Late Neoproterozoic–Silurian tectonic evolution of the Rödingsfjället Nappe Complex, orogen-scale correlations and implications for the Scandian suture

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Abstract: The Scandinavian Caledonides consist of disparate nappes of Baltican and exotic heritage, thrust southeastwards onto Baltica during the Mid-Silurian Scandian continent–continent collision, with structurally higher nappes inferred to have originated at increasingly distal positions to Baltica. New U–Pb zircon geochronological and whole-rock geochemical and Sm–Nd isotopic data from the Rödingsfjället Nappe Complex reveal 623 Ma high-grade metamorphism followed by continental rifting and emplacement of the Umbukta gabbro at 578 Ma, followed by intermittent magmatic activity at 541, 510, 501, 484 and 465 Ma. Geochemical data from the 501 Ma Mofjellet Group is indicative of arc magmatism at this time. Syntectonic pegmatites document pre-Scandian thrusting at 515 and 475 Ma, and Scandian thrusting at 429 Ma. These results document a tectonic history that is compatible with correlation with peri-Laurentian and/or peri-Gondwanan terranes. The data allow correlation with nappes at higher and lower tectonostratigraphic levels, including at least parts of the Helgeland, Kalak and Seve nappe complexes, implying that they too may be exotic to Baltica. Neoproterozoic fragmentation of the hypothesized Rodinia supercontinent probably resulted in numerous coeval, active margins, producing a variety of peri-continental terranes that can only be distinguished through further combined geological, palaeomagnetic and palaeontological investigations.

Supplementary material: U–Pb zircon, whole-rock geochemistry and Sm–Nd data are available at https://doi.org/10.6084/m9.figshare.c.4951464

The Scandinavian Caledonides contain a record of Neoproterozoic tectonic activity at the Laurentian and/or Baltican and/or other, presently unidentified margins, followed by late Cambrian–Ordovician closure of the Iapetus Ocean. The current form of the orogen principally reflects Silurian continent–continent collision (Scandian Orogeny) and later extensional reworking, superimposed on a poorly known, highly variable Neoproterozoic–Ordovician evolution. Since the 1980s, the evolution and nappe architecture of the Scandinavian Caledonides have been conceptualized within the framework of a series of allochthons (Gee *et al.* 1985; Roberts and Gee 1985; Stephens *et al.* 1985) that are ordered tectonostratigraphically (Fig. 1). The Lower and Middle allochthons consist of low- to high-grade metasedimentary rocks interpreted to have been deposited on the western (present-day coordinates) margin of Baltica, tectonically interleaved with crystalline Baltican basement. The overlying Upper Allochthon

From: Murphy, J. B., Strachan, R. A. and Quesada, C. (eds) 2021. *Pannotia to Pangaea: Neoproterozoic and Paleozoic Orogenic Cycles in the Circum-Atlantic Region*. Geological Society, London, Special Publications, **503**, 279–304.

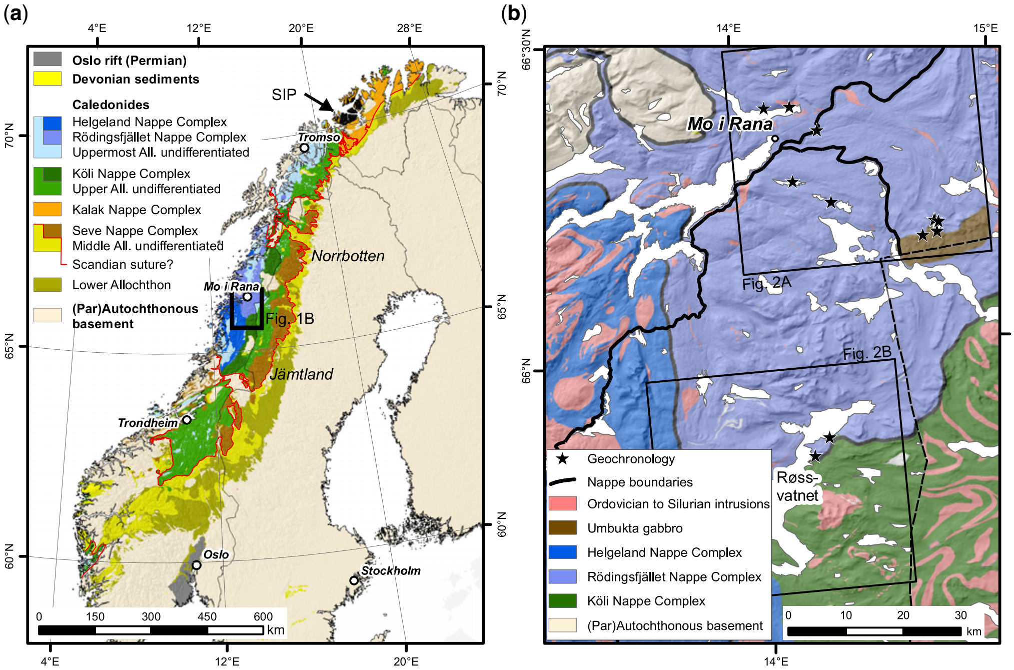

Fig. 1. (**a**) Simplified map of the Scandinavian Caledonides, based on Roberts and Gee (1985). The red line indicates the boundary between units above (to the NW), which may arguably have a origin exotic to Baltica, and units below, which are most likely of Baltican ancestry. (**b**) Study areas in the Rödingsfjället Nappe Complex. Abbreviation: SIP, Seiland Igneous Complex.

contains variably dismembered ophiolites from the Iapetan realm, whereas the Uppermost Allochthon is interpreted as vestiges of the eastern margin of Laurentia that collided with Baltica (Stephens and Gee 1989). This rather straightforward framework has served as a powerful guide in investigations of Caledonian evolution for decades. In recent years, however, increased access to geochronological datasets has shown that many units, at several tectonostratigraphic levels, contain a pre-Caledonian tectonomagmatic and tectonometamorphic history that has complicated this picture (Corfu *et al.* 2007; Kirkland *et al.* 2007; Gasser *et al.* 2015). Corfu *et al.* (2014) discuss many of the issues related to the dual tectonostratigraphic/provenance allochthon framework and, following these authors, we generally refer to particular nappes or nappe complexes rather than allochthon, with allochthon affinity in parentheses where reference to this framework is pertinent.

Here, we present new U–Pb zircon geochronological and whole-rock geochemical and Sm–Nd isotopic data from the central parts of the Scandinavian Caledonides currently assigned to the Rödingsfjället Nappe Complex (RNC) of the Uppermost Allochthon (Fig. 1a). The data constrain the timing of magmatic, metamorphic and deformational events, and characterize the magmatic activity. This new information provides a basis for interpreting the Neoproterozoic–Ordovician evolution of the RNC and discuss the potential for correlation with other, well-characterized units within the orogen and the implications for orogenic architecture.

Geological background

The main study areas form part of the RNC near Mo i Rana and Røssvatnet (Figs 1 & 2) that, along with the structurally overlying Helgeland Nappe Complex (HNC), constitute the Uppermost Allochthon. Although distinct in many ways from the underlying Köli Nappe Complex (Upper Allochthon), particularly with respect to depositional, magmatic and metamorphic evolution (Roberts *et al.* 2007), there are indications that all three nappe complexes formed at, or outboard of, the Laurentian margin and had largely been assembled prior to Early Silurian Scandian continent–continent collision (Pedersen *et al.* 1992; Meyer *et al.* 2003; McArthur *et al.* 2014; Slagstad and Kirkland 2018).

The supracrustal successions in the RNC and HNC comprise voluminous marbles, and associated

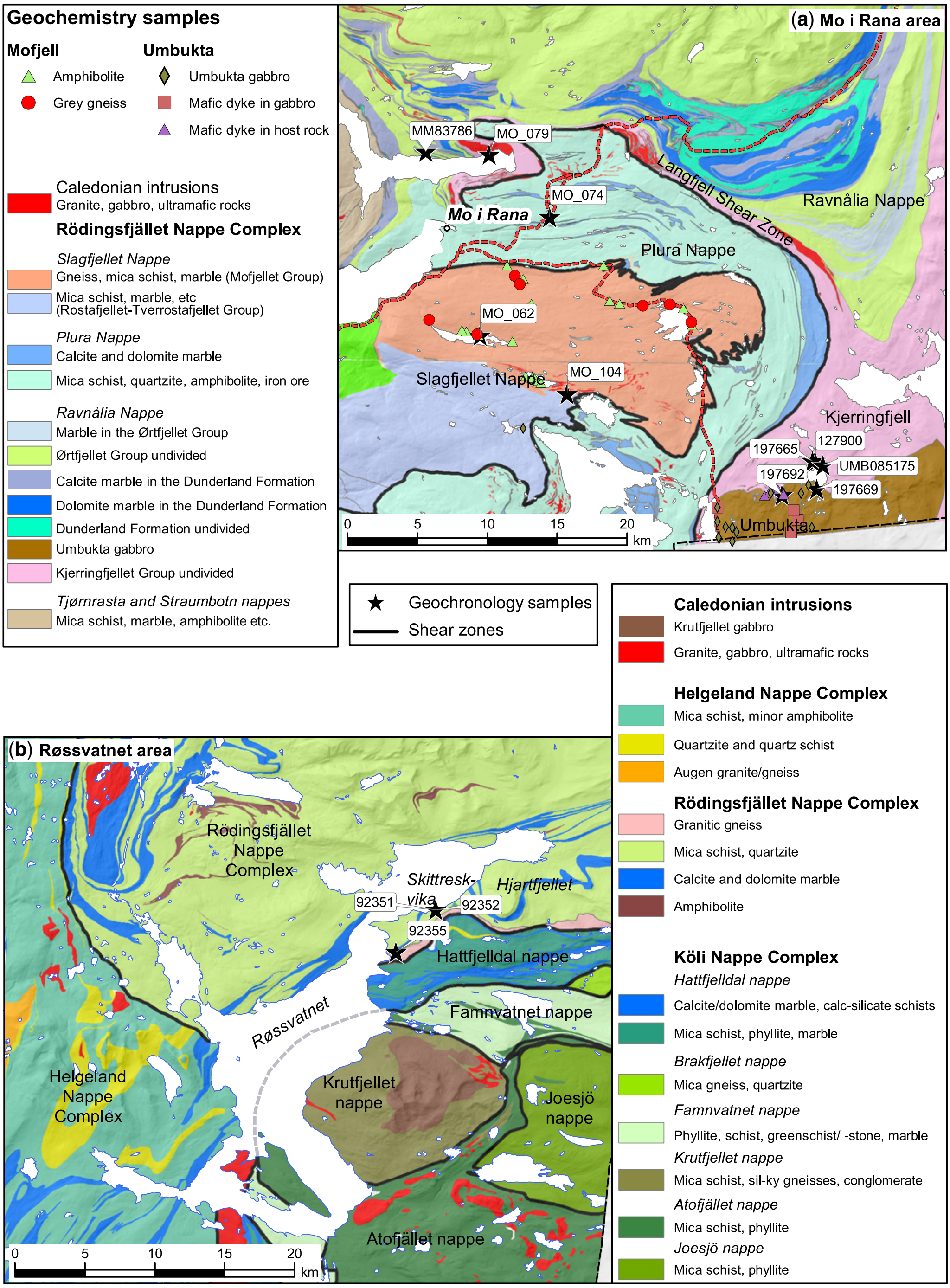

Fig. 2. (**a**) Simplified geological map of the study area near Mo i Rana, based on Søvegjarto *et al.* (1988, 1989), Gjelle *et al.* (1991) and Marker *et al.* (2012). (**b**) Simplified geological map of the study area east of northern Røssvatnet, based on Gustavson (1981) and Gjelle *et al.* (2003), and new mapping by NGU (Bjerkgård *et al.* 2018). The black stars show locations of dated samples.

iron formations and pelitic schists, deposited in platformal, shelf-edge and shelf-slope environments during the Late Neoproterozoic–Early Silurian (Melezhik *et al.* 2002, 2015, 2018; Barnes *et al.* 2007; Slagstad and Kirkland 2017). The metasedimentary rocks were intruded by voluminous, Ordovician–Early Silurian arc-type granitoid plutons and batholiths (Nordgulen *et al.* 1993; Barnes *et al.* 2007), and coeval, voluminous magmatism is recorded in the British, Irish and Greenland Caledonides (e.g. Flowerdew *et al.* 2005; Rehnström 2010). Early Caledonian, NW-vergent thrusting (Roberts *et al.* 2002; Yoshinobu *et al.* 2002) in the HNC has been correlated with NW-vergent Taconian/Grampian deformation along the Laurentian margin (Prave *et al.* 2000). These geological features are compatible with, and generally interpreted to reflect, active-margin processes along the Laurentian margin of Iapetus, prior to continent–continent collision in the Late Silurian (Roberts *et al.* 2007).

The Köli Nappe Complex is characterized by numerous, Early Ordovician, fragmented arc and ophiolite complexes, most of which have compositions attributed to formation in oceanic arc and back-arc basins (Grenne *et al.* 1999; Slagstad *et al.* 2013). Fossil evidence suggests formation of these complexes outboard of the Laurentian margin (Bruton and Bockelie 1980; Pedersen *et al.* 1992), consistent with coeval and tectonically similar (i.e. active-margin related) arc-related ophiolites in the Newfoundland and Quebec Appalachians (e.g. van Staal *et al.* 1998; Lissenberg *et al.* 2005*a*). These ophiolites are typically correlated with coeval, compositionally similar ophiolite complexes in the HNC (Furnes *et al.* 1988; McArthur *et al.* 2014), highlighting the pre-Scandian relationship between these nappe complexes.

The Seve and Särv nappe complexes (Middle Allochthon) comprise low- to high-grade metamorphic metasedimentary and meta-igneous rocks commonly interpreted to represent the Neoproterozoic–Early Paleozoic western margin of Baltica (Gee *et al.* 2017). The structurally highest Seve Nappe Complex (SNC) is usually inferred to represent the outermost margin of Baltica and locally preserves mafic dyke swarms dated at *c.* 615–600 Ma (Svenningsen 2001; Gee *et al.* 2017; Kjøll *et al.* 2019; Tegner *et al.* 2019), which is interpreted to reflect continental break-up and opening of the Iapetus Ocean, placing the SNC at the continent–ocean transition zone (Andréasson 1994; Andréasson *et al.* 1998; Gee *et al.* 2017). Two areas that preserve evidence of high-pressure–ultrahigh-pressure (HP–UHP) metamorphism have been subjected to numerous studies. One is in the Norrbotten region and the other is in Jämtland (Fig. 1). The Norrbotten SNC comprises quartzites, feldspathic and calc-silicate-bearing psammites, minor marble, and pelite. The Norrbotten SNC records a comparatively long tectonomagmatic and tectonometamorphic history, with magmatism at 945 ± 31 (Albrecht 2000) and 845 ± 14 Ma (Paulsson and Andréasson 2002), and *c.* 637 and 607 Ma titanite and 603 Ma monazite ages (Rehnström *et al.* 2002; Root and Corfu 2012; Barnes *et al.* 2019). These ages may be related to heating from the intrusion of mafic dyke swarms; however, the 637 Ma titanite age is too old to be related to mafic dyke emplacement, and the interpretation of the 603 Ma monazite is cryptic due to textural complexities (Barnes *et al.* 2019). Eclogite-facies mafic rocks (former dykes) in the Norrbotten SNC record pressure–temperature conditions of 26–27 kbar and 680–780°C (Barnes *et al.* 2019). Various attempts at dating this metamorphic event using Ar–Ar, Sm–Nd isochrons and U–Pb on monazite and zircon have yielded ages between *c.* 505 and 482 Ma (Mørk *et al.* 1988; Essex *et al.* 1997; Root and Corfu 2012; Barnes *et al.* 2019).

The Jämtland SNC comprises rocks similar to those in the Norrbotten SNC but lacks evidence of a Neoproterozoic tectonometamorphic history. Eclogite-facies rocks in the Jämtland SNC record roughly similar pressure–temperature conditions (25–26 kbar, 650–700°C: Fassmer *et al.* 2017) but yield Sm–Nd and Lu–Hf mineral ages of around 460 Ma (Brueckner and van Roermund 2007; Fassmer *et al.* 2017), and even younger, *c.* 446 Ma, zircon crystallization ages (Root and Corfu 2012). The Västerbotten area, between the Norrbotten and Jämtland SNC, is poorly exposed and not well investigated. Thus far, there is no evidence of similar (U)HP metamorphism in Västerbotten, possibly because of more extensive retrogression (Gee *et al.* 2013).

The Kalak Nappe Complex (KNC) in the northern Norwegian Caledonides (Roberts 1985) has traditionally been correlated with the SNC (Andréasson *et al.* 1998). The KNC dominantly comprises variably metamorphosed sedimentary rocks that were laid down in several depositional cycles between *c.* 1000 and 700 Ma (Slagstad *et al.* 2006; Kirkland *et al.* 2007), and record tectonometamorphic and tectonomagmatic events throughout much of the Neoproterozoic (Kirkland *et al.* 2007, 2016; Gasser *et al.* 2015), including emplacement of the mafic–ultramafic Seiland Igneous Province mostly at *c.* 570–560 Ma (Roberts *et al.* 2006). The Seiland Igneous Province rocks have chemical compositions and field relationships compatible with formation in a possibly plume-influenced continental rift (Krill and Zwaan 1987; Grant *et al.* 2016; Larsen *et al.* 2018), similar to the *c.* 615–600 Ma mafic dyke magmatism in the SNC, interpreted to be related to the opening of the Iapetus Ocean and the Central Iapetus Magmatic Province (Tegner *et al.* 2019). The youngest components of the Seiland Igneous

Province are subordinate nepheline syenite dykes dated at *c.* 525 Ma (Pedersen *et al.* 1989). The complex Neoproterozoic evolution of parts of the KNC, with multiple phases of tectonometamorphic activity that correlate with events in the Mesoproterozoic–Neoproterozoic sequences of Scotland and East Greenland, has led several authors to suggest an origin exotic to Baltica (Corfu *et al.* 2007; Kirkland *et al.* 2007; Slagstad and Kirkland 2018).

Geology of the study areas

Rödingsfjället Nappe Complex near Mo i Rana

The study area near Mo i Rana consists of three nappes with disparate metasedimentary and meta-igneous rock suites (Fig. 2a). The field observations that form the basis for the geochronological investigation in this area have been presented by us in various theses, reports and maps, including: Marker (1983), Søvegjarto *et al.* (1988, 1989), Gjelle *et al.* (2003), Marker *et al.* (2012), Bjerkgård *et al.* (2013), Høyen (2016) and Storruste (2017). This work has established a local tectonostratigraphy for this part of the Rödingsfjället Nappe Complex consisting of, from structural bottom to top: the Ravnålia, Plura and Slagfjellet nappes. Each of the nappes are subdivided into one or more 'groups' or 'formations'; however, as discussed below, it is possible that cryptic nappe boundaries between some of these groups and formations have gone undetected. The nappes are described in detail below, from structural bottom to top, with particular emphasis on the dated units.

Ravnålia Nappe

Kjerringfjell Group. The Kjerringfjell Group is dominated by variably migmatitic, garnet–biotite ±muscovite, ±staurolite, ±kyanite gneisses, locally with irregular layers of quartzite and garnet-bearing amphibolite, intruded by numerous pegmatite sheets, the Umbukta gabbro and associated fine-grained, mafic dykes (Høyen 2016). The mica gneisses are typically medium grained and preserve what appears to be centimetre-scale primary bedding, along with a tectonic foliation and migmatitic leucosomes (Fig. 3c, d). The rocks preserve evidence of several generations of deformation but the structures in the Kjerringfjell Group have not yet been mapped out in detail. The Umbukta gabbro is medium–coarse grained and generally undeformed (Fig. 3e), although local growth of garnet and a general retrogression of pyroxene to hornblende are telltale signs of metamorphic overprinting (Storruste 2017). Primary igneous textures are typically well preserved, and olivine is preserved locally, giving the rocks a characteristic brown, weathered surface. Mafic dykes associated with the Umbukta gabbro are typically up to a few decimetres thick and cut the high-grade fabrics in the gneissic host rock (Fig. 3f); similar dykes are also found inside the gabbro. In addition, remnants of older mafic dykes, now thoroughly deformed and amphibolitized, are common, indicating pre-metamorphic mafic magmatism.

Ørtfjellet Group and Dunderland Formation. In addition to the Kjerringfjell Group, the Ravnålia Nappe consists of the Ørtfjellet Group and the Dunderland Formation. The main lithologies of these units include amphibolite-facies dolomite and calcite marble, compositionally variable mica schists and minor diamictite (Fig. 3g) interpreted to be of glacial origin (Melezhik *et al.* 2015), and minor intrusive bodies including tonalite. A characteristic feature of the Ørtfjellet Group and Dunderland Formation is numerous dismembered, stratiform iron formations in close proximity to the marbles. Carbon and Sr isotope chemostratigraphy of the marbles implies a depositional age of 800–730 Ma for the Dunderland Formation and a depositional age of *c.* 660 Ma for the Ørtfjellet Group (Melezhik *et al.* 2015).

Langfjell Shear Zone. The Langfjell Shear Zone separates the Plura and Ravnålia nappes. The shear zone consists of high-strain schists and gneisses intruded by locally abundant dismembered sheets of pegmatite (Fig. 3h). Detailed structural mapping of the Langfjell Shear Zone suggests that it reflects pre-Scandian shearing followed by Scandian folding (Marker 1983).

Plura Nappe. The Plura Nappe comprises amphibolite-facies mica schists and gneisses, grey gneiss, quartzite, amphibolite, dolomite, and calcite marble along with minor iron ore (Søvegjarto *et al.* 1988, 1989; Gjelle *et al.* 1991; Marker *et al.* 2012). The grey gneisses probably have igneous protoliths (discussed below), and locally preserve what looks like primary bedding (Fig. 3b), suggesting a volcanic origin. Carbon and Sr isotope chemostratigraphy of the marbles yields a depositional age of 700–670 Ma (Melezhik *et al.* 2015). Previous dating of detrital zircon from a garnet–mica schist in the Plura Nappe yielded ages between *c.* 1.8 and 1.0 Ga (Slagstad and Kirkland 2017).

Slagfjellet Nappe

Mofjellet Group. The Mofjellet Group consists of complexly folded, fine- to medium-grained grey gneisses with persistent layers of amphibolite and aluminous biotite and muscovite gneisses. The grey gneisses are dominantly dacitic and rhyolitic with abundant quartz and plagioclase, and subordinate biotite and muscovite, and are probably of igneous (perhaps volcanic) origin (Fig. 3a). The commonly garnet-bearing amphibolites contain pods and stripes

Fig. 3. (**a**) Grey migmatitic gneiss, Mofjellet Group (sample MO_104). (**b**) Grey gneiss, apparently with primary bedding, Plura Nappe (sample MO_074). (**c**) & (**d**) Migmatitic, folded mica schists, Kjerringfjell Group (leucosomes dated by sample 85175). (**e**) Umbukta gabbro, with a primary, magmatic texture (sample 197692). (**f**) Mafic dyke related to the Umbukta gabbro cutting high-grade metamorphic fabric and leucosomes in the Kjerringfjell host rock. (**g**) Diamictite associated with marbles and iron formation in the Ørtfjellet Group.

of calc-silicate rock and are interpreted by us to represent strongly deformed pillow lavas with small amounts of sediment infilling between the pillows. The more schistose and micaceous type of gneiss most likely represents greywacke-type metasediments. The biotite and muscovite gneisses or schists are generally rich in quartz and aluminosilicates in addition to mica. They may form separate, generally persistent layers but grade into each other with changing proportions of biotite and muscovite. Biotite-dominated types may also contain amphibole, and grade into hornblende-biotite gneisses. The biotite gneisses contain abundant kyanite in addition to garnet and staurolite, while the muscovite gneisses are mostly poor in these minerals. The biotite (±hornblende) and muscovite gneisses invariably

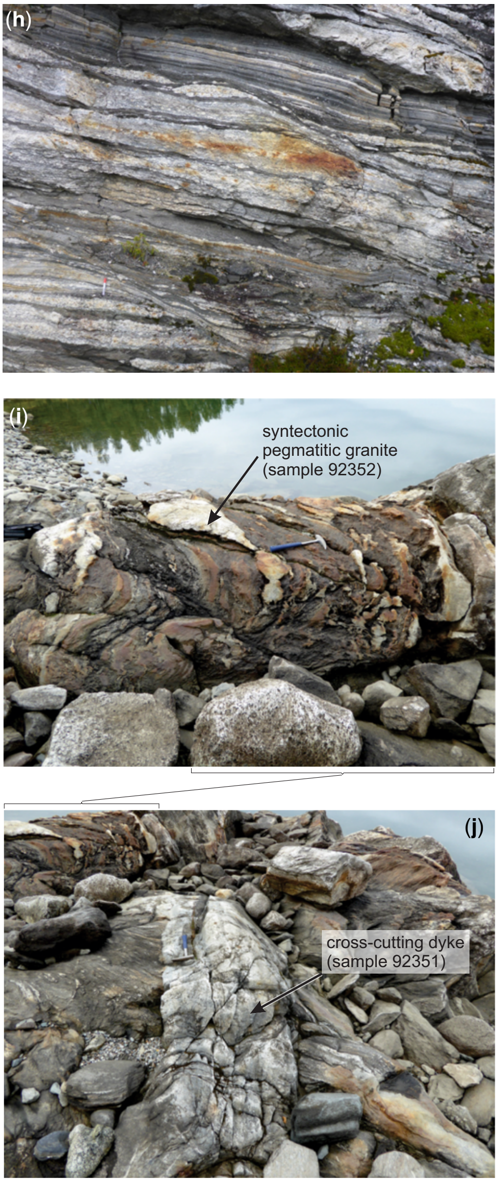

Fig. 3. *Continued.* (**h**) Langfjell Shear Zone with layers and lenses of deformed pegmatite (sample MO_079). (**i**) Syntectonic pegmatitic granite, east of northern Røssvatnet (sample 92352). (**j**) Cross-cutting granitic or tonalitic dyke, east of northern Røssvatnet (sample 92351).

contain disseminated pyrite as well as quartz-rich exhalites. The exhalite zones can be traced for several kilometres along strike and are important hosts for stratabound Zn–Pb–Cu sulfide mineralizations in the Mofjellet Group (Bjerkgård *et al.* 2013).

Rödingsfjället Nappe Complex east of northern Røssvatnet

The RNC is exposed on Hjartfjellet and the eastern and southern shoreline of northern Røssvatnet (Fig. 2b). Unfortunately, very little detailed mapping has been conducted in the region between our two study areas and we are currently unable to correlate units in the two areas. Our new mapping east of northern Røssvatn shows that the rocks in this area comprise garnet and kyanite–garnet mica schists, and quartzo-feldspathic mica gneisses with intercalations of marble. The main foliation of the schists and gneisses represents an already transposed and isoclinally folded layering (S_n). This foliation S_n is represented in thin sections by a compositional layering and discontinuous, probably isoclinally folded quartz layers and rootless isoclinal folds. Tight folding of this layering represents a subsequent deformation stage, F_{n+1}. Variably thick foliation-parallel, leucocratic, fine-grained to pegmatitic granitic veins (Fig. 3i) were emplaced syntectonically parallel to the foliation (S_{n+1}) that formed during F_{n+1} folding, leading to boudinage or folding of the intruding veins during ongoing deformation. Folding occurred at high temperatures and was accompanied by shearing along the fold limbs. Crenulation cleavage oblique to F_{n+1} axial planes and spatial variations in the orientation of F_{n+1} orientation indicates a likely third pre-Scandian folding phase that requires verification and further studies. Different generations of granitic sheets, pods and larger bodies are common in the gneisses and schists (Fig. 3i, j); they formed at different stages in the polyphase tectonometamorphic evolution of the schists and gneisses. In the area east of Røssvatnet, the RNC is located in a regional-scale Scandian synform that also includes structurally underlying nappes traditionally assigned to the upper Köli Nappe Complex.

Methods

U–Pb zircon dating

Zircon crystals were separated using standard techniques (Wilfley or Rogers water table, heavy liquid, Frantz magnetic separation). Zircons from the non-magnetic fraction were picked under alcohol, mounted in 1 inch-diameter epoxy resin mounts and polished to expose an equatorial section through the grains.

The analyses were carried out at the Geological Survey of Norway (NGU) on an ELEMENT XR single-collector, high-resolution ICP-MS, coupled to a UP193–FX 193 nm short-pulse excimer laser ablation system from New Wave Research. The laser was set to ablate single, up to 60 µm-long lines, using a spot size of 20 or 15 µm, a repetition rate of 10 Hz and an energy corresponding to a fluence of 4–5 J cm^{-2}. Each analysis included 30 s of background measurement followed by 30 s of ablation. Masses 202, 204, 206–208, 232 and 238 were measured. The reference material GJ-1 (Jackson *et al.* 2004) was used for fractionation correction of isotopic ratios, whereas 91500 (Wiedenbeck *et al.* 1995) and an in-house standard (OS-99-14, 1797 ± 3 Ma: Skår 2002) were used to check precision and accuracy. The data were not corrected for common lead but monitoring of the signal for 204 allowed exclusion of data deemed to be influenced by common Pb from further calculations. The data were reduced using GLITTER® (Van Achterbergh *et al.* 2001) and plots were made using Isoplot (Ludwig 2003).

Whole-rock geochemistry

Whole-rock geochemical analyses were conducted at ALS Chemex in Sweden using methods ME-ICP06 (fused bead, acid digestion and inductively coupled plasma atomic emission spectroscopy (ICP-AES)) and ME-MS81 (fused bead, acid digestion and inductively coupled plasma mass spectrometry (ICP-MS)).

Sm–Nd isotopes

Sm–Nd isotope data on whole-rock samples from the Umbukta gabbro and its host rock were obtained in the Geology Laboratory of Université Blaise Pascal (Clermont-Ferrand, France) using isotope dilution thermal ionization mass spectrometry (ID-TIMS). Basaltic samples were decomposed by standard acid dissolution procedures with hydrofluoric acid (HF). Sample decomposition of metasedimentary rocks was achieved by fusion with a $LiBO_2$ flux in an induction furnace at *c.* 1150°C, as described by Le Fèvre and Pin (2005). Isolation of Nd and Sm was carried out by cation exchange and extraction chromatography methods similar to (samples dissolved with HF), or derived from (samples fused with $LiBO_2$), those described by Pin and Santos Zalduegui (1997). Sm and Nd concentrations were measured by isotope dilution using a mixed ^{149}Sm–^{150}Nd tracer and TIMS, allowing determination of $^{147}Sm/^{144}Nd$ ratios with a precision of 0.2%. Sm isotope dilution measurements were made in Clermont-Ferrand after sample loading in a droplet of *c.* 5 M phosphoric acid on single Ta filaments using an automated VG54E mass spectrometer operated in single collection mode. Nd isotopic ratios were determined with double Re filament assemblies using a Thermo Finnigan Triton TI instrument at Nîmes University, in the static multi-collection mode, with normalization to $^{146}Nd/^{144}Nd = 0.7219$. During the period of analyses, five measurements of the JNdi-1 isotopic standard (Tanaka *et al.* 2000) gave a mean $^{143}Nd/^{144}Nd$ of 0.512102 ($SD = 3 \times 10^{-6}$). The USGS rhyolite standard RGM-1 was analysed in duplicate, using the HF-dissolution and the $LiBO_2$-fusion methods, in order to check for the overall reproducibility and accuracy of the method.

Results

U–Pb zircon age dating

The U–Pb zircon data are presented in Supplementary material 1. Table 1 presents a summary of the data and sample coordinates.

Detrital zircons, metasedimentary rocks, Kjerringfjell Group, Ravnålia Nappe. One hundred and eight detrital zircon grains from four samples collected just north of the Umbukta gabbro in the Kjerringfjell Group yield dominantly Mesoproterozoic and late Paleoproterozoic ages between 1.9 and 1.0 Ga, with sparse Archean grains (Fig. 4a). The youngest analysis is 97% concordant with an age of *c.* 865 Ma; a relatively low Th/U ratio of 0.15 may, however, suggest some effects of metamorphism, as discussed further below. The youngest identifiable population consists of four analyses that yield a concordia age of 1030 ± 17 Ma ($MSWD = 0.13$), considered the best estimate of the maximum age of deposition.

Neoproterozoic high-grade metamorphism, Kjerringfjell Group, Ravnålia Nappe. A leucosome from a migmatitic psammite, cut by a mafic dyke related to the Umbukta gabbro (Fig. 3f), was sampled for dating. The zircons from this sample are typically 100–150 µm and rounded to elongate. Internally, the zircons commonly display oscillatory-zoned cores with cathodoluminescence (CL)-dark (U-rich) mantles with faint oscillatory to irregular zoning, or CL-dark grains with variable oscillatory and irregular zoning (Fig. 5). Twenty-three analyses of oscillatory-zoned cores yield ages ranging between 1630 and 889 Ma, with a youngest population of *c.* 1034 Ma (Fig. 4b). Seventeen analyses of CL-dark rims and discrete grains yield several reversely discordant analyses due to high U content and, judging from the post-analysis CL images, core–rim mixtures cannot be confidently excluded in some cases. Nevertheless, 10 analyses yield a weighted mean $^{206}Pb/^{238}U$ age of 623 ± 6 Ma ($MSWD = 2.1$: Fig. 4b), interpreted to represent the crystallization age of the leucosome and thus the age of high-grade metamorphism in the Kjerringfjell Group.

Late Neoproterozoic magmatism, Kjerringfjell and Ørtfjellet groups, Ravnålia Nappe. The zircons

Table 1. *Summary of new U–Pb zircon age data*

Sample	Easting	Northing	Rock type	Tectonostratigraphy	Age (Ma)	Interpretation
MO_062	464 384	7 349 849	Syntectonic granite sheet	Mofjellet Group, Slagfjellet Nappe	429 ± 4	Crystallization, deformation
MO_104	470 631	7 345 673	Grey granitic gneiss	Mofjellet Group, Slagfjellet Nappe	501 ± 3	Crystallization
MO_074	469 368.002	7 358 329	Grey gneiss, metavolcanic	Plura Nappe	510 ± 6	Crystallization
MO_079	465 033	7 362 800	Syntectonic pegm.	Langfjell Shear Zone	475 ± 5	Crystallization, deformation
MM83786	460 507	7 363 000	Tonalite	Ørtfjellet Group, Ravnålia Nappe	541 ± 6	Crystallization
85175(2)	488 941	7 340 561	Leucosome, migm. psammite	Kjerringfjell Group, Ravnålia Nappe	623 ± 6	Migmatization
197692	485 990	7 338 443	Umbukta gabbro	Kjerringfjell Group, Ravnålia Nappe	578 ± 6	Crystallization
85175(1)	488 941	7 340 561	Psammitic gneiss	Kjerringfjell Group, Ravnålia Nappe	Detrital	Mainly 1.9–1.0 Ga, sparse *c.* 2.7 Ga grains, deposition <1030 Ma
127900	488 358	7 340 841	Psammitic gneiss	Kjerringfjell Group, Ravnålia Nappe	Detrital	
197665	488 191	7 340 870	Psammitic gneiss	Kjerringfjell Group, Ravnålia Nappe	Detrital	
197699	488 718	7 340 688	Psammitic gneiss	Kjerringfjell Group, Ravnålia Nappe	Detrital	
92351	466 531	7 304 969	Cross-cutting granite dyke	Røssvatnet area	484 ± 11	Crystallization, deformation
92352	466 531	7 304 969	Syntectonic pegm. dyke	Røssvatnet area	515 ± 5	Crystallization, deformation
92355	463 694	7 301 938	Granitic gneiss	Røssvatnet area	464 ± 4	Crystallization

Coordinates: UTM zone 33, WGS84.

from the Umbukta gabbro, Kjerringfjell Group (sample 197692) are long prismatic, *c.* 250–300 µm, with well-developed, rather broad, oscillatory zoning. Nine of 10 analyses yield a concordia age of 578 ± 6 Ma (Fig. 4c: MSWD = 2.5), interpreted to represent the crystallization age of the mafic magma. This age is similar to an earlier date of 576 ± 7 Ma, interpreted as the age of magmatic crystallization (Senior and Andriessen 1990). The significance of the single excluded analysis is unclear.

The zircon crystals from a tonalitic gneiss in the Ørtfjellet Group (sample MM83786) resemble those in the Umbukta gabbro, both in size and internal zoning. Thirteen of 15 analyses yield a weighted mean ^{206}Pb/^{238}U age of 541 ± 6 Ma (Fig. 4d: MSWD = 1.2). The age is interpreted to reflect crystallization of the tonalitic magma. Of the two analyses not used in the age calculation, one is strongly discordant, whereas the other yields a *c.* 430 Ma age that is interpreted to reflect modification or growth during Scandian overprinting.

Cambrian and Ordovician magmatism. Sample MO_104 from the Mofjellet Group, Slagfjellet Nappe is a fine-grained, light-grey quartzofeldspathic orthogneiss with sparse migmatitic leucosomes. The zircons from this sample are comparatively small, typically around 100 µm, equidimensional to stubby, with well-developed oscillatory zoning. The zoning is commonly transected by CL-bright irregular veins, suggesting some later alteration. Thirty analyses cluster around 500 Ma, 20 of which yield a concordia age of 501 ± 3 Ma (Fig. 4e: MSWD = 0.19), interpreted to represent the crystallization of the orthogneiss protolith. The analyses which do not fit the concordia age are interpreted to reflect

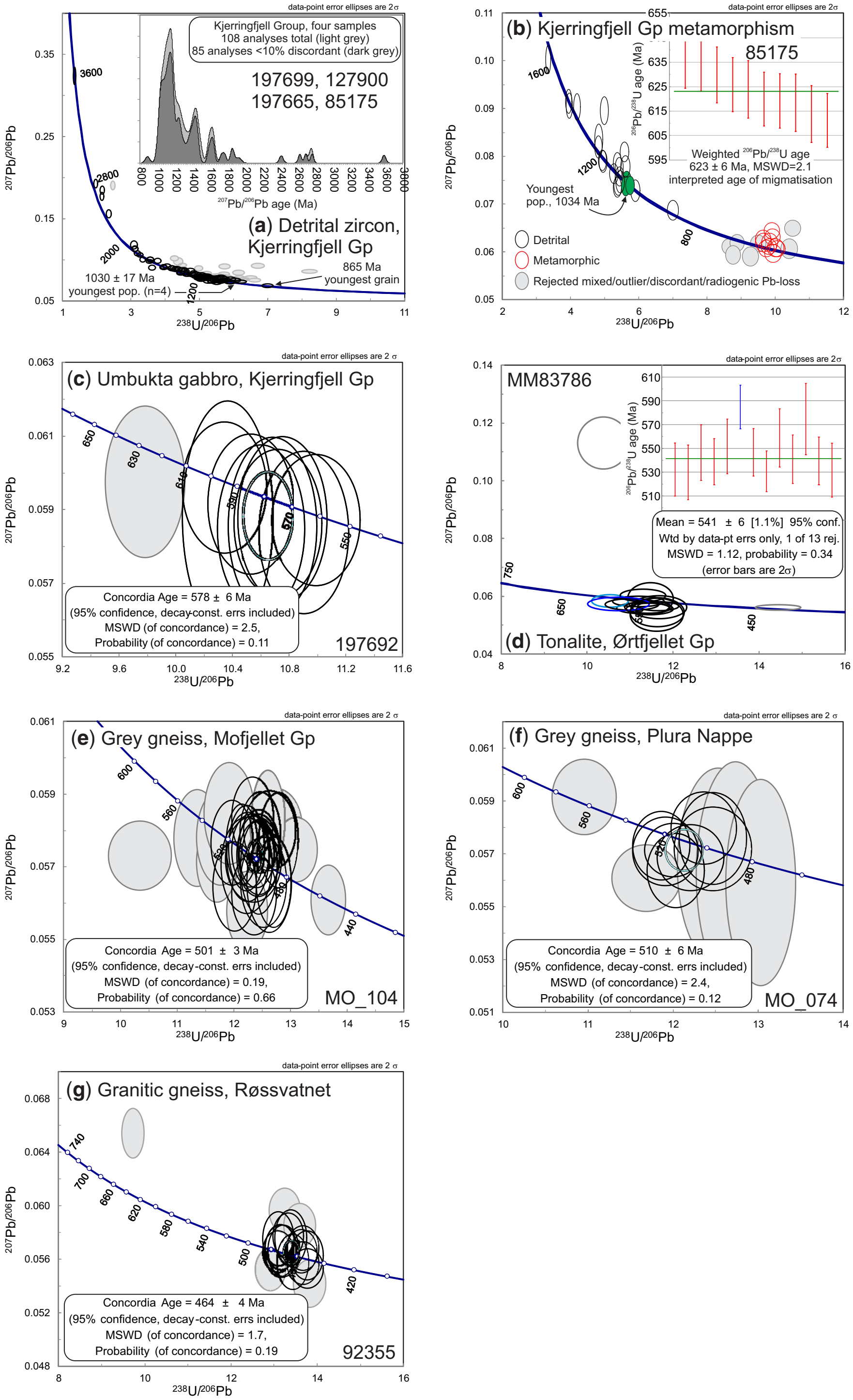

Fig. 4. (**a**)–(**g**) U–Pb zircon geochronological data from metasedimentary and meta-igneous rocks from the two study areas. Sample numbers are indicated on the figure. Filled grey ellipses are excluded from the age calculation, as discussed in the text.

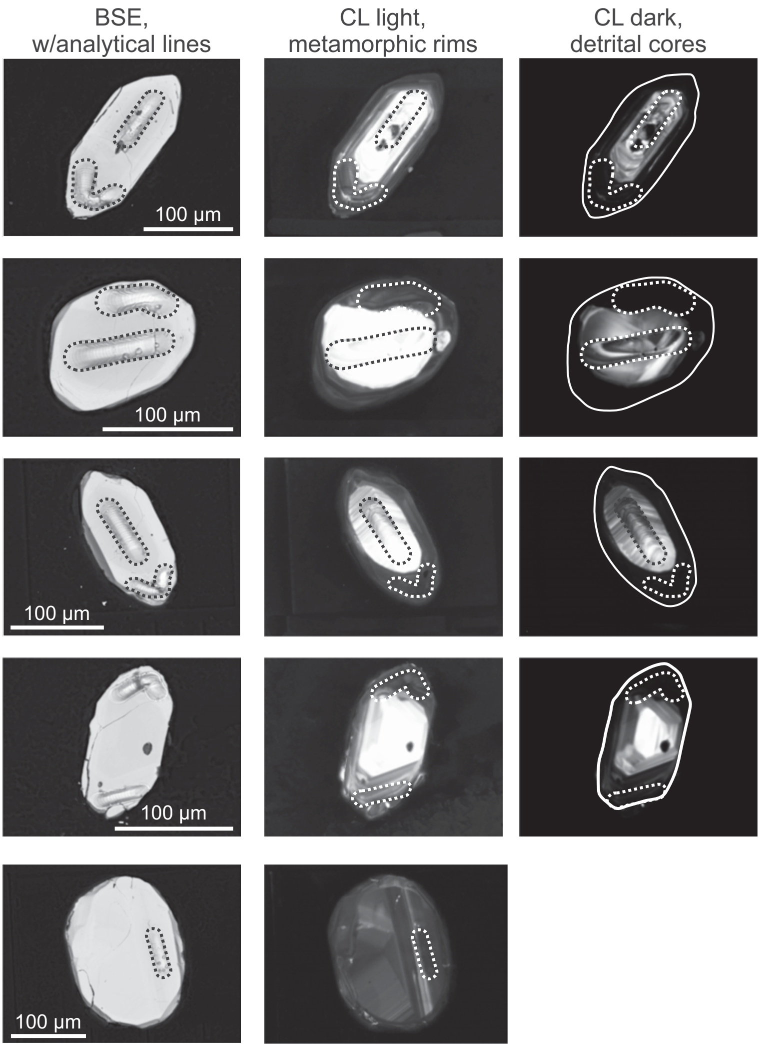

Fig. 5. Backscattered electron (BSE) and cathodoluminescence (CL) images of selected zircons from the leucosome in the Kjerringfjell Group metapsammite showing well-developed core–rim relationships.

alteration, indicated by the CL-bright veins in many of the grains.

Sample MO_074 from the Plura Nappe is a foliated, fine-grained, light-grey homogeneous metagranite with disseminated biotite, garnet and muscovite. The zircons from this sample resemble those of sample MO_104, typically around 100 μm, stubby with well-developed oscillatory zoning. Of 13 analyses, three have large $^{207}Pb/^{206}Pb$ errors, one is strongly reversely discordant (16%) and one is a concordant outlier at *c.* 565 Ma, which may have some inherited component. The remaining eight analyses yield a concordia age of 510 ± 6 Ma (Fig. 4f: MSWD = 2.4), interpreted to represent the crystallization age of the metagranite on the basis of magmatic zircon CL texture. The significance of the *c.* 565 Ma outlier is unknown but is similar to the magmatic activity in the Ravnålia Nappe.

Sample 92355, from east of Røssvatnet, is a medium-grained granitic gneiss layer. The zircons from this sample are 100–300 μm, stubby to prismatic, with CL-dark, oscillatory-zoned interiors. Five of 16 analyses are discordant, with the other 11 yielding a concordia age of 464 ± 4 Ma (Fig. 4g: MSWD = 1.7), interpreted to reflect crystallization of the granitic magma.

Cambrian–Silurian (Scandian) deformation. Several samples were dated in an attempt to constrain the age of deformation. The samples include dykes showing syntectonic relationships with the surrounding rocks or cross-cut tectonic fabrics in those rocks.

Sample 92352, from east of Røssvatnet (Fig. 2b), is a syntectonic pegmatite sheet. The sampled outcrop is located on the shoreline at Skittreskvika and comprises intensely folded quartzofeldspathic mica gneisses. The gneissic layering represents a transposed foliation (S_n) that has subsequently been affected by another folding phase (F_{n+1}). During this phase, porphyritic granite intruded sub-parallel to the layering, forming incoherent pinching and swelling veins, and lens-shaped boudins due to ongoing deformation. The layering and granite veins have been folded to tight metre-scale NW-facing folds with moderately WSW-plunging F_{n+1} fold axes. One of the boudinaged granites was sampled for geochronology (sample 92352) inferred to provide an age of folding. The zircons from this sample are typically 200–300 µm, prismatic, and dark and featureless in CL due to very high U contents. One outlier yields a slightly reversely discordant age of *c.* 540 Ma, and another is strongly discordant and omitted from further discussion. The remaining 16 analyses plot in two groups, with three discordant analyses plotting partly between the two groups. The older group consists of nine analyses and yields a concordia age of 515 ± 5 Ma (Fig. 6a: MSWD = 0.38), whereas the other group yields a concordia age of 480 ± 8 Ma (MSWD = 4.5). The older age is interpreted to date crystallization of the syntectonic pegmatite, thus dating deformation, whereas the younger group is interpreted to reflect later Pb loss. The three discordant analyses between these concordant age components are interpreted to represent physical mixtures of different age domains, consistent with the interpretation of two distinct age components in this sample.

Sample MO_079 is from a syntectonic pegmatite in the Langfjell Shear Zone, separating the Ravnålia and Plura nappes. The zircons from this sample are large, typically 200–400 µm, prismatic and dark in

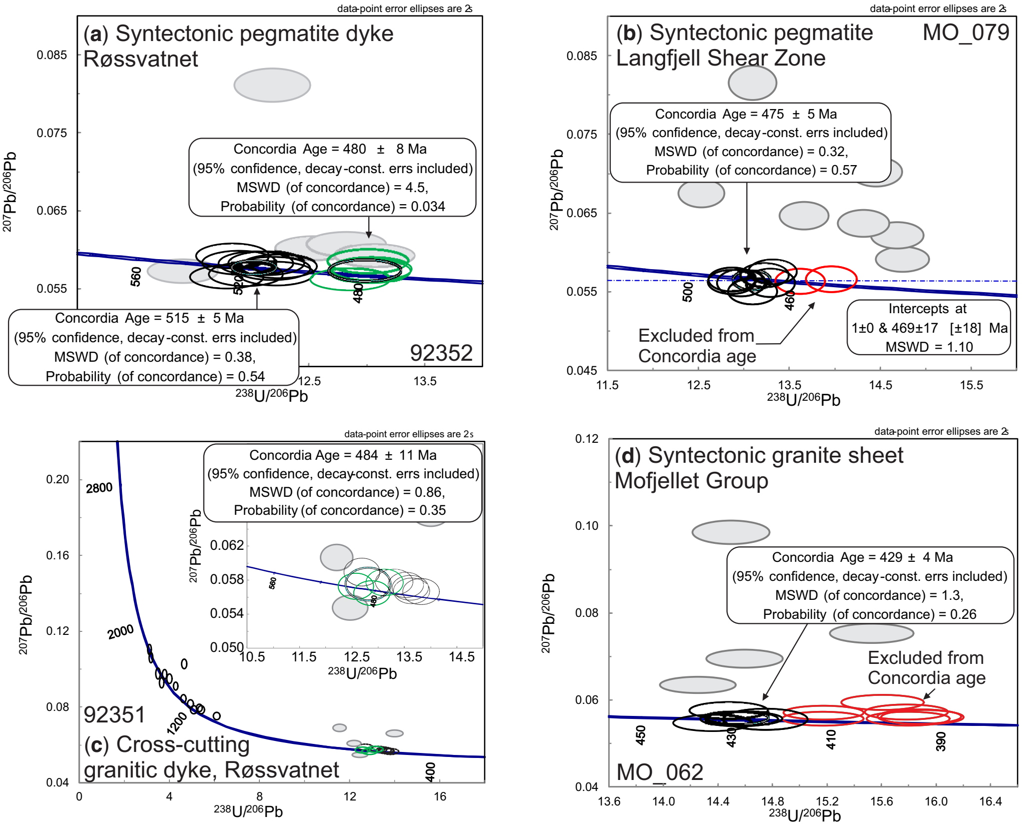

Fig. 6. (**a**)–(**d**) U–Pb zircon geochronological data constraining ages of deformation in the two study areas. Sample numbers are indicated on the figures. Filled grey ellipses are excluded from the age calculation, as discussed in the text.

CL, but in many cases with clearly discernible oscillatory zoning. Seven of 16 analyses are strongly discordant and not considered further. The remaining nine analyses cluster around *c.* 475 Ma, with two analyses yielding slightly younger ages. A regression through all nine analyses yields an upper intercept of 469 ± 11 Ma (MSWD = 1.2), with an imprecise future lower intercept of −305 ± 930 Ma. Excluding the two slightly younger analyses, the remaining seven analyses yield a concordia age of 475 ± 5 Ma (Fig. 6b: MSWD = 0.32), interpreted as the best estimate of the crystallization age of the pegmatite,and thus dating deformation along the Langfjell Shear Zone. The two younger analyses are interpreted to have undergone recent radiogenic Pb loss.

Sample 92351 was collected at Skittreksvika (Fig. 2b), from a fine-grained granitic to granodioritic dyke, which cuts the foliation in the host mica gneiss at a high angle and clearly post-dates the main deformation (i.e. folding and foliation development, as well as high-grade metamorphism) in this outcrop. The zircon crystals from this sample are *c.* 100–150 µm, prismatic to irregular with CL-bright, oscillatory-zoned cores surrounded by thick, CL-dark, oscillatory-zoned mantles; the latter also form separate grains. The cores yield ages between *c.* 1080 and 1805 Ma, whereas nine CL-dark mantles and grains yield ages that spread along concordia between *c.* 490 and 450 Ma; the older analyses are generally more concordant. Four discordant analyses are omitted from further discussion. Extracting an age from the young group of analyses is not straightforward. A regression through the group yields a discordia that is nearly parallel to concordia, resulting in apparently meaningless, very imprecise, upper and lower intercepts. Caledonian Pb loss is a distinct possibility and the three oldest analyses yield a concordia age of 484 ± 11 Ma (Fig. 6c: MSWD = 0.86), which may represent a best estimate of the age of crystallization of granite dyke. This date would also then provide a minimum age of deformation of the host mica gneiss. The dispersion along concordia to younger ages is interpreted to reflect Caledonian Pb loss. The population of inherited detrital cores is similar to that documented from the Kjerringfjell Group, Ravnålia Nappe.

Sample MO_062 is a syntectonic granite sheet within the Mofjellet Group, Slagfjellet Nappe. The zircons from this sample are 100–150 µm and prismatic, with well-developed oscillatory zoning. Sixteen analyses yield ages dispersed along concordia from *c.* 430 to 400 Ma, with four discordant analyses excluded from further discussion. The five oldest analyses are concordant to somewhat discordant (up to 16%), whereas the seven younger analyses are between 10 and 31% discordant. The oldest population of five analyses yields a concordia age of 429 ± 4 Ma (Fig. 6d: MSWD = 1.3), considered the best estimate of the crystallization age of the syntectonic granite, corresponding to the Scandian tectonic event.

Whole-rock geochemistry and Sm–Nd isotopes

The whole-rock chemical and Sm–Nd isotopic data, along with sample coordinates, are presented in Electronic Supplements 2 and 3, respectively.

Mofjellet Group. The meta-igneous suite in the Mofjellet Group comprises grey gneisses and amphibolites that classify as dacite/rhyolite and basalt/basaltic andesite, respectively (Fig. 7a). The grey gneisses are calc-alkaline with enriched chondrite-normalized light REE (LREE) patterns, enriched in large ion lithophile elements (LILEs) and Pb relative to high field strength elements (HFSEs), and depleted in Nb, Ta and Ti when normalized to primitive mantle (Fig. 7b, c). In commonly used tectonic discrimination diagrams, the grey gneisses plot in the volcanic arc field (Fig. 7e).

The amphibolites straddle the line between tholeiitic and calc-alkaline compositions and have slightly LREE-depleted to LREE-enriched patterns (Fig. 7b). Like the grey gneisses, the amphibolites are depleted in Nb and Ta, and enriched in Pb in the primitive-mantle-normalized diagram, and enriched in LILEs relative to MORB (Fig. 7b–d). The amphibolites plot in the field of arc basalts in the tectonic discrimination diagrams (Fig. 7f).

Umbukta gabbro and related mafic dykes. The whole-rock chemical data include samples from the medium- to coarse-grained gabbro itself, in addition to fine-grained mafic dykes inside the gabbro and dykes cutting older metamorphic fabrics in the metasedimentary host rock around the gabbro. In general, there are no systematic differences in composition between the gabbro and the dykes, suggesting that the gabbro samples roughly reflect melt compositions; a few exceptions, where the gabbros have lower incompatible trace element concentrations, may represent a higher proportion of cumulate phases.

The mafic rocks range between 42 and 58 wt% SiO_2, and dominantly correspond to ‘basalt’ and more rarely ‘basaltic andesite’ in the SiO_2 v. $K_2O + Na_2O$ diagram (Fig. 8a). They are enriched in incompatible trace elements, have fractionated REE patterns with chondrite-normalized REE values typically several tens to more than hundreds of times chondrite, and little or no Eu anomaly (Fig. 8b). The primitive-mantle-normalized diagram displays a relatively flat pattern with no particular anomalies, apart from a positive Pb anomaly (Fig. 8c), and the MORB-normalized diagram displays a characteristic ‘hump’ shape (Fig. 8d). Ratios of Zr/Nb are

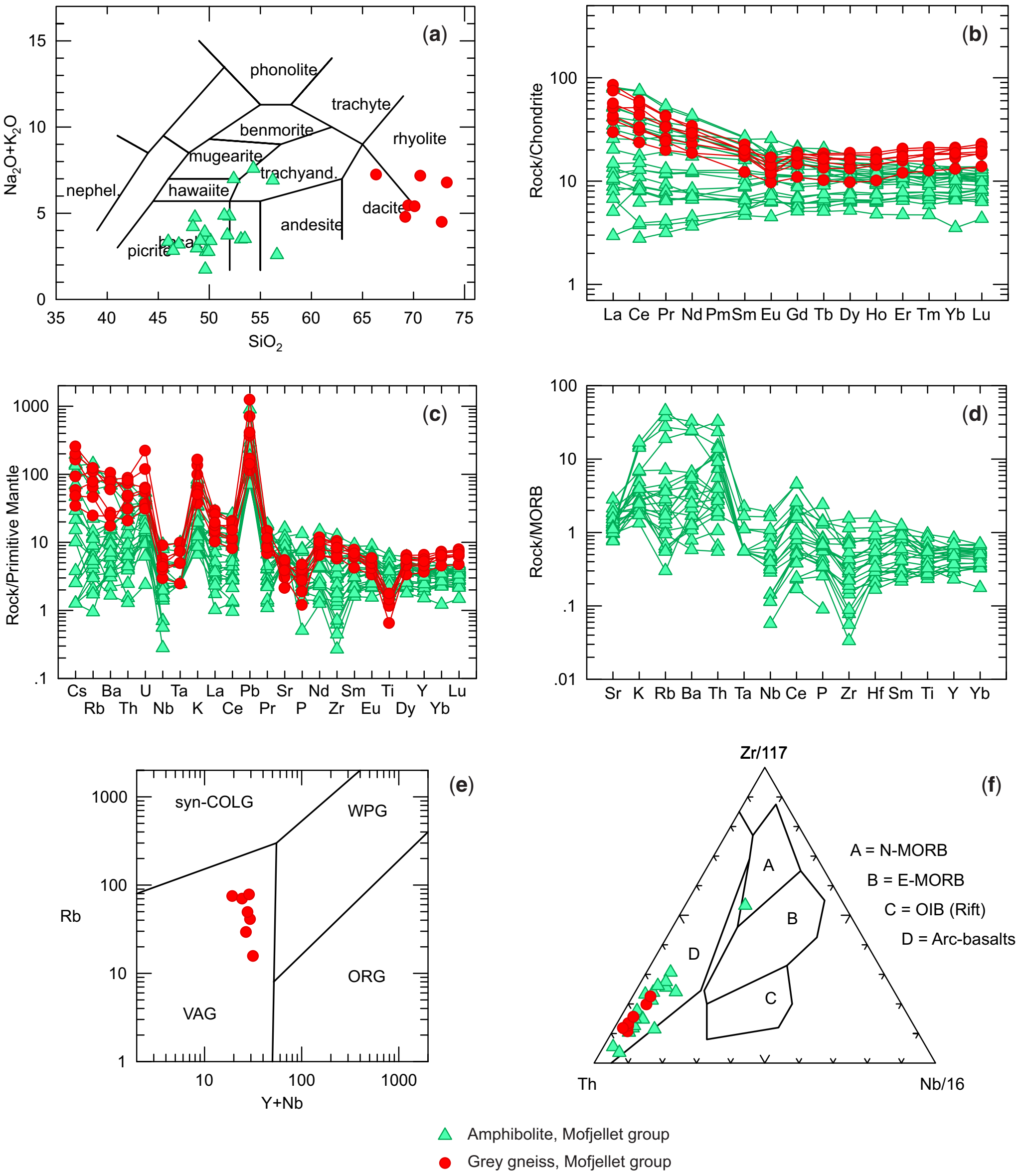

Fig. 7. (**a**)–(**f**) Major and trace element plots of the grey gneisses and amphibolites in the Mofjellet Group. Rock-type fields in the SiO$_2$ v. Na$_2$O$_2$ + K$_2$O diagram are from Cox *et al.* (1979), the chondrite and primitive mantle values are from Sun and McDonough (1989), and the MORB (mid-ocean ridge basalt) values are from Pearce (1983). Tectonic discrimination diagrams in (**e**) & (**f**) are from Wood (1980) and Pearce *et al.* (1984), respectively.

sensitive indicators of enrichment of the mantle source, with low ratios (*c.* 3) indicating high degrees of enrichment, and high ratios (*c.* 30–40) typically encountered in strongly depleted MORB (Weaver *et al.* 1983; Pin and Paquette 1997). Apart from one sample, the data from the Umbukta gabbro and related dykes have low Zr/Nb ratios between 5 and 9 (not shown in the figure). These results, together with results from several tectonic discrimination diagrams (Fig. 8e, f), are consistent with an enriched mantle source and a within-plate tectonic setting for the Umbukta gabbro, which, in turn, is consistent with emplacement into continental rocks that did not appear to undergo orogenic activity at the time.

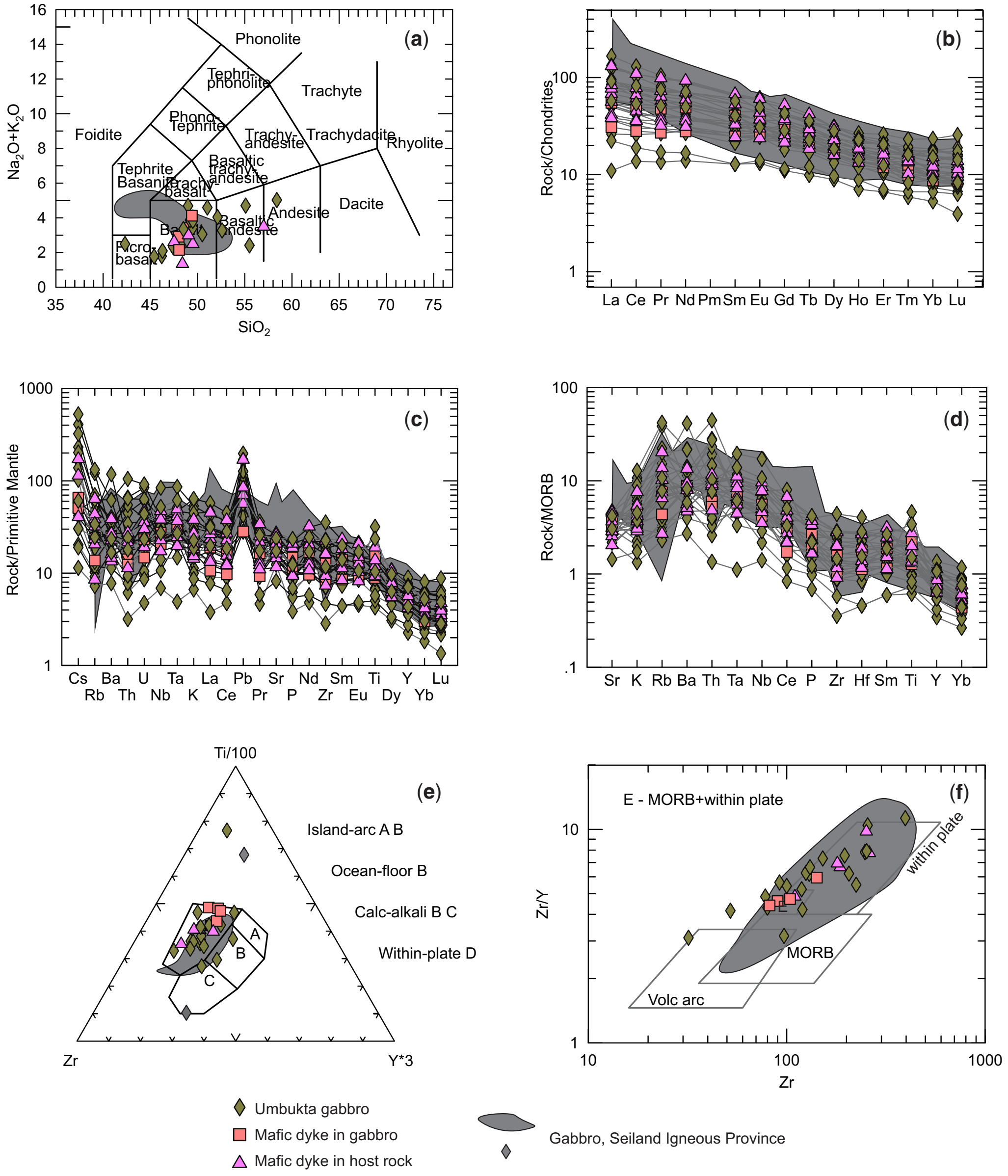

Fig. 8. (**a**)–(**f**) Major and trace element plots of the Umbukta gabbro and associated mafic dykes, both within the gabbro and intruding the metasedimentary host rock. Rock-type fields in the SiO$_2$ v. Na$_2$O$_2$ + K$_2$O diagram are from Cox *et al.* (1979), the chondrite and primitive mantle values are from Sun and McDonough (1989), and the MORB (mid-ocean ridge basalt) are values from Pearce (1983). Tectonic discrimination diagrams in (**e**) and (**f**) are from Pearce and Cann (1973) and Pearce and Norry (1979), respectively.

The shaded field in the diagrams represent the range of chemical compositions from gabbros in the Seiland Igneous Province (Roberts 2007), which is generally interpreted to have formed in a within-plate rift setting, possibly in association with plume activity (Roberts *et al.* 2006; Grant *et al.* 2016; Larsen *et al.* 2018). The gabbroic rocks from the two areas are indistinguishable.

Sm–Nd analyses of nine mafic samples and one garnet mica schist host-rock sample show a large spread in ε_{Nd}(575 Ma) values (ε_{Nd} values calculated for an age of 575 Ma), from 5.6 (i.e. close to depleted mantle at 575 Ma) to −2.5, probably reflecting contamination with the metasedimentary host rocks, one sample of which yields an ε_{Nd}(575 Ma) value of −8.2 (Fig. 9a). Th/Nb ratios are sensitive indicators of crustal contamination in mantle melts because the former have significantly higher Th/Nb ratios than the latter. The contamination may result from assimilation during ponding and ascent through the crust or from contamination of the mantle source during subduction and recycling of continental detritus. Typically, uncontaminated mantle melts have very low Th/Nb ratios (<0.1), regardless of whether their source is depleted or enriched. The Umbukta gabbro and related mafic dykes have Th/Nb ratios between 0.04 and 0.12, whereas two samples with significantly lower $\varepsilon_{\text{Nd}}(t)$ values (−2.5 and −1.7) have significantly higher Th/Nb ratios of 0.32 and 0.38 (Fig. 9b). There is no apparent correlation between the ε_{Nd}(575 Ma) value and proximity to the metasedimentary host rocks, indicated, for example, by a relatively high ε_{Nd}(575 Ma) value of 4.5 for a mafic dyke intruding the host rock. This lack of correlation suggests that contamination took place at depth, consistent with apparently relatively cold host rocks. Gabbros from the Seiland Province (Tegner *et al.* 1999) yield a similar range of ε_{Nd} values (Fig. 9a) and a comparatively wide range of zircon Lu–Hf isotope values (Roberts 2007).

Interestingly, there is a large contrast in the dominantly positive ε_{Nd} values of the gabbro, indicative of a time-integrated depleted mantle source, and the enriched incompatible element signature. These features are indicative of enrichment of the source slightly before or at the time of the igneous event.

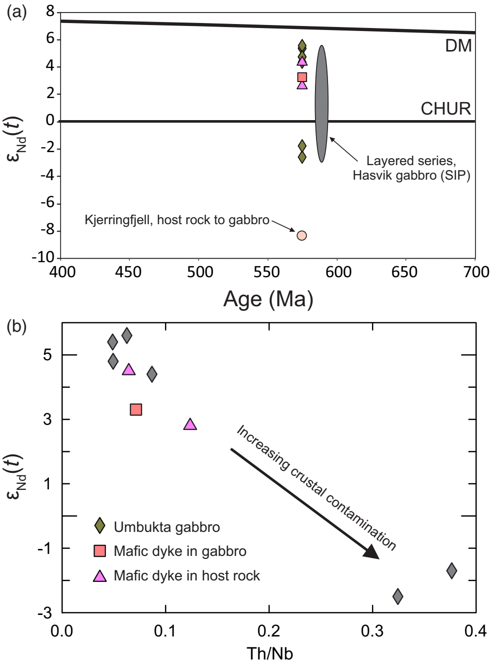

Fig. 9. (**a**) ε_{Nd}(575 Ma) plot of Sm–Nd isotopic compositions of the Umbukta gabbro, associated mafic dykes and host rock. The range of ε_{Nd} values from the Seiland Igneous Province are from Tegner *et al.* (1999), (**b**) Th/Nb vs ε_{Nd}(t) plot of samples from the Umbukta gabbro and associated mafic dykes.

Discussion

Neoproterozoic depositional, tectonomagmatic and tectonometamorphic events in the Rödingsfjället Nappe Complex, north-central Norway

Figure 10 presents schematic cross-sections of the two study areas and summarizes the available data from the investigated units. A distinct feature of the Scandinavian Caledonides is metasedimentary rocks with indistinct detrital zircon populations between *c.* 1.8 and 1.0 Ga, with relatively minor late Archean input (Slagstad and Kirkland 2017). The detrital zircon dataset presented here is rather small and limited to the Kjerringfjell Group, the host rock to the Umbukta gabbro, but nonetheless seems to be similar to other metasedimentary units in the Caledonides, including previously published detrital zircon data from the Plura Nappe (Slagstad and Kirkland 2017). A maximum age of deposition for the metasedimentary protolith to the Kjerringfjell Group is given by the youngest *c.* 1030 Ma population. Strontium and carbon chemostratigraphic data on the widespread marbles in the RNC yield apparent depositional ages of 800–730 Ma in the Dunderland Formation, *c.* 660 Ma in the Ørtfjellet Group, constituting the uppermost unit in the Ravnålia Nappe, and 700–670 Ma in the Plura Nappe (Melezhik *et al.* 2015). The possible existence of a tectonic contact between the Dunderland Formation and the Ørtfjellet Group cannot be excluded, but the data seem to point towards a long – but not necessarily continuous – depositional history in the RNC. Migmatization at 623 Ma and magmatism at 578 and 541 Ma document a change from a depositional to a tectonically more active environment. The significance of this change and the implications for correlation with other units in the Scandinavian Caledonides are discussed further below.

Cambrian–Ordovician active-margin processes: the 501 Ma Mofjellet arc

Cambrian magmatism is generally unknown from the Scandinavian Caledonides but detrital zircons

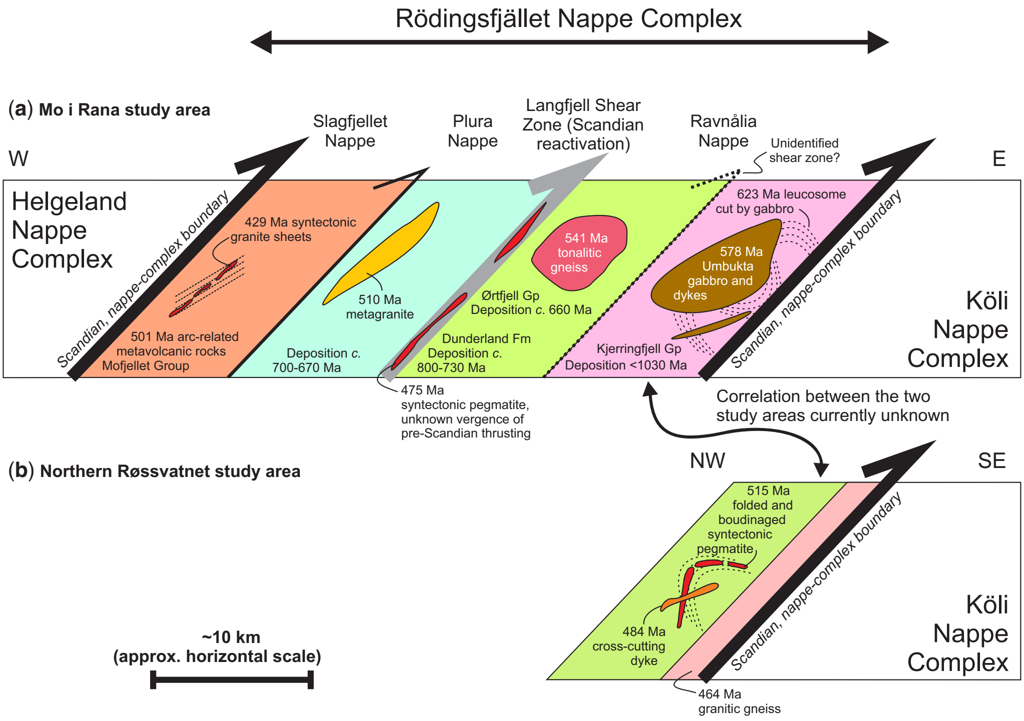

Fig. 10. Schematic cross-sections of the the study areas near (**a**) Mo i Rana and (**b**) northern Røssvatnet, summarizing the new data presented herein. The simplified geometries in the cross-sections reflect the situation following Scandian thrusting (i.e. dominantly SE-vergent thrusting). Complexities related to folding have not been incorporated.

of this age in the HNC led McArthur *et al.* (2014) to infer the existence of one or more proximal arc sources. The 501 Ma age and chemical data from the Mofjellet Group suggest that it, and possibly rocks in the adjacent Plura Nappe (510 Ma), may represent a Cambrian arc capable of sourcing detrital zircon of this age. The 515 ± 5 Ma age of a syntectonic, boudinaged granite pegmatite in the RNC at northern Røssvatnet is indicative of a Cambrian contractional tectonic event, consistent with the arc-related magmatism in Mofjellet. The geographical extent of this event is currently poorly constrained. Deformation as early as 515 Ma is previously unknown from the Scandinavian Caledonides, with an age of 497 Ma from the suprasubduction-zone-related Leka ophiolite being the temporally closest recognized event (Dunning and Pedersen 1988; Furnes *et al.* 1988), and interpreted to represent convergence within the Iapetus Ocean. Elsewhere in the Caledonian–Appalachian system, the subduction-zone-related Little Port ophiolite in Newfoundland has yielded an age of 505 Ma (Jenner *et al.* 1991), suggesting Mid-Cambrian convergence in Iapetus. The 515 Ma age of deformation and the 510 Ma age of arc-related magmatism reported here may either record stages of a distinct pre-Caledonian/pre-Taconian Cambrian evolution or may, alternatively, mark the incipient stages of Taconian orogenic development. In either case, these 515–500 Ma ages push the onset of convergence in the Iapetan system further back in time. The 480 ± 21 Ma dyke (sample 92351) cross-cuts metamorphic fabrics, and clearly post-dates Cambrian folding and metamorphism (Fig. 10b). It provides evidence for a polyphase (at least two stages) tectonothermal evolution of the wall rocks prior to *c.* 480 Ma. This dyke is coeval with the 475 Ma syntectonic pegmatite from the Langfjell Shear Zone (Fig. 10a), separating the Ravnålia and Plura nappes, whose age is similar to well-documented Taconian deformation in the HNC (Yoshinobu *et al.* 2002), and appears to overlap with ages of ophiolite obduction in the Scandinavian Caledonides (Slagstad *et al.* 2013). Following Late Cambrian arc-related magmatism, deformation and ophiolite obduction, widespread Mid-Ordovician magmatism in the Helgeland and Köli nappe complexes (Meyer *et al.* 2003; Barnes *et al.* 2007) suggests renewed active-margin activity indicative of a coupling between the two nappe complexes at least from that time.

Lastly, the RNC preserves evidence of the climactic Scandian event at *c.* 429 Ma, reflecting a collision between Baltica and Laurentia. This event may have been widespread throughout the Caledonian tectonostratigraphy (Majka *et al.* 2012; Engvik *et al.* 2014; Froitzheim *et al.* 2016; Bender *et al.* 2019); however, considering that some nappes record several hundred million years of discontinuous tectonic activity (Kirkland *et al.* 2007; Gasser *et al.* 2015; this work), the sparsity of data constraining metamorphic and deformational events in the Caledonides suggests we have a long way to go before we are able to resolve Scandian from pre-Scandian effects.

Implications of correlating geological events across Caledonian tectonostratigraphy

The tectonostratigraphic subdivision of the Scandinavian Caledonides into four allochthonous levels (Gee *et al.* 1985; Roberts and Gee 1985) has served as a basis for studies of the pre-Caledonian tectonic evolution of the Iapetus Ocean, as well as processes related to continent–continent collision for decades. An important aspect of this framework is that units at increasingly higher tectonostratigraphic levels are increasingly exotic to Baltica. A growing geochronological database has, however, resulted in many workers questioning the relationship between structural level and provenance (Kirkland *et al.* 2007; Corfu *et al.* 2014), with some authors arguing that distinguishing Baltica-derived from Laurentia-derived terranes with any degree of confidence is far from trivial with currently available data (Slagstad and Kirkland 2017). Others have argued that terranes derived from other continents, such as Gondwana, may also be present (Corfu *et al.* 2007). Many authors assume that Baltica and Laurentia were conjoined until Iapetus opening at *c.* 600 Ma (but see Slagstad *et al.* 2019 for a discussion of alternative scenarios), in which case the various terranes making up the Caledonides only had about 160 myr to develop their own, distinct characteristics prior to collision. Determining the provenance (Baltica, Laurentia or some other continent) of units within the Scandinavian Caledonides has been a major effort for decades (Roberts 1988; Corfu *et al.* 2007; Gee *et al.* 2014). A major obstacle is that Laurentia and Baltica have had a similar evolution through much of geological history, which means there are few unique and, hence, diagnostic features by which to make a distinction. Nonetheless, faunal evidence from Early Ordovician sedimentary rocks deposited on top of eroded ophiolite fragments shortly after obduction in the central and southwestern Scandinavian Caledonides suggest derivation from the Laurentian side of Iapetus (Bruton and Bockelie 1980; Pedersen *et al.* 1992). This interpretation is consistent with the recent suggestion by Slagstad and Kirkland (2018) that a distinct suite of 438–434 Ma mafic layered intrusions in the Köli and correlative nappe complexes is only found in the upper plate of the Scandian continent–continent collision. Hence, if we accept that the Köli and correlative nappe complexes are Laurentia-derived, the presence of the Leka and other similar ophiolite fragments in the HNC (McArthur *et al.* 2014), along with overlapping ages and styles of Ordovician magmatic activity in both allochthons (Meyer *et al.* 2003), is consistent with the widely accepted Laurentian ancestry of the HNC. A characteristic feature of the HNC is Early Ordovician, *c.* 475 Ma top-to-the-west thrusting, interpreted to reflect accretion and obduction of arc and back-arc assemblages (including ophiolites) that is typically correlated with the Taconian Orogeny in northeastern North America (Yoshinobu *et al.* 2002; Barnes *et al.* 2007; Roberts *et al.* 2007). The new data presented from the RNC suggests that evidence of a Taconian event is also present in other nappe complexes, and that some units may have undergone even earlier Cambrian tectonic events.

As shown in Figure 2a, the Ravnålia Nappe consists of two quite distinct units: the Kjerringfjell Group, consisting of high-grade metasedimentary rocks that underwent partial melting at 623 Ma prior to intrusion of the Umbukta gabbro at 578 Ma; and the Ørtfjell Group/Dunderland Formation, consisting of lower-grade schists and voluminous marble and banded iron formations. It cannot be ruled out that these two units are separated by a tectonic contact, and in effect constitute two nappes (Fig. 10a). However, the Taconian-age Langfjell Shear Zone seems to link the Kjerringfjell Group and the RNC to the HNC, based on the similar ages of thrusting there. The similarities between the Umbukta gabbro and its high-grade metasedimentary host rocks and the Seiland Igneous Province and its high-grade metasedimentary host rocks are quite compelling. Correlating these units means assigning the Seiland Igneous Province and its KNC host rocks to an origin unrelated to Baltica (Corfu *et al.* 2007; Kirkland *et al.* 2007; Slagstad and Kirkland 2018).

The implication of assigning a non-Baltican origin to the KNC is that the correlative SNC (e.g. Andréasson *et al.* 1998) also comes under scrutiny, as it has in other recent contributions (Corfu *et al.* 2007; Kirkland *et al.* 2011). There is an apparent difference between the tectonometamorphic evolution of the SNC in Norrbotten and Jämtland (Fig. 1). In Jämtland, the SNC rocks underwent UHP metamorphism at pressure–temperature conditions of 25–27 kbar and 650–760°C at *c.* 458 Ma (Brueckner and van Roermund 2007; Fassmer *et al.* 2017), whereas the SNC rocks in Norrbotten may have undergone eclogite-facies metamorphism at 12–15 kbar and 500–630°C at *c.* 505 Ma (Mørk *et al.* 1988) or, as suggested by later work, between *c.* 500 and 480 Ma (Root and Corfu 2012; Barnes *et al.* 2019). Other features of the Norrbotten SNC worth mentioning here include subordinate volcanism at 945 ± 31 Ma (Albrecht 2000), titanite ages at 637 and 607 Ma (Rehnström *et al.* 2002; Root and Corfu 2012), and a monazite age of 603 Ma (Barnes *et al.* 2019). As discussed by Barnes *et al.* (2019), the dated monazite preserves a patchy zoned texture consistent with a partial dissolution process, in which case the 603 Ma age may represent resetting of an even older generation of monazite. If correct, this would imply the presence of older Neoproterozoic tectonic events, as indicated by the 637 Ma titanite and even older volcanic activity. Thus, unlike the Jämtland SNC, the Norrbotten SNC preserves evidence, albeit limited, of a long Neoproterozoic–Ordovician magmatic and metamorphic history that predates the HP metamorphic evolution recorded in the Jämtland SNC, and shares many similarities with that of both the KNC and RNC. Gee *et al.* (2013) and Barnes *et al.* (2019) noted that the (U)HP metamorphism in the Norrbotten SNC coincided with Early Ordovician obduction of arc/back-arc assemblages (ophiolites) recorded mainly in the Köli and Helgeland nappe complexes, and argued for a causative link between the two events. As discussed above, however, these oceanic assemblages almost certainly formed and were obducted on the Laurentian side of Iapetus; thus for a causative link to work, the Norrbotten SNC would also have to be located on the Laurentian side.

The Jämtland SNC lacks a documented Neoproterozoic history, possibly because of a younger (<730 Ma) depositional age (Kirkland *et al.* 2011); however, the 458 Ma age of UHP metamorphism is conspicuously similar to the *c.* 460 Ma age for UHP metamorphism in the Tromsø Nappe (Corfu *et al.* 2003; Ravna *et al.* 2017), which is typically correlated with the HNC and RNC (Corfu *et al.* 2014) and their inferred Laurentian heritage. Based on the data from the Jämtland SNC and the Tromsø Nappe, Brueckner and van Roermund (2007) argued for coeval UHP metamorphism on both margins of Iapetus at this time, whereas Janák *et al.* (2012) argued that the structurally higher position of the Tromsø Nappe could reflect out-of-sequence thrusting, resulting in a 'mismatch' between tectonostratigraphic position and provenance. However, probable Ordovician eclogites are also known from the Newfoundland Appalachians (Jamieson 1990), suggesting that there is no reason per se that the Tromsø Nappe eclogites could not have formed near the Laurentian margin. The age of 460 Ma for UHP metamorphism in the Jämtland SNC is interesting as it matches a period of reduced magmatic activity, between 460 and 450 Ma, in the HNC (Barnes *et al.* 2007), which may have been related to crustal thickening, possibly as a result of collision with a microcontinent. Thus, a case can be made that tectonothermal events recorded in the Jämtland and Norrbotten SNCs can be correlated with events in units that preserve geological and fossil evidence of formation at or outboard of the Laurentian margin.

Exotic components in the Scandinavian Caledonides and their origin

Classically, most units of the Scandinavian Caledonides were thought to have formed prior to, and synchronous with, the generation and destruction of the Iapetus Ocean between Laurentia and Baltica (Roberts 2003). Units of Gondwanan heritage, although well established in the British and Irish Caledonides and Appalachians, were not considered to be components of the Scandinavian margin until rather more recently (Corfu *et al.* 2007). A brief summary of the Neoproterozoic and Early Paleozoic evolution of the 'Iapetus-facing' margins of Baltica, Laurentia and Gondwana is presented below, and is also shown schematically in Figure 11. This information highlights possible origins for some of the units making up the Scandinavian Caledonides. The positions and orientations of the continents essentially follow that proposed by Domeier (2016) but we highlight that complexities related to choice of pole for Baltica exist (e.g. McCausland *et al.* 2007).

Iapetus break-up starting at *c.* 750–600 Ma is commonly understood with reference to the *c.* 1000 Ma Rodinia supercontinent (Li *et al.* 2008); however, although the proximity of Laurentia and Gondwana in Rodinia is relatively well established, the position and orientation of Baltica is not (Hartz and Torsvik 2002; Slagstad *et al.* 2019). Neoproterozoic tectonomagmatic events in Baltica are sparse. Extension of unknown magnitude in SW Baltica (present-day coordinates) at 616 Ma (Bingen *et al.* 1998), central Baltica at *c.* 580 Ma (Meert *et al.* 1998) and Neoproterozoic sedimentation (Nystuen *et al.* 2008) implies that the Baltican margin was relatively quiescent to extensional through the Neoproterozoic (Fig. 11a). Only an enigmatic Timanian orogenic event in NE Baltica at *c.* 600–560 Ma might imply localized tectonic activity in this section of the margin (Gee and Pease 2004; Pease *et al.* 2008). Thus, Neoproterozoic tectonometamorphic activity in parts of the KNC, that reached temperatures and pressures of at least 750–800°C and 10–11 kbar at *c.* 710 Ma (Kirkland *et al.* 2016), is not readily explained as having taken place on Baltica. Slagstad *et al.* (2019) suggested that tectonic activity may have continued outboard of Baltica following retreat of the Sveconorwegian active margin; however, at present, there is little direct evidence to support this idea. In contrast, numerous papers argue that parts of the Laurentian margin were active until Laurentia–Gondwana break-up at around 600 Ma (Kirkland *et al.* 2007; Cawood *et al.* 2010; Strachan *et al.* 2013). Rifting and drifting of Laurentia and Gondwana at *c.* 615–530 Ma caused widespread extension-related magmatism along the incipient Iapetan margin of Laurentia (see the summary in McCausland *et al.* 2007); importantly, the duration of extension-related magmatism provides a nearly perfect match to the 615–525 Ma magmatic activity recorded in the Rödingsfjället, Kalak and Seve nappe complexes (Fig. 11a). In addition, Laurentia-derived units currently located in the northern Appalachians record Neoproterozoic (*c.* 765–680 Ma) magmatism interpreted, at least in part, to reflect extension, possibly related to incipient attempted rifting (Cawood *et al.* 2001; Tollo *et al.* 2004); this evolution is similar to at least part of the Neoproterozoic history recorded in the Rödingsfjället and Kalak nappe complexes. Mafic dykes in the Kjerringfjell Group, now thoroughly amphibolitized, must have intruded after *c.* 1030 Ma and before high-grade metamorphism at 623 Ma, and may record similar activity.

In Gondwana (Avalonia), a convergent-margin setting is recorded around 765 Ma by the appearance of juvenile arcs indicating subduction of oceanic lithosphere (Murphy *et al.* 2013). Arc magmatism probably continued until at least 540 Ma, and records both contractional and extensional periods; and northwards drift of peri-Gondwanan fragments (illustrated by Avalonia and Ganderia) across the Iapetus probably started in the Early Ordovician (Fig. 11b) (Linnemann *et al.* 2008). These rocks

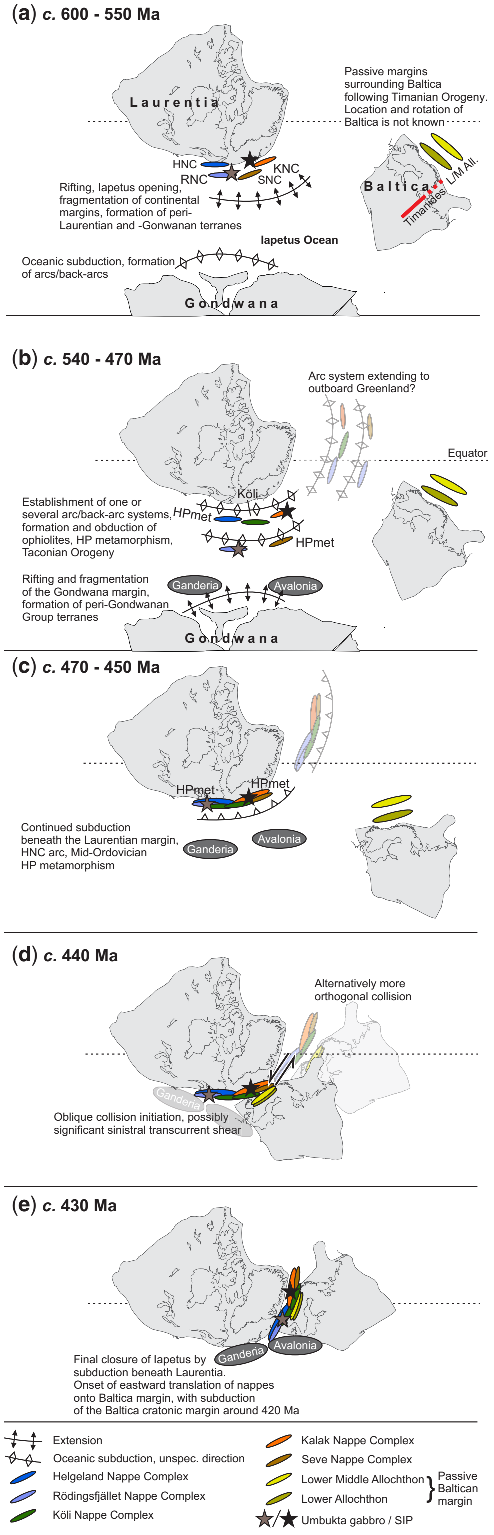

Fig. 11. Schematic illustration of the late Neoproterozoic–Mid-Silurian temporal and spatial evolution of nappes currently located in the Scandinavian Caledonides, according to the interpretations presented in this paper. The locations and orientations of continents are from Domeier (2016). Gondwana is only shown in (**a**) & (**b**) (i.e. between 600 and 470 Ma), by which time the continental fragments that later became incorporated into the Appalachian–Caledonian orogenic belt had separated from Gondwana. The location of the Timanian Orogen is indicated by a thick, red line in (**a**) and its possible westwards (present-day coordinates) extension across the Varanger Peninsula (Roberts and Siedlecka 2002) is shown as a dashed line. Abbreviations: HPmet, high-pressure metamorphism; L/M All., Lower/Middle Allochthon; HNC, Helgeland Nappe Complex; KNC, Kalak Nappe Complex; RNC, Rödingsfjället Nappe Complex; SNC, Seve Nappe Complex; SIP, Seiland Igneous Province.

are currently located in the Appalachians and UK Caledonides, where they accreted around 450–440 Ma or slightly thereafter, shortly before final closure of the Iapetus Ocean.

The Laurentian margin was almost certainly active from the Late Cambrian through to the Ordovician (Fig. 11c) (van Staal *et al.* 1998; Lissenberg *et al.* 2005*b*; Zagorevski *et al.* 2006), with formation and accretion of arcs, ophiolites and rifted continental fragments of both peri-Laurentian and peri-Gondwanan origin, including episodes of HP metamorphism (Jamieson 1990).

The Appalachian–Caledonian Orogen is characterized by long, linear features that can be traced for up to several hundred kilometres. This linearity may, at least in part, be a result of one or several oblique accretionary events, both prior to, as well as during, final continent–continent collision. As discussed by van Staal *et al.* (1998), such oblique collision may result in a misleadingly simple linearity, concealing complexities that may render unique reconstructions all but impossible. Several workers have argued that oblique accretion and collision in the northern Appalachians and UK–Scandinavian Caledonides resulted in major sinistral shearing (Soper and Hutton 1984; Soper *et al.* 1992), possibly resulting in translation of nappes over distances of a few thousand kilometres (Pettersson *et al.* 2010). Although translation of nappes over such distances is not strictly required by the model presented in Figure 11, it provides an appealing process for transporting units that resemble those of the northern Appalachians and UK Caledonides to the northern parts of the Scandinavian Caledonides (Fig. 11d, e). Following sinistral shear, the collision may have become more orthogonal (Soper *et al.* 1992), possibly obscuring evidence of earlier lateral shearing.

The rocks in the Upper and Uppermost allochthons in the Scandinavian Caledonides, including at least parts of the Kalak and Seve nappe complexes, record a very similar tectonometamorphic and tectonomagmatic evolution to that observed in units formed at or outboard of the Laurentian and Gondwanan margins. Thus, in the absence of clear evidence of an active Baltican margin, these similarities warrant an interpretation where large parts of the Scandinavian Caledonides are exotic rather than endemic to Baltica, as we have illustrated in Figure 1a.

Conclusions

New U–Pb zircon geochronology from the Rödingsfjället Nappe Complex (RNC) reveals a record of Late Neoproterozoic, high-grade metamorphism followed by continental rifting and mafic magmatism at *c.* 575 Ma, with continued intermittent magmatic activity at *c.* 540, 510-500, 480 and 465 Ma. Dating of syntectonic pegmatite at *c.* 515 and 475 Ma demands pre-Scandian thrusting, as well as later Scandian thrusting at *c.* 430 Ma. Such constraints on deformation show that potentially significant nappe stacking had taken place well before terminal continent–continent collision.

The RNC has a tectonomagmatic history that prompts correlation with peri-Laurentian and/or peri-Gondwanan terranes, consistent with the nappes' high tectonostratigraphic level and Laurentian faunal assemblages.

Crystallization of the *c.* 575 Ma Umbukta gabbro was coeval with emplacement of the Seiland Igneous Province in the Kalak Nappe Complex (KNC). These magmatic units have strikingly similar and distinct geochemical and isotopic signatures, which, together with a comparable Neoproterozoic tectonic history recorded in their host rocks, present a robust basis for correlating the KNC with units at high tectonostratigraphic levels within the assembled nappe pile.

Components of the Seve Nappe Complex (SNC) preserve a comparable tectonic history to the KNC, suggesting that these nappes may all be exotic to Baltica.

The paradigm of Scandinavian Caledonide tectonostratigraphic position is steeped in connotations of palaeogeographical derivation, yet much of the conventionally considered Middle Allochthon – such as the SNC – is more robustly correlated with units of undisputed exotic origin.

Acknowledgements Reviewers Deta Gasser and Fernando Corfu provided insightful comments and constructive criticism that helped clarify many of our arguments. Some of the work presented herein was conducted as part of the CAMOC (Centre for Advanced Mineral and Ore Characterisation) collaboration between the NGU and the Department of Geoscience and Petroleum at NTNU; this is CAMOC contribution No. 3.

Funding T. Slagstad received funding from Norges Geologiske Undersøkelse.

Author contributions **TS**: writing – original draft (lead), writing – review & editing (lead); **KS**: writing – original draft (supporting); **CLK**: writing – original draft (supporting); **ABH**: writing – original draft (supporting); **BKS**: writing – original draft (supporting); **NC**: writing – original draft (supporting); **CP**: writing – original draft (supporting); **MM**: writing – original draft (supporting); **TB**: writing – original draft (supporting); **AK**: writing – original draft (supporting); **AS**: writing – original draft (supporting); **RB**: writing – original draft (supporting); **TL**: writing – original draft (supporting); **RBL**: writing – original draft (supporting).

Data availability statement All data generated or analysed during this study are included in this published article (and its supplementary information files).

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