NGU REPORT 2017.030

NGF/NPF Field-Trip Guide,
11. June 2017

GEOLOGY FOR SOCIETY

SINCE 1858

GEOLOGICAL
SURVEY OF
NORWAY
- NGU -

NORGES GEOLOGISKE UNDERSØKELSE
- NGU -

REPORT

Geological Survey of Norway
P.O.Box 6315 Sluppen
NO-7491 TRONDHEIM
Tel.: 47 73 90 40 00

Report no.: 2017.030

ISSN: 0800-3416 (print)
ISSN: 2387-3515 (online)

Grading: Open

The "*Better to burn out than to fade away*" tour: magma-driven, high-grade metamorphism in the Sveconorwegian Province, SW Norway during the terminal stages of Fennoscandian Shield evolution. NGF/NPF field-trip guide, 11. June 2017.

Authors: Trond Slagstad, with major contributions from Mogens Marker, Nick Roberts, Nolwenn Coint.

Client:

County: Rogaland

Commune:

Map-sheet name (M=1:250.000)

Map-sheet no. and -name (M=1:50.000)

Deposit name and grid-reference:

Number of pages: Price (NOK): 135,-

Map enclosures:

Fieldwork carried out:

Date of report: 06.06.2017

Project no.: 352800

Person responsible:

Summary:

The exposed rocks in Rogaland, that we will study on this field trip, provide insight into processes in the lower and middle crust of a long-lived, late Mesoproterozoic continental-margin arc, on tens of million year time scales.

Keywords: Sveconorwegian	Mesoproterozoic	Sirdal Magmatic Belt
Rogaland Igneous Complex	Magmatism	Metamorphism
Orogeny	Rogaland	Fennoscandia

CONTENTS

1. Abstract 4

2. Introduction to the geology of Rogaland and Vest-Agder 5

2.1 Pre-Sveconorwegian rocks 5

2.2 Sveconorwegian magmatism 6

2.3 Emplacement history and tectonic setting of the SMB 10

3. Field-trip program in brief 12

4. Field-trip program in detail 15

4.1 STOP 1 – Migmatitic orthogneiss, Hana båtforening 15

4.2 STOP 2 – SMB porphyritic granite, Lundane, Daleveien 16

4.3 STOP 3 – Granitic gneiss, Gjesdal 17

4.4 STOP 4 – Metapelite, Gyadalen metapelites, Skurve 18

4.5 STOP 5 – Quartzite and oxide-rich gneiss, Faurefjell metasediments, Nedrebø 19

4.6 STOP 6 – Anorthosite with high-Al opx megacrysts, Sørskog 22

4.7 STOP 7 – Fayalite granite, Undheim 24

5. Magmatic and metamorphic evidence of a long-lived, evolving continental margin arc 26

5.1 Establishment of a magmatic arc, 1070–1010 Ma 26

5.2 A changing arc, ca. 1010–1000 Ma 26

5.3 Renewed, ferroan magmatism and continued high-grade metamorphism, 1000–920 Ma 28

6. Anorthosite emplacement related to doming in an extending continental arc 30

7. Long-lived, high-grade metamorphism in the lower- to middle crust of a magmatic arc and the quality of different lithological recorders 34

7.1 High-grade metamorphism as a result of crustal thickening? 34

7.2 High-grade metamorphism as a result of repeated basaltic underplating? 36

8. A few conclusions 37

9. References 37

1. Abstract

The Sveconorwegian orogeny in SW Baltica comprised a series of geographically and tectonically discrete, accretionary events between 1140 and 920 Ma. These events took place behind a long-lived, active continental margin characterised by episodic voluminous magmatism and high-grade metamorphism. Voluminous I-type granitic magmatism is recorded between 1070 and 1010 Ma, with a peak around 1050–1030 Ma. Granitic magmatism picked up again around 1000–990 Ma, but with more ferroan compositions, suggesting a change in source and/or melting conditions. This ferroan magmatism was continuous until 920 Ma, and included emplacement of an AMCG (anorthosite–mangerite–charnockite–granite) complex (Rogaland Igneous Complex, RIC), typically interpreted to have intruded at ca. 930–920 Ma resulting in a wide (20 km) contact aureole. High-temperature (HT) metamorphic rocks more than ca. 20 km away from the RIC yield metamorphic ages of 1050–1030 Ma, corresponding to the first peak in magmatic activity, with little evidence of younger metamorphism. In contrast, HT and ultra-HT (UHT) rocks closer to the RIC yield ages between 1100 and 920 Ma, with an apparent age peak at ca. 1000 Ma. Ti-in-zircon temperatures from these rocks increase from ca. 760°C to 820°C at ca. 970 Ma, well before the inferred emplacement age of the RIC. This observation suggests that UHT metamorphism was not directly linked to the emplacement of the RIC, but more likely to reflect nearly continuous heating from mantle-derived magmas. The present-day regional distribution of UHT/HT and low-grade rocks probably reflects late-stage orogenic doming rather than contact metamorphism.

The exposed rocks in Rogaland, that we will study on this field trip, provide insight into processes in the lower and middle crust of a long-lived, late Mesoproterozoic continental-margin arc, on tens of million year time scales.

2. Introduction to the geology of Rogaland and Vest-Agder

The rocks investigated on this field trip span ca. 600 Myr, from 1.5 to 0.9 Ga. Although focus is on the period from 1060 to 920 Ma, the preceding history is important as it allows the identification of suites of rocks and because it may have primed some rocks prior to Sveconorwegian high-grade metamorphism (cf., Clark et al., 2011). We therefore briefly describe the main lithological units in the study area, subdivided according to age. Fig. 1 shows a simplified map of the area, based on a compilation of recent mapping by the Geological Survey of Norway (NGU) and the Mandal 1:250,000 map sheet (Falkum, 1982).

2.1 Pre-Sveconorwegian rocks

The oldest rocks in the southwestern part of the Sveconorwegian Province are ca. 1.5 Ga orthogneisses, with plutonic and volcanic protoliths (Bingen et al., 2005; Roberts et al., 2013). The 1.5 Ga orthogneisses have been variably metamorphosed, and in SW Rogaland are generally migmatitic (Fig. 2A). These rocks are, therefore, referred to as **migmatitic orthogneisses** in this guide. Mafic sheets and dykes are commonly observed in these rocks, suggesting a later, mafic magmatic event that has not yet been dated directly. Although field relationships are obscured by strong deformation, the 1.5 Ga orthogneisses appear to have formed the basement for (semi)pelitic sediments, now metamorphosed at high grade (Fig. 2B, C, D) (Tomkins et al., 2005; Blereau et al., 2016). These supracrustal rocks are referred to as the **Gyadalen paragneisses** (Gyadal garnetiferous migmatites of Hermans et al., 1975). The age of deposition of the Gyadalen paragneisses is poorly constrained. Detrital zircons display a clear peak at ca. 1.5 Ga (Tomkins et al., 2005; Slagstad et al., submitted; Drüppel et al., 2013), with a few grains extending down to ca. 1.25 Ga, but extracting a reliable <1.5 Ga maximum age of deposition is difficult. Like the migmatitic orthogneisses, the Gyadalen paragneisses also contain sheets of mafic rock, though with primary contacts obscured by deformation. The migmatitic orthogneisses and Gyadalen paragneisses were intruded by voluminous **granitoid orthogneisses** (Fig. 3E) dated at 1.20 to 1.23 Ga (Slagstad et al., unpublished data), with ages as old as 1.28 Ga farther east in Setesdalen (Pedersen et al., 2008). Unlike the older migmatitic orthogneisses and Gyadalen paragneisses, the ca. 1.20–1.23 Ga granitoid orthogneisses (and younger rocks, described below) do not contain mafic dykes, providing a minimum age for this mafic magmatism. The last pre-Sveconorwegian event to take place in SW Norway was deposition of the **Faurefjell metasediments** (Hermans et al., 1975), comprising quartzite, impure marble, calc-silicate gneiss (Fig. 3F) and distinct oxide-rich layers (Fig. 3G) that have been interpreted to represent metamorphosed laterite (Bol et al., 1989).

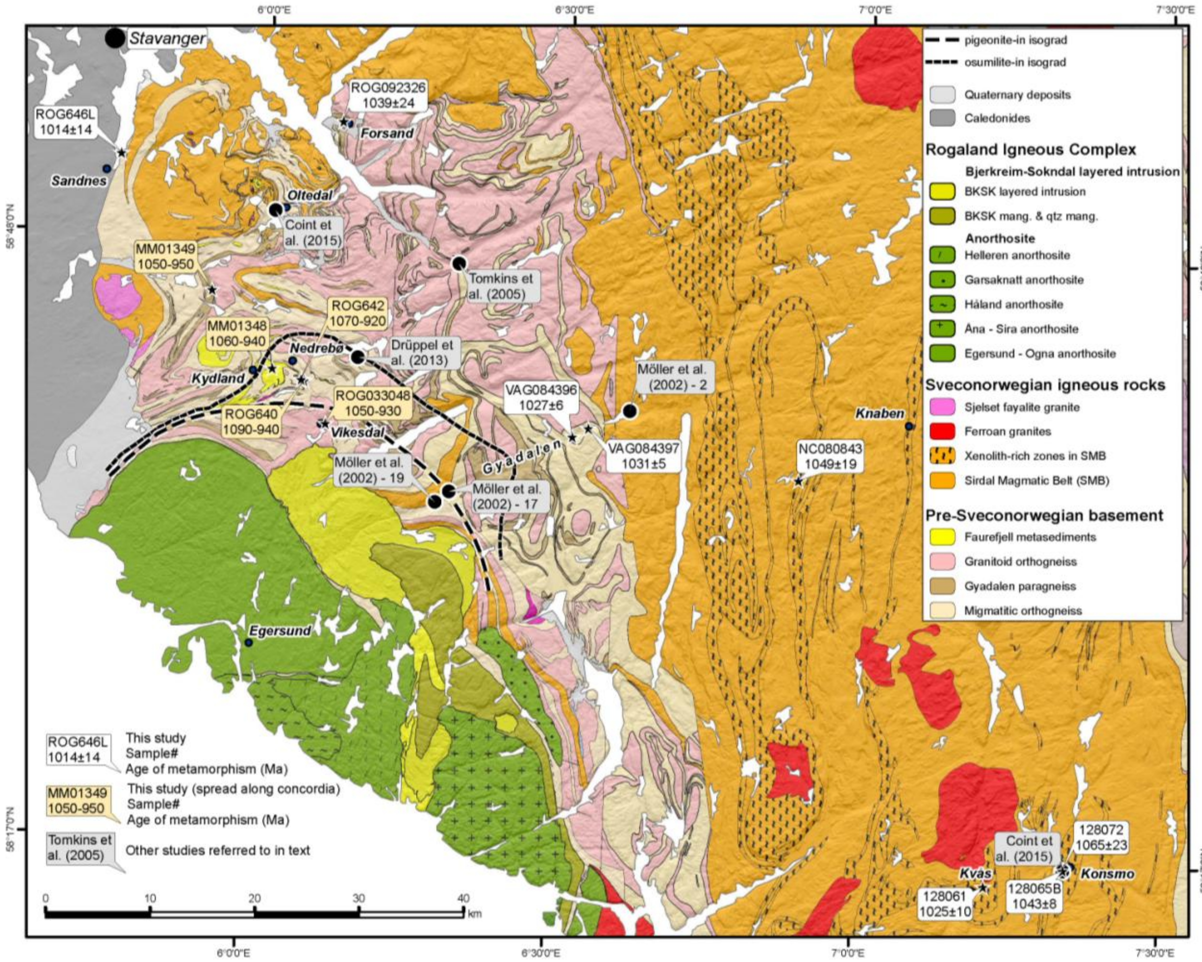

Figure 1. Detailed geological map of the main study area in SW Norway. The map is compiled from the 1:250,000-scale Mandal map sheet (Falkum, 1982), the 1:75,000-scale map of the Rogaland Anorthosite Province (Marker et al.*, 2003), and mapping by the Geological Survey of Norway (NGU) since the early 2000s (Marker* et al.*, 2012; Marker, 2013, in prep.; Marker & Slagstad, in prep., in press-b, a). Also shown on the map are locations of samples dated by Slagstad* et al. *(submitted) that have a bearing on the metamorphic evolution of the area, as well as previously published samples that are discussed in the text. The lithologies under the labels 'Pre-Sveconorwegian basement' and 'Rogaland Igneous Complex' define the 'core area' referred to in the text. The core area is bounded to the east and north by the Sirdal Magmatic Belt (SMB).*

2.2 Sveconorwegian magmatism

The oldest Sveconorwegian rocks in the study area comprise the **Sirdal Magmatic Belt (SMB)**, a ca. 1070–1020 Ma granite batholith, mainly comprising K-feldspar-porphyritic

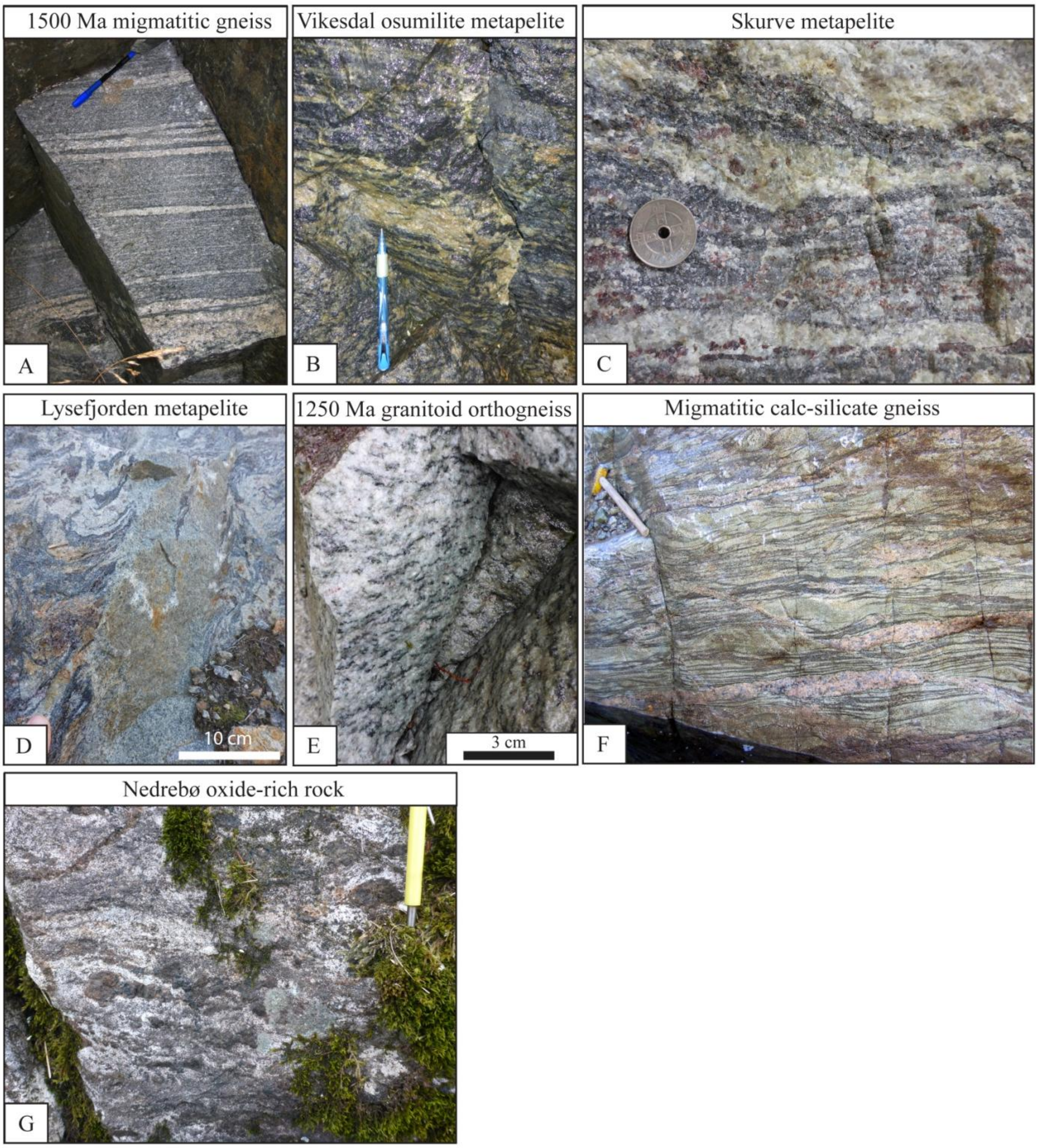

Figure 2. Field photos of the investigated HT and UHT gneisses. (A) 1500 Ma migmatitic orthogneiss; migmatisation at ca. 1014 Ma. (B) Osumilite-bearing metapelite from Vikesdal; high-grade metamorphism between 1050 and 930. This, and other metapelitic gneisses in the study area, are typically referred to as the 'Gyadalen paragneisses'. (C) Metapelite from Skurve with leucocratic, garnet-bearing leucosome and dark-blue, garnet-bearing melanosome; high-grade metamorphism between 1050 and 950 Ma. (D) Metapelite from the outlet of Lysefjorden with folded and disrupted cordierite-garnet-spinel-sillimanite-bearing melanosome and garnet bearing leucosome. The metapelite is cut by a 5 cm thick, fine-grained dyke. High-grade metamorphism at 1039 Ma. (E) High-grade metamorphic orthogneiss with a protolith of ca. 1250 Ma. This is the dominant lithology in the core area. (F) Quartz-diopside gneiss, part of the 'Faurefjell metasediments', recording high-grade metamorphism between 1060 and 940 Ma. (G) Oxide-rich, orthopyroxene-spinel-bearing gneiss at Nedrebø, part of the Faurefjell metasediments; high-grade metamorphism between 1070 and 920 Ma.

granites (Fig. 3A) and described in detail by Slagstad et al. (2013a) and Coint et al. (2015). The SMB is roughly 50 km wide and extends almost 150 km northwards, from the southern tip of Norway, before it swings west and disappears under the Palaeozoic Caledonian nappes. The SMB has been interpreted to represent a continental arc on the SW margin of Baltica. Magmatism in the SMB ceased at ca. 1020 Ma, and was succeeded by widespread, long-lived granitic and bimodal magmatism between ca. 990 and 920 Ma (e.g., Vander Auwera et al., 2003; Slagstad et al., 2013a; Jensen & Corfu, 2016). The granites in this age range form relatively large, seemingly isolated bodies throughout the orogen, except farthest east, in the Eastern Segment. They are typically grouped into the so-called **HBG suite** (hornblende-biotite granites, Fig. 3B), and their **ferroan** (A-type like) compositions have led most workers to favour formation in an extensional setting, either as a result of post-orogenic collapse (Vander Auwera et al., 2003) or extension behind an active continental margin (Slagstad et al., 2013a). The **Rogaland Igneous Complex (RIC)** comprises two distinctly different units, the **Rogaland Anorthosite Province (RAP)** and the **Bjerkreim–Sokndal Layered Intrusion (BKSK)**. The RAP comprises three separate massifs – Egersund–Ogna, Håland–Helleren and Åna–Sira – whereas the BKSK is a large, layered intrusion consisting of anorthosite through norite to quartz mangerite (Wilson et al., 1996; Charlier et al., 2010). The age of the BKSK is well constrained at ca. 930 Ma (Vander Auwera et al., 2011), and the generally agreed-upon interpretation has been that the RAP is the same age (Schärer et al., 1996; Westphal et al., 2003). The anorthosites only contain zircon in association with locally abundant high-Al orthopyroxene megacrysts (Fig. 3C, HAOM); however, the relationship (e.g., exsolution, xenocryst, or grown from late-stage melt pockets) between zircon and HAOM has never been directly observed, leaving the significance of these ca. 930 Ma ages (Schärer et al., 1996) uncertain. This uncertainty was confounded in a recent study by Bybee et al. (2014) that yielded a 1041 ±17 Ma Sm–Nd isochron age for the HAOM from the Egersund–Ogna anorthosite massif, which they interpreted to reflect growth from the basaltic magma that gave rise to the anorthosite. In the same study, exsolution lamellae of plagioclase and their HAOM hosts yielded a Sm–Nd isochron age of 968 ± 43 Ma, which Bybee et al. (2014) interpreted as reflecting decompression during emplacement of the anorthosite. This age overlaps with the 930 Ma age from Schärer et al. (1996), and supports their suggestion that the zircons may have grown from more evolved melts, relatively late in the magmatic evolution of the anorthosites.

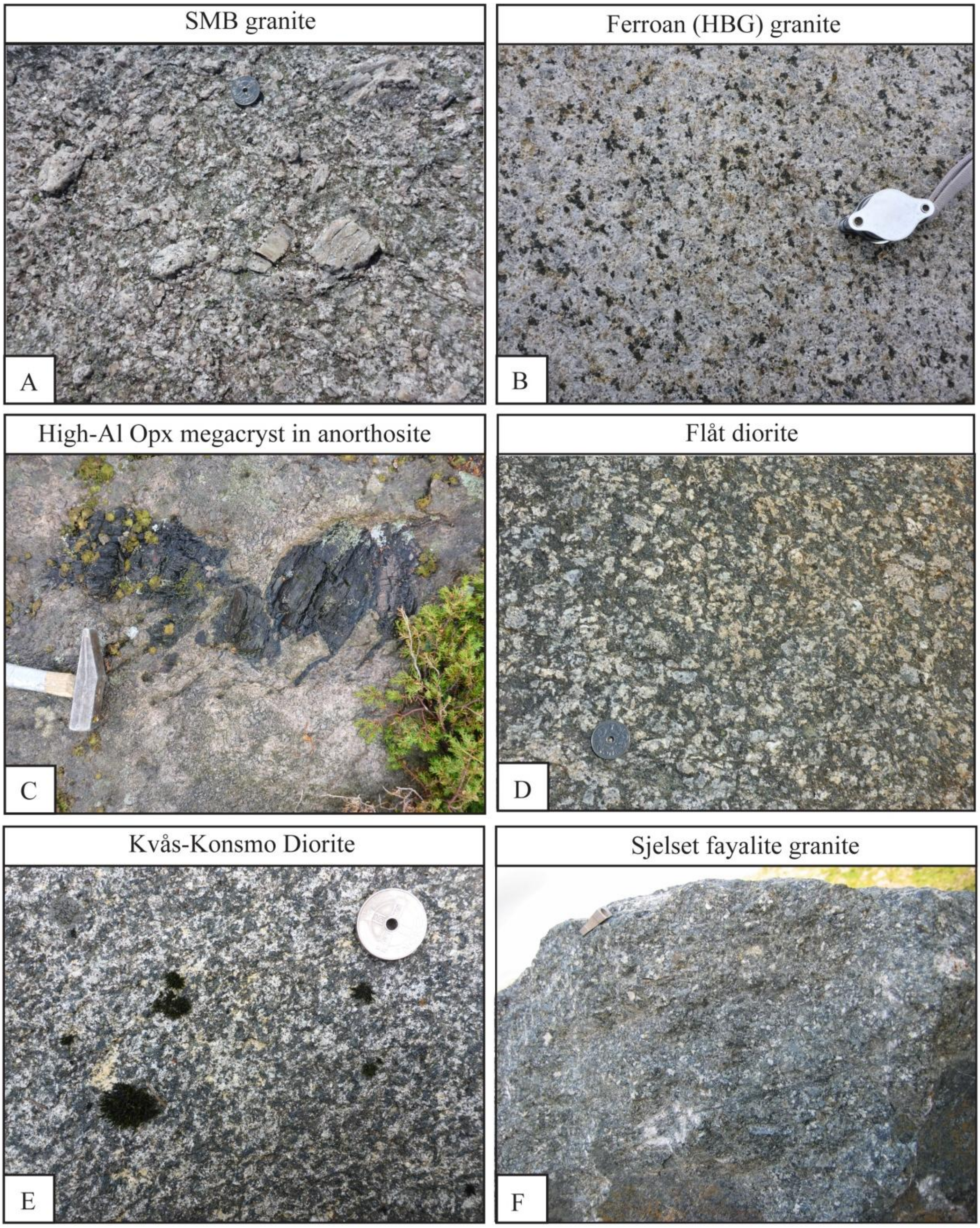

Figure 3. Field photos of Sveconorwegian-age magmatic rocks. (A) Porphyritic granite from the Sirdal Magmatic Belt (SMB). (B) Hornblende-phyric granite from the HBG suite. (C) High-alumina orthophyroxene megacryst (HAOM) from the Egersund–Ogna anorthosite. (D) Flåt diorite, Ni-bearing diorite. (E) Kvås–Konsmo diorite, intruding the SMB. (F) Sjelset fayalite granite. The Flåt (D) and Kvås–Konsmo diorites will not be visited on this field trip.

2.3 Emplacement history and tectonic setting of the SMB

Emplacement of the SMB started at ca. 1070–1060 Ma and ceased at ca. 1010 Ma, i.e., representing at least 50 million years of apparently continuous granitic magmatism. A growing geochronological database suggests that the intensity in magmatic activity may have varied, with peaks at ca. 1050 and 1035 Ma, however, more detailed mapping within the SMB is needed to determine time-integrated magma volumes. To this end, we have started to undertake detailed mapping of xenolith-rich zones (Fig. 1b) that we think, based on field and geochronological data, may represent contact zones between different intrusive bodies. If this is correct, the map pattern suggests that much of the SMB is composed of N–S-oriented, gently folded, sheet-like intrusions.

Estimates of crystallisation pressures yield a rather narrow range of pressures between 4 and 5 kbar, corresponding to mid-crustal depths of 12–15 km assuming an average density of 3 g/cm^3. The similar pressures recorded in northern and south-central parts of the SMB suggest minor post-emplacement tilting of the belt. This implies that the trend of granulite-facies to amphibolites-facies metamorphism that is recorded in pre-SMB rocks from southwest to the north and east, respectively, is not due to any syn- or post-Sveconorwegian tilting.

Determining the tectonic affinity of the SMB granites through petrological means is inherently difficult due to their strongly evolved compositions (Slagstad et al., 2013a and unpublished data), and crustal isotopic signatures (Bingen et al., 1993; Vander Auwera et al., 2011). It is possible that the arc-like geochemical signature of the SMB granites (Bingen & van Breemen, 1998; Slagstad et al., 2013a) is solely an inherited source characteristic, e.g., from 1.5 Ga calc-alkaline metavolcanic and -granitoid rocks that underlie much of S Norway (Bingen et al., 2005; Roberts et al., 2013), and does not reflect the tectonic setting in which the granites formed. Several lines of evidence, listed below, nevertheless argue for formation in an Andean- or Cordilleran-type, accretionary setting.

The emplacement of large, linear belts of granite batholiths over several tens of millions of years, such as the SMB, is characteristic of Andean-type accretionary orogens (e.g., Weaver et al., 1990). The duration and apparent peaks and lulls in magmatic activity resemble that observed for Cordilleran systems (Ducea & Barton, 2007; DeCelles et al., 2009). Recently, Bybee et al. (2014) showed that high-alumina opx megacrysts in the Rogaland anorthosites have rather juvenile isotopic compositions and probably grew at 1041 ± 17 Ma, i.e., during SMB emplacement. These high-alumina opx megacrysts probably represent cumulates from the crystallising basaltic magma that may have ponded at the MOHO and eventually given rise to the anorthosites (and SMB through lower-crustal melting). The age of the basaltic underplate corresponds to the age of the crystallisation of the SMB, which provides a potential heat source for generating such large volumes of granite. A long-lived Andean-type margin appears to be the most likely setting for such a long-lived magmatic system (Slagstad et al., 2013a; Bybee et al., 2014).

Alternative mechanisms for the formation of the SMB include continental collision and post-orogenic extension. In both cases, the granites likely would have formed from partial melting of lower to middle crustal sources, both permissible from geochemical and isotopic data. During collision, the magmatism would have resulted from crustal thickening and thermal relaxation, whereas decompression melting could be envisaged in a post-orogenic setting. However, both models require a phase of orogen-wide crustal thickening that preceded the onset of magmatism by at least 10–20 million years, and no such available data suggest that any crustal thickening took place prior to the earliest SMB magmatism at ca. 1070–1060 Ma. Thus, currently an Andean- or Cordilleran-type setting remains the preferred choice of tectonic setting.

3. Field-trip program in brief

Departure	Arrival	Geology	Duration
0830 Stavanger	0850 Ruten, Sandnes		10 min
0900 Ruten, Sandnes	0910 Hana båtforening	1. Migmatite	30 min
0940 Hana båtforen.	0950 Lundane, Dalevn.	2. SMB granite	30 min
1020 Lundane	1055 Gjesdal	3. Granitic gneiss	20 min
1115 Gjesdal	1130 Skurve	4. Metapelite	25 min
1155 Skurve	1215 Nedrebø	5. Oxide-rich gneiss	25 min
1240 Nedrebø	1250 Vikeså	**Lunch**	30 min
1320 Vikeså	1405 Sørskog	6. Anorthosite, opx	30 min
1435 Sørskog	1520 Undheim	7. Fayalite granite	20 min
1540 Undheim	1630 Ruten		10
1640 Ruten, Sandnes	1700 Stavanger		

*The program may change *en route, depending on time (which, as we all know, is relative).*

STOP 1 – Migmatitic orthogneiss, Hana båtforening

Coordinates: 312996E / 6529819N, UTM 32, WGS84 (Fig. 4).

Typical migmatitic orthogneiss with folded, granitic leucosomes. The orthogneiss protolith is ca. 1500 Ma, whereas partial melting took place at 1014 ± 14 Ma. Note also layers of amphibolite in this rock; such layers are only found in the migmatitic orthogneiss and Gyadalen metapelite, but not in younger rocks.

STOP 2 – SMB porphyritic granite, Lundane, Daleveien

Coordinates: 314336E / 6532446N, UTM 32, WGS84 (Fig. 4).

Porphyritic granite with abundant prismatic K-feldspar phenocrysts, up to several cm long. This rock has been dated at 1028 ± 20 and is a typical representative of the Sirdal Magmatic Belt (SMB), a voluminous granite batholith formed between 1070 and 1010 Ma, which stretches N–S for at least 400 km, from Mandal to past Bergen.

STOP 3 – Granitic gneiss, Gjesdal

Coordinates: 323650E / 6519232N, UTM 32, WGS84 (Fig. 4).

This is a homogeneous, medium-grained, light grey granitoid with a distinct planar fabric, dated at 1227 ± 11 Ma. These granitic gneisses intrude the migmatitic orthogneisses and

Gyadalen metapelites, and represent a major, but poorly understood, magmatic period that remodified the Fennoscandian lithosphere as far northeast as central Sweden.

STOP 4 – Metapelite, Gyadalen metapelites, Skurve

Coordinates: 321482E / 6516539N, UTM 32, WGS84 (Fig. 4).

The Gyadalen metapelites are fine- to medium-grained and contain abundant medium-grained granitic leucosome. These rocks are highly reactive and excellent recorders of high-grade metamorphism. As this locality, the rocks preserve evidence of nearly continuous high-grade metamorphism between ca. 1050 and 940, i.e., more than 100 Myr.

STOP 5 – Quartzite and oxide-rich gneiss, Faurefjell metasediments, Nedrebø

Coordinates: 330349E / 6508129N, UTM 32, WGS84 (Fig. 4).

The Faurefjell metasediments comprise quartzite, impure marble, calc-silicate gneiss and distinct oxide-rich layers that have been interpreted to represent metamorphosed laterite. At this locality we will look at strongly sheared quartzite and oxide-rich gneiss, the latter also a very reactive lithology suggesting high-grade conditions between 1080 and 920 Ma.

STOP 6 – Anorthosite with high-Al opx megacrysts, Sørskog

Coordinates: 315757E / 6489628N, UTM 32, WGS84 (Fig. 4).

Polycrystalline, high-Al orthopyroxene megacrysts are ubiquitous in Proterozoic anorthosite massifs around the world, and this locality is nothing short of world-class. Individual orthopyroxene megacrysts range from 10 to 20 cm in length, are variably oriented and hosted by coarse-grained to pegmatitic anorthosite. They preserve interesting, but admittedly confusing, age data that will be discussed at this locality.

STOP 7 – Fayalite granite, Undheim

Coordinates: 314651E / 6510490N, UTM 32, WGS84 (Fig. 4).

The Sjelset fayalite granite is coarse-grained with anhedral feldspar crystals up to 3 mm and anhedral pyroxene crystals around 1 mm in size. It has been dated at 935 ± 8 Ma, coeval with emplacement of the Bjerkreim–Sokndal layered intrusion, and represents one of the last Sveconorwegian magmatic events.

Figure 4. Field-trip locations.

4. Field-trip program in detail

4.1 STOP 1 – Migmatitic orthogneiss, Hana båtforening

Migmatitic granitic gneiss, with cm-thick light grey, folded granitic leucosomes (Fig. 5), and several dm-thick layers of amphibolite. Zircons from this sample are between 100 and 200 µm, and display nice core-mantle relationships with CL-bright, oscillatory-zoned cores surrounded by rather thick, CL-dark, oscillatory-zoned mantles (Fig. 5). The cores yield ages around 1500 Ma, interpreted as the crystallisation age of the migmatitic orthogneiss protolith; three mantles yield an age of ca. 1280 Ma (Fig. 5), and the remaining mantles (16 analyses) yield a weighted average $^{207}Pb/^{206}Pb$ age of 1014 ± 14 Ma (MSWD = 1.2; Fig. 5). The ca. 1280 Ma mantles are tentatively interpreted to reflect a hitherto poorly constrained pre-Sveconorwegian metamorphic event (note the discussion on the significance of the ca. 1.25 Ga magmatic event on Stop 3 of this field trip), whereas the 1014 ± 14 Ma age is interpreted as the age of leucosome crystallisation.

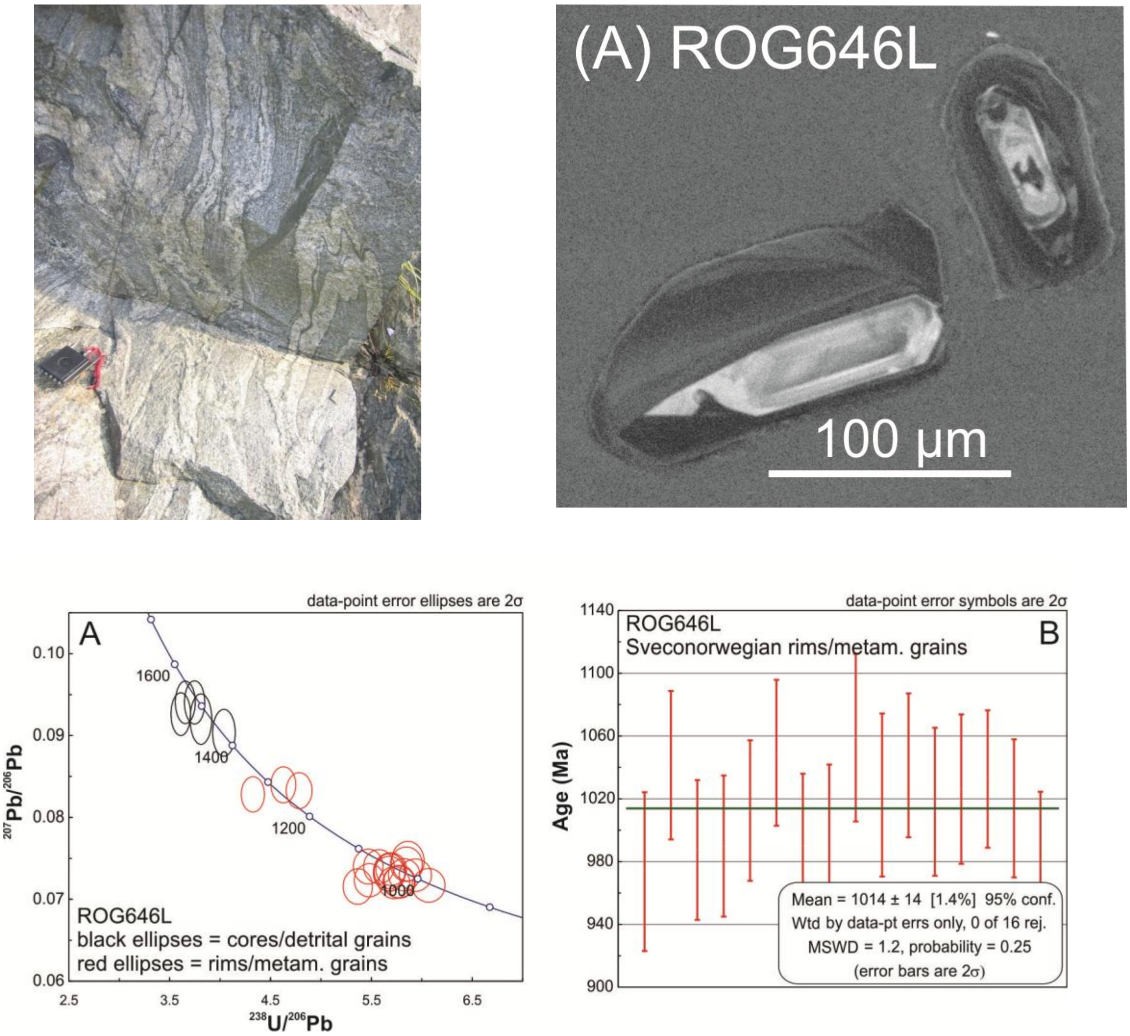

Figure 5. Field photo, CL image of zircons, and age data from migmatitic orthogneiss, sample ROG646L.

Metavolcanic and –plutonic rocks dated at ca. 1500 Ma are widespread in SW Norway and are the oldest exposed crust currently dated (Bingen et al., 2005; Pedersen et al., 2008; Roberts et al., 2013). Whole-rock geochemical and zircon U–Pb, Hf and O data from such rocks in the Suldal area suggests that the most likely tectonic setting for this ca. 1500 Ma magmatism in a continental margin arc, not unlike that of the Phanerozoic western US Cordillera, with both addition of juvenile, mantle-derived material and recycling of older, continental crust (Roberts et al., 2013).

4.2 STOP 2 – SMB porphyritic granite, Lundane, Daleveien

By far the most common rock type in the SMB is porphyritic biotite granite to minor granodiorite, locally containing amphibole. These rocks are characterised by a medium-grained, biotite-bearing groundmass with 2–3 cm, prismatic to stubby, reddish K-feldspar phenocrysts (Fig. 6). The proportion of phenocrysts is variable, from non-existent or sparse to constituting more than 80% of the rock, the latter representing a K-feldspar cumulate. Phenocryst sizes are also variable, ranging from ca. 1 to 6–7 cm, and there seems to be a rough correlation between phenocryst abundance and size. Magmatic foliations defined by the alignment of K-feldspar phenocrysts are common, but not observed at this locality, and post-crystallisation deformation with development of gneissic textures is rare. Structural observations from other parts of the SMB suggest it was emplaced synkinematically with top-to-west thrusting (Stormoen, 2015).

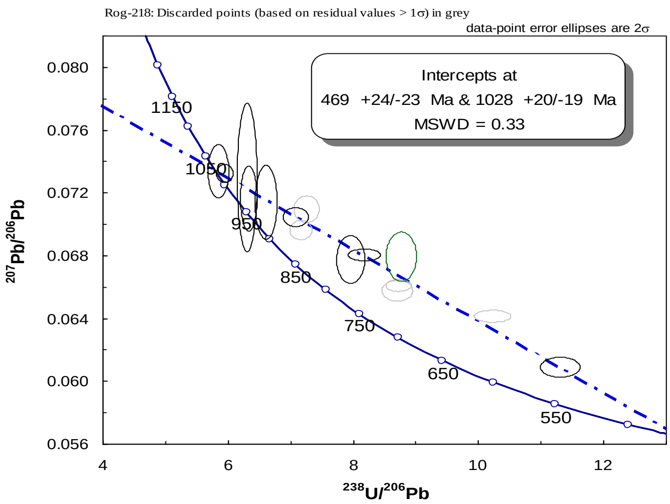

Figure 6. Field photo and age data from SMB granite at Stop 2. Notice Caledonian lower intercept; we are just below the contact to the overlying Caledonian nappe stack here.

4.3 STOP 3 – Granitic gneiss, Gjesdal

Homogeneous, medium-grained, light grey granitoid with a distinct planar fabric (Fig. 7). U–Pb age data from the bt-striped granitoid yields an age of 1227±11 Ma (Fig. 7). Regionally, these granites intrude the ca. 1500 Ma migmatitic granitic and the pelitic gneisses, providing a minimum age of deposition of the latter. In contrast to the ca. 1500 Ma migmatitic granitic and pelitic gneisses, the bt-striped granitoids do not contain amphibolite, suggesting mafic magmatism prior to 1210–1230 Ma. The 1210–1230 Ma granitoids have not been investigated in detail, but formed during widespread, extension-dominated magmatism throughout much of the Fennoscandian Shield.

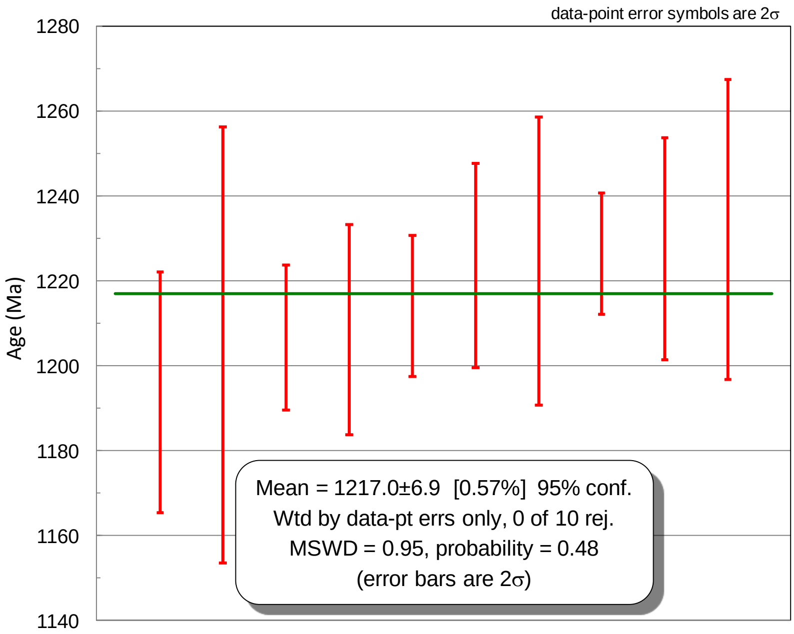

Figure 7. Field photo and age data from non-migmatitic granitic gneiss in Gjesdal, MM01341.

4.4 STOP 4 – Metapelite, Gyadalen metapelites, Skurve

The Gyadalen metapelites (Hermans et al., 1975) are fine- to medium-grained and contain abundant medium-grained granitic leucosome. In addition to quartz and feldspar, the metapelites contain garnet, sillimanite, cordierite and spinel. The metapelites typically contain layers of amphibolite that may either represent mafic dykes or syn-depositional mafic volcanism. The amphibolites are typically rather heterogeneous (layered), lending some support to a supracrustal origin. Locally, one also finds thin quartzitic layers in the metapelites.

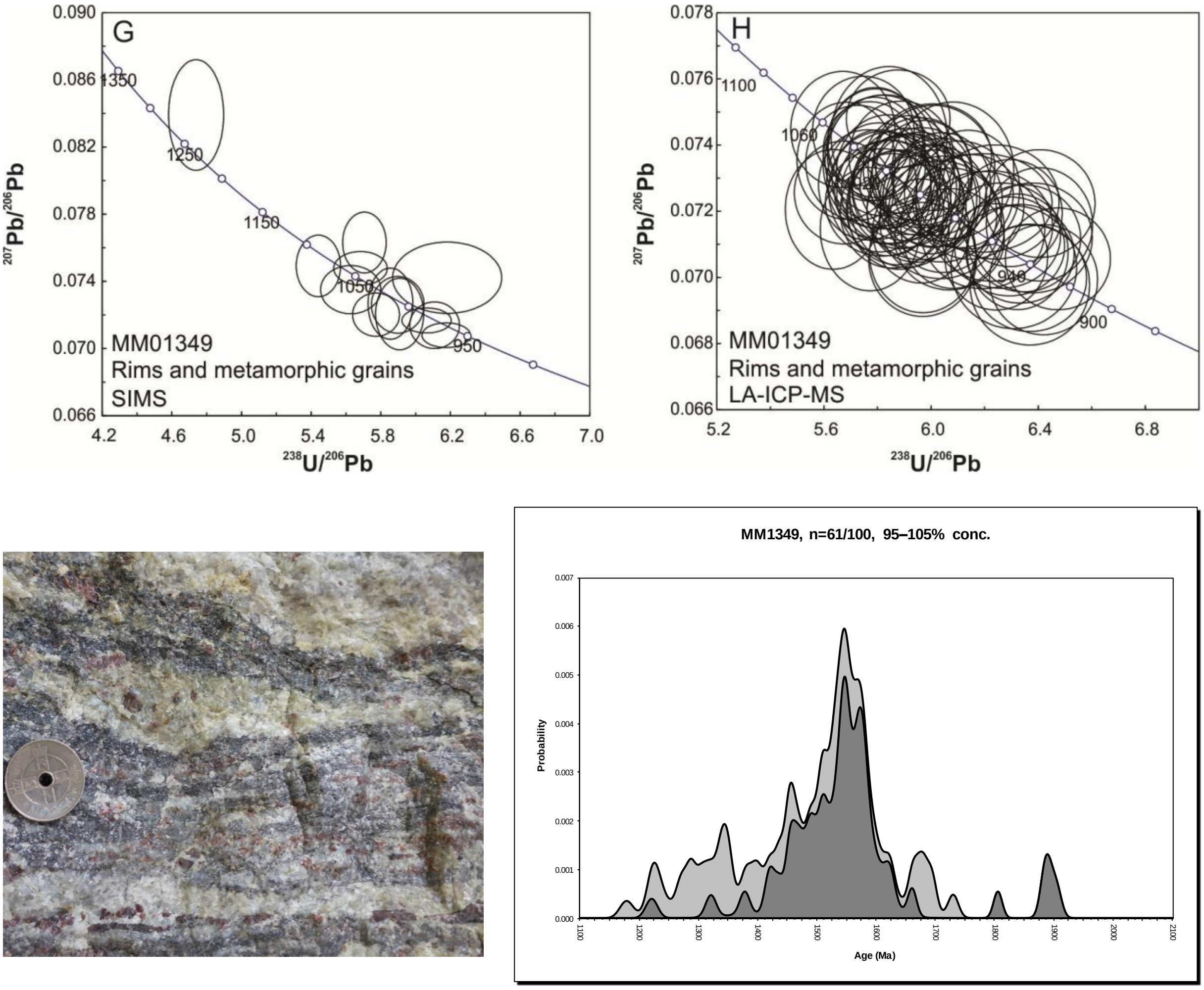

Figure 8. Field photo and U–Pb zircon age data from high-grade metamorphic metapelite at Skurve. Plot on lower right shows age data from detrital zircon grains.

The LA–ICP–MS and SIMS data from metamorphic zircon grains and rims of this sample yields a range of concordant ages between ca. 1050 and 940 Ma (Fig. 8), interpreted to reflect nearly continuous (within resolution of the geochronological data) high-grade metamorphism. Detrital grains yield ages between 1620 and 1420 Ma, with very few older and younger analyses, suggesting a maximum age of deposition around 1420 Ma.

The data from this outcrop, as well as from the calc-silicate- and oxide-rich rocks of the Faurefjell metasediments (Stop 5), illustrate the highly variable ability of different lithologies to record extended periods of high-grade metamorphism. For example, the ca. 1.2 Ga granitoid orthogneisses (Stop 3) yield only a limited number of early Sveconorwegian (ca. 1030 Ma) metamorphic ages (Slagstad et al., unpublished data) or even Caledonian lower intercepts (Stop 3), and reveal little about the duration of Sveconorwegian metamorphism. The ca. 1.5 Ga migmatitic orthogneisses have ca. 1050–1015 Ma leucosomes, but also appear to have been poor recorders of the following 100 Myr of high-grade metamorphism. The calc-silicate- and oxide-rich rocks of the Faurefjell metasediments and the metapelitic rocks of the Gyadalen paragneisses, on the other hand, have recorded virtually the whole metamorphic evolution in the ultra high-temperature area, although one sample does not necessarily record the entire history (e.g., Möller et al., 2002). Contrasts in different lithologies' ability to record metamorphic events must, therefore, be taken into account when assessing the significance of geochronological data.

4.5 STOP 5 – Quartzite and oxide-rich gneiss, Faurefjell metasediments, Nedrebø

The Faurefjell metasediments (Hermans et al., 1975) are the youngest of the two sedimentary units in southern Rogaland and have their main distribution in a 10–15 km-wide zone north of the Rogaland Igneous Complex. The Faurefjell metasediments form layers and wide belts within ca. 1500 Ma, granulite-facies migmatitic granitic gneisses.

The dominant rock type of the Faurefjell metasediments is quartz-diopside gneiss; a quartz-rich migmatitic gneiss with diffuse red or reddish leucosome veins and local red pegmatite, indicative of a more hydrous composition than the surrounding granulite-facies gneisses (Fig. 9). Dark minerals are biotite, diopside and locally garnet. These rocks are, however, not well exposed at this stop.

At Nedrebø, the inferred base of the Faurefjell metasediments is preserved. It comprises a layered sequence of quartzite, marble, iron oxide-rich rocks in addition to pale quartz-rich gneisses. These lithologies indicate that the Faurefjell metasediments were deposited in a platform-type environment. Near the base, one commonly finds layers or thick bodies of coarse-grained hydrothermal quarts, which seem to have originated from the Faurefjell metasediments (probably recrystallised quartzite). In contrast to the Gyadalen metapelites and ca. 1500 Ma migmatitic orthogneisses, amphibolite does not occur in the Faurefjell unit. Since some of these amphibolites may represent deformed pre-1230 Ma mafic dykes (discussed earlier on this trip), it appears that the Faurefjell metasediments were deposited later than ca. 1230 Ma, consistent with the detrital zircon age data.

Detrital zircons from the quartz-diopside gneiss at Oltedalsvatnet and quartzite at Nedrebø and Stølsfjellet show that Late Palaeoproterozoic to mid Mesoproterozoic ages dominate, with a youngest peak (sample ROG 644) at ca. 1170 Ma, providing a maximum age of deposition (Fig. 9). The distribution of detrital ages and the maximum depositional age suggest that the Faurefjell metasediments may be correlative to the youngest parts of the Telemark supracrustals, e.g., the Eidsborg formation (Lamminen, 2011).

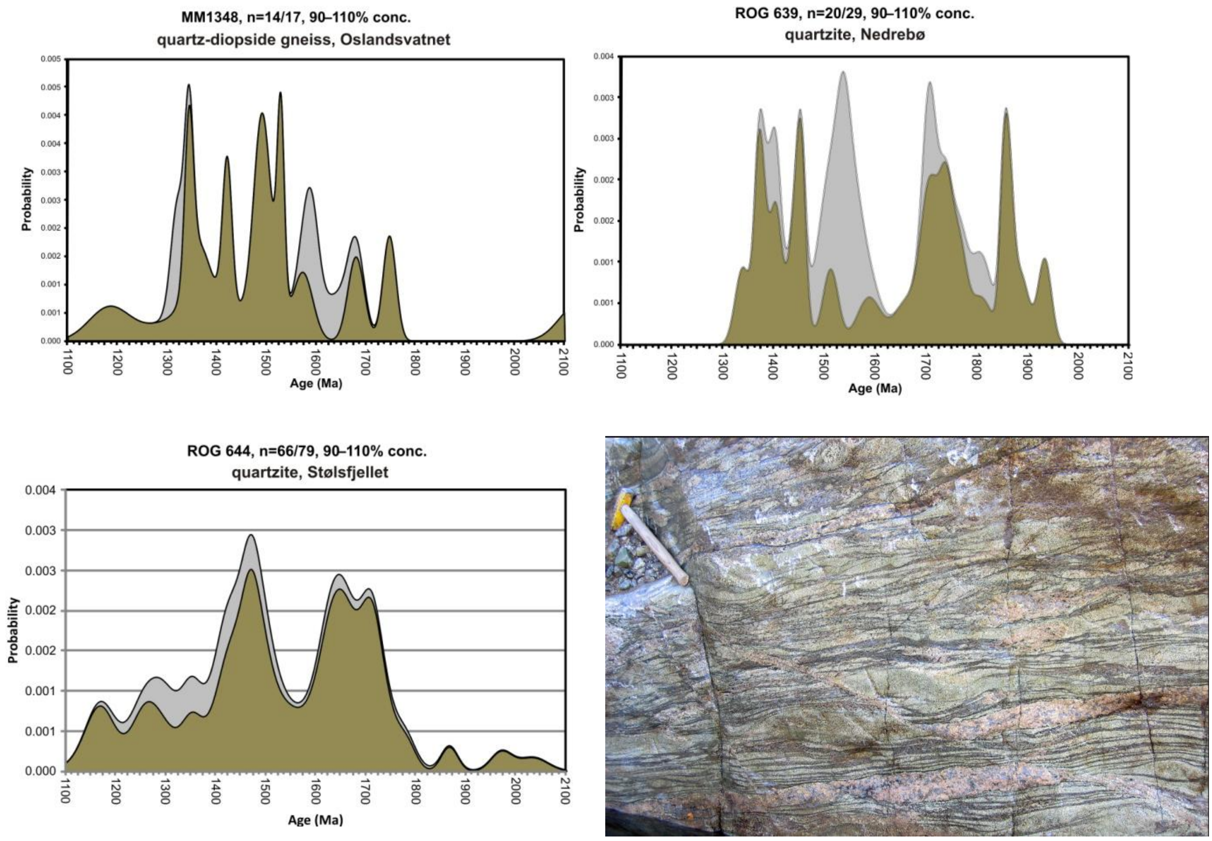

Figure 9. Field photo and detrital zircon U–Pb age data from quartz-diopside gneiss and quartzite, Faurefjell metasediments. The photo is from a locality a few km closer to Kydland.

Sample ROG642 is an oxide-rich cordierite-spinel-orthopyroxene gneiss from this locality. The texture is highly variable, from medium grained equigranular to granoblastic to locally symplectitic (Fig. 10). The main silicates are plagioclase, orthopyroxene and cordierite. Plagioclase is anhedral in the granoblastic part of the thin section, and becomes subhedral in the equigranular part. In the latter area, plagioclase is antiperthitic, displays undulated contacts with K-feldspar and evidence of late resorption. K-feldspar, where present, is interstitial between subhedral plagioclase. Opaque minerals are abundant, comprising up to 20% of the thin section, and form large anhedral clusters associated with green spinel.

The zircons from sample ROG642 are large, typically >150 μm, irregular, with highly complex zoning including cores with multiple rims and several generations of diffusely zoned zircon (Fig. 10). Geochronological analysis consistently yields a range of concordant ages between ca. 1080 and 920 Ma (Fig. 10), interpreted as reflecting long-lived high-grade conditions which may have been quasi-continuously maintained for ca. 150 million years. Although we cannot rule out that the array of ages reflects differential resetting, the CL images show that the different ages come from different domains within the zircon grains (Fig. 10), suggesting extensive resorption and regrowth of zircon rather than resetting.

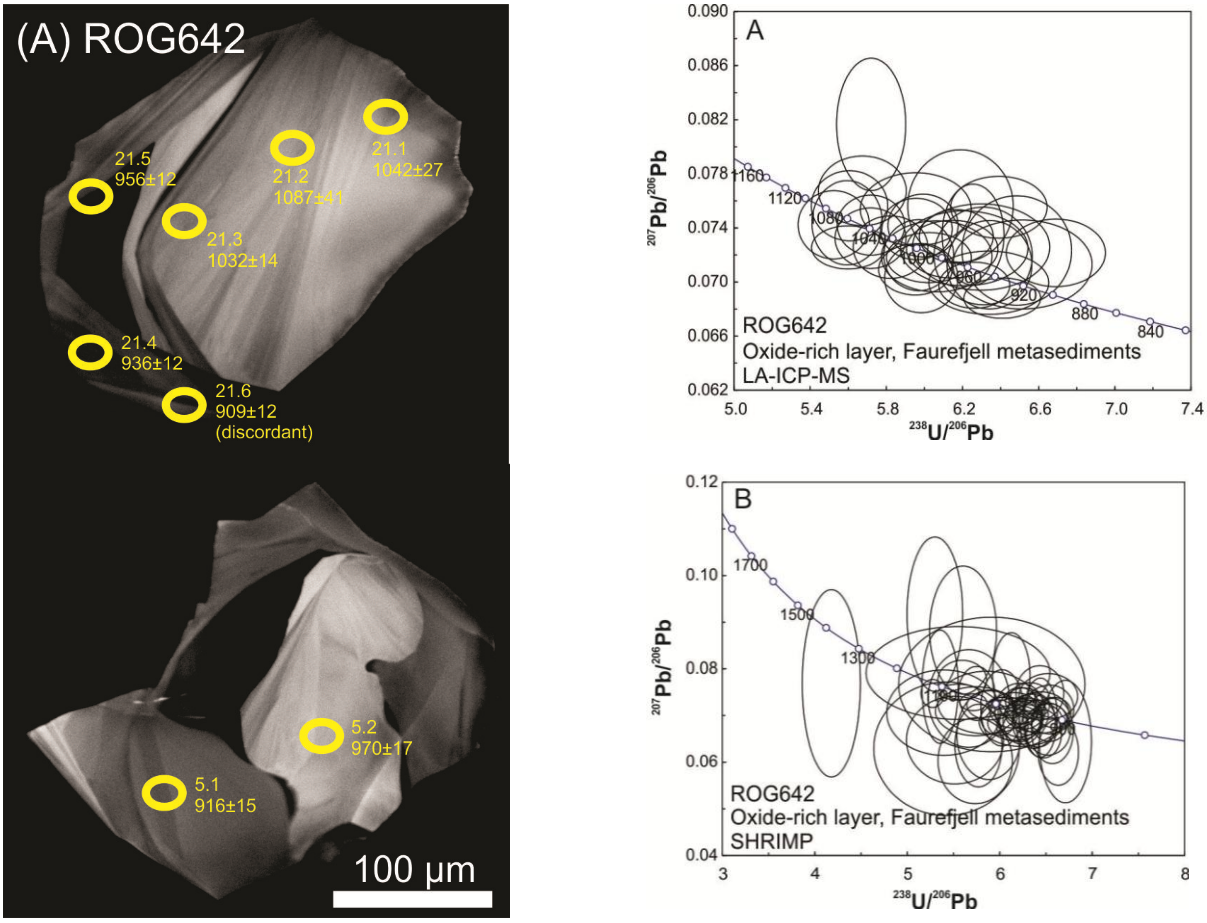

Figure 10. CL images and U–Pb geochronological data from zircons in sample ROG642.

In addition, calculated alpha doses (a measure of radiation damage) do not correlate with age (Fig. 11), also arguing against partial resetting. Calculated Ti-in-zircon temperatures are between 740 and 780°C for most of the recorded time interval, but increases to ca. 840°C from ca. 970 Ma onwards (Fig. 11). The increase in recorded temperature starts well before the inferred emplacement age of the RIC. This observation suggests that UHT metamorphism was not directly linked to the emplacement of the RIC, but more likely to reflect heating from mantle-derived magmas followed by late-stage orogenic doming, rather than contact metamorphism. This interpretation is compatible with the work of Drüppel et al. (2013), who argued for regional geological UHT metamorphism, followed by contact metamorphism related either to emplacement of the RIC (Blereau et al., 2017), or alternatively only the BKSK.

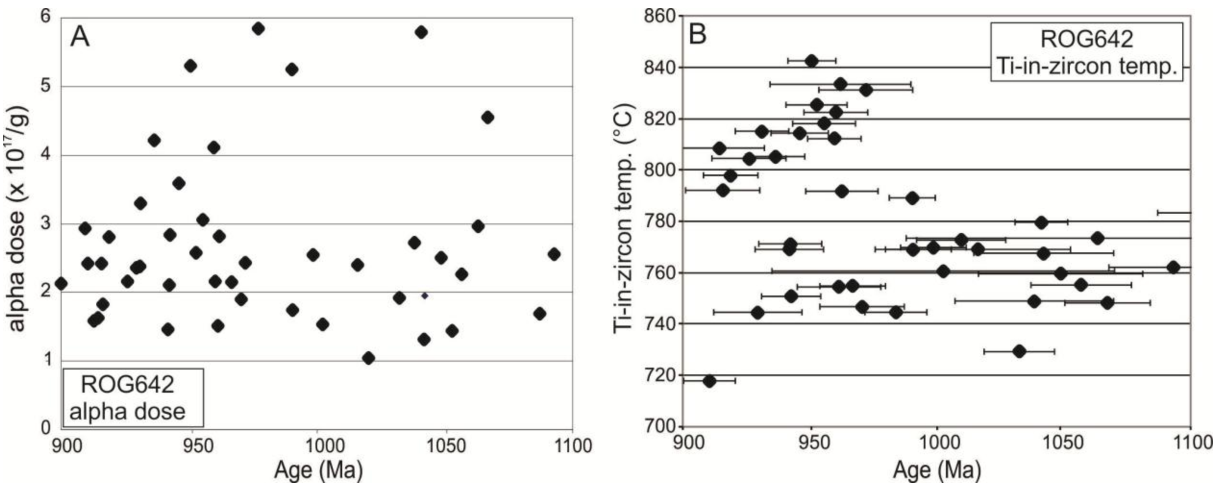

Figure 11. Calculated alpha doses and Ti-in-zircon temperatures versus $^{207}Pb/^{206}Pb$ age for sample ROG642. Alpha doses calculated following Murakami et al. *(1991), and Ti-in-zircon temperatures following Watson* et al. *(2006).*

4.6 STOP 6 – Anorthosite with high-Al opx megacrysts, Sørskog

Polycrystalline, high-Al orthopyroxene megacrysts are ubiquitous in Proterozoic anorthosite massifs and this sample represents a typical example of such an occurrence (Fig. 12). Individual orthopyroxene megacrysts range from 10 to 20 cm in length, are variably oriented and hosted by coarse-grained to pegmatitic anorthosite (*sensu lato*). Plagioclase lamellae are observed in most of the megacrysts at this locality. Several of the orthopyroxene megacrysts are embayed by large, lath-like plagioclase crystals. Protrusions and veins of plagioclase into and between megacrysts are notable and potentially provide sites for late-stage zircon crystallisation. Alternatively, the zircon may have formed as a decompression exsolution product along with plagioclase and Fe–Ti oxide phases, or simply as inclusions within the orthopyroxene megacrysts.

Figure 12. High-alumina orthophyroxene megacryst (HAOM) from the Egersund–Ogna anorthosite.

The zircon grains from sample OPX033146 are between 50 μm and 200 μm, stubby and generally oscillatory zoned (Fig. 13). Ten SIMS (SHRIMP II) analyses from 10 zircons correlate with common Pb (R^2 = 0.78); we therefore calculate a discordia anchored in a $^{207}Pb/^{206}Pb$ composition of 0.93, which yields a lower intercept of 941 ± 14 Ma (MSWD = 1.8; Fig. 13). Nineteen LA–ICP–MS analyses from 11 zircons yield <5% reversely discordant data with a weighted mean $^{207}Pb/^{206}Pb$ age of 932 ± 6 Ma (MSWD = 0.36), which overlaps within error of the SIMS age. These ages are similar, within error, to those obtained from HAOM-related zircons by Schärer et al. (1996).

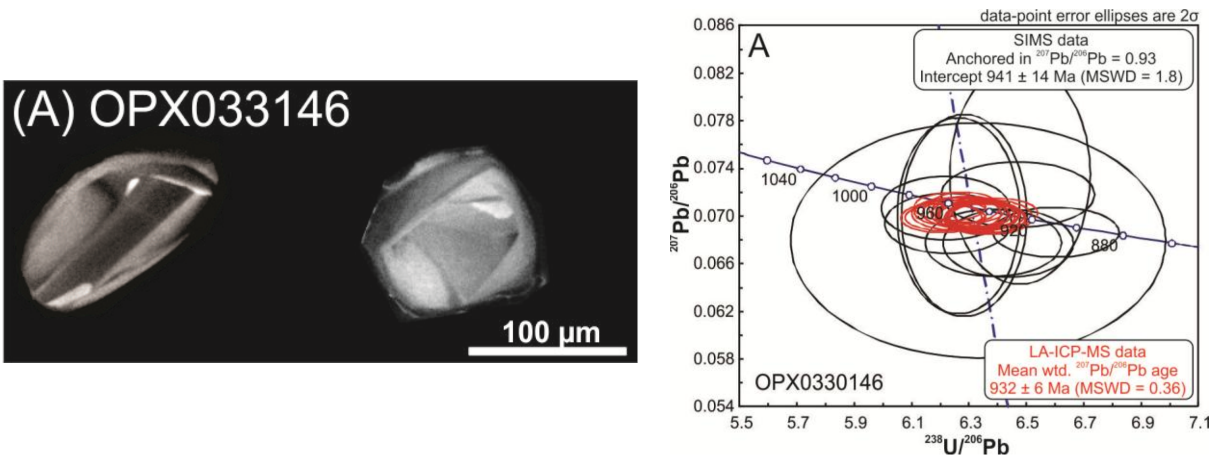

Figure 13. CL images and U–Pb geochronological data from zircons in sample OPX033146.

A similar suite of high-Al (>8 wt.% Al_2O_3) orthopyroxene megacrysts from the Egersund–Ogna massif yielded a Sm–Nd isochron age of 1041 ± 17 Ma (MSWD = 0.25) (Bybee et al., 2014). In addition, when three point isochrons are constructed between the plagioclase decompression exsolution lamellae, surrounding orthopyroxene and whole-rock megacryst compositions, an age of 968 ± 43 Ma is recorded. This age documents the time (albeit imprecisely) at which plagioclase exsolved from these Al-rich megacrysts as anorthositic diapirs were emplaced in the mid- to upper crust (Bybee et al., 2014).

4.7 STOP 7 – Fayalite granite, Undheim

The Sjelset fayalite granite is coarse-grained with anhedral feldspar crystals up to 3 mm and anhedral pyroxene crystals around 1 mm in size (Fig. 14). The most abundant pyroxene is inverted pigeonite, but clinopyroxene and orthopyroxene can be found as well. Strongly fractured subhedral to anhedral olivine (fayalite) can be found, with crystals up to 1 mm. Brown-green anhedral hornblende locally forms a discontinuous rim around the mafic silicates. Plagioclase and perthitic K-feldspars are subhedral, whereas quartz is subhedral to anhedral. Only the accessory minerals zircon and apatite are subhedral to euhedral. They are found associated with clusters of mafic silicates. Apatite is found as inclusions in all mafic silicates and oxides (magnetite and ilmenite). Small rounded pyrite crystals with rare inclusions of chalcopyrite are commonly associated with the oxides. The cores of subhedral plagioclase are strongly sericitised and locally pyroxene is retrogressed into chlorite.

Figure 14. Despite the dark colour, this is actually a granite. Fayalite is the Fe-end member of olivine, which, contrary to what one learns as a petrology undergraduate, can coexist with quartz. The presence of fayalite, therefore, indicates an Fe-rich magma composition.

Sample ROG 147, Sjelset fayalite granite. The zircons of sample ROG 147 range in size between 100 and 250 µm, are mostly prismatic and subhedral, with well-developed oscillatory zoning (Fig. 15). Eighteen SIMS (SHRIMP II) analyses from 16 zircons show a strong relationship between $^{207}Pb/^{206}Pb$ age and common Pb (R^2 = 0.95). To arrive at an age for these data, we therefore calculate a discordia anchored at a $^{207}Pb/^{206}Pb$ composition of 0.93, which yields a lower intercept of 935 ± 8 Ma (MSWD = 1.3; Fig. 15). Sixteen LA–ICP–MS analyses from 14 zircons yield nearly concordant data with a weighted mean $^{207}Pb/^{206}Pb$ age of 926 ± 6 Ma (MSWD = 0.29), overlapping within uncertainty of the SIMS age.

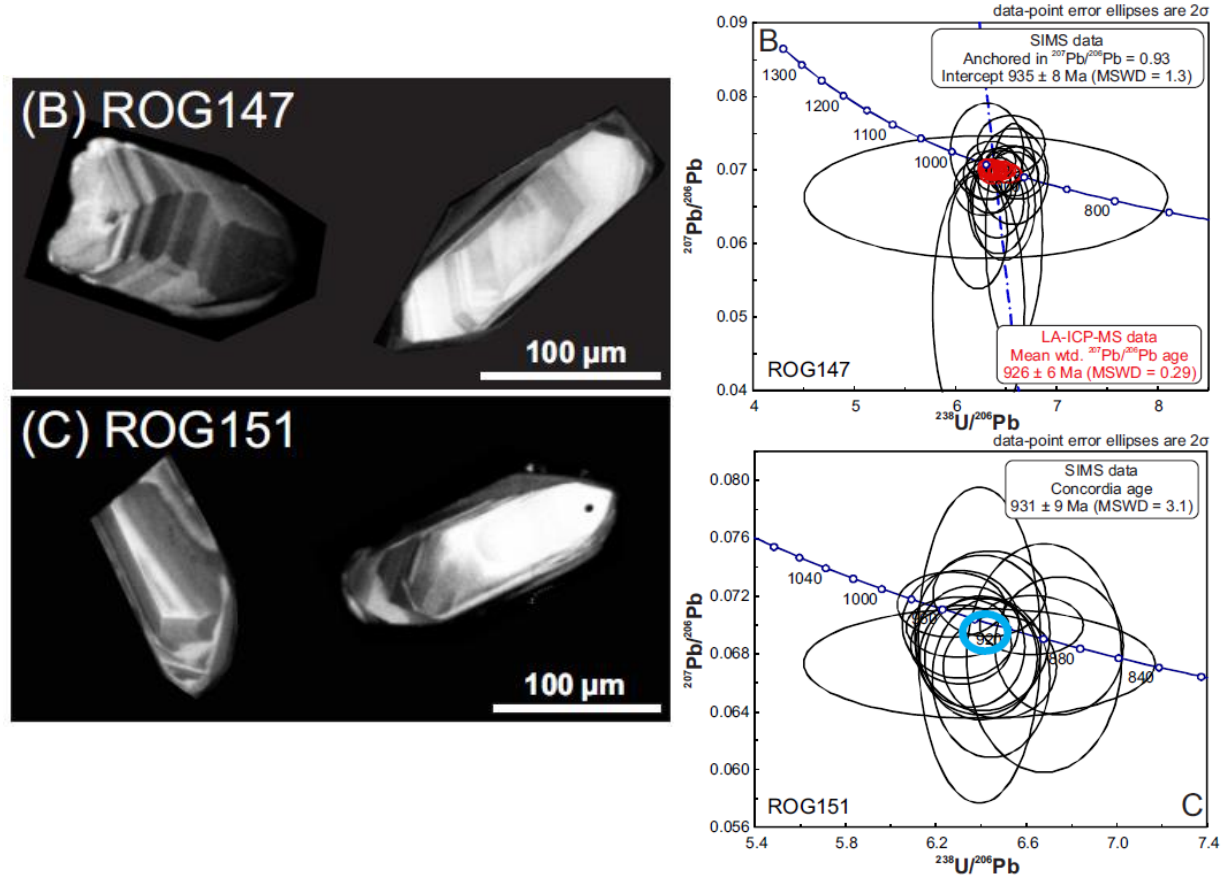

Figure 15. Cl images of dated zircons, and U–Pb age data from the Sjelset fayalite granite.

Sample ROG 151, Sjelset fayalite granite. The zircons from sample ROG151 are similar to those from ROG147 (Fig. 15). Unlike the analyses from ROG147, the sixteen SIMS (SHRIMP II) analyses from 14 zircons in this sample do not correlate with common Pb; anchoring a discordia in a common Pb composition is, therefore, unwarranted. The analyses yield a concordia age of 931 ± 9 Ma (MSWD = 3.1; Fig. 15), which is similar to the dates obtained from sample ROG147 from the same unit.

5. Magmatic and metamorphic evidence of a long-lived, evolving continental margin arc

Although much work remains to fully elucidate the orogenic evolution of the western part of the Sveconorwegian orogen, the currently available data do allow some first-order interpretations. Fig. 16 summarises relevant published magmatic ages, including those presented here, grouped into SMB and HBG based on age and composition (1070–1010 Ma, calc-alkaline = SMB; 1000–920 Ma, ferroan = HBG). The figure also presents available age data from the RIC. The presented metamorphic ages only include those reported here, but these results are discussed in relation to previously published data below. The figure also includes a generalised tectonic cartoon illustrating the main stages of arc evolution.

5.1 Establishment of a magmatic arc, 1070–1010 Ma

Formation of the SMB may have started as early as ca. 1070 Ma, with apparently continuous granitic magmatism until ca. 1010 Ma. SMB magmatism was associated with high-grade metamorphism, including migmatisation (Coint et al., 2015; Slagstad et al., submitted), with an apparent peak during the later stages of its history, around 1040–1030 Ma; however, the SMB largely escaped high-grade overprinting except for its SW part, closest to the RIC (Coint et al., 2015). Slagstad et al. (2013a) suggested that the heat source for SMB magmatism could be a basaltic magmatic underplate, which was corroborated by Bybee et al. (2014) who argued that the RIC HAOMs crystallised from underplated, mantle-derived basaltic magma at 1041 ± 17 Ma. The new geochronological data from the diorite at Flåt (1025 ±13 Ma) and the high-grade diorite in Gyadalen (1031 ± 5 Ma) provide the first direct evidence of syn-SMB mafic magmatism, and give further credence to this hypothesis.

5.2 A changing arc, ca. 1010–1000 Ma

Although most earlier workers have argued for a long-lived metamorphic event (termed M1) between ca. 1035 and 970 Ma (Möller et al., 2002; Bingen et al., 2008b), a change in tectonic regime is clearly recorded at ca. 1010 Ma by the cessation of SMB magmatism, interpreted to reflect a shallowing of the subducting slab (Slagstad et al., 2013a). Such a shallowing is likely to result in compression and crustal thickening (Collins, 2002), although, as discussed below, there is no evidence to suggest significant crustal thickening in SW Norway at this time. The high-grade rocks between the SMB and RIC record continuous growth of zircon at this time, with different authors arguing for different metamorphic peaks: 1006 ± 11 Ma (Möller et al., 2002), 1035 ±9 Ma (Tomkins et al., 2005), 1010 ± 7 and 1006 ± 4 Ma (Drüppel et al., 2013); 1032 ±5, 1002 ± 7 and 990 ± 8 Ma (Bingen et al., 2008a). Fig. 16 shows a probability plot of zircon U–Pb geochronological data from the UHT core area, between the SMB and RIC (Slagstad et al., submitted). 185 spot analyses, all <5% discordant, reveal a range of ages from around 1100 Ma to 900 Ma, with a clear peak at ca. 1000 Ma. The pre-1020 Ma dates probably record the same event as observed in high-grade xenoliths in the SMB and its immediate host rock, whereas the peak at 1000 Ma is significantly younger, coinciding with the transition between SMB and HBG magmatism. We interpret this peak in metamorphic ages around 1000 Ma to reflect increased dissolution and growth of metamorphic zircon. Somewhat surprisingly, this event is not recorded in the SMB, suggesting that it remained at relatively high crustal levels during thickening. The significance of these features is discussed in more detail below.

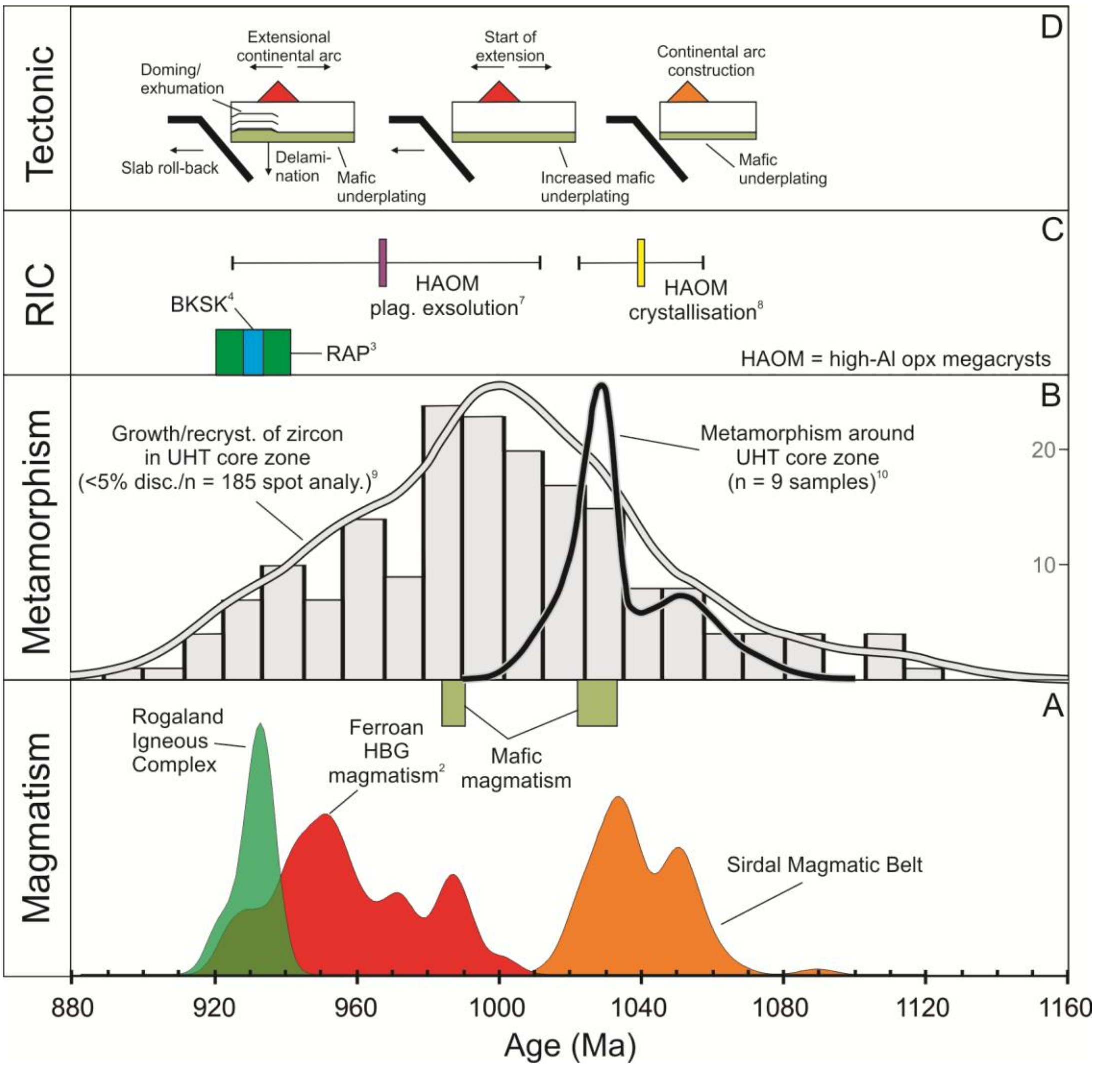

Figure 16. Plots summarising available geochronological data pertaining to (A) Sveconorwegian magmatism, (B) high-grade metamorphism in core area, and (C) RIC magmatism. (D) Sketches illustrating the interpreted tectonic evolution of the SW Sveconorwegian Province. Abbreviations: RIC–Rogaland Igneous Complex; HAOM–high-alumina orthopyroxene meacrysts; BKSK–Bjerkreim–Sokndal layered intrusion; RAP–Rogaland Anorthosite Province.

5.3 Renewed ferroan magmatism and continued high-grade metamorphism, 1000–920 Ma

The earliest trace of renewed magmatism following the magmatic minimum is at 1000 ± 8 Ma, marking the onset of emplacement of the ferroan HBG suite, which appears to have lasted until ca. 920 Ma and affected the entire orogen apart from the easternmost Eastern Segment (Vander Auwera et al., 2003; Vander Auwera et al., 2011). The ferroan, A-type-like composition of the HBG suite has led most workers to infer formation in an extensional setting, related to gravitationally driven extension and delamination of the orogen. As discussed by Slagstad et al. (2013a), such a driving mechanism is difficult to reconcile with the long duration of magmatism and the very large time gap (>100 Myr) between high-grade metamorphism, reflecting crustal thickening, and purported delamination in some areas. They suggest instead that the HBG suite formed during continental back-arc extension as a result of slab steepening and roll-back. This interpretation, however, posits that all the granites currently labelled HBG granites ('ferroan granites' in Fig. 1) formed the same way, which is not necessarily correct. For example, the easternmost HBG granites formed quite late, at ca. 920–930 Ma (Eliasson & Schöberg, 1991; Bingen et al., 2008b) and are strongly enriched in heat-producing elements (Slagstad, 2008). In contrast, the HBG granites intruding the SMB, much farther west in the orogen, are comparatively low in heat-producing elements. Other elements also show distinct differences between HBG granites east and west in the orogen (our unpublished data), and it is possible that there is more than one group of HBG granites, as has been suggested by Andersen et al. (2002) and Brueckner (2009).

Brueckner (2009) suggested that the late-orogenic magmatism in the Sveconorwegian Province was caused by partial melting of subducted continental crust ("crustal tongues"). In this model, the easternmost, high heat-producing granites formed by partial melting of upper crust, which was tectonically peeled off during subduction, leaving behind a more mafic lower crust that could melt to form both the westernmost HBG granites and the RAP. Although this interpretation needs to be tested chemically and isotopically, the general idea is consistent with the suggestion by Slagstad et al. (2017) that the Sveconorwegian orogen formed by a series of accretionary events between ca. 1140 and 980 Ma. These events may have variably modified and refertilized the lower crust and upper mantle (Slagstad et al., in review) and given rise to magmas of different composition.

At present, it appears likely that there is more than one group of ferroan, HBG granites, and that they may reflect variations in either source or tectonic setting from east to west and/or through time. Thus far, most work has focussed on the HBG granites in western parts of the orogen, where existing data suggest isotopically similar sources to the SMB (Vander Auwera et al., 2003; Vander Auwera et al., 2011). Our tentative interpretation is that the ferroan HBG granites formed by high-temperature melting of the same lower-crustal source as the SMB, with the added heat derived from basaltic underplating during extension of the arc (cf., Landenberger & Collins, 1996; Slagstad et al., 2004; Zhao et al., 2016). This differs from the interpretation proposed by Slagstad et al. (2013a) in that it argues that the position of the arc remained unchanged since formation of the SMB. This alternative interpretation makes the westernmost HBG granites arc related, rather than back-arc related, although the overall tectonic setting is similar. Formation in an arc is also supported by aeromagnetic data, which show that the HBG granites constitute a major, linear granite batholith, more similar to the SMB than previously recognized.

We are currently investigating the ferroan HBG granites to see if there are temporal and/or geographical trends in chemical and isotopic composition that can elucidate and distinguish the different interpretations. We have already mentioned the east-to-west compositional variations, and when excluding the easternmost ferroan granites (Idefjord–Bohus and Flå granites), the remaining granites cover a much narrower age range than the generally accepted 990–920 Ma period. Disregarding ages from the RIC and associated charnockites and fayalite granites, the ferroan granites mainly yield ages between 970 and 940 Ma (Fig. 16), which we interpret to represent peak activity in a re-established active continental-margin arc. By this time, the entire orogen was in extension, with mafic dykes intruding the eastern parts of the orogen and its foreland (Söderlund et al., 2005), and development of major, extensional shear zones (Viola et al., 2011). Although crustal thickening at 990–970 Ma in the eastern part of the orogen may have resulted in gravitationally driven extension a few tens of million years later (Viola et al., 2011), this process is unlikely to have caused extension and mafic magmatism in the orogenic foreland that did not experience crustal thickening, nor in more westerly parts of the orogen, where thickening in many cases preceded extension by nearly 100 Myr. We therefore suggest that extension driven by slab roll-back in a retreating subduction zone is the most likely candidate, which provides a plausible scenario in which the lower-arc crust beneath the SMB, depleted and dehydrated by the extraction of the SMB granitic melts, may have melted to give rise to granites of more ferroan compositions.

6. Anorthosite emplacement related to doming in an extending continental arc

The southwestern parts of the Sveconorwegian orogen have not been subjected to detailed structural study and analysis, in contrast to the eastern and central parts of the orogen (cf., Henderson & Ihlen, 2004; Viola et al., 2011). An exception is the work by Stormoen (2015) around Knaben, in the central parts of the SMB (Fig. 17). Regional mapping by NGU over the last 10+ years has, however, amassed abundant structural and map data that allow us to make some first-order interpretations regarding the overall structure of SW Norway.

A major difference in structural style and metamorphic grade is observed between the high-grade, strongly deformed gneisses in the UHT core area and the little-deformed, non-metamorphic SMB to the east and north, and the RIC to the southwest (Fig. 1). Although the margins of the RIC tend to be strongly deformed, with host-rock fabrics generally parallel to the shape of the intrusive bodies, this is likely to be an effect of emplacement rather than post-intrusion tectonic deformation (e.g., Barnichon et al., 1999; Bolle et al., 2002).

Also important to our model is the fact that the pigeonite-in and osumilite-in isograds, related to emplacement of the RIC (or possibly only the BKSK), transect host rock structures at high angles (Fig. 1), suggesting that the host rocks were deformed prior to RIC emplacement.

Figs. 17 and 18 present detailed maps and ca. 550 foliation measurements from the central (Knaben area) and northern (mouth of Lysefjorden) parts of the SMB. The foliations include both tectonic foliations and foliations interpreted to represent magma flow, in order to get an impression of the overall geometry of the region. In both areas, the lithological make up of the SMB is characterized by screens and xenolith-rich zones (Coint et al., 2015) surrounded and intruded by SMB granites. In the Knaben area, these sheet-like zones consistently dip ca. 30° to the east, whereas they are subhorizontal in the northern part, along Lysefjorden (Fig. 18). The overall structure of the SMB therefore appears to outline the flank of a large dome-like structure with the UHT rocks and RIC in the core.

Pressure estimates from close to the RIC suggest contact metamorphism at ca. 5 kbar, with slightly lower pressure at 3–4 kbar ca. 10 km away from the contact (Blereau et al., 2016), similar to the pressure of emplacement of the SMB (Coint et al., 2015). The pressure estimates for contact metamorphism are consistent with emplacement or exhumation of the RIC in a broad, dome-like structure, as suggested by the general geometry of the area, which also constrains the timing of doming to be coeval with or after anorthosite emplacement. U–Pb zircon ages from cordierite coronas around garnet suggest decompression at 955 ± 8 Ma

(Tomkins et al., 2005), within uncertainty of the 968 ± 43 Ma age constraining RAP ascent and emplacement obtained by Bybee et al. (2014), and the 941 ± 14 Ma SHRIMP age obtained here for HAOM zircon crystallisation. Although the significance of the HAOM zircons is unclear, the apparent spatial relationship with the HAOM suggests they did not grow directly from the anorthositic melt (or, more appropriately, anorthositic mush), or the parental melt to the anorthosites, but are somehow related to the presence of the HAOM. At present, we therefore favor the hypothesis by Schärer et al. (1996) that the zircons most likely grew from small amounts of evolved melt trapped between HAOM aggregates. Although this evolved, residual melt would initially have been homogenously distributed in the crystallising anorthosite mush, the presence of the rigid HAOM might have created local low-pressure sites into which the residual melt migrated and concentrated, as has been observed in some migmatites (e.g., Slagstad et al., 2015). We therefore interpret the zircons to have grown from the last vestiges of melt in the anorthosite. An alternative hypothesis is that these zircon-forming vestiges represent partial melting related to heating from later, adjacent anorthosite bodies, which implies an incremental emplacement history for the anorthosites. Field relationships and mapping, for example, show that ductile fabrics related to emplacement of the Egersund–Ogna anorthosite are cut by the later Helleren anorthosite (Marker et al., 2003), suggesting that the system had time to cool between emplacement of the two anorthosite bodies.

The ages of zircons from the Egersund–Ogna massif range from 930 Ma (Schärer et al., 1996) to 941 Ma (this study), but overlap within uncertainty. Blereau et al. (2016) suggested that melts may have been present in the host rocks to the RIC for up to 100 Myr, consistent with the zircon data presented here. It is, therefore, possible that the range of ages obtained from the Egersund–Ogna massif reflects crystallisation of residual melts in the anorthosite over a long period of time, or even that the younger ages reflect remelting during a late-stage thermal event, such as that related to emplacement of the BKSK. Also noteworthy in this regard is the observed increase in Ti-in-zircon temperature in metamorphic zircon in the RIC contact aureole at ca. 970 Ma, well before the inferred emplacement age of the RIC. This observation suggests that if UHT metamorphism was related to emplacement of the RIC, this event took place significantly earlier than 930 Ma. Based on regional structural, metamorphic and geochronological data, we interpret the anorthosites to have been emplaced around 950–930 Ma, i.e., over a protracted period of time, during doming of the crust. As discussed by Slagstad et al. (2013a; 2017), the entire Sveconorwegian orogen appears to have been in extension at this time, which offers a plausible stress regime for doming (e.g., Yin, 2004). At

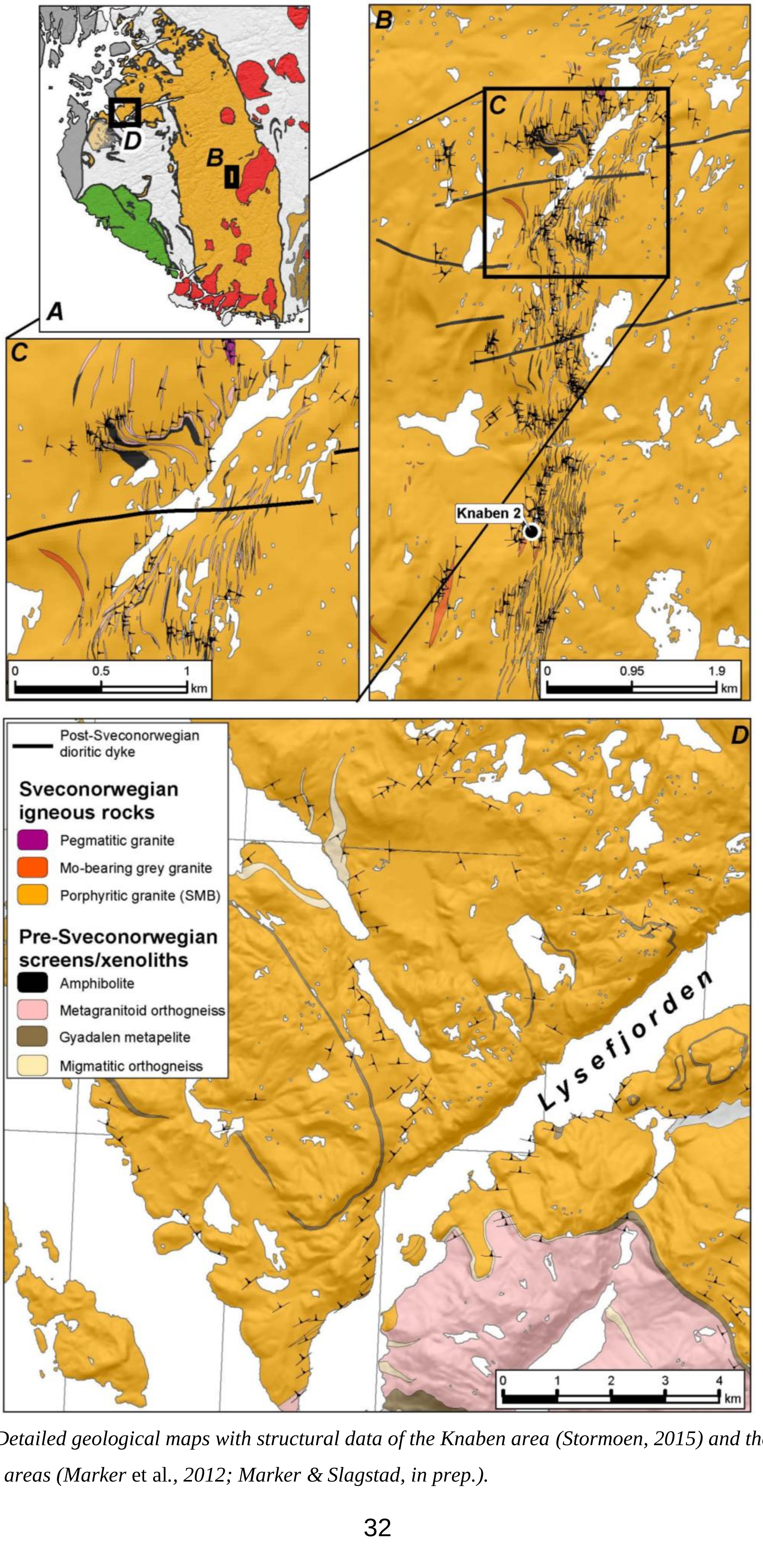

Figure 17. Detailed geological maps with structural data of the Knaben area (Stormoen, 2015) and the Lysefjorden areas (Marker et al.*, 2012; Marker & Slagstad, in prep.).*

present, we are unable to document the existence of large-scale extensional structures that one would expect to accompany such doming. We note, however, the existence of a several hundred metre-wide zone of E–W-trending, high-strain rocks with extensional structures north of Nedrebø (Marker & Slagstad, in press-a, b) that appears to separate high-grade rocks with an apparently simple metamorphic history on the flank of the purported dome, from high-grade rocks which preserve evidence of long-lived metamorphic overprinting towards the core of the dome. This zone may, therefore, represent part of an otherwise cryptic tectonic contact within the high-grade area, further disrupting an already complex geology. Further structural and geochronological work is, however, needed to prove the existence of such a structure(s). A ca. 950 Ma age of extension and doming suggests it was coeval with voluminous ferroan magmatism in the region, indicating that these processes were related.

The doming suggested here is different from that proposed by Bingen et al. (2006). First of all, our proposed dome is significantly smaller, limited to the SW part of the Rogaland–Vest-Agder sector, and delineated by non-metamorphosed SMB rocks to the east and north that show no evidence of high-grade metamorphism after 1035 Ma. Furthermore, we argue that the doming is related to externally driven orogenic extension rather than post-orogenic collapse, an interpretation made more likely by evidence arguing against significant crustal thickening, discussed below. It follows from our interpretation that the presence of Sveconorwegian UHT rocks and anorthosite may be much more widespread than hitherto known, and that their confinement to SW Norway is related to exposure limited to this relatively late-orogenic dome. Anorthosite and jotunite-mangerite dated at 965 and 951 Ma, respectively (Lundmark et al., 2007; Lundmark & Corfu, 2008), in the Caledonian Lindås and Jotun nappes north of our study area, are associated with rocks that preserve evidence of high-grade metamorphism from >954 Ma to 930 Ma (Lundmark et al., 2007). To the east of the study area, geographically widespread pegmatites were emplaced as late as ca. 910 Ma (Seydoux-Guillaume et al., 2012), possibly as a result of still-ongoing mafic underplating (Müller et al., 2015), attesting to the widespread and long-lived nature of such arc/back-arc processes (e.g., Currie & Hyndman, 2006).

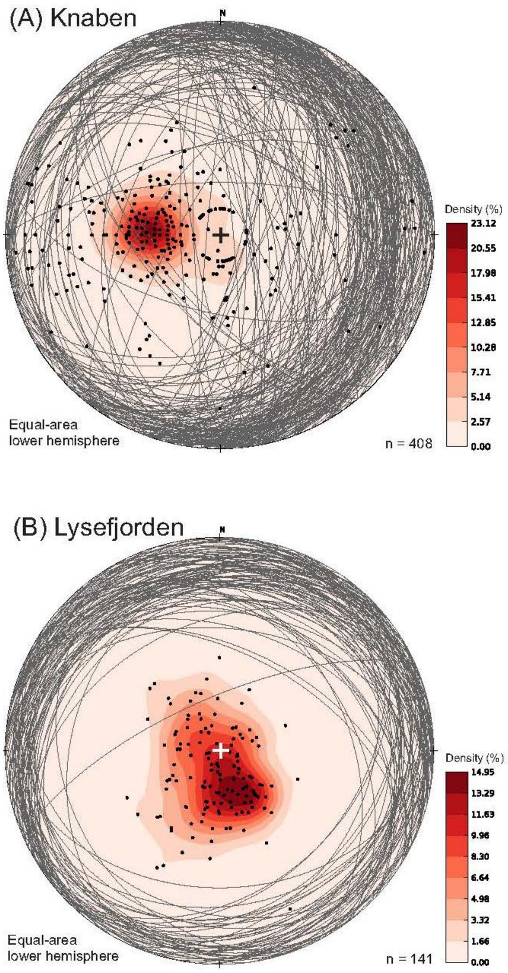

Figure 18. Lower-hemisphere stereoplots presenting foliation measurements (tectonic and magmatic) from the areas shown in Fig. 17.

7. Long-lived, high-grade metamorphism in the lower- to middle crust of a magmatic arc and the quality of different lithological recorders

If our interpretation that the westernmost part of the Sveconorwegian orogen was an active continental-margin arc between ca. 1070 and 920 Ma, and that the later part of this period was characterized by doming and uplift, it allows an unprecedented view into the lower to middle crust of a long-lived, Mesoproterozoic continental-margin arc. The complexities that such a setting entail are reflected in the variety of interpretations proposed by different authors, in particular regarding the timing and conditions of high-grade metamorphism, P–T paths and tectonic significance.

7.1 High-grade metamorphism as a result of crustal thickening?

The metamorphic framework outlined above supersedes traditional interpretations in which the metamorphic evolution can be understood within the framework of initial crustal thickening followed by consequent orogenic collapse, and finally contact metamorphism related to emplacement of the RIC. Firstly, the available metamorphic age data presented here and elsewhere do not allow distinct metamorphic episodes to be identified. Granted, one particular sample may show distinct episodic growth of metamorphic zircon or titanite (e.g., Möller et al., 2003; Laurent et al., 2016); however, when a larger number of samples is considered, these 'events' tend to blur. A major challenge for further work on the metamorphic evolution of SW Norway is, therefore, to distinguish between 'events' recorded by a particular sample that bear a regional, tectonic significance, and 'events' that simply reflect the conduciveness of that sample to react, producing datable minerals, at particular times. The latter may be more closely related to local conditions, such as the availability of fluids (e.g., melt, H_2O, CO_2), than to regional, orogenic processes. The work by Laurent et al. (2016), where monazite age data are linked to sulphate concentrations, may be one such venue whereby metamorphic ages can be correlated over a larger area.

Long-lived (>100 Myr), UHT metamorphism has become increasingly recognized as a common feature of Precambrian orogenic terrains (e.g., Korhonen et al., 2013; Walsh et al., 2015), and identifying the mechanisms and tectonic setting(s) responsible for attaining and sustaining such conditions has been a prime target for numerous recent studies. Clark et al. (2011) suggested that long-lived UHT conditions could result from orogenic thickening of highly radioactive crust, and this mechanism was proposed by Drüppel et al. (2013) to explain long-lived UHT metamorphism in SW Norway. The crust in SW Norway is, however, not particularly radioactive (Slagstad, 2008; Slagstad et al., 2009), and there is no geological evidence of significant crustal thickening. For example, the ca. 1040 Ma age for high-alumina orthopyroxene megacrysts in the RAP (Bybee et al., 2014) constrain crustal thickness to <33 km (i.e., <11 kbar; Charlier et al., 2010) at that time, and no major structures exist that could accommodate later, major crustal thickening. Granitic magmatism is continuous through the period of high-grade metamorphism, and although more work is needed to determine the exact source(s) of this magmatism, there is no evidence that garnet was ever stable in the inferred lower-crustal source (Demaiffe et al., 1990; Slagstad et al., 2013a), limiting crustal thickness to around 10 kbar (Behn & Kelemen, 2006). Slagstad et al. (2013b, a) argued that an apparent magmatic hiatus between ca. 1020 and 990 Ma could be interpreted to reflect flat-slab subduction and compression, which could have triggered crustal thickening and high-grade metamorphism. The new data presented here suggest, however, that there is no real hiatus, but rather a lull in magmatic activity, concomitant with widespread high-grade metamorphism. We therefore conclude that long-lived, UHT metamorphism in SW Norway is unlikely to have resulted from crustal thickening.

7.2 High-grade metamorphism as a result of repeated basaltic underplating?

Most studies on the mechanisms of long-lived UHT metamorphism invoke mantle-derived heat in the form of mafic magmatism resulting from extensional/compressional tectonics in arc/back-arc settings (e.g., Brown, 2006; Currie & Hyndman, 2006; Walsh et al., 2015), similar to the tectonic-switching model of Collins (2002). Emerging evidence from the Sveconorwegian Province, including this study and that of Wiest (2016) near Bergen, and Jensen & Corfu (2016) at Finse, show that the Sveconorwegian orogeny was accompanied by geographically widespread mafic magmatism. A marked increase in Ti-in-zircon temperatures at ca. 970 Ma in the UHT core area coincides with emplacement of voluminous ferroan granites farther east, consistent with widespread extension and ponding of mafic magma at the base of relatively thin (or at least not significantly thickened) crust.

A range of possible scenarios exist that can explain the observed lull in magmatic activity and coeval increase in metamorphism. Ridge subduction, for example, will result in a flattening of the subduction zone and decrease in arc magmatic activity, while at the same time increasing crustal heat flow by allowing asthenospheric material to impinge on the lower crust (Li & Li, 2007; Santosh & Kusky, 2010). Flattening from subduction of an oceanic plateau, or simply a change in convergence rate, may achieve the same effect if preceded by extension and basaltic underplating (Collins, 2002), and is consistent with evidence for significant mafic underplating both before and after ca. 1000 Ma (i.e., tectonic switching). A third possibility is that the lower-crustal source of SMB magmatism was becoming infertile by ca. 1010 Ma, explaining the magmatic lull, and that a steepening of the subduction zone at ca. 1000 Ma resulted in increased basaltic underplating, allowing the less-fertile source to be remelted and increasing heat flow. This latter model does not require compression at all.

A long line of evidence from the Sveconorwegian Province points towards protracted accretionary processes, with marked differences in tectonic style in different parts of the orogen (Slagstad et al., 2017). These repeated accretionary events are likely to have had a 'stop-and-go' effect on subduction along the plate margin by affecting the movements of the upper, continental plate, which would have been ideal for the type of extension-compression tectonic regime inferred to be responsible for sustained UHT conditions. This coupling between seemingly unrelated tectonic events in different parts of the orogen provides a framework in which orogen-scale variations in metamorphic and magmatic evolution can be understood.

In detail, several different interpretations can explain the observed magmatic and metamorphic evolution of SW Norway, including ridge subduction, tectonic switching or compositional changes in the lower crust. In all cases, however, mounting evidence suggests that long-lived, repeated basaltic underplating was the main driving force for sustaining high-grade conditions and continuous crustal melting and magmatism for ca. 150 Myr at the SW margin of Fennoscandia.

8. A few conclusions

New age data from magmatic rocks suggests nearly continuous granitic magmatism, with emplacement of the calc-alkaline SMB between 1070 and 1010 Ma, followed shortly thereafter by ferroan, HBG magmatism between 1000 and 920 Ma.

Aeromagnetic data suggest that the HBG granites form a major, N–S-trending batholith rather than relatively small, isolated plutons, consistent with formation in a magmatic arc. Geochemical and isotopic data suggest that the HBG granites may have formed by re-melting of the depleted and dehydrated SMB lower-crustal source during extension in the arc resulting in mafic underplating.

The orogenic evolution reflects a series of accretionary events, with repeated extension in the SW part of the orogen. There is no evidence of significant crustal thickening in the study area, and mantle-derived heat appears to have been the main driver, resulting in widespread lower-crustal melting and high-grade metamorphic conditions that were sustained for ca. 150 million years.

Long-lived, Sveconorwegian UHT metamorphism and coeval mafic and felsic magmatism between ca. 1070 and 920 Ma mark final assembly and stabilisation of the Fennoscandiam Shield.

9. References

Andersen, T., Andresen, A. & Sylvester, A.G. 2002: Timing of late- to post-tectonic Sveconorwegian granitic magmatism in South Norway. *Norges Geologiske Undersøkelse Bulletin 440*, 5-18.

Barnichon, J.D., Havenith, H., Hoffer, B., Charlier, R., Jongmans, D. & Duchesne, J.C. 1999: The deformation of the Egersund–Ogna anorthosite massif, south Norway: finite-element modelling of diapirism. *Tectonophysics 303*, 109-130.

Behn, M.D. & Kelemen, P.B. 2006: Stability of arc lower crust: Insights from the Talkeetna arc section, south central Alaska, and the seismic structure of modern arcs. *Journal of Geophysical Research: Solid Earth 111*, n/a-n/a.

Bingen, B., Demaiffe, D., Hertogen, J., Weis, D. & Michot, J. 1993: K-rich calc-alkaline augen gneisses of Grenvillian age in SW Norway: Mingling of mantle-derived and crustal components. *Journal of Geology 101*, 763-778.

Bingen, B. & van Breemen, O. 1998: Tectonic regimes and terrane boundaries in the high-grade Sveconorwegian belt of SW Norway, inferred from U-Pb zircon geochronology and geochemical signature of augen gneiss suites. *Journal of the Geological Society of London 155*, 143-154.

Bingen, B., Skår, Ø., Marker, M., Sigmond, E.M.O., Nordgulen, Ø., Ragnhildstveit, J., Mansfeld, J., Tucker, R.D. & Liégeois, J.-P. 2005: Timing of continental building in the Sveconorwegian orogen, SW Scandinavia. *Norwegian Journal of Geology 85*, 87-116.

Bingen, B., Stein, H.J., Bogaerts, M., Bolle, O. & Mansfeld, J. 2006: Molybdenite Re–Os dating constrains gravitational collapse of the Sveconorwegian orogen, SW Scandinavia. *Lithos 87*, 328-346.

Bingen, B., Davis, W.J., Hamilton, M.A., Engvik, A.K., Stein, H.J., Skår, Ø. & Nordgulen, Ø. 2008a: Geochronology of high-grade metamorphism in the Sveconorwegian belt, S. Norway: U-Pb, Th-Pb and Re-Os data. *Norwegian Journal of Geology 88*, 13-42.

Bingen, B., Nordgulen, Ø. & Viola, G. 2008b: A four-phase model for the Sveconorwegian orogeny, SW Scandinavia. *Norwegian Journal of Geology 88*, 43-72.

Blereau, E., Johnson, T.E., Clark, C., Taylor, R.J.M., Kinny, P.D. & Hand, M. 2016: Reappraising the P–T evolution of the Rogaland–Vest Agder Sector, southwestern Norway. *Geoscience Frontiers*.

Blereau, E., Johnson, T.E., Clark, C., Taylor, R.J.M., Kinny, P.D. & Hand, M. 2017: Reappraising the P–T evolution of the Rogaland–Vest Agder Sector, southwestern Norway. *Geoscience Frontiers 8*, 1-14.

Bol, L.C.G.M., Maijer, C. & Jansen, J.B.H. 1989: Premetamorphic lateritisation in Proterozoic metabasites of Rogaland, SW Norway. *Contributions to Mineralogy and Petrology 103*, 306-316.

Bolle, O., Trindade, R.I.F., Luc Bouchez, J. & Duchesne, J.-C. 2002: Imaging downward granitic magma transport in the Rogaland Igneous Complex, SW Norway. *Terra Nova 14*, 87-92.

Brown, M. 2006: Duality of thermal regimes is the distinctive characteristic of plate tectonics since the Neoarchean. *Geology 34*, 961-964.

Brueckner, H. 2009: Subduction of continental crust, the origin of post-orogenic granitoids (and anorthosites?) and the evolution of Fennoscandia. *Journal of the Geological Society of London 166*, 753-762.

Bybee, G.M., Ashwal, L.D., Shirey, S.B., Horan, M., Mock, T. & Andersen, T.B. 2014: Pyroxene megacrysts in Proterozoic anorthosites: Implications for tectonic setting, magma source and magmatic processes at the Moho. *Earth and Planetary Science Letters 389*, 74-85.

Charlier, B., Duchesne, J.-C., Vander Auwera, J., Storme, J.-Y., Maquil, R. & Longhi, J. 2010: Polybaric fractional crystallization of high-alumina basalt parental magmas in the Egersund-Ogna massif-type anorthosite (Rogaland, SW Norway) constrained by plagioclase and high-alumina orthopyroxene megacrysts. *Journal of Petrology 51*, 2515-2546.

Clark, C., Fitzsimons, I.C.W., Healy, D. & Harley, S.L. 2011: How does the continental crust get really hot? *Episodes 7*, 235-240.

Coint, N., Slagstad, T., Roberts, N.M.W., Marker, M., Røhr, T. & Sørensen, B.E. 2015: The Late Mesoproterozoic Sirdal Magmatic Belt, SW Norway: Relationships between magmatism and metamorphism and implications for Sveconorwegian orogenesis. *Precambrian Research 265*, 57-77.

Collins, W.J. 2002: Hot orogens, tectonic switching, and creation of continental crust. *Geology 30*, 535-538.

Currie, C.A. & Hyndman, R.D. 2006: The thermal structure of subduction zone back arcs. *Journal of Geophysical Research: Solid Earth 111*, n/a-n/a.

DeCelles, P.G., Ducea, M.N., Kapp, P. & Zandt, G. 2009: Cyclicity in Cordilleran orogenic systems. *Nature Geosci 2*, 251-257.

Demaiffe, D., Bingen, B., Wertz, P. & Hertogen, J. 1990: Geochemistry of the Lyngdal hyperites (S.W. Norway): Comparison with the monzonorites associated with the Rogaland anorthosite complex. *Lithos 24*, 237-250.

Drüppel, K., Elsäßer, L., Brandt, S. & Gerdes, A. 2013: Sveconorwegian mid-crustal ultrahigh-temperature metamorphism in Rogaland, Norway: U–Pb LA-ICP-MS geochronology and pseudosections of sapphirine granulites and associated paragneisses. *Journal of Petrology 54*, 305-350.

Ducea, M.N. & Barton, M.D. 2007: Igniting flare-up events in Cordilleran arcs. *Geology 35*, 1047-1050.

Eliasson, T. & Schöberg, H. 1991: U-Pb dating of the post-kinematic Sveconorwegian (Grenvillian) Bohus granite, SW Sweden: Evidence of restitic zircon. *Precambrian Research 51*, 337-350.

Falkum, T. 1982: Geologisk kart over Norge, berggrunnskart MANDAL, 1:250,000, 1:250,000, *Norges geologiske undersøkelse*.

Henderson, I.H.C. & Ihlen, P.M. 2004: Emplacement of polygeneration pegmatites in relation to Sveco-Norwegian contractional tectonics: examples from southern Norway. *Precambrian Research 133*, 207-222.

Hermans, G.A.E.M., Tobi, A.C., Poorter, R.P.E. & Maijer, C. 1975: The high-grade metamorphic Precambrian of the Sirdal-Ørsdal area, Rogaland/Vest-Agder, south-west Norway. *Norges Geologiske Undersøkelse 318*, 51-74.

Jensen, E. & Corfu, F. 2016: The U–Pb age of the Finse batholith, a composite bimodal Sveconorwegian intrusion. *Norwegian Journal of Geology 96*.

Korhonen, F.J., Clark, C., Brown, M., Bhattacharya, S. & Taylor, R. 2013: How long-lived is ultrahigh temperature (UHT) metamorphism? Constraints from zircon and monazite geochronology in the Eastern Ghats orogenic belt, India. *Precambrian Research 234*, 322-350.

Lamminen, J. 2011: Provenance and correlation of sediments in Telemark, South Norway: status of the Lifjell Group and implications for early Sveconorwegian fault tectonics. *Norwegian Journal of Geology 91*, 57-75.

Landenberger, B. & Collins, W.J. 1996: Derivation of A-type granites from a dehydrated charnockitic lower crust: Evidence from the Chaelundi complex, eastern Australia. *Journal of Petrology 37*, 145-170.

Laurent, A.T., Seydoux-Guillaume, A.-M., Duchene, S., Bingen, B., Bosse, V. & Datas, L. 2016: Sulphate incorporation in monazite lattice and dating the cycle of sulphur in metamorphic belts. *Contributions to Mineralogy and Petrology 171*, 94.

Li, Z.-X. & Li, X.-H. 2007: Formation of the 1300-km-wide intracontinental orogen and postorogenic magmatic province in Mesozoic South China: A flat-slab subduction model. *Geology 35*, 179-182.

Lundmark, A. & Corfu, F. 2008: Late-orogenic Sveconorwegian massif anorthosite in the Jotun Nappe Complex, SW Norway, and causes of repeated AMCG magmatism along the Baltoscandian margin. *Contributions to Mineralogy and Petrology 155*, 147-163.

Lundmark, A.M., Corfu, F., Spürgin, S. & Selbekk, R.S. 2007: Proterozoic evolution and provenance of the high-grade Jotun Nappe Complex, SW Norway: U–Pb geochronology. *Precambrian Research 159*, 133-154.

Marker, M., Schiellerup, H., Meyer, G.B., Robins, B. & Bolle, O. 2003: An introduction to the geological map of the Rogaland Anorthosite Province 1:75,000. *In* Duchesne, J.C. & Korneliussen, A. (eds.): *Ilmenite deposits and their geological environment*, Norges geologiske undersøkelse Special Publication *9,* NGU, Trondheim, pp. 109-116.

Marker, M., Slagstad, T., Schiellerup, H., Solli, A. & Lutro, O. 2012: Bedrock geology map, Jørpeland 1213 II, 1:50,000, *Geological Survey of Norway*.

Marker, M. 2013: Bedrock geology map, Sokndal 1311 IV, 1:50,000, *Geological Survey of Norway*.

Marker, M. in prep.: Bedrock geology map, Nærbø 1212 III, 1:50,000, *Geological Survey of Norway*.

Marker, M. & Slagstad, T. in prep.: Bedrock geology map, Lyngsvatnet 1313 III, 1:50,000, *Geological Survey of Norway*.

Marker, M. & Slagstad, T. in press-a: Bedrock geology map, Høle 1212 I, 1:50,000, *Geological Survey of Norway*.

Marker, M. & Slagstad, T. in press-b: Bedrock geology map, Bjerkreim 1212 II, 1:50,000, *Geological Survey of Norway*.

Möller, A., O'Brian, P.J., Kennedy, A. & Kröner, A. 2002: Polyphase zircon in ultrahigh-temperature granulites (Rogaland, SW Norway): Constraints for Pb diffusion in zircon. *Journal of Metamorphic Geology 20*, 727-740.

Möller, A., O'Brien, P.J., Kennedy, A. & Kröner, A. 2003: Linking growth episodes of zircon and metamorphic textures to zircon chemistry: An example from the ultrahigh-temperature granulites of Rogaland (SW Norway). *In* Vance, D., Müller, W. & Villa, I.M. (eds.): *Geochronology: Linking the Isotopic Record with Petrology and Textures. Geological Society of London, Special Publication 220,* pp. 65-81.

Müller, A., Ihlen, P.M., Snook, B., Larsen, R.B., Flem, B., Bingen, B. & Williamson, B.J. 2015: The chemistry of quartz in granitic pegmatites of southern Norway: petrogenetic and economic implications. *Economic Geology 110*, 1737-1757.

Murakami, T., Chakoumakos, B.C., Ewing, R.C., Lumpkin, G.R. & Weber, W.J. 1991: Alpha-decay event damage in zircon. *American Mineralogist 76*, 1510-1532.

Pedersen, S., Andersen, T., Konnerup-Madsen, J. & Griffin, W.L. 2008: Recurrent Mesoproterozoic continental magmatism in South-Central Norway. *International Journal of Earth Sciences (Geologische Rundschau) doi:10.1007/s00531-008-0309-0*.

Roberts, N.M.W., Slagstad, T., Parrish, R.R., Norry, M.J., Marker, M. & Horstwood, M.S.A. 2013: Sedimentary recycling in arc magmas: geochemical and U–Pb–Hf–O constraints on the Mesoproterozoic Suldal Arc, SW Norway. *Contributions to Mineralogy and Petrology 165*, 507-523.

Santosh, M. & Kusky, T. 2010: Origin of paired high pressure–ultrahigh-temperature orogens: a ridge subduction and slab window model. *Terra Nova 22*, 35-42.

Schärer, U., Wilmart, E. & Duchesne, J.-C. 1996: The short duration and anorogenic character of anorthosite magmatism: U-Pb dating of the Rogaland complex, Norway. *Earth and Planetary Science Letters 139*, 335-350.

Seydoux-Guillaume, A.-M., Montel, J.-M., Bingen, B., Bosse, V., de Parseval, P., Paquette, J.-L., Janots, E. & Wirth, R. 2012: Low-temperature alteration of monazite: Fluid mediated coupled dissolution–precipitation, irradiation damage, and disturbance of the U–Pb and Th–Pb chronometers. *Chemical Geology 330–331*, 140-158.

Slagstad, T., Culshaw, N.G., Jamieson, R.A. & Ketchum, J.W.F. 2004: Early Mesoproterozoic tectonic history of the southwestern Grenville Province, Ontario: Constraints from geochemistry and geochronology of high-grade gneisses. *In* Tollo, R.P., Corriveau, L., McLelland, J. & Bartholomew, M.J. (eds.): *Proterozoic tectonic evolution of the Grenville orogen in North America*, Geological Society of America Memoir *197,* pp. 209-241.

Slagstad, T. 2008: Radiogenic heat production of Archaean to Permian geological provinces in Norway. *Norwegian Journal of Geology 88*, 149-166.

Slagstad, T., Balling, N., Elvebakk, H., Midttomme, K., Olesen, O., Olsen, L. & Pascal, C. 2009: Heat-flow measurements in Late Palaeoproterozoic to Permian geological provinces in south and central Norway and a new heat-flow map of Fennoscandia and the Norwegian-Greenland Sea. *Tectonophysics 473*, 341-361.

Slagstad, T., Roberts, N.M.W., Marker, M., Røhr, T.S. & Schiellerup, H. 2013a: A non-collisional, accretionary Sveconorwegian orogen. *Terra Nova 25*, 30-37.

Slagstad, T., Roberts, N.M.W., Marker, M., Røhr, T.S. & Schiellerup, H. 2013b: A non-collisional, accretionary Sveconorwegian orogen – Reply. *Terra Nova 25*, 169-171.

Slagstad, T., Willemoes-Wissing, B., Coint, N., Stampolidis, A., Ganerød, M. & Ofstad, F. 2015: Geology and metallogenic potential of the northwesternmost Norrbotten Province around Altevatn in Troms, northern Norway. *Norwegian Journal of Geology 95*, 445-466.

Slagstad, T., Roberts, N.M.W. & Kulakov, E. 2017: Linking orogenesis across a supercontinent; the Grenvillian and Sveconorwegian margins on Rodinia. *Gondwana Research 44*, 109-115.

Slagstad, T., Maystrenko, Y.P., Maupin, V. & Gradmann, S. in review: Tomographic snapshot of an extinct, Late Mesoproterozoic mantle wedge beneath SW Fennoscandia. *Terra Nova*.

Söderlund, U., Isachsen, C., Bylund, G., Heaman, L., Patchett, J.P., Vervoort, J. & Andersson, U. 2005: U–Pb baddeleyite ages and Hf, Nd isotope chemistry constraining repeated mafic magmatism in the Fennoscandian Shield from 1.6 to 0.9 Ga. *Contributions to Mineralogy and Petrology 150*, 174-194.

Stormoen, M.A. 2015: *Synkinematic intrusion of granitoid sheets, with implications for molybdenite deposits in the Knaben Zone*, Norwegian University of Science and technology, NTNU, 131 pp.

Tomkins, H.S., Williams, I.S. & Ellis, D.J. 2005: In situ U-Pb dating of zircon formed from retrograde garnet breakdown during decompression in Rogaland, SW Norway. *Journal of Metamorphic Geology 23*, 201-215.

Vander Auwera, J., Bogaerts, M., Liégeois, J.-P., Demaiffe, D., Wilmart, E., Bolle, O. & Duchesne, J.-C. 2003: Derivation of the 1.0_0.9 Ga ferro-potassic A-type granitoids of southern Norway by extreme differentiation from basic magmas. *Precambrian Research 124*, 107-148.

Vander Auwera, J., Bolle, O., Bingen, B., Liégeois, J.-P., Bogaerts, M., Duchesne, J.-C., De Waele, B. & Longhi, J. 2011: Sveconorwegian massif-type anorthosites and related granitoids result from post-collisional melting of a continental arc root. *Earth Science Reviews 107*, 375-397.

Viola, G., Henderson, I.H.C., Bingen, B. & Hendriks, B.W.H. 2011: The Grenvillian-Sveconorwegian orogeny in Fennoscandia: Back-thrusting and extensional shearing along the "Mylonite Zone". *Precambrian Research 189*, 368-388.

Walsh, A.K., Kelsey, D.E., Kirkland, C.L., Hand, M., Smithies, R.H., Clark, C. & Howard, H.M. 2015: P–T–t evolution of a large, long-lived, ultrahigh-temperature Grenvillian belt in central Australia. *Gondwana Research 28*, 531-564.

Watson, E.B., Wark, D.A. & Thomas, J.B. 2006: Crystallization thermometers for zircon and rutile. *Contributions to Mineralogy and Petrology 151*, 413-433.

Weaver, S.G., Bruce, R., Nelson, E.P., BRUECKNER, H.K. & LeHuray, A.P. 1990: The Patagonian batholith at 48°S latitude, Chile; Geochemical and isotopic variations. *In* Kay, S.M. & Rapela, C.W. (eds.): *Plutonism from Antarctica to Alaska*, Geological Society of America Special Paper *241,* Boulder, Colorado, pp. 33-50.

Westphal, M., Schumacher, J.C. & Boschert, S. 2003: High-temperature metamorphism and the role of magmatic heat sources at the Rogaland Anorthosite Complex in southwestern Norway. *Journal of Petrology 44*, 1145-1162.

Wiest, J. 2016: *Mesoproterozoic to Early Devonian Evolution of the Lyderhorn Gneiss (Øygarden Complex, SW Norway)*. MSc thesis, University of Bergen, 128 pp.

Wilson, J.R., Robins, B., Nielsen, F., Duchesne, J.C. & Vander Auwera, J. 1996: The Bjerkreim-Sokndal layered intrusion, Southwest Norway. *In* Cawthorn, R.G. (ed.): *Layered Intrusions* Elsevier, Amsterdam, pp. 231-256.

Yin, A. 2004: Gneiss domes and gneiss dome systems. *Geological Society of America Special Papers 380*, 1-14.

Zhao, J.-L., Qiu, J.-S., Liu, L. & Wang, R.-Q. 2016: The Late Cretaceous I- and A-type granite association of southeast China: Implications for the origin and evolution of post-collisional extensional magmatism. *Lithos 240–243*, 16-33.

GEOLOGICAL
SURVEY OF
NORWAY
- NGU -

Geological Survey of Norway
PO Box 6315, Sluppen
N-7491 Trondheim, Norway

Visitor address
Leiv Eirikssons vei 39
7040 Trondheim

Tel (+ 47) 73 90 40 00
E-mail ngu@ngu.no
Web www.ngu.no/en-gb/