Age and origin of thin discontinuous gneiss sheets in the distal domain of the magma-poor hyperextended pre-Caledonian margin of Baltica, southern Norway

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Abstract: The vestiges of the pre-Caledonian magma-poor hyperextended margin of Baltica are preserved in a mélangé zone in southern Norway. The rock assemblage in the distal domains of magma-poor hyperextended margins includes extensional allochthons and basement slivers, which share a pre rift tectonometamorphic history with the non-rifted basement. After incorporation into an orogenic belt, these distinct fingerprints may be used to test whether such heterogeneous mélange units were derived from the basement units below or have been transported to the orogen from elsewhere. Later magmatic additions and tectonometamorphic events may provide additional information on the geological evolution of the margin. We present U-Pb results from 12 gneisses and meta-igneous rocks from the mélange zone. We find Proterozoic gneisses of Telemarkian affinity over the length of the mélange zone that support the formation of the mélange along the ancient Baltican margin. We also find latest Cambrian–early Ordovician meta-igneous rocks that may be linked either to shortening of transitional crust formed in the Ediacaran or, alternatively, to an episode of extension in the Ordovician. Scandinavian thrusting initiated between 438 and 427 Ma and was followed by the emplacement of syntectonic ‘Scandian’ granitoids at 421 Ma; that emplacement coincides with peak metamorphism.

Supplementary material: A high-resolution photomicrograph of the chlorite schist from Stølsheimen is available at https://doi.org/10.6084/m9.figshare.c.3592064.

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The distal domain of magma-poor hyperextended margins exhibits a characteristic lithological assemblage, consisting of exhumed subcontinental mantle, synrift deep-marine basin sediments and coarse-grained sediments derived from pre-rift supracrustal rocks and basement (e.g. Péron-Pinvidic et al. 2013). In addition, the rock assemblage may contain minor syntectonic mafic magmatic or volcanic rocks as well as laterally discontinuous slivers of upper and lower continental crust, known as extensional allochthons (Beltrando et al. 2014; Chew & Van Staal 2014; Manatschal et al. 2014). Such lithological associations are increasingly recognized in orogenic belts; for example, in the Alps (Manatschal 2004; Mohn et al. 2011; Beltrando et al. 2014), the Pyrenees (Lagabrielle et al. 2010; Clerc et al. 2014) and in Alpine Corsica (Brovarone et al. 2013; Lagabrielle et al. 2015).

The constituents of the distal domain, although very heterogeneous, are not exotic or suspect with respect to the rifted margin but they match the basement and supracrustal rocks from which they were detached, if not overprinted or obliterated during later geological events. Thus, the geological fingerprint of the basement slivers and extensional allochthons within such heterogeneous units may be used to identify the original rifted margin. Furthermore, later magmatic additions and tectonometamorphic overprints provide important information on the post-rift history.

The Norwegian Caledonides contain a heterogeneous unit characterized by a rock assemblage typical for the distal domain of a hyperextended margin, in the following non-genetically referred to as mélange. It underlies large Proterozoic crystalline nappe complexes having both Baltican and exotic affinities (Fig. 1) (Andersen et al. 2012; Corfu et al. 2014). Earlier interpretations of the origin of the mélange predate our modern understanding of magma-poor hyperextended margins, in particular, that sub-continental mantle can be exhumed in the distal domain of a hyperextended margin. In the Scandinavian Caledonides, solitary serpentinite bodies, also called Alpine-type peridotites, were commonly explained as part of dismembered ophiolites or incorporated into the metasedimentary units during thrust tectonics. As a consequence, the mélangé, as described by Andersen et al. (2012), was not viewed as a single tectonic unit but has been variously assigned either to the phyllite–mica schist décollement in low tectonostratigraphic levels or to oceanic island-arc related assemblages high in the nappe stack (e.g. Fossen 1995b; Slama & Pedersen 2015). We present new U-Pb isotope dilution thermal ionization mass spectrometry (ID-TIMS) ages of minor intrusive units and thin gneiss sheets interleaved with the metasediments and serpentinites in the mélange zone. We discuss the origin of the gneisses (i.e. whether the gneisses can be linked to Baltican basement units) and how they may have been incorporated in the mélange, as well as some implications for the evolution of the mélange and the regional geology of the Scandinavian Caledonides.

Geological setting

The classic plate-tectonic model for the evolution of the Scandinavian Caledonides begins with the opening of the Iapetus in the Neoproterozoic (e.g. Wilson 1966; Torsvik & Cocks 2005; Li et al. 2008). The palaeogeographical position of Baltica within the supercontinent Rodinia and its position on the way to collision with Laurentia have, however, been disputed, particularly for the period from the Ediacaran to the early Cambrian (Torsvik et al. 1996; Hartz & Torsvik 2002; Cawood & Psarshevsky 2006). As a consequence, the conjugate rift-segment to the pre-Caledonian margin of Baltica is uncertain (Dalziel 1992, 1997; Hartz & Torsvik 2002; Cawood et al. 2003; Psarshevsky et al. 2003).
Onset of plate convergence at c. 495 Ma is recorded by the formation, and later obduction, of numerous supra-subduction ophiolites onto the Laurentian margin (Dunning & Pedersen 1988; Slagstad et al. 2014), and by eclogite formation at about 482 Ma, and again at 446 Ma, in parts of the Seve Nappe Complex (Root & Corfu 2011). The Iapetus closure was completed by 430 Ma, dated by the cessation of subduction-related arc magmatism (Torsvik & Cocks 2005; Corfu et al. 2006) and by the obduction of the youngest c. 440 Ma magmatic arcs and ophiolites (e.g. Andersen et al. 1990; Furnes et al. 2012). Plate convergence, however, continued for c. 30 myr, during which the basement of Baltica was deeply subducted to high- and ultrahigh-pressure conditions beneath the Laurentian margin (Andersen et al. 1991) and the Caledonian nappes were transported southeastward onto Baltica. Thrusting was accompanied (at high structural levels) and succeeded by late- to post-orogenic extension in the Devonian, during which major Caledonian thrusts were reactivated during the backsiding of the nappes towards the NW (e.g. Fossen 1992, 1993a; Andersen 1998).

Structurally, the mélangé is positioned close to the basal thrust of the Caledonides (Andersen et al. 2012; Fauconnier et al. 2014). The main fabric developed during the Scandian thrusting and was variably overprinted during the extensional top-to-the-west backsiding of the nappe-stack. Peak metamorphic conditions in the mélangé are estimated at c. 500 ± 20°C by Raman spectroscopy of carbon-rich material (RSCM) and 0.7 – 1 GPa by thermodynamic calculations (Fauconnier et al. 2014; Kjelberg 2015; Enger 2016).

### Geochronology

#### Analytical procedure

The U–Pb analyses were carried out by ID-TIMS following the general procedure of Krogh (1973). The method for this laboratory has been summarized by Corfu (2004). A mixed $^{206}$Pb-$^{205}$Pb-$^{235}$U spike was used, and zircons were abraded using the chemical abrasion procedure of Mattinson (2005) and the air abrasion method of Krogh (1982). The data are calculated using the decay constants and compositions of Jaffey et al. (1971) and plotted and calculated using the Add-in Isoplot for Excel by Ludwig (2012). The U–Pb results are presented in Table 1.
Eleven gneiss sheets within the mica schist units and one chlorite schist in a detrital serpentinite body were sampled in four areas: the Samnanger Complex 25 km east of Bergen, Stølsheimen, Bøverdalen and the Vågåmo–Otta area (Fig. 1a–d). Solitary serpentinite bodies abound in these areas. Amphibolite, metagabbro and meta-dolerite are commonly scarce or absent in the Bøverdalen area, in Stølsheimen and in the Vågåmo–Otta area, but occur more frequently in the Samnanger Complex. In the following sections we briefly introduce the regional geology of each of the four areas from SW to NE. Each of the introductions is followed by the sample descriptions and the interpretations of the U–Pb results in chronological order of their crystallization ages.

**Samnanger Complex**

In the Samnanger area of the Major Bergen Arc (Fig. 1b and c), gneisses of the Western Gneiss Region are overlain by the Lower Bergsdalen Nappe Complex and thin sheets of mica schists, which are in turn overlain by rocks of the mélange, referred to as the Samnanger Complex (sensu lato, Færseth et al. 1977). Structurally above the rocks of the Samnanger Complex is the Lindás Nappe...
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1. Z, zircon; R, rutile; T, titanite; eu, euhedral; eq, equant; sb, subhedral; an, anhedral; fr, fragment; lp, long-prismatic (l/w > 5); sp, short-prismatic (l/w < 5); y, yellow; cl, clear; br, brown; rd, red; AA, treated with air abrasion; CA, chemical abrasion; NA, not abraded; [1], number of grains.
2. Weight and concentrations are known to better than 10%, except for those near and below the c. 1 μg limit of resolution of the balance.
3. Th/U model ratio inferred from 208/206 ratio and age of sample.
4. Pb Is initial common Pb (corrected for blank).
5. PbC is total common Pb in sample (initial + blank).
6. Raw data corrected for fractionation.
7. Corrected for fractionation, spike, blank and initial common Pb; error calculated by propagating the main sources of uncertainty: Initial common Pb corrected with compositions calculated with Stacey & Kramers (1975) model, except for rutile in C-13-20 for which the composition of coexisting titanite was used: 206/204 = 18.226 (±0.5%), 207/204 = 15.525 (±0.5%). Spike (202/205/235) calibrated relative to ET100 solution.
Complex, which in turn is overthrust by rocks of the early Ordovician Gullfjellet Ophiolite Complex (Dunning & Pedersen 1988). Unconformably overlying the Gullfjellet Ophiolite Complex are the fossiliferous metasediments of the Holdhus and Ulven groups of late Ordovician–early Silurian (Ashgill) age (Færseth et al. 1977; Fossen & Dunlap 2006).

The mélange comprises a matrix of heterogeneous mica schists, which are locally garnetiferous or graphitic. We also find thin zones of micritic marble together with meta-sandstone and meta-dolerite, which are locally garnetiferous or graphitic. We also find thin zones of micritic marble together with meta-sandstone and meta-dolerite, which are locally garnetiferous or graphitic.

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Mylonitic augen gneiss (HAUK-02-15)

The mostly felsic Haukenes gneiss in Samnanger (Fig. 1c) forms an up to 500 m wide and c. 40 km long belt in the Major Bergen Arc (Færseth et al. 1977). The textures observed in the Haukenes gneiss vary from cataclastic to mylonitic and ultramylonitic. Færseth et al. (1977) reported relics of orthopyroxene and perthite from the more massive interior of the Haukenes gneiss, indicating that it may have had a granulite-facies mineralogy prior to the development of the Caledonian fabrics.

The sample was collected south of Samnangerfjorden from a well-foliated section of the Haukenes gneiss, characterized by a matrix of plagioclase + white mica + chlorite ± quartz surrounding augen of microcline and plagioclase (Fig. 2a). Accessory minerals include zircon and secondary carbonate. Zircon occurs as euhedral and subrounded grains. No titanite or rutile was found in the sample.

Three zircon grains, one subrounded and two euhedral, yield (sub-) concordant analyses showing a slight scatter, which is interpreted as reflecting variable Pb loss during the Sveconorwegian and Caledonian events (Fig. 3a). The age of 1495 ± 10 Ma is a conservative estimate constrained by the two bounding reference lines.

Mylonitic augen gneiss (HAUK-06-15)

A second sample from the Haukenes Gneiss was collected north of Samnangerfjorden from a coarse-grained, well-foliated portion of the gneiss with abundant feldspar augen and with the same mineralogy as above, but for the presence of titanite. Some of the large brown titanite grains show lamellar twinning.

Four zircon grains, two subrounded and two euhedral, yield results that are grouped on or slightly below the concordia curve and slightly scattered (Fig. 3b), which is interpreted as the result of Pb loss during different events. This interpretation is supported by the occurrence of two populations of titanite, brown and colourless. One fraction of three brown titanite grains with high Th/U of 2.45 is about 3% discordant and a line calculated through this point and a zircon analysis indicates mainly Caledonian Pb loss. In contrast, a fraction of 11 clear titanite grains low in U and Th/U yields a somewhat discordant analysis indicating formation during the Sveconorwegian orogeny (1093 ± 57 Ma). Based on the convergence of the two discordant trends, the zircon (and brown titanite) data constrain an age of 1495 ± 5 Ma.

Pegmatitic metagabbro (SAM-13-14)

Several lenticular bodies of metagabbro (up to 1.5 km long) occur within the Samnanger Complex (Fig. 1c). Some contain relics of sub-opitical textures, but become increasingly foliated towards the margins (Færseth et al. 1977). Locally the metagabbro contains dolerite dykes with preserved chilled margins (Fig. 2b) and pegmatitic pockets, from which the sample was collected. The original igneous texture is preserved at outcrop scale and at the sample locality it is not overprinted by later fabrics. The sampled rock is characterized by a fine-grained zoisite–epidote matrix surrounding blasts of chlorite and amphibole. Accessory minerals include rutile, titanite and zircon.

The few recovered zircon grains are fragmented or anhedral but mostly clear. Three zircon grains were analysed (Fig. 3c). The two zircon grains with the lowest U content (about 10 ppm) yield a mean 206Pb/238U age of 487 ± 1 Ma whereas the third grain, richer in U (190 ppm; Table 1), is slightly younger and was presumably affected by slight Pb loss.

Mylonitic augen gneiss (SAM-12-14)

Several elongate sheets of quartz–feldspathic augen gneiss with a well-developed foliation occur in the Samnanger Complex (Fig. 1c). The mylonitic augen gneiss contains porphyroclasts of plagioclase and alkali feldspar and commonly exhibits an increasing strain.

Fig. 2. (a) Well-foliated mylonitic augen-phyric portion of the Haukenes gneiss. (b) Doleritic dyke cutting the pegmatitic section of the metagabbro in the Samnanger Complex. The sample was collected from a similar pegmatitic section of the metagabbro. (c) K-feldspar lens in well-foliated mylonitic granitoid in the Samnanger Complex, east of the Haukenes Gneiss. (d) Hand specimen of sample SAM-16-14, Samnanger Complex. (Note the mostly pristine igneous fabric.) Small green spots are magmatic epidote. (e) Boudins of blackwall chlorite schist in serpentinite sandstone and conglomerate in Stølsheimen. Field book for scale. (f) Photomicrograph of the chlorite schist presented in (e). Crossed polarizers. The unusually high number of minute zircon grains should be noted (indicated by red circles).
towards the contacts with the mica schists, where ultra-mylonite is locally developed (Færseth et al. 1977).

The sampled mylonitic, granitic augen gneiss is separated from the Haukenes Gneiss by a thin zone of mica schists. It is characterized by a matrix of plagioclase + alkali feldspar + quartz + white mica ± chlorite surrounding porphyroblasts of plagioclase and locally occurring K-feldspar lenses up to 30 cm in length (Fig. 2c). Accessory minerals include epidote, titanite, carbonate and zircon.

Three groups of zircon were recovered from the sample: clear euhedral crystals, broken tips and clear stubby grains, which could potentially contain cores. Two grains from each of the first two groups were selected for analysis. These yield concordant and overlapping data with a mean $^{206}\text{Pb}/^{238}\text{U}$ age of 476 ± 2 Ma (Fig. 3d), which is interpreted as the crystallization age of the rock.

Granitoid dyke (HANA-01-14)
This sample was collected from a mostly undeformed granitoid dyke between a soapstone–serpentinite conglomerate and an albite muscovite schist. The contacts of the granitoid with the surrounding

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**Fig. 3.** Concordia diagrams for zircon and titanite for sampled gneisses and meta-igneous rocks from the Samnanger Complex.
rocks were not exposed. The rock is retrogressed with recrystallized plagioclase, alkali feldspars, quartz, secondary muscovite, chlorite and epidote.

The sample contains clear, stubby, euhedral zircon grains and anhedral, cloudy zircons. Four grains of the first group range from concordant to discordant, together defining a discordia line with an upper intersection at about 930 Ma, which indicates the age of the inherited component (Fig. 3c). The youngest concordant point has a \(^{206}\text{Pb}/^{238}\text{U}\) age of 420.9 ± 1.1 Ma interpreted to date magmatic crystallization.

**Granitoid dyke (SAM-16-14)**

This sample was collected north of Samnangerfjorden from a mostly undeformed granitoid (Fig. 2d), recently made accessible by construction work. Contacts with the surrounding schists are not exposed. The main mineral constituents are plagioclase, alkali feldspar, microcline, quartz and muscovite. Accessory minerals include magmatic epidote, carbonate, titanite and zircon.

Two populations of zircons were recovered; a group of clear prismatic grains and a group of pink prismatic grains. Three grains of the first group yielded concordant results with \(^{206}\text{Pb}/^{238}\text{U}\) ages between 417 and 422 Ma (Fig. 3f). The younger analysis is considered to have been affected by some Pb loss. The other two data points combine to a \(^{206}\text{Pb}/^{238}\text{U}\) age of 421 ± 3 Ma, which is the preferred age of crystallization.

**Stølsheimen**

In Stølsheimen, basement gneisses of the Western Gneiss Region underlie Proterozoic para- and orthogneisses of the Lower Bergsdalen Nappe Complex (Kvale & Dons 1960; Pringle et al. 1975; Fossen 1993b), which in turn are overlain by the rocks of the mélange. A second suite of Proterozoic gneisses, known as the Upper Bergsdalen Nappe Complex, structurally rests on and interfingers with the mélange (Fig. 1b).

The mélange in Stølsheimen comprises SW-dipping, locally garnetiferous mica schists and phyllites interleaved with minor amphibolitic horizons, quartz-rich metasandstones, pebbly metasandstones and conglomerates that contain vein-quartz clasts and pebbles of a Proterozoic granitoid (Fig. 1b) (Andersen et al. 2012; Kjelberg 2015). There are several thin sheets of mafic and felsic orthogneisses, and variably talcified solitary serpentinite bodies up to 1.5 km long (Enger 2016); more unexposed serpentinite bodies are recorded in drill cores (Troennes 1988).

**Granitic gneiss (C-13-26)**

The rock represents one of a few occurrences of granitic gneiss hosted in the mica schists. It is characterized by large biotite flakes, parallel to the foliation, that separate bands of plagioclase, microcline and quartz together with minor white mica, chlorite and garnet. Accessory minerals include titanite, rutile, zircon and epidote.

Two representative zircon grains, short-prismatic and euhedral to subhedral, yield discordant analyses plotting on a line with an upper intersection at about 1495 Ma (Fig. 4a). The sample contains brown titanite grains with local rims of pale titanite, zircon and Fe-oxides.

**Metadiorite (C-14-20)**

The sample was collected from a mafic gneiss within the mica schists, structurally below the Mesoproterozoic granitoid gneiss (sample C-13-26). The sampled melanocratic gneiss is well foliated, strikes parallel to the local fabric, and dips SE. The mineral assemblage consists of actinolite with minor feldspar and quartz and accessory epidote, titanite, rutile and zircon.

The zircon crystals occur as clear prisms and fragments but yield variable results owing to low U contents. Two analyses yielded only about 4 ppm U and relatively poor precision (Fig. 4b). Two others had 20–30 ppm U and gave more reliable results with a \(^{206}\text{Pb}/^{238}\text{U}\) age of 471 ± 2 Ma. The titanite is also low in U; four fractions overlap within error and yield a \(^{206}\text{Pb}/^{238}\text{U}\) age of 438 ± 6 Ma (Fig. 4c). A fraction of 12 euhedral rutile grains yields a younger \(^{206}\text{Pb}/^{238}\text{U}\) age of 415 ± 2 Ma (Fig. 4c).

**Chlorite schist (VIK-21-14)**

The sample was collected from a fine-grained chlorite schist domain within a soapstone body less than 20 m across (Figs 1b and 2e). The soapstone is a strongly talcified detrital sandy serpentinite with some conglomeratic domains. The sample was collected to test whether the protolith was a layer of siliciclastic sediments or an intrusion that later recrystallized to a chlorite schist during blackwall alteration. The chlorite schist is characterized by a mineral assemblage of chlorite + dolomite + magnetite + serpentine + talc and an unusual high amount of minute zircon grains (Fig. 2f).

The zircon grains extracted from this sample are prismatic to stubby euhedral and anhedral to subrounded. They are clear or brownish-yellow with some inclusions. Four grains were analysed and yield \(^{206}\text{Pb}/^{238}\text{U}\) ages between 919 and 362 Ma. The Precambrian zircon is presumably a detrital grain whereas the latter age may have been affected by Pb loss. The two grains of Caledonian age overlap within error and define a mean \(^{206}\text{Pb}/^{238}\text{U}\) age of 427 ± 2 Ma (Fig. 4g), and probably represent zircon grown during blackwall alteration of the chlorite schist’s protolith.

**Bøverdalen**

In the Bøverdalen area, gneisses of the Western Gneiss Region are structurally overlain by a thin band of phyllites and Precambrian quartzitic paragneisses. The paragneisses trail out to the SW but can be traced to the NE until Vågåmo (Fig. 1d). The quartzitic paragneisses are overlain by the mélange, which in turn is overlain by the Proterozoic Jotun Nappe Complex (Lutro & Tveten 1996). The mélange in Bøverdalen comprises SE-dipping phyllites and locally garnetiferous or graphicitic mica schists. Rarely, small lenses (~1 m in length) and clasts of limestone and marble occur within the mica schists. The mica schists and phyllites are interleaved with locally calcareous metasandstones and quartzite-pebble-dominated conglomerates. One conglomerate is in depositional contact with the underlying phyllites and grades upwards into a locally phyllitic calcareous metasandstone. Four solitary serpentinite bodies, up to 1 km in size, are enclosed in the mica schists and are locally associated with blackwall type actinolite schists along their margins. Four thin sheets of mafic, felsic and banded gneiss were identified in the mica schist and phyllite unit, structurally above and below the solitary serpentinite bodies. Contacts between the different lithologies are commonly sharp and overprinted by secondary shear fabrics.

**Amphibolite gneiss (C-07-47)**

The sample was collected from a sheet of amphibolite, structurally below the serpentinite bodies (Fig. 1c). The gneiss is characterized by a fine-grained matrix of amphibole + plagioclase + biotite + quartz surrounding plagioclase porphyroblasts. Small pale garnets occur within thin felsic bands. Accessory minerals include epidote, titanite, zircon and Fe-oxides.
Zircon is abundant and occurs mainly as partially resorbed irregular fragments, possibly the product of an initial skeletal growth in a mafic rock (e.g. Corfu et al. 2003). Three zircon analyses define a discordia line with an upper intersection at 1496 ± 7 Ma and a lower intersection at 930 ± 110 Ma (Fig. 4e), which probably represent the ages of crystallization and metamorphism, respectively.

Banded amphibolite gneiss (BO-63-14)

The sample was collected from a c. 2 m thick mafic band of a banded and locally mylonitic augen gneiss, structurally above the serpentinite bodies, and which was formerly mapped as a metaarkose. The thickness of the gneiss sheet varies from a few metres to
The appearance of the banded gneiss is strongly heterogeneous. Felsic bands dominate and consist of a fine-grained matrix of plagioclase + quartz + muscovite ± biotite ± chlorite ± epidote ± titanite surrounding augen of plagioclase. The felsic bands also contain some large augen of K-feldspar (up to 1 cm in size) as well as abundant microscopic augen of microcline, albite and mesoperthite. Locally, the mesoperthite constitutes almost all the feldspar augen. The mafic bands consist of amphibole + biotite + chlorite + plagioclase + epidote ± quartz surrounding augen of amphibole and plagioclase. Accessory minerals include titanite and scarce zircon.

Three zircon grains yield discordant but collinear analyses defining a line with a poorly defined lower intersection at 641 ± 180 Ma, probably reflecting mixed Sveconorwegian and Caledonian Pb loss. The upper intersection is at 1229 ± 21 Ma (Fig. 4f) and is regarded as the crystallization age of the protolith.

**Vågåmo–Otta area**

In the Vågåmo–Otta area, the basement and nappes are exposed along a major, late, east–west-striking antiform, referred to as the Gudbrandsdalen Antiform (Sturt & Ramsay 1997). The autochthonous Fennoscandian basement is exposed in the Western Gneiss Region to the west and in several basement windows further to the east (Fig. 1d). The autochthon is overlain by paragneisses of Neoproterozoic proximal rift deposits ('sparagmite') as well as lower Palaeozoic platform sediments and phyllites (e.g. Nystuen 1981), which in turn are overthrust by metasandstones of a sequence of marine shelf deposits (Nystuen 1983). Paragneisses in the Vågåmo–Otta area can be linked along-strike with the lithological assemblages further to the SW. A sliver of Proterozoic gneisses (Lamminen et al. 2011b), referred to as the Høvringen Gneiss Unit, is found amongst the sandstones NW of Vågåmo. The Høvringen Gneiss Unit is unconformably overlain by the Rosten Formation, a rift-related Neoproterozoic conglomerate and sandstone sequence (Lamminen et al. 2011a). In the northern part, the Høvringen Gneiss Unit is structurally overlain by solitary serpentinite-bearing metasediments (Fig. 1d).

The Rudihø Crystalline Complex, with orthogneisses of similar origin to the Jotun Nappe Complex, is tectonically overlain by the Heidal Series, which is dominated by clastic metasedimentary rocks in addition to garnet–mica schist and amphibolite. Both are cut by tonalitic to granitic dykes, of apparent Silurian age (F. Corfu, unpublished data).

In the Vågåmo–Otta area, the mélangé unit discussed in this paper includes the mafic and ultramafic rocks previously referred to as the Vågåmo ophiolite as well as the dominantly metasedimentary rocks of the Heidal Series and Sel Group (Strand 1951; Sturt et al. 1991; Bøe et al. 1993). Locally, monomict serpentinite–soapstone conglomerates in the Vågåmo–Otta area contain well-preserved faunas of early Ordovician age (Fig. 1d). The Otta fauna has been studied in considerable detail and contains fossil gastropods, brachiopods, cephalopods, bivalves and trilobites of a mixed Baltic and Laurentian, so-called Celtic, affinity (Bruton & Harper 1981; Harper et al. 2008, 2009).

**Felsic gneiss (C-13-20)**

A foliated felsic gneiss occurs together with greenstones referred to as the Vågåmo Ophiolite (Sturt et al. 1991) (Fig. 1d). The main fabrics in the gneiss and the greenstones are Scandinavian and we interpret the gneiss as a felsic intrusive rock that truncated the greenstones prior to the Scandinavian orogeny. However, because of the close proximity of the gneiss to the pre-Scandinian Otta thrust (e.g. Sturt et al. 1991; Bøe et al. 1993) and the structural complexity of the region, it cannot be fully excluded that the gneiss is a thrust slice from the structurally underlying Heidal Series. The mineral assemblage of the gneiss consists mainly of quartz and plagioclase with rare occurrences of epidote, chlorite, titanite, actinolite and rutile.

The zircon population consists mainly of variously resorbed, short-prismatic grains. Four of the grains yield sub-concordant analyses defining a shallow discordia line with intersections at 1095 and 863 Ma (Fig. 5). However, a discordia line projected from 970 ± 20 Ma, a major metamorphic event in southern Norway, intersects the concordia at 1154 ± 75 Ma. A discordia line projected from 430 Ma through a single point intersects at 1147 Ma. Discordia lines projected from 430 and 970 Ma though a single point intersect the concordia at 1509 and 1534 Ma, respectively (inset in Fig. 5), and hint at a Telemarkian (1.55 – 1.48 Ga) origin of the xenocryst.

**Fig. 5.** Concordia diagrams for zircon from a felsic gneiss in the Vågåmo–Otta area.
The results for rutile and titanite (the latter replacing corroded rutile, as seen in some grains) are characterized by very low U contents and non-radiogenic Pb. The rutile analysis, corrected with initial Pb from the titanite, indicates a Caledonian age (Table 1; not plotted in Fig. 5).

Discussion

Sheets of Proterozoic rocks in the mélange

Discontinuous sheets of Proterozoic gneiss are important constituents of the mélange unit between Bergen and Otta (Fig. 1). Four of the gneisses investigated have ages of about 1495 Ma. Two of the 1495 Ma units contain secondary titanite, which, although imprecise, indicates formation close to 1100 Ma. These ages match major magmatic and metamorphic events in the Telemarkia Terrane of southern Norway. The bulk of the Telemarkia Terrane was built between 1550 and 1480 Ma and was affected by a major metamorphic event between 1160 and 1080 Ma (e.g. Bingen et al. 2008b).

Zircons from a mafic band in a heterogeneous banded gneiss are dated at 1229 ± 21 Ma, an age identical within error to that of local felsic (e.g. rhyolite and granitic) magmatism in the Telemarkia Terrane at 1228 Ma (Pedersen et al. 2009).

The preferred age of the felsic gneiss at Vågåmo of 1154 ± 75 Ma is consistent with periods of crustal additions in the Telemarkia Terrane (e.g. Bingen et al. 2008b) and is comparable with the age of 1185 ± 8 Ma reported by Lamminen et al. (2011b) for a phase of the Høvringen Gneiss Unit. Therefore, the greenstones in the Vågåmo–Otta area may be, at least in part, of Proterozoic age and the ‘Vågåmo Ophiolite’ and the Høvringen Gneiss Unit may occupy a tectonostratigraphic position comparable with that of the Lower Bergsdalen Nappe Complex. The Proterozoic rocks in the Vågåmo–Otta area are allochthonous ortho- and paragneisses structurally below or within the mélange, which in turn is underlying the Jotun Nappe Complex and rocks of the exotic outboard terranes, referred to as Kåli Nappe Complex (Roberts & Gee 1985) (Fig. 1d).

The combination of events recorded in the Proterozoic gneisses is a specific signature of the Telemarkia Terrane, which differs from that of the Gothian terranes. The Gothian terranes were shaped by principal events at 1700–1550 Ma and 1000–900 Ma (e.g. Bingen et al. 2008a) and include the Western Gneiss Region, and the Jotun and Lindås nappes complexes. Several other of the Caledonian nappes, such as the Bergsdalen Nappes Complex and the Dyrskard, Eikefjord and Espedalen nappes, are instead characterized by a Telemarkian affinity (Kvale 1945; Rofleis et al. 2012; Corfu & Andersen 2016).

The U–Pb results indicate that the basement slivers in the mélange between Bergen and Otta are linked to the Telemarkia Terrane and that the mélange appears to lack Gothian elements. Furthermore, the Telemarkian ages of the gneiss sheets, together with the structural position of the mélange below large crystalline nappes of Baltic affinity (Upper Bergsdalen, Lindås and Jotun nappe complexes), support a Baltic origin for the mélange.

Latest Cambrian–early Ordovician rocks in the mélange

Some of the dated meta-igneous rocks in the mélange from Samnanger and Stolsheimen have latest Cambrian–early Ordovician ages similar to (471 Ma) or older than (476 and 487 Ma) that of the fossiliferous serpentinite conglomerates in Otta. In addition, Slama & Pedersen (2015) showed that the youngest detrital zircons found in the metapelites of the mélange and in the phyllites of the décollement zone are typically also of early Ordovician age (Fig. 1b and d).

In terms of age, these Cambrian–Ordovician rocks in the mélange are similar to the ophiolite and island arc rocks in the outboard terranes of the Scandinavian Caledonides (e.g. Dunning & Pedersen 1988; Barnes et al. 2007; Furesz et al. 2012; Slagstad et al. 2014). The latter occur at high levels in the tectonostratigraphy and are associated with fossiliferous rocks of Laurentian affinity. These ophiolite–island arc complexes are thought to have been generated during the Taconian events on the Laurentian side of the Iapetus, and later to have been emplaced onto Baltica during the Scandian collision (e.g. Dunning & Pedersen 1988; Slagstad et al. 2014). The Laurentian affinity of these outboard sequences is also supported by the common presence of inherited Archaean zircons, which are uncommon in the basement of Baltica in south Scandinavia (Pedersen & Dunning 1997) and the mélange sediments, which are mainly sourced by detritus similar in age to the Sveconorwegian or younger basalts (Andersen et al. 2012; Slama & Pedersen 2015).

Other intrusive rocks of similar age associated with ultramafic bodies and sediments have been described from the Meråker belt (Bjerggård & Björlykke 1994) and from the lower Kåli Nappe Complex (Grimmer & Greiling 2012; Nilsson & Roberts 2014). The above-cited researchers linked the intrusive rocks to ophiolites, island arc or fore-arc basin settings, formed inboard of the Gula Nappe Complex.

In principle, the Cambrian–Ordovician magmatic rocks in the mélange could be tectonic fragments of the overlying outboard terranes. Alternatively, the Ordovician rocks may have formed by independent magmatic processes in the distal domain of the Baltic margin as is indicated by the Baltic basement slivers and the paucity of Archaean clastic zircons (Slama & Pedersen 2015).

The origin of the mélange: a hyperextended magma-poor margin

The mélange lies structurally above autochthonous basement and its thin late Precambrian to early Palaeozoic cover and the lowest crystalline nappes. This tectonostratigraphic position and the dominantly metapelitic composition of its rocks suggest that the basin formed outboard of the Neoproterozoic rift-sediments, yet close enough to (slivers of) Baltic basement to receive coarse sandstones and conglomerates (Andersen et al. 2012).

In present-day passive margins, as well as in several well-studied examples from orogenic belts (Alps, Corsican Alps, Pyrenees), basement slivers detached by extensional faulting form large allochthonous crustal blocks as well as highly attenuated bodies of continental crust are common constituents of the lithological assemblage characteristic for the distal domain (e.g. Manatschal et al. 2001; Corre et al. 2016). Although in the present case the large-scale pre-Caledonian structures are mostly obliterated, the diverse lithological stacking and association are compatible with a similar origin.

The various sheets making up the Lower and Upper Bergsdalen nappes (Kvale 1945; Fossen 1993b) may have constituted an array of highly attenuated continental basement and extensional riders in the distal, hyperextended magma-poor margin between an outboard lying microcontinent(s) and the non-rifted Baltica platform (Fig. 6). These would have detached from Baltica and would have been separated from each other by a zone (or more) of exhumed mantle and fine-grained deep basin sediments, now found as metapelites.

Age of hyperextension and the mélange

There are two lines of evidence that are relevant for the time of hyperextension. One of these arises from considerations of the regional context and analogies with other domains of the Scandinavian Caledonides where indications for extensional processes and opening of Iapetus in the Ediacaran are well established. This evidence includes the analogy with mafic dyke swarms in the Sarek and other parts of the Seve Nappe Complex (Andréasson 1994; Svenningsen 2001; Abdelmalak et al. 2015), where the extensional processes are well constrained by the ages of the dykes at 610–590 Ma. Also relevant is the timing and mode of...
deposition of late Precambrian clastic sequences of the sparagmite basins, where geochronology and the presence of glacial deposits constrain sedimentation to the Ediacaran and tectonic reconstructions place the basins to the NW of their present position (Nystuen et al. 2008; Bingen et al. 2011). There are, moreover, c. 600 Ma dyke swarms in the Särvt nappe and in the autochthonous basement of southern Norway, further documenting the extensional regime. These analogies suggest that the magma-poor extensional segments described here also developed during the same large-scale events.

The other line of evidence that needs to be considered is the presence of Ordovician detrital zircons in the fine-grained sedimentary rocks of the mélangé, of intrusive rocks also of Ordovician age, and locally of fossils of Ordovician age. This evidence leads to two possible explanations concerning the timing of events: (1) the mélangé is the product of Ediacaran hyperextension, but underwent a period of reworking associated with the emplacement of intrusive rocks in the latest Cambrian–early Ordovician; or (2) the mélangé formed entirely in the latest Cambrian–Ordovician. The two alternatives are considered below in turn.

Ediacaran age and Ordovician reactivation …?

Latest Cambrian–Ordovician rocks occur over the length of the mélangé between Bergen and Otta. If the mélangé was formed in the Ediacaran in the distal Baltic margin, the presence of these rocks requires tectonomagmatic activity in the Ordovician in the distal domain of the hyperextended margin. Lundin & Doré (2011) proposed that the distal domains of hyperextended margins represent long-term weakened segments of the crust and are prone to deformation. Therefore, a reactivation of the pre-Caledonian margin may have been focused on an inherited rift-weakened zone. Tectonic reactivation of the margin may have involved crustal shortening, a renewed phase of extension (e.g. in a back-arc basin setting), or a combination of both.

Andersen et al. (1991) and Andersen & Andresen (1994) followed by Pedersen (1997) and Pedersen et al. (2015) suggested that the mélangé represented the remnants of an oceanic seaway separating outboard crystalline basement nappes, including the Jotun and Lindås nappe complexes, from the Baltic margin. In these models the solitary serpentinites and mafic rocks in the mélangé were considered to be parts of dismembered ophiolites that were subsequently chaotically mixed with continental basement slivers and basin sediments during the Scandian collision. However, the ‘ophiolite model’ does not explain the intricate mixture of mantle lithologies and detrital serpentinites, continentaly derived quartz-feldspathic sediments and the Proterozoic gneisses or the conspicuous paucity of true oceanic crust in the mélangé zone between Bergen and Otta.

However, the mélangé may have formed in a narrow basin between a ‘Jotun microcontinent’ and the Baltic craton. The architecture of conjugate rifted margins of narrow oceanic basins or seaways is most probably identical to that of rifted margins of wide or mature oceanic basins (Chenin et al. 2016). Shortening of a narrow basin, partly floorerd by exhumed mantle and probably also some embryonic oceanic crust (Nilsson & Roberts 2014), between an outboard lying microcontinent(s) and the non-rifted Baltic margin may have occurred in the early Ordovician. This may have led to short-lived collisional tectonics or subduction complexes with only minimal melt production instead of the formation of a magmatic arc (Fig. 6). The tectonic regime may have been analogous to those suggested for inverted aulacogens (Burke et al. 1971; Burke 2011) and those of several inverted, narrow oceanic basins in the Variscan orogen that locally underwent blueschist-facies metamorphism during shortening but apparently lack magmatic arcs (Franke 2006; Chenin et al. 2016).

Locally, the shortening of the transitional crust may also have mobilized serpentinite to rise as protrusions and form isolated islands, which probably were source regions for the fossiliferous Otta serpentinite conglomerates. The time of final closure of the basin in the middle Ordovician may be indicated by the ages of the youngest detrital zircons within the fine-grained sediments; that is, shortly after c. 468 Ma (Slama & Pedersen 2015).

… or Ordovician extension?

The alternative is that (back-arc) extension, which formed the mélangé, occurred in the Ordovician and was thus a separate process, distinct from the Ediacaran phase that developed the magma-rich margins. A plausible mechanism would be the rifing off of narrow ribbon microcontinents, such as ‘Jotunøya’ postulated by Rice (2005). Creation of continental ribbons is a common process, but generally requires the establishment of, for example, a subduction system outboard of the microcontinent to drive the process (e.g. Domeier 2015). The lack of any Ordovician magmatic activity in the crystalline parts of the Jotun and associated nappe complexes would seem to argue against such a possibility. On the other hand, however, the ubiquitous presence of Ordovician detritus in the sedimentary rocks of the mélangé, and of mafic and felsic intrusive rocks may just represent the evidence of the required arc magmatism. This solution would also explain the apparent conundrum of how an oceanic basin formed at 600 Ma could remain devoid of sediments for over 100 myr, as the dominant sedimentary rocks in the mélangé, when tested, all yielded Ordovician or younger ages (Slama & Pedersen 2015). Subduction of part of the Seve Nappes at 482 Ma (Root & Corfu 2011) could be a by-product of these processes.

The role of the mélangé during Scandian thrusting

The onset of the Scandian thrusting affecting the mélangé in southern Norway was in the middle Silurian (e.g. Hacker & Gans
also form at lower pressures (Dubińska et al. 2004) and from rodinite in the Western Tianshan serpentinite complex (Li et al. 2010). Hydrothermal zircon can form during fluid–rock alteration with alkaline, Ca-rich, zirconium-bearing fluids (Li et al. 2010). Such fluids can be released during the dehydration of serpentinites at significant lower grade metamorphic conditions (e.g. 270–300°C and c. 1 kbar (Dubińska et al. 2004)) than estimated for the rocks in Stolsheimen (Fauconnier et al. 2014; Kjelberg 2015). Because no detrital zircons in the mélange younger than 468 Ma were documented (Fig. 1b) (Slama & Pedersen 2015) and because of the unusually high amount of minute zircon grains in the chlorite schist, we tentatively suggest that the age of 427 ± 2 Ma records the onset of Scandian thrusting by the formation of hydrothermal zircon during blackwall alteration rather than sedimentation of detrital zircon grains into the basin after 427 Ma. The metamorphic ages of 438 ± 6 and 427 ± 2 Ma are broadly coeval with eclogite metamorphism in the Lindås Nappe Complex, dated at c. 430 Ma (Glodny et al. 2008; Kofke et al. 2012), and with obduction of the Solund–Stavfjord Ophiolite onto the felsic middle Silurian Heland Group (Andersen et al. 1990). By c. 420 Ma, rocks of the mélangé in Sammanger and in the Lindås Nappe Complex were locally intruded by granitoid rocks, which contain magmatic epidote. Peak metamorphic conditions for the mélangé are remarkably consistent and are estimated at about 500°C and 0.7–1 GPa (Fauconnier et al. 2014; Kjelberg 2015). The P–T estimates are commensurate with the conditions required for the crystallization of magmatic epidote in granitic melts. It is suggested that magmatic epidote in granitic rocks forms typically at moderate to high pressures of 0.6–0.8 GPa (Naney 1983; Zen & Hammarskio 1984; Schmidt & Poli 2004), but it may apparently also form at lower pressures (Sial et al. 2008). In general, a fast upward transport is regarded as necessary to prevent complete epidote resorption (Brandon et al. 1996). Other granitoid dykes in the Lindås Nappe Complex (425–418 Ma) also crystallized at estimated pressures of 0.75–1 GPa (Austreim 1990; Kühn et al. 2002). This suggests that the mélangé was close to the estimated peak metamorphism when the youngest rocks in the mélangé, the granitoid dykes, were emplaced. The contemporaneous truncation by granitoid dykes at comparable pressures and temperatures in the mélangé and the Lindås nappe suggests a close spatial relationship between the two units near the Silurian–Devonian boundary before the final emplacement onto Baltica.

Conclusions

Twelve rocks from the mélangé zone were sampled for U–Pb analysis. Five gneiss sheets crystallized in the Mesoproterozoic at about 1495, 1229 and 1154 Ma. Two gneisses contain secondary titanite that formed close to 1100 Ma. The ages of crystallization and metamorphism are similar to those of the Telemarkia Terrane in southern Norway. The tectonostratigraphic position in combination with the U–Pb results strongly supports a Baltic origin for the Mesoproterozoic gneisses in the mélangé, which probably were detached from the basement and emplaced in the mélangé between an outboard lying microcontinent and the non-rifted pre-Caledonian magma-poor margin of Baltica during hyperextension.

Three meta-igneous rocks yielded latest Cambrian–early Ordovician crystallization ages, similar to or older than the ages of the youngest detrital zircons found in the metapelites (Slama & Pedersen 2015) and similar to or older than the age of the Otta fauna (Bruton & Harper 1981). The emplacement of the lower Ordovician meta-igneous rocks is interpreted to be linked either to shortening within a narrow basin floored by transitional crust inboard of a microcontinent or to hyperextension in a back-arc basin setting in the Orдовician.

Scandian thrusting and main inversion of the hyperextended margin began at c. 438–427 Ma. The pre-Caledonian extensional allochthons of continental basement and slivers in the distal margin were imbricated with the mantle and deep-marine basin deposits and were emplaced as a regional nappe unit onto Baltica. At c. 420 Ma, the westernmost parts of the mélangé were locally truncated by granitoid intrusive rocks. Dyke emplacement took place at conditions close to the estimated peak metamorphic conditions. This implies that the mélangé was already deeply buried and constituted an internal part of the growing Caledonian mountain belt at the Silurian–Devonian boundary.

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