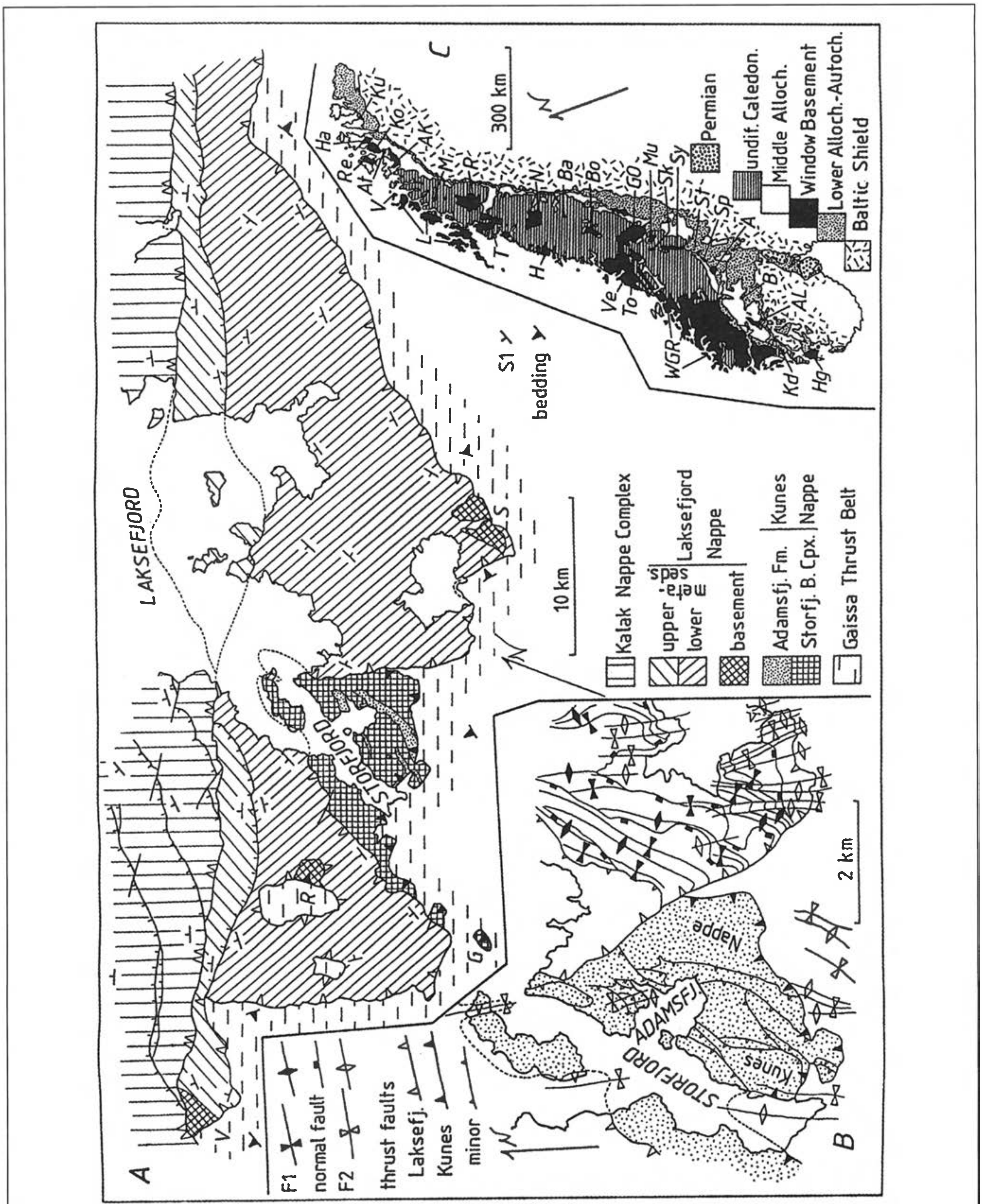


*Fig 1A. Geological map of the Laksefjord and Kunes Nappes (after Roberts 1998); G-Guor´gabmir, R-Rohtojávri, S-Sieidejávri, V-Vieksa. B. Structural map of the Lower Laksefjord Nappe and the Kunes Nappe, showing F1 and F2 axes, minor thrusts and inter F1-F2 extensional faults (after Føyn et al. 1983). C. Simplified tectonostratigraphic map of the Caledonides, showing the Window Basement units exposed and inferred (modified after Gee et al. 1985a); A-Atnsjøen, AK-Alta-Kvænangen, AL-Aurdal-Laerdal, At-Altenes, Bo-Børgefjell, Ba-Banganoaive, B-Beito, GO-Grong-Olden, H-Høgtuva, Ha-Hatteras, Hg-Haugesund, Kd-Kikedalen, Ko-Komagfjord, Ku-Kunes, L-Lofoten, M-Mauken, Mu-Mullfjället, N-Nasafjell, R-Rombak, Re-Revsbotn, Sk-Skardøra, Sp-Spekedalen, St-Steinfjellet, Sy-Sylarna, T-Tysfjord, To-Tømmerås, V-Vanna, Ve-Vestranden, WGR-Western Gneiss Region.*

1989, Schouenborg 1989, Robinson 1997). Only rarely do pre-Neoproterozoic III rocks lie on the Window Basement (Bossekop Group; Føyn 1985). The successions on Vanna (Vanna Group; northern Lofoten Window Basement), the Rombak Window Basement (Gearbeljávri Formation) and the NW parts of the Alta-Kvænangen and Komagfjord Window Basement (Burfjord/Lomvatn Formations) are of uncertain age (Milnes & Ritchie 1962, Binns et al. 1981, Pharoah 1985, Bax 1989, Opheim & Andresen 1989).

(2) The Window Basement is often imbricated, especially along its internal margin, with a transport direction parallel to that in the overlying nappes, typically SE-directed (Fareth 1979, Gee 1980, Thelander et al. 1980, Pharoah et al. 1983, Bax 1989, Opheim & Andresen 1989, Greiling et al. 1993). However, there is evidence of later E- to ESE-directed displacement, parallel to that in the nearby Lower Allochthon (Bax 1989, Rice 1998).

(3) Caledonian metamorphism in the external part of the Window Basement is slightly higher, or essentially the same grade as in the internal part of the Lower Allochthon (Kisch 1980, Binns et al. 1981, Lindqvist 1987, 1990, Anderson 1989, Rice et al. 1989, Warr et al. 1996);

(4) Window Basement units form a domal to periclinal structure in the overlying nappes. In the central to northern parts of the orogen, this folding has been ascribed to a footwall shortcut thrusting through an earlier extensional fault, forming a basement pip under the previously emplaced nappes; sometimes this was accentuated by antiformal stacking within the basement (Gayer et al. 1987, Greiling et al. 1993; see below). Further south, doming by the Western Gneiss Region and Vestranden Window Basement has been related to exhumation along late- to post-orogenic normal faults, although this does not constrain the allochthonous/autochthonous status of these units (Fossen 1992, Andersen 1998, Rice 1999, 2001, Braathen et al. 2000). In central Finnmark, large-scale antiforms in the Middle Allochthon, shallowly underlain by basement rocks (Åm 1975), have been ascribed to buried Window Basement units (Fig. 1C; Hatteras and Revsbotn Basement Horses; Gayer et al. 1987). A similar interpretation

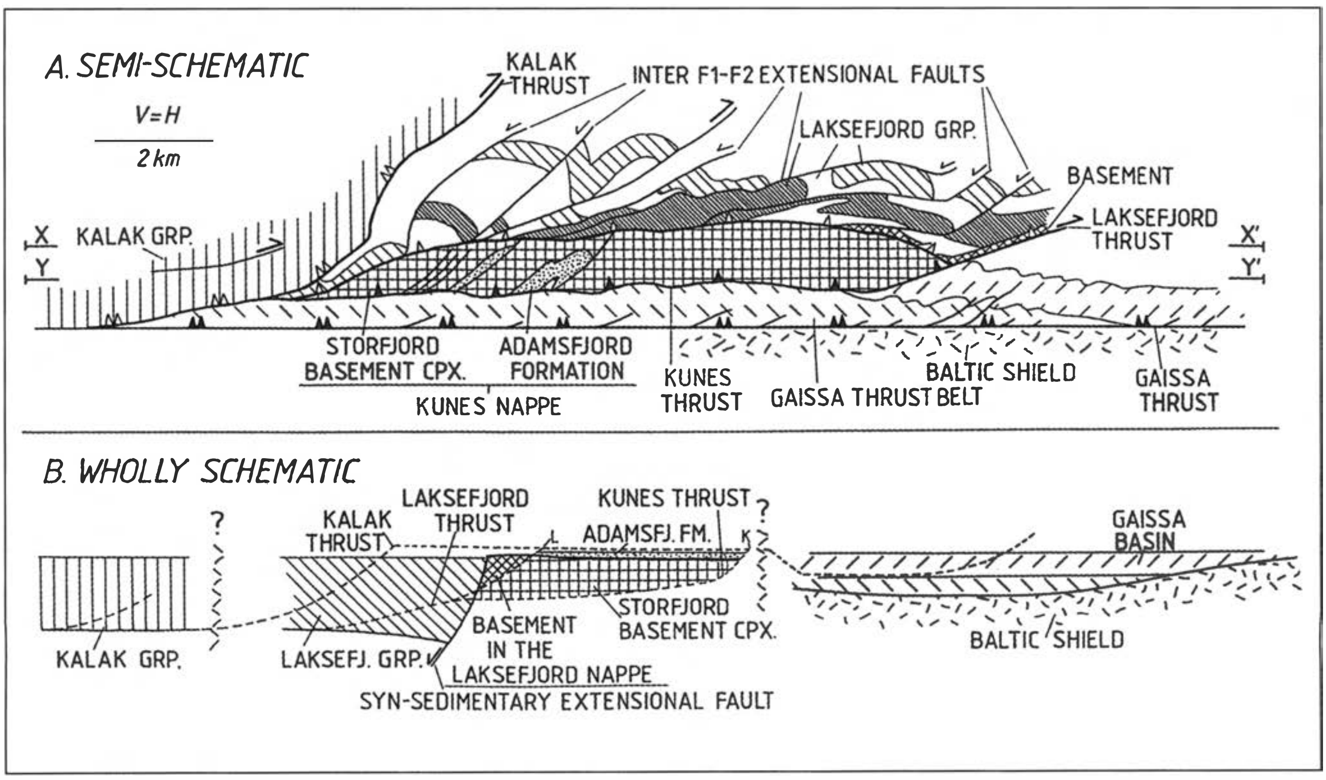


*Fig 2. Cross-section and restored section through the Adamsfjord-Storfjord area (Kunes Nappe) using essentially the same symbols as in Fig 1A. A. Semi-schematic cross-section based on section B-B′ of Føyn et al. (1983) and balanced section C-C′ of Chapman et al. (1985), both of which are slightly oblique to the ~WNW-ESE section-line illustrated here. The geology of the Laksefjord Nappe in the Chapman et al. (1985) section has been projected up-plunge to the southeast and superimposed upon the Kunes Nappe in the Føyn et al. (1983) section. Within these constraints, the section is true-scale (ie V=H). The Kunes Nappe has been extended to the southeast, as proposed in the text, to show the proposed antiformal geometry in the overlying Laksefjord Nappe. Section line NOT shown on the Fig 1, as it does not correspond to any real section. B. Schematic restored cross-section, based on the model of Gayer et al. (1987), showing the restored position of the thrust planes. The formation of the Window Basement (Kunes Nappe) occurred by footwall-shortcut thrusting through a pre-existing syn-sedimentary extensional fault. The model shown here can be applied to many, but not all of the Window Basement units within the orogen.*

was made for the Skardöra Antiform in the central part of the orogen, based on seismic data (Fig. 1C, Palm et al. 1991).

(5) Window Basement units lie at the trailing edge of the Neoproterozoic succession in the Lower Allochthon, where this is developed. Obviously, the latter excludes the basement dominated part of the Lower Allochthon of Gee et al. (1985a) which is here included in the Window Basement.

There are exceptions to all of these `rules´ and some of the features can also be found in other units. However, the association of several of these criteria is typical of the Window Basement.

Basement rocks are also present in considerable quantities in the Middle Allochthon (Gee et al. 1985a), but these do not, in general, have the features defined above. The sedimentary successions overlying the Middle Allochthon basement generally commence in the early Neoproterozoic and are typically thick, often exceeding several kilometres (Føyn et al. 1983, Gayer & Greiling 1989, Hossack et al. 1985). The metamorphic grade is noticeably higher than in the nearby Lower Allochthon and although there are windows cored by Middle Allochthon rocks, these are uncommon compared to the number cored by Window Basement (Gee et al. 1985a). This suggests that the Middle Allochthon was typically formed in a hinterland dipping nappe system, rather than in antifomal stacks.

## The Laksefjord Nappe

The Laksefjord Nappe is overlain by the Kalak Nappe Complex (Middle Allochthon) and in turn overlies the Kunes Nappe and the trailing edge of the Gaissa Thrust Belt (Fig 1A). The mylonites at the base of the Kalak Nappe Complex indicate a predominantly SE-directed movement, but E-to ESE-directions occur in the lowest part (Townsend 1987, Rice 1998). The two imbricates of the Laksefjord Nappe comprise minor basement slivers overlain by sediments of the Laksefjord Group. This comprises clastic rocks of uncertain age, passing from predominantly alluvial-fan deposits at the base (Ifjord Formation), through fluvial/marine sandstones to fine-grained black shales (Føyn et al. 1983, Kumpulainen & Nystuen 1985). The total thickness is ca. 8 km, but as the sediments were deposited in a series of progradational wedges, the thickness at any point was less (Føyn et al. 1983). The ca. 3 km thickness of the Ifjord Formation constrains the minimum amount of syn-sedimentary extensional faulting, and thus the topography of the basement-cover interface.

The sediments were deformed by SE-directed ductile shearing, forming large-scale F1 tight to isoclinal folds with NE-SW trending axial surfaces and an epizone (lower greenschist) grade axial-planar slaty cleavage in pelitic rocks. This was followed by the main phase of thrusting and then by extensional faulting (Chapman 1980). Subsequent folding along NNW-SSSE to NNE-SSW oriented axes (F2) at intermediate- to small-scales, was clearly contemporary with E- to ESE-directed imbrication of the underlying upper-anchizone grade Gaissa Thrust Belt, since fold axes have been mapped continuing across the Laksefjord Thrust (Fig 1C; Chapman et al. 1979, Føyn et al. 1983, Milton & Williams 1981, Rice et al. 1989).

## The Kunes Nappe

The Kunes Nappe, which has a minimum thickness of ca. 1.5 km (Føyn et al. 1983), comprises the Storfjord Basement Complex and a thin cover succession, the Adamsfjord Formation (Fig. 1A, B; Roberts 1998). The nappe includes the Guor´gabmir klippe (Føyn 1984), but it is uncertain if the basement in the Rohntojávri Window is part of the Kunes Nappe (G & R, Fig 1A).

The basement complex comprises adamellites and alkali-granites, locally gneissic, gabbros, diorites, granodiorites, quartz-diorites and mafic dykes. This assemblage is comparable to parts of the crystalline Archaean to Early Proterozoic basement in E. Finnmark and is distinct from the supracrustal Karelian Raipas Supergroup in the Komagfjord Window Basement (Pharoah et al. 1983). The overlying Adamsfjord Formation is ca. 145 m thick; a possible basement-cover unconformity has been seen at one locality (Føyn et al. 1983). The succession, which comprises dolostones, limestones and subordinate dark grey siltstones, cannot be reliably correlated with other sedimentary successions in northern Scandinavia, although several suggestions have been proposed (Findlay & Elverson 1977, Føyn et al. 1983, Gayer & Rice 1989).

The structural development of Kunes Nappe was similar to that of the Laksefjord Nappe. Early deformation produced large-scale tight to isoclinal folds (F1) in the Adamsfjord Formation, forming a lower greenschist facies peak metamorphic penetrative axial planar foliation (S1). The basement was also affected locally, but a penetrative foliation did not form. F1 structures have NW-SE striking axial-surfaces, although small-scale fold-axes in the carbonates plunge moderately steeply to the NW (Chapman 1980), possibly due to rotation in ongoing deformation. F1 was followed by thrusting, imbricating the basement-cover sequence and causing major nappe translation. Basement mylonitization occurred where the cover was thin or absent; elsewhere the sediments acted as an easy-slip horizon. The N-S to NE-SW trending imbricate thrusts are spaced at 0.2 – 1.2 km, with imbricate thicknesses of up to 0.75 km. During F2, both large and small-scale NNW-SSE to NNE-SSW trending east-vergent folds formed within the basement and cover, but no cleavage developed (Chapman 1980). Due to the massive nature of the Storfjord Basement Complex, F2 folds are more open to gentle structures than their equivalents in the Laksefjord Nappe.

Regionally, the roof thrust of the Kunes Nappe is a sub-vertical drop fault on the north-east side, whilst on the west side it dips gently westwards, so that overall the Laksefjord Nappe is domed. Elsewhere, the Laksefjord Thrust is infolded (F2) within the Kunes Nappe along N-S oriented axes (Fig. 1A, B).

The available data thus indicate that the Kunes Nappe was overridden by the Laksefjord Nappe and then accreted into the orogenic wedge, during SE-directed displacement (F1 deformation). Subsequently, E- to ESE-directed out-of-sequence deformation cut down from the base of the Kalak Nappe Complex (Townsend 1987), through the Laksefjord and Kunes Nappes (F2; Føyn et al. 1983), contemporary with the E- to ESE-directed shortening in the Gaissa Thrust Belt.

Based on restored balanced cross-sections, branch-line diagrams and metamorphic criteria, the Laksefjord Nappe Complex was restored to a position along strike from the restored Komagfjord Antiformal Stack (Gayer & Rice 1989), an internal position relative to the sediments of the Gaissa Thrust Belt. The Ifjord Formation was deposited on the hanging wall of a major extensional fault, which was later cut through by footwall shortcut thrusting, forming the Kunes Nappe as a basement pip (see below).

## Discussion

Although small, the Kunes Nappe displays features typical of Window Basement. (1) The Storfjord Basement Complex is (unconformably?) overlain by a thin cover sequence, the Adamsfjord Formation. This is of unknown age, typical for many Window Basement cover successions in N. Norway. (2) The Kunes Nappe was affected by an initial SE-directed deformation, causing internal imbrication. Assuming, not unreasonably, that the nappe is an erosional relict of a larger thrust slice, these imbricates lie on the internal side. Later E- to ESE-directed deformation was contemporary with imbrication in the underlying Gaissa Thrust Belt (see above). (3) The lowest greenschist facies metamorphic grade of the Kunes Nappe is slightly higher than the upper anchizone alteration in the underlying Gaissa Thrust Belt. (4) The Kunes Nappe domes the overlying nappes, although the deep level of erosion, and hence its small size, makes this effect rather minor. (5) The Kunes Nappe overlies and restores to the western margin of the Gaissa Thrust Belt (Lower Allochthon).

The model proposed is illustrated in Fig. 2. The deformed cross-section (Fig. 2A) shows the Laksefjord Nappe overlying the relatively thick basement slice of the Kunes Nappe. Since the leading edge of the Kunes Nappe lies on the hinterland side of the leading edge of the Laksefjord Nappe (which lies beyond the section length), the latter has a domal structure, with *some* parts dipping towards the foreland. Horizontal sections through the profile reflect varying levels of erosional exhumation. Those above the leading edge of the Kunes Nappe (X-X'; Fig. 2) produce a tectonic window geometry, cored by the Window Basement, this being the geometry generally associated with Window Basement throughout the orogen. In contrast, sections lower than the leading edge (Y-Y') result in the surface geology seen today in the Adamsfjord-Storfjord area - Window Basement with an exposed floor thrust.

In the schematic restored section (Fig. 2B), the Kunes Nappe and minor slices of basement rocks within the Laksefjord Nappe lie in the footwall of a syn-sedimentary extensional fault, whilst the Laksefjord Group sediments overly the extensional fault. To produce a domal structure in the Laksefjord Nappe, the leading edge of the Laksefjord Nappe (L) must move to the hinterland side of the leading edge of the Kunes Nappe (K) before the latter unit is displaced along a footwall shortcut thrust fault; this produces antiformal stack geometry.

Note also that the Kunes Nappe lies along the ENE trend of Window Basement units defined by the trend of the Alta-Kvænangen, Altenes and Komagfjord Window Basement, reflecting the regional clockwise curvature of the nappe boundaries in the northern part of the orogen (cf Gee et al. 1985a; Fig. 1C). In essence, it lies *exactly* where one would expect a Window Basement unit to lie.

Of course, these features alone do not unequivocally demonstrate that the Kunes Nappe is the structural 'along-strike' equivalent of the Window Basement seen further south and west in the orogen. The Kunes Nappe may originally have been thrust over another, now wholly eroded, sequence of Laksefjord Group sediments, in which case a position within a Laksefjord Nappe *Complex* would be better. However, the 3 km thickness of the Ifjord Formation, and the overall geometry of the Laksefjord Group sediments makes this very unlikely. The similar position of the Kunes Nappe in restored balanced cross-sections to other Window Basement units, and the similarities outlined above, strongly support a Window Basement structural interpretation for the Kunes Nappe.

Chapman (1980) and Føyn et al. (1983) included the Storfjord Basement Complex in the Laksefjord Nappe Complex. Although no specific reason for this was given, apart from their similar metamorphic grades, it was probably due to both the similarity of the Storfjord Basement Complex lithologies with the basement rocks in the other imbricates of the Laksefjord Nappe (Fig. 1A) and, critically, the lack of any other place to put it in the then regionally accepted tectonic framework. However, this reason is rather spurious; Raipas Supergroup basement rocks form the lowest imbricate of the Kalak Nappe Complex northwest of the Komagfjord and Alta-Kvænangen Window Basement (Zwaan & Roberts 1978) but no-one has suggested combining them into one unit.

By following Pharoah (1985), in loosely correlating the Laksefjord Group with the Lomvatn Formation in the NW part of Komagfjord Window Basement, Gayer & Rice (1989) were able to include the Laksefjord Nappe Complex in the Lower Allochthon. However, this correlation ignored the Adamsfjord Formation, and is, anyway, rather tenuous. In contrast, Gee et al. (1985a) placed the Laksefjord Nappe Complex in the Middle Allochthon, probably due to the ductile nature of the deformation and the lack of lithostratigraphic correlation between the Laksefjord Group and the Gaissa Thrust Belt. Similarly, however, a stratigraphic correlation cannot be made between the Laksefjord Group and the metasediments in the Kalak Nappe Complex. Thus the tectonic status of the Laksefjord Nappe remains a vexed question, but a Middle Allochthon correlation is more likely if the Kunes Nappe is placed in the Window Basement.

Although the affinities of a particular tectonic unit within the nappe pile may appear to be of little significance, it is clear that such assignations exert a very profound constraint on how geologists perceive a unit. By being placed in a Laksefjord Nappe Complex, which was subsequently included in either the Middle or Lower Allochthon, the anomalous nature of the Kunes Nappe has been effectively hidden from view and its value in understanding the structural development of the basement rocks within the tectonic windows overlooked. Recognition that the Kunes Nappe is neither Middle nor Lower Allochthon, but an unusually deeply exhumed fragment of Window Basement, in which the window structure has been lost, provides a critical insight into the deeper, buried parts of the orogen in more southerly areas, in that it gives field evidence supporting the hypothesis of an allochthonous status for the Window Basement.

It is not considered very likely that some Window Basement units are par-autochthonous and others allochthonous. The Scandinavian Caledonides display a very large degree of along-strike continuity – to the extent that most of the seven fundamental structural divisions within the orogen have been traced from its southernmost to northernmost parts (Gee et al. 1985a) and, with only local exceptions, the same Neoproterozoic to early Ordovician stratigraphy has been recorded from all regions of the preserved Iapetus Baltoscandian margin (cf Gee & Sturt 1985). This suggests that the same *broad* palaeogeographic model should apply to all the Window Basement units. This does not mean that the Window Basement units were all accreted into the orogen by the same mechanism – significantly different mechanisms occurred, but outlining all of these is outside the scope of this article. However, note that although the post-Caledonian extension has been a major structural factor in central to southern Norway, lateral displacements between the lower units of the Iapetus Baltoscandian continental margin (Autochthon, Lower Allochthon & Window Basement) during this deformation were at most very minor and are not, therefore, a significant factor in palinspastic reconstructions of these units.

The wider significance of this re-interpretation should not be underestimated because of its seemingly small-scale, regional, nature. Although the possibility that the Window Basement is allochthonous was discussed, Palm et al. (1991) completely ignored the well constrained balanced and restored cross-sections from Finnmark and Västerbotten (Gayer et al. 1987, Gayer & Greiling 1989), both of which not only show that the Window Basement *is* allochthonous but also indicate its palinspastic position in the Iapetus Baltoscandian miogeocline. Further, few recent papers relating to the evolution of the Western Gneiss Region have considered the possibility that it, too, is allochthonous – a condition implied by combining the work of Gee (1980) and Krill (1980) with the superb balanced sections of Morley (1986). Clearly, there remains a very wide gap between what has been demonstrated with a considerable degree of certainty in less fashionable parts of the orogen and what is intellectually understood by much of the geological community. This gap needs to be closed before a proper understanding of the orogen can be established.

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