Chapter 58

Evidence of late Neoproterozoic glaciation in the Caledonides of NW Scandinavia

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Abstract: The northwestern part of the Scandinavian Caledonides, formed by SE- to ESE-directed thrusting through the Neoproterozoic W. Baltica continental shelf, contains numerous small and often isolated outcrops of diamictite and associated strata. No precise biostratigraphic or isotopic data are available to constrain the age of these sediments, but, on the basis of their stratigraphic position, most are correlated with the Mortensnes Formation (Fm.) in E. Finnmark and also presumed to be of glaciogenic origin. The Mortensnes Fm. has been correlated with the 580 Ma Gaskiers glacial event on the basis of $\delta^{13}C$ isotope studies. Structurally, the deposits occur in the Autochthon (below the Torneträsk Fm.), within an external imbricate zone (Lower Allochthon), within cover successions lying unconformably on allochthonous basement (Window Allochthon) palaeogeographically derived from below or outboard of the Lower Allochthon and, more rarely, within the Middle Allochthon, derived from outboard of the Window Allochthon. Evidence for a glaciogenic origin is typically poor or lacking. Only in the Komagfjord Antiformal Stack (Window Allochthon), where an up to 40-m-thick succession of three fining upwards cycles has been mapped, are the deposits comparable in thickness and complexity to the Mortensnes Fm. Other sequences are sometimes <1 m thick and unconformably overlain by post-'glacial' deposits. The Vakkejokk Breccia, a submarine slump in the Torneträsk area of the Autochthon closely underlies the correlative Precambrian–Cambrian lithostratigraphic boundary in E. Finnmark but overlies the first appearance of the boundary marker fossil *Treptichnus pedum*. Although sometimes interpreted as periglacial, this seems unlikely in view of the 30–50° palaeolatitude during deposition. Calcite nodules (<1 cm size) in the Vakkejokk Breccia have previously been interpreted as glendonite, but the microstructure and palaeolatitude makes this unlikely; they are likely a replacement of gypsum. Diamictites of uncertain origin have also been found in the Ediacaran Lower Siltstone Member of the Torneträsk Fm. and unconformably under the ?Lower Cambrian Lomvatn Fm. in the Komagfjord Antiformal Stack.

This chapter primarily covers (meta-)sediments correlated with the Mortensnes Fm., the younger of the two glaciogenic units of E. Finnmark, N. Norway (cf Rice *et al.* 2011). Such deposits typically occur as small and isolated outcrops within both the Autochthon and nappes of the Scandinavian Caledonides, often resting unconformably on basement rocks (Kumpulainen 2011; Kumpulainen & Greiling 2011; Nystuen & Lamminen 2011) After restoration of the Caledonian nappes, these diamictite outcrops indicate that glacial deposits covered an area of some 140 000 km^2 in N. Scandinavia (including E. Finnmark).

Studies in Norrbotten, Sweden, in the southernmost part of the area covered here (Fig. 58.1), led Kulling (1951) to introduce the term *Varangeristiden* (Varang(er)ian glaciation) to encompass both the glacial events described here and the earlier Smalfjord Fm. (Marinoan). However, for reasons summarized below, this term should no longer be used.

Structural framework

Restoration of the Scandinavian Caledonides, using balanced cross-sections, demonstrates that the NNE–SSW-trending (present orientation) continental shelf of W. Baltica comprised an outboard basin lying adjacent to the continental edge and an intermittently developed, somewhat shallower inboard basin (Fig. 58.2; Gayer *et al.* 1987; Gayer & Greiling 1989; Rice 1998, 2001, 2006). In NE Scandinavia, this continental shelf linked with the WNW–ESE-trending Timanian Basin (Siedlecka 1985; Gayer & Rice 1989; Siedlecka *et al.* 2004; *cf* Rice *et al.* 2011) that formed after the accretion of several minor terranes to Baltica in the middle Neoproterozoic (cf Cocks & Torsvik 2005). The Timanian Basin has been divided into northerly deep water and southerly shelf parts (Siedlecka *et al.* 1995, 2004), separated by the Trollfjorden–Komagelva Fault (cf Rice *et al.* 1989). In Scandinavia, the shelf part comprises the Gaissa Basin, which, in the west, was also an inboard basin of the NNE–SSW-trending W. Baltica shelf.

Predominantly in-sequence ESE- to SE-directed Caledonian shortening occurred mostly in Silurian–Devonian times. This passed through the outboard basin (Middle Allochthon), then a palaeogeographic basement-high (Window Allochthon, Rice 2001) and then the inboard basin, forming an external imbricate zone (external Lower Allochthon), finally emplacing the nappe pile onto the Autochthon. In some areas, the internal part of the Lower Allochthon restores to above the Window Allochthon and was imbricated earlier (Fig. 58.2). Both basins have essentially the same lithostratigraphy; in most areas, the basement-high was finally drowned in late Ediacaran to mid-Cambrian–Tremadocian times, essentially contemporary with the mainland to the SE. In the Tysfjord-Akkajaure area, both the Middle and Lower Allochthons

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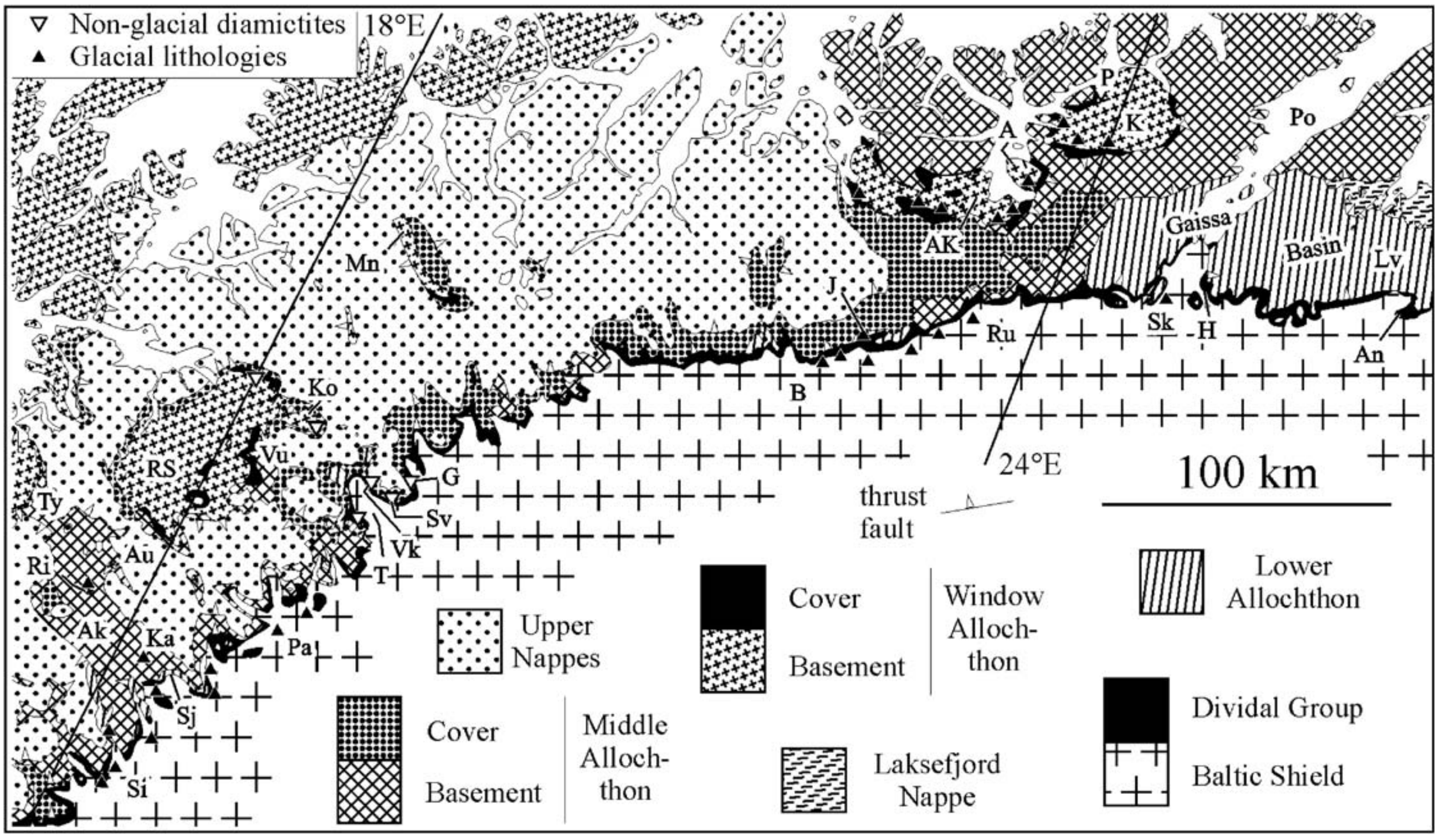

Fig. 58.1. Map of north Scandinavian Caledonides showing the distribution of glaciogenic lithologies and non-glaciogenic diamictites outside the E. Finnmark (Laksefjordvidda-Tanafjord-Mortensnes) area. A, Altenes Window; An, Andabakoaivi; Ak, Akkajaure; AK, Alta-Kvænangen Window; Au, Autajaure Window; B, Bulljovagge; G, Gæv'dnjajav'ri; H, Halkavarre; J, Jerta; K, Komagfjord Window; Ka, Karnjelajåkka; Ko, Kuokkel Window; Lv, Laksefjordvidda; Mn, Mauken Window; P, Porsavatn; Po, Porsangerfjord; Pa, Paittasjärvi; Ri, Ritsemjaure Window; RS, Rombak-Sjangeli Window; Ru, Ruođđojokka; Si, Sitojaure; Sj, Stora Sjöfallet; Sk, Skoganvarre; Sv, Sarvapakte; T, Torneträsk; Ty, Tysfjord; Vk, Vakkejåkka (now called Sarvájohka); Vu, Vuojtasrika.

are dominated by basement rocks, with only a thin cover succession (Björklund 1985, 1989), indicating that very restricted basin development occurred in this region.

In the area covered here, much of the Middle Allochthon comprises pre-Caledonian basement (Björklund 1985, 1989; Kirkland *et al.* 2006). Window Allochthon rocks are exposed in the cores of large domal/periclinal structures, with the major units being the Komagfjord Antiformal Stack (Komagfjord, Altenes & Alta-Kvaenangen Windows combined), the Rombak-Sjangeli, and adjacent Kuokkel Windows, and to the south, the relatively small Autajaure and Ritsemjaure Windows (Fig. 58.1). Although a basal thrust is typically not exposed, their allochthonous status has been inferred from structural and metamorphic criteria (Gayer *et al.* 1987; Anderson 1989; Bax 1989; Björklund 1989; Rice 2001).

The Gaissa Thrust Belt (derived from the inboard, Gaissa Basin), with 50% shortening in the west (Townsend *et al.* 1986, 1989), is the main development of the Lower Allochthon. On

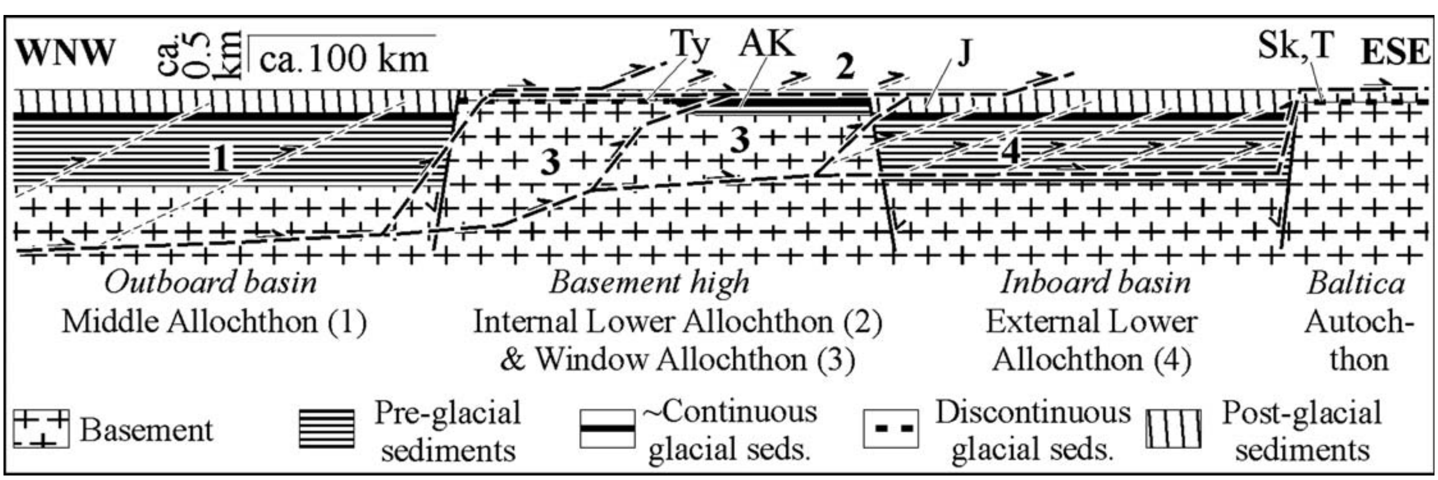

Fig. 58.2. Schematic (V ≠ H) WNW–ESE-oriented palinspastic cross-section showing the development of inboard and outboard basins in pre-diamictite times, separated by a basement high. The basins and basement high were then buried under glacial and post-glacial deposits. The main tectonic units are numbered in the order of their imbrication, with schematic main and minor thrusts. Localities along the top are given in the caption to Figure 58.1. Note that in many areas only one basin formed and in some areas neither basin formed.

Laksefjordvidda and to the east (Fig. 58.1), shortening decreases to *c.* 15% (Chapman *et al.* 1985). SW of Ruođđojokka, most of the Lower Allochthon has been eroded away (cf. Hossack & Cooper 1986; Anderson 1989), although several relicts have been preserved (Fig. 58.1; Jerta Nappe, Rautas Complex, Lower Thrust Complex – see below).

Stratigraphy

The deposits documented here are associated with condensed sequences correlated directly or indirectly with the late Precambrian sediments exposed in E. Finnmark (predominantly the Vestertana Group; cf. Rice *et al.* 2011; Fig. 58.3).

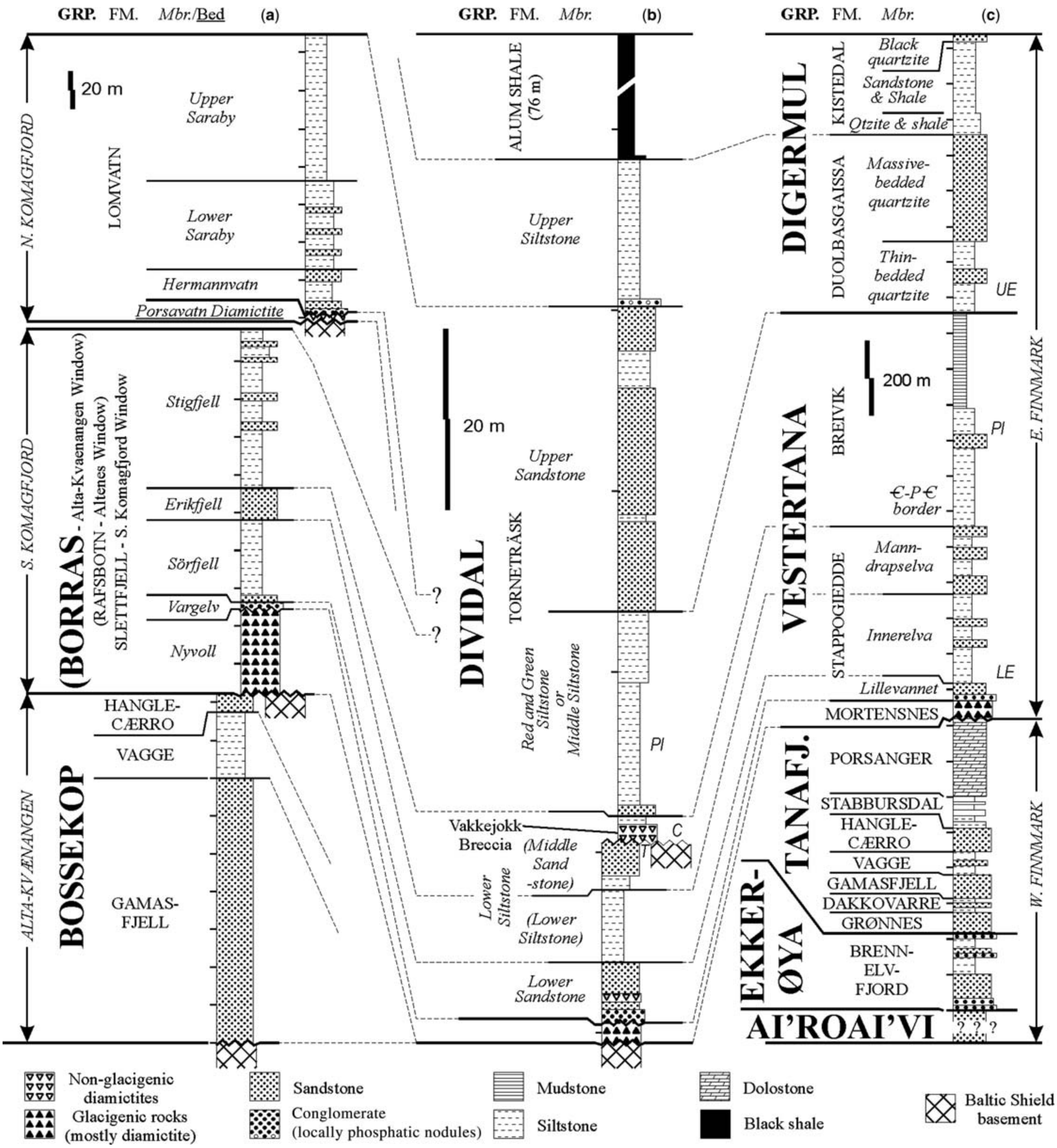

Fig. 58.3. Regional stratigraphic profiles. (**a**) *Alta-Kvaenangen*, *S. Komagfjord* and *N. Komagfjord* refer to where each part of the log-section was measured. In the S. Komagfjord zone, *Borras Group*, *Rafsbotn Fm.* and *Slettfjell Fm.* are the three lithostratigraphic equivalents from the three tectonic windows (from south to north) in the Komagfjord Antiformal Stack. The section shown is of the Slettfjell Fm. (Pharaoh 1985). (**b**) Section from Torneträsk (Thelander 1982; modified after Bax 1984 and Stodt 1987). (**c**) *E. Finnmark* and *W. Finnmark* refer to the successions in the eastern (Johnson *et al.* 1978) and western (Williams 1976; Rice & Townsend 1996) parts of the Gaissa Basin. *Pl*, *Platysolenties antiquissimus*; *T*, *Treptichnus pedum*; *UE, LE*, upper and lower limit of reported Ediacaran fauna; C, calcite nodules.

West of Andabakoaivi (Fig. 58.1), the Caledonian Autochthon comprises the Dividal Group, correlated with the post-Mortensnes Fm. part of the Vestertana Group and overlying Digermul Group in E. Finnmark (Fig. 58.3; Kulling 1964; Føyn 1967; Vogt 1967; Thelander 1982). The constituent Torneträsk (*c.* 100–260 m) and overlying Alum Shale (*c.* 80 m) formations are locally separated from the underlying pre-Caledonian basement (often a regolith; Bax 1984; Stodt 1987) by small patches of diamictite (Fig. 58.1); typically these are unnamed. The locally developed, but important Vakkejokk Breccia (cf. Kulling 1964; Thelander 1982; Stodt 1987) cuts across the lower part of the Torneträsk Fm. (Fig. 58.3). Although Kulling (1964) defined a Middle Sandstone Fm. (≡ unit C of Vogt 1967), Thelander (1982), who downgraded the rank of all the units from formations to members, merged this into the Lower Siltstone Member (Fig. 58.3). (Note that the Vakkejokk Breccia type locality, Vakkejåkka, or Orddajohka on some maps, is now called Sarvájohka; but this is not the same as the Sarvajåkka, now Sarvágorsa, described by Thelander, 1982).

In the western part of the Gaissa Thrust Belt (external Lower Allochthon; imbricated Gaissa Basin; Fig. 58.2; Townsend *et al.* 1986, 1989), the Tanafjord Group is thinner than in the type area, although correlatives of the Grasdal and Lille Molvika formations (Stabbursdal plus Porsanger formations and Brennelvfjord Fm., respectively; Fig. 58.3) are thicker (cf. Rice & Townsend 1996). The poorly studied Airoaivi Group is thinner and lithologically different to the Vadsø Group, its possible chronostratigraphic equivalent (Townsend *et al.* 1989; Rice & Townsend 1996). No diamictite has been preserved from this part of the Gaissa Basin.

In the Jerta Fm. (Jerta Nappe; Lower Allochthon), Skjerlie & Tan (1961; Fig. 58.1) recorded a predominantly clastic sequence with a basal diamictite. This whole sequence, estimated at *c.* 500 m thick, is likely a correlative of the Vestertana Group, although the presence of pyritiferous black shales suggest it may be partially correlated with the Digermul Group/Alum Shale Fm. (Reading 1965; Thelander 1982). The successions in both the Rautas Complex and the Lower Thrust Complex (near Torneträsk and Stora Sjöfallet, respectively; Fig. 58.1) have been reliably correlated with the tectonically underlying autochthonous Dividal Group (Björklund 1985; Bax 1989).

In the Komagfjord Antiformal Stack (Window Allochthon), the cover sequence youngs northwards, with <185 m of Bossekop Group (≡ Tanafjord Group; Fig. 58.3; Føyn 1964, 1985) lying unconformably on the basement in the Alta-Kvaenangen Window (Fig. 58.1). The Bossekop Group is unconformably overlain by the Borras Group, correlated with the post-Nyborg Fm. part of the Vestertana Group, including *c.* 10 m of basal diamictite (Fig. 58.3; Føyn 1964, 1985). In the Altenes and southern part of the Komagfjord Window, patchy outcrops of diamictite up to 40 m thick rest directly on the basement and are overlain by a <150-m-thick sequence again directly comparable to the lower part of the Torneträsk Fm. (Rafsbotn & Slettfjell formations; Roberts & Fareth 1974; Pharaoh 1985) whereas in the northern part of the Komagfjord Window a small patch of diamictite (here termed the Porsavatn Diamictite Bed) is overlain by <160 m of the Lomvatn Fm. (Pharoah 1985), broadly correlated in this chapter with the upper parts of the Torneträsk Fm. (Fig. 58.3).

Other successions within the area, from the Lower, Window and Middle Allochthons, that overlie diamictites have been directly correlated with the Dividal Group and have not been given local stratigraphic names.

Glaciogenic and associated deposits

Autochthon

Near Skoganvarre, Siedlecka (1987; Fig. 58.1) recorded three outcrops of polymict conglomerate within a 1 km distance, comprising 1–50 cm clasts of amphibolite, gneiss and quartzite, lying below the distinctive basal conglomerate of the Torneträsk Fm. To the SW of Ruođđojokka, Holmsen (1956) noted a very variable stratigraphy under the Torneträsk Fm.; in some places only occasional lonestones are present at the base of the sequence, essentially lying on the basement, whereas elsewhere 2–4 m of grey diamictite, with 1 m clasts, is overlain by 0.5–1 m of carbonate-bearing sandstone. At Bulljovagge, *c.* 2 m of red brown and grey diamictite overlie quartzitic sandstone, but the contact with the basement is not exposed (Holmsen 1957; Mathiesen *in* Skjerlie & Tan 1960). In these outcrops, the diamictite is often dominated by clasts derived from the immediately underlying rocks. In the Paittasjärvi–Sitojaure area and further south (Fig. 58.1), Kautsky (1949) described undeformed chloritic diamictites (Sito diamictite; Stromberg 1981) up to 4 m thick, with a dark matrix. The unsorted, angular to poorly rounded blocks are up to cubic metres in size and were derived from the underlying basement, which shows no signs of pre-diamictite weathering. The matrix is siliciclastic, comprising small quartz and felspar fragments; no carbonate is present. Near Sitojaure, the diamictite is overlain by >30 m of green mudstones with frequent blue quartzites and these are probably overlain by the Dividal Group, which directly overlies diamictites in nearby areas (Kulling 1951). Kulling (1951) also recorded banded silts and clays in the Sitojaure area. Other thin diamictites in this region were documented by Kulling (1951; Fig. 58.1), some with faceted clasts, although it is often unclear whether the outcrops documented belong to the Autochthon or overlying Lower Allochthon (cf Strömberg 1981).

The Vakkejokk Breccia lies in the upper part of the Lower Siltstone Member of the Torneträsk Fm. on the NE side of Torneträsk (Kulling 1964; Thelander 1982; Stodt 1987; Figs 58.1 & 58.3), thinning from 3–10 m (authors disagree on the thickness) in the Vakkejåkka (Sarvágorsa) area to *c.* 0.5 m some 7.5 km to the ESE. This locally cuts down through the Lower Sandstone Member to the basement (Stodt 1987). Where the breccia is thin, it may be overlain by sandstones of the uppermost part of the Lower Siltstone Member (Thelander 1982). Stodt (1987) documented four breccia types.

- Type A (recorded only at Gaev'dnjajav'ri; Fig. 58.1): conglomerate with <4-cm-sized, well-rounded dark-grey clay-silt clasts and some quartz fragments, forming the base of a 12-cm-thick $Bouma_{ABCD}$ sequence lacking a structureless sandstone and dewatering structures. This lies with an erosional contact on the underlying thin-bedded sandstones of the Lower Siltsone Member, *c.* 1 m below the base of the Middle Siltstone Member.
- Type B: angular to rounded granitic, vein-quartz, silt and shale matrix-supported clasts up to 15 cm in size in sandstone beds up to 30 cm thick. Platy clasts are bedding parallel. In some cases, the beds show normal grading. Matrix sandstone grains are rounded to well-rounded and predominantly quartz. The carbonate cement may have been derived from a carbonate-mud matrix.
- Type C: normally $>90\%$ granitic clasts with minor elongate, randomly oriented sedimentary clasts, often folded. The former are predominantly clast-supported, equidimensional to slightly elongate, mostly angular but sometimes well-rounded. Intraclasts are platy and show abundant fold structures. The matrix comprises grey, green and red silt/sandstone, often internally brecciated. Two such flows have been recognized, except at Vakkejåkka, where five flows occur. South of Sarvapakte (Sarvabakti; Fig. 58.1) one flow contains up to 1-cm-sized calcite nodules interpreted as glendonite by Stodt (1987; but see 'Discussion'). The flows usually lie conformably or slightly erosively on the Lower Siltstone Member.
- Type D: granitic blocks 2–100 m in size, lying either within and above siltstones that are often folded and disturbed or on type C breccias, along sharp boundaries, exposed for *c.* 4 km east of Vakkejåkka. SE of Vakkejåkka, 2–3 m clasts lie directly

on the basement. Some breccia clasts, derived from earlier flows, are also present (breccia-in-breccia structure). Granitic blocks and clasts are basement-derived.

Lower Allochthon

No outcrops of diamictites have been recorded within the Gaissa Thrust Belt in the Porsangerfjord area; exposures from areas further east are reviewed in Rice *et al.* (2011). In the Jerta Fm., Skerlie & Tan (1960; Fig. 58.1) described a diamictite with 5–30 cm angular to rounded, unsorted clasts of light grey, yellow-weathering dolomite, as well as greenstones and quartzites. The matrix is dark to brownish-grey, with angular dolomite and smaller poorly rounded quartz grains. Some finer, stratified and possibly graded beds are also present. No thicknesses were given, but photographs indicate a *c.* 2 m or greater thickness.

To the north of Sitojaure, in the Stora Sjöfället area, Kulling (1948, 1951, 1982) reported a close association of thinly bedded calcareous shales and diamictite or diamictite-like deposits with lithologies similar to the diamictites in the Ritsemjaure Window (see below).

Window Allochthon

In the Alta-Kvaenangen window, the most southerly part of the Komagfjord Antiformal Stack, 185 m of quartzites and shales of inferred shallow marine origin (Bossekop Group) are unconformably overlain by *c.* 10 m of red-brown diamictite at the base of the Borras Group, passing up gradually to conglomerates correlated with the base of the Torneträsk Fm. and thence to sandstones and shales (Føyn 1964, 1985; Fig. 58.3). Further north, in the Altenes Window, Roberts & Fareth (1974) very locally found *c.* 2 m of reddish-brown diamictite with clasts (<30 cm size; 30% of the rock) of mixed cover and basement lithologies, many derived from the immediate substrate, lying on the basement. Nearby, the Rafsbotn Fm., comprising a basal well-rounded pebble-sized quartz conglomerate, *c.* 1 m thick, and then by green and red mudstones, slates and siltstones, directly overlies the basement. The Rafsbotn Fm. is equivalent to the basal part of the Torneträsk Fm.

Along the southern rim of the Komagfjord Window (northern part of the Komagfjord Antiformal Stack), outcrops of the essentially undeformed Nyvoll Tillite Member (Slettfjell Fm.) are preserved as lenses up to 1 km long and 44 m thick (although this particularly thick outcrop thins to nothing in 300 m along strike; Pharaoh 1980, 1985). Pharaoh (1980) described four facies, with up to three fining-upwards cycles:

- Facies A: poorly sorted, unstratified polymict diamictites with >20% clasts in a reddish-brown matrix, locally clast supported at the base, where the clast content may rise to 40%. Most clasts are <5 cm across, but range up to 60 cm in size and vary from angular to sub-rounded, and are sometimes facetted. A large percentage was locally derived, although gneiss, granite and quartzite clasts might have been externally derived. This facies is up to 5 m thick and always forms the base of the sequence, grading up into Facies B, although it reappears higher in the sequence.
- Facies B: poorly sorted polymict diamictite similar to facies A, but with significantly fewer (<20%) and smaller clasts (*c.* 10 cm max.), locally with a carbonate matrix/cement towards the top. Thickness varies from 1 to over 20 m.
- Facies C: poorly sorted, poorly stratified diamictite, gradational from facies B by a continued decline in clast size (<1 cm) and content (<5%). 'Bedding' is defined by thin laminae of quart grains in a reddish brown muddy matrix. This facies is generally thinly developed, although a thickness of 23 m occurs in one section.
- Facies D: intercalated sandstones and mudstone in bands 1–5 cm thick, usually reddish brown, although the sandstones may be paler and greyish-green. Sandstones are frequently graded, with microconglomeratic erosive bases, ripples, load casts and intraformational mud-flake breccias. Impact pits are present, as is evidence of soft-sediment folding and both thrust and normal soft-sediment faulting.

Bedding in the diamictite is parallel to that in the overlying basal conglomerate of the Vargelv Member (Fig. 58.3), indicating that diamictite thickness variations reflect a syn-sedimentary uneven basement surface; a palaeorelief, up to 3 m high, has been preserved at outcrops and an overall pre-diamictite topography of 40 m has been mapped. Pharaoh (1980) suggested that the Nyvoll Member was deposited in a NW–SE-trending palaeovalley *c.* 1 km wide and up to 40 m deep, accounting for the sequence having a thickness atypical outside the E. Finnmark area (cf Rice *et al.* 2011). The northern margin of the valley is poorly defined due to scarce exposure. Clasts in the diamictites comprise feldspathic metasandstones, jasper, vein quartz, metagabbro, serpentinite and trondjemite, all locally derived; sometimes they can be linked to nearby palaeo-topographic highs. These sediments are overlain by a quartz conglomerate, with little topographic relief at the contact, and then by red and green siltstones/shales, comparable with the Borras Group/Rafsbotn Fm. to the south (Fig. 58.3).

In the northern part of the Komagfjord Window, a <0.5-m-thick, very poorly sorted matrix-supported diamictite (Pharaoh 1985), here termed the Porsavatn Diamictite Bed, comprising 0.5–3 cm angular clasts of vein quartz and quartzite in a grey muddy matrix, underlies the 180-m-thick Lomvatn Fm. at one area (Figs 58.1 & 58.3). Elsewhere, the 0.6–2-m-thick basal conglomerate of this formation, consisting of well-rounded vein quartz and quartzite pebbles, rests unconformably on the basement and is overlain by sandstones and shales (Pharaoh 1985), probably correlatives of the upper part of the Torneträsk Fm. (Fig. 58.3).

The Gearbeljávri Fm., a thin sedimentary veneer that crops out around the rim of the Rombak-Sjangeli and Kuokkel Windows and on minor tectonic klippen within them, has also been correlated with the basal part of the Torneträsk Fm. (Fig. 58.1, Brown & Wells 1966; Tull *et al.* 1985; Bax 1989, 2001). In places, a basal conglomerate lies at the basement–cover contact, but elsewhere the contact grades from unweathered basement, through regolith into quartzites. At Vuojtasrika, Brown & Wells (1966) documented 0.5-m-deep, diamictite-filled fissures in the basement, but Bax (unpublished data) reinterpreted these as fault breccias. Along the northern margin of the Rombak-Sjangeli Window, Tull *et al.* (1985) described grey to white arkosic cross-bedded sandstones, interlayered with conglomerates and pelitic schists, locally overlain by diamictites with clasts of granitic, ?dioritic and pelitic lithologies up to 25 cm in diameter. Coarsely graded sequences are common. Current directions indicate flow to the south to SSW, although the basement–cover contact is a palaeopeneplain.

At one outcrop in the SE part of the Kuokkel Window, a 1-m-thick diamictite is underlain by quartzites correlated with Lower Sandstone Member (Torneträsk Fm.). This diamictite, which lies *c.* 2 m above the basement–cover unconformity, although the contact is not exposed directly here (Bax 1984), comprises angular, unsorted, carbonate and sandstone clasts (no basement clasts) up to 20 cm in size, surrounded by a fine-grained matrix. No clast sorting or preferred orientation has been observed. Upwards in the section, above the overlying cross-bedded sandstones, ripple marks are common in sandy layers interbedded with brown shales (Bax 1984).

In the Ritsemjaure Window, within the Middle Allochthon (Akkajaure Nappe Complex), vertical fissure fillings trending 010° occur in mesoperthitic granite. The fissures have highly irregular margins and widths of up to 5 m, but are of unknown depths (Fig. 58.1; Björklund 1989). The fissures are filled with an unsorted sedimentary breccia, consisting of a dark grey, silty matrix, chaotically mixed with all sizes (<1 m) of angular clasts from the host granite and very subordinate shale and dolomite clasts. The same type of breccia overlies the basement granite, but with smaller (<10 cm) clasts. Microscopic clasts reflect the mesoperthitic feldspars of the subjacent granite. The breccias grade upwards into dark conglomerates with up to pebble-sized clasts and a weak clast size stratification and thence into dark shales with <5 cm lonestones. Local shearing within the diamictite sequence makes thickness estimates uncertain, but the diamictite lying on the granite is 5–8 m thick and the overlying conglomeratic to shaly part is *c.* 5 m thick in the least disturbed areas. Overlying this, along a sharp contact, is a <3-m-thick, typically blue-grey orthoquartzite with a basal quartz conglomerate including porphyry clasts, correlated with the base of the Torneträsk Fm. (Björklund 1989).

Further west, on the NE side of the Tysfjord Culmination, several local pockets of strongly sheared <0.5-m-thick schistose unsorted diamictites with granite clasts in a dark grey matrix have been mapped with irregular contacts on the basement (Fig. 58.1; Björklund 1989). These are overlain by *c.* 1-m-thick white to grey quartzites and thence by overthrust rocks of the Lower Allochthon.

Middle Allochthon

In the eastern part of the lowest imbricate of the Akkajaure Nappe Complex (in Karnjelajåkka; Fig. 58.1), a 1–2-m-thick diamictite with centimetre-sized angular mesoperthitic granite clasts in a carbonate-bearing matrix rests on an uneven granitic basement surface. The diamictite is sharply overlain by a *c.* 5-m-thick conglomerate with sub-rounded to sub-angular quartz and less common mesoperthite clasts fining upwards to gravelly quartzite, followed by grey quartz phyllite, all correlated with the base of the Torneträsk Fm. Westwards within this imbricate, a transition from mesoscopic clast-rich diamictites to strongly weathered calcite-dolomite mica schists occurs, overlain by quartz mylonites. Clast size diminishes westwards. The schists have microscopic sub-angular clasts of mesoperthite, quartz and albite similar to those in the diamictite; chemically, the calcite-dolomite mica schists and the diamictite matrix are very similar (Björklund 1989). On the higher, more westerly derived thrust sheets, micaceous marbles are interlayered with these schists.

Boundary relations with overlying and underlying non-glacial units

The sediments (mostly diamictites) generally lie unconformably on autochthonous or allochthonous Baltic Shield-derived basement rocks and are unconformably overlain by the distinctive quartz-rich basal conglomerate of the Torneträsk Fm. or (deformed) correlatives. In some cases, a few metres of finer-grained sediments lie between the diamictites and the basal conglomerate. The succession in the Komagfjord Antiformal Stack differs in that in the south, around the Alta-Kvaengen Window, the diamictites lie on a condensed sequence correlated with the mid- to upper part of the Tanafjord Group (Fig. 58.3; Føyn 1964, 1985), whilst further north they lie on allochthonous basement (Roberts & Fareth 1974; Pharoah 1985). The upper contact in the Komagfjord Antiformal Stack is also atypical, in that it is gradational with the Borras Group and Slettfjell formations, correlatives of the Lillevatn Fm. (= base Torneträsk Fm.) in E. Finnmark (Føyn 1964; Pharaoh 1980, 1985). The upper contact of the Porsavatn Diamictite Bed is erosively overlain by the Lomvatn Fm. (Fig. 58.3).

In contrast, the diamictite in the Kuokkel Window lies *within* a sandstone/quartzite succession correlated with the Lower Sandstone Member of the Torneträsk Fm., above the basal conglomerate. Rather similarly, the Vakkejokk Breccia rests with a marked erosive unconformity on the underlying sediments of the Torneträsk Fm., cutting down-section to, very locally, the basement, and is conformably overlain by younger sediments (Stodt 1987).

Chemostratigraphy

No stable isotope data are available due to the general lack of carbonates in the sequence. $\delta^{13}C$ values from calcite nodules in the Vakkejokk Breccia range between –4.03 and 0.79‰ (VPDB; mean, –1.57‰, ±1.38, $N = 11$; crystals were drilled out and analysed using the technique of Halverson *et al.* 2005).

Palaeolatitude and palaeogeography

Well-dated palaeopoles that can be used to constrain the Ediacaran palaeogeogeography of Baltica are scarce (cf Torsvik *et al.* 1996; Bingen *et al.* 2005; Cocks & Torsvik 2005). The southern rim of an inverted Baltica lay at *c.* 15°S at *c.* 750 Ma (Hartz & Torsvik 2002). At 616 Ma, data from mafic dykes in southern Scandinvia indicate that Baltica lay at 75°S although by *c.* 550 Ma, the area covered here lay at *c.* 45–50°S (Cocks & Torsvik 2005). In contrast, Cawood & Pisarevsky (2006) and Pisarevsky *et al.* (2008) place Baltica in a more equatorial position (*c.* 30°), although whether it lay in the northern or southern hemisphere is unclear.

Geochronological constraints

No robust isotopic age constraints are available from this area. Correlation of the sub-Dividal Group sediments with the Mortensnes Fm. gives a broad age constraint of *c.* 580 Ma, by correlation with the Gaskiers glaciation (Bowring *et al.* 2003). Although it is likely that the Gaskiers event was diachronous, the close association of the Mortensnes Fm. with extremely negative $\delta^{13}C$ values in Finnmark, correlated with the Wonoka anomaly (Halverson *et al.* 2005; Rice *et al.* 2011), probably makes the effect of diachroneity on the timing of glaciation relatively small.

The Vakkejokk Breccia is closely underlain (within a few metres) by the fossil-rich Kullingia Beds, within which *Treptichnus pedum* has been recorded (Stodt 1987). Although *Treptichnus pedum* was established as the index trace fossil for the base of the Cambrian (Brasier *et al.* 1994), it has subsequently been found in the youngest Ediacaran successions (Gehling *et al.* 2001). Thus the Vakkejokk Breccia is constrained to very latest Precambrian to early Cambrian times. This boundary lies somewhat below the lithostratigraphic correlation with the proposed Precambrian–Cambrian boundary from E. Finnmark (Fig. 58.3).

Discussion

In East Finnmark, the glaciogenic Smalfjord Fm. has a typical Marinoan-type cap dolostone, forming the base of the Nyborg Fm. (cf Halverson *et al.* 2005; Rice *et al.* 2011). Thin dolostones in the upper part of the Nyborg Fm. (Member E; Edwards 1984; Fig. 58.3) have $\delta^{13}C$ values of –7.6 and –9.9‰ (VPDB); these have been correlated with the extreme negative $\delta^{13}C$ values recorded in the Wonoka anomaly in other parts of the world (down to –12‰; cf. Halverson *et al.* 2005, Le Guerroué *et al.* 2006) to suggest that the almost immediately overlying Mortnesnes Fm. is broadly a correlative of the 580 Ma Gaskiers diamictite (cf Halverson *et al.* 2005). Correlation of the sub-Tornetäsk

Fm. diamictites and other 'glaciogenic' sediments in the present area with the Mortensnes Fm. is based on the robust lithostratigraphic correlation of the Stappogiedde Fm. in the Vestertana area with the Dividal Group in the Andabakaoaivi-Halkavarre area (Føyn 1967) and from there to regions to the SW (Føyn 1964; Vogt 1967; Thelander 1982, and references cited above). The limited palaeontological data (*Platysolenites antiquissimus* Eichwald, *Treptichnus pedum*) support these correlations (Kulling 1964; Hamar 1967; Føyn & Glaessner 1979; Stodt 1987; Crimes & McIlroy 1999; Fig. 58.3).

The outcrops documented here are often small and rather uninspiring. Some have little or no direct (reported) evidence of glacial activity and it is their stratigraphic position, underlying the distinctive quartz-conglomerate forming the base of the Dividal Group, that has been used to infer a glacial (direct or very indirect) origin. Exposures such as the polymict conglomerates near Skoganvarre (Siedlecka 1987) are clearly of this type. Similarly, the finer-grained, stratified deposits associated with diamictites in the Jerta Fm. (Skerlie & Tan 1960) were inferred to be fluvioglacial solely based on the presence of diamictites; however, these are also an unreliable indicator of glaciogenic facies.

Criteria used for suggesting a glacial origin include faceted clasts, impact pits (reflecting dropstones), soft-sediment folding and faulting, taken to reflect glacial shear stresses, and the diamictitic composition and texture of the rocks. In the Komagfjord Window, Pharoah (1980) recognized small roches moutonées forming part of the 3-m-high palaeorelief within the 40-m-deep palaeovalley. The presence of regular 'varved' sequences associated with diamictite has also been cited as evidence of glacial activity (Kulling 1951). Although most of these criteria are no longer regarded as being unequivocally diagnostic of glacial activity, their co-occurrence, together with their stratigraphic position, forms a reasonably compelling argument for a glacial (*sensu lato*) origin; whether the diamictites are tillites or slightly reworked material is unknown.

Within the lowest imbricate of the Akkajaure Nappe Complex there is some evidence for a transition from coarse diamictites in the ESE to finer-grained diamictites (now schists) in the WNW. Both lithologies have comparable angular mesoperthitic clasts, with clast sizes decreasing to the west, and similar geochemistries. This has been inferred to reflect a transition from a proximal glacial to a more distal, possibly glaciomarine, depositional environment (Björklund 1989).

Kulling (1951) suggested that the Vakkejokk Breccia is a tillite, but later studies indicated a mass-flow origin (cf Stodt 1987). A peri-glacial environment has been proposed (Strömberg 1981; Thelander 1982) and this seemed to be confirmed by the discovery of glendonite in the breccia (Stodt 1987). Similarly, the breccia clasts found in the Type D breccia (breccia-in-breccia structure) were interpreted to indicate that the material was frozen during transportation. Stodt (1987) also reported up to 20-cm-diameter lonestones in the Lower Siltstone Member, under the Vakkejokk Breccia, although no dropstones were seen. However, detailed examination of the 'glendonite' does not show any evidence for the 30% volume loss associated with the breakdown of ikaite. Instead, each radial 'arm' comprises a single, slightly distorted calcite crystal, with curved (strained) twin planes and radially varying (undulose) extinction orientations. Essentially, the internal microstructure seems too regular to be a replacement of ikaite and is instead thought to represent replacement of an initial gypsum nodule (Peckmann, pers. comm. 2011). The nodules are too irregular, partly due to bedding parallel pressure solution, to make a diagnostic determination of the crystal form. This non-glacial reinterpretation is consistent with the palaeomagnetic data and the lack of widespread glacial deposits in places nearer the poles at that time.

The type A conglomerate in the Vakkejokk Breccia is likely a rapidly accumulated mid-fan deposit. In the overlying breccias, the parallelism of platy clasts indicates laminar flow and the internal brecciation is indicative of rigid plugs, both typical of debris flows (Stodt 1987). Stodt (1987) proposed that the breccia formed due to the uplift and collapse of a palaeotopographic high; based on the asymmentry of soft-sediment folds within the breccia, this lay to the west, with east-directed slumping. Similar, but slightly younger normal faulting has been documented at the Caledonian front SW of Akkajaure (Hansen 1989).

The diamictites at the northern margin of the Rombak-Sjangeli Window and in the SE corner of the Kuokkel Window also lie within, rather than under, sediments correlated with the lower part of the Torneträsk Fm. (Bax 1984; Tull *et al.* 1985). Although it cannot be wholly discounted, it seems unlikely that these are tillites. A more likely origin is that they are debris-flows, possibly reworked nearby sub-Torneträsk Fm. tills or the commonly reported regolith in the area (Stodt 1987; Bax 1989).

The most northerly part of the Komagfjord Antiformal Stack, a palaeo-basement high, lay well above the Mortensnes post-glacial sea level, with drowning occurring some time after it occurred in more southerly parts of the high; glacial sediments deposited in this area would thus have been strongly affected by erosion, with a low preservation potential. The Porsavatn Diamictite Bed, lying under a sharp erosional contact with the basal conglomerates of the Lomvatn Fm. is the only potential relict of such deposits found (Fig. 58.3) and, if of glaciogenic origin (*sensu lato*) is most likely reworked (debris-flow), rather than primary.

Kulling (1951) introduced the term Varangeristiden (Varang(er)ian ice age) in a discussion of diamictites in northern Sweden. Although these deposits are now correlated solely with the Mortensnes Fm., the term originally encompassed all the Neoproterozoic glaciogenic rocks of the Smalfjord and Mortensnes formations in E. Finnmark (and elsewhere in Scandinavia). The Smalfjord and Mortensnes formations have now been correlated with the Marinoan and Gaskiers glacial events based on, respectively, the development of a typical Marinoan cap dolostone and a close association with extreme negative $\delta^{13}C$ values taken to reflect the Wonoka anomaly (Halverson *et al.* 2005; Rice *et al.* 2011). One glacial event was worldwide in scope, while the other was much more localized. Taking a 12 Ma duration of the Marinoan glaciation (Bodiselitsch *et al.* 2005) and 1 Ma for the Gaskiers (Bowring *et al.* 2003) implies a total time span of 647–579 Ma for the two glacial events, of which only 13 Ma (18%) were actually spent under ice, scarcely enough to justify the term 'ice age'. Further, Harland *et al.* (1989) used the term for a Precambrian epoch. In view of the very confused implications given by the term, we discourage the use of the term Varang(er)ian in any sense.

In summary, the many isolated, but regionally persistent sub-Dividal Group diamictites in northern Scandinavia, occurring in the Autochthon and at all tectonic levels of the Caledonian nappes derived from Baltica, testify to a mid-Ediacaran glaciation broadly equated with the 580 Ma Gaskiers event (which was probably diachronous). Lithological, structural and mineralogical characteristics suggest terrestrial as well as glaciomarine depositional environments. These deposits covered an area of 140 000 km^2 in the region considered. Applying the same structural model as used here to the whole orogen (cf Gayer & Greiling 1989; Rice 2006) indicates that patches of Mortensnes Fm. equivalents (Kumpulainen 2011; Kumpulainen & Greiling 2011; Nystuen & Lamminen 2011) cover a restored area of *c.* 780 000 km^2.

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