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Neoproterozoic basin evolution in Fennoscandia, East Greenland and Svalbard

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Neoproterozoic successions of Fennoscandia, East Greenland and Svalbard are related to crustal extension and formation of sedimentary basins along the margins of northern Baltica (Fennoscandia) and eastern Laurentia (East Greenland and Svalbard), preceding final break-up of Rodinia. The early rift stage (late Tonian–Cryogenian) is characterized by up to 16 km thick sedimentary successions of deep-marine sandstones and conglomerates linked to rift and strike-slip basins. Pericratonic basins expanded during Cryogenian–Cambrian coastal onlap. Cryogenian tropical climate is reflected by carbonate and evaporitic formations, most of which predate Cryogenian–Ediacaran glaciations. Glacial units, collectively referred to the Varanger Ice Age, may be equivalent to the Marinoan (c. 630 Ma) and the Gaskiers (c. 580 Ma) glacial periods. The final stage in break-up of Rodinia commenced with the emplacement of dolerite dyke swarms along the Baltoscandian margin at c. 600 Ma and the opening of the Iapetus Ocean and other sea ways. No such dyke swarms have been recorded along the East Greenland segment of the Laurentian margin. Several Tonian–Cambrian tectonic and magmatic events recorded within the Kalak Nappe Complex in northern Finnmark make this unit an exotic terrane relative to the autochthonous Baltoscandian platform.

neighbouring plates were Laurentia and Amazonia (Li et al., 2008) (Figure 1).

The Fennoscandian part of Baltica was limited by the Timanian margin to the northeast and the Baltoscandian margin towards the northwest and west (referring to present coordinates); both margins hosted Neoproterozoic successions. Neoproterozoic strata in East Greenland and Svalbard were deposited along the eastern margin of Laurentia. These successions are correlated by achritarch stratigraphy (Vidal, 1985; Knoll and Walter, 1992). The Neoproterozoic rocks were variably affected by deformation and metamorphism within the Timanian and Caledonian orogenic belts. Reconstruction of the Neoproterozoic basin configuration requires restoration of Caledonian nappe displacements, strike-slip movements along plate margins and Cenozoic sea-floor spreading in the North-Atlantic and Arctic domains. Neoproterozoic successions in the Scandinavian Caledonides are described according to their tectonostratigraphic position as Autochthon, Lower, Middle and Upper Allochthons (Gee et al., 1985a). The objectives of this review are to emphasise basin evolution and controlling factors such as tectonics, climate and sea-level changes. The review starts at the Timanian margin in eastern Finnmark of Arctic Norway; it then proceeds from Autochthon to Upper Allochthon in the Caledonides and from north to south in Scandinavia, before describing the East Greenland and Svalbard successions (Figure 2). Summaries of the Neoproterozoic successions in the different areas and their correlations are shown in Figure 3. Discussion of Tonian orogenic and igneous activity within the Sveconorwegian (Grenvillian) orogenic belts in southwestern Fennoscandia and Svalbard and Eastern Greenland is beyond the scope of this paper and described elsewhere in this volume.

Introduction

The Neoproterozoic comprises the Tonian (1,000–850 Ma), Cryogenian (850–630 Ma) and the Ediacaran (630–542 Ma) of Gradstein et al. (2004). In northern Europe, the Russian terms Riphean and Vendian have previously been used, corresponding approximately to Mesoproterozoic+Tonian+Cryogenian and the Ediacaran, respectively. During the Cryogenian and Ediacaran, between c. 825 and 600 Ma, the supercontinent Rodinia broke up into several large and small plates. One of these, *Baltica*, includes the present Fennoscandian Shield (e.g., Pease et al., 2008). Major

Figure 1 Plate reconstruction showing relative position of Baltica and Laurentia at 630 Ma. From Li et al. (2008).

Timanian margin: Eastern Finnmark

The Neoproterozoic sedimentary rocks at Tanafjorden and the Varanger Peninsula in eastern Finnmark (Figure 2) are important reference successions for the global Neoproterozoic stratigraphy. The strata were deposited along the Timanian margin of northeastern Baltica, from about 1000 Ma until the end of Ediacaran.

The WNW-ESE-trending Trollfjorden-Komagelva Fault Zone (TKFZ) divides the Varanger Peninsula into the Tanafjorden-Varangerfjorden Region (TVR) to the southwest and the Barents Sea Region (BSR) to the northeast. The fault zone continues into Russia along the northern coast of Kola Peninsula and the Pechora Basin, forming here the south-western margin of the Timanian Basin (c. 1000–630 Ma) and the foreland of the Timanian orogenic belt (c. 590–540 Ma). Towards the northwest, the TKFZ probably intersected the Baltoscandian margin in a triple junction (Siedlecka et al., 2004). Caledonian thrust tectonics and the Timanian orogeny affected the sedimentary succession on both sides of the TKFZ, the Caledonian deformation being most pronounced in the northwest. The Ediacaran strata at Tanafjorden close to the front of the Gaisa Nappe Complex (see below) pass into Cambrian beds. The successions beside Varangerfjorden rest on denudated Baltica basement rocks.

The Barents Sea Region, located NE of TKFZ, comprises the Barents Sea (c. 9,000 m) and the Løkvikfjellet groups (c. 6,000 m). These two groups are separated by a major unconformity. The substratum of the Barents Sea Group is unknown. The group commences with submarine turbidite fan sandstones (Kongsfjord Fm >2,500 m), continuing upwards into deltaic, coastal and fluvial beds. Subordinate platform carbonates with local stromatolites and traces of evaporites occur in the upper part of the group. Achritarchs (Båtsfjord Fm) provide evidence of a Cryogenian (late Riphean) age (Vidal and Siedlecka, 1983).

Figure 2 Northern Europe and Greenland in plate tectonic position in early Cenozoic time. Outcrop areas of Neoproterozoic successions in Fennoscandia, East Greenland and Svalbard are shown by grey shading. AF = Ardenaple Fjord, CEG = Central East Greenland, ENG = eastern North Greenland, PB = Peterman Bjerg, Vi = Visingö Group, Vättern Basin.

The Løkvikfjellet Group is entirely terrigenous and consists of predominantly shallow-marine and subordinate fluvial sandstone, mudstone and siltstone. No deposits of glacial origin are present in the succession. Metadolerite dykes, some of late Neoproterozoic age, penetrate the sedimentary successions of the Barents Sea Region (Siedlecka et al., 2004).

Rocks of the Barents Sea Region were displaced along the TKFZ towards the ESE at the end of the Timanian Orogeny and juxtaposed to the Neoproterozoic successions presently cropping out on the southwestern side of the fault zone. The succession preserved southwest of the TKFZ unconformably onlaps the Baltican crystalline basement, forming a pericratonic basin. The succession consists of the Vadsø (oldest), Tanafjorden and Vestertana groups, with an accumulated thickness of 3,000 m. Several unconformities and hiatus indicate tectonic activity during sedimentation. The Cryogenian (late Riphean) Vadsø and Tanafjorden groups are dominated by fluvial sandstone in the lower part and shallow-marine sandstone and mudstone in upper part, terminating with stromatolite-bearing dolomite (Grasdal Fm). A warm tropical climate prevailed at the end of Cryogenian in TVR, as well as in the BSR (Båtsfjord Fm). Carbonate platforms likely formed in response to rise in sea level in a late Cryogenian 'carbonate transgression' (Siedlecka et al., 2004).

The Cryogenian strata are cut by a low-angle unconformity, with increasing hiatus towards the south. Overlying Ediacaran successions consist almost entirely of siliciclastic deposits and commence with the Varangerian glacial deposits: the Smalfjord and Mortensnes tillite formations and the interglacial Nyborg Formation which is predominantly terrigenous, but with some marine carbonates, including the bottom bed. The tillite outcrops in TVR are among the world's most well-known and best studied Neoproterozoic glacial successions (Figure 4). The tillite-bearing formations may correspond to the Marinoan (c. 630 Ma) and Gaskiers (c. 580 Ma) glacial periods elsewhere, referred to as the Neoproterozoic III and IV glaciations by Rice and Hoffmann (2000).

The post-glacial Ediacaran record consists predominantly of various marine deposits and passes upwards into shallow-marine Early Cambrian to Tremadocian beds. Ediacara trace fossils are recorded on the Digermulen Peninsula (Siedlecka et al., 2004).

Stratigraphic correlations across the TKFZ between BSR and TVR show that the lower Barents Sea Group and the bulk of the Vadsø Group are correlative and indicate that the lateral translation of the BSR along the TKFZ is much less than the 500 km previously interpreted on geophysical grounds (e.g., Siedlecka and Roberts, 1992; Rice, 1994; Siedlecka et al., 2004).

Baltoscandian platform and margins

Cryogenian-Cambrian autochthonous successions along the Caledonian nappe front and in tectonic windows

Late Ediacaran-Cambrian successions rest on older Precambrian basement in outcrops along the Caledonian nappe front as the Dividal Group of central Finnmark, northeastern Troms and northern Sweden and correlatives further southwards to South Norway (Figure 5).

The Dividal Group begins with post-Varangerian accumulations and continues through Lower Cambrian beds with *Platysolenites antiquissimus* into the Middle Cambrian Alum Shale Formation. Fluvial sandstones and alluvial debris-flow conglomerates in the lower part are followed by coastal and shelfal terrigenous strata. Kulling (1972) found at Torneträsk *Kullingia concentrica*, the first discovery of Ediacara fossils in Scandinavia. The Ediacaran-lower Cambrian sandstone and shale beds along the nappe front locally starts with Varangerian tillite (Siedlecka et al., 2004).

Successions similar to those at the nappe front occur along margins of tectonic windows (antiformal stacks) in the nappe region; the strata rest with erosional contact on older Baltican rocks. Tillite-

Figure 3 Neoproterozoic stratigraphy in Fennoscandia with Barents Sea Region (BSR), Tanafjorden-Varangerfjorden Region (TVR), Risbäck Basin (RB), Tossåsfjället Basin (TB) and western Hedmark Basin (HBW), East Greenland with central East Greenland (CEG) and eastern North Greenland (ENG), and Svalbard with Nordaustlandet and Ny Friesland (NA-NY).

bearing rocks of the windows in western Finnmark are correlatives of the upper Tanafjorden and Vestertana groups of East Finnmark, respectively. Discontinuous tillite units overlain by Ediacaran-Cambrian quartz conglomerate, quartz arenite, siltstone and shale rest directly on crystalline basement in a series of windows further south in the Scandinavian Caledonides (e.g., Siedlecka et al., 2004).

Figure 4 The Bigganjargga tillite at Oibaccanjarga in Varangerboth, East Finnmark, North Norway. Diamictite of the basal tillite facies of the Smålfjord Formation was deposited unconformably on a striated pavement of older quartzitic sandstone.

Neoproterozoic of the Lower Allochthon

The Gaissa Nappe Complex

The Neoproterozoic pericratonic deposits of TVR continue westwards for a distance of about 200 km into the Porsanger area, as a part of the Gaissa Nappe Complex. Correlations indicate that these successions extend another 200 km southwestwards to Kvænangen. The lower, fluvially dominated parts of the succession occur southwest of the Porsangerfjorden. In the Porsangerfjorden area, marine sandstone and dolomite with evidence of evaporitic conditions correlate with sandstone and carbonate formations, respectively, in the Cryogenian Tanafjorden Group. Ediacaran rocks continue westward to the Laksefjorden area, while further to the west only scattered tillites occur (Siedlecka et al., 2004).

Jämtlandian nappes and the Osen-Røa Nappe Complex: the Risbäck and Hedmark basins

Attenuated thrust sheets of Lower Allochthon occur along the Caledonian nappe front in Arctic Sweden, thickening in the Central and Southern Scandinavian Caledonides. Besides the Neoproterozoic successions the nappe complexes contain slices of Baltican basement rocks (Gee et al., 1985a); tectonic transport exceeds 150 km (Kumpulainen and Nystuen, 1985).

Jämtlandian nappes in central-west Sweden carry a Neoproterozoic to lower Cambrian succession, the Risbäck and Sjøutälven groups. The pre-Varangerian Risbäck Group (c. 1,500 m), deposited in the Baltoscandian Risbäck Basin, consists of feldspathic sandstones and minor debris-flow conglomerates and shale units, includ-

Figure 5 Main features of the Scandinavian Caledonides showing major outcrop areas of Neoproterozoic strata.

ing a dolomite at the top (Kalverberget Fm). The dolomite formation is unconformably overlain by the Långmarkberg tillite, followed by Ediacaran to lower Cambrian sandstone and shale in the Sjøutälven Group (Kumpulainen and Nystuen 1985).

Neoproterozoic-Cambrian rocks in the Osen-Røa Nappe Complex in southern Norway and Härjedalen of western Sweden have traditionally been named 'sparagmites', from the term *sparagmite* (feldspar-rich sandstone). The Sparagmite Region hosts the more than 5,000 m thick Hedmark Group, a reference succession of Neoproterozoic stratigraphy in southern Scandinavia, deposited in the Hedmark (rift) Basin (Kumpulainen and Nystuen, 1985). Fluvial sandstones form the initial deposits, followed by at least 4,000 m of thick deep-marine turbidite sandstones and black shales (Brøttum Fm) in the west and equivalent alluvial arkoses and conglomerates in the east. Achritarchs in marine shales indicate a late Cryogenian-early Ediacaran age (cf. Nystuen, 1999).

Tholeiitic basalt flows and deep-marine conglomeratic fans (Nystuen, 1999) are indicative of considerable crustal extension. The Biskopåsen conglomerate contains the first Precambrian fossil ever found in Norway, *Papillomembrana compta* (Spjeldnæs, 1967). Carbonate beds with local stromatolites interbedded with black shales

(Biri Fm) formed during the 'carbonate transgression' of Baltica (Siedlecka et al., 2004).

The Varangerian glacial epoch in South Norway is represented by the Moelv tillite formation, correlated with the younger tillite formation in Finnmark (Siedlecka et al., 2004). Post-Varangerian time is characterized by siltstone, followed by latest Ediacaran-Cambrian deltaic and fluvial feldspathic sandstone and Early Cambrian shallow-marine quartz arenite (Nystuen, 1999).

Neoproterozoic of the Middle Allochthon

The Laksefjord Nappe Complex

The Laksefjord Nappe Complex in central Finnmark includes Paleoproterozoic basement rocks with a Meso- to Neoproterozoic metasedimentary cover stratigraphically below the c. 8,000 m thick Laksefjord Group. The Laksefjord Group starts with diamictites formed in alluvial fans, grades upwards into braided stream feldspathic sandstones (psammites) and terminates with shoreline to shelfal mudstone and siltstone (phyllites) with local carbonate interbeds. The age of the Laksefjord Group remains unknown, though a Neoproterozoic age is a reasonable assumption with possible correlation with the Løkvikfjellet Group (Siedlecka et al., 2004). Dolerite dykes penetrate the Laksefjord Group (Gayer et al., 1987).

Särv, Offerdal, Stalon, Kvittvåla, Valdres and other nappe complexes

A series of Neoproterozoic basin successions are present within the Middle Allochthon in the north-central to southern Scandinavian Caledonides. Baltican basement rocks occur as tectonic slices in several of the nappe complexes (Gee et al., 1985a) displaced about 400–600 km towards the east and southeast (e.g., Kumpulainen and Nystuen, 1985).

The Särv Nappe Complex is a major thrust unit within the central eastern Caledonides in Sweden and Norway, comprising the Neoproterozoic-Cambrian Tossåsfjället Group, deposited in the pericratonic Tossåsfjället Basin (Kumpulainen and Nystuen, 1985). Pre-Varangerian strata consist of c. 2,000 m of fluvial feldspathic sandstones with minor lacustrine shale intercalations. A dolomite formation, supposed to correlate with other late Cryogenian transgressive carbonate units (above), occurs in the middle part of the Group and is unconformably overlain by the Lillfjället tillite. This inferred Varangerian formation is succeeded by c. 2,000 m thick Ediacaran-Cambrian shale and sandstone. The Tossåsfjället Group is penetrated by the Ottfjället dolerite dykes, correlated with the Sarek Dyke Swarm in northern Sweden, c. 610 Ma (Svenningsen, 2001). Psammitic successions, some with associated carbonate beds and intruded by dolerite dykes, are present in a number of thrust sheets of the Särv Nappe Complex northwards in Sweden and in south-central Norway.

The Offerdal Nappe of the Middle Allochthon in west-central Jämtland contains a Neoproterozoic succession of about 1,500 m strongly deformed, partly mylonitized conglomerates and sandstones. The succession has been correlated with the upper part of the Risbäck Group in the Lower Allochthon, derived from a rift basin supposed to have been located adjacent to the Risbäck Basin (Plink-Björklund et al., 2005). Sandy turbidites including conglomerates, probable correlatives of the Risbäck Group, occur in the Stalon Nappe in the Kvikkjokk area (Greiling and Kumpulainen, 1989).

The Engerdalen Group of the Kvitvola Nappe Complex, filling the *Engerdalen Basin*, is characterized by up to several thousand metres thick pre-Varangerian fluvial to marine sandstone. A formation of dolomite, with evaporitic magnesite, chert and black shale, is unconformably overlain by a glacial diamictite (Koppang Fm). A several hundred meters thick Ediacaran sandstone formation succeeds the tillite. The Engerdalen Group lacks dolerite intrusions, suggesting this basin was located in a more cratonward position than the Tossåsfjället Basin (Kumpulainen and Nystuen, 1985).

The Valdres Group and the lower part of the Mellsenn Group in the Valdres Nappe Complex, represents the *Valdres Basin*, a minor rift basin formed within a terrain of high-grade gneisses and gabbroic rocks now present as crystalline thrust sheets, similar to those in the overlying Jotun Nappe Complex. The Valdres Group is dominated by more than 4,000 m thick pre-Varangerian alluvial coarse-grained arkoses and conglomerates (Nickelsen et al., 1985). A marble unit probably corresponds to the pre-Varangerian 'carbonate transgression' level, and a tillite unit on top of the group is correlated with the Moelv tillite in the Hedmark Group. It is succeeded by the Mellsenn Group, containing in the lower part late Ediacaran-Cambrian green slate and fluvial to shallow-marine sandstone.

The Heidal and Høydal groups in central South and West Norway, respectively, are dominated by psammitic rocks, cut by mafic dykes and thought to represent Neoproterozoic successions derived from remote segments of the Baltoscandian margin, or from an outboard terrane. Except for small rift basin successions (Offerdahl, Stalon, Valdres) the majority of thick metasedimentary rocks in the Middle Allochthon have the character of being pericratonic basin successions (Siedlecka et al., 2004).

Neoproterozoic of Upper Allochthon: the Seve Nappe Complex

The Seve Nappe Complex (SNC) occurs along the eastern part of the Caledonides in Sweden and northeastern Troms County in Norway. In northern Sweden, the Neoproterozoic rock suite of the SNC is dominated by psammities, quartzites and various schists with marble beds, graphitic schists, evaporitic magnesite and diamictite horizons (Siedlecka et al., 2004); further to the south SNC also contains thick marble units (Kulling, 1972).

In the northern part of the Seve Nappe Complex, c. 850 Ma anatectic granite (Paulsson and Andréasson, 2002) postdate parts of the metasedimentary rocks; Rehnstöm et al. (2002) also inferred a 637 Ma deformational event in the Caledonides of northern Sweden. The sedimentary successions of the SNC are cut by the 615–550 Ma 'Baltoscandian dolerite dyke swarms' (Paulsson and Andréasson, 2002), including the Sarek Dyke Swarm (c. 610 Ma; Svenningsen, 2001).

Stretching lineations in the Seve Nappe Complex indicate transport towards the east-southeast, and the SNC is considered to be derived from a distant position of the peri-continental Baltoscandian margin (e.g., Gee et al., 1985b).

Middle and/or Upper Allochthon: The Kalak Nappe complex of northern Finnmark

In eastern Troms County of Norway, the Seve Nappe Complex appears to pass into the several thousand meters thick Kalak Nappe Complex (KNC) of northern Finnmark, ascribed to the Middle Allochthon by Gee et al. (1985a) and, in part, to the Upper Allochthon by Zachrisson (1986).

The Kalak Nappe Complex includes slices of Precambrian crystalline rocks and metasedimentary units dominated by psammities, and including muscovite-schists, marbles, calc-silicates and graphitic schists. The Complex is intruded by mafic dykes (amphibolites), granites, pegmatites, and the alkaline magmatic suite of the Seiland Igneous Province (570–520 Ma, Corfu et al., 2007).

Crystalline basement rocks and some of the psammities are intruded by c. 980 Ma granites. Granitic rocks and migmatites fur-

thermore represent three main deformation events, c. 876–826 Ma, 710–680 Ma, and 602 Ma. Thus, the oldest part of the KNC is of early Tonian age, or even older, and the rock suit of the nappe complex has been affected by several Tonian–early Ediacaran orogenic events (e.g., Kirkland et al., 2006; Corfu et al., 2007).

The KNC has been considered to be derived from a distant northwestern position of the Baltican margin (Siedlecka et al., 2004 and references therein). However, this has been contested by Kirkland et al. (2006) and Corfu et al. (2007).

Other Neoproterozoic rocks in southern Scandinavia

The *Vättern Basin* is a small Neoproterozoic rift basin in southern Sweden, running NNE-SSW along the Lake Vättern. The Vingsö Group (c. 1,000 m) consists of deltaic sandstone and marine shale, debris-flow and fluvial conglomerates followed by interchanging marine sandstone and shale beds and dolomitic limestone with stromatolites in the uppermost part of the Group. The dolomite is correlated with other pre-Varangerian carbonate formations in Fennoscandia, East Greenland and Svalbard (Vidal, 1985).

The *Gardnos Impact Crater* (French et al., 1997) in central-south Norway was likely formed in Neoproterozoic time when a bolide fell down in a shallow sea (French et al., 1997), perhaps an epicontinental sea formed during the pre-Varangerian 'carbonate transgression'.

The *Egersund dolerite dykes* (c. 616 Ma) in the Precambrian basement of southwestern Norway is interpreted to reflect initiation of the Iapetus Ocean (Bingen et al., 1998). These dykes act as reference rocks for pre-Iapetus Neoproterozoic dolerite dyke swarms in the Caledonian nappes.

The *Fen and Alnö carbonatite complexes* in South Norway and central-east Sweden, respectively, originated at small volcanic centres for about 580 Ma ago and are thought to be related to continental crustal break-up at the end of the Precambrian (Meert et al. 2007).

Neoproterozoic of East Greenland

The Neoproterozoic deposits of East Greenland occur in several scattered outcrops in central East Greenland and eastern North Greenland (Figure 2). The strata occur in three different structural settings: (1) as relatively thin autochthonous to parautochthonous, Cryogenian-Ediacaran, pericratonic sandstone-carbonate deposits in the Caledonian foreland in the west, (2) as thin, local Ediacaran tillites, resting on Paleoproterozoic basement in tectonic windows in the nappe region, and as (3) up to several thousand metres thick ?uppermost Tonian to lower Paleozoic rift-basin successions within Caledonian thrust sheets (Higgins et al., 2001).

The outcrops around Kejser Joseph Fjord and Kong Oscar Fjord in central East Greenland hold the most complete sections, with the Eleonore Bay Supergroup (Figure 6) as a reference succession for the Neoproterozoic in East Greenland (Sønderholm and Tirsgaard 1993).

Sønderholm and Tirsgaard (1993) subdivided the up to 16 km thick Eleonore Bay Supergroup, from base upwards, into the Nathorst Land (up to c. 11,000 m), the Lyell Land (up to c. 3,000 m), the Ymer Ø (900–1,500 m) and the Andrée Land (900–1,500 m) groups, overlain by the Tillite Group (c. 800 m).

A slight angular unconformity separates the Eleonore Bay Supergroup from the underlying latest Mesoproterozoic/Early Neoproterozoic Krummedal supracrustal succession. The lower boundary of the supergroup is, however, in most localities obscured by deformation, metamorphism and Caledonian granite intrusions, or by late- to post-Caledonian extensional faults.

The Nathorst Land and Lyell Land groups consist of alternating sandstone and mudstone. Both fluvial and marine settings have been proposed for the Nathorst Land Group, whereas marine shelf setting is suggested for the Lyell Land Group, dominated by fine-grained

sandstone and mudstone (Sønderholm and Tirsgaard 1993). An about 6,300 m thick succession of sandstone and mudstone (Petermann Bjerg Gp) around Petermann Bjerg is variably metamorphosed and intruded by Caledonian granites. The succession is correlated with the two lowermost groups of the Eleonore Bay Supergroup.

Carbonate platform, slope and deep-marine basinal environments dominate the Ymer Ø and Andrée Land groups. A peritidal environment of arid climatic setting is inferred for carbonate beds in the upper part of Andrée Land Group, sharply overlain by the first glacial diamictite (Ulvesø Fm, c. 50 m) in the Tillite Group. The Ulvesø glacial formation is succeeded by offshore dolomitic shales and a sandstone-shale succession (Arena Fm, c. 200 m). The second glacial unit (Storeelv Fm, c. 200 m) is also capped by offshore dolomitic shale. Both glacial formations represent mixed terrigenous and glaciomarine deposits and are correlated with the Petrov tillite member (Elbobreen Fm) and the Wilsonbreen Formation, respectively, on northeastern Svalbard (Fairchild and Hambrey, 1995) (see below).

In eastern North Greenland, a Neoproterozoic rift basin, the *Hekla Sund Basin*, existed at the eastern Laurentian margin. The Hekla Sund Basin was bordered to the west by a down-to-the-E master fault. East of this fault, about 7 km of syn-rift deposits (Rivieradal Gp) make up the lower part of the basin succession. In the proximal, western part of the basin several upward-coarsening fan delta units occur. Sandstones, pelites, semipelites and calcareous pelites make up the eastern distal parts of the Rivieradal Group (Higgins et al., 2001).

The Rivieradal Group is overlain by the post-rift Hagen Fjord Group, in lower part composed of inter- to supratidal siltstones, sandstones, stromatolitic dolostones (Campanuladal Fm) and reddish brown limestone (Kap Bernhard Fm), and in upper part of dolostones of the Fyn Sø Formation. The carbonate formations record carbonate-platform settings. The post-rift succession is also identified in a pericratonic position on the autochthonous rift-shoulder west of the Hecla Sund Basin. A marked hiatus separates the Fyns Sø Formation from the overlying early Cambrian Kap Holbæk Formation. Glacial deposits are not recorded from the Hekla Sund Basin succession (Higgins et al., 2001).

The age of the Rivieradal and Hagen Fjord groups and their relationship to the Eleonore Bay Supergroup is uncertain. Higgins et al. (2001) proposed, as the most likely correlation, to link the change from the Rivieradal Group to the transgressive Hagen Fjord Group to the shift from siliciclastic facies of the Nathorst Land and Lyell Land groups to the carbonate dominated deposits of the Ymer Ø and Andrée Land groups in the Eleonore Bay Supergroup.

Neither rift-related dolerite dykes, nor volcanic or pyroclastic deposits have been identified in the Eleonore Bay Supergroup and its correlatives in the Hekla Sund Basin succession. This probably indicates that the Neoproterozoic basins of the eastern Laurentian mar-

gin in East Greenland were located in a cratonward position relative to the rift zone that later developed into sea-floor spreading and the opening of the Iapetus.

Neoproterozoic of Svalbard

Three terranes dominate the Caledonian bedrock of Svalbard—Northeastern, Northwestern and Southwestern, making up the pre-Devonian ('Hecla Hoek') basement.

Neoproterozoic sedimentary successions are present within two of these terranes (Northeastern and Southwestern Terranes). The most complete and best studied sections (Harland et al., 1993; Halverson et al. 2004, 2005; Maloof et al. 2006) occur within the Northeastern Terrane (Nordaustlandet and eastern Ny Friesland). Diamictites, of which some are interpreted to be glacial, are interbedded with a wide range of different lithologies in the Southwestern Terrane (Harland et al., 1997). Deciphering stratigraphy and depositional environments within the latter two terranes is difficult due to Caledonian deformation and metamorphism, as well as later Eocene contractional and extensional deformation.

Northeastern Terrane

The Northeastern Terrane exposes a 7 km thick succession of Neoproterozoic–Middle Ordovician strata. According to Harland (1997), the Neoproterozoic part consists, from base upwards of the Veteranen (3800 m), Akademikerbreen (1350–2500 m) and Polarisbreen (767 m) groups. An extensional fault separates the Veteranen Group from the underlying Planetfjella Group, a mixed sedimentary and volcanic unit of unknown depositional age and origin.

The Veteranen Group consists, in the lower part, of quartzite and subordinate limestone and in the upper part of quartzite, greywacke and shale. The Akademikerbreen Group is characterized by dolostones and limestones, partly stromatolitic; well preserved cyanobacteria in chert are correlated to the 700–800 Ma Bitter Springs biota of Australia (Knoll and Walter, 1992). The Polarisbreen Group, succeeding conformably the Akademikerbreen Group, is dominated by shale and carbonate beds with two distinct stratigraphic levels of glacial diamictites and shale with dropstones, interpreted to represent subglacial till and glaciomarine mud, respectively.

The glaciogenic Polarisbreen Group and its underlying Akademikerbreen Group have recently gained great interest with regard to age and dynamics of the Earth's Neoproterozoic glaciations (e.g., Halverson et al., 2004). The lower, Petrovbreen Member (Elbobreen Fm) in the Polarisbreen Group is a thin glaciomarine diamictite that lacks a cap carbonate. About 350–400 m shale and siltstone separate this glaciogenic unit from the younger and thicker Wilsonbreen Formation which comprises terrestrial ice-contact deposits and is draped by a 3–18 m thick transgressive cap dolostone. The ^{13}C isotopic profile of the capping carbonate unit is identical to that of post-Marinoan cap carbonates elsewhere (Halverson et al. 2004). Halverson et al. (2004, 2005) interpreted the Petrovbreen and Wilsonbreen glacial units to represent the first and last phases of the Marinoan glaciation, respectively. Halverson et al. (2005) argued that the Sturtian glaciation might be present by the onset of the Polarisbreen Group, but this correlation is undocumented.

Maloof et al. (2006) suggested that the Veteranen Group repre-

Figure 6 The Neoproterozoic Eleonore Bay Supergroup in the southeast-facing cliffs of Berzelius Bjerg (Segelsølskapets Fjord), East Greenland. The brownish weathering, cliff-forming lower part of the section with thin white sandstone beds represents the Nathorst Land and Lyell Land Groups. The change in slope in the upper part marks the transition to the carbonate dominated Ymer Ø Group. Height of wall c. 1,500 m.

sents syn-rift sediments linked to a rift phase in the time interval c. 850–825 Ma, an interpretation in agreement with 940 Ma U-Pb ages of basement granites of Nordaustlandet (Gee et al., 1995; Johansson et al., 2001).

Southwestern Terrane

Large areas of West-Spitsbergen and Prins Karls Forland are composed of intensely deformed, greenschist-grade carbonate-siliciclastic deposits with diamictites and pebbly siltstones. Two glaciogenic diamictite formations in the Kapp Lyell Group have been correlated with the Petrovreen and Wilsonbreen glacial units in the Polarisbreen Group of NE Svalbard, respectively (Harland et al., 1993; Harland, 1997). Abrupt lateral variations in thickness and facies indicate that the rocks in the lower part of the succession were deposited in discontinuous, fault-bounded deep-marine basins. As neither cap carbonates, nor chemostratigraphic data exist from this part of Svalbard, correlation with other Neoproterozoic successions in the North Atlantic region is uncertain.

Bjørnøya

Rocks believed to be Neoproterozoic in age (Russehamna Fm) also exist on Bjørnøya, but their depositional age is uncertain, although microfossils indicate an Ediacaran age for parts of the succession (Harland, 1997).

Discussion

Relative position of the segments of Baltica and Laurentia margins

The relative position between Baltica and Laurentia after the Rodinia break-up has been much debated; right-way-up and upside-down orientations (current coordinates) of Baltica have been suggested. The present data set appear to fit best the right-way-up model with the Baltoscandian margin juxtaposed the Scotland-SE Greenland segment of Laurentia (e.g., Cawood and Pisarevsky, 2006; Li et al., 2008). Within this paleogeographic framework (Figure 1), Svalbard's Southwestern Terrane was located north of Greenland in Neoproterozoic time (e.g., Fairchild and Hambrey, 1995). This terrane, with its deep-marine glacial debris-flow deposits, is today located geographically between Ediacaran shelf deposits in the Northeastern Terrane of Svalbard and in East Greenland. A possible original site of these western terranes on Svalbard might be to the east of present central East Greenland, representing a deep-marine trough east of the shelfal environment represented by the Ediacaran succession in the Eleonore Bay Group, as proposed by Andresen (2004). Later (Devonian) strike-slip movements may then have displaced Svalbard's western terranes to their present positions.

The Seve and Kalak nappe complexes: Baltican or non-Baltican origin?

The Kalak and Seve nappe complexes have long been considered of Baltican affinity, displaced 400 km or more from the north-western Baltoscandian margin. The rock suites of the two nappe complexes have been inferred to be genetically related within a 'Seve-Kalak Superterrane' (Andreasson et al., 1998). A Baltican origin for the nappe complexes is argued by general similarity in lithology with the sedimentary successions of the well-known Neoproterozoic of the Baltoscandian margin, as well as from their dolerite dyke swarms (c. 600 Ma), typical of crustal segments of unquestioned Baltoscandian origin. Roberts (2007) argued from paleo-current data from fluvial psammites in lower thrust sheets of the KCN that sedimentary transport was from south to north, thus linking a Baltic source to a KNC basin sink.

On the other hand, the Tonian to Cambrian complex depositional, deformational and igneous history encountered in KNC are exotic to the autochthon of central and northern parts of the Baltoscandian margin; for this reason a Laurentian or peri-Gondwanan ancestry has been suggested for the KNC and, perhaps the whole Seve-Kalak Superterrane (Corfu et al., 2007; Kirkland et al., 2006, 2007).

Siedlecka et al. (2004) suggested that the KNC, in terms of Cryogenian-Cambrian compressional and extensional events, might be related to a complexity of plate-tectonic movements along the distant northern Baltoscandian margin, similar to those along the Timanian margin.

Basin development

The several thousand metres thick Tonian to early Cryogenian successions along the Timanian and Baltoscandian margins and the eastern margin of Laurentia (Figure 3) reflect deeply subsiding *continental to marine basins*. Initial Tonian or early Cryogenian basins might have been pre-rift sag basins that later developed into rift or/and strike-slip basins. The enormous volumes of terrigenous clastic sediments reflect high hinterland relief, effective mechanical weathering and erosion with high runoff, likely in humid climatic conditions. One may speculate that montane glaciation at times may have contributed to the high sediment production.

Cryogenian *pericratonic basins* (TVR, Tossåsfjället, Engerdalen, East Greenland, Northeastern Svalbard and others) formed when rift basins were still active in more cratonward positions of Baltica (Risbäck, Valdres, Hedmark, Vättern basins). The 'carbonate transgression' took place within this stage; pre-Marinoan (Varangerian) carbonate platforms along the eastern Laurentian margin may be related to the same sea-level high-stand, as indicated by achritarch correlations (Vidal, 1985; Knoll and Walter, 1992). Evaporitic magnesite, dolomite and chert, together with very low siliciclastic sediment input indicate high-temperature conditions in an arid climatic region.

Cryogenian(?) to Ediacaran glaciations reflect a dramatic change in climate. Basal tills were deposited on glaciated cratons and upon pericratonic strata (TVR, Tossåsfjället, Engerdalen, East Greenland and Northeast Svalbard) and rift basin successions (Risbäck, Valdres, Hedmark). The Laurentian marine basins of Greenland and Svalbard still possessed space for infill of very thick accumulations of terrestrial glacial and glaciomarine deposits. Correlation of glacial units and their absolute ages remain very uncertain (cf. Meert, 2007).

Post-glacial Ediacaran to Cambrian basin development reveals similar trends along the Baltoscandian margin, East Greenland and Svalbard. In the Baltica domain, but not in the Arctic Laurentian domain, dolerite dyke intrusions (c. 590–615 Ma) are supposed to reflect the final break-up of Rodinia, leading to the birth of the Iapetus Ocean in the region. Shoreline retrogradation and flooding of the denudated continents took place. Compressional tectonics still operated along some margin segments, as within the Timanian margin. The Ediacaran-Cambrian magmatism in the Seiland Igneous Province and Fen and Alnö carbonatite volcanoes indicate localized high mantle heat flow accompanying final break-up and early Iapetus sea-floor spreading.

Concluding remarks

A series of problems are left for future studies of the Neoproterozoic in the region covered by this review. Better constraints are needed of (i) the break-up history of Rodinia, (ii) depositional systems, biostratigraphy and palaeoecology, and (iii) absolute age and correlation of the Neoproterozoic glacial units. Despite these major problems, we conclude that the Neoproterozoic of the northwesternmost Timanian margin in eastern Finnmark, Baltoscandian margin, central East Greenland,

eastern North Greenland and Svalbard can be subdivided into the following major stages of basin development:

1. Tonian to early Cryogenian (c. 900–850 Ma). Initial basin formation (sag-basins?) along northeastern Baltica and eastern Laurentia.
2. Cryogenian (c. 850–630 Ma). Initial break-up of Rodinia, with formation of rift- and strike-slip basins along future margins of northern Baltica and eastern Laurentia. Compressional tectonics along some plate margins. General overall shift in climate from humid to warm and arid. Development of wide epicratonic basins.
3. Latest Cryogenian to Early Ediacaran (c. 630–580 Ma). Main interval of overall climatic cooling and glaciations, generally referred to the Varangerian Ice Age in northern Baltica, central Eastern Greenland and Svalbard. The oldest Varangerian glacial units may correspond to the Marinoan (c. 630 Ma) and the youngest to the Gaskiers (c. 580 Ma).
4. Ediacaran (c. 615–542 Ma). Final break-up of Rodinia with Iapetus-related rifting and dolerite dyke swarms, magmatism in the Seiland Igneous Province and the intra-Baltica plate Fen and Alnö carbonatite volcanic centres. Compressional tectonics along the Timanian margin, possibly including the northernmost segment of the Baltoscandian margin. Pericratonic basins changed from continental and paralic to open-marine epicontinental seas in Cambrian times.

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