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Restoration of the external Scandinavian Caledonides

Category – Original article

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Short title – Restoration of the external Scandinavian Caledonides

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Abstract

Three models are evaluated for restoring basement rocks coring tectonic windows (Window-Basement) in the Scandinavian Caledonides; parautochthonous (Model I) and allochthonous (Models II/III), with initial imbrication of the Window-Basement post-dating or pre-dating, respectively, that in the external imbricate zone (Lower Allochthon). In Model I, the Window-Basement comes from the eastern margin of the basin now imbricated into the Lower Allochthon whilst in Models II/III it comes from the western margin of the Lower Allochthon. In Model II, the Window-Basement formed a basement-high between Tonian-Cryogenian sediments imbricated into the Middle and Lower Allochthons; in Model III deposition in the Lower Allochthon commenced in Ediacaran times. Balanced cross-sections and branch-line restorations of four Transects (Finnmark-Troms, Västerbotten-Nordland, Jämtland-Trøndelag, Telemark-Møre og Romsdal) show similar restored lengths for the Models in two Transects and longer restorations for Model II/III in the other Transects. Model I can result in ~280 km wide gaps in the restored Lower Allochthon, evidence for which is not seen in the sedimentology. The presence of <3 km thick alluvial-fan deposits at the base of the Middle Allochthon indicates proximal, rapidly uplifting basement in the Tonian/Cryogenian, taken as the origin of the Window-Basement during thrusting in Model II/III. Model I requires multiple changes in thrusting-direction and predicts major thrusts or back-thrusts, currently unrecognised, separating parts of the Lower Allochthon; neither are required in Models II/III. Metamorphic data are consistent with Models II/III. Despite considerable along-strike structural variability in the external Scandinavian Caledonides, Models II/III are preferred for the restoration of the Window-Basement.

Key words: Lower Allochthon, External imbricate zone, Basement massif, Tectonic window, Structure, Balanced cross-section, Branch-line.

1. Introduction

Basement rocks crop out in tectonic windows in many orogens, doming the structurally overlying units (Rodgers, 1995). Although such rocks (here neutrally called Window-Basement) occur throughout the Scandinavian Caledonides (Fig. 1; Gee *et al.*, 1985a, 2008), their structural status remains uncertain, causing problems in palaeogeographic reconstructions and interpretations of the late-to post-Caledonian structural evolution (extension) of Baltica.

FIG 1 NEAR HERE

Here, two previously proposed structural and palaeogeographic models for the restoration of the external parts of the Scandinavian Caledonides (i.e. the structurally lower and predominantly brittle deformed parts) are compared from four areas; Model I presumes that the Window-Basement is parautochthonous and Model II that it is allochthonous. A third model (Model III), combining aspects of the other Models, is proposed for some parts of the orogen.

Restorations of the areas selected (E. Finnmark to E. Troms, Västerbotten to Nordland, Jämtland to N. Trøndelag, Telemark to Møre og Romsdal) have been published previously (Fig. 1; Gayer & Roberts, 1973; Gee, 1975a, 1978; Gayer *et al.*, 1987; Gayer & Greiling, 1989; Rice, 2005, 2014; Andersen *et al.* 2012). Definitive new restorations are not necessarily given here, due to some uncertainties in the input data. Rather, a range of alternatives are critically evaluated; at issue is whether the Models are equally valid and must the same Model must be applied throughout the orogen.

All deformation and metamorphic grades referred to here are of Caledonian age. In this text, *basement* refers to rocks formed (deposited/intruded) prior to the Caledonian Wilson Cycle, whilst *cover* refers to rocks formed during the Caledonian Wilson Cycle. *Allochthonous* and *autochthonous* refer, respectively, to whether rocks were, or were not, deformed (thrust-transported, extended) during the Caledonian Orogeny. These give four possibilities - autochthonous basement, autochthonous cover, allochthonous basement and allochthonous cover - all of which are relevant here. This paper is *not* concerned with basement-cover (unconformity) relationships.

2. Scandinavian Caledonides overview

The Scandinavian Caledonides have been divided into the Uppermost, Upper, Middle and Lower Allochthons, overlying an Autochthon (Gee *et al.*, 1985a, 2008; Fig. 1), although the value of these terms has been criticised recently (Corfu *et al.*, 2014). To simplify regional correlations between the cover sediments in the Autochthon, the Lower and Middle Allochthons and the Window-Basement, which were all derived from the Iapetus Baltoscandian continental margin and are lithologically comparable (e.g. Nystuen & Siedlecka, 1988; Nystuen *et al.,* 2008), the stratigraphy has here been divided into nine informal Successions (S1a-S8; Table 1). In the following text, the Succession number is given, without further reference to Table 1. Except for the basal thrust sheets, the Middle Allochthon is generally not discussed here.

TABLE 1 NEAR HERE

The Autochthon comprises dominantly clastic rocks overlying the crystalline Baltic Shield. The sediments are, except in northeast Norway, of syn- to post Gaskiers glaciation (S5, late Ediacaran, ~580 Ma; Bowring *et al.*, 2003) or younger age, and typically have a condensed thickness (<~300m) compared to equivalent units in the Lower Allochthon (Føyn, 1967, 1985; Gee *et al.*, 1974; Andresen, 1978; Rickard *et al.,* 1979; Thelander, 1982; Bockelie & Nystuen, 1985; Gayer & Greiling, 1989; Bierlein & Greiling, 1993; Page, 1993; Nielsen & Schovsbo, 2006). The upper part frequently comprises mechanically weak graphitic shales

(S7; Gee *et al.*, 1974; Thelander, 1978; Morley, 1986; Gayer & Greiling, 1989; Bierlein & Greiling, 1993). Metamorphic studies (mostly illite crystallinity) indicate a diagenetic-lower anchizone alteration (Bergström, 1980; Kisch, 1980; Snäll, 1988; Anderson, 1989; Rice *et al.*, 1989a; Warr *et al.*, 1996).

The Lower Allochthon (external imbricate zone) overlies the Autochthon along the Caledonian basal décollement, except in Telemark and Varanger (south and northeast Norway, respectively; Fig. 1), where deformation dies out gradually, without a major thrust (Morley, 1986; Townsend, 1987). Hossack & Cooper (1986) suggested that the pre-erosional Caledonian thrust-front in the central Scandinavian Caledonides lay ~90-120 km east of the present-day front. Anderson (1989) used metamorphic criteria to constrain the pre-erosion front in the Rombak area (Fig. 1) to ~120 km east of the present-day eroded thrust front; this is very similar to the 110 km proposed by Hossack & Cooper (1986). In contrast, Garfunkel & Greiling (1998) estimated that the pre-erosional thrust-front lay ~80 m east of the eroded thrust front in the Västerbotten area, considerably less than the 120 km inferred by Hossack & Cooper (1986).

Brittle imbrication in the Lower Allochthon, mostly with thrust shortening of <60% (Chapman *et al.*, 1985; Hossack *et al.*, 1985; Morley, 1986, 1987a, b; Townsend *et al.*, 1986, 1989; Gayer & Greiling, 1989; Bierlein & Greiling, 1993; Greiling *et al.*, 1993) occurred during diagenetic zone to anchizone metamorphism (Kisch, 1980; Anderson, 1989; Rice *et al.*, 1989a; Warr *et al.*, 1996; Angerer & Greiling, 2012).

The Lower Allochthon preserves a fluvial to shallow-marine, predominantly clastic, sedimentary succession of Tonian to Devonian age (S1-S8; Gee *et al.*, 1974; Bjørlykke *et al.,* 1976; Johnson *et al.*, 1978; Nystuen, 1982, 1987; Basset *et al.*, 1985; Kumpulainen & Nystuen, 1985; Nystuen & Siedlecka, 1988; Roberts & Stephens, 2000; Nystuen *et al.*, 2008).

The Middle Allochthon comprises ductilely deformed nappes of both cover and basement lithologies (Fig. 1). The cover includes predominantly clastic, fluvial to shallow-marine sediments of Tonian and younger ages (S1b-S7; Kumpulainen, 1980; Føyn *et al.*, 1983; Bockelie & Nystuen, 1985; Kumpulainen & Nystuen, 1985; Nickelsen *et al.*, 1985; Greiling, 1989), sometimes with very thick, proximally-derived alluvial-fan basal conglomerates (S1a; Nickelsen, 1974; Hossack, 1978; Føyn *et al.*, 1983; Gayer & Greiling, 1989; Plink-Björklund *et al.*, 2005; Nystuen *et al.*, 2008; Table 2).

TABLE 2 NEAR HERE

The Window-Basement crops out throughout the length of the orogen (Fig. 1), with different tectonic windows showing slightly different features. For example, the Western Gneiss Region is extremely large and underwent ultra-high pressure metamorphism in its internal parts (Hacker *et al.*, 2003) whilst the Kunes Nappe (Rice, 2001a) is very small and underwent low- to middle greenschist facies alteration (Føyn *et al.*, 1983). The Nasafjäll Window-Basement comprises two exposed, relatively large, basement-cover slices (Thelander, 1980), as do several other areas of Window-Basement in Central Scandinavia (Tømmerås, Grong-Olden, Mullfjället, Western Gneiss Region; Fig. 1), whilst the Bångonåive Window-Basement comprises a large number of small and thin basement-cover imbricates (Greiling *et al.*, 1993). Other Window-Basement units comprise a single *exposed* slice of basement (Aurdal-Lærdal, Vang, Beito, Atnsjøen, Spekedalen, Børgefjell, Rombak, Alta-Kvænangen, Altenes, Komagfjord, Kunes), although these may have minor amounts of internal shortening (e.g. Fareth, 1979; Greiling, 1988).

Despite this variability, the Window-Basement can be summarised as consisting of a central tectonic unit (Parautochthon of Gee *et al.*, 1985a), often with a lithologically comparable upper unit (Gee, 1980; Krill, 1980, 1985; Thelander *et al.*, 1980; Roberts, 1989, 1997; Fig. 1). Both units may locally have an unconformable cover succession, usually of Ediacaran (S5) or younger age and condensed compared to the Lower and Middle Allochthon successions, but similar to those forming the Autochthon (Brown & Wells, 1966; Gee, 1980; Krill, 1980; Thelander *et al.*, 1980; Nystuen & Ilebekk, 1981; Siedlecka & Ilebekk, 1982; Lindqvist, 1984, 1988; Føyn 1985; Pharaoh 1985; Björklund, 1987; Bax, 1989; Gayer & Greiling, 1989; Schouenborg, 1989; Greiling, *et al.*, 1993).

The metamorphic grade of the Window-Basement cover sediments is higher or equivalent to that in the adjacent Lower Allochthon and generally, but not always, lower or equivalent to that in the overlying Middle Allochthon (e.g. Andréasson & Gorbatschev, 1980; Lindqvist & Johansson, 1987; Anderson, 1989; Rice *et al.*, 1989a; Lindqvist, 1990; Table 3).

TABLES 3, 4 & 5 NEAR HERE, ON FACING PAGES FOR EASY COMPARISON

Construction of a 'generalised' cross-section through the orogen is not possible, not only because of the uncertainty in the restoration of the Window-Basement, which has an important effect on the geometry of the basal décollement towards the hinterland, but also because significant along-strike changes in the development of the orogen, including the variable development of the Uppermost and Lower Allochthons and the also amount of basement in the Lower and Middle Allochthons (e.g. Björklund, 1985, Unpub. Ph.D. thesis, Chalmers Tekniska Högskola, Göteborgs Univ., Sweden, 1989; Fig. 1), preclude any such cross-section at a meaningful level.

3. Published restorations of the Window-Basement

Only thrusting-related models for the restoration of the Window-Basement are reviewed here. Models in which exposure of the Window-Basement is linked to post-Caledonian normal faulting (Osmundsen *et al.,* 2005) are evaluated in the Discussion.

FIG 2 NEAR HERE

3.a. One basin model - parautochthonous Window-Basement (MODEL I)

In central Jämtland, Gee (1975) and Dyrelius *et al.* (1980) proposed that the Müllfjället and Tømmerås Window-Basement (Fig. 1) were derived from steps in the basement topography at the eastern margin of the Tonian-Cryogenian basin (S1b, S2) that was subsequently imbricated to form the Lower Allochthon (Fig. 2a). Hence the Window-Basement was imbricated during late shortening in the Lower Allochthon and is parautochthonous (or allochthonous, but not far-travelled, if an upper imbricate of Window-Basement). The thin, late Ediacaran to lower Palaeozoic autochthonous sedimentary cover succession (S6, S7) was inferred to continue unbroken from the Caledonian front to the Window-Basement, everywhere resting directly on the basement, giving an at least ~200 km wide autochthonous cover. This inference was supported by borehole data in the Tåsjön area that traced autochthonous sediments (S7) for 30 km west of the Caledonian front (Gee *et al.*, 1978) and by seismic data (Palm *et al.*, 1991; Fig. 3). Gee *et al.* (1985b) presented a similar model, in which the shelf deepened stepwise to the west, reflecting the eastwards onlap of the cover onto the Window-Basement (Fig. 4). Although the scales are approximate in Figure 4, the distances from Östersund to Müllfjället and Tømmerås are essentially the present-day distances (Fig. 1). Further, the youngest sediments in the basin (S8) have been restored to above or west of the Tømmerås Window-Basement, whereas currently they lie east of Tømmerås. In Model I, the Middle Allochthon sediments represent a continuation of the Lower Allochthon basin, reflecting a westward deepening of the continental shelf towards Iapetus, deposited directly outboard of the Window-Basement (Fig. 4; Gee, 1978).

FIGS 3 & 4 NEAR HERE

3.b. Two basin model - allochthonous Window-Basement (MODEL II)

In Finnmark, Gayer & Roberts (1973) determined a 35 km displacement from the NW for the Tonian-Cryogenian sediments (S1b, S2) of the Lower Allochthon because its branch-line overlapped the autochthonous Ediacaran sediments (S6) around Lakselv (Fig. 1). Rhodes (unpub. Ph.D. thesis, Univ. College Cardiff, Wales, 1976) noted that the restored Lower Allochthon overlay the unconformable Ediacaran cover (S5, S6) on the Komagfjord Window-Basement (Fig. 1) and estimated a ~15 km displacement for the Window-Basement from the NW. Hence, the Komagfjord Window-Basement was incorporated into the orogen *prior to* deformation in the Lower Allochthon. Since the Lower Allochthon is continuously exposed from Lakselv to East Finnmark, with no reported major thrusts (Føyn, 1967), the possibility of moving the Lower Allochthon to the hinterland side of the Komagfjord Window-Basement was not considered. Subsequent restorations included shortening of up to 60% within the Lower Allochthon and also postulated the presence of two buried Window-Basement units based on large-scale antiformal structures in the Middle Allochthon (Chapman *et al.*, 1985; Townsend *et al.*, 1986; Gayer *et al.*, 1987; Rice, 2014). In this model, the Window-Basement formed a palaeo-topographic high separating two sedimentary basins, imbricated into the Middle and Lower Allochthons (Fig. 2b).

4. Orogenic Transects

Only Transects where both the Lower Allochthon and the Window-Basement are well developed are useful when considering their inter-relationships. Hence, a Transect across the Nasafjäll Window, in which the Window-Basement is particularly well documented (Thelander *et al.,* 1980), is not included; the Lower Allochthon is very poorly developed (Fig. 1). However, Anderson (1989) presented a restoration of the Rombak Basement-Window (Fig. 1) relative to the poorly preserved Lower Allochthon (Rautas Complex) in northern Scandinavia, based on metamorphic criteria.

In all descriptions, the Window-Basement is documented last, to avoid prejudging the conclusions. Much of the lithological, structural and metamorphic data are summarized in Tables 2-5.

4.a. Transect 1 - E. Finnmark to Troms

Transect 1, from eastern Varangerhalvøya to Kvænangen, is ~325 km long (Figs. 1, 5). All localities are shown in Figure 5.

West of Andabakoaivi, the Autochthon comprises the Torneträsk Fm (S6, <260 m; Føyn, 1967; Thelander, 1982). East of Andabakoaivi, the age of the Autochthonous cover increases, down to the Vadsø Gp (S1b, ~600 m thick; Johnson, 1978). The Autochthon is overlain by the East Finnmark Parautochthon, with the Hanadalen Thrust (base Hanadalen Thrust Sheet) forming the base of the Lower Allochthon (Gaissa Thrust Belt; Rice, 2014; Fig. 5).

FIG 5 NEAR HERE

The same lithostratigraphy occurs in the East Finnmark Autochthon, East Finnmark Parautochthon and Gaissa Thrust Belt. In E. Finnmark, this comprises Tonian to Tremadocian deposits (Vadsø, Ekkerøya, and Tanafjord gps, S1b-S2, ~2.5 km, overlain by the Vestertana and Digermul gps, S3-S8, ~2.5 km; Johnson *et al.*, 1978; Føyn & Siedlecki, 1980; Edwards, 1984; Rice & Townsend, 1996; Røe, 2003). In the Porsangerfjord area, similar Tonian-Cryogenian deposits occur (Airoaivi, Ekkerøya and Tanafjord gps, S1b-S2; Williams, 1976; Townsend *et al.*, 1989; Rice & Townsend, 1996). The total thickness is unknown, due to uncertainties in the Airoaivi Gp thickness (S1b), but is likely >2 km.

The predominantly E- to ESE-directed shortening in the Gaissa Thrust Belt increased from 16% in the Hanadalen Thrust Sheet to 59% in the Munkavarri Imbricate Zone (Chapman *et* *al.*, 1985; Townsend, 1987; Townsend *et al.*, 1986, 1989; Rice 2014; Fig. 5). The metamorphic grade increased from lower anchizone-diagenetic zone in the east to epizone-upper anchizone in the west (Rice *et al.*, 1989a).

Although the Middle Allochthon is basement-dominated (Kirkland *et al.* 2006), the basal unit (Laksefjord Nappe; Fig. 5) comprises 7.1 km of the Laksefjord Gp, with proximally-derived basal alluvial-fan conglomerates (Ifjord Fm, S1a, ~3 km; Chapman, Unpub. Ph.D. thesis, Univ. College Cardiff, Wales, 1980; Føyn *et al.*, 1983).

Caledonian thrusting was predominantly SE-directed in the Kalak Nappe Complex, but E- to ESE-directed movement occurred in the basal mylonites (Townsend, 1987; Rice, 1998). Metamorphism in the Laksefjord Nappe reached epizone grade (Rice *et al.*, 1989b) during SE-directed thrusting (Milton & Williams, 1981). Later brittle out-of-sequence thrusting may have been E- to ESE-directed (Williams *et al.*, 1984: cf Rice, 2014).

Window-Basement in the (1) Komagfjord, (2) Altenes and (3) Alta-Kvænangen tectonic windows (Fig. 5) is unconformably overlain by (1) the Slettfjell (S5, S6) and Lomvatn fms (?S1b), (2) the Rafsbotn Fm (S5, S6) and (3) the Bossekop (S1b) and Borras (S5, S6) gps, respectively (Føyn, 1985; Pharaoh, 1985). An epizone grade metamorphism occurred during SE-directed thrusting (Rice *et al.*, 1989b; Torgersen *et al.*, 2014). Two other buried Window-Basement units, the Hatteras and Revsbotn Basement Horses have been postulated, underlying the Middle Allochthon (Chapman *et al.*, 1985; Gayer *et al.*, 1987; Fig. 5).

The Kunes Nappe Window-Basement (Fig. 5) comprises basement unconformably overlain by dolomites (S2). These were deformed at lower greenschist facies during SE-directed thrusting, doming the Laksefjord Nappe (Føyn *et al.*, 1983; Rice, 2001a).

4.b. Transects 2 and 3 - Västerbotten to Nordland and Jämtland to Trøndelag

These two transects have similar regional geologies (Figs. 1, 6). Transect 2, from north of Vilhelmina, in Västerbotten, to east of Børgefjell, in Nordland is ~140 km long. Transect 3, from north of Östersund, in Jämtland, to Steinkjer, in Nord Trøndelag, is ~205 km long. When extended to the pre-erosional thrust-front (Hossack & Cooper, 1986), the Transects are ~120 & 90 km longer, respectively. All localities are shown in Figure 6.

Both Transects are cut by low-angled detachment faults (Fig. 6; Rice, 1999; Osmundsen *et al.*, 2003, 2005; Grimmer *et al.*, 2015; Robinson *et al.,* 2016). These are reviewed in the Discussion (section 6.f).

FIG 6 NEAR HERE

The Jämtland Supergp (~1.1-1.7 km thick; Gee *et al.*, 1974, 1985b; Basset *et al.*, 1982) forms the Autochthon, Lower Allochthon and cover units in the Window-Basement.

4.b.1 Transect 2 - Västerbotten to Nordland

On Transect 2 (Fig. 6), the Autochthon comprises the Sjoutälven Gp (Gärdsjön Fm, S6, <5 m) overlain by the Tåsjön Gp (Fjällbränna Fm, S7, <10 m; Gayer & Greiling, 1989), at diagenetic to lower anchizone metamorphic grades (Warr *et al.*, 1996).

In the Lower Allochthon (Blaik Nappe Complex) the Risbäck Gp crops out in the east (S1a, b, ~600 m; S2, 110 m; Fig. 6). The overlying Sjoutälven Gp comprises the Långmarkberg (S5, 50m) and Gärdsjön (S6, 280 m) fms, overlain by the Tåsjön Gp (Fjällbränna Fm, S7, 80 m; Gayer & Greiling, 1989; Kumpulainen & Greiling, 2011). These were deformed by E- to ESE-directed thrusting during anchizone to epizone metamorphism (Gayer & Greiling, 1989;

Bierlein & Greiling, 1993; Warr *et al.*, 1996; Angerer & Greiling, 2012). Gayer & Greiling (1989) estimated a bulk 50% shortening.

The Middle Allochthon crops out (1) above the Lower Allochthon near the Caledonian front, (2) in the Fjällfjäll Window through the Upper Allochthon and (3) around the Børgefjell Window-Basement (Fig. 6). Near the Caledonian front, Greiling (1989) described two units. The lower, the Stalon Nappe Complex, comprises >250 m conglomerates (S1a) with large basement-derived clasts, overlain by >750m of sandstones (S1b) (the S1a conglomerates *may* partly be younger; Greiling, pers. comm. 2016). These are overlain by 'pebbly sandstone', possibly of glacial origin (S5, >250 m; Greiling, 1985; Gayer & Greiling, 1989). The upper part of the Middle Allochthon consists of the Särv Nappe (see Transect 3) cut by WPB-MORB dykes (Greiling *et al.*, 2007).

The lower part of the Middle Allochthon occurs around the Børgefjell Window-Basement (Rainesklumpen and Dearka Units) whilst the upper part (Fjällfjäll Unit) is exposed in the Fjällfjäll Window and above the Rainesklumpen Unit (Zachrisson, 1964, 1969; Greiling, 1985, 1989; Fig. 6).

The Middle Allochthon was affected by SE-directed ductile deformation during upper greenschist to lower amphibolite facies metamorphism (Greiling, 1989).

The Børgefjell Window-Basement consists of two or more thrust sheets (Greiling, 1988, Fig. 6), with thin cover successions of the Långmarkberg Fm (S5, ~2.5m), Gärdsjön Fm (S6, 16 m) and Fjällbränna Fm (S7, >2 m). Both the cover and the directly underlying basement underwent ESE-directed deformation during middle to lower greenschist facies (epizone) metamorphism (Gayer & Greiling, 1989).

4.b.2 Transects 3 - Jämtland to Trøndelag

On Transect 3 (Fig. 6), the Autochthon comprises the Tåsjön Gp (Fjällbränna Fm, S7, 20-40 m; Gee *et al.*, 1985b). Conodont Alteration Index (CAI) values of 3.5-5 suggest a lower anchizone metamorphism (Bergström, 1980). However, comparison of CAI data from the Lower Allochthon (Bergström, 1980), where it can be directly compared with illite crystallinity data (Kisch, 1980), suggests that the equivalent illite crystallinity grade for the CAI from the Autochthon is diagenetic zone. The latter estimate is used, since illite crystallinity has been more widely applied to constrain metamorphic grades in the Scandinavian Caledonides.

Within the Blaik Nappe Complex (Lower Allochthon), the oldest sediments exposed (Gärdsjön Fm, S6, <200 m) crop out at St. Grässjön, unconformably overlying allochthonous basement (Sveriges Geologiska Undersökning 1984, Fig. 6). Elsewhere, the Tåsjön Gp (Fjällbränna Fm, S7, 50 m and Norråker Fm, S8, 200-600 m) is overlain by the Änge Gp (S8, 270 m; Gee *et al.*, 1974, 1985b; Basset *et al.*, 1982). The maximum known thickness on this Transect is thus up to 1.12 km.

No detailed structural data are available for the Blaik Nappe Complex; the shortening vector and bulk strain from Transect 2 have been assumed (E- to ESE-directed; 50% shortening). This is supported by the outcrop pattern, which shows pervasive NNE-trending folding (Sveriges Geologiska Undersökning, 1984; more detailed maps are available on line at http://www.sgu.se/). Deformation occurred during diagenetic/lower anchizone metamorphism in the east, rising to epizone grade in the west (Kisch 1980, Bergström 1980).

The Middle Allochthon, exposed north and south of the section (Fig. 6), comprises thick imbricates of basement and cover; only the latter are described here. The Offerdal Nappe, the lowest cover thrust sheet, has been divided into three units (Plink-Björklund, *et al.*, 2005). The basal part contains proximal, basement-derived alluvial-fan conglomerates (S1a, >300m). The overlying units consist predominantly of turbidites and fluvial sandstones (S1b, ~1.2 km). Gee (1975) correlated these rocks with the Risbäck Group.

The 4.5-6 km thick Tossåsfjället Gp in the overlying Särv Nappe (Kumpulainen 1980) consists of sandstones (Lunndörrsfjällen and Kråkhammeren fms, S1b, ~4 km) overlain by dolomites (Storån Fm, S2, ~100 m) and thence by glacial deposits (Lillfjället Fm, S5, ~120 m but maybe >600 m; Kumpulainen, 2011) and shales, sandstones and conglomerates (Lövan Fm, S6, ~1.5-2.0 km). These are cut by abundant metadolerite dykes (Solyom *et al.*, 1979).

The Upper and Lower Leksdal Nappes, exposed around the Tømmerås Window-Basement, are equivalent to the Offerdal and Särv Nappes (Fig. 6; Gee, 1977; Andréasson *et al.*, 1979). In the Norwegian coastal area, Meakin (1983) recorded a thinned package of the Middle Allochthon, with metadolerite dykes comparable to those in the Särv Nappe (Solyom *et al.*, 1979), complexly infolded with other nappes and the Western Gneiss Region Window-Basement.

The Middle Allochthon was affected by SE-directed deformation during upper greenschist to lower amphibolite facies metamorphism (Andréasson & Gorbatschev, 1980; Gilotti & Kumpulainen, 1986; De Paor & Simpson, 1997).

The Tømmerås and Grong-Olden Window-Basement both contain two major exposed basement-cover slices (Fig. 6; Gee, 1980; Roberts, 1989, 1997). The cover successions

(Bjørndalen and Graståmoen fms, respectively, S6-S8, <65m; Andréasson, 1980; Gee, 1980; Roberts & Stephens, 2000) have been lithostratigraphically correlated with, and were presumed to be direct continuations of the Autochthon cover succession (Gee, 1975, 1978, 1980; Gee *et al.*, 1985b). The Grong-Olden Window-Basement was affected by middle greenschist facies in the east (biotite grade; Johansson, unpub. Ph.D. thesis, Univ. Lund, 1986) with SE-directed deformation (Sjöström & Talbot, 1987; Stel, 1988). The Tømmerås Windows Basement was affected by SE-directed deformation during middle to upper amphibolite facies metamorphism (Gee, 1980; Lindqvist, 1990).

Near Foldafjord, arkoses/conglomerates lie unconformably on the Vestranden Window-Basement (Fosså Fm, 70 m; Schouenborg, 1989; Fig. 6). As no lithologically diagnostic rocks of the Jämtland Supergroup are present (essentially S5 & S7) correlations are uncertain. The Vestranden Window-Basement was emplaced during SE-directed shortening (Kruhl, 1984) and granulite facies metamorphism (Johansson & Möller, 1986; Möller, 1988).

Gee (1975, 1978) used very simple linear ‘branch-lines’ to infer large thrust-displacements for the nappes along Transect 3. However, no shortening was inferred within the Lower Allochthon and no displacement was proposed for the Window-Basement, since the Offerdal Conglomerate, at the base of the Middle Allochthon, was restored to directly west of the present-day outcrop of the Tømmerås Window-Basement (cf fig 5. in Gee, 1978; Fig. 4). Further, the significance of extension within the middle to upper parts of the orogen was unrecognised (cf Norton, 1986; Rice, 1999; Osmundsen *et al.*, 2003, 2005; Robinson *et al.* 2014; Grimmer *et al.*, 2015). Hence the estimates, which in any event do not incorporate the strain within the rocks under discussion here, are no longer structurally admissible.

4.c. Transect 4 - Telemark to Møre og Romsdal

The branch-line restoration of Transect 4 is constrained by the ~490 km long section from Langesund, in southern Telemark, to Kristiansund, in W. Norway. This line was chosen as it includes the widest and best studied part of the Lower Allochthon (Bjorlykke *et al.*, 1976; Nystuen, 1981, 1982, 1983, 1987; Bockelie & Nystuen, 1985; Morley, 1986, 1987a, b). The internal part of the Window-Basement is very complexly deformed (Krill, 1980, 1985; Robinson *et al.*, 2014); a proper restoration of this ductile strain is beyond the scope of the paper. All localities are shown in Figure 7.

FIG 7 NEAR HERE

On Hardangervidda, the Autochthon comprises undeformed and unmetamorphosed (taken as diagenetic zone alteration) rocks of the Bjørno Member (S7, <30 m) at the base of the Vidda Group, underlying strongly deformed rocks of the Vidda Group at lower greenschist facies, here presumed to be part of the internal Lower Allochthon (Fig. 7; S7-S8, 400 m; Andresen, 1978, unpub. Ph.D. thesis, Univ. of California, Davis, 1982, pers. comm. 2016; Andresen & Færseth, 1982). Note that in Figures 1 and 7, both of these units are shown as Autochthon.

At Langesund, the Autochthon consist of ~1.1 km of clastic and carbonate deposits (S7-S8) overlain by the Bruflat Sandstones (S8, 0.5-1 km; Bockelie & Nystuen, 1985; Worsley *et al.*, 2011).

The Osen-Røa Nappe Complex (Lower Allochthon; Fig. 7) consists of three hanging wall flats linked by ramps (Morley, 1986). The first flat lies in the Alum Shale Fm (S7) overlain by S8 (820 m). The basal thrust cuts 320 m down-section in the hanging wall at the first ramp, to the Moelv Tillite or Ekre Shale (S5-base S6) and on the second ramp ~3 km, to the base of the Brøttum Fm (S1a/S1b), with a pre-S7 thickness of ~3.4 km in the Hedmark Basin (Nystuen, 1982; Kumpulainen & Nystuen, 1985; Morley, 1986).

Thrusting in the Osen-Røa Nappe Complex was SE-directed in the north and SSE-directed in the south (Nystuen, 1981, 1983; Morley, 1986, 1987a, b), with the metamorphic grade changing from epizone grade in the north to diagenetic zone in the south (Bergstrom, 1980, Robinson & Bevins, pers. comm. 1986). Shortening dropped from 60% in the north to ~0% in the south, with a bulk shortening of 50% (Morley, 1986).

The upper part of the Lower Allochthon comprises the Aurdal and Synnfjell Duplexes and the Strondafjord Fm (Hossack *et al.*, 1985; Fig. 7). The Aurdal Duplex imbricates ~350 m of Dalselvi and Ørnberget fms (S6-S8) overlying ~10m of autochthonous shales (S7; Nickelsen *et al.*, 1985). The Synnfjell Duplex imbricates ~410 m of Successions S6-S8. The duplexes were formed during SE-directed shortening, with 63 and 84% shortening, respectively (Hossack *et al.*, 1985), at lower- to middle greenschist facies in the Synnfjell Duplex (Nickelsen *et al.*, 1985).

The Middle Allochthon comprises the Valdres and overlying Jotun Nappes, with similar cover and basement rocks (Fig. 7). The cover consists of the Valdres Gp (S1b, S5, S6, >4 km), including the thick Bygdin and Ormtjernskampen basal conglomerates (S1a; Table 2), overlain by the Mellsenn Gp (S6-S7, 250 m; Nickelsen, 1974; Nickelsen *et al.*, 1985; Hossack, 1978; Hossack *et al.*, 1985).

The Valdres and Jotun Nappes are separated by a zone containing ultramafic (serpentinite) to basic nodules, interpreted by Banham *et al.* (1979) as a Caledonian suture. Rice (2005) took these rocks as evidence for a minor ocean (Fjordane Sea) between the Valdres and Jotun Nappes. Andersen *et al.* (2012) suggested that the 'ophiolitic' material represented a hyper-extended continental margin, separating the Valdres and Jotun Nappes.

The Window-Basement comprises the small outcrops of the Tufsingdalen, Steinfjell, Spekedalen, Atnsjøen, Beito, Vang, Borlaug and Aurdal-Lærdal Window-Basement (here together called the *External Window-Basement*) and the very large Western Gneiss Region Window Basement (Figs. 1 & 7). A <150 m thick succession (S5-S8) unconformably overlies the Atnsjøen-Spekedalen Window-Basement, affected by NW-SE oriented deformation, possibly at greenschist facies metamorphic conditions (based on the description of the rocks as phyllites and as having a Caledonian stretching [ductile] lineation; Nystuen & Ilebekk, 1981; Siedlecka & Ilebekk, 1982). NW-SE oriented greenschist facies lineations also occur in the Beito Window (Hossack, 1976), but tectonic contacts in this area may have been affected by relative extension (Andersen, 1998).

The basement in the Western Gneiss Region at Skjølden is comparable to the Fillefjell-Beito Basement Complex (Beito and Vang Window-Basement; Milnes & Koestler, 1985; Fig. 7). This suggests that the Window-Basement is contiguous between the Western Gneiss Region and the External Window-Basement, under the nappes. Near Døvrefjell, the Gjevilvatnet Gp (S5?-S7, <300 m) unconformably overlies basement (Gee, 1980; Robinson, *et al.* 2014); similar cover rocks occur elsewhere within the Western Gneiss Region (Hacker *et al.*, 2003; Andersen *et al.*, 2012). Deformation and metamorphism in the Western Gneiss Region involved burial to ultra-high pressure conditions at its NW margin (Hacker *et al.*, 2003). This was followed by rapid exhumation, involving relative top-hinterland deformation between the Western Gneiss Region and the overlying nappes. Two models for this have been presented. (1) In the eduction model (Andersen *et al.*, 1991; Andersen *et al.*, 2012), the Western Gneiss Region is autochthonous and exhumation occurred by absolute top-hinterland movement of the overlying nappes. (2) In the buoyancy model, the Western Gneiss Region is allochthonous and exhumation occurred through gravitational forces along the subduction channel, contemporary with orogenic shortening (Hacker *et al.*, 2003; Rice, 2005); top-hinterland movements were only relative to the hanging wall and footwall, not absolute compared to the Baltic Shield.

Seismic studies across the Western Gneiss Region revealed a 4 km thick low velocity zone at 14 km depth (Mykkeltveit *et al.*, 1980). This was interpreted as oceanic sediments separating autochthonous crystalline basement from a Laurentia-derived Western Gneiss Region (see Fig. 7 for seismic line). Rice (2005) proposed that the sediments were a relict of the Hedmark Basin (S1a, b and younger), underlying Baltica-derived Window-Basement.

Late-orogenic extension occurred in the area, orthogonal to the thrusting direction in the nappes (Robinson *et al.*, 2014). Most of this, but not all, affected rocks above the structural levels this paper is concerned with (Fig. 7). Such movement will have resulted in material moving out of the cross-section plane. The *assumption* here is that the material that moved out was replaced by similar material moving in, such that no significant difference is present.

5. Alternative restorations

For each Transect two or more restorations based on the Models outlined in Figure 2 are given. These are then evaluated in the Discussion. A summary of the restored section lengths and shortening for each restoration is given in Table 6.

5.a. Restoration Transect 1 - E. Finnmark to E. Troms

The restorations presume a planar basal décollement as far west as the trailing branch-line of the Komagfjord Antiformal Stack or Revsbotn Basement Horse (Window-Basement; cf Gayer *et al.*, 1987; Fig. 5). Hence the Komagfjord Antiformal Stack and the still buried Hatteras and

Revsbotn Basement Horses must be restored to an internal position relative to this line, a minimum distance of 99 km. Alternatives to this constraint are reviewed in the Discussion.

For all the models outlined below, restoration of the more internal units (Børselv Duplex, Kunes and Laksefjord Nappes and Kalak Nappe Complex; Fig. 5) essentially follows that given in Rice (2014).

FIG 8 NEAR HERE

Branch-line restoration of the East Finnmark Parautochthon and Hanadalen and Ruoksadas Thrust Sheets in the Gaissa Thrust Belt moves the trailing branch-line of the Ruoksadas Thrust Sheet 59 km to the WNW (Rice 2014). This removes the stratigraphic repetition of the Tanafjord and Ekkerøy gps (S1b, Gaissa Thrust Belt) over the Torneträsk Fm (S6, Autochthon) near Lakselv (Figs. 5, 8). Further restorations depend on the Model used (Fig. 2).

For Model I, two alternative restorations are given. In Model 1A (Fig. 8a), further in-sequence restoration of the Gaissa Thrust Belt places the trailing branch-line of the eastern Munkavarri Imbricate Zone directly adjacent to the leading branch-line of the Hatteras Basement Horse after it has been restored by the minimum distance of 99 km (Fig. 8a).

Subsequent restoration of the E-to ESE-directed shortening in the western Munkavarri Imbricate zone leads to a stratigraphic overlap of the Tanafjord Gp (S1b, S2) over the unconformable Window-Basement cover (S5-S6). In the Model, this can only be corrected by moving the western Munkavarri Imbricate Zone to W- to WNW of the Window-Basement, such that the Window-Basement crops out 'within' the Munkavarri Imbricate Zone (Fig. 8a). The two parts of the Munkavarri Imbricate Zone are separated by a minimum of ~103 km.

During deformation, therefore, the western Munkavarri Imbricate Zone must be thrust over the Window-Basement as far as the eastern Munkavarri Imbricate Zone. The *total* restoration of the trailing branch-line of the eastern Munkavarri Imbricate Zone, from its deformed position in Porsangerfjord, is 124 km. Thus, after 25 km of this shortening, ESE-directed displacement of the Window-Basement (99 km total displacement) started.

Deformation *within* the Window-Basement was SE-directed, with ~3 km shortening (Gayer *et al.*, 1987; Torgersen & Viola, 2014). When this displacement occurred is uncertain. If it was directly after SE-directed shortening in the Kalak Nappe Complex and Laksefjord and Kunes Nappes, and hence prior to E- to ESE-directed thrusting, deformation in the western Munkavarri Imbricate Zone would have been out-of-sequence. (Strictly, this scenario does not conform to Model I, in which deformation in the Window-Basement starts *after* the onset of imbrication in the Lower Allochthon.) Conversely, if thrusting was in-sequence, then the SE-directed internal shortening in the Window-Basement represents a short-term change in thrusting direction during the dominant E- to ESE-directed phase of shortening.

In Model 1A, the restored length of the East Finnmark Parautochthon and Gaissa Thrust Belt is 491 km, with the Window-Basement displaced by 99 km (Fig. 8a). Combined shortening in these units was 51%.

For Model IB (Fig. 8b), in contrast, *all* the pre-S3 rocks in the Porsangerfjord area (Fig. 5) have been restored to W- to WNW of the Window-Basement, since a division of the Tanafjord Gp, reflecting the ~103 or more km separating the eastern and western Munkavarri Imbricate Zones in Model 1A (Fig. 8a) has not been recognised in the sedimentology (White, 1968, 1969; Roberts, 1974; Williams, 1976a, 1976b; Tucker, 1976, 1977). This not only requires that the contact between the Tanafjord Gp (S1b) and the overlying Vestertana Gp

(S3, S4) within the western Ruoksadas Thrust Sheet be re-interpreted as a major back-thrust (Figs. 5, 8b) but also creates a >90 km gap in the restoration, between the restored Vestertana Gp (S5, S6) of the Ruoksadas Thrust Sheet and the leading edge of the Hatteras Basement Horse (after restoration by 99 km). The two parts of the Gaissa Thrust Belt are separated by ~230 km.

In this Model, the Munkavarri Imbricate Zone (both parts) and the low-strain southwest part of the Ruoksadas Thrust Sheet are imbricated and thrust over the Window-Basement for 230 km, with a back-thrust sense relative to the hanging wall during at least the last stages of this movement (to under the Vestertana Group in the western part of the Ruoksadas Thrust Sheet). The same arguments for the 3 km of SE-directed shortening within the Window-Basement documented for Model 1A apply here as well.

In Model IB, the restored length of the East Finnmark Parautochthon and Gaissa Thrust Belt is 624 km, with the Window-Basement displaced by 99 km (Fig. 8b). Combined shortening in these units was 61%. This model more closely follows the definition of Model I (Fig. 2a), as all S1 and S2 rocks were restored to west of the Window-Basement and deformation in the Lower Allochthon started before that in the Window-Basement.

For Model II (Fig. 8c), the Window-Basement, Laksefjord and Kunes Nappes and Kalak Nappe Complex are all pinned to the trailing edge of the Gaissa Thrust Belt and moved towards the hinterland during restoration of all E- to ESE-directed deformation (Rice 2014). During the final 99 km of this movement, the Window-Basement moves down its footwall ramp to its restored position WNW of the Lower Allochthon. Subsequently, SE-directed thrusting in the Børselv Duplex (Gaissa Thrust Belt), Window-Basement and Kunes and

Laksefjord Nappes was sequentially restored (cf Rice, 2014 for details). No significant gaps are present within the restored section.

In Model II, the restored length of the East Finnmark Parautochthon and Gaissa Thrust Belt is 396 km (Fig. 8c). Combined shortening in these units was 39%. If the Window-Basement is included, the length is 501 km, with the Window-Basement displaced by 157 km. The overall shortening is 31%.

5.b. Restoration Transect 2 - Västerbotten to Nordland

The dimensions of the Børgefjell Window-Basement in the semi-schematic deformed profile were estimated from inferring a planar basal décollement (except where the restoration subsequently necessitates otherwise; see below) dipping 2° WNW (cf Palm *et al.*, 1991; Fig. 3) and 30° ramp angles. A horizontal topography was extrapolated westwards from the present-day Caledonian front, which gives an initial thickness of 4.7 km for the Børgefjell Window-Basement (Fig. 9 section 2.1). This horizontal line is also taken as the boundary between Successions 1a-2 and Successions 5-8.

FIG 9 NEAR HERE

For the basement rocks of the Autochthon and Window-Basement, vertical and horizontal scales are the same. Cover sediment thicknesses are semi-schematic; the Risbäck Gp is modelled as being ~1.6 km thick, not 0.7 km, to make it visible on the sections. Hence, thickening of the Window-Basement towards the hinterland is slightly exaggerated in Figure 9 sections 2.5, 2.6.

Shortening occurred within the Window-Basement (Fig. 6; Greiling, 1988), but this cannot be modelled due to the lack of published data. Including this deformation would increase the restored section lengths.

A 30 km-long buried Autochthonous cover succession (S7 and younger) is extrapolated from the Tåsjön area (Gee *et al.*, 1978) and a pre-erosion thrust front ~120 km east of the present front is assumed (Hossack & Cooper, 1986; Fig. 9 sections 2.1-2.8). This value has been used, rather than the ~80 km proposed by Garfunkel & Greiling (1998), but, as shown below, the actual value chosen makes little difference, since the fully restored section length is controlled by the position of the Børgefjell Window-Basement.

Restoration of an inferred bulk shortening of 20% is needed in the eroded segment of the Lower Allochthon to move the Gärdsjön Fm (S6) in the preserved Lower Allochthon to the west of the 30 km wide Autochthon (S7) preserved under the nappes (Fig. 9; cf Gee *et al.*, 1978).

In Model I, the Børgefjell Window-Basement is restored during restoration of the eroded part of the Lower Allochthon; that is, it was imbricated essentially during the latest phase of thrusting in the Lower Allochthon. The leading edge of the footwall ramp is inferred to be coincident with the trailing edge of the deformed Window-Basement (r in Fig. 9 section 2.2), such that there is no overlap of the deformed and restored positions of the Børgefjell Window-Basement. A more easterly position can be used for the footwall ramp, giving an overlap in deformed and restored positions, but this results in a thicker Window-Basement block (see Fig. 9 sections 2.5-2.8).

Subsequent restoration of the 50% shortening in the Lower Allochthon (Gayer & Greiling, 1989) places its trailing edge close to the leading edge of the restored Børgefjell Window-Basement (Fig. 9 section 2.3). To move the Risbäck Fm to the west side of the Børgefjell Window-Basement, required for Model I, a part of the Lower Allochthon has to be moved 44 km to the WNW (Fig. 9 section 2.4), creating a ~44 km wide gap in the section. This is here shown between the leading edge of the preserved Lower Allochthon and the trailing edge of the restored eroded part. Increasing the shortening in the eroded part to 38 % closes this gap (not shown in Fig. 9).

For Model I, the restored section length is 306 km, with a bulk shortening in the Lower Allochthon (including the eroded part) of 42%. The Børgefjell Window-Basement was displaced 27 km (Fig. 9).

In Model II, two possible restorations have been shown, differing only in the restoration of the 62 km gap in the section between the trailing edge of the Lower Allochthon and the leading edge of the Børgefjell Window-Basement. In both alternatives, restoration of the eroded part of the Lower Allochthon is the same as that in Model I. During subsequent restoration of the preserved part of the Lower Allochthon, the Risbäck Gp is restored to its final position, forming a step in the basement-cover interface (and hence, later, a ramp in the basal décollement; r in Figure 9 section 2.6) under the present position of the Børgefjell Window-Basement. To fill the space in the deformed section created by this ramp, the Window-Basement must thicken to the west (Fig. 9 section 2.5).

During restoration of the Lower Allochthon, the Børgefjell Window-Basement must be restored to the WNW, since, in Model II, imbrication of the Window-Basement occurs prior to shortening in the Lower Allochthon. The same distance (62 km) must be kept between the trailing edge of the Lower Allochthon and the leading edge of the Window-Basement as seen now in the deformed section (Fig. 9 sections 2.5, 2.6). This implies that any Jämtland Supergroup sediments that lay between the Window-Basement and the preserved Lower Allochthon were thrust over the Lower Allochthon, in the footwall of the Middle Allochthon, prior to imbrication of the Børgefjell Window-Basement, and have been eroded away (Fig. 9 sections 2.5, 2.6).

Alternatively, the Lower Allochthon might continue to the west, buried under the structurally higher nappes, as far as the leading edge of the Window-Basement, with 50% shortening. Restoration of this model would move the Børgefjell Window-Basement 124 (2 x 62) km to the WNW of the trailing edge of the Lower Allochthon (Fig. 9 sections 2.7, 2.8). In this model, the material from this gap, now shortened, still lies buried under the structurally higher nappes.

For Model IIA, the restored section length is 354 km, with a bulk shortening in the Lower Allochthon (including the eroded part) of 32% (Fig. 9). The Børgefjell Window-Basement was displaced 85 km. For Model IIB, the restored section length is 416 km, with a bulk shortening in the Lower Allochthon (including the eroded part) of 38%. The Børgefjell Window-Basement was displaced 147 km.

5.c. Restoration Transect 3 - Jämtland to Trøndelag

The initial parameters for constructing the deformed section (Fig. 10) are the same as for Transect 2 (first paragraph), except that the eroded part of the Lower Allochthon is 90 km wide (Hossack & Cooper, 1986). In all restorations, the eroded part has been restored using the same shortening value (20%) as in Transect 2, giving a displacement of 23 km; this does not move the preserved Lower Allochthon to the hinterland of the 30 km wide buried Autochthon (Fig. 10), but, since both hanging wall and footwall lie in the Fjällbränna Fm (S7), an absence of stratigraphic overlap is assumed.

FIG 10 NEAR HERE

The section cuts the lower imbricate of the Grong-Olden Window-Basement and both imbricates of the Tømmerås Window-Basement (Fig. 6); lateral continuity between the lower imbricates of these two units has been assumed. Taking a planar basal décollement, the lower imbricate of the Grong-Olden Window-Basement is 3.7 km thick and of the Tømmerås Window-Basement 6.2 km, linked by an inferred 1.6 km thick basement slice (Fig. 10 section 3.7 east of kilometre 286 shows this presumed initial geometry). Reducing the thickness of this slice would affect the final modelled thickness of the Window-Basement, by a similar amount, in Model IA (Fig. 10 sections 3.1, 3.2). A branch-line has been constructed around the upper imbricate and restored to the WNW until it does not overlap the Bjørndalen Fm in the lower imbricate of the Tømmerås Window-Basement, a displacement of 66 km (Fig. 6).

For Model I, two alternative restorations are shown; one in which the lower imbricate of the Grong-Olden Window-Basement is inferred to be a single slice of basement 3.7 m thick and one in which it is inferred to comprise two equally thick basement slices, both overlain by a cover succession (Fig. 10 sections 3.1-3.4),

In Model IA, the 3.7 km thick lower imbricate of the Grong-Olden Window-Basement has been restored by the shortest possible amount (21 km) that keeps the thickness of this part of the unit the same in the deformed and restored sections. (If the footwall ramp were moved to the east, the Window-Basement would thicken dramatically). This restoration was done during restoration of the 20% shortening in the eroded part of the orogen (23 km); hence it is modelled as a very late event.

Since, in this model, the Grong-Olden and Tømmerås Window-Basement presently overlie their restored positions, and the restored upper surface of the Window-Basement (excluding the cover sediments) is kept at the level of the basement-cover interface at the eroded

Caledonian front (lines U in Fig. 10), the Window-Basement must thicken westwards. Essentially, the Window-Basement at x (Fig. 10, section 3.1) restores to y, with the depth to the basal décollement below the planar basement-cover unconformity constrained by the thickness at x (see x′, Fig. 10 section 3.2). As the deformed basement-cover contact at y lies above the restored position, the basement that moves onto y during deformation must be thicker than that at x. Similarly for the basement at z, moving onto y (see x′, y′, z′ in Fig. 10 section 3.2). Thus the basement wedge thickens gradually to the west with these constraints, until the lower imbricate of the Window-Basement has been fully restored. In the model, the maximum depth of the basal décollement (at the WNW end) is 14.8 km.

West of the deformed position of the trailing branch-line of the Tømmerås Window-Basement, the thickness of the Window-Basement has been kept constant at ~13 km, until the upper imbricate of the Tømmerås Window-Basement is restored using the branch-line geometry documented above (Fig. 10 section 3.2). As the section line does not cut the branch-line around the upper imbricate of the Grong-Olden Window-Basement, a gap is present in all the restorations of this Transect, between the restored positions of the upper and lower thrust sheets of the Tømmerås Window Basement.

For Model IA, the restored section length is 372 km, with ~21 km displacement for the lower imbricate of the Tømmerås Window-Basement. Shortening in the Lower Allochthon, including the eroded part, is 42%.

In restoration Model IB (Fig. 10 sections 3.3, 3.4), the lower imbricate of the Grong-Olden Window-Basement is presumed to consist of two equally thick basement slices (w and x), both with a cover succession. These imbricates restore to w′ and x′ and together define the length of y, which is overlain by the inferred 1.6 km thick basement slice joining the Grong-

Olden and Tømmerås Window-Basement. Since the west end of y lies east of the leading edge of the Tømmerås Window-Basement, the Window-Basement can retain its original thickness, rather than thickening (part z). Further, since the trailing edge of z′ lies west of the trailing edge of the deformed Tømmerås Window-Basement (r, Fig. 10 section 3.3), the latter does not thicken significantly more when restored (compare with the position of r relative to the Tømmerås Window-Basement in Figure 10 section 3.1).

In this restoration, the Window-Basement does not continue to the west as a thick slice of basement (for example, as thick as at y′) and hence the upper imbricate of the Tømmerås Window-Basement is restored to ~10 km below the top of the upper imbricate (Fig. 10 section 3.3).

In Model IB, the restored section length is 397 km, with ~40 km displacement for the lower imbricate of the Tømmerås Window-Basement. Shortening in the Lower Allochthon, including the eroded part, was 46%.

For both alternatives, it has been assumed that there is no stratigraphic repetition between the restored Lower Allochthon and the Grasåmoen Fm. However, the Gärdsjön Fm crops out directly south of the transect line and this overlaps the Bjørndalen Fm at the southern end of the Tømmerås Window-Basement (G & B, Fig. 10 sections 3.1-3.4). If this is taken into consideration, the restored lengths increase to 349 and 369 km, respectively, giving 43% and 46% shortening in the Lower Allochthon (including eroded part).

In Model II, restoration of the 20 % shortening in the eroded part and the 50% shortening in preserved part of the Lower Allochthon places its trailing edge 333 km WNW of the eroded thrust front (Fig. 10 sections 3.6, 3.8). The lower imbricate of the Grong-Olden Window-Basement is presumed to comprise two thin basement-cover sheets.

For Model IIA (Fig. 10 sections 3.5, 3.6), the basement in the Grong-Olden Window-Basement has been restored to below the restored Lower Allochthon, since it underlies the deformed Lower Allochthon now, to avoid back-thrusting. The most westerly position possible for the Window-Basement is constrained by the 50% shortening inferred for the Lower Allochthon lying to the hinterland of the leading edge of the Grong-Olden Window Basement. In the model, this must be shortened prior to thrusting of the lower imbricate of the Grong-Olden Window-Basement. Thus, in Figure 10 section 3.6, the trailing edge of the restored cover of the Grong-Olden Window-Basement (at 292 km) must lie by the length of the restored cover (292-251=41 km) to the foreland of the restored trailing-edge of the Lower Allochthon (at 333 km). This puts the restored position of the Window-Basement partially under its deformed position and hence the Tømmerås Window-Basement must be thicker than initially drawn (compare thicknesses in Fig. 10 sections 3.5, 3.7). Restoration of the lower imbricate of the Window-Basement places the trailing edge of the Tømmerås Window-Basement 128 km to the hinterland of the leading edge of the Grong-Olden Window-Basement. The upper imbricate of the Window-Basement is restored by 66 km, using the branch-line geometry in Figure 6; this places the trailing edge of the Window-Basement at 466 km from the eroded thrust front.

During deformation, the trailing-edge of the Lower Allochthon (at 333 km) was shortened until it was coincident with the trailing edge of the restored cover on the Grong Olden Window-Basement (at 292 km). This started after, but was partly coincident with the 66 km emplacement of the upper imbricate of the Window-Basement. As shortening is set at 50%, deformation in the Lower Allochthon during this period progressed towards the leading edge of the cover on the Grong-Olden Window-Basement (at 251 km). As deformation in the Lower Allochthon reached the leading edge of each of the two minor thrust slices within the lower imbricate of the Grong-Olden Window-Basement, shortening in this lower imbricate occurred. The combined Window-Basement and Lower Allochthon were then transported together, towards the foreland.

For Model IIA, the restored section length is 448 km, with ~90 km displacement for the lower imbricate of the Tømmerås Window-Basement. Shortening in the Lower Allochthon, including the eroded part, was 40%.

In Model IIB (Fig. 10 sections 3.7, 3.8), the Window-Basement has been restored completely to the hinterland side of the restored Lower Allochthon. Subsequent restoration of the minor thrust slices in the in the lower imbricate of the Window-Basement moves its trailing branch-line 16 km more towards the hinterland. The upper imbricate of the Window-Basement is restored a further 66 km, using the branch-line restoration in Figure 6.

During thrusting, emplacement of the upper imbricate and shortening within the lower imbricate of the Window-Basement is followed by thrusting of the lower imbricate *under* the Lower Allochthon, which undergoes 50% shortening at the same time. The trailing edge of the Lower Allochthon must back-thrust 42 km relative to the trailing edge of the cover on the Grong-Olden Window-Basement. The amount of back-thrusting decreases as imbrication moves towards the foreland.

For Model IIB, the restored section length is 530 km, with 173 km displacement for the lower imbricate of the Tømmerås Window-Basement. Shortening in the Lower Allochthon, including the eroded part, was 40%, the same as Model IIA, but includes up to 42 km of relative back-thrusting on its floor thrust.

5.d. Restoration Transect 4 - Telemark to Møre og Romsdal

The average shortening estimate of 50% (Morley, 1986) has been used everywhere for restoring imbrication within the Osen-Røa Nappe Complex (Lower Allochthon). No constraints are made for the depth to the basal décollement, although Morley (1986) gave depths for the Osen-Røa Nappe Complex. The similarity of the basement in the Western Gneiss Region and External Window-Basements (Milnes & Koestler, 1985) indicate that they can be taken as a single unit ~221 km wide from NW to SE. No net internal shortening or stretching has been assumed in the Window-Basement (Fig. 11a, b).

FIG 11 NEAR HERE

In both Models, branch-line restoration of the SSE-directed shortening in the Osen-Røa Nappe Complex in the Oslo Graben places its trailing branch-line ~308 km NNW of its leading-edge; this is coincident with the Autochthon at the south end of the section (Fig. 11a, b). This restoration causes a stratigraphic repetition of Moelv Tillite/Ekre Shale (S5, S6) in the Lower Allochthon above S8 in the External Window-Basement cover (Morley, 1986; Nystuen & Ilebekk, 1981).

In Model I, restoration of the Window-Basement, required by the stratigraphic repetition described, occurs during restoration of the later stages of thrusting in the Lower Allochthon in the Oslo Graben (Fig. 2a). Thrust emplacement of all the Window-Basement must also, therefore, have been SSE-directed. In Figure 11b, a displacement of 70 km has been shown for the Window-Basement, but, in the absence of a proper balanced section, this is schematic. A minimum value (~42 km) is constrained by the trailing branch-line of the restored Oslo Graben part of the Osen-Røa Nappe Complex.

NNW-directed restoration of the Hedmark Basin part of the Osen-Røa Nappe Complex during restoration of the Oslo Graben part, places the Brøttum Fm (S1a, b and younger; Kumpulainen & Nystuen, 1985) above the Gjevilvatnet Gp and other comparable rocks (S7 and younger) lying unconformably on Døvrefjell (Fig. 4) and many other parts of the Western Gneiss Region (Gee, 1980; Hacker, 2003; Andersen *et al.*, 2012). Hence the Hedmark Basin must be restored to NW of the Western Gneiss Region Window Basement, a displacement of 281 km, consistent with Model I (Fig. 2a). Restoration of imbrication within the Hedmark Basin gives it a width of 283 km parallel to the SE-directed thrusting direction (Fig. 11b). The two parts of the Lower Allochthon are separated by ~280 km.

The Synnfjell Duplex (S6-S8) repeats the Hedmark Basin stratigraphy (S1a-S8) and must be restored 86 km to the northwest. As Hossack *et al.* (1985) documented 63% shortening in the southeastern part but the northwestern part underwent thinning and top-NW extension (Milnes & Koestler, 1985; Milnes *et al.*, 1997), the 'restored' Synnfjell Duplex is here kept the same size as the deformed duplex (Fig. 11b).

For Model I, the combined length of the restored section is 980 km, with the Window-Basement displaced 70 km. Total shortening in the Osen-Røa Nappe Complex was 66%. The Synnfjell Duplex was not included in the shortening calculation due to its complex deformation history (cf Krill, 1985; Robinson *et al.*, 2014).

In Model II (Fig. 11a), the Hedmark Basin part of the Osen-Røa Nappe Complex is restored to the NNW of the restored Oslo Graben part and then the internal shortening (50%; Morley, 1986) is restored to the NW, giving a restored width of 283 km. The Synnfjell Duplex is here restored with the same constraints as Model I; an 86 km offset to the NW relative to the fully restored Hedmark Basin and no net length change.

The amount of NW-directed restoration of the Window-Basement, which was pinned to the trailing edge of the Osen-Roa Nappe Complex, relative to the Synnfjell Duplex, depends on the extent of the cover succession preserved on the Window-Basement. Since Andersen *et al.* (2012) suggest that cover sediments are widespread on the Western Gneiss Region, only those parts of the External Window-Basement without a cover succession are overlain by the Synnfjell Duplex in the model (Fig. 11a).

For Model II, the combined length of the restored section is 830 km, with the Window-Basement displaced 314 km. Shortening in the Lower Allochthon was 50% (as given in Morley, 1986). The Synnfjell Duplex was not included in the shortening calculation due to its complex deformation history (cf Krill, 1985; Robinson *et al.*, 2014).

6. Discussion

The basal thrust of the Window-Basement is, by definition, not exposed. Thus, indirect evidence must be used to evaluate which Model is more likely correct. The critical question is whether intial deformation in the Window-Basement preceded the onset of deformation in the Tonian-Cryogenian deposits (S1a, b, S2) in the Lower Allochthon or *vice-versa*. Or, to put it another way, whether the basal thrust of the Window-Basement underlies or overlies the Tonian-Cryogenian sediment of the Lower Allochthon. Seismic data in the central Scandinavian Caledonides (Palm *et al.,* 1991; Fig. 3) was interpreted to give support for Model I. In contrast, Rice (2001) showed that the Kunes Nappe in Finnmark (Fig. 5) was essentially comparable to the Window-Basement and that it clearly overlay the S1b and S2 sediments in the Lower Allochthon, supporting Model II.

6.a. Restoration techniques

The balanced cross-sections used (Figs. 9, 10) are semi-schematic, with a brittle-style ramp-flat geometry applied to the Window-Basement, although this underwent ductile deformation (e.g. Krill, 1980, 1985; Sjöstrom & Talbot, 1987; Robinson *et al.*, 2014; Torgersen & Viola, 2014). This was done to ensure that material was not lost from the sections during restoration. Further, the top-hinterland strain in the Western Gneiss Region and Synnfjell Duplex on Transect 4 (Milnes & Koestler, 1985; Milnes *et al.* 1997) has been presumed to cancel earlier top-foreland shortening (Hossack *et al.*, 1985). Although these are important simplifications, they have been applied to both Models, giving internal consistency for each Transect.

In Transects 2 and 3, horizontal dimensions from Gee *et al.,* (1985a) were combined with a 2° planar basal décollement (cf Palm *et al.,* 1991) to obtain an initial first-order estimate of the thicknesses of the Window-Basement units (4.7 km Børgefjell; 6.2 km Tømmerås lower imbricate, 3.7 km Grong-Olden lower imbricate). These are underestimates, but similar to the 6 km thickness of the complete Müllfjället Window-Basement (Palm *et al.,* 1991; Fig. 3) and some restorations indicated that the thickness could be greater (Fig. 10 sections 3.1, 3.3), giving a greater depth to décollement. Where multiple imbricates were inferred, comparable to the Bångonåive Window-Basement (Greiling *et al.,* 1993), a shallower depth to décollement develops, but the section-length increases (Fig. 10 sections 3.3-3.8).

The branch-lines used in restorations of Transects 1, 3 and 4 (Figs. 8, 10 & 11) are partly based on balanced cross-sections (Morley, 1986; cf Rice, 2014). Where only the surface outline of a unit was used to define the branch-line, the sub-surface ramps will make these larger, but not enough to significantly affect restorations.

6.b. Restoration Lengths and Displacements

For Transect 1, the restored lengths of the Lower Allochthon and Window-Basement for Models IA and II are similar (Fig. 8a, c; 491 and 501 km, respectively; Table 6). Model IB is longer (624 km), in part because a planar basal décollement was assumed to underlie the deformed Window-Basement (cf Gayer *et al.,* 1987), forcing a minimum displacement of 99 km for the Window-Basement. Without this constraint, the length could be reduced by having the footwall ramp directly under the Window-Basement.

TABLE 6 NEAR HERE

On Transects 2 and 3, deformation in the Window-Basement was a very late event in Model I (Figs. 9, 10) and so the leading edge of the Window-Basement must only be restored by a minor distance to achieve a planar upper surface. With no stratigraphic repetition inferred for most/all of the restored Lower Allochthon and the Window-Basement cover, the former can be partially restored to above the latter, giving shorter restored section lengths than Model II. Only the Risbäck Group (S1a-S2) is older than the Børgefjell Window-Basement cover and must be restored to the hinterland of the Window-Basement.

In Model II, deformation started in the Window-Basement, and so the leading edge of the Window Basement is pinned in most cases to the trailing edge of the Lower Allochthon during restoration of the latter (Fig. 9 sections 2.5-2.8 and Fig. 10 sections 3.7, 3.8). On Transect 3, Model IIA (Fig. 10 sections 3.5, 3.6), however, the leading edge of the Grong-Olden Window Basement is pinned to the immediately overlying Lower Allochthon, such that sediments currently lying west of the leading edge have been restored to a similar relative position. Thus part of the Lower Allochthon restores to above the Window-Basement. Nevertheless, thrusting in the Window-Basement still started in the upper imbricate before that in the Lower Allochthon in Model IIA. For Model IIB, no overlap of the restored Lower

Allochthon onto the Window-Basement is inferred, making this restored section longer than both Model I and Model IIA (Fig. 10 sections 3.7, 3.8).

For Transect 4, Model I is 150 km longer than Model II (Fig. 11). However, the 70 km displacement for the Window-Basement in Model I is ~28 km longer than the absolute minimum. Also, the partial overlap of the trailing edge of the Synnfjell Duplex and the leading edge of the External Window-Basement, based on the lack of exposed cover on the Window-Basement, shortens Model II by 80 km (Fig. 11b). Combining these reduces the difference in restored lengths to ~40 km, not markedly significant.

Thrust displacement of the trailing edge of the Window-Basement is significantly greater than that of the leading edge only on Transect 3 (Fig. 10), because there are two major Window-Basement imbricates (Fig. 6). Dividing the lower imbricate of the Grong-Olden Window-Basement into two thin slices only lengthens the restored sections by 16 km (199-215 km; Fig. 10 sections 3.3, 3.4 and the same distance for Fig. 10 sections 3.6 & 3.8).

In summary, displacement of the Window-Basement is always less for Model I than Model II (Table 6), but Model I restorations are not necessarily shorter than those from Model II.

6.c. Constraints on models

6.c.1. Sedimentological constraints

All Transects have thick basement-derived alluvial-fan deposits at the base of the Middle Allochthon (S1a; Table 2; Nickelsen, 1974; Hossack, 1978; Føyn *et al.,* 1983; Plink-Björklund *et al.,* 2005), indicating a proximal uplifting basement source-area. Gee (1975) correlated the conglomerates of the Offerdal Nappe (Plink-Björklund *et al.,* 2005) with the Risbäck Group but did not show specifically the syn-sedimentary relationship between the

Lower and Middle Allochthons. Nystuen & Kumpulainen (1985) correlated the Tossåsfjället Group with the Offerdal and Risbäck Groups, but also gave no detailed palaeogeographic model.

In Model I, the basement source-area must have been drowned at the end of alluvial-fan deposition, to allow conglomerate-free deposits to pass through the Lower Allochthon basin into the Middle Allochthon basin (Fig. 2a). In Model II, the basement-high persisted until at least the Gaskiers glaciation (S5; the Alta-Kvænangen Window-Basement is an exception; Føyn, 1985), since diamictites often form the base of the cover succession of the Window-Basement but it was certainly drowned before/during deposition of the middle Cambrian to early Ordovician S7 black shales (Gee 1980, Siedlecka & Ilebekk, 1981; Lindqvist, 1984; Pharaoh, 1985; Gayer & Greiling, 1989; Fig. 2b). Even then, subsidence was slower than in the adjacent basins, since thicknesses are lower (Table 4).

Palaeocurrents reflecting a northwesterly basement source-area in the Lower Allochthon have only been recorded in Finnmark (Tucker 1977). Sedimentary structures are poorly preserved within the Risbäck Group along Transect 2 (Greiling, pers. comm. 2016) and the palaeogeography of the Hedmark Basin (NW-SE trending rift; Nystuen, 1987) make such a distinction invalid. This scarcity is surprising considering the size of the source-area required for the alluvial-fan deposits in the Middle Allochthon.

In Model I on both Transects 1 and 4, the Lower Allochthon is restored into two distinct parts, separated by the Window-Basement. In neither area has any sedimentological evidence for such gaps been recorded; thicknesses, lithologies and facies are unbroken across the proposed gap, which may be ~280 kilometres wide (Figs. 8a, b, 11b; Roberts, 1974; Bjørlykke *et al.,* 1976; Williams, 1976; Nystuen, 1982, 1987; Bockelie & Nystuen, 1985; Morley, 1986).

Essentially, it was impossible to identify a realistic place where such a division could be made; the divisions used are entirely artificial.

6.c.2. Structural constraints

Soper *et al.* (1992) documented a consistent change in thrusting direction; SE-directed in the Middle Allochthon and E- to ESE-directed in the Lower Allochthon, except in southernmost Norway, where it was SE- and SSE-directed. If Model I is correct, evidence of E- to ESE-directed or SSE-directed deformation should be seen in the Window-Basement, similar to that in the external part of the Lower Allochthon; if Model II is correct, SE- and/or E- to ESE-directed lineations should be preserved (Morley, 1986; Townsend, 1987; Gayer & Greiling, 1989). On Transects 1, 3 and 4, deformation in the Window Allochthon was SE-directed (Table 5; Hossack, 1976; Nystuen & Ilebekk, 1981; Stel, 1988; Lindqvist, 1990; Torgersen & Viola, 2014) whilst on Transect 2 it is E- to ESE-directed (Gayer & Greiling, 1989). This indicates Model II is applicable. In Transect 1, stretching lineations at the base of the Middle Allochthon preserve the change from SE-directed to E- to ESE-directed movement (Townsend, 1987; Rice, 1998).

Model I divides the Lower Allochthon into two parts on Transects 1 and 4. To bring these parts together implies thrusts with displacements of up to ~280 km (Figs. 8a, b & 11a. No evidence for such thrusts has been found (Føyn, 1967; Nystuen, 1983; Morley, 1986; Townsend, 1987; Gayer *et al.,* 1987). On Transect 1, the inferred thrust for Model IA was placed along Porsangerfjord (Fig. 8a), where exposure is ‘poor’, despite numerous islands. For Model IB, on Transect 1 (Fig. 8b), a back-thrust offset is required along the contact of Successions 1b-2 and 3-4. No evidence for this has been found (Føyn *et al.*, 1983).

Back-thrusting is also inferred for Model IIB on Transect 3 (Fig. 10 sections 3.7, 3.8), between the Lower Allochthon and the Grong-Olden Window-Basement. As there is no field-evidence for this, the Model is rejected; Ediacaran and younger sediments now lying to the hinterland of the leading edge of the Window Basement must be restored to a similar relative position.

6.c.3. Metamorphic constraints

In-sequence thrust sheets within collisional orogens show a general increase in metamorphic grade from foreland to hinterland (Daly *et al.,* 1989), reflecting higher structural levels within the orogen and thus more internal restored positions. Once rocks have been imbricated into the orogen, tectonic burial ceases and erosion of the orogenic wedge, combined with accretion of more units into the footwall, leads to decreasing P, with subsequent falling T (Rice, 1987). Anderson (1989) used across-strike and along-strike metamorphic grade variations in cover rocks of the Autochthon, the Lower Allochthon (Rautas Complex) and Windows-Basement to argue for restoration of the Rombak Window-Basement to a position significantly outboard of their equivalents in the Lower Allochthon.

Both out-of-sequence thrusting and syn-orogenic hinterland directed extension (e.g. Grasemann *et al.*, 1999) can disturb this pattern. The latter process has been documented in the Scandinavian Caledonides at the contact of the Seve (Middle Allochthon) and Köli (Upper Allochthon; Grimmer *et al.*, 2015) nappes. More significantly, the internal parts of the Window-Basement on Transect 4 (and also on Transect 3, in part of the Window Basement not included here) were subducted to/exhumed from UHP/HP conditions (cf Möller, 1988; Hacker *et al.,* 2003), disturbing the in-sequence pattern of metamorphism.

A gradual but irregular increase in metamorphic grade occurs on all Transects from the Autochthon (diagenetic zone-lower anchizone) to the internal part of the Lower Allochthon (anchizone to lower/middle greenschist facies; Table 3; Bergström, 1980; Kisch, 1980; Nickelsen *et al.* 1985; Rice *et al.,* 1989a; Warr *et al.,* 1996).

In Model I, peak metamorphism in the Window-Basement occurred after that in the internal part of the Lower Allochthon, since it was imbricated later, and should have a lower metamorphic grade than the more internally derived overlying Lower Allochthon. However, restoration of the Window-Basement to 'within' (Transects 1 & 4) or under (Transects 2 & 3) the Lower Allochthon places higher grade rocks (epizone to eclogite facies) to the foreland of lower grade rocks of the same orogenic cycle.

Model II, in contrast, generally preserves a gradual increase in metamorphic grade from the internal parts of the Lower Allochthon to the lower imbricate or external part of the Window-Basement. The only possible exception is on Transect 4, in which the Synnfjell Duplex underwent lower- to middle greenschist facies metamorphism (Nickelsen *et al.,* 1984) whilst the External Window Basement, which underlies the Synnfjell Duplex (Fig. 11) underwent greenschist alteration; further definition of the grade from the published data is not possible (Hossack, 1976; Nystuen & Ilebekk, 1981; Table 3)

The East Finnmark Autochthon and the Autochthon at Lakselv (Fig. 5) are >150 km apart, but the metamorphic grade is diagenetic zone-lower anchizone in both areas (Rice *et al.,* 1989a). Similarly, the Autochthon at Langesund and 150-200 km further north (normal to the SSE-directed thrusting direction), on Hardangervidda are both diagenetic zone (Fig. 7; Robinson & Bevins, pers. comm. 1986; Andresen, pers. comm. 2016). Extending this length-scale from the eroded thrust-front of Hossack & Cooper (1986) to Transects 2 and 3, indicates that the

Autochthon should still be at or below lower anchizone conditions under the eastern part of the Grong-Olden Window-Basement and not much higher under the Børgefjell and lower imbricate of the Tømmerås Window-Basement. The available data indicates grades of epizone to middle greenschist facies (Table 3) in these areas, indicating that the Window-Basement has been transported a considerable distance.

6.c.4. Summary of preferred models: Models II & III

The previous sections indicate that in-sequence deformation started in the Window-Basement and subsequently cut-down into the Tonian-Cryogenian sediments of the Lower Allochthon.

Model II, by definition, implies imbrication of a sedimentary basin comprising Tonian-Cryogenian sediments (S1a, S1b, S2; Table 1; Fig. 2b) in the Lower Allochthon. On Transect 3, the oldest sediments, the Gärdsjön Fm (<200 m), at St. Grässjön, are of Ediacaran (S6) age and these unconformably overlie a slice of allochthonous basement (Fig. 6; Sveriges Geologiska Undersökning, 1984; Gee *et al.,* 1985b). The Jämtland Supergroup on Transect 3 has an S6-S8 thickness of up to 1.12 km (Gee *et al.,* 1974, 1985b). Assuming 50% tectonic shortening, thus 100% thickening, implies a ~2.2 km depth to the Caledonian basal décollement under the exposed Lower Allochthon. This is consistent with the geophysical data of Palm *et al.* (1991) at the eastern side of the Seve Nappes in the Åre Synform (2.4 km depth to décollement; Fig. 3). Thus the preferred restoration for Transect 3 combines the allochthonous Window-Basement status of Model II with the Model I palaeogeography espoused by Gee (1975), in which the Window-Basement lies at the western margin of a shelf overlain by S7 and younger sediments. This is shown as Model III in Figure 2c.

The difference between Model III and that proposed by Gee (1975, 1980) partly lies in the restoration of the Lower Allochthon. Gee (1975, 1980), like Gayer & Roberts (1973) in

Transect 1, made no attempt to restore the deformation within the external imbricate zone; such methods were not available (cf Elliot & Johnston, 1980; McClay & Price, 1981). Restoration of the shortening within the Lower Allochthon (Gaissa Thrust Belt) in Transect 1, presented at the Uppsala Caledonide Congress in 1981 (Chapman *et al.,* 1985), led, from the ensuing stratigraphic overlap, to the realisation that the Window-Basement must be far-travelled. The alternative, that the Lower Allochthon was derived from the hinterland of the Window-Basement was not considered. The lack of stratigraphic overlap between the Lower Allochthon and Window-Basement cover successions in central Scandinavia (Gee 1975, Gee *et al.* 1985b) allowed the par-autochthonous Model I to be retained.

6.d. Imbrication of the Lower Allochthon

The differences between Models II and III have consequence for the deformation history. In Model III (Fig. 2c), imbrication of the Ediacaran and younger sediments (S6-S8) deposited unconformably on the Window-Basement must have occurred prior to imbrication of the underlying Window-Basement (unless out-of-sequence thrusting is invoked). Thus the base of the Lower Allochthon *overlies* the Window Allochthon. If the displacement due to this early imbrication is minor, the sediments may still partially overlie the Window-Basement, as with the lower imbricate of the Grong-Olden Window-Basement on Transect 3. In Model II (Fig. 2b), imbrication of the Window-Basement occurred prior to thrusting within the Tonian-Cryogenian sediments (S1a, S1b, S2) in the Lower Allochthon. Thus the base of the Lower Allochthon *underlies* the Window-Basement. In both cases, the Window-Basement can be considered as a separate unit to the Lower Allochthon, either under- or overlying it.

In areas where both Tonian-Cryogenian and Ediacaran-Ordovician sediments occur both above and to the foreland of the Window-Basement, on the same transect through the orogen, the deformation sequence is likely to have been complex. By definition, the basal thrust of the

Lower Allochthon would underlie the Window-Basement, whilst the roof thrust would lie above it, making the Window-Basement a part of the Lower Allochthon. It is not clear if such an area is preserved within the Scandinavian Caledonides; in areas where Tonian-Cryogenian sediments are preserved in the Lower Allochthon, the sediments younger than those lying unconformable on the Window-Basement were imbricated in the footwall of the Middle Allochthon prior to deformation in either the Window-Basement or the Lower Allochthon. The difference in deformation history could be ascribed to the differing requirements needed to keep a stable critical taper.

If the sediments deposited on the Window-Basement are thrust transported beyond the leading edge of the Window-Basement, then no structural evidence of where they were deposited remains. In Transect 3, Model IIA (Fig. 10 sections 3.5-3.6) the minimum structural constraint was used to avoid back-thrusting and this is consistent with the metamorphic data. This indicates that sections with Tonian-Cryogenian sediments in the Lower Allochthon are likely to be much more useful in evaluating the Caledonian structural history/restoration of the Window-Basement.

6.e Basement architecture and the basal décollement

Two Window-Basement geometries are shown in Transects 2 and 3 (Figs. 9 & 10), although, in all cases, the depth to the Autochthonous basement increases towards the hinterland, with a maximum modelled depth of 14.8 km (within the constraints of the semi-schematic models). In Transect 3, Model 1A (Fig. 10 sections 3.1, 3.2) the lower imbricate of the Window-Basement is shown as a thick slice continuing to the west, with the upper imbricate derived from above this, whilst in the other models (Fig. 10 sections 3.3-3.8), the lower imbricate thins-out immediately west of the restored position of the Window-Basement seen in outcrops and the upper imbricate is restored to directly above the Autochthon. Restorations of Transect 2 follow the latter model (although there is no upper imbricate; Fig. 9 sections 2.1, 2.2).

In part, these differences result from the different internal structures inferred for the lower imbricate of the Grong-Olden Window-Basement. Where this has been left as a single slice of basement (Fig. 10 sections 3.1, 3.2), thickening (compared to the initial inferred thickness) of the lower Window-Basement imbricate to the west continues to underneath the Tømmerås Window-Basement; where it has been divided into thinner slices, as in the Bångonåive Window-Basement (Greiling *et al.,* 1993; Fig. 10 sections 3.3-3.8), it does not thicken as much. However, for Model IA on Transect 3, the lower imbricate of the Window-Basement *could* have been drawn to thin down to the level of the basal décollement immediately west of the restored position of the exposed lower imbricate of Tømmerås Window-Basement (at km 286 in Fig. 10 sections 3.1, 3.2), with the upper imbricate taken as a slice from the Autochthon (as in the other models). Equally, for Models IB, IIA and IIB the restored lower imbricate of the Tømmerås Window-Basement (and the Borgefjell Window-Basement on Transect 2) *could* have been drawn as a thick, buried unit continuing further west than the shown trailing edge. It is in this sense that no definitive reconstruction is shown here, just a range of options.

If the Window-Basement in Transect 3 is continued westward as a thick slice, this could be taken as a continuation of the Window-Basement exposed along the Norwegian coast (Vestranden; Figs. 1 & 6), forming the northern part of the Western Gneiss Region; this is seen in the northwest part of the Grong-Olden Window (Roberts, 1989, 1997). The 14.8 km depth to the basal décollement in Model IA (Fig. 8 section 3.1, 3.2) is comparable to that seismically imaged in the Trøndelag area; much of this thickness is filled by a basement antiformal stack (Hurich *et al.,* 1989). The modelled 11.5 km thickness of the basement slice is also of the same order of magnitude as the estimated thickness of the Western Gneiss Region Window-Basement (~14 km; Mykkeltveit *et al.,* 1980).

However, space is required to the hinterland side of the Window Basement for the deposition of the alluvial-fans of the Offerdal conglomerates (S1a, S1b, 1.5 km; Plink-Björklund *et al.,* 2005) and the > 6 km thick Tossåsfjället Group (S1b – S6; Kumpulainen, 1980). Thus the sedimentary basin must have deepened somewhere west of the cover sediments on the upper imbricate of the Tømmerås Window Basement. In a profile across the Western Gneiss Region, Rice (2005) restored the Valdres Nappe (with the Bygdin and Ormtjernskampen S1a conglomerates; Nickelsen, 1974; Hossack, 1978) to northwest of the Western Gneiss Region Window-Basement.

6.f. Detachment - footwall uplift model

Osmundsen *et al.* (2003, 2005) proposed that the Børgefjell, Nasafjäll and Rombak Window Basement areas are wholly autochthonous and formed by footwall-uplift (presumably isostatically controlled) as a result of low- and high-angled normal faulting. Such normal faults trending parallel to the Norwegian coastline occur close to the western margins of these tectonic windows. (**Fig. 6**; Nesna Shear Zone; Gaukarelv Shear Zone; Osmundsen *et al.,* 2003, 2005)).

Taking a simplistic approach, the initial constraints used in the balanced cross-sections along Transect 2 indicates that the topographic difference between an isostatically uplifted crest of the Børgefjell Window-Basement and the undisturbed basal décollement dipping at 2° to the WNW from the Caledonian front (Palm *et al.,* 1991) is ~4.7 km. As a horizontal topography projecting from the eroded Caledonian thrust-front was used to derive this thickness, this is a *minimum* value. Isostatic uplift of the Caledonian basal décollement necessitates an equivalent uplift of the crust-mantle boundary. Balancing the added ~4.7 km of mantle with loss of overlying continental rocks suggests that 5.5 km of the Caledonian nappe pile must have been removed, either tectonically or by erosion (using mantle and crust densities of 3300 and 2800 kg/m^{-3}).

Seismic studies show that where major high-angled Mesozoic faults have developed within the Norwegian continental shelf (Lofoten area), the Moho has been uplifted under relatively small-scale blocks, reflecting isostatic re-adjustment (Faleide *et al.,* 2008).

Although there is relatively little on-shore seismic data available, Kinck *et al.* (1993) showed that the depth to Moho under the Scandinavian Caledonides increases rapidly from ~30 km along the Norwegian coast to ~ 40-45 km under the Caledonian front. More recent studies (Ottermöller & Midzi 2003; Ebbing, 2007; Kolstrup *et al.,* 2012) have largely confirmed these findings. In detail, the 40 km Moho depth line passes directly through the Børgefjell, Nasafjäll and Rombak Window-Basement, with the 45 km depth contour close to the eastern margin of the Børgefjell and Nasafjäll Window-Basement.

Although Osmundsen *et al.* (2005) indicated that the Komagfjord Window Basement was not formed as a gneiss-cored dome, the northwest margin of the Window Basement is cut by the > 200 km long Vargsund Fault, for which a Mesozoic component of movement has been proposed (Fig. 5; Lippard & Roberts, 1987; Roberts & Lippard, 2005). Gayer *et al.* (1987) estimated a throw of ~600 m for the Vargsund Fault at the west margin of the Komagfjord Window-Basement. In contrast, no normal faults occur at the northwest margins of the inferred Hatteras and Revsbotn Basement Horses, in the same area as the Komagfjord

Window-Basement, and these remain buried under the Middle Allochthon (Figs. 5; Gayer *et al.,* 1987).

The field evidence (structural and metamorphic) outlined above indicate that the Window-Basement *is* allochthonous. Seismic data in the central part of the Scandinavian Caledonides has also shown this, and that the underlying basal décollement is essentially planar (Fig. 3; Palm *et al.*, 1991, Juhlin *et al.*, 2016). Equally, that post-Caledonian extensional faults have modified a pre-existing Window-Basement topography is most probable; basement imbrication almost certainly also occurred in the areas *between* the observed Window-Basement, but is not exposed. Thus a combination of processes seems more likely, with initially thrust-developed basement culminations controlling the positioning of late-to post-Caledonian extensional shear-zones that modified and enhanced the doming. In particular, the foliation in the nappes adjacent to the steeply dipping roof-thrusts of the west side of the Window-Basement may have acted as easy-slip horizons, compared to cutting through the Window-Basement. Since the thickness of the Børgefjell Window-Basement used here was derived from a horizontal projection from the eroded Caledonian thrust front, at ~0.3 km a.s.l and the Børgefjell Window-Basement has an altitude of ~1,5 km, at least 1.2 km of footwall uplift during late- to post-Caledonian extension can be accommodated by the model presented here.

6.g. Combined palaeogeography

Fig. 12 shows the allochthonous Window-Basement restoration for the four Transects superimposed on the geology of the present-day Scandinavian Caledonides, using Models II and III. For Transects 1 and 4, the complete branch-line restorations for the Lower Allochthon and Window-Basement have been shown, whilst, for Transects 2 and 3, only the restored positions of the Window-Basement are shown. Between Transects 1 and 2, the Rombak, Bångonåive and lower imbricate of the Nasafjäll Window-Basement (Andersen, 1989; Bax 1989; Thelander, 1980; Greiling *et al.,* 1993) have been restored by the same amount as the Børgefjell Window-Basement (essentially pinned together). The upper imbricate of the Nasafjäll Window-Basement (Thelander *et al.,* 1980) and the Høgtuva Window-Basement (Lindqvist, 1990) have been pinned and restored by the minimum amount to remove the basement-cover overlap in the Nasafjäll Window-Basement.

FIG 12 NEAR HERE

For Transects 1-3, where the thrusting directions within the orogen are parallel, with an early SE-directed shortening followed by E- to ESE-directed shortening (Soper *et al.,* 1992) this restoration gives an eastern margin to the Window-Basement that lies close to the Norwegian coastline (Fig. 12).

Similarly in the south, the leading edge of the External Window-Basement delineates a boundary between the Lower Allochthon and Window-Basement that lies ca. 100 km offshore (Fig. 12). Joining these lines, however, presents major problems, not only because the restored Window-Basement of Transects 3 and 4 overlap, but also because there is no space in the restoration for either the Mullfjället or Sylarna Window-Basement, as well as several smaller Window-Basement units, nor for the Vemdalen Nappe (Lower Allochthon) between Transects 3 and 4 (Fig. 1). In their restored positions, the Tømmerås and Spekedalen Window-Basement are essentially adjacent whilst in the deformed position they lie close to 180 km apart.

The failure of the restored segments of Transects 3 and 4 to link together poses a major problem in understanding the pre-orogenic palaeogeography of Baltica. This is due to the SE and SSE-directed transport directions recorded within the Lower Allochthon on Transect 4 (Morley, 1986) compared to the E- to ESE-directed shortening in the Lower Allochthon elsewhere (e.g. Townsend, 1987; Gayer & Greiling, 1989). The nature of the boundary between the E- to ESE-directed and SE- and SSE-directed shortening areas of the Lower Allochthon is currently unknown.

7. Conclusions

1. Four Transects across the Scandinavian Caledonides (Finnmark-Troms, Västerbotten-Nordland, Jämtland-Trøndelag, Telemark-Møre og Romsdal) have been restored using a combination of balanced cross-sections and branch-line maps.

2. Each Transect is different in detail. Transect 1 has a Lower Allochthon basal décollement in late Ediacaran-early Cambrian sediments (S6), whilst in Transects 2-4, the mid-Cambrian-early Ordovician 'Alum Shales' (S7) is an easy-slip horizon. Transects 1, 2 and 4 have Tonian-Cryogenian basins in the Lower Allochthon, whilst Transect 3 has only Ediacaran and younger sediments. Transects 3 and 4 underwent (ultra)-high pressure metamorphism along the internal margin of the Window-Basement. Thus there is no Transect or area that can be taken geologically as 'typical' of the external part of the Scandinavian Caledonides.

3. On Transects 1 and 4, Model I results in the Lower Allochthon being divided into two parts, separated by up to 280 km; neither sedimentological nor structural data has been found for such divisions.

4. Thrusting in Model II show a gradual swing from SE-directed in the hinterland to E- to ESE-directed in the foreland on Transects 1-3 and from SE-directed to SSE-directed on Transect 4. In Model I, thrusting directions show complex changes when the Window-Basement is accreted into the orogen.

5. The lack of Tonian-Cryogenian sediments on Transect 3, reflecting a different early to middle Neoproterozoic basin geometry along the Baltoscandian continental margin, makes this profile less reliable for establishing the relationships between the Lower Allochthon and the Window-Basement. For this Transect, Model III is proposed; allochthonous Window-Basement with no pre-Ediacaran basin in the Lower Allochthon.

5. Despite the along-strike variability in geology, the four Transects all suggest that Model II (or III) is more likely correct and can be applied along the whole orogen. There remain, however, considerable unsolved problems in linking the restorations of Transects 3 and 4.

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Figure captions

Fig. 1. Distribution of the main tectonic units within the Scandinavian Caledonides (modified from Gee *et al.,* 1985a). Areas covered by Figs. 5, 6 and 7 are shown. Window-Basement (from north to south): U-Kunes, K-Komagfjord, AK-Alta-Kvænangen, R-Rombak, N-Nasafjäll, H-Høgtuva, Ba-Bångonåive, B-Børgefjell, V-Vestranden, GO-Grong-Olden, T-Tømmerås, M-Mullfjället, S-Sylarna, P-Spekedalen. J-Atnsjøen, BV-Beito, Vang, L-Aurdal-Lærdal, W-Western Gneiss Region.

Fig. 2. Schematic representation of the models used to restore the Window-Basement and external part of the Scandinavian Caledonides. (a) Paratochthonous, one-basin model (Gee, 1975); (b) Allochthonous two-basin model (Gayer & Roberts, 1973); (c) Combined model with allochthonous Window-Basement and one basin. See Discussion for details.

Fig. 3. Upper 10 km of the seismic interpretation of the structure of the central part of the Scandinavian Caledonides (from Palm *et al.*, 1991). Note the smoothed ramp-flat appearance of the basal décollement. See Fig. 6 for the profile line.

Fig. 4. Semi-schematic restored profile through the eastern part of the central Scandinavian Caledonides from Gee *et al.* (1985b) showing the relative restored positions of the Tømmerås and Mullfjället Window-Basement and the Lower and Middle Allochthons.

Fig. 5. Geological map of the Finnmark Caledonides (Transect 1; Fig. 1). TKF - Trollfjorden-Komagelva Fault; EFPA - East Finnmark Parautochthon; HTS - Hanadalen Thrust Sheet; eRTS – east part of Ruoksadas Thrust Sheet; wRTS - west part of Ruoksadas Thrust Sheet;

eMIZ/LD – eastern part of Munkavarri Imbricate Zone and Lakkaskaidi Duplex; wMIZ - western part of Munkavarri Imbricate Zone; BAS - Betusordda Antiformal Stack; BD - Børselv Duplex; Kf, At, AK - Komagfjord, Altenes and Alta-Kvænangen tectonic windows; H, R - branch-lines around Hatteras and Revsbotn Basement Horses; K - branch-line around the Komagfjord Antiformal Stack. An - Andabakoaivi; Kv - Kvænangen; L - Lakselv. VF - Vargsund Fault. Arrows indicate thrusting direction. Modified from Rice (2014).

Fig. 6. Geological map of the central Scandinavian Caledonides (Transects 2 & 3; Fig. 1). Modified from Gee *et al.* (1985a).

Fig. 7. Geological map of the southern Scandinavian Caledonides (Transect 4; Fig. 1). Modified from Gee *et al.* (1985a).

Fig. 8. Branch-line restorations based on Models I and II for Transect 1 in the north Norwegian Caledonides (Fig. 5; see text for details).

Fig. 9. Balanced cross-sections showing restorations based on Models I and II for Transect 2 in the central Scandinavian Caledonides (Fig. 6; see text for details).

Fig. 10. Balanced cross-sections showing restorations based on Models I and II for Transect 3 in the central Scandinavian Caledonides (Fig. 6; see text for details).

Fig. 11. Branch-line restorations based on Models I and II for Transect 4 in the south Norwegian Caledo**b**or details). External Window-Basement units: A-L - Aurdal-Lærdal, A - Atnsjøen, B - Beito, Bo - Borlaug, H - Haugesund, K- Kikedalen. M - Mykkeltveit *et al.* (1980) seismic line.

Fig. 12. Summary of restorations of the Window-Basement (in red and blue) superimposed on a simplified geology of the Scandinavian Caledonides (from Gee *et al.,* 1985a). The lower imbricate of the Nasafjäll and Rombak Window-Basement units were pinned to the Børgefjell Window-Basement for restoration. The Høgtuva and upper imbricate of the Nasafjäll Window-Basement was restored until no basement-cover overlap occurred with the lower imbricate. The green restoration shows where the Vestranden, Tømmerås and Grong-Olden Window-Basement units should lie with respect to the Western Gneiss Region Window-Basement, based on their present-day relative positions.

TABLE 1. Simplified lithostratigraphy of the Iapteus Baltoscandian continental margin

Succ-ession	Age	Lithologies
S8	Post-early Ordovician-Devonian	carbonate and clastic
S7	Middle Cambrian-early Ordovician	(anoxic) black shale + carbonates
S6	Ediacaran-early Cambrian	fluvial to marine clastics & carbonates
S5	Ediacaran (ca. 580 Ma)	Gaskiers glacial deposits
S4	Ediacaran	fluvial to marine clastics
S3	Late Cryogenian (ca. 640 Ma)	Marinoan glacial deposits
S2	Cryogenian	marine dolomites & fine clastics
S1b	Tonian-Cryogenian	fluvial to marine clastics
S1a	Tonian-Cryogenian	coarse conglomerates

TABLE 2. Succession 1a conglomerates in the base of the Middle Allochthon

Tran-sect	Structural unit	Stratgraphic unit	Thick-ness (km)	Reference
1	Laksefjord Nappe Complex	Ifjord Fm	3.0	Føyn *et al.,* 1983
2	Stalon Nappe Complex	Risbäck Gp*	0.25	Greiling 1989
3	Offerdal Nappe	Offerdal Congl	>0.3	Plink-Björklund *et al.*, 2005
4	Valdres Nappe	Ormtjernskampen Congl	0.8	Nickelsen 1974
4	Valdres Nappe	Bygdin Congl	2.4	Hossack 1978

*These may partly be younger than S1a (Greiling pers. comm. 2016).

TABLE 3. Variation in peak metamorphic grade across the Transects

Transect	Tectonic Units						
	MA upper	**MA lower**	**WB upper/ internal**	**WB lower/ external**	**LA internal**	**LA external**	**PA/A**
1	x	Ep	+	Ep	Ep-D	LAn/D	D
2	LAm-UG	LAm-UG	x	MG-Ep	Ep-An	+	LAn-D
3	LAm-UG	LAm-UG	UAm-MAm	MG	Ep-D	+	D
4	x	MG	Ec	(M-L?)G	MG-LG/Ep	D	D

x - data not available; + - unit not preserved (eroded away) or not developed. L, M, U – lower, middle, upper; Ec, Am, G, Ep, An, D – Eclogite, Amphibolite, Greenschist, Epizone, Anchizone, Diagenetic zone facies alteration. See text for data sources.

TABLE 4. Variations in thickness (km) of the stratigraphic units (cf. Table 1; S not written) across the Transects.

Tran-sect		**|-------------------------------**			**Tectonic Units**			**--------------------------------|**	
		MA upper	**MA lower**	**WB upper/ intern.**	**WB lower/ extern.**	**LA intern.**	**LA extern.**	**A west**	**A east**
1	succes.	-	1a, 1b-?	-	1a /5, 6	1b-2	1b-8	5-6	1b
	thick.	-	7.1	-	0.19/0.20	>2.0	5.0	<0.26	0.60
2	succes.	1b, 2, 5, 6	1a, 1b, ?5	S5, S6	S5, S6	1a-2, 5-7	-	6-7	-
	thick.	4.5-6	1.25	0.02	0.02	1.12	-	0.02	-
3	succes.	1b, 2, 5, 6	1a/1b	6-8	6-8	6-8	-	7	-
	thick.	4.5-6	>0.3/1.2	<0.07	<0.07	1.12	-	<0.04	-
4	success.	-	1a, 1b, 5-7	?5-7	5-8	1a-2, 5-6	7-8	7-8	7-8
	thick.	-	4.3	<0.3	0.15	3.4	0.8	0.4	<2.2

succes. = Successions; thick. = thickness. See text for data sources.

TABLE 5. Variation in thrust transport directions across the Transects.

Transect	Tectonic Units						
	MA upper	**MA lower**	**WB upper/ internal**	**WB lower/ external**	**LA west**	**LA east**	**A**
1	*SE*	SE+ESE/E	-	SE	ESE/E	ESE/E	-
2	SE	SE	ESE	ESE	ESE/E	-	-
3	SE	SE	SE	SE	ESE/E*	-	-
4	SE	SE	SE	SE	SE	SSE	-

*Data for the Lower Allochthon on Transect 3 is taken from Transect 2.

TABLE 6. Summary of restored Transects (all lengths & depths in km)

Tran-sect	Model (Fig. 2)	Section Length		Shortening (%)		Displacement Window-Basement		Max. Depth Basal Décoll.
		Rest-ored	Defor-med	Overall Section Length	Lower Alloch-thon	Trailing edge	Leading edge	
1	IA	491	343	30	51	99	96	-
1	IB	624	343	45	61	99	96	-
1	IIA	501	343	32	39	158	155	-
2	I	306	262	14	42	27	27	5.1
2	IIA	354	262	26	32	85	85	6.4
2	IIB	416	262	37	32	147	147	6.4
3	IA	372	286	23	43	86	18	14.8
3	IB	397	286	28	46	106	23	11.4
3	IIA/III	448	289	35	40	159	75	9.8
3	IIB/III	530	286	46	40	244	157	82
4	I	517	980	47	66	70	70	-
4	II	520	830	37	50	314	314	-

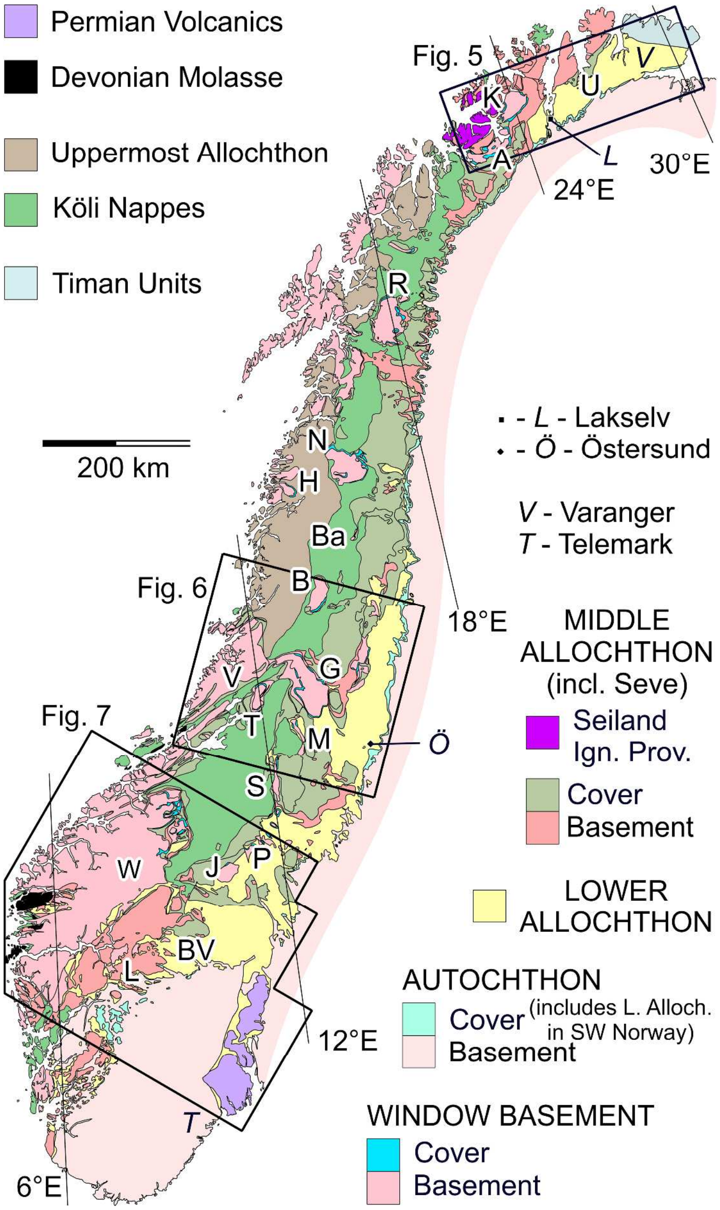

Fig. 1. Distribution of the main tectonic units within the Scandinavian Caledonides (modified from Gee et al., 1985a). Areas covered by Figs. 5, 6 and 7 are shown. Window-Basement (from north to south): U-Kunes, K-Komagfjord, AK-Alta-Kvænangen, R-Rombak, N-Nasafjäll, H-Høgtuva, Ba-Bångonåive, B-Børgefjell, V-Vestranden, GO-Grong-Olden, T-Tømmerås, M-Mullfjället, S-Sylarna, P-Spekedalen. J-Atnsjøen, BV-Beito, Vang, L-Aurdal-Lærdal, W-Western Gneiss Region.
134x226mm (600 x 600 DPI)

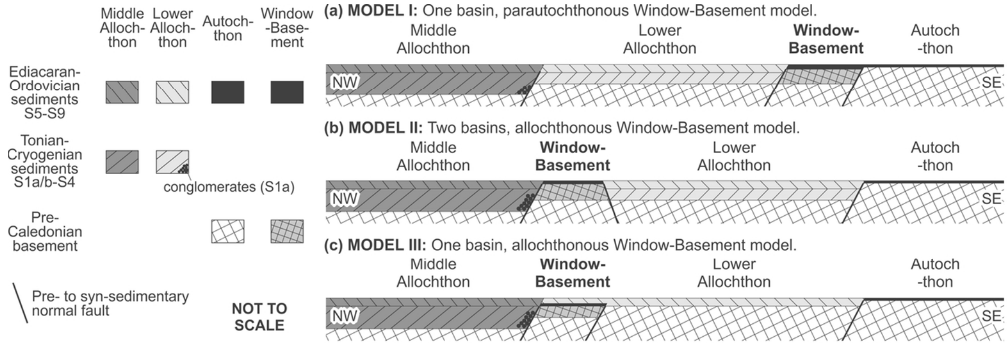

Fig. 2. Schematic representation of the models used to restore the Window-Basement and external part of the Scandinavian Caledonides. (a) Paratochthonous, one-basin model (Gee, 1975); (b) Allochthonous two-basin model (Gayer & Roberts, 1973); (c) Combined model with allochthonous Window-Basement and one basin. See Discussion for details.

56x19mm (600 x 600 DPI)

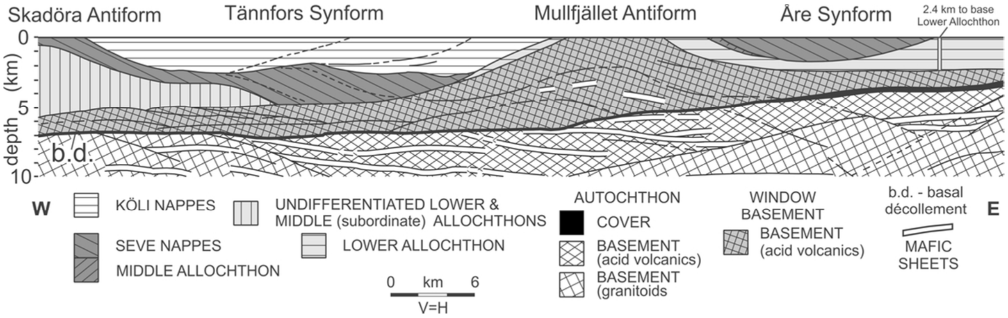

Fig. 3. Upper 10 km of the seismic interpretation of the structure of the central part of the Scandinavian Caledonides (from Palm et al., 1991). Note the smoothed ramp-flat appearance of the basal décollement. See Fig. 6 for the profile line.
50x15mm (600 x 600 DPI)

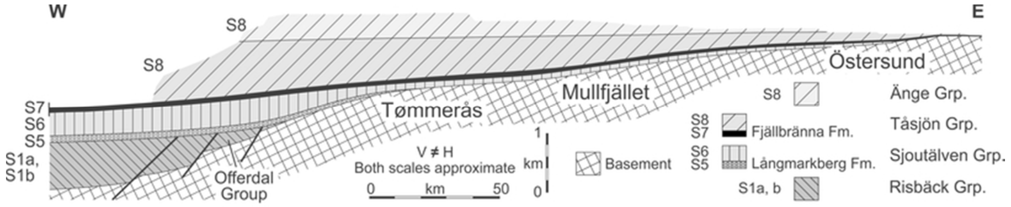

Fig. 4. Semi-schematic restored profile through the eastern part of the central Scandinavian Caledonides from Gee et al. (1985b) showing the relative restored positions of the Tømmerås and Mullfjället Window-Basement and the Lower and Middle Allochthons.
34x7mm (600 x 600 DPI)

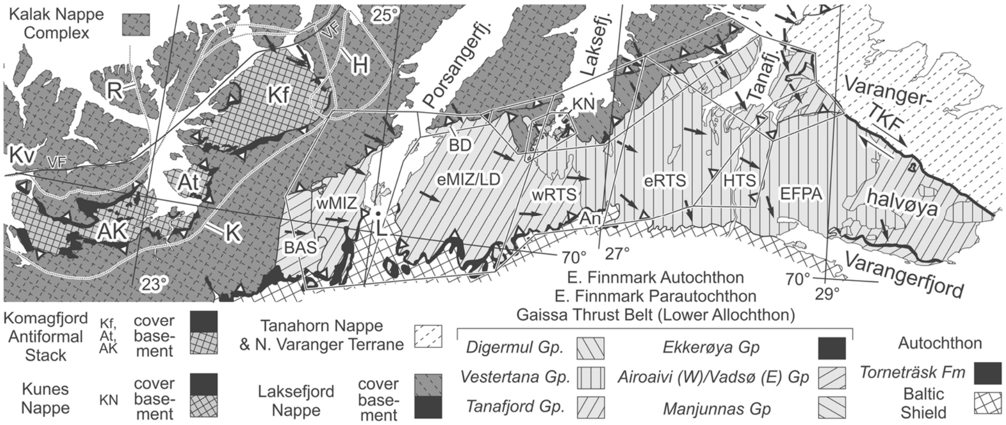

Fig. 5. Geological map of the Finnmark Caledonides (Transect 1; Fig. 1). TKF - Trollfjorden-Komagelva Fault; EFPA - East Finnmark Parautochthon; HTS - Hanadalen Thrust Sheet; eRTS – east part of Ruoksadas Thrust Sheet; wRTS - west part of Ruoksadas Thrust Sheet; eMIZ/LD – eastern part of Munkavarri Imbricate Zone and Lakkaskaidi Duplex; wMIZ - western part of Munkavarri Imbricate Zone; BAS - Betusordda Antiformal Stack; BD - Børselv Duplex; Kf, At, AK - Komagfjord, Altenes and Alta-Kvænangen tectonic windows; H, R - branch-lines around Hatteras and Revsbotn Basement Horses; K - branch-line around the Komagfjord Antiformal Stack. An - Andabakoaivi; Kv - Kvænangen; L - Lakselv. VF - Vargsund Fault. Arrows indicate thrusting direction. Modified from Rice (2014).
71x30mm (600 x 600 DPI)

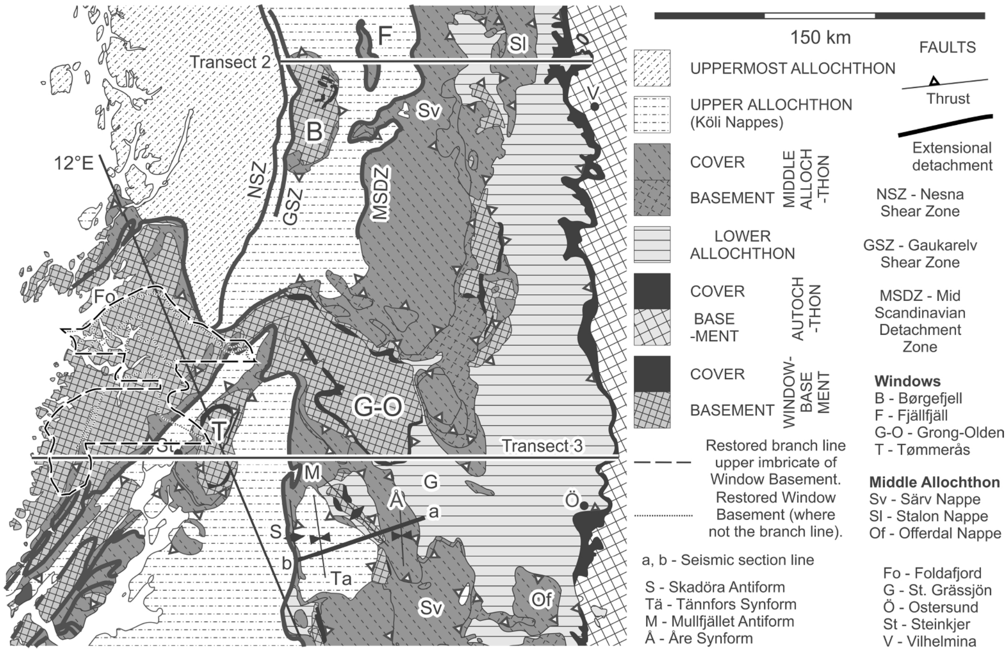

Fig. 6. Geological map of the central Scandinavian Caledonides (Transects 2 & 3; Fig. 1). Modified from Gee et al. (1985a).
104x67mm (600 x 600 DPI)

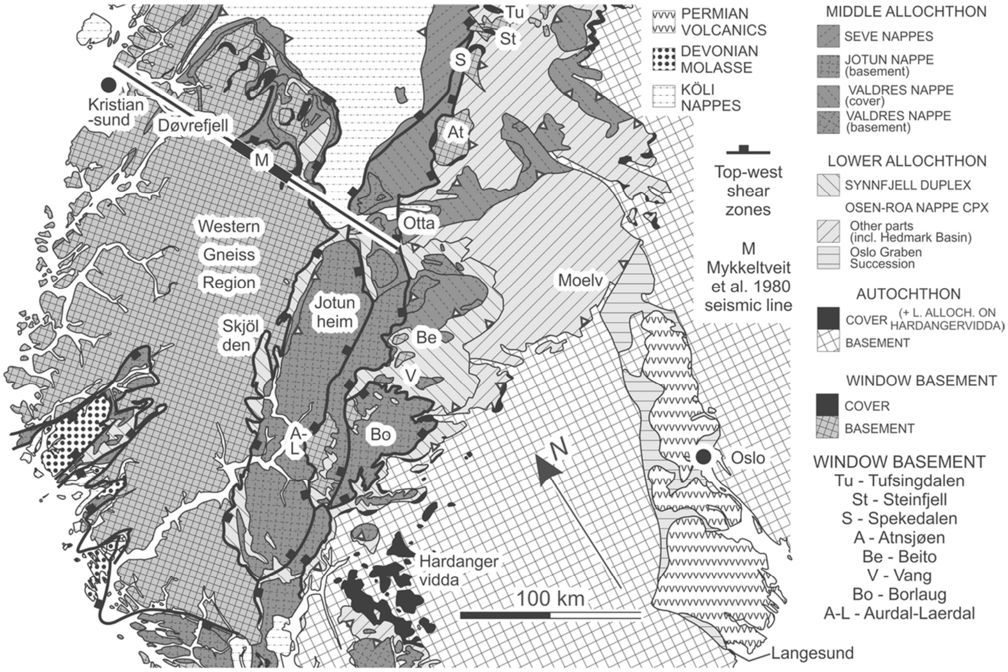

Fig. 7. Geological map of the southern Scandinavian Caledonides (Transect 4; Fig. 1). Modified from Gee et al. (1985a).
111x75mm (300 x 300 DPI)

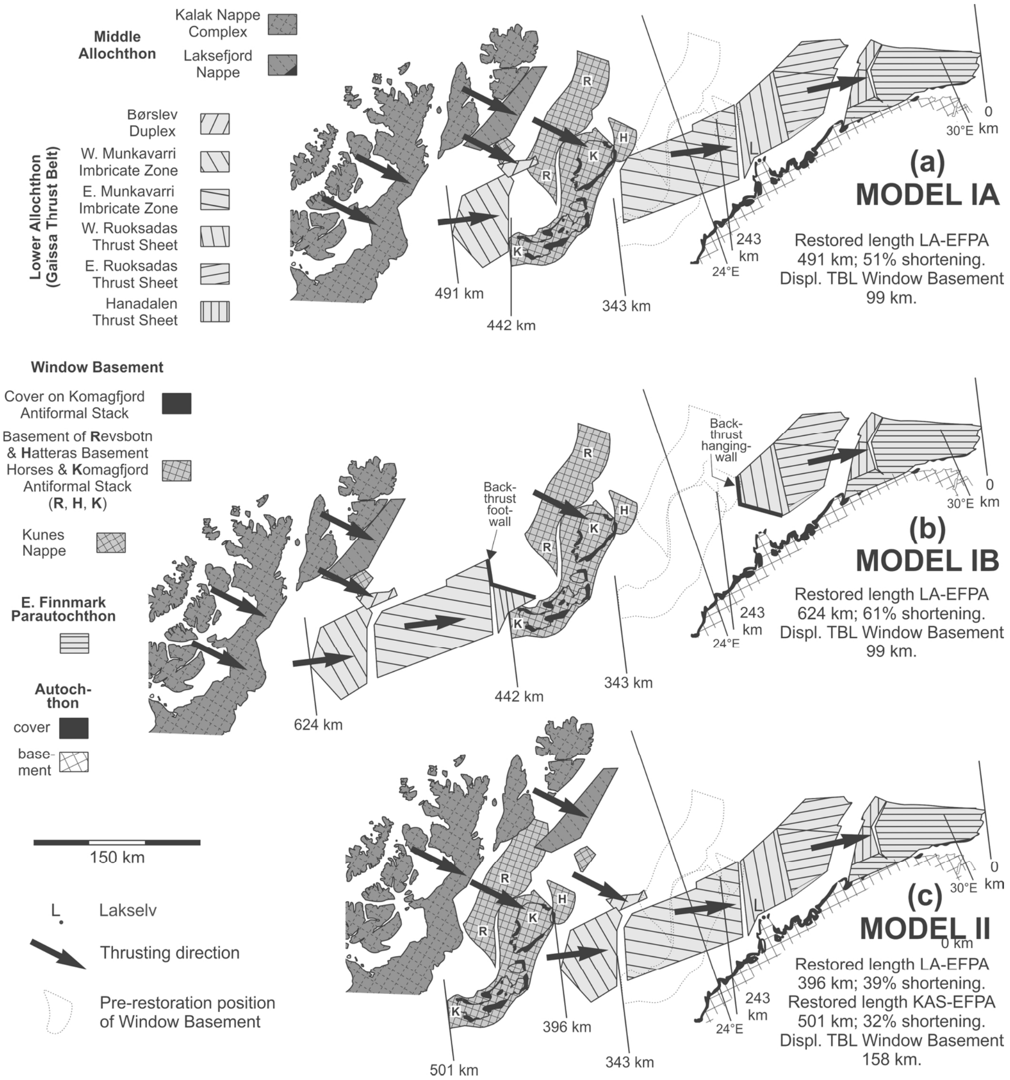

Fig. 8. Branch-line restorations based on Models I and II for Transect 1 in the north Norwegian Caledonides (Fig. 5; see text for details).
177x190mm (300 x 300 DPI)

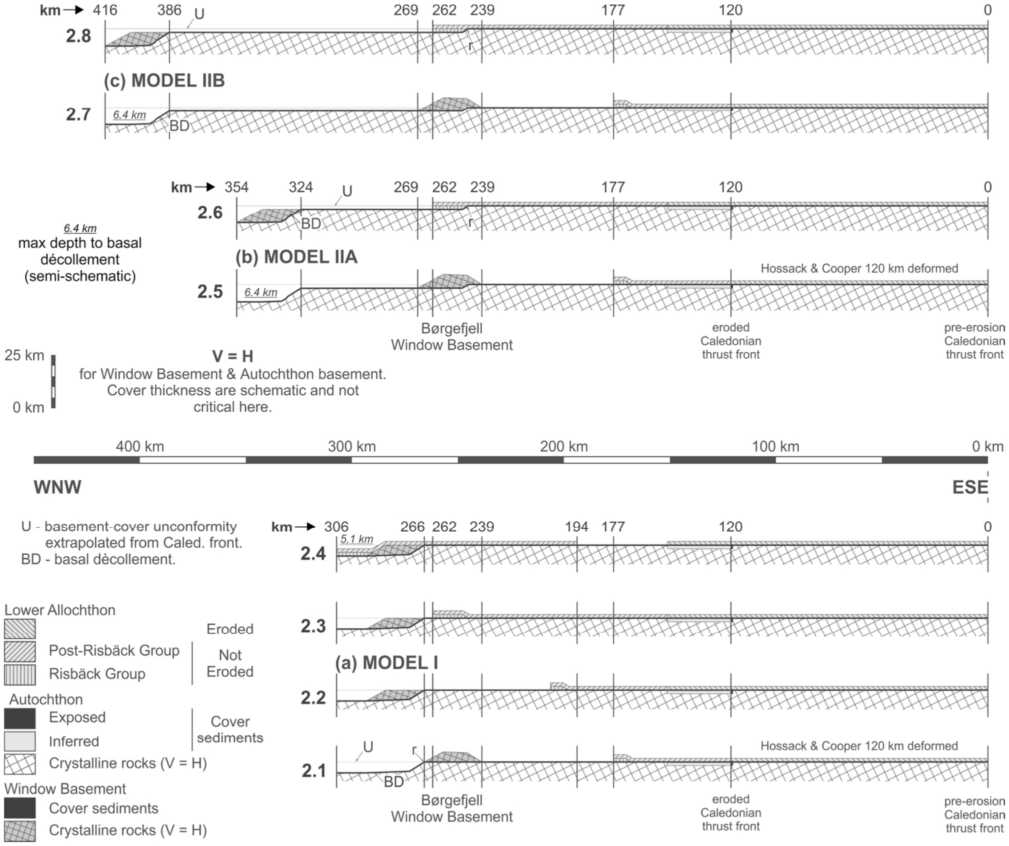

Fig. 9. Balanced cross-sections showing restorations based on Models I and II for Transect 2 in the central Scandinavian Caledonides (Fig. 6; see text for details).
161x135mm (300 x 300 DPI)

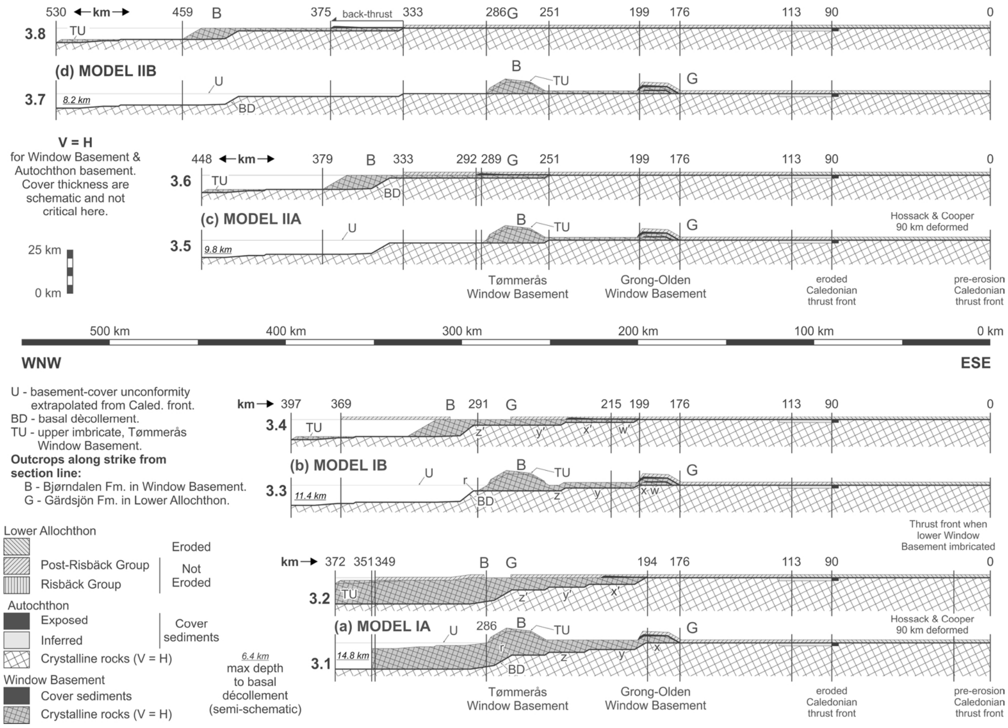

Fig. 10. Balanced cross-sections showing restorations based on Models I and II for Transect 3 in the central Scandinavian Caledonides (Fig. 6; see text for details).
166x119mm (300 x 300 DPI)

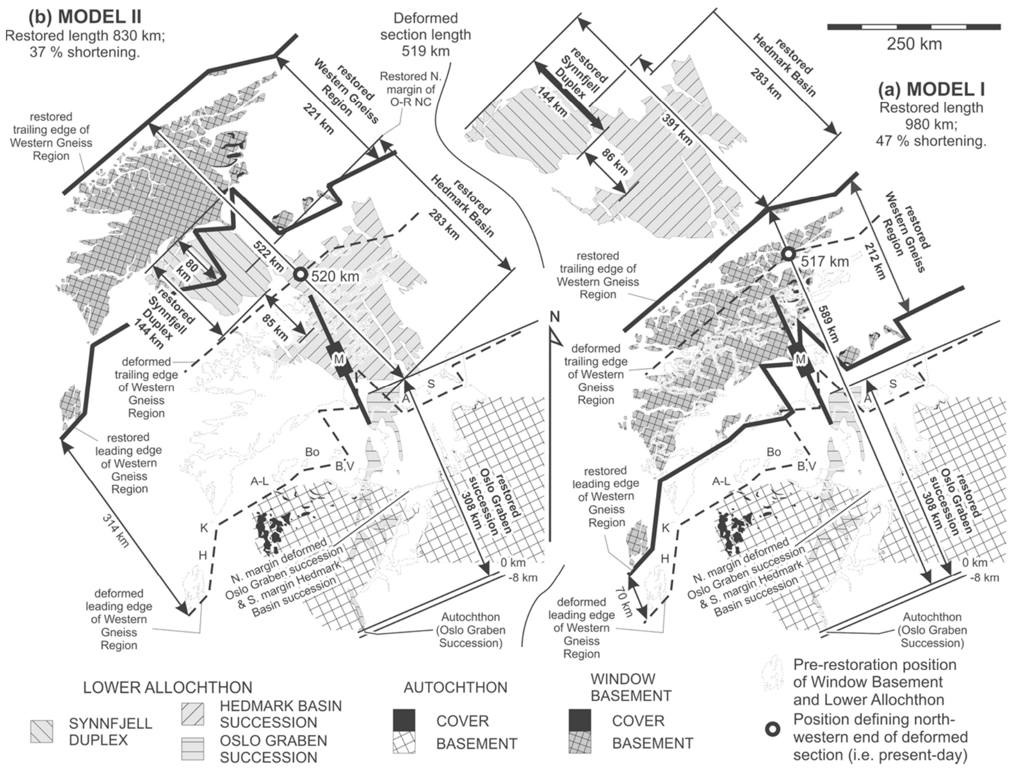

Fig. 11. Branch-line restorations based on Models I and II for Transect 4 in the south Norwegian Caledobor details). External Window-Basement units: A-L - Aurdal-Lærdal, A - Atnsjøen, B - Beito, Bo - Borlaug, H - Haugesund, K- Kikedalen. M - Mykkeltveit et al. (1980) seismic line.
126x95mm (300 x 300 DPI)

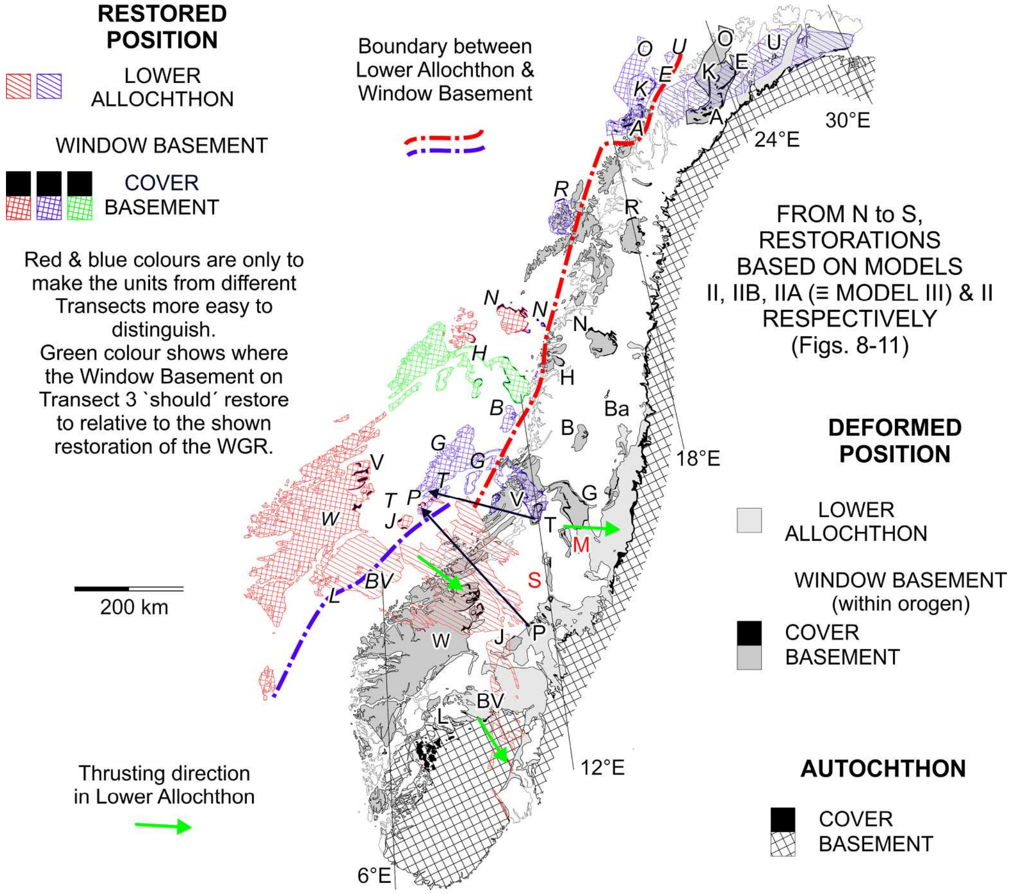

Fig. 12. Summary of restorations of the Window-Basement (in red and blue) superimposed on a simplified geology of the Scandinavian Caledonides (from Gee et al., 1985a). The lower imbricate of the Nasafjäll and Rombak Window-Basement units were pinned to the Børgefjell Window-Basement for restoration. The Høgtuva and upper imbricate of the Nasafjäll Window-Basement was restored until no basement-cover overlap occurred with the lower imbricate. The green restoration shows where the Vestranden, Tømmerås and Grong-Olden Window-Basement units should lie with respect to the Western Gneiss Region Window-Basement, based on their present-day relative positions.
109x97mm (600 x 600 DPI)