Earth-Science Reviews 192 (2019) 513–528

Contents lists available at ScienceDirect

Earth-Science Reviews

journal homepage: www.elsevier.com/locate/earscirev

A review and reinterpretation of the architecture of the South and South-Central Scandinavian Caledonides—A magma-poor to magma-rich transition and the significance of the reactivation of rift inherited structures

Johannes Jakob*, Torgeir B. Andersen, Hans Jørgen Kjøll

The Centre for Earth Evolution and Dynamics, Department of Geosciences, University of Oslo, Norway

ARTICLE INFO

Keywords:
(6) Scandinavian Caledonides
Rift-inheritance
Hyperextension
Magma-poor to magma-rich transition, ocean-continent transition, tectonostratigraphy

ABSTRACT

Interpretations of the pre-Caledonian rifted margin of Baltica commonly reconstruct it as a simple, tapering, wedge-shaped continental margin dissected by half graben, with progressively more rift-related magmas towards the ocean-continent transition zone. It is also interpreted to have had that simple architecture along-strike the whole length of the margin. However, present-day rifted margins show a more complex architecture, dominated by different and partly diachronous segments both along and across strike. Here, we show that the composition and the architecture of the Baltican-derived nappes of the South and South Central Scandinavian Caledonides are to a large extend rift-inherited. Compositional variations of nappes in similar tectonostratigraphic positions can be ascribed to variations along-strike the rifted margin, including a magma-rich, a magma-rich to magma-poor transition zone, and a magma-poor segment of the margin. The architecture of the nappe stack that includes the Baltican-derived nappes was formed as a result of the reactivation of rift-inherited structures and the stacking of rift domains during the Caledonian Orogeny.

1. Introduction

The present architecture of the Scandinavian Caledonides is principally the result of the Silurian–Devonian Scandian continental collision of Baltica-Avalonia with Laurentia, the subsequent late- to post-orogenic extension, and deep erosion (e.g. Fossen, 2010; Corfu et al., 2014). During the Scandian collision and in parts during the early-Caledonian events affecting the distal margin of Baltica, the rifted continental margin of Baltica was deeply buried beneath Laurentia and a complex stack of nappes was thrust over great distances towards the south-east onto Baltica. The underlying autochthon comprises Archean to Palaeoproterozoic basement in the north and Mesoproterozoic basement in the south that is covered by (par)autochthonous metasediments of Neoproterozoic to latest Silurian age. The nappe-stack comprises allochthons of Baltican, transitional oceanic-continental, oceanic, and Laurentian affinity.

The allochthons of Baltican affinity include Neoproterozoic pre- to post-rift successions as well as post-rift continental margin deposits of Cambrian to Silurian age and foreland basin sediments deposited in front of and incorporated into the advancing thrust sheets during the Scandian Orogeny (e.g. Nystuen et al., 2008). Baltican-derived basement and basement-cover nappes are commonly referred to as the Lower and Middle Allochthons and are interpreted to contain transgressive sequences deposited along the Iapetus margin of Baltica (Roberts and Gee, 1985; Stephens and Gee, 1989). Ophiolite/island arc assemblages and nappes of Laurentian affinity are commonly referred to as the Upper and Uppermost Allochthons, respectively.

In the traditional tectonostratigraphic scheme, all units with ocean-floor-like lithologies are referred to as ophiolites or dismembered ophiolites and are interpreted to have initially formed in an ocean, outboard of all rocks with continental affinity (Roberts and Gee, 1985). The traditional interpretations assume that a mostly uniform and continuous tectonostratigraphy with the same palaeogeographic significance can be traced along the entire length of the Scandinavian Caledonides (e.g. Gee et al., 2016). However, present-day understanding of continental margins and their remnants within mountain belts is that rifted margins have a more complex architecture, dominated by different and partly diachronous segments both along and across strike. Such segmentations may include very different fault geometries and structural styles, producing major variations in width and length of basins and highs as well as more fundamental and larger-scale variations with magma-poor and magma-rich segments (e.g. Mohn et al., 2010; Péron-Pinvidic and Manatschal, 2010).

On a regional scale, passive margins may also be decorated with

---

* Corresponding author.
E-mail address: johannes.jakob@geo.uio.no (J. Jakob).

https://doi.org/10.1016/j.earscirev.2019.01.004
Received 13 June 2018; Received in revised form 4 January 2019; Accepted 8 January 2019
Available online 10 January 2019
0012-8252/ © 2019 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY license (http://creativecommons.org/licenses/BY/4.0/).

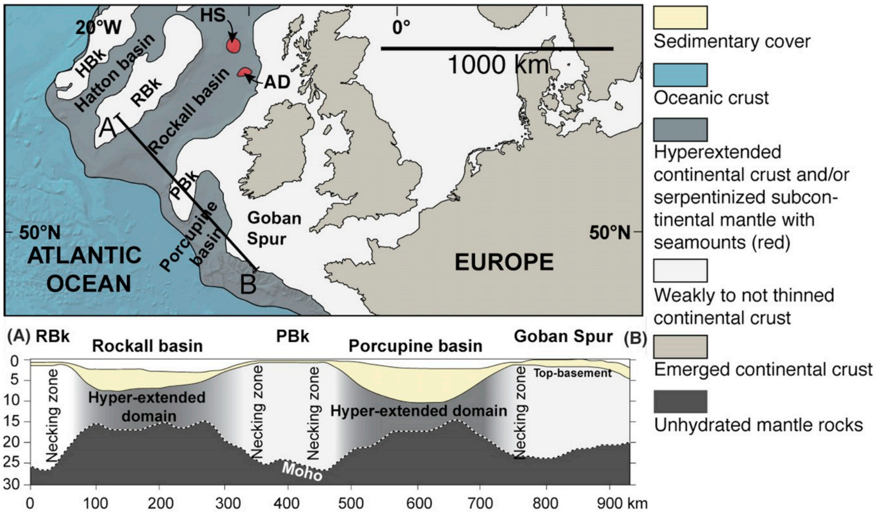


Fig. 1. Map of the hyperextended domains of the southern North Atlantic. Figure redrawn after Mohn et al. (2014); map originally modified from Péron-Pinvidic and Manatschal (2010) and Lundin and Doré (2011); profile modified from Welford et al. (2012). Please note the presence of seamounts in the northern Rockall basin. HBk, Hatton Bank; RBk, Rockall Bank; PBk, Porcupine Bank; AD, Anton Dohrn Seamount; HS, Hebrides Seamount.

relatively narrow failed-rift basins that separate thicker and variably sized continental slivers or blocks from the adjacent continent (e.g. Péron-Pinvidic and Manatschal, 2010; Chenin et al., 2017). Such basins may be floored by stretched to hyperextended/hyper-thinned continental crust, transitional crust or embryonic oceanic crust. The Orphan, Porcupine and Rockall basins off-shore Newfoundland and the British and Irish Isles as well as the Norway Basin adjacent to the Jan Mayen continental ridge and the margin of Norway, are good present-day examples (Kimbell et al., 2017; Péron-Pinvidic et al., 2012). Within the thinned crust, guyots may also be present, e.g. the Anton Dohrn and Hebrides seamounts or the Rosemary bank in the northern continuation of the Rockall trough (Fig. 1). These seamounts are attributed to episodic magmatic pulses of the Iceland plume during opening of the North Atlantic (O'Connor et al., 2000). Another modern-day analogue of an across-strike, complexly structured, rifted margin is provided by the Red Sea detachment systems in Eritrea (Talbot and Ghebreab, 1997). Later inversion and incorporation of such complexly configured passive margins into a mountain belt, as discussed by Beltrando et al. (2014), results in a tectonostratigraphy with laterally changing nappe characteristics that may include previous extensional slivers of continental basement associated with hyperextended deep basins, sediments with or without spreading-related magmatism, and in several cases also exhumed hydrated/carbonated mantle peridotites (e.g. Müntener et al., 2009). A structural succession with such characteristics does not easily comply with the traditional, belt-long, tectonostratigraphic correlations and the traditional nomenclature used in the Scandinavian Caledonides.

Here, we describe and discuss a re-interpretation of the tectonostratigraphy of the South and South-Central Scandinavian Caledonides. A key area for the understanding of the architecture and re-interpretation of the tectonostratigraphy is where the southern magma-poor segment (Andersen et al., 2012; Jakob et al., 2017a, 2017b) faces the northern magma-rich segment (e.g. Andréasson, 1994; Tegner et al., 2019; Kjøll et al., in press). We suggest that lithostratigraphic units, previously assigned to the Upper Allochthon and hence of suspect to outboard status have typical characteristics of magma-poor and magma-rich continental margins and ocean-continent transitions (OCT). In the Caledonides, these rocks are, however, variably overprinted by orogenic deformation and metamorphism (e.g. Jakob et al., 2017b, Kjøll et al. in press). Nevertheless, many of their lithological characteristics are well-enough preserved to be compared with present-day passive margins and examples of fossil OCT zones in other mountain belts, for example the Alps and the Pyrenees (e.g. Lagabrielle et al., 2010; Beltrando et al., 2014).

We show that a gradual transition from the magma-rich to the magma-poor segment was related to the formation of a large Jotun-type basement microcontinent/continental sliver and its termination in the Gudbrandsdalen area in central-south Norway. Furthermore, we also suggest that the nappes of Baltican affinity can be divided into rift domains that are well-established from present-day rifted margins, i.e. a proximal/necking domain, an extended domain; a distal/outer domain, and a microcontinent.

2. Tectonostratigraphic units in the South and South-Central Caledonides

2.1. The South Scandinavian Caledonides

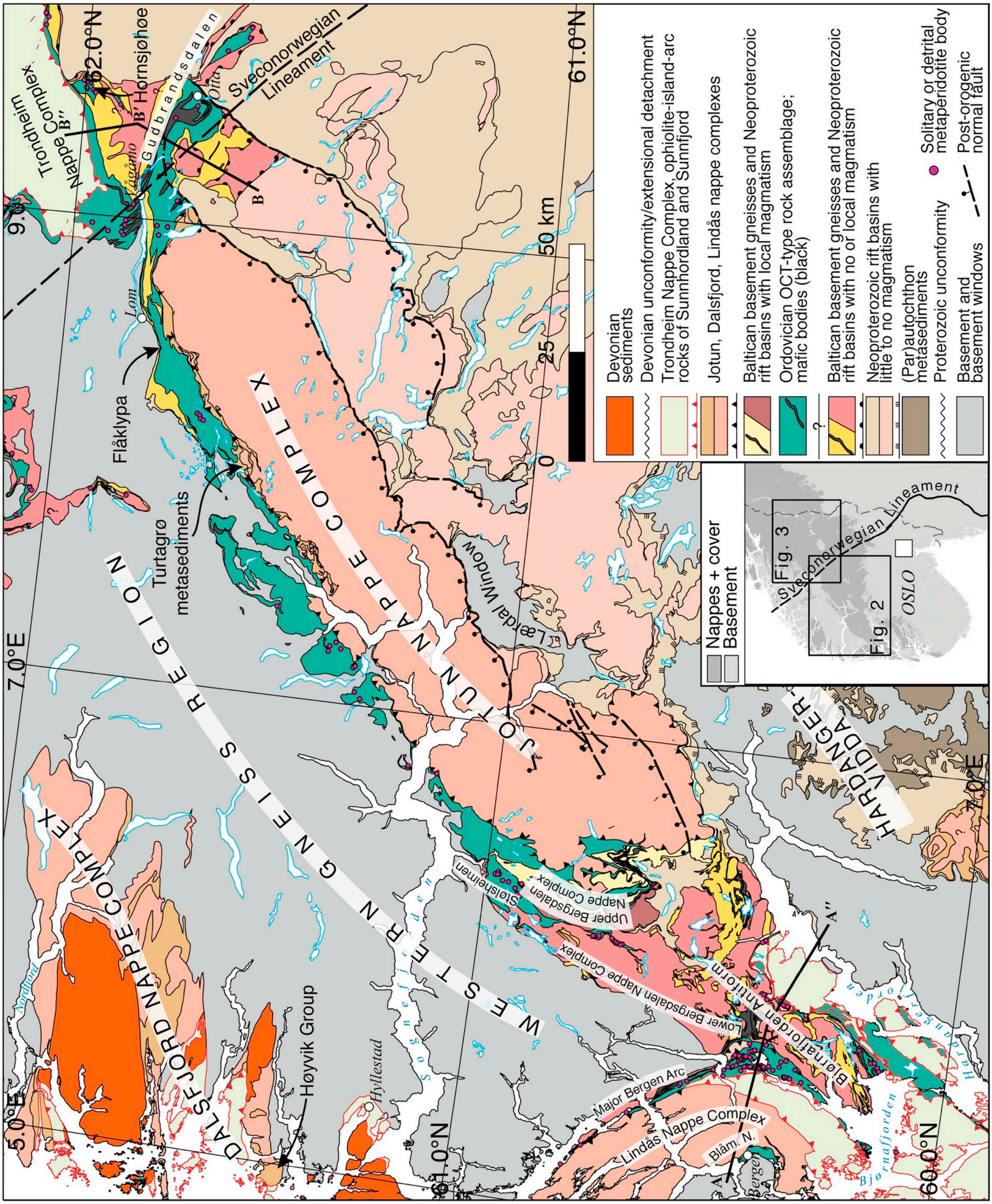
2.1.1. Neoproterozoic syn-rift basins with little to no syn-rift magmatic rocks

In southern Norway (Fig. 2), Late Proterozoic to Lower Palaeozoic continentally derived deposits locally lie unconformable on Baltican basement or on allochthonous crystalline rocks (Bingen et al., 2011). These include the Osen-Røa, Kvitvola, Synnfjell, Valdres NCs (Nystuen, 1983; Nickelsen et al., 1985). The Late Proterozoic successions are interpreted to represent proximal pre- and *syn*-rift sediments, which vary from fluvial to marine deposits (Nickelsen et al., 1985; Nystuen et al., 2008). Marinoan (~630 Ma) and/or the younger Gaskiers glaciogenic deposits (~580 Ma) are present in several of these units (e.g. Lamminen et al., 2015; Nystuen et al., 2008). In some cases, the Neoproterozoic sediments are stratigraphically overlain by Cambrian to Lower Ordovician post-rift black-shale and carbonate successions, which in turn, are locally overlain by Lower to Middle Ordovician turbidites that grade from distal at the base to proximal at the top (e.g. Greiling and Garfunkel, 2007; Nickelsen et al., 1985; Owen et al., 1990).

In other areas, mostly in south-western Norway, the fossiliferous Cambrian–Ordovician overlies a glacially striated basement floor in Hardangervidda (Fig. 2) and are in turn overthrust by mica schists (Holmasjø Formation) of unknown age (see Gabrielsen et al., 2015). With the exception of the ~616 Ma Egersund mafic dykes, minor volcanics and dykes in the Hedmark basin and a horizon of basaltic volcanics on Hardangervidda (Nystuen, 1987; Bingen et al., 1998; Andresen and Gabrielsen, 1979), mafic magmatic rocks are absent in the Baltican basement and the Neoproterozoic–Ordovician succession in the foreland area of South-Scandinavia.

2.1.2. The Lower Bergsdalen Nappe

The Lower Bergsdalen Nappe includes crystalline basement and Proterozoic metasediments, which are associated with metamorphosed basic to intermediate plutons and volcanics (Kvale, 1945; Fossen, 1993). Interleaved with the coarse-grained metasediments and



(continued on next page)

Fig. 2. Tectonostratigraphic map of the South Scandinavian Caledonides between Bergen and Gudbrandsdalen showing the first-order thrust of the main tectonic units. Cross section shown in Fig. 5. The Sunnfjord region encompasses the fjord region E and NE of the island Atløy, which is marked with "Høyvik Group".

magmatic rocks are phyllites and mica schists (Kvale, 1945). The metasediments are mainly coarse-grained meta-arkoses and quartzites. Some of the granites in the crystalline sheets were dated by the Rb-Sr whole-rock method at 1274–953 Ma (Pringle et al., 1975; Gray, 1978). Kvale (1945) interpreted the quartzites to be the oldest rocks of the Lower Bergsdalen Nappe because mafic and felsic magmas intrude into the metasediments. Consequently, the quartzites were interpreted to be pre-Sveconorwegian in age (> 1274 Ma).

The Lower Bergsdalen Nappe is positioned structurally above the Western Gneiss Region (WGR), a thin discontinuous cover of mica schists (Wennberg et al., 1998) and allochthonous metasediments, which are possibly equivalent to the Synnfjell NC. It is structurally overlain by a unit of metasediments that contain a number of detrital and solitary metaperidotite bodies (see Section 2.1.3). The Lower Bergsdalen Nappe can be traced around the core of the Bjørnafjorden Antiform (Fig. 2), as originally defined by Kvale (1945).

2.1.3. *Metaperidotite-bearing metasedimentary complexes*

Between the Bergen Arcs and Lom (Fig. 2) a prominent metasediment-dominated complex, which contains numerous mantle-derived metaperidotite lenses (< 2 km long) and local clastic serpentinites, including detrital breccias, conglomerates, and sandstones has been mapped (Andersen et al., 2012). The metasedimentary matrix is dominated by originally fine-grained sediments, now mica-schist and phyllite. Because of its mixed character, this unit has been non-genetically referred to as a mélange by Andersen et al., 2012; Jakob et al., 2017a, 2017b. However, to avoid confusion with other metaperidotite-bearing mélanges, such as those that have been formed at the plate interface in subduction zones and because of its resemblance with reworked OCT assemblages in other mountain belts (Andersen et al., 2012; Jakob et al., 2017a, 2017b; Beltrando et al., 2014), we refer to this unit as an OCT assemblage.

The OCT assemblage structurally overlies the WGR and Lower Bergsdalen NC. From the Major Bergen Arc and around the Bjørnafjorden Antiform, it can be traced below both the allochthonous crystalline rocks of the Lindås NC (Section 2.1.5), the Upper Bergsdalen NC (Section 2.1.4), as well as the main ophiolite/island-arc nappe complexes of the Iapetus (Section 2.1.6). From Stølsheimen across Sognefjorden, NE-wards to Lom (Fig. 2), the same OCT unit has been mapped continuously below the western flank of the Jotun NC.

The mostly pelitic metasediments also contain lenses of metaconglomerate and metasandstone as well as thin calcareous horizons, up to 40 km long and thin (< 1 km) discontinuous sheets of Proterozoic gneisses, minor gabbro and granodiorite of Late Cambrian to early Middle Ordovician age (487 to 471 Ma) and lenses of undated mafic rocks in the SW (Jakob et al., 2017b). Conglomerates and sandstones with a continental source (quartzite, vein quartz, granite clasts, one dated at 1033 Ma) indicate a Baltican-affine source (Andersen et al., 2012). Detrital zircons show that sedimentation continued at least into the Middle Ordovician (468 Ma) (Slama and Pedersen, 2015).

Late Scandian (~427 to 415 Ma) syn-orogenic granitoids intrude both the metasediments of the Major Bergen Arc, including the OCT assemblage, as well as the Jotun and Lindås NCs in western Norway (Austrheim, 1990; Jakob et al., 2017a; Wennberg et al., 2001; Lundmark and Corfu, 2007). The mafic and granitoid intrusives, which occur near the southern termination of the Jotun NC, in the Major Bergen Arc, and at Stølsheimen are unknown between Stølsheimen and Lom (Fig. 2).

The entire OCT assemblage experienced upper greenschist to amphibolite facies metamorphism during the Scandian Orogeny after ~430 Ma (Jakob et al., 2017a, 2017b). Because of its characteristic lithological assemblage that resembles those of inverted magma-poor hyperextended margins in other orogens (e.g. Beltrando et al., 2014), the OCT assemblage is interpreted to have formed by pre-Scandian hyperextension and exhumation of subcontinental mantle or by the reworking of a magma-poor hyperextended rifted margin in the Ordovician (Andersen et al., 2012; Jakob et al., 2017b).

2.1.4. *The Upper Bergsdalen and Blåmannen nappes*

The Upper Bergsdalen NC represents a second sequence of allochthonous Baltican basement gneisses and metamorphosed continental margin sequences that are intercalated with Lower Palaeozoic phyllites and mica schists; similar to the Lower Bergsdalen Nappe (Kvale, 1945). The southern part of the Upper Bergsdalen NC is structurally overlain by the Jotun NC (Section 2.1.5), whereas south of Sognefjorden, the rocks of the Upper Bergsdalen NC trail out into the mica schists of the OCT assemblage (Fig. 2). The metaperidotites of the OCT assemblage, however, consistently occur structurally below the Upper Bergsdalen NC. The lower thrust sheets of the Upper Bergsdalen NC are dominated by crystalline gneisses whereas the upper thrust sheets are mostly composed of metasediments that are locally associated with mafic igneous rocks.

A meta-rhyolite of the Upper Bergsdalen NC was dated at 1219 ± 111 Ma (Rb-Sr whole rock analysis, Gray, 1978). The magmatic history of the Upper Bergsdalen NC is apparently similar to that of the Lower Bergsdalen Nappe. However, a number of undated mafic sheets and dykes cutting metasediments occur in both of the Bergsdalen nappes, and their complete Proterozoic and younger (?) intrusive history is not yet known. The Blåmannen Nappe in the minor Bergen Arc is another sliver of basement-cover rocks that structurally overlies the OCT assemblage. It consists of allochthonous crystalline basement that is unconformably overlain by a sedimentary sequence, including a tillite, that is suggested to have been deposited in the Proterozoic (Fossen, 1988, 1989).

2.1.5. *The Jotun, Dalsfjord and Lindås nappe complexes*

The Jotun, Dalsfjord and Lindås NCs are large nappes of crystalline basement of Baltican affinity (Fig. 2), some of which are associated with or partly unconformably overlain by Neoproterozoic continental margin sequences, including the Turtagrø metasediments on the western flank of the Jotun NC and the Høyvik Group in the Dalsfjord NC (Heim et al., 1977; Nickelsen et al., 1985; Andersen et al., 1998). The crystalline rocks of these NCs are Mesoproterozoic in age and are dominantly anorthosite-mangerite-charnockite-granite (AMCG) magmatic rocks, which experienced high-grade metamorphism during the Sveconorwegian orogeny (e.g. Austrheim, 1987; Corfu and Emmet, 1992; Bingen et al., 2001; Corfu and Andersen, 2002; Lundmark and Corfu, 2007, 2008).

Unlike the continental metasediments in the Osen-Røa, Kvitvola, Synnfjell and Valdres nappes, the Høyvik Group of the Dalsfjord NC contains a mid-ocean ridge-type mafic dyke-swarm and minor pillow-basalts at high stratigraphic levels (Andersen et al., 1998). The Høyvik Group and the dykes were deformed and metamorphosed before the deposition of the Middle Silurian (Wenlock) Herland Group (Andersen et al., 1998). ^{40}Ar/^{39}Ar cooling ages of phengitic mica in the Høyvik metasediments show that the deformation occurred before 447–449 Ma (Andersen et al., 1998; Eide et al., 1999). The Herland Group metasandstones and metaconglomerates are unconformably overlain by the Sunnfjord obduction mélange and the ~443 Ma Solund-Stavfjord Ophiolite Complex (Andersen et al., 1990; Furnes et al., 1990; Dunning and Pedersen, 1988). The Herland Group deposition and transgression, and the deposition of the Sunnfjord mélange is interpreted to herald the obduction and emplacement of the Solund-Stavfjord ophiolite (Andersen et al., 1990; Skjerlie and Furnes, 1990).

The Lindås NC is another AMCG basement nappe of Baltican affinity, which is structurally positioned above the OCT assemblage (Fig. 2). The composition and age of the Lindås NC is similar to those of the Dalsfjord NCs. The north-western trailing end of the Lindås NC contains ~430 Ma eclogites (Austrheim, 1990; Glodny et al., 2008) indicating an early Scandian deep burial and metamorphism of the Lindås NC. Unlike the Dalsfjord NCs, the Lindås NC contains minor Late Scandian (430–418 Ma) *syn*-orogenic granitoids (Austrheim, 1990; Wennberg et al., 1999, Kühn et al., 2002).

The Jotun NC is a large sheet of crystalline mostly AMCG rocks that is similar to those discussed-above. On its western flank, the Jotun NC includes highly strained metasediments, which are referred to as the Turtagrø metasediments. The Turtagrø metasediments are similar to the sparagmites of the Valdres NC and are apparently also free of syn-rift magmatic rocks (Koestler, 1983). Locally, there are abundant Late Scandian syn-orogenic granitoid dykes (~427 Ma Årdal Dyke Complex) intruding the Jotun NC (Lundmark and Corfu, 2007).

In this study, we treat the Jotun, Dalsfjord and Lindås NCs as a large composite unit due to their similar AMCG-lithologies, geochronological fingerprints, and tectonostratigraphic position structurally above the OCT assemblage and below the outboard nappes of Iapetus and Laurentian origin.

2.1.6. Ophiolites and magmatic arc rocks of western Norway

The structurally highest Scandian thrust nappes of the SW Caledonides consist of a complex assemblage of ophiolite-island-arc and magmatic intrusive complexes (e.g. Andersen and Andresen, 1994). In the Major Bergen Arc the ~489 Ma Gullfjellet ophiolite (Dunning and Pedersen, 1988) was emplaced above the Lindås NC, as well as the OCT assemblages (Fig. 2). The ophiolite/island-arc complexes occur again structurally above the Baltican-affine continental rocks between Hyllestad and Nordfjord, and structurally above OCT assemblages near the north-eastern termination of the Jotun NCs (see Section 2.2.4). The Dalsfjord NC and its sedimentary cover is structurally overlain by the ~443 Ma Solund-Stavfjord ophiolite, which was constructed on the remnants of early Ordovician ophiolite/island-arc in a back-arc basin setting (Furnes et al., 1990). The Late Cambrian to Early Ordovician ophiolite island-arc complexes in the SW Caledonides are interpreted to have originated along the Laurentian margin of the Iapetus. They record a protracted history of subduction, arc-continent collision, volcanism and sedimentation, as well as Early-Caledonian metamorphism and deformation prior to Scandian thrusting of the nappes onto Baltica (e.g. Andersen and Andresen, 1994; Furnes et al., 2012).

2.2. The South-Central Caledonides

2.2.1. Autochthon and Neoproterozoic syn-rift sediments with little to no syn-rift magmatic rocks

In the South-Central Caledonides (Fig. 3), the basement and minor (par)autochthonous metasediments are exposed in a series of tectonic windows, including the WGR, the Atnsjøen Window and the core of the Skardøra Antiform (e.g. Sjöström, 1984; Nystuen, 1987). The structurally lowest nappes are the Osen-Røa and Kvitvola nappes (Fig. 4), which preserve continental margin sequences that contain little to no *syn*-rift igneous rocks (see also Section 2.1.1). A few isolated minor occurrences of tholeiitic basalt can be found stratigraphically overlying quartzites of the Osen-Røa NC (Nystuen, 1987). Towards the north-east into Sweden, these (par)autochthonous and allochthonous continental margin successions can be correlated with the Dividal Group and the Risbäck NC (Törnebohm, 1896; Føyn and Glaessner, 1979; Gee et al., 1985).

2.2.2. Sheets of crystalline basement gneisses

Structurally above the proximal *syn*-rift to post-rift sediments of the Osen-Røa and Kvitvola NCs is a series of crystalline basement gneisses that can be traced from Norway across the Skardøra Antiform into Sweden (Fig. 3). In Sweden, east of the Skardøra Antiform (Fig. 3), the gneisses are referred to as the Tännäs Augen Gneiss. The Tännäs Augen Gneiss is Mesoproterozoic in age (~1685–1610 Ma, Claesson, 1980) and is locally mylonitised along tectonic contacts at its base and top. These gneisses are apparently without Ediacaran syn-rift intrusives.

West of the Skardøra Antiform, the gneisses can be traced as a thin band, at a consistent tectonostratigraphic level, along-strike into the Gudbrandsdalen Antiform (Fig. 3). Here, the gneisses are referred to as the Høvringen Gneiss Complex, Rudihø Crystalline Complex and Mukampen Suite (Gjelsvik, 1945; Strand, 1951; Lamminen et al., 2011; Heim and Corfu, 2017). The allochthonous gneisses of the Rudihø and the Mukampen Suite are 1700–1200 Ma and experienced high-grade metamorphism associated with some magmatism at 920 to 900 Ma (Lamminen et al., 2011; Heim and Corfu, 2017). A late tonalitic dyke cutting the Mukampen Suite was dated at ~430 Ma (Heim and Corfu, 2017). Similar to the Tännäs Augen Gneiss east of the Skardøra Antiform, no Ediacaran *syn*-rift intrusives have been reported from these gneisses. Thus, the gneisses at Høvringen, Rudihø and Mukampen are similar in age, composition and metamorphic history to the Tännäs Augen Gneiss and some of the large crystalline nappes of the South Norwegian Caledonides.

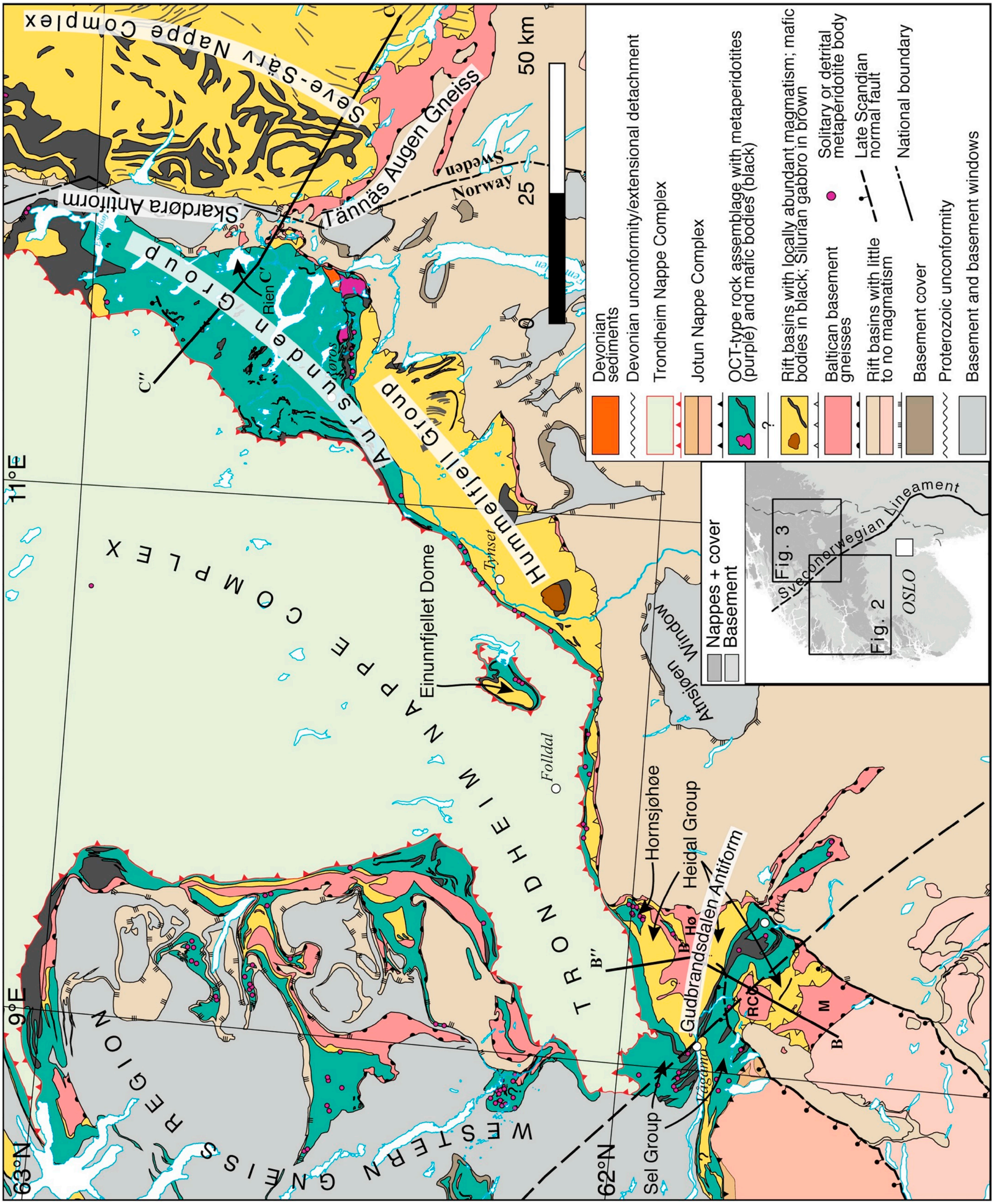
2.2.3. Neoproterozoic syn-rift sediment basins with syn-rift magmatic rocks

Structurally above the sheets of Baltican basement gneisses are Neoproterozoic metasedimentary complexes in the Särv and Seve NCs, as well as in the Hummelfjell and Heidal Groups (Fig. 3). The Särv and the structurally overlying Seve NCs comprise Neoproterozoic pre- to syn-rift continental margin sediments that contain a large volume of rift-related mafic dykes and local volcanics (Solyom et al., 1979; Hollocher et al., 2012; Kumpulainen et al., 2016; Tegner et al., 2019). The Särv and Seve metasediments experienced greenschist facies Scandian metamorphism in the east (Särv) (Gilotti and Kumpulainen, 1986) and an increase in Scandian metamorphism towards the west (Seve). Regionally, the Seve NC experienced diachronous amphibolite to eclogite (ultra-)high-pressure (UHP) metamorphism in the Early (~482 Ma) to Late Ordovician (~445 Ma) (Root and Corfu, 2012; Majka et al., 2014; Klonowska et al., 2017).

The mafic dyke swarms and plutons in the Särv and Seve NCs, including the ~596 Ma Ottfjället Dyke Swarm, are interpreted to represent Iapetus break-up magmatism (e.g. Andersen and Andresen, 1994; Kumpulainen et al., 2016, Tegener et al., in press). Regional studies of the Seve NC in Central and North Sweden show that pre-Caledonian continental margin-type metasediments in most parts are densely intruded by pre-Caledonian, Ediacaran mafic dyke swarms. These complexes are interpreted to represent the magma-rich segment of the Baltican rifted margin (e.g. Andersen and Andresen, 1994; Svenningsen, 2001; Tegner et al., 2016, 2019). The regional geochemistry of the ~1000 km long Scandinavian Dyke Swarm indicates that formation of the melts was related to a large igneous province (LIP) formed by a mantle plume associated with the Central Iapetus Magmatic Province (Tegner et al., 2019). The Seve NC also contains a number of solitary metaperidotite bodies and detrital serpentinites (e.g. Stigh, 1979), and the Ediacaran OCT is considered to be represented by the upper sections of the Seve NC (e.g. Andersen et al., 1991; Svenningsen, 2001; Kjøll et al., 2017, in press).

The Särv and Seve NCs can be correlated with the Hummelfjell and Heidal Groups in Norway (Figs. 3, 4) (Gjelsvik, 1945; Rui and Bakke, 1975; Nilsen, 1988). The Hummelfjell and Heidal metasediments are mostly composed of Neoproterozoic quartzites and meta-arkoses that locally grade upwards into metapelites, and experienced similar metamorphic conditions as the adjacent Seve NC in Sweden (Törnebohm, 1896; Holmsen, 1943; Nilsen and Wolff, 1989).

The metasediments of the Hummelfjell Group contain a number of undated mafic intrusives and volcanics, which traditionally have been correlated with the rift-related igneous rocks in the Särv and Seve NCs (Törnebohm, 1896; Holmsen, 1943). The number and volume of mafic



(continued on next page)

Fig. 3. Tectonostratigraphic map of the South-Central Scandinavian Caledonides between Gudbrandsdalen and the Skardøra Antiform showing the first-order tectonic units of the Scandian Orogeny. Cross section shown in Fig. 5.

igneous rocks within these Neoproterozoic successions decrease in south-westerly direction from the Särv and Seve NCs towards the Heidal Group. However, some mafic intrusives are reported from the upper sections of the Heidal Group (Gjelsvik, 1945; Strand, 1951). Gjelsvik (1945) also reported granitoid dykes cutting the mafic intrusives within the Heidal Group. However, none of these rocks have yet been dated.

2.2.4. Metaperidotite-bearing metasedimentary complexes

Between Vågåmo and the Skardøra Antiform (Fig. 3), metaperidotite-bearing metasediments structurally above the Heidal and Hummelfjell groups are referred to as the Sel Group (Bøe et al., 1993; Nilsson et al., 1997; Sturt et al., 1995) and Aursunden Group (Nilsen, 1988; Nilsen and Wolff, 1989). A lithological assemblage similar to those of the Sel and Aursunden groups also occurs in the Einunnfjellet Dome area (Fig. 3) overlying Neoproterozoic quartzites correlated with the Hummelfjell Group (Nilsen and Wolff, 1989; McClellan, 1994, 2004).

The mica schist matrix of the metaperidotite-bearing complexes between Vågåmo and the Skardøra Antiform are similar to the OCT assemblages further southwest, and contain both solitary and detrital metaperidotites, siliciclastic metaconglomerates and metasandstones as well as layers and lenses of turbidite-deposits. A major difference to the OCT assemblages between Stølsheimen and Lom is that the metaperidotite-bearing complexes between Vågåmo and the Skardøra Antiform also contain a large number of metamorphosed mafic bodies of unknown age. South of lake Rien (Fig. 3), an undeformed quartz diorite pluton intrudes schists of the Aursunden Group and contains xenoliths of the surrounding schists. Similar to some of the Late Scandian granitoids in the Major Bergen Arc (Jakob et al., 2017b) the granitoid at Rien contains euhedral magmatic epidote indicating emplacement of the granitoid at pressures above 4 kbar (Naney, 1983; Zen and Hammarstrom, 1984; Schmidt and Poli, 2004).

The Sel Group in the Gudbrandsdalen Antiform (Sturt and Ramsay, 1997, 1999) contains numerous discontinuous lenses of monomict detrital serpentinites. Near Otta, one locality also hosts an island-type Dapingian–Darriwilian fauna (Bruton and Harper, 1981; Harper et al., 2008), which shows that sedimentation at this stratigraphic level took place in the Early–Middle Ordovician. The Aursunden Group is also suggested to be of Cambrian–Ordovician age (Nilsen and Wolff, 1989). Both the Sel and the Aursunden Group are considered to have been deposited on the uppermost metasediments of the Heidal Group as well as on sheets of mafic crystalline rocks at the base of the Ordovician metasedimentary complexes, which, in turn are supposed to have tectonic contacts with the Heidal and Hummelfjell Groups below (e.g. Sturt et al., 1991; Bøe et al., 1993; Nilsson et al., 1997; Sturt and Ramsay, 1999). Apparent depositional contacts between the metaperidotite-bearing complexes and the units structurally below are exposed, e.g., at Vågåmo and Hornsjøhøe (Fig. 3).

2.2.5. The Trondheim Nappe complex

The rocks of the Trondheim NC are dominated by three separate tectonic units, i.e. the Støren, Gula and Meråker nappes, all of which are composed of oceanic, ophiolite and island-arc assemblages (Guezou, 1978; Wolff, 1979; Gee et al., 1985; Nilsen et al., 2003, 2007; Slagstad et al., 2014) (Fig. 3). All units of the Trondheim NC are intruded by ~440–430 Ma bimodal plutons (Dunning and Grenne, 2000; Nilsen et al., 2003, 2007). The Silurian plutons also intrude and are associated with older Cambrian–Ordovician ophiolite/arc rocks, e.g. in the Trondheim area or near Folldal, and with low-grade sediments containing Laurentian fossils as well as a Middle Silurian trondhjemite pluton, which contains inherited zircons of Archean age (Bruton and Bockelie, 1980; Nilsen et al., 2003, 2007; Slagstad et al., 2014). Thus, the plutonic history of the Trondheim NC is similar to that of the ophiolite/island-arc complexes in the SW Caledonides (Section 2.1.6).

The Gula nappes were commonly believed to be of Baltican origin. However, the assumption of a Baltican origin of the Gula nappes was founded on Tremadocian graptolites and similarities in trace element geochemistry of black shales from the Gula nappes and the Cambrian (par)autochthon of Baltica (e.g. Gee, 1981). The *Rhapdinopora flabelliformis sociale* fossils in the so-called Dictyonema shales of the Gula nappes have also been described from the Tremadoc in Argentina, China, Belgium, and Newfoundland and are considered to be near cosmopolitan (e.g. Wang and Servais, 2015). Similarly, the high contents of V, Mo and U in black shales from the Gula nappes and the (para)autochthonous Cambrian–Ordovician of Baltica are rather indicators for the depositional environment than of provenance. Because of the lack of evidence for unequivocal Baltican origin and the common intrusive history in all nappes of the Trondheim NC as well as the faunal

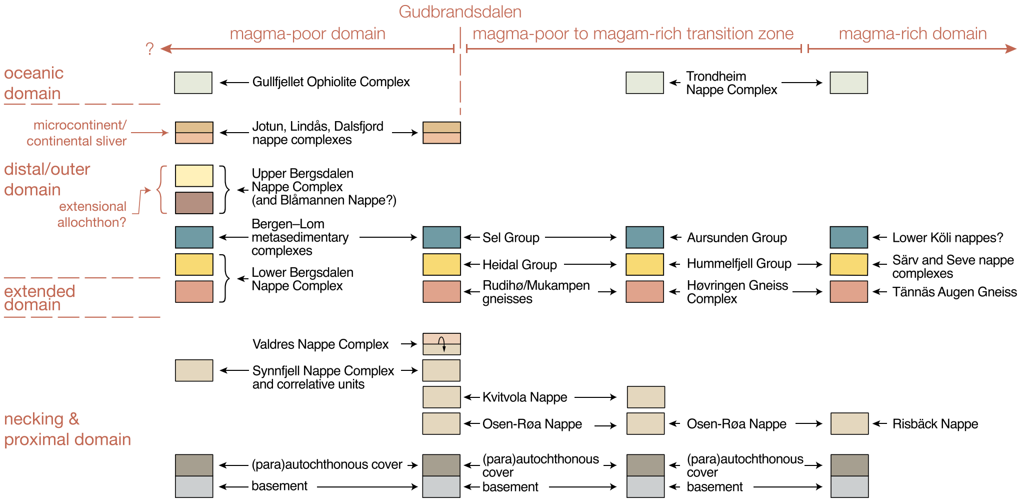


Fig. 4. Tectonostratigraphic correlations between the South and South-Central Scandinavian Caledonides. Interpretation of the main tectonic units with respect to rift-inheritances in red. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

indications for a Laurentian affinity in the western Trondheim NC, we consider the entire Trondheim NC to be exotic with respect to Baltica.

Sturt et al. (1995) followed by Nilsson et al. (1997) suggested that the Sel and Aursunden groups are also unconformable on the Gula nappes. However, an unconformity below the Ordovician metasediments and on top of the Heidal and Hummelfjell groups, as well as their continuation into the Särv and Seve nappes, would stich the continental margin successions together with the oceanic assemblages of the Trondheim NC nappes as early as the Early–Middle Ordovician. The presence of such a terrane-link would require moving the Neoproterozoic metasediments of the Heidal and Hummelfjell Groups and as well the Ediacaran sediments of the Särv and Seve nappes structurally below the Trondheim NC before the deposition of the Sel and Aursunden groups. Moreover, the Laurentian, Baltican and Celtic faunas were highly diverse at the time of the deposition of the OCT assemblages in the Early-Middle Ordovician and did not unify before the Wenlock (Harper et al., 2009; Torsvik and Cocks, 2017a). We therefore consider it to be highly unlikely, and not demonstrated that the Sel and Aursunden Groups are unconformable on the rocks of the Trondheim NC in the Early-Middle Ordovician.

3. Discussion

3.1. The Jotun Microcontinent

Because the Jotun as well as the Dalsfjord and Lindås NCs display similar AMGC lithologies and geochronological histories as the Baltican craton (Bingen et al., 2001; Corfu and Andersen, 2002, 2015; Lundmark and Corfu, 2007, 2008; Roffeis and Corfu, 2014; Corfu and Andersen, 2015), these nappes are all considered to have a Baltican ancestry. However, because the Jotun and Lindås NCs structurally overlie the OCT assemblage, in theory, they could have been detached from the Baltican plate in the Ediacaran and moved independently throughout the Cambrian–Ordovician, or they may even be exotic with respect to Baltica and originate, e.g., from Gondwana or Laurentia. Unfortunately, there are no palaeomagnetic or other constraints on the Cambrian–Ordovician latitudinal position of these units and no fossils have been described from the metasediments associated with the crystalline rocks of the Jotun, Dalsfjord or Lindås NCs. Therefore, their plate tectonic history remains partly speculative and can only be inferred based on the lithological/geochronological dataset, its tectonic relationships with the other nappes and the lithostratigraphic correlations along the mountain belt.

An outboard origin of the large crystalline nappes of Southern Scandinavia would require that these rocks were near the leading edge of the upper plate during the Cambrian–Silurian, either near the Laurentian margin or the peri-Gondwanan terranes, see e.g. Domeier (2015) for a review of the closure of the Iapetus. However, the lack of magmatic arc rocks in the crystalline basement nappes of Southern Norway and the occurrence of Late Ordovician to early Silurian metamorphic rocks including eclogites in the Dalsfjord and Lindås NCs suggest that these NCs were part of the lower plate, i.e. Baltica, during the closure of the Iapetus.

Similar problems arise if we consider a scenario where these large basement nappes rifted off Baltica in the Ediacaran and subsequently moved independently of Baltica for ~200 million years, until the Scandian Orogeny, just to be juxtaposed with each other and Baltica after the continental collision in the Silurian. In this context it is important to consider that the Iapetus did not close by simple orthogonal convergence, but involved large-scale clockwise and counter-clockwise rotations of Baltica as well as major changes in plate-motion directions throughout the Cambrian to Silurian (Cocks and Torsvik, 2011; Torsvik and Cocks, 2005; Domeier, 2015).

The radiometric ages of magmatic and metamorphic minerals from the crystalline nappes are similar to those of the Baltican autochthonous basement and are of Gothian age (1.7–1.6 Ga). The Gothian autochthonous domains closest to the crystalline nappes lie partly to the NE of the present-day position of the crystalline nappes. A SE directed emplacement of these NCs agrees with the Scandian kinematics (e.g. Fossen, 1993) and may indicate that the Baltican craton continued to the NW beyond the present-day North-Atlantic continental margin. Such a pre-Caledonian continuation of Baltica has previously been suggested by, e.g., Lamminen et al. (2011, 2015), but is inherently difficult to test due to pervasive overprint by Caledonian Orogeny and the limits of the present-day continental margin.

Although a direct causal relationship is difficult to demonstrate, the NE termination of the Jotun NC near Vågåmo (Figs. 2, 3) correlates remarkably well with a major NW-SE trending change in the Baltican basement structure, which coincides with a Sveconorwegian lineament across southern Scandinavia (e.g. Kolstrup and Maupin, 2013; Frasetto and Thybo, 2013; Olesen et al., 2010). Whereas the outboard Caledonian nappes continue across this boundary, the transition from a magma-rich to a magma-poor domain also coincides with this lineament. We suggest that the magma-rich to magma-poor as well as the termination of the very large Baltican basement NCs both represent primary features of the pre-Caledonian margin of Baltica that most likely were inherited from the Middle Proterozoic structure of Baltica, which has been surprisingly little discussed in the large-scale architecture of the Scandinavian Caledonides.

By using the OCT assemblage as a reference level in the tectonostratigraphy, a first order architecture of the Pre-Caledonian margin of Baltica can be deduced by "unstacking" the nappes. Orthogneisses and metasediments of the Jotun NC structurally overlie the OCT assemblage on the western side of the Jotun NC. The OCT assemblage can be traced into the Gudbrandsdalen area where it structurally overlies the Heidal Group and sheets of basement gneisses (Figs. 3 and 4), which, in turn, structurally overly the proximal rift-basins, including the Osen-Røa, Kvitvola, Synnfjell and Valdres NCs. Therefore, before the inversion of the Caledonian margin of Baltican, a basin, which was floored by transitional crust (the OCT assemblage), separated the proximal basins and thinned continental crust to the SE from the rocks of the Jotun NC.

Whereas, the Neoproterozoic metasediments of the proximal basins structurally below the Jotun NC contain no *syn*-rift igneous rocks, the rocks of the Høyvik Group and the orthogneisses of the Dalsfjord NC contain mafic dykes and pillow basalts (Andersen et al., 1990, 1998; Corfu and Andersen, 2002). We suggest that the dyke swarm in the Høyvik Group and other correlative units of the Dalsfjord NC indicate that these rocks represent the ocean facing NW (present-day coordinates) magma-rich rifted segment of a crystalline block(s) outboard of the OCT assemblage. The distal position with respect to Baltica is also indicated by the Middle Ordovician deformation and metamorphism which affected the Dalsfjord-Høyvik basement-cover pair before ~449 Ma (Andersen et al., 1998), whereas the proximal part of the rifted margin in the south apparently was little affected by this event.

With regard to the points discussed above, we support the model that interprets the large crystalline basement nappes of South Norway as a former microcontinent. Although separated from the main Baltica continent by hyperextension and formation of the magma-poor OCT-unit, it still formed part of the Baltican lithospheric plate in the period between the Ediacaran and the Silurian. An outboard palaeoposition of these continental blocks was already suggested by Andersen et al. (1991, 2012) and Jakob et al. (2017b), who interpreted these continental units as part of a microcontinent or continental sliver, referred to as the Jotun Microcontinent (Andersen et al., 1991). We suggest that the microcontinent included the Dalsfjord, Lindås, and Jotun NCs, if not all the large AMCG–nappe complexes in Southern Norway.

3.2. The magma-rich to magma-poor transition zone

Almost all the Neoproterozoic sedimentary sequences that are structurally above the sheets of allochthonous Baltican basement, including the Lower Bergsdalen NC, Tännäs, Høvringen, Rudihø and

Mukampen gneisses, contain mafic igneous rocks. Because, these metasediments are interpreted to represent Meso–Neoproterozoic pre- to *syn*-rift sediments that were deposited on the thinned Baltican craton, the mafic (and minor felsic) intrusions within these sedimentary sequences must be younger. The rocks of the Heidal Group, Hummelfjell Group, as well as the Särv and Seve nappes can be correlated by their petrology, depositional age, and tectonostratigraphic position. Several of them contain diamictites interpreted as tillites and some also contain newly discovered stomatolites (Kjøll et al. in press). Therefore, we follow the classical interpretations of Törnebohm (1896) and Holmsen (1943), that the mafic intrusives in the Neoproterozoic sequences of the Hummelfjell Group can be correlated with those in the Särv and Seve NCs, which were emplaced by LIP–magmatism (Tegner et al., 2019; Kjøll et al. in press) at ~605–596 Ma (see Section 2.2.3 and Fig. 4).

The regional correlation of these units results in a relatively simple tectonostratigraphy for the South-Central Caledonides (Fig. 4), i.e. from base to top: 1) basement with cover (also in windows); 2) Neoproterozoic metasediments mostly without mafic igneous rocks; 3) a level of thin allochthonous basement gneisses; 4) Neoproterozoic metasediments with mafic igneous rocks; 5) Cambro-Ordovician metasedimentary complexes with abundant meta-peridotite bodies; and 6) the outboard ophiolite/island-arc complexes, including the Trondheim NC.

Although masked by some additional complexities, this simple tectonostratigraphy of the South-Central Caledonides can also be recognised in the South Caledonides. The structural position of the Upper Bergsdalen NC between the Jotun NC (above) and the metaperidotite-bearing metasediments (below), suggests that it originated outboard of the transitional crust basin. Because the Upper Bergsdalen NC trails out into the Ordovician OCT assemblage near Sognefjorden (Fig. 2), it apparently was also separated from the Jotun Microcontinent; at least during the shortening of the margin but perhaps since the Ediacaran. Because of the presence of a mafic dyke swarm in the Høyvik Group of the Dalsfjord NC and a lack of mafic intrusions in the units structurally below the Jotun NC and in the metasediments of the Blåmannen Nappe, we suggest that the magma rich margin of Baltica was diverted to the outboard side of the Jotun Microcontinent. Because of the similarities of the Neoproterozoic succession, it is possible that mafic dykes in the quartzites of the Lower and Upper Bergsdalen NCs may also have been emplaced during the Ediacaran; although this remains to be substantiated by radiometric dating.

As discussed above, the rift-inherited domains of the Pre-Caledonian margin along strike of the orogen include a magma-rich part preserved in the Särv and Seve NCs a magma-poor part that is presently structurally below the remnants of the Jotun Microcontinent (Fig. 4). The Neoproterozoic continental margin successions between the magma-rich part in the north-east and the magma-poor part in the south-west are characterised by a south-westerly decrease in the abundance of *syn*-rift mafic plutons and volcanics. We interpret this progressive reduction of mafic igneous rocks in the Hummelfjell and Heidal groups to represent a magma-rich to magma-poor transition zone that stretches for about 200 km from the Särv (Tossåsfjället basin) and Seve NCs to the north-eastern termination of the Jotun NC (Heidal Group). It is also noteworthy that the transition also coincides with the pre-rift Sveconorwegian lineament parallel to Gudbrandsdalen (see above; inset map in Figs. 2 & 6). The radiometric evidence as well as the pre-deformation and metamorphic relative ages of the mafic intrusives within the Seve and Särv NC, which correlates with the Hummelfjell Group, demonstrate that the magma-poor to magma-rich transition zone is a primary rift-inherited feature of the Central Caledonides and Ediacaran in age.

3.3. Correlation of Ordovician sequences in the South-Central Caledonides

The correlation of the tectonic units in the South and South-Central Caledonides presented above is further corroborated by the continuity of the peridotite-bearing OCT assemblages from the Bergen Arcs to the Skardøra Antiform (Figs. 2, 3, 4). The cross sections A to C (Figs. 2, 3, 5) demonstrate the consistent organisation of the nappe complexes (see Section 3.2). However, a complexity is added by the presence of the Jotun Microcontinent and the Bergsdalen NCs in the SW. The Neoproterozoic successions are not present between Stølsheimen and Lom. It is likely that these units were excised by the post-orogenic extension during exhumation of the WGR (e.g. Andersen et al., 1991; Fossen, 2010). However, the Cambrian to Ordovician metaperidotite-bearing OCT metasediments can be traced almost seamlessly between Bergen and the Skardøra Antiform. These Cambrian–Ordovician units can be correlated by the litho- and tectonostratigraphy and also a continuous metamorphic signature as well as their depositional age across the Gudbrandsdalen Antiform.

3.3.1. Early–Middle Ordovician reworking of an older rifted margin vs. an Ordovician extensional formation of the Ordovician units

Whereas the depositional and magmatic history of the Neoproterozoic metasedimentary complexes is relatively well-constrained, the origin and significance of the Cambro–Ordovician OCT assemblages is more uncertain due to the paucity of datable rocks in this unit. For the origin of the OCT assemblages three key characteristics must be addressed: (1) the resemblance with other OCT assemblages; (2) the duration of deposition of the matrix sediments into the Middle Ordovician (~470 Ma; Slama and Pedersen, 2015) and (3) the intrusion of minor mafic to granitoid plutons dated at 487–471 Ma (Jakob et al., 2017b). Two scenarios for the formation of the metaperidotite-bearing metasedimentary units might be proposed: (1) The OCT assemblage was formed by reworking of an older Ediacaran basin and OCT zone in the Late Cambrian to Middle-Ordovician; or (2) it was formed by thinning of the crust in the Late Cambrian to Middle Ordovician, which was accompanied or followed by minor intrusions.

In the first scenario, the reworking of an older OCT zone assemblage may have been linked to compression along the Baltican margin in the Late Cambrian to Middle Ordovician. The reworking of transitional crust inboard of the Jotun Microcontinent was accompanied by the emplacement of minor mafic to felsic igneous rocks into older sediments at 487, 476 and 471 Ma (Jakob et al., 2017b) and continued sedimentation with detrital zircons as young as 468 Ma into the Dapingian–Darriwilian (Bruton and Harper, 1981; Slama and Pedersen, 2015). Resetting of zircons at 482 Ma in the Øygarden basement window (Fig. 2) west of the Lindås NC (Wiest et al., 2018) may also be linked to this event.

Because, there is no radiometric evidence for Pre-Scandian penetrative deformation and metamorphism in the Baltican autochthon of South Norway except at Øygarden (Wiest et al., 2018), the Early-Caledonian reworking likely involved only the outermost part of the Baltica margin, including nappes that comprise the OCT in the magma-rich part of the margin, e.g. the Seve NC, and along the western margin (Høyvik-Dalsfjord segment) of the Jotun Microcontinent.

Other indications for compression, uplift and erosion along the Baltican margin in the Early Ordovician are provided by 482 Ma eclogites in the northernmost Seve NC (Root and Corfu, 2012), the occurrences of turbidites that overly and are intercalated with Early–Middle Ordovician metapelites, which also include the Cr- and Ni-rich Elnes Formation in the Oslo region (Bjørlykke and Englund, 1979; Bruton et al., 2010), the Föllinge Formation in Sweden (Greiling and Garfunkel, 2007) and Cambrian–Ordovician successions of the proximal basins (Nickelsen et al., 1985). Moreover, from the Gudbrandsdalen area towards the north-east (Fig. 3), the OCT assemblage contains an increasing number of mafic bodies. Thus, the Ordovician units may reflect the increase of mafic igneous rocks of the underlying Neoproterozoic successions (Section 3.2) and may further support the notion that the metasedimentary complexes between Gudbrandsdalen and the Skardøra Antiform represent the remnants of the reworked outermost rifted margin of Baltica. However, except for one 618 Ma garnet (Cutts and Smit, 2018) no Ediacaran crystallisation ages have been reported from the OCT assemblage.

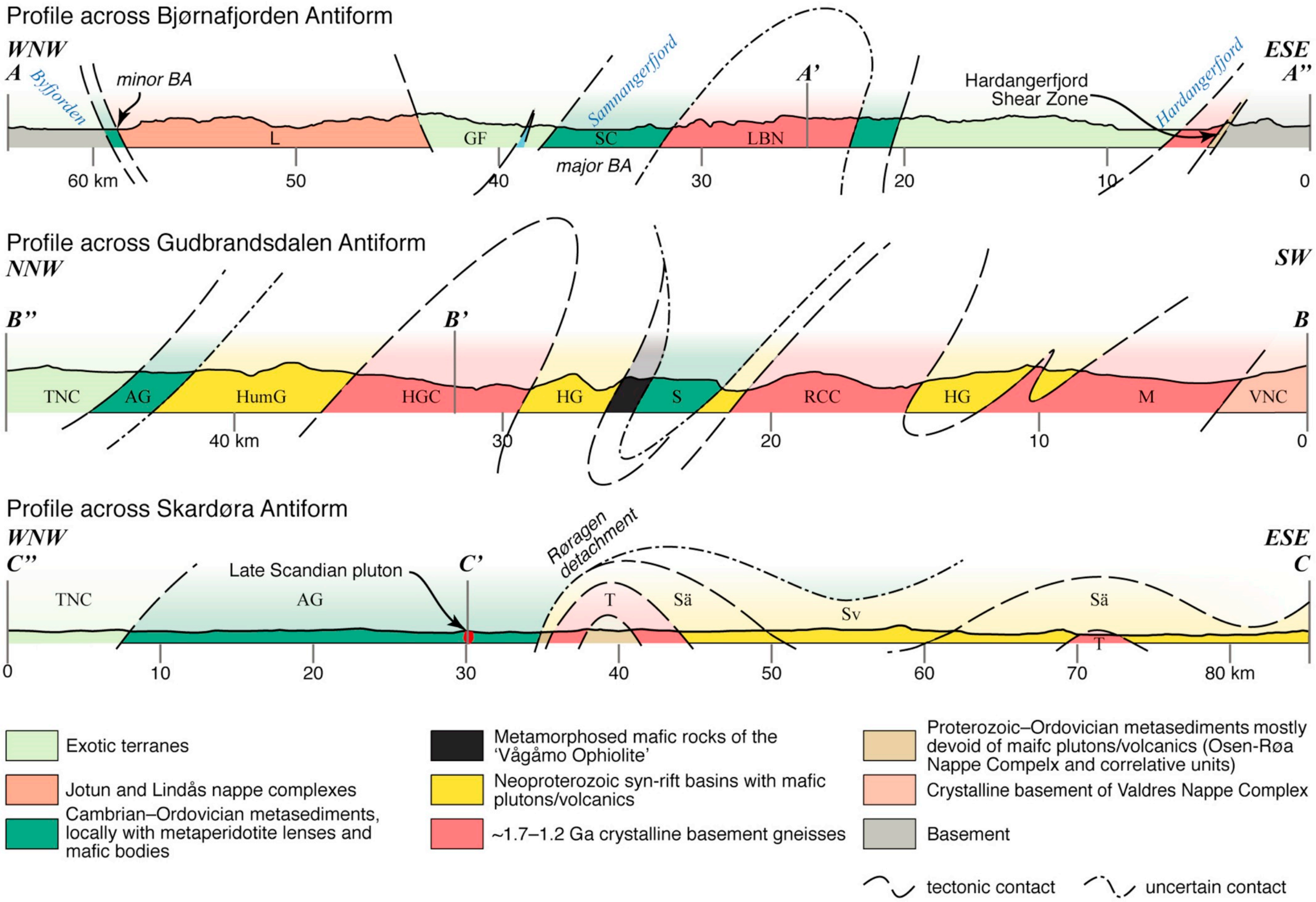


Fig. 5. Simplified cross sections across the OCT-type assemblages in South and Central Norway illustrating the tectonostratigraphic consistency of the units (Figs. 2, 3). No vertical exaggeration. Note that original thrust-related orientations of the contacts have been rotated during extensional tectonics and that, therefore, a precise reconstruction of fold geometries is difficult. **AG**–Aursunden Group; **BA**–Bergen Arc; **LBN**–Lower Bergsdalen Nappe; **GF**–Gullfjellet Complex; **HC**–Heidal Complex; **HGC**–Høvringen Gneiss Complex; **HumG**–Hummelfjell Complex; **JNC**–Jotun Nappe Complex; **L**–Lindås Nappe Complex; **M**–Mukampen Suite; **RCC**–Rudihø Crystalline Complex; **S**–Sel Group metasediments; **SC**–Samnanger Complex; **Sv**–Seve Nappe Complex; **Sä**–Särv Nappe Complex; **T**–Tännäs Augen Gneiss; **TNC**–Trondheim Nappe Complex; **VNC**–Valdres Nappe Complex.

The closure of the OCT basin inboard of the Jotun Microcontinent and the reworking of the OCT assemblage, is comparable with the closure of narrow oceanic basins in the Alpine Tethys realm as described by Chenin et al. (2017). The difference in style of the pre-Scandian deformation and metamorphism in the South and the Central Caledonides may be directly linked to the presence of the large, strong and mostly intact Mesoproterozoic continental crust of the Jotun Microcontinent, which thwarted pre-Scandian deep burial and deformation compared to deep burial and high-pressure metamorphism of rocks in the Seve NC and along the westernmost Dalsfjord-Høyvik area.

However, except for the 618 Ma garnet, no other rocks in the OCT assemblages yielded Ediacaran ages that could be linked to the opening of the Iapetus whereas Lower Ordovician ages abound. And, because, the minimum age of some of the peridotite-bearing metasediments predate a minor 487 ± 2 Ma gabbro in the Bergen Arcs (Jakob et al., 2017a), these assemblages may have formed during a second phase of rifting in the Cambrian to Middle Ordovician (≥487–468 Ma). A modern-day analogue for this scenario could be the Tyrrhenian basin, that opened in the Pliocene–Quaternary during a phase of hyperextension and rifting after initial phase of opening of the Sardinia Province Basin in the Oligocene–Miocene (e.g. Prada et al., 2016; Savelli and Ligi, 2017). However, the Tyrrhenian opened in an upper plate, back-arc setting, for which there is little evidence in the Caledonides. None of the Baltican nappes are associated with an arc of that age and the (HPLT) metamorphism in the Høyvik-Dalsfjord and Seve NC rather indicate a lower plate configuration for the distal margin of Baltica.

The OCT assemblage may also have formed by thinning of a forearc basin and subsequent obduction of the Ordovician units onto the Ediacaran sequences. Forearc extension has been suggested for the highly dismembered south Tibetan ophiolites (Maffione et al., 2015). However, because of the lack of evidence for an (intraoceanic) arc along the Baltican margin of that time, the Baltican affinity of discontinuous slivers of crystalline gneisses within the OCT assemblage metasediments (Jakob et al., 2017a) and the structural position of the large crystalline NCs, it is difficult to explain the formation of the OCT assemblages in a forearc setting.

As an alternative to an upper plate configuration of Baltica, the OCT assemblage may have been formed with Baltica being the lower plate. On these terms the second stage of rifting and thinning may also have been related to the subduction of the northern part of the Baltica margin at about 482 Ma and may be comparable with the opening of the South China Sea (e.g. Morley, 2002; Clift et al., 2008; Bai et al., 2015; Larsen et al., 2018).

3.4. Early Scandian shortening of a wide Baltica rifted margin

The main large-scale nappe translation onto Baltica took place during the final continent-continent collision, and the penetrative deformation and (U)HP metamorphism of the Baltican basement occurred

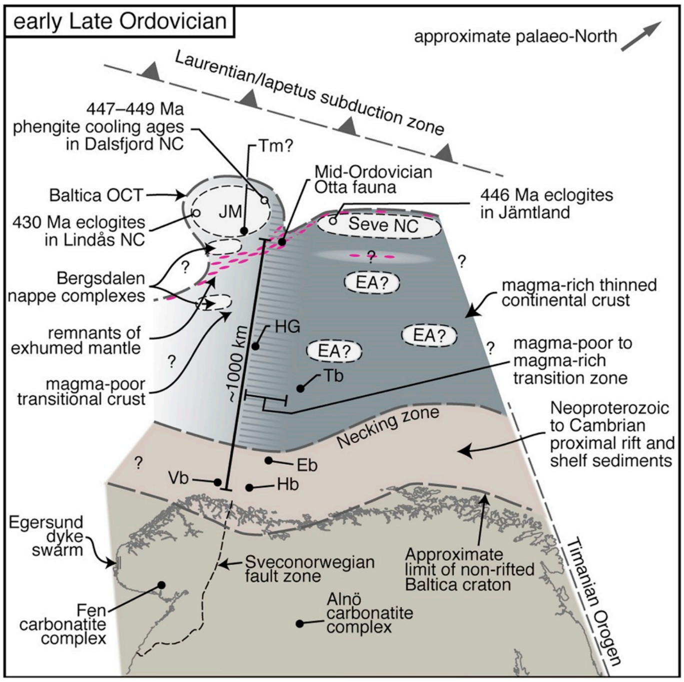


Fig. 6. Cartoon representation of the architecture of the rifted margin of Baltica in the early Late Ordovician before onset of prolonged Scandian inversion. Figure redrawn from Jakob et al. (2017b); Nystuen et al. (2008). Purple ellipses represent mantle exposed at the sea floor. The island type Otta fauna is placed ~1000 km away from the Baltic craton margin. The size of the Jotun Microcontinent is approximately 200 × 300 km. Black circles indicate the palaeoposition of thrust nappes. Open circles indicate the palaeoposition of tectonic units and geological events at some time after onset of earliest Scandian inversion of the margin. EA, extensional allochthon; Eb, Engerdalen basin; HG, Heidal Group; Hb, Hedmark basin; JM, Jotun Microcontinent; NC, nappe complex; Tb, Tossåsfjället basin; Tm, Turtagrø metasediments; Vb, Valdres basin. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

in the Late Silurian to Early Devonian, as demonstrated by the continuous SE-NW metamorphic gradient along the floor thrust and into the WGR (e.g. Hacker et al., 2010; Fauconnier et al., 2014; Jakob et al., 2017b). The outermost parts of the Baltican margin, however, may have experienced shortening as early as ~450 Ma (see above). In Figs. 6 and 7 the palaeogeographic position of the basin with the OCT assemblage is constrained by the island-type Otta fauna, for which we estimate a minimum distance to the Baltican craton of about 1000 km, a distance great enough for the Otta fauna not to mix with the Baltican (or Laurentian) cratonic faunas. The Jotun Microcontinent is estimated to have had a minimum size of about 200 × 300 km based on the present extent of the Jotun, Lindås and Dalsfjord NCs. Thus, the distance between the outboard margin of the Jotun Microcontinent and the cratonic margin of Baltica was in the order of 1200 km.

Palaeo-plate tectonic models for the closure of the Iapetus Ocean (e.g. Domeier, 2015) indicate that a far outboard Jotun Microcontinent inboard of a seaway as well as hyperextended to rifted segments would have been in contact with the Laurentian cratonic margin at ~450 Ma. The arrival of the Jotun Microcontinent at the Iapetan/Laurentian subduction zone is constrained by the deformation of the Høyvik-Dalsfjord and Seve NC at ~450 Ma as well as by the eclogitisation of the Lindås NC at ~430 Ma. The age constraints for the Scandian deformation are based on the obduction and thrusting of the ~443 Ma Solund-Stavfjord back-arc ophiolite onto the fossil-bearing Wenlockian (433–427 Ma) Herland Group (see summary in Fig. 7). The shortening of the thinned margin was completed at the time the two necking domains of the Laurentian and Baltican continents collided, which coincided with the cessation of subduction-related magmatism, the earliest subduction of the WGR and the emplacement of *syn*-collisional granitoids in Baltican and Laurentian nappes, including the 430–415 Ma granitoids in the Norwegian allochthons (described-above) and 435–415 Ma granitoids on Greenland and Svalbard (Kalsbeek et al., 2008; Gasser, 2013).

The shortening of ~1200 km of the Baltican margin between ~450 and 435 Ma would have required convergence rates between the Laurentian and Baltican cratons of about 8 cm/yr, which is well within the limits of those of published plate tectonic models (e.g. Torsvik et al., 1996; Torsvik and Cocks, 2005; Domeier, 2015). Crustal thickening with maximum burial of the WGR and the thrusting onto the foreland, however, continued into the Lower Devonian.

The eclogites (446 Ma) in mafic dyke swarms hosted by the continental sediments of the Seve NC in Jämtland, Sweden, indicate that this part of the Seve NC was in a similar outboard position (≥1200 km) as the Jotun Microcontinent (Fig. 4). The even older HP metamorphic ages in the Seve NC further north (~480 to 460 Ma; Root and Corfu, 2012; Klonowska et al., 2017) may indicate that the onset of deformation along of the Baltican margin was oblique and diachronous, and that the northern part of the Baltican margin was affected before

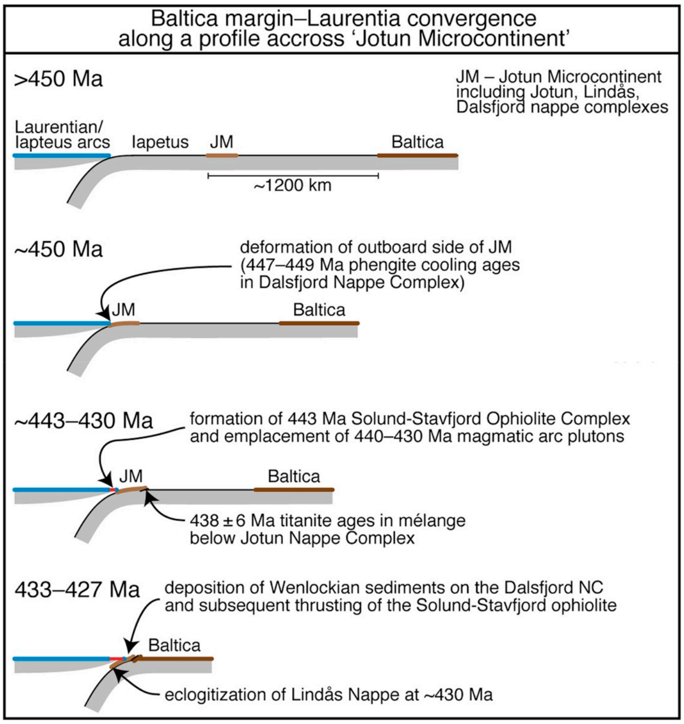


Fig. 7. Cartoon representation of Iapetus closure and the prolonged inversion of the very wide Baltica rifted margin before the Scandian collision.

the segments in the south. However, Early–Middle Ordovician faunas of Laurentia, Baltica and at Otta are distinct and the Iapetus probably was at its widest at this time (Torsvik and Cocks, 2017b). Therefore, alternative to an Early-Middle Ordovician incipient oblique closure of the Iapetus, the outermost Baltica margin may have experienced a collision (arc-continent?) in the late Cambrian–early Middle Ordovician. However, direct evidence for an arc arriving at the pre-Caledonian Baltica margin at that time is lacking.

3.5. Rift-inheritances in the South and Central Caledonides

3.5.1. Rift-inherited domains across-strike in the Scandinavian Caledonides

It is commonly suggested that rift-inherited structures in continental margins are reactivated during collision and have paramount influence on the architecture in mountain belts (e.g. Mohn et al., 2011, 2014; Vitale Brovarone et al., 2013; Epin et al., 2017). It is therefore, important to identify possible rift-inherited structures in the Caledonides and to include those into the tectonic evolution of the orogen.

The rift-inherited magma-rich and magma-poor segments are linked by a strike-parallel transition zone of approximately 200 km width (Section 3.2). Rift inheritance is also seen in transverse sections of the mountain belt. The consistency of the tectonostratigraphy and the characteristic lithological assemblages within the main tectonic units play a key-role in this interpretation (Figs. 4, 5, 6). In particular, the sediment-hosted metaperidotite-bearing assemblages represent a ‘marker horizon’ that links the South-West with the Central Caledonides. This OCT zone-remnants are at a consistent structural level and allow for a re-interpretation of the across-strike architecture of the mountain belt. The traditional use of Lower, Middle and Upper Allochthon is inadequate as previously outlined by Corfu et al. (2014), because, the tectonostratigraphy is inherited from the highly irregular rifted margin and is not a result of shortening of a continuous and uniform rifted margin. Therefore, the nappe stack is better described in terms of rift-domains defined by comparison with present-day margins, including the proximal and necking domains and as well as hyperextended and distal domains, with or without major magmatic components (e.g. Péron-Pinvidic et al., 2013).

The proximal/necking domain of the Scandinavian Caledonides includes the (par)autochthonous and allochthonous Neoproterozoic successions that contain little to no *syn*-rift magmatism, e.g. the Osen-Røa, Synnfjell, Dividal and Risbäck NCs (see also Fig. 4). These proximal rift basins record a dominantly siliciclastic input until the occurrence of minor mafic plutons and volcanics (Nystuen, 1983; Nystuen et al., 2008; Lamminen et al., 2011). After the early rift-phase and minor mafic magmatism, the sediment system changes from siliciclastic dominated to carbonate and carbonate-shale dominated (e.g. the Biri Formation). Similar carbonate and carbonate-shale successions are also reported from the rift basins of eastern Laurentia (e.g. Nystuen et al., 2008), which indicate a comprehensive rift-wide change of the system.

Relative changes in sea level move the sedimentary depo-centres either continent-ward or ocean-ward during transgression or regression events, respectively. However, changes in the tectonic activity comprehensively changes the sediment influx into the rift system (e.g. Mohn et al., 2010). For example, the cessation of tectonic activity in proximal rifted-margin basins is believed to coincide with and to be linked to the development of so-called thinning faults due to localization of extension in the future necking and distal domains and the onset of lithospheric break up (Mohn et al., 2010; Mohn et al., 2011). Therefore, the contemporaneous occurrence of carbonate and shale formations, immediately after a phase of minor mafic magmatism, that seal the previously deposited, siliciclastic, main-rift sequences in many proximal rift basins along the Baltican and Laurentian margins, may indicate the cessation of tectonic activity within these proximal basins. We suggest that the proximal basins record an early rift-phase of initial distributed extension until the localization of extension in the future necking and distal domains and that the localization of extension was broadly contemporaneous with the *syn*-rift magmatism.

With the exception of the nappes comprised of continental metasediments structurally below the Jotun NC, the proximal basins are consistently overthrust by a series of thin crystalline basement nappes with Baltican affinity (Lower Bergsdalen Nappe, Tännäs, Høvringen, Rudihø and Mukampen gneisses). A simple restoration of these nappes require that these gneisses originally were positioned outboard of the proximal domain of the margin. Moreover, their consistent structural position indicates that they represent a regional structural element in the continental margin rather than local imbrications. In present-day passive margins, the hyperextended domain (if identified) is positioned between the necking domain and the zone of exhumed mantle in magma-poor margins, or inboard the zone of main syn-rift magmatism in magma-rich margins (e.g. Péron-Pinvidic et al., 2013; Abdelmalak et al., 2017). Because there is little evidence for Ediacaran magmatism reported from these basement nappes, and because of their structural position between the proximal basins and the Neoproterozoic successions, in which syn-rift igneous rocks abound, we suggest that these gneisses represent rift-inherited thinned continental crust (≤10 km), that were outboard of the necking domain after rifted margin formation.

In the magma-poor to magma-rich transition zone and the magma-rich segment of the margin, these gneisses are overlain by Neoproterozoic successions containing abundant syn-rift magmatic rocks, which we interpret as the distal domain of the rifted margin. In the magma-poor segment of the margin the distal domain is characterised by metaperidotite bearing units that are dominantly composed of fine grained metasediments but also include coarser grained metasediments and slivers of continental crust (extensional allochthones). In the South Caledonides, those distal domain assemblages are structurally overlain by the Jotun microcontinent (Figs. 3, 4, 5, 6).

3.5.2. The importance of the rift-inherited margin architecture during the Scandian orogeny

By comparing our observations from the Caledonides with studies in the Alps, we find that structures inherited from the rifted margins were reactivated and developed as major 1st order thrust systems during the orogenic shortening of the Baltica margin (e.g. Jakob et al., 2017b; Manatschal, 2004; Mohn et al., 2011, 2014; Epin et al., 2017) (Fig. 8). An imbrication of the rift domains was likely accommodated by smaller 2nd order thrusts exploiting discontinuities within the units, e.g. changes in rheology or along rift-inherited faults. The thrusting during the main orogenic events which probably were separated in time (Ordovician and Silurian to Devonian) was apparently in sequence, because, the stacking-order of Baltican nappes reflects cross-sections of the pre-Caledonian margin. Therefore, for simplicity, the shortening of the Baltica margin is in the following depicted as a single phase of shortening, neglecting possible pre-Scandian tectonism and metamorphism of the outermost margin.

In the Caledonides, nappes that contain the outermost margin of Baltica including the OCT, the extensional basement allochthons, exhumed meta-peridotites, probably also embryonic oceanic crust (or seamounts) at Vågåmo and Røros, as well as other dismembered ophiolites were emplaced onto the Neoproterozoic successions that host the rift-related mafic dyke swarms. Consecutively, the assemblages of the magma-rich and the magma-rich to magma-poor transition zone were thrust over thinned continental crust of the distal domain. The nappes of the distal domain were, in turn, thrust over the Neoproterozoic successions of the proximal/necking domain by a thrust system, which may represent the reactivated thinning faults of the necking domain. Internal imbrication of the individual domains was accommodated by sub-sets of thrust with smaller offsets.

4. Summary and conclusions

New data and field observations as well as re-interpretations based

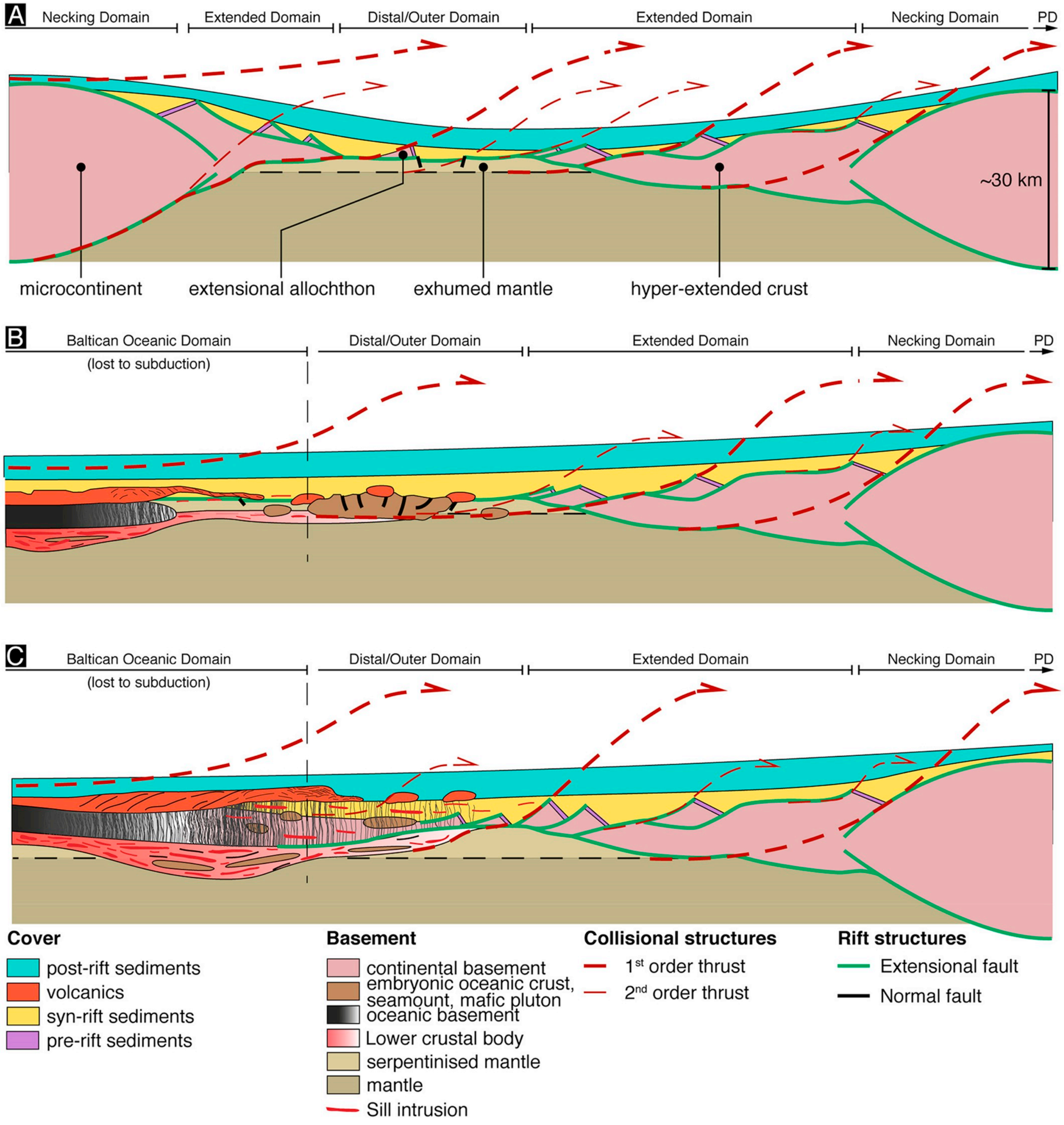


Fig. 8. Conceptual collisional reactivation of rift inherited structures of three rift segments along strike the rifted margin. **A**) Closure of a hyperextended thinned magma-poor narrow oceanic basin between thinned continental crust of the cratonic rifted margin and a microcontinent. (Figure redrawn from Epin et al., 2017). **PD**—Proximal Domain. **B**) Conceptual collisional reactivation of rift inherited structures in a section across a magma-poor to magma-rich transition zone. **C**) Conceptual collisional reactivation of rift inherited structures in a section across a magma-rich segment of a continental margin.

on a modern understanding of present-day continental margins, put new constraints on the evolution and architecture of the pre-Caledonian margin of Baltica. We suggest that the major differences along strike in the mountain belt originated by the highly irregular and discontinuous template related to the formation of the pre-Caledonian margin of Baltica. The most important change occurred where the large (> 200 × 300 km) Jotun Microcontinent rifted away from Baltica in the Neoproterozoic. The NE-termination of the microcontinent may have been inherited from a Middle Proterozoic basement structure, because, the termination of the crystalline nappes correlates with the trace of the Sveconorwegian lineament across southern Scandinavia (Figs. 1 and 7). This structure appears to be a fundamental lithospheric lineament in Scandinavia as seen by the change from shallow to deeper MOHO from SW to NE as well as magnetic anomaly studies (Kolstrup and Maupin, 2013; Frasetto and Thybo, 2013; Olesen et al., 2010). This pre-Caledonian lineament also coincides with the magma-poor to magma-rich segmentation along the continental margin as described-above. We suggest that large-scale discontinuities in the

Sveconorwegian basement across south Scandinavia were important structural elements both during the construction of the pre-Caledonian margin of Baltica as well as during the Caledonian plate-convergence and Scandian collision.

This study shows that the present-day tectonostratigraphy of the South and South-Central Caledonides was formed by the orogenic shortening of a highly irregular, Ediacaran, pre-Caledonian, rifted margin of Baltica. The nappe stack from its base to the top reflects a cross section from proximal to distal rift domains. A summary of observations and interpretations presented above include:

a) After the post-Sveconorwegian assembly of Rodinia, followed a long (~200 Ma) period of attempted continental rifting, widespread stretching of the shield area and deposition of thick sedimentary successions through the Cryogenic and into the Ediacaran as described by Nystuen et al. (2008).
b) The continental break-up and the eventual formation of the pre-Caledonian continental margin of Baltica may have been associated with the arrival of a mantle plume and widespread plume-magmatism at ~615–595 Ma (e.g. Bingen et al., 1998; Svenningsen, 2001; Baird et al., 2014; Tegner et al., 2018, in press; Kjøll et al., in press).
c) Most of the pre-Caledonian margin of Baltica facing the Iapetus Ocean, including the less-well preserved westernmost margin of the Jotun Microcontinent was apparently magma-rich. However, inboard of the Jotun Microcontinent opened a magma-poor basin and seaway that was floored by hyperextended to transitional crust (Andersen et al., 2012; Jakob et al., 2017b). Rift-related mafic igneous rocks have not been identified in this basin or in the adjacent autochthon of Baltica except for the mafic ~615 Ma dyke swarm in the Egersund area (Bingen et al., 1998).
d) The along-strike transition from the magma-rich to the magma-poor part took place over an approximately 200 km long orogen-parallel zone between Røros and Vågåmo. This magma-rich to magma-poor transition zone is preserved in the Neoproterozoic successions of the Hummelfjell and Heidal Groups, which represent a continuation of the Särv and Seve NCs into Norway. Additional elements of the magma-rich to magma-poor transition are the incipient formation of oceanic crust in the OCT zone, which locally may be preserved between Vågåmo and Røros as well as in the continuation of OCT assemblage into Sweden (Nilsson and Roberts, 2014).
e) A poorly-understood early subduction and shortening of the outermost Baltica margin may have occurred already during latest Cambrian to the Middle Ordovician and affected mainly the Seve NC. This pre-Scandian event may have been associated with or coincident with the reworking of the older hyperextended margin or a second phase of extension in the South Caledonides.
f) Major shortening of the Baltican margin started at about 450 Ma when the outermost parts of the very wide (≥1200 km) Baltican rifted margin entered subduction zone(s) in front of Laurentia.
g) Deformation in the proximal/necking domains as well as the large-scale nappe translation over the Baltican craton, Scandian metamorphism and associated granite magmatism took place during the Scandian Orogeny (continent–continent collision) in the late Silurian (after ~430 Ma) into the Early Devonian.
h) The across-strike architecture of the nappe stack can be attributed to the stacking of rift domains. In the Central Caledonides, the stacked rift domains, from top to base, include the distal margin with the fossil OCT and break-up magmatism, remnants of the hyperextended domain and proximal rift basins. In the South Caledonides, the nappe stack also includes the Jotun Microcontinent thrust over the remnants of a failed rift hyperextended basin, floored by transitional crust. In the NE it is transitional into magma-poor to magma-rich transition zone and overlies the proximal Neoproterozoic basins. In the SW, the Upper and Lower Bergsdalen NCs, near the southern termination of the Jotun Microcontinent, were originally outboard and inboard of the hyperextended basin, respectively, and all units were thrust over the proximal basins. All of the rift-inherited tectonic units are structurally overlain by the outboard nappes with origins in the Iapetus and Laurentia.

Acknowledgements

We thank Geoffroy Mohn for fruitful discussions during field trips in the Scandinavian Caledonides as well as the Alps. Johan Petter Nystuen is thanked for many discussions regarding the pre-Caledonian Margin of Baltica. Comments by reviewers Håkon Fossen, Trond Slagstad and Othmar Müntener improved greatly the manuscript. The Centre for Earth Evolution and Dynamics is funded by CoE-Grant 223272 from the Research Council of Norway and this research is funded by is funded by Grant 250327/F20 from the Research Council of Norway to the project “Hyperextension in magma-poor and magma-rich domains along the pre-Caledonian passive margin of Baltica”.

References

Abdelmalak, M.M., Faleide, J.I., Planke, S., et al., 2017. The T-reflection and the deep crustal structure of the vøring margin, offshore mid-Norway. Tectonics 36, 2497–2523.

Andersen, T.B., Andresen, A., 1994. Stratigraphy, tectonostratigraphy and the accretion of outboard terranes in the Caledonides of Sunnhordland, W. Norway. Tectonophysics 231, 71–84.

Andersen, T.B., Skjerlie, K.P., Furnes, H., 1990. The Sunnfjord Melange, evidence of Silurian ophiolite accretion in the West Norwegian Caledonides. J. Geol. Soc. **147**, 59–68.

Andersen, T.B., Jamtveit, B., Dewey, J.F., Swensson, E., 1991. Subduction and eduction of continental crust major mechanisms during continent-continent collision and orogenic extensional collapse, a model based on the south Norwegian Caledonides. Terra Nova **3**, 303–310.

Andersen, T.B., Berry IV, H.N., Lux, D.R., Andresen, A., 1998. The tectonic significance of pre-Scandian 40Ar39Ar phengite cooling ages in the Caledonides of western Norway. J. Geol. Soc. **155**, 297–309.

Andersen, T.B., Corfu, F., Labrousse, L., Osmundsen, P.-T., 2012. Evidence for hyper-extension along the pre-Caledonian margin of Baltica. J. Geol. Soc. **169**, 601–612.

Andréasson, P.-G., 1994. The Baltoscandian margin in neoproterozoic-early Palaeozoic times. Some constraints on terrane derivation and accretion in the Arctic Scandinavian Caledonides. Tectonophysics 231, 1–32.

Andresen, A., Gabrielsen, R.H., 1979. Major element chemistry of metavolcanic rocks and tectonic setting of the Precambrian Dyrskard Group, Hardangervidda, south Norway. Nor. J. Geol. 59, 47–57.

Austrheim, H., 1987. Eclogitization of lower crustal granulites by fluid migration through shear zones. Earth Planet. Sci. Lett. **81**, 221–232.

Austrheim, H., 1990. Fluid Induced Processes in the Lower Crust as Evidenced by Caledonian Eclogitization of Precambrian Granulites, Bergen Arcs, Western-Norway. Doctoral Thesis. University of Oslo.

Bai, Y., Wu, S., Liu, Z., et al., 2015. Full-fit reconstruction of the South China Sea conjugate margins. Tectonophysics **661**, 121–135.

Baird, G.B., Figg, S.A., Chamberlain, K.R., 2014. Intrusive age and geochemistry of the Kebne Dyke complex in the Seve Nappe complex, Kebnekaise Massif, arctic Sweden Caledonides. GFF 136, 556–570.

Beltrando, M., Manatschal, G., Mohn, G., et al., 2014. Recognizing remnants of magma-poor rifted margins in high-pressure orogenic belts: the alpine case study. Earth Sci. Rev. **131**, 88–115.

Bingen, B., Demaiffe, D., van Breemen, O., 1998. The 616 Ma old Egersund basaltic dike swarm, SW Norway, and Late Neoproterozoic opening of the Iapetus Ocean. J. Geol. 106, 565–574.

Bingen, B., Davis, W.J., Austrheim, H., 2001. Zircon U-Pb geochronology in the Bergen arc eclogites and their Proterozoic protoliths, and implications for the pre-Scandian evolution of the Caledonides in western norway. Geol. Soc. Am. Bull. **113**, 640–649.

Bingen, B., Belousova, E.A., Griffin, W.L., 2011. Neoproterozoic recycling of the Sveconorwegian orogenic belt: Detrital-zircon data from the Sparagmite asins in the Scandinavian Caledonides. Precambrian Res. **189**, 347–367.

Bjørlykke, K., Englund, J.O., 1979. Geochemical response to upper precambrian rift basin sedimentation and lower paleozoic epicontinental sedimentation in South Norway. Chem. Geol. **27**, 271–295.

Bøe, R., Sturt, B.A., Ramsay, D.M., 1993. The conglomerates of the Sel Group, Otta-Vaga area, Central Norway: an example of a terrane-linking succession. Geol. Surv. Norway Bull. 425, 1–23.

Bruton, D.L., Bockelie, J.F., 1980. Geology and Paleontology of the Hølonda area, Western Norway—A Fragment of North America? The Caledonides in the USA. D. R. Wones. 2. Memoirs, Virginia Polytechnic Institute and State University, Department of Geological Science, Blacksburg, VA, pp. 41–55.

Bruton, D.L., Harper, D.A.T., 1981. Brachiopods and trilobites of the early Ordovician serpentine Otta Conglomerate, south central Norway. Nor. J. Geol. **61**, 153–181.

Bruton, D.L., Gabrielsen, R.H., Larsen, B.T., 2010. The Caledonides of the Oslo Region, Norway – stratigraphy and structural elements. Nor. J. Geol. 90, 93–121.

Chenin, P., Manatschal, G., Picazo, S., et al., 2017. Influence of the architecture of magma-poor hyperextended rifted margins on orogens produced by the closure of narrow versus wide oceans. Geosphere **13**, 559–576.

Claesson, S., 1980. A Rb-Sr isotope study of granitoids and related mylonites in the Tännäs Augen Gneiss Nappe, southern Swedish Caledonides. Geologiska Föreningen i Stockholm Förhandlingar **102**, 403–420.

Clift, P., Lee, G.H., Anh Duc, N., et al., 2008. Seismic reflection evidence for a dangerous grounds miniplate: no extrusion origin for the South China Sea. Tectonics **27** (n/a-n/a).

Cocks, L.R.M., Torsvik, T.H., 2011. The Palaeozoic geography of Laurentia and western Laurussia: A stable craton with mobile margins. Earth-Sci. Rev. 106, 1–51. https://doi.org/10.1016/j.earscirev.2011.01.007.

Corfu, F., Andersen, T.B., 2002. U–Pb ages of the Dalsfjord complex, SW Norway, and their bearing on the correlation of allochthonous crystalline segments of the Scandinavian Caledonides. Int. J. Earth Sci. 91, 955–963.

Corfu, F., Andersen, T.B., 2015. Proterozoic magmatism in the southern scandinavian caledonides, with special reference to the occurrences in the Eikefjord Nappe. GFF 138, 102–114. https://doi.org/10.1080/11035897.2015.1077886.

Corfu, F., Emmet, T., 1992. U-Pb age of the Leirungsmyran gabbroic complex, Jorun Nappe, southern Norway. Nor. J. Geol. 72, 369–374.

Corfu, F., Gasser, D., Chew, D.M., 2014. New perspectives on the Caledonides of Scandinavia and related areas: introduction. Geol. Soc. Lond., Spec. Publ. 390, 1–8.

Cutts, J.A., Smit, M.A., 2018. Rates of deep continental burial from Lu-Hf garnet chronology and Zr-in-rutile thermometry on (ultra)high-pressure rocks. Tectonics 37, 71–88. https://doi.org/10.1002/2017tc004723.

Domeier, M., 2015. A plate tectonic scenario for the Iapetus and Rheic oceans. Gondwana Res. **36**, 275–295.

Dunning, G.R., Grenne, T., 2000. U-Pb age dating and paleotectonic significance of trondhjemite from the type locality in the Central Norwegian Caledonides. Geol. Surv. Norway Bull. 437, 57–65.

Dunning, G.R., Pedersen, R.-B.S., 1988. U/Pb ages of ophiolites and arc-related plutons of the norwegian caledonides: implications for the development of Iapetus. Contrib. Mineral. Petrol. 98, 13–23.

Eide, E.A., Torsvik, T., Andersen, T.B., Arnaud, N.O., 1999. Early Carboniferous unroofing in Western Norway: A tale of alkali feldspar thermochronology. J. Geol. 107, 353–374.

Epin, M.E., Manatschal, G., Amann, M., 2017. Defining diagnostic criteria to describe the role of rift inheritance in collisional orogens: the case of the Err-Platta nappes (Switzerland). Swiss J. Geosci. 1–20. https://doi.org/10.1007/s00015-017-0271-6.

Fauconnier, J., Labrousse, L., Andersen, T.B., et al., 2014. Thermal structure of a major crustal shear zone, the basal thrust in the Scandinavian Caledonides. Earth Planet. Sci. Lett. **385**, 162–171.

Fossen, H., 1988. The Ulriken Gneiss Complex and the Rundemanen Formation: a basement-cover relationship in the Bergen Arcs, West Norway. Geol. Surv. Norway Bull. 412, 67–86.

Fossen, H., 1989. Geology of the Minor Bergen Arc, West Norway. Geological Survey of Norway Bulletin. 416. pp. 47–62.

Fossen, H., 1993. Structural evolution of the Bergsdalen nappes, Southwest Norway. Geol. Surv. Norway Bull. 424, 23–49.

Fossen, H., 2010. Extensional tectonics in the North Atlantic Caledonides: a regional view. Geol. Soc. Lond., Spec. Publ. 335, 767–793.

Føyn, S., Glaessner, M.F., 1979. Platysolenites, other animal fossils, and the precambrian-cambrian transition in Norway. Nor. J. Geol. **59**, 25–46.

Frasetto, A., Thybo, H., 2013. Receiver function analysis of the crust and upper mantle in fennoscandia – isostatic implications. Earth Planet. Sci. Lett. 381, 234–246. https://doi.org/10.1016/j.epsl.2013.07.001.

Furnes, H., Skjerlie, K.P., Pedersen, R.B., et al., 1990. The solund-stavfjord ophiolite complex and associated rocks, west Norwegian Caledonides: geology, geochemistry and and tectonic environment. Geol. Mag. **127**, 209–224.

Furnes, H., Dilek, Y., Pedersen, R.B., 2012. Structure, geochemistry, and tectonic evolution of trench-distal backarc oceanic crust in the western Norwegian Caledonides, Solund-Stavfjord ophiolite (Norway). Geol. Soc. Am. Bull. 124, 1027–1047.

Gabrielsen, R.H., Nystuen, J.P., Jarsve, E.M., Lundmark, A.M., 2015. The Sub-Cambrian Peneplain in southern Norway: its geological significance and its implications for post-Caledonian faulting, uplift and denudation. J. Geol. Soc. **172**, 777–791.

Gasser, D., 2013. The caledonides of greenland, svalbard and other Arctic areas: status of research and open questions. Geol. Soc. Lond., Spec. Publ. 390, 93–129.

Gee, D.G., 1981. The Dictyonema-bearing phyllites at Nordaunevoll, eastern Trondelag, Norway. Nor. J. Geol. 61, 93–95.

Gee, D.G., Guezou, J.-C., Roberts, D., Wolff, F.C., 1985. The central-southern part of the Scandinavian Caledonides. In: Gee, D.G., Sturt, B.A. (Eds.), The Caledonian Orogen—Scandinavia and Related Areas. John Wiley & Sons Ltd.

Gee, D.G., Andréasson, P.-G., Li, Y., Krill, A., 2016. Baltoscandian margin, Sveconorwegian crust lost by subduction during caledonian collisional orogeny. GFF 139, 36–51.

Gilotti, J.A., Kumpulainen, R.A., 1986. Strain softening induced ductile flow in the Särv thrust sheet, Scandinavian Caledonides. J. Struct. Geol. 8, 441–455.

Gjelsvik, T., 1945. Anorthosittkolpekset i Heidal. Nor. J. Geol. 26, 58.

Glodny, J., Kühn, A., Austrheim, H., 2008. Geochronology of fluid-induced eclogite and amphibolite facies metamorphic reactions in a subduction-collision system, Bergen Arcs, Norway. Contrib. Mineral. Petrol. 156, 27–48.

Gray, J.W., 1978. Structural History and Rb-Sr Geochronology of Eksingedalen, West Norway. Doctoral Dissertation. University of Aberdeen.

Greiling, R.O., Garfunkel, Z., 2007. An Early Ordovician (Finnmarkian?) foreland basin and related lithospheric flexure in the Scandinavian Caledonides. Am. J. Sci. **307**, 527–553.

Guezou, J.-C., 1978. Geology and structure of the Dombås-Lesja Area, Southern Trondheim Region, South-central Norway. Geol. Surv. Norway Bull. 340, 1–34.

Hacker, B.R., Andersen, T.B., Johnston, S., et al., 2010. High-temperature deformation during continental-margin subduction & exhumation: The ultrahigh-pressure Western Gneiss Region of Norway. Tectonophysics **480**, 149–171.

Harper, D.A.T., Bruton, D.L., Rasmussen, C.M.Ø., 2008. The Otta brachiopod and trilobite fauna palaeogeography of early palaeozoic terranes and biotas across baltoscandia. Fossils Strata **54**, 31–40.

Harper, D.A.T., Owen, A.W., Bruton, D.L., 2009. Ordovician life around the Celtic fringes: diversifications, extinctions and migrations of brachiopod and trilobite faunas at middle latitudes. Geol. Soc. Lond., Spec. Publ. 325, 157–170.

Heim, M., Corfu, F., 2017. Heidal revisited - new light on critical elements in the allochthon of the classical Otta region (South Norway). EGU Gen. Assem. **2017** (Poster).

Heim, M., Schärer, U., Milnes, A.G., 1977. The nappe complex in the Tyin-Bygdin-Vang region, central southern Norway. Nor. J. Geol. **57**, 171–178.

Hollocher, K., Robinson, P., Walsh, E., Roberts, D., 2012. Geochemistry of amphibolite-facies volcanics and gabbros of the Storen Nappe in extensions west and southwest of Trondheim, western gneiss region, Norway: a key to correlations and paleotectonic settings. Am. J. Sci. 312, 357–416.

Holmsen, P., 1943. Geologiske og petrografiske undersøkelser i området Tynset-Femunden. Geol. Surv. Norway Bull. **158**, 1–65.

Jakob, J., Alsaif, M., Corfu, F., Andersen, T.B., 2017a. Age and origin of thin discontinuous gneiss sheets in the distal domain of the magma-poor hyperextended pre-Caledonian margin of Baltica, southern Norway. J. Geol. Soc. **174**, 557–571.

Jakob, J., Boulvais, P., Andersen, T.B., 2017b. Oxygen and carbon isotope compositions of carbonates in a prominent lithologically mixed unit in the central South Norwegian Caledonides. Int. J. Earth Sci. 107, 1445–1463. https://doi.org/10.1007/s00531-017-1551-0.

Kalsbeek, F., Higgins, A.K., Jepsen, H.F., et al., 2008. Granites and granites in the East Greenland Caledonides. In: Memoir 202: The Greenland Caledonides: Evolution of the Northeast Margin of Laurentia.

Kimbell, G.S., Stewart, M.A., Gradmann, S., et al., 2017. Controls on the location of compressional deformation on the NW European margin. Geol. Soc. Lond., Spec. Publ. 447, 249–278.

Kjøll, H.J., Andersen, T.B., Corfu, F., Labrousse, L., Tegner, C., Abdelmalak, M.M. & Planke, S. in press. Timing of break-up and thermal evolution of a pre-Caledonian Neoproterozoic exhumed magma-rich rifted margin. *Tectonics*.

Kjøll, H.J., Andersen, T.B., Tegner, C., Corfu, F., Planke, S., 2017. Wilson cycle-kick-off: Constraining the Influence of a LIP during the Neoproterozoic Evolution of the Pre-Caledonian Margin of Baltica and Laurentia. Nordic Geological Winter Meeting, Copenhagen.

Klonowska, I., Janák, M., Majka, J., et al., 2017. Microdiamond on Åreskutan confirms regional UHP metamorphism in the seve nappe complex of the Scandinavian Caledonides. J. Metamorph. Geol. **35**, 541–564.

Koestler, A., 1983. Zentralkomplex und NW-Randzone der Jotundecke, West-Jotunheimen, Südnorwegen. Strukturgeologie und Geochronologie. Mitteilungen aus dem geologischen Institut der eidg. technischen Hochschule und der Universität Zürich **242**, 225.

Kolstrup, M.L., Maupin, V., 2013. A Proterozoic boundary in southern Norway revealed by joint-inversion of P-receiver functions and surface waves. Precambrian Res. **238**, 186–198.

Kühn, A., Glodny, J., Austrheim, H., Råheim, A., 2002. The Caledonian tectono-metamorphic evolution of the Lindås Nappe Constraints from U-Pb, Sm-Nd and Rb-Sr ages of granitoid dykes. Nor. J. Geol. 82, 45–57.

Kumpulainen, R.A., Hamilton, M.A., Söderlund, U., Nystuen, J.P., 2016. A new U-Pb baddeleyite age from the Ottfjället dolerite dyke swarm in the Scandinavian Caledonides – a minimum age for late Neoproterozoic glaciation in Baltica. In: Nordic Geological Wintermeeting, Helsinki, Finland.

Kvale, A., 1945. Petrologic and structural studies in the Bergsdalen quadrangle, Western norway, part 1: petrography. Bergens museums årbok **1**, 201.

Lagabrielle, Y., Labaume, P., de Saint Blanquat, M., 2010. Mantle exhumation, crustal denudation, and gravity tectonics during Cretaceous rifting in the Pyrenean realm (SW Europe): Insights from the geological setting of the lherzolite bodies. Tectonics **29**, 26.

Lamminen, J., Andersen, T., Nystuen, J.P., 2011. Zircon U-Pb ages and Lu-Hf isotopes from basement rocks associated with Neoproterozoic sedimentary successions in the Sparagmite Region and adjacent areas, South Norway: the crustal architecture of western baltica. Nor. J. Geol. 91, 35–55.

Lamminen, J., Andersen, T., Nystuen, J.P., 2015. Provenance and rift basin architecture of the Neoproterozoic Hedmark Basin, South Norway inferred from U–Pb ages and Lu–Hf isotopes of conglomerate clasts and detrital zircons. Geol. Mag. 152, 80–105. https://doi.org/10.1017/S0016756814000144.

Larsen, H.C., Mohn, G., Nirrengarten, M., Sun, Z., Stock, J., Jian, Z., Klaus, A., Alvarez-Zarikian, C.A., et al., 2018. Rapid transition from continental breakup to igneous oceanic crust in the South China Sea. Nat. Geosci. 11, 782–+. https://doi.org/10.1038/s41561-018-0198-1.

Lundin, E.R., Doré, A.G., 2011. Hyperextension, serpentinization, and weakening: a new paradigm for rifted margin compressional deformation. Geology 39, 347–350. https://doi.org/10.1130/G31499.1.

Lundmark, A.M., Corfu, F., 2007. Age and origin of the Ardal dike complex, SW Norway: False isochrons, incomplete mixing, and the origin of Caledonian granites in basement nappes. Tectonics 26, 13.

Lundmark, A.M., Corfu, F., 2008. Late-orogenic Sveconorwegian massif anorthosite in the Jotun Nappe complex, SW Norway, and causes of repeated AMCG magmatism along the Baltoscandian margin. Contrib. Mineral. Petrol. 155, 147–163.

Maffione, M., et al., 2015. Forearc hyperextension dismembered the south Tibetan ophiolites. Geology 43 (6), 475–478.

Majka, J., Rosén, Å., Janák, M., et al., 2014. Microdiamond discovered in the Seve Nappe (Scandinavian Caledonides) and its exhumation by the “vacuum-cleaner” mechanism. Geology **42**, 1107–1110.

Manatschal, G., 2004. New models for evolution of magma-poor rifted margins based on a review of data and concepts from West Iberia and the Alps. Int. J. Earth Sci. **93**, 432–466.

McClellan, E., 1994. Contact relationships in the southeastern Trondheim Nappe complex, central-southern Norway Implications for early Paleozoic tectonism in the Scandinavian Caledonides. Tectonophysics **231**, 85–111.

McClellan, E., 2004. Metamorphic conditions across the Seve-Köli Nappe boundary, southeastern Trondheim region, Norwegian Caledonides: Comparison of garnet-biotite thermometry and amphibole chemistry. Nor. J. Geol. 54, 257–282.

Mohn, G., Manatschal, G., Müntener, O., Beltrando, M., Masini, E., 2010. Unravelling the interaction between tectonic and sedimentary processes during lithospheric thinning in the Alpine Tethys margins. Int. J. Earth Sci. 99, 75–101. https://doi.org/10.1007/s00531-010-0566-6.

Mohn, G., Manatschal, G., Masini, E., Müntener, O., 2011. Rift-related inheritance in orogens: a case study from the Austroalpine nappes in Central Alps (SE-Switzerland and N-Italy). Int. J. Earth Sci. **100**, 937–961.

Mohn, G., Manatschal, G., Beltrando, M., Haupert, I., 2014. The role of rift-inherited hyper-extension in Alpine-type orogens. Terra Nova **26**, 347–353.

Morley, C.K., 2002. A tectonic model for the Tertiary evolution of strike-slip faults and rift basins in SE Asia. Tectonophysics **347**, 189–215.

Müntener, O., Manatschal, G., Desmurs, L., Pettke, T., 2009. Plagioclase peridotites in ocean-continent transitions: refertilized mantle domains generated by melt stagnation in the shallow mantle lithosphere. J. Petrol. 51, 255–294. https://doi.org/10.1093/petrology/egp087.

Naney, M.T., 1983. Phase equilibria of rock-forming ferromagnesian silicates in granitic systems. Am. J. Sci. 283, 993–1033.

Nickelsen, R.P., Hossack, J.R., Garton, M., Repetsky, J., 1985. Late Precambrian to Ordovician stratigraphy and correlation in the Valdres and Synnfjell thrust sheets of the Valdres area, southern Norwegian Caledonides; with some comments on sedimentation. In: The Caledonide Orogen—Scandinavia and Related Areas. John Wiley and Sons Ltd.

Nilsen, O., 1988. The Tectonostratigraphic setting of Stratabound Sulphide Deposits in the southern Trondheim Region, Central Norwegian Caledonides. Geol. Surv. Norway Bull. 412, 55–66.

Nilsen, O., Wolff, F.C., 1989. Geolgisk Kart Over Norge, Berggrunnskart Roros & Sveg. Geolgical Survey of Norway, Trondheim.

Nilsen, O., Sundvoll, B., Roberts, D., Corfu, F., 2003. U-Pb geochronology and geochemistry of trondhjemites and a norite pluton from the SW Trondheim Region, Central Norwegian Caledonides. Geol. Surv. Norway Bull. 441, 5–16.

Nilsen, O., Corfu, F., Roberts, R.J., 2007. Silurian gabbro-diorite-trondhjemite plutons in the Trondheim Nappe complex, Caledonides, Norway: petrology and U-Pb geochronology. Nor. J. Geol. 87, 329–342.

Nilsson, L.P., Roberts, D., 2014. A trail of ophiolitic debris and its detritus along the Trøndelag-Jämtland border correllations and palaeoge. Geol. Surv. Norway Bull. 453, 29–41.

Nilsson, L.P., Sturt, B.A., Ramsay, D.M., 1997. Ophiolitic ultramafites in the Folldal-Røros tract, and their Cr-(PGE) mineralisation. Geol. Surv. Norway Bull. **433**, 10–11.

Nystuen, J.P., 1983. Nappe and Thrust Structures in the Sparagmite Region, Southern Norway. Geol. Surv. Norway Bull. 380, 67–83.

Nystuen, J.P., 1987. Synthesis of the tectonic and sedimentological evolution of the late Proterozoic–early Cambrian Hedmark Basin, the Caledonian Thrust Belt, Southern Norway. Nor. J. Geol. **67**, 395–418.

Nystuen, J.P., Andresen, A., Kumpulainen, R.A., Siedlecka, A., 2008. Neoproterozoic basin evolution in Fennoscandia, East Greenland and Svalbard. Episodes 31, 35–43.

O'Connor, J.M., Stoffers, P., Wijbrans, J.R., et al., 2000. Evidence from episodic seamount volcanism for pulsing of the Iceland plume in the last 70 Myr. Nature **408**, 954–958.

Olesen, O., Gellein, J., Gernigon, L., Kihle, O., Koziel, J., Lauritsen, T., Mogaard, J.O., Myklebust, R., et al., 2010. Magnetic Anomaly Map, Norway and Adjacent Areas.

Owen, A.W., Bruton, D.L., Bockelle, J.F., Bokelle, T.G., 1990. The Ordovician successions of the Oslo Region, Norway. Geol. Surv. Norway Spec. Publ. 4, 54.

Péron-Pinvidic, G., Manatschal, G., 2010. From microcontinents to extensional allochthons: witnesses of how continents rift and break apart? Pet. Geosci. 16, 189–197.

Péron-Pinvidic, G., Gernigon, L., Gaina, C., Ball, P., 2012. Insights from the Jan Mayen system in the Norwegian-Greenland Sea-I. Mapping of a microcontinent. Geophys. J. Int. 191, 385–412.

Péron-Pinvidic, G., Manatschal, G., Osmundsen, P.T., 2013. Structural comparison of archetypal Atlantic rifted margins: a review of observations and concepts. Mar. Pet. Geol. **43**, 21–47.

Prada, M., Ranero, C.R., Sallarès, V., et al., 2016. Mantle exhumation and sequence of magmatic events in the Magnaghi–Vavilov Basin (Central Tyrrhenian, Italy): New constraints from geological and geophysical observations. Tectonophysics **689**, 133–142.

Pringle, I.R., Kvale, A., Anonsen, L.B., 1975. The age of the Hernes granite, Lower Bergsdalen Nappe, western Norway. Nor. J. Geol. 55, 191–195.

Roberts, D., Gee, D.G., 1985. An introduction to the structure of the Scandinavian Caledonides. In: Gee, D.G., Sturt, B.A. (Eds.), The Caledonides Orogen—Scandinavia Nad Related Areas. Wiley & Sons Ltd, Chichester.

Roffeis, C., Corfu, F., 2014. Caledonian nappes of southern Norway and their correlation with Sveconorwegian basement domains. Geol. Soc. Lond., Spec. Publ. 390, 193–221. https://doi.org/10.1144/sp390.13.

Root, D., Corfu, F., 2012. U–Pb geochronology of two discrete Ordovician high-pressure metamorphic events in the Seve Nappe complex, Scandinavian Caledonides. Contrib. Mineral. Petrol. 163, 769–788.

Rui, I.J., Bakke, I., 1975. Stratabound sulphide mineralization in the Kjøli Area, Røros district, Norwegian Caledonides. Nor. J. Geol. 55, 51–75.

Savelli, C., Ligi, M., 2017. An updated reconstruction of basaltic crust emplacement in Tyrrhenian Sea, Italy. Sci. Rep. 7, 18024.

Schmidt, M.W., Poli, S., 2004. Magmatic epidote and its petrologic significance. Rev. Mineral. Geochem. 56, 399–430.

Sjöström, H., 1984. The Seve—Köli Nappe complex of the Handöl—Storlien—Essandsjøen area. Scandinavian Caledonides Geologiska Föreningen i Stockholm Förhandlingar 105, 93–117.

Skjerlie, K.P., Furnes, H., 1990. Evidence for a fossil transform fault in the Solund-Stavfjord Ophiolite Complex: West Norwegian Caledonides. Tectonics 9, 1631–1648. https://doi.org/10.1029/TC009i006p01631.

Slagstad, T., Pin, C., Roberts, D., et al., 2014. Tectonomagmatic evolution of the early Ordovician suprasubduction-zone ophiolites of the Trondheim Region, Mid-Norwegian Caledonides. Geol. Soc. Lond., Spec. Publ. 390, 541–561.

Slama, J., Pedersen, R.-B.S., 2015. Zircon provenance of SW Caledonian phyllites reveals a distant Timanian sediment source. J. Geol. Soc. **172**, 465–478.

Solyom, Z., Andreasson, P.G., Johansson, I., 1979. Geochemistry of amphibolites from Mt. Sylarna, Central Scandinavian Caledonides. GFF 101, 17–25.

Stephens, M.B., Gee, D.G., 1989. Terranes and polyphase accretionary history in the Scandinavian Caledonides. Geol. Soc. Am. Spec. Pap. **230**, 17–30.

Stigh, J., 1979. Ultramafites and detrital serpentinites in the central and southern parts of the Caledonian allochthon in Scandinavia. Doctoral Thesis. University of Gothenburg.

Strand, T., 1951. The Sel and Vågå map areas – Geology and Petrology of a part of the Caledonides of central southern Norway. Geol. Surv. Norway Bull. 178, 116.

Sturt, B.A., Ramsay, D.M., 1997. The Gudbrandsdalen Antiform – A major Late Caledonian structure. Geol. Surv. Norway Bull. **433**, 12–13.

Sturt, B.A., Ramsay, D.M., 1999. Early Ordovician terrane-linkages between oceanic and continental terranes in the central Scandinavian Caledonides. Terra Nova **11**, 79–85.

Sturt, B.A., Ramsay, D.M., Neuman, R.B., 1991. The Otta Conglomerate, the Vågåmo Ophiolite – Further indications of early Ordovician Orogenesis in the Scandinavian Caledonides. Nor. J. Geol. **71**, 107–115.

Sturt, B.A., Bøe, R., Ramsay, D.M., Bjerkgård, T., 1995. Stratigraphy of the Otta-Vågå tract and regional stratigraphic implications. Geol. Surv. Norway Bull. **427**, 25–28.

Svenningsen, O.M., 2001. Onset of seafloor spreading in the Iapetus ocean at 608 Ma Precise age of the Sarek Dyke Swarm, northern Swedish Caledonides. Precambrian Res. **110**, 241–254.

Talbot, C.J., Ghebreab, W., 1997. Red Sea detachment and basement core complexes in Eritrea. Geology 25 (7).

Tegner, C., Andersen, T.B., Corfu, F., Planke, S., Kjøll, H.J., Torsvik, T.H., 2016. The pre-Caledonian Large Igneous Province and the North Atlantic Wilson Cycle. European Geoscience Union General Assembly, Vienna, Austria.

Tegner, C., Andersen, T.B., Kjøll, H.J., Brown, E., Hagen-Peter, G., Corfu, F., Planke, S., Torsvik, T.H., 2019. A mantle plume origin for the Scandinavian Dyke Complex: a “piercing point” for 615 Ma plate reconstruction of Baltica? Geochem. Geophys. Geosyst. 20, 1075–1094.

Törnebohm, A.E., 1896. Grunddagen af det centrala Scandinaviens bergbyggnad (mit einem Résumé in deutscher Sprache) Kongl. Svenska vetenskaps-akademiens handlingar 28, 210.

Torsvik, T.H., Cocks, L.R.M., 2005. Norway in space and time: a centennial cavalcade. Nor. J. Geol. **85**, 73–86.

Torsvik, T.H., Cocks, L.R.M., 2017a. Silurian. In: Earth History and Palaeogeography, pp. 124–134.

Torsvik, T.H., Cocks, L.R.M., 2017b. Ordovician. In: Earth History and Palaeogeography, pp. 101–123.

Torsvik, T.H., Smethurst, M.A., Meert, J.G., et al., 1996. Continental break-up and collision in the Neoproterozoic and Palaeozoic—A tale of Baltica and Laurentia. Earth Sci. Rev. **40**, 229–258.

Vitale Brovarone, A., Beyssac, O., Malavielle, J., et al., 2013. Stacking and metamorphism of continuous segments of subducted lithosphere in a high-pressure wedge: the example of Alpine Corsica (France). Earth Sci. Rev. 116.

Wang, W., Servais, T., 2015. A re-investigation of the Rhabdinopora flabelliformis fauna from the early Tremadocian 'Dictyonema Shale' in Belgium. Geol. Belg. **18**, 66–77.

Welford, J.K., Shannon, P.M., O'Reilly, B.M., Hall, J., 2012. Comparison of lithosphere structure across the Orphan Basin-Flemish Cap and Irish Atlantic conjugate continental margins from constrained 3D gravity inversions. J. Geol. Soc. 169, 405–420. https://doi.org/10.1144/0016-76492011-114.

Wennberg, O.P., Milnes, A.G., Winsvold, i., 1998. The northern Bergen Arc Shear Zone – an oblique-lateral ramp in the Devonian extensional detachment system of western Norway. Nor. J. Geol. 78, 169–184.

Wennberg, O.P., Skjerlie, K.P., Dilek, Y., 2001. Field relationships and geochemistry of the Ostereide Dykes, Western Norway Implications for Caledonian tectonometamorphic evolution. Nor. J. Geol. 81, 305–320.

Wiest, J.D., Jacobs, J., Ksienzyk, A.K., Fossen, H., 2018. Sveconorwegian vs. Caledonian orogenesis in the eastern Øygarden Complex, SW Norway – geochronology, structural constraints and tectonic implications. Precambrian Res. 305, 1–18. https://doi.org/10.1016/j.precamres.2017.11.020.

Wolff, F.C., 1979. Beskrivelse til de berggrunnsgeologiske kart Trondheim og Østersund 1:250 000 (med fargetrykt kart). Geol. Surv. Norway Bull. 353, 1–76.

Zen, E.-A., Hammarstrom, J.M., 1984. Magmatic epidote and its petrologic significance. Geology **12**, 515–518.