Gondwana Research 91 (2021) 31–39

Contents lists available at ScienceDirect

Gondwana Research

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

Multi-isotope tracing of the 1.3–0.9 Ga evolution of Fennoscandia; crustal growth during the Sveconorwegian orogeny

Anette Granseth [a,1,*], Trond Slagstad [b], Nick M.W. Roberts [c], Graham Hagen-Peter [b], Christopher L. Kirkland [d], Steinar H.H. Møkkelgjerd [a], Torkil S. Røhr [b], Nolwenn Coint [b], Bjørn Eske Sørensen [a]

[a] Department of Geoscience and Petroleum, Norwegian University of Science and Technology, S.P. Andersens veg 15a, 7031 Trondheim, Norway
[b] Geological Survey of Norway, 7491 Trondheim, Norway
[c] Geochronology and Tracers Facility, British Geological Survey, Nottingham NG12 5GG, UK
[d] Timescales of Mineral Systems Group, Centre for Exploration Targeting – Curtin Node, The Institute for Geoscience Research, School of Earth and Planetary Sciences, Curtin University, Perth, Australia

ARTICLE INFO

Article history:
Received 5 March 2020
Received in revised form 21 October 2020
Accepted 31 October 2020
Available online 9 December 2020

Keywords:
Fennoscandia
Sveconorwegian
Granitoids
Zircon Hf
Rb-Sr
K-feldspar Pb

ABSTRACT

Magmatism between 1.3 and 0.9 Ga at the southwestern margin of Fennoscandia, comprising mainly granitic batholiths and subordinate bimodal volcanic rocks, provides a nearly continuous magmatic record of the Fennoscandian tectonic evolution. Here, we present new and published zircon Hf, K-feldspar Pb and whole-rock Sr isotopic data from the granitic rocks. The εHf isotopic evolution since 1300 Ma starts out as relatively juvenile, with a flat superchondritic trend at 1300–1130 Ma followed by a steeper trend towards lower, but still superchondritic values at 1070–1010 Ma. During the 1000–920 Ma period, the trend flattens out at near-chondritic values. The variations between flat and steep εHf trends correspond to previously documented extensional and compressional periods, respectively. Although the change to a steeper εHf trend at ca. 1100 Ma may indicate the emergence of a new isotopic reservoir (i.e. a colliding continent), there is no corresponding change in the K-feldspar Pb or whole-rock Sr isotopic composition. We argue that the trends are better explained by varying proportions of isotopically evolved crust and juvenile mantle in the magma source regions, similar to Nd and Hf isotopic pull-downs and pull-ups observed in many accretionary orogenic systems. We therefore conclude that continuous accretionary processes without involvement of exotic sources is the best explanation for the isotopic evolution before and during the Sveconorwegian orogeny, and that the orogeny involved generation of significant volumes of new crust to the SW margin of the Fennoscandia.

1. Introduction

Two fundamental processes of active continental margins are trench advance and trench retreat, which are recorded in both the metamorphic (Collins, 2002) and magmatic record (DeCelles et al., 2009). These processes have a major impact on the tectonic evolution of the active margin, with trench advance resulting in compression across the active margin, while trench retreat results in extension. Compression, in turn, results in crustal thickening and a larger degree reworking of the pre-existing crust (e.g. Hawkesworth et al., 2019), while extension allows addition of more juvenile components into arc magmas. The input of juvenile components into arc magmas leads to isotopic “pull-ups”, while isotopic “pull-downs” indicate reworking of pre-existing crust (Boekhout et al., 2015; DeCelles et al., 2009; Kemp et al., 2009; Kohanpour et al., 2019). In εHf and εNd space, pull-ups represent trends towards more radiogenic, juvenile compositions and positive ε values, while pull-downs represent trends towards lower and more evolved ε values. Conversely, when the tectonic setting transitions from an active margin to continent collision, the magmatism changes from arc-related to collision-related. This implies a change from a mixed crust-mantle source to a dominantly (or exclusively) crustal source. In this case, even if the exotic and indigenous crustal source have similar isotopic compositions the result is a strong isotopic pull-down (Collins et al., 2011). The Himalaya and Caledonides are examples of well-understood collisional orogenic belts that display a mixed-to-crustal evolution (e.g. Kalsbeek et al., 2008; O'Brien, 2001). In cases where the tectonic setting is unclear, such as in ancient orogens, the isotopic record may provide a means to identify the underlying tectonic setting and evolution (e.g. Spencer et al., 2019).

The southwestern Fennoscandian margin underwent protracted tectonic activity and magmatism between 1.5 and 0.9 Ga. The Fennoscandian margin experienced widespread magmatism and crustal growth at ca. 1.5 Ga (Bingen et al., 2005; Roberts et al., 2013;

---

[*] Corresponding author.
E-mail address: anette.granseth@ngu.no (A. Granseth).
[1] Current address: Geological Survey of Norway, 7491 Trondheim, Norway

https://doi.org/10.1016/j.gr.2020.10.019
1342-937X/

Roberts and Slagstad, 2015), followed by an apparent hiatus until ca. 1.3 Ga. Between 1.3 and 1.1 Ga crustal extension dominated the geodynamic regime, resulting in widespread bimodal magmatism and sedimentation (Andersen et al., 2007; Bingen et al., 2002; Bingen et al., 2003; Brewer et al., 2004; Laajoki et al., 2002; Pedersen et al., 2009; Roberts et al., 2011; Slagstad et al., 2020; Spencer et al., 2014). This period was followed by a compressional regime from ca. 1.1 Ga, marking the onset of the Sveconorwegian orogeny (Bingen et al., 2008b; Roberts and Slagstad, 2015; Slagstad et al., 2020), with voluminous magmatism between 1070 and 920 Ma (Bingen and Solli, 2009; Coint et al., 2015; Slagstad et al., 2013; Slagstad et al., 2018). Recent work argues that the oldest Sveconorwegian magmatic rocks formed during compression between 1.1 and 1.0 Ga, with the lower crust being a significant melt source, and that after ca. 1.0 Ga, the orogen underwent renewed extension that facilitated input of increasing proportion of juvenile, mantle-derived melts (Coint et al., 2015; Granseth et al., 2020; Slagstad et al., 2018). The tectonic evolution of the Sveconorwegian orogen has been attributed to a series of accretionary events along and behind an active continental margin (Slagstad et al., 2013, 2017, 2019, 2020). An alternative interpretation argues for collision between Fennoscandia and another continent, typically inferred to be Amazonia at 1.1–1.0 Ga (e.g. Bingen et al., 2008b; Möller et al., 2015). To distinguish between the two tectonic models for the Sveconorwegian orogeny it is essential to outline the isotopic evolution of the Fennoscandian margin between 1.3 and 0.9 Ga. This record allows us to estimate the varying proportions of evolved continental crust and juvenile mantle melts in the source region of the magmatic rocks, providing constraints on the most likely tectonic evolution for the Sveconorwegian orogen.

In this study, we focus on the western and central parts of the Sveconorwegian orogen that experienced magmatism between 1.3 and 0.9 Ga, and present new and compiled zircon Hf, whole-rock Sr and K-feldspar Pb isotope compositions. The data are used to examine the isotopic evolution of the 1.3–0.9 Ga magmatic rocks and to discuss the implications on the tectonic evolution of the Fennoscandian margin.

2. Geological background

The Sveconorwegian Province consists of five lithotectonic units that are bounded by major, probably crustal-scale shear zones (Bingen et al., 2008b) (Fig. 1). Each lithotectonic unit has a distinct magmatic, metamorphic and depositional history that reflects a stepwise assembly justifying their distinction as a lithotectonic unit (Slagstad et al., 2020). The units comprise late Palaeo- through early Mesoproterozoic protoliths that young progressively from east to west, probably reflecting advancing growth along a retreating Fennoscandian continental margin (Åhäll and Connelly, 2008; Roberts et al., 2013; Roberts and Slagstad, 2015).

The Eastern Segment comprises 1.80–1.65 Ga granitoids of the Transscandinavian Igneous Belt (TIB) (Högdahl et al., 2004). The Nd and Hf isotopic compositions of the TIB reflect reworking of Archaean through Palaeoproterozoic Svecofennian crust with minor juvenile input (Andersen et al., 2009a; Andersson, 1997; Petersson et al., 2015a). The Idefjorden lithotectonic unit consists of plutonic, volcanic and sedimentary sequences that formed in continental and/or oceanic arc systems between 1.66 and 1.52 Ga and accreted to Fennoscandia shortly thereafter (Åhäll and Connelly, 2008; Brewer et al., 1998). The Bamble-Kongsberg lithotectonic units comprise orthogneisses of plutonic and volcanic origin that formed between ca. 1.65 and 1.48 Ga, with associated interlayered metasedimentary complexes (Bingen and Viola, 2018; Nijland et al., 2014; Slagstad et al., 2020). The Telemark lithotectonic unit consists of 1.58–1.48 Ga volcanic and plutonic suites (Bingen et al., 2005; Roberts et al., 2013; Slagstad et al., 2020), though isotopic and geochemical data suggest that Telemark may have a crustal substrate that is older than the rocks that are currently exposed (Andersen et al., 2009b; Andersen et al., 2001). The Telemark lithotectonic unit was later intruded by a bimodal volcanic and plutonic suite at ca. 1.28–1.2 Ga. (Bingen et al., 2002; Brewer et al., 2004; Pedersen et al., 2009; Slagstad et al., 2020). The isotope data for both the 1.5 Ga and 1.28–1.20 Ga suites indicate that they represent relatively juvenile magmatism along the Fennoscandian margin, and they are generally interpreted to represent arc and back-arc magmatism, respectively (Brewer and Menuge, 1998; Brewer et al., 2004; Roberts et al., 2013). Between ca. 1.38 and 1.14 Ga, the Telemark lithotectonic unit underwent rifting, sedimentation and associated bimodal magmatism (Brewer et al., 2004; Laajoki et al., 2002; Pedersen et al., 2009; Spencer et al., 2014). Juvenile and near-juvenile magmas formed at ca. 1.2 Ga as a result of mafic underplating and lower crustal melting (Andersen et al., 2007; Pedersen et al., 2009).

The Sveconorwegian orogeny is typically interpreted to have commenced with a ca. 1140 Ma granulite-facies event in the Bamble lithotectonic unit (Bingen et al., 2008a), followed by the onset of high- to ultrahigh temperature (HT–UHT) metamorphism in the western parts of the Telemark lithotectonic unit shortly after 1100 Ma (Blereau et al., 2017; Drüppel et al., 2013; Laurent et al., 2018a; Laurent et al., 2018b; Slagstad et al., 2018). Dating of high-grade rocks in the southwestern parts of the province shows that the HT–UHT metamorphism was long-lived and continued until the termination of orogenic activity at ca. 930 Ma, most likely sustained by voluminous, long-lived mafic underplating driven by active-margin processes west of the currently exposed parts of the province (Slagstad et al., 2018). East in the province, closer to the orogenic foreland, high-pressure metamorphism is recorded at ca. 1050 Ma in the Idefjorden lithotectonic unit (Söderlund et al., 2008), followed by eclogite-facies metamorphism at 990 Ma in the Eastern Segment (Möller et al., 2015; Tual et al., 2017). The 1050 Ma event is probably related to final assembly of the Idefjorden lithotectonic unit (Söderlund et al., 2008), whereas eclogite-facies metamorphism at 990 Ma most likely reflects subduction of the Eastern Segment beneath the Idefjorden lithotectonic unit (Möller et al., 2015; Tual et al., 2017).

The major contrasts in metamorphic evolution east and west in the orogen have been known since the 1980s (e.g. Falkum and Petersen, 1980) and the close link between metamorphic and magmatic evolution is becoming increasingly clear (Granseth et al., 2020; Slagstad et al., 2018). The onset of voluminous granitic magmatism in the Telemark lithotectonic unit at ca. 1080 Ma coincides with the earliest metamorphic ages, and the ca. 150 Myr duration of the magmatic activity matches the duration of high-grade metamorphism (Slagstad et al., 2018). The Sveconorwegian granitoids formed by reworking of heterogeneous lower crust, with variable input of mantle-derived material (Andersen et al., 2002; Andersen et al., 2009b; Granseth et al., 2020). Contrasts in the geochemical and isotopic signatures of the granitoids east and west in the province probably reflect differences in tectonic regime, as indicated by the metamorphic data. The western part of the province is characterised by a two-stage magmatic evolution, with the emplacement of the Sirdal Magmatic Belt (SMB) at 1080–1010 Ma during regional compression (Henderson and Ihlen, 2004; Stormoen, 2015) that resulted in N-S-elongated sheet-like intrusions (Coint et al., 2015; Slagstad et al., 2018). A change to a dominantly extensional tectonic regime after ca. 1000 Ma led to widespread melting of the lower-crustal SMB residue, as well as lower crust farther east in the Telemark lithotectonic unit, forming the HBGin suite and the HBGout suite, respectively (Granseth et al., 2020). The HBGin and HBGout stands for hornblende-biotite-bearing granitoids located within and outside the SMB, respectively. While the western parts of the Sveconorwegian province experienced more than 150 million years of voluminous magmatism, magmatic activity in the eastern parts was restricted to the Flå-Iddefjord-Bohus (FIB) suite that intruded the Idefjorden lithotectonic unit at ca. 925 Ma (Bingen et al., 2008b; Eliasson and Schöberg, 1991; Granseth et al., 2020; Lamminen et al., 2011). Isotopic, geochemical and geochronological data of the FIB suite are consistent with derivation from a source influenced by the underlying Eastern

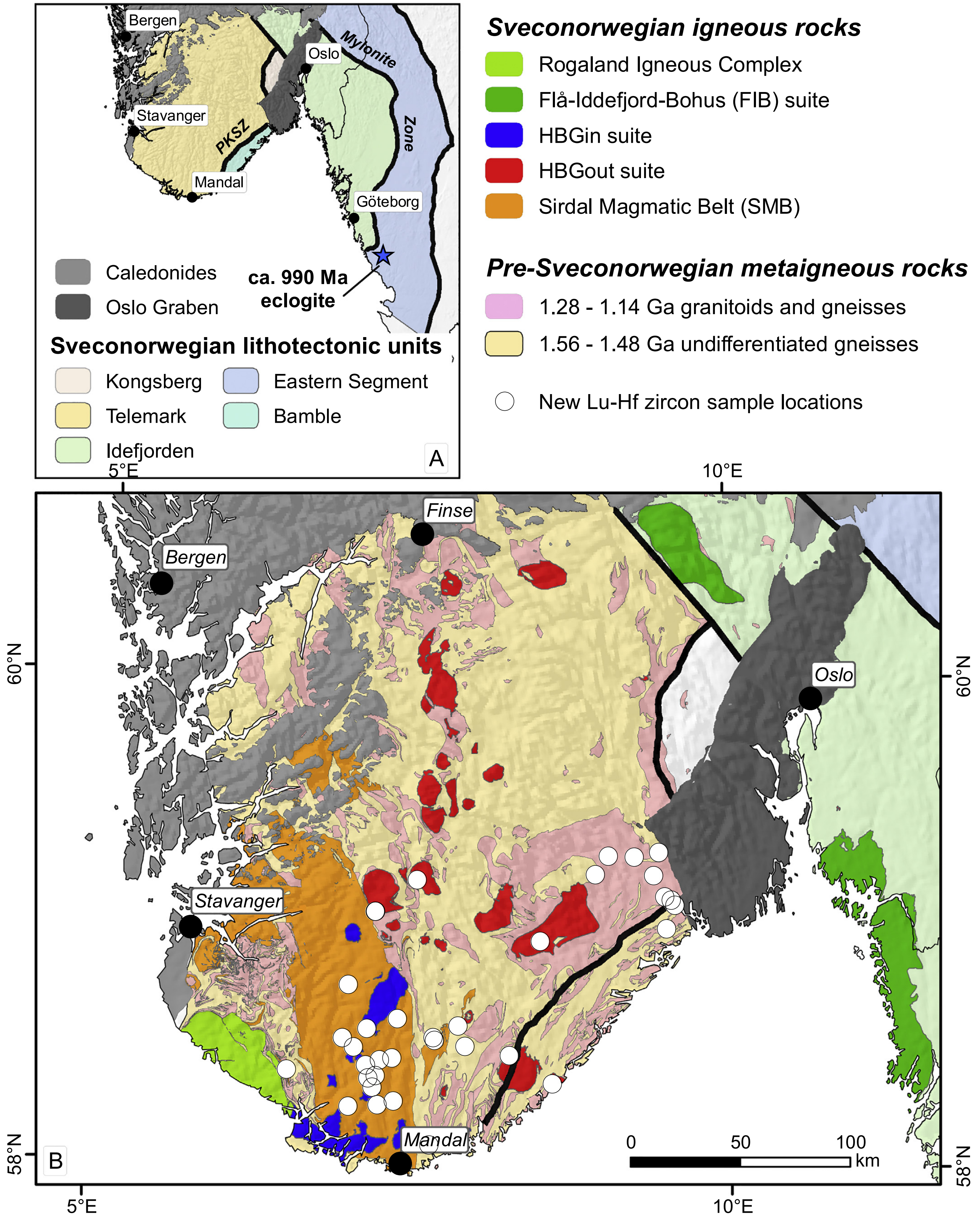

Fig. 1. (A) Main lithotectonic units of the Sveconorwegian orogen, separated by shear zones. The location of ca. 990 Ma eclogite in the Eastern Segment is indicated. (B) A more detailed map of the western and central parts of the Sveconorwegian orogen showing the sample locations of the new Hf isotope data.

Segment and the Transscandinavian Igneous Belt crust (Granseth et al., 2020).

3. Results

The samples used in this study are from the Telemark and Bamble lithotectonic units and comprise 59 previously dated samples analysed for Hf, 34 samples for whole-rock Sr and 20 samples for Pb in K-feldspar. In addition, available published data have been compiled. The analytical methods are described in detail in Electronic Supplement 1. The new and published isotopic data for Hf, Sr and Pb are presented in Electronic supplements 2, 3 and 4, respectively.

3.1. Zircon Lu—Hf isotopes

Lu—Hf isotopes in magmatic zircon were measured in 59 samples representing magmatic activity in the region between 1300 and 920 Ma (Fig. 2). The new and published data are split into three separate magmatic periods based on regional geological constraints, as discussed above. The 1300–1130 Ma period was characterised by rifting, basin formation with sediment infill, and bimodal magmatism; the 1070–1010 Ma period featured magmatism during regional compression (SMB suite), followed by renewed extension and magmatism between 1000 and 920 Ma (HBG suite). One sample at 1103 Ma partly fills the gap between the first two periods. A Lowess curve was used to evaluate the overall Hf isotopic trend through time. The curve was calculated using only the new data (plotted in colour) as much of the older, published data show large variations in εHf values within a single sample.

The 1300–1130 Ma period was characterised by relatively high εHf values (~0–10) that decrease gradually with time. The new data are on average more juvenile than the full dataset but overlap with the published data. Both the comparatively large spread in εHf values and shallow negative trend is compatible with significant addition of juvenile material. The 1070–1010 Ma period was dominated by granitic SMB magmatism with εHf values between −3 and + 5 and a steeper trend towards lower εHf values. Generally, the smaller spread in εHf values and steeper trend are consistent with a smaller contribution of juvenile material and increased crustal reworking during this period. Following SMB magmatism, HBG magmatism between 1000 and 920 Ma saw the return of a larger spread in the εHf values when including all published data. The Lowess curve reveals an isotopic trend that flattens out and increases towards more juvenile Hf compositions after 950 Ma. The variations in the HBG Hf isotopic composition, with a comparatively large spread in εHf values and the relatively flat isotopic trend, are similar to that observed for the 1300–1130 Ma period, with significant input of juvenile material during a period characterised by an extensional tectonic setting.

3.2. Whole-rock Rb—Sr isotopes

The initial Sr (Sr_i) composition of the granitoid suites shows consistent values throughout the 150 million years of Sveconorwegian magmatism, plotting at around $Sr_i = 0.7052$ (Fig. 3A). Three samples representing magmatism at ca. 1250 Ma display more juvenile compositions compared to the Sr_i of the Sveconorwegian granitoids, with values between 0.700 and 0.695. The SMB suite shows Sr_i values between 0.709 and 0.695. The coeval HBGin and HBGout suites shows complete overlap around 0.7052, though both higher and lower values are found.

3.3. K-feldspar Pb—Pb isotopes

The Pb isotopic compositions show that the suites are characterised by overlapping Pb ratios that change slightly towards less radiogenic compositions through time (Fig. 3B-D). Individual plutons and samples

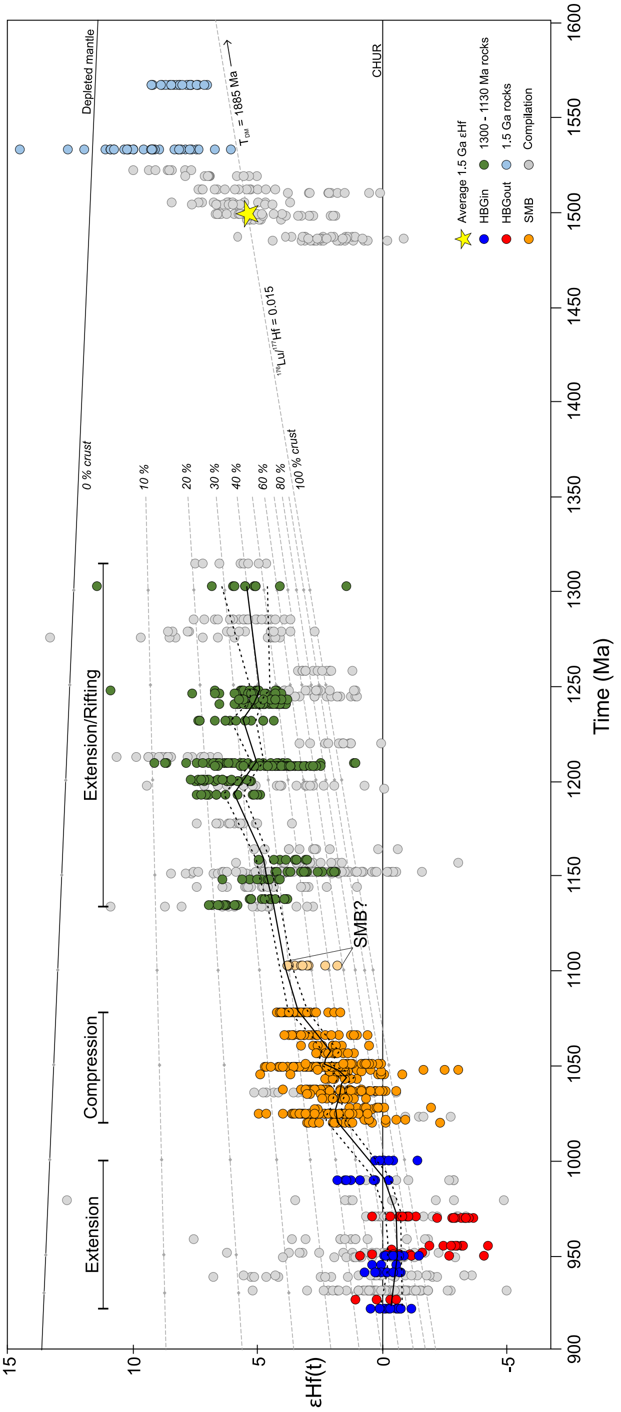

Fig. 2. New and published Lu—Hf data plotted as εHf(t) versus magmatic age. New data and data from Møkkelgjerd (2019) is plotted with colour, whereas the remaining published data is plotted in light grey..The Lowess curve is calculated using the new data and is shown with bootstrapped errors. Hf modelling is indicated by the stippled lines reflecting the proportion of an evolved crustal 1.5 Ga source relative to a depleted mantle source. The Lu—Hf data from 1300 900 Ma are compiled from Andersen et al. (2002), Andersen et al. (2009b), Lamminen et al. (2011) and Pedersen et al. (2009), where some of the data were available through Roberts and Slagstad (2015)'s compilation on Fennoscandian Lu—Hf data. The compiled 1.5 Ga Lu—Hf data are from Roberts et al. (2013), while one 1.5 Ga sample (Ro-102b) is from Roberts (2010) and two samples from Møkkelgjerd (2019). Nine analyses from the 1300 900 Ma published data yield εHf values lower than −7 and are outside the bounds of this plot. Please see Andersen et al. (2002) and Roberts and Slagstad (2015) for discussion on the significance of these extreme εHf values. The new and published Lu—Hf data for 1300 900 Ma period with recalculated εHf(t) values can be found in Electronic Supplement 2. Undated HBGin and HBGout intrusions have been assigned an age of 950 Ma, which is the suggested age of peak HBG magmatic activity (Slagstad et al., 2018).

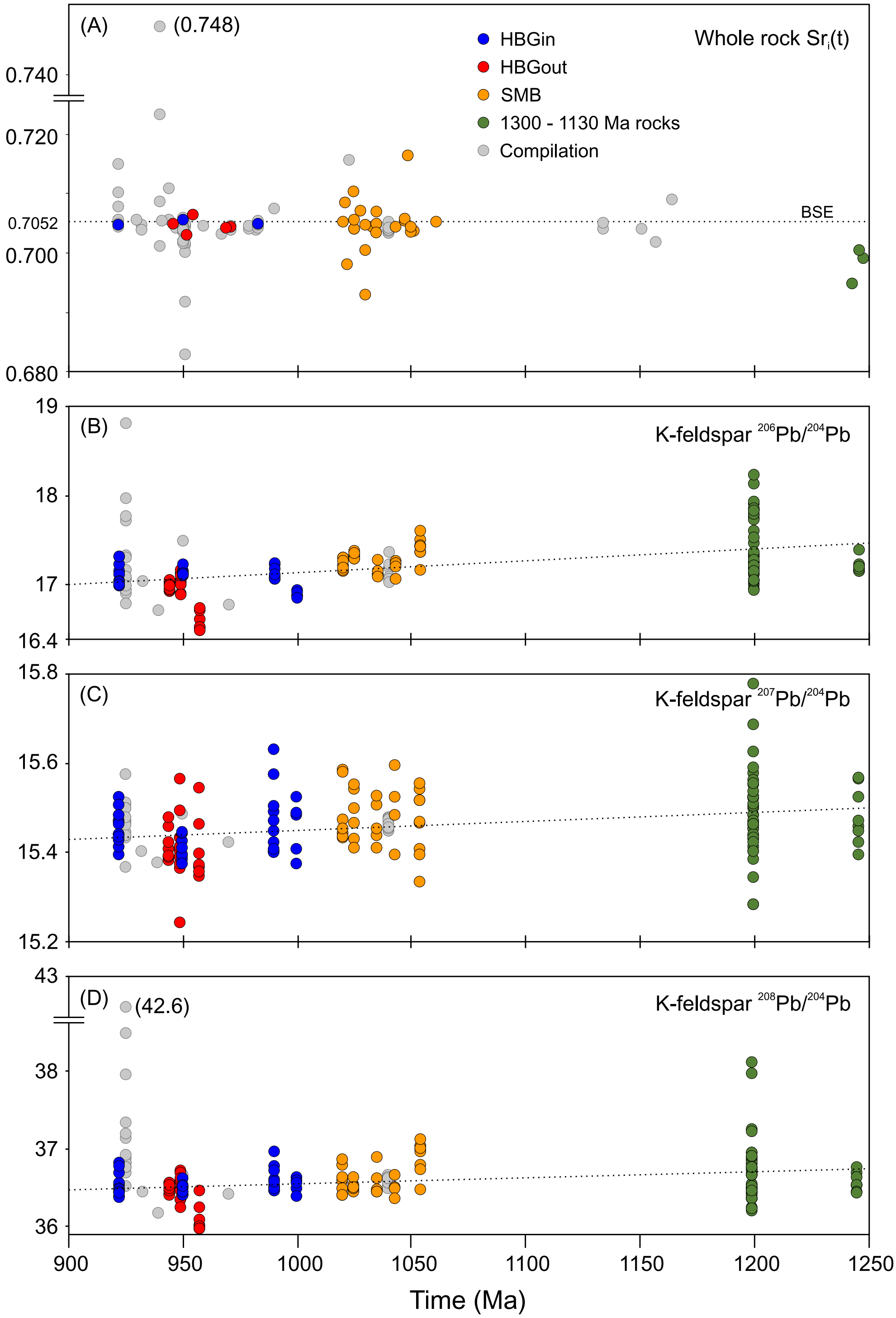

Fig. 3. (A) Strontium initial composition versus the magmatic age of the associated granitoids. The compiled data in light grey is from Andersen (1997), Andersen et al. (2001), Bingen et al. (1993), Bogaerts et al. (2003) and Vander Auwera et al. (2003). Bulk Silicate Earth (BSE) value for $^{87}Sr/^{86}Sr_{BSE} = 0.7052$ is from table 6.5 in Rollinson (1993). The Rb—Sr data can be found in Electronic Supplement 3. (B-D) Pb isotopic ratios versus the magmatic age of the associated granitoids. The dotted line is a linear regression curve that has been fitted to the Pb data. The compiled data in light grey is from Andersen et al. (2001) and Bingen et al. (1993). Bingen et al. (1993)'s samples have been given an average age of 1040 Ma. Undated HBGin and HBGout intrusions have been assigned an age of 950 Ma, which is the suggested age of peak HBG magmatic activity (Slagstad et al., 2018). Note that samples from the compilation may represent a single sample per intrusion. The Pb—Pb data can be found in Electronic Supplement 4.

show a spread in Pb ratio values of similar magnitude to the entire suite, with $^{207}Pb/^{204}Pb$ data showing the largest spread. Overall, the SMB suite is slightly more radiogenic than the HBGin and HBGout suites and characterised by $^{206}Pb/^{204}Pb = 17.04–17.83$, $^{207}Pb/^{204}Pb = 15.34–15.60$ and $^{208}Pb/^{204}Pb = 36.36–37.51$. The HBGin suite has $^{206}Pb/^{204}Pb = 16.86–17.53$, $^{207}Pb/^{204}Pb = 15.38–15.64$ and $^{208}Pb/^{204}Pb = 36.20–36.97$, while the HBGout is the least radiogenic suite with $^{206}Pb/^{204}Pb = 16.49–17.49$, $^{207}Pb/^{204}Pb = 15.25–15.57$ and $^{208}Pb/^{204}Pb = 35.97–36.72$. There are in total five samples that represent the magmatism at ca. 1.2 Ga, where four are from the Telemark lithotectonic unit and one from the Bamble lithotectonic unit, while a sixth sample from Telemark is dated to 1246 Ma. The 1.2 Ga Bamble and Telemark samples overlap completely in their Pb composition and display a much larger spread compared to the Sveconorwegian granitoids, with $^{206}Pb/^{204}Pb = 16.94–18.23$, $^{207}Pb/^{204}Pb = 15.29–15.78$ and $^{208}Pb/^{204}Pb = 36.21–37.25$. The 1246 Ma sample overlaps with the Sveconorwegian granitoids.

4. Discussion

4.1. Implications for Sveconorwegian geodynamics and crustal growth

Recent studies argue that 1.5 Ga basement forming the Telemark lithotectonic unit represents the crustal source to most of the magmatic suites in the Sveconorwegian Province (Granseth et al., 2020; Roberts and Slagstad, 2015), although Andersen et al. (2002) suggest that an older crustal source with TIB/Svecofennian age contributed to the Sveconorwegian granitoids. Most of the available Lu—Hf data for the Sveconorwegian granitoids in the Telemark lithotectonic unit show a trend starting at 1.5 Ga that follows through the Sveconorwegian orogen (Fig. 7 in Roberts and Slagstad, 2015); whereas only a few inherited zircon grains indicate a Palaeoproterozoic source (Andersen et al., 2002). The oldest period considered here (1300–1130 Ma) is characterised by relatively juvenile signatures with a large spread in positive εHf values. The 1300–1130 Ma magmatism that is characterised by more evolved Hf compositions (lower εHf) follows a trend that can be traced back to the 1.5 Ga rocks. This feature suggests that these rocks are the result of mixing of a 1.5 Ga source with juvenile, mantle-derived magmas. The Hf isotopic signatures of the subsequent SMB (1070–1010 Ma) and HBG (1000–920 Ma) magmatic suites fall along the same general trend, as shown by Roberts and Slagstad (2015) and Spencer et al. (2019). However, the new Hf isotopic data presented here provides higher resolution and more details of the Fennoscandian tectonic evolution during the 1.3–0.9 Ga period.

Most workers favour an extensional, continental back-arc setting for the 1300–1130 Ma bimodal magmatism and sedimentation (Bingen et al., 2002; Brewer et al., 2004; Spencer et al., 2014; Söderlund et al., 2006). The new Hf isotopic data show a shallowly decreasing trend between 1300 and 1130 Ma, consistent with significant addition of juvenile material. The data show periods of changing εHf trends, possibly reflecting a shift in the tectonic activity, such as intermittent compression and increased crustal reworking. However, a larger dataset is necessary to reveal such small-scale isotopic variations and to determine if they are caused by geodynamic change or heterogeneities in the source region. Interestingly, sparse U—Pb geochronological data on metamorphic zircon rims from pelitic lithologies from the Telemark lithotectonic unit indicate metamorphism at ca. 1280 Ma (Slagstad et al., 2020), interpreted to reflect a compressive event during a period dominated by extension.

Although the cause of compression is debated (Möller et al., 2013; Slagstad et al., 2013), it is generally accepted that there was a shift to compression at ca. 1140 Ma marking the onset of the Sveconorwegian orogeny (Bingen et al., 2008b; Bingen and Viola, 2018; Slagstad et al., 2020). The shift in tectonic regime is indicated in the εHf data as a steepening of the slope towards more negative εHf values. Generally, a steepening of the slope can be explained by either removal of the juvenile source or input of an exotic, more evolved crustal source.

We used a mixing model to look at the resulting εHf composition when mixing various proportions of the older 1.5 Ga crust and depleted mantle between 1300 Ma and 900 Ma, representing the time prior to and during the Sveconorwegian orogeny. The assumed crustal endmember is the 1.5 Ga rocks from Roberts et al. (2013), using their bulk rock Hf = 5.1 ppm, average εHf value = 5.4 and an average crustal $^{176}Lu/^{177}Hf$ of 0.015. The 1.5 Ga rocks yields an average model age of 1885 Ma, which is taken as the starting point of the crustal evolution in our model. The $^{176}Hf/^{177}Hf$ composition of the crustal endmember was calculated using the depleted mantle composition at 1885 Ma (Griffin et al., 2000) with the average crustal evolution $^{176}Lu/^{177}Hf = 0.015$ and the time elapsed since 1885 Ma. The juvenile end-member composition was calculated based on the Hf compositions of depleted mantle with present-day $^{176}Hf/^{177}Hf$ of 0.283251 and $^{176}Lu/^{177}Hf = 0.0384$, from Griffin et al. (2000), and Hf concentration of 1.23 ppm corresponding to the concentration in a primitive arc lava from Whattam (2018).

The resulting mixing lines allow εHf trajectories to be drawn through points of constant depleted mantle/crust ratio through time (Fig. 2). Any divergence from the trajectories (i.e. slope of a magmatic system) suggests a change in the depleted mantle/crust ratio or a change in the composition of one or the other end member. The mixing calculations suggest considerable and relatively constant contributions of crust in the 1300–1130 Ma period (10–60% crust), with greater contributions in the 1080–1010 Ma SMB suite (30–100% crust), followed by a decrease in crustal component and more juvenile input throughout in the 1000–920 Ma HBG suite (50–100% crust).

The steepening of the slope at 1080 Ma is similar to the isotopic pull-downs observed in modern active margins (DeCelles et al., 2009; Kemp et al., 2009). Although Collins et al. (2011) and Spencer et al. (2019) also observed slope steepening in εHf space in settings undergoing continent-continent collision, the data from the Sveconorwegian Province suggest continuous input of a significant (>50%) proportion of depleted mantle, which is incompatible with continent-continent collision. Thus, rather than dominantly reworking of pre-existing continental crust as is observed in most collisional settings, the Sveconorwegian orogeny appears to have been associated with significant crustal growth through magmatism to Fennoscandia. To help constrain the significance of the varying Hf isotope signatures, we compare these signatures to the Sr and Pb isotope datasets. Both whole-rock Sr and K-feldspar Pb datasets are smaller than for Hf, and a continuous record from before and during the Sveconorwegian orogeny is currently unavailable. However, the available data do not indicate a major shift in composition related to the Sveconorwegian orogeny. This implies that magmatism was sourced from a single or several similar reservoirs over time. Collision with another continent during the Sveconorwegian orogeny would conceivably have added a new continental source and hence significantly changed the proportion of the other components, e.g., removing any influence of the depleted mantle. We suggest that such a change in setting could not have a non-observable effect on the type of magmatic rocks produced and their isotopic signature. The consistent Sr and Pb isotopic signatures, imply that it is unlikely that a new, significant, exotic source (continent) was involved in the Sveconorwegian orogeny.

Granseth et al. (2020) ascribed the formation of the west-central Sveconorwegian granitoids between 1070 and 920 Ma to two-stage melting of the 1.5 Ga lower crustal source, mixed with variable proportions of juvenile material. The transition from SMB to HBG magmatism is related to a change from a compressive to an extensional setting, which allowed for increased asthenospheric upwelling and underplating. This process raised the temperature in the lower crust allowing for widespread melting of the Sveconorwegian residual lower crust. Granseth et al. (2020)'s model provides a strong genetic link between the SMB and the HBG suites, as the magmas were derived from a single, evolving crustal source over time, mixed with juvenile, mantle-derived magma. This link is difficult to reconcile with a continent-continent collision and is more in line with active-margin processes involving alternating periods of trench advance and retreat. The zircon Hf, whole-rock Sr and K-feldspar Pb isotope data presented here support a tectonomagmatic model where magmatism resulted from protracted active-margin processes.

4.2. A long-term cyclicity?

Ascribing the western part of the Sveconorwegian Province to an active margin with varying behaviour of the subducting and upper plate is similar to that presented by Spencer et al. (2019) based on Hf isotope analyses in detrital zircon; however, the stronger geological constraints on the data we present (as a function of being from constrained magmatic samples) here and the combination with other isotope systems, allow more nuances to be discerned in this evolution. In particular, the Hf isotope data appear to reveal a cyclicity on a roughly 100 Myr time scale during the Sveconorwegian orogeny. A cyclic Fennoscandian evolution was first suggested by Pedersen et al. (2009) for southern Norway and the new data presented here support this idea on a regional scale. Cyclicity is well-documented in recent active-margin systems, such as the North American Cordillera (DeCelles et al., 2009; Kirsch et al., 2016; Paterson and Ducea, 2015), and global compilations show that cyclicity on different time scales, reflecting different underlying causes, is a common feature in the geological record (Gardiner et al., 2016; Mitchell et al., 2019; Nance et al., 2014). Although the amount of isotopic data available from the late Palaeo- through Mesoproterozoic active Fennoscandian margin is probably still too small to definitively reveal a similar cyclicity (e.g. Andersen et al., 2009b; Andersen et al., 2009a; Petersson et al., 2015b), a cyclic evolution/recurrent magmatism taking place on a continuous Fennoscandian basement has been suggested (Andersen et al., 2001; Pedersen et al., 2009). Nonetheless, the tectonomagmatic record does seem to suggest a cyclic evolution on time scales of 100–200 Myr prior to 1.3 Ga (Roberts and Slagstad, 2015) on Fennoscandian crust with an extended crustal history (Åhäll et al., 2000). This record includes formation of the Transscandinavian Igneous Belt at 1850–1650 Ma (Högdahl et al., 2004), followed by the Gothian–Telemarkian orogeny at 1650–1480 Ma (Åhäll and Connelly, 2008). The nature of the transition at ca. 1650 Ma is unclear, but the magmatic activity appears to have moved outboard of the margin (Åhäll and Connelly, 2008), suggesting a period of trench retreat, prior to renewed convergence. An extensional tectonic regime is also documented for the last stages of the Gothian–Telemarkian orogeny, expressed as bimodal magmatism at ca. 1500 Ma (Menuge and Brewer, 1996), before renewed compression during the Hallandian–Danopolonian event at ca. 1470–1440 Ma (Brander and Söderlund, 2009).

The Palaeo- through Mesoproterozoic Fennoscandian margin is typically interpreted to have been contiguous with the southeastern Laurentian margin (Condie, 2013; Karlstrom et al., 2001). A similar ca. 100 Myr cyclicity appears to be preserved there, with significant crustal growth/tectonic events at ca. 1.8 Ga (Penokean), ca. 1.7 Ga (Yavapai–Killarnean), ca. 1.6 Ga (Mazatzal–Labradorian), ca. 1.45 Ga (Eastern Granite-Rhyolite Province–Pinwarian), ca. 1.25 Ga (Elzevirian), ca. 1.15 Ga (Shawinigan). Although, these events form part of a continuum, their subdivision does indicate a certain waxing and waning in tectonic activity, some of which can be ascribed to alternating periods of compressional and extensional at and behind the active continental margin (Dickin and McNutt, 1989; Holland et al., 2020; Rivers and Corrigan, 2000; Slagstad et al., 2009). At the southeastern Laurentian margin, this long-lived process came to an end during the collisional Grenville orogeny (Rivers, 2015); in contrast, alternating compression and extension appears to have continued through Sveconorwegian orogenesis at the southwestern Fennoscandian margin, consistent with a contrasting tectonic setting. These differences are reflected in the Hf isotopic composition of the two areas (Spencer et al., 2019), with the work presented herein providing additional, higher-resolution data. The results presented herein demonstrate the ability of zircon Hf isotopes to provide time-resolved, qualitative estimates of crustal and juvenile contributions to magmatism, whereas other isotopic systems, such as Pb in K-feldspar and whole-rock Sr, can be used to detect the appearance of exotic sources – provided that the exotic source has a contrasting isotopic composition.

5. Conclusions

The zircon Hf data on the mainly granitic rocks between 1.3 and 0.9 Ga provide a nearly continuous record of the tectonomagmatic evolution before and during the Sveconorwegian orogeny, where each magmatic period is uniquely characterised in time and in Hf isotope trend. The Hf data suggest that there is a change in the isotopic trends between the magmatic periods, where it shifts from flat (1300–1130 Ma) to steep (1070–1010 Ma) and back to flat (1000–920 Ma). At the same time, the whole-rock Sr and K-feldspar Pb data show no significant change through the same time period. We consider these isotopic trends to reflect active-margin processes, with the alternating input of juvenile material and crustal reworking related to extension and compression during the 1300–920 Ma period. We find no compelling proofs that a new exotic reservoir (i.e. a colliding continent) was introduced during the Sveconorwegian orogeny, suggesting that a collisional scenario where Fennoscandia is supposed to have collided with another continent is unlikely. The geological record in southwest Fennoscandia prior to the Sveconorwegian orogeny has been interpreted to reflect a long-lived accretionary orogen (Petersson et al., 2015a; Roberts and Slagstad, 2015). This study supports the interpretation that the final stages of the Sveconorwegian orogen were also characterised by accretionary processes with significant crustal growth; a cyclic evolution with variable contributions of juvenile input and crustal reworking taking place in an active continental margin.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This study is a part of Anette Granseth's PhD project on the granitoid magmatism in the Sveconorwegian Province, funded by the Department of Geoscience and Petroleum, Faculty of Engineering, at the Norwegian University of Science and Technology (NTNU), Norway. This is CAMOC contribution no. 5. We would like to thank Tom Andersen and an anonymous reviewer for their constructive and thoughtful comments on the manuscript.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gr.2020.10.019.

References

Åhäll, K.-I., Connelly, J.N., 2008. Long-term convergence along SW Fennoscandia: 330m. y. of Proterozoic crustal growth [Precam Res 161 (2008) 452–472]. Precambrian Res. 163, 402–421.

Åhäll, K.-I., Connelly, J.N., Brewer, T.S., 2000. Episodic rapakivi magmatism due to distal orogenesis?: Correlation of 1.69–1.50 Ga orogenic and inboard,“anorogenic” events in the Baltic Shield. Geology 28, 823–826.

Andersen, T., 1997. Radiogenic isotope systematics of the Herefoss granite, South Norway: an indicator of Sveconorwegian (Grenvillian) crustal evolution in the Baltic Shield. Chem. Geol. 135, 139–158.

Andersen, T., Andresen, A., Sylvester, A.G., 2001. Nature and distribution of deep crustal reservoirs in the southwestern part of the Baltic Shield: evidence from Nd, Sr and Pb isotope data on late Sveconorwegian granites. J. Geol. Soc. 158, 253–267.

Andersen, T., Griffin, W., Pearson, N., 2002. Crustal evolution in the SW part of the Baltic Shield: the Hf isotope evidence. J. Petrol. 43, 1725–1747.

Andersen, T., Griffin, W.L., Sylvester, A.G., 2007. Sveconorwegian crustal underplating in southwestern Fennoscandia: LAM-ICPMS U–Pb and Lu–Hf isotope evidence from granites and gneisses in Telemark, southern Norway. Lithos 93, 273–287.

Andersen, T., Andersson, U.B., Graham, S., Åberg, G., Simonsen, S.L., 2009a. Granitic magmatism by melting of juvenile continental crust: new constraints on the source of Palaeoproterozoic granitoids in Fennoscandia from Hf isotopes in zircon. J. Geol. Soc. 166, 233–247.

Andersen, T., Graham, S., Sylvester, A.G., 2009b. The geochemistry, Lu–Hf isotope systematics, and petrogenesis of Late Mesoproterozoic A-type granites in southwestern Fennoscandia. Can. Mineral. 47, 1399–1422.

Andersson, U.B., 1997. Petrogenesis of some Proterozoic Granitoid Suites and Associated Basic Rocks in Sweden (Geochemistry and Isotope Geology). Institutionen för geovetenskap. Uppsala Universitet, Uppsala, p. 214.

Bingen, B., Solli, A., 2009. Geochronology of magmatism in the Caledonian and Sveconorwegian belts of Baltica: synopsis for detrital zircon provenance studies. Norwegian J. Geol./Norsk Geologisk Forening 89.

Bingen, B., Viola, G., 2018. The early-Sveconorwegian orogeny in southern Norway: Tectonic model involving delamination of the sub-continental lithospheric mantle. Precambrian Res. 313, 170–204.

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. J. Geol. 101, 763–778.

Bingen, B., Mansfeld, J., Sigmond, E.M., Stein, H., 2002. Baltica-Laurentia link during the Mesoproterozoic: 1.27 Ga development of continental basins in the Sveconorwegian Orogen, southern Norway. Can. J. Earth Sci. 39, 1425–1440.

Bingen, B., Nordgulen, Ø., Sigmond, E.M., Tucker, R., Mansfeld, J., Högdahl, K., 2003. Relations between 1.19–1.13 Ga Continental Magmatism, Sedimentation and Metamorphism, Sveconorwegian Province, S Norway. Precambrian Res. 124, 215–241.

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 J. Geol. / Norsk Geologisk Forening 85, 87–116.

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 J. Geol./Norsk Geologisk Forening 88.

Bingen, B., Nordgulen, Ø., Viola, G., 2008b. A four-phase model for the Sveconorwegian orogeny, SW Scandinavia. Nor. Geol. Tidsskr. 88, 43.

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. Geosci. Front. 8, 1–14.

Boekhout, F., Roberts, N.M.W., Gerdes, A., Schaltegger, U., 2015. A Hf-isotope perspective on continent formation in the south Peruvian Andes. Geol. Soc. Lond., Spec. Publ. 389, 305–321.

Bogaerts, M., Scaillet, B., Liégeois, J.-P., Vander Auwera, J., 2003. Petrology and geochemistry of the Lyngdal granodiorite (Southern Norway) and the role of fractional crystallisation in the genesis of Proterozoic ferro-potassic A-type granites. Precambrian Res. 124, 149–184.

Brander, L., Söderlund, U., 2009. Mesoproterozoic (1.47–1.44 Ga) orogenic magmatism in Fennoscandia; Baddeleyite U–Pb dating of a suite of massif-type anorthosite in S. Sweden. Int. J. Earth Sci. 98, 499–516.

Brewer, T.S., Menuge, J.F., 1998. Metamorphic overprinting of Sm-Nd isotopic systems in volcanic rocks: the Telemark supergroup, southern Norway. Chem. Geol. 145, 1–16.

Brewer, T.S., Daly, J.S., Åhäll, K.-I., 1998. Contrasting magmatic arcs in the Palaeoproterozoic of the South-Western Baltic Shield. Precambrian Res. 92, 297–315.

Brewer, T.S., Åhäll, K.I., Menuge, J.F., Storey, C.D., Parrish, R.R., 2004. Mesoproterozoic bimodal volcanism in SW Norway, evidence for recurring pre-Sveconorwegian continental margin tectonism. Precambrian Res. 134, 249–273.

Coint, N., Slagstad, T., Roberts, N.M., 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 Res. 265, 57–77.

Collins, W.J., 2002. Nature of extensional accretionary orogens. Tectonics 21 6-1-6-12.

Collins, W.J., Belousova, E.A., Kemp, A.I., Murphy, J.B., 2011. Two contrasting Phanerozoic orogenic systems revealed by hafnium isotope data. Nat. Geosci. 4, 333–337.

Condie, K., 2013. Preservation and recycling of crust during accretionary and collisional phases of Proterozoic orogens: a bumpy road from Nuna to Rodinia. Geosciences 3, 240–261.

DeCelles, P.G., Ducea, M.N., Kapp, P., Zandt, G., 2009. Cyclicity in Cordilleran orogenic systems. Nat. Geosci. 2, 251–257.

Dickin, A., McNutt, R., 1989. Nd model age mapping of the southeast margin of the Archean foreland in the Grenville province of Ontario. Geology 17, 299–302.

Drüppel, K., Elsäßer, L., Brandt, S., Gerdes, A., 2013. Sveconorwegian Mid-Crustal Ultrahigh-Temperature Metamorphism in Rogaland. U–Pb LA-ICP-MS Geochronology and Pseudosections of Sapphirine Granulites and Associated Paragneisses. Journal of Petrology, Norway.

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

Falkum, T., Petersen, J., 1980. The Sveconorwegian orogenic belt, a case of late-Proterozoic plate-collision. Geol. Rundsch. 69, 622–647.

Gardiner, N.J., Kirkland, C.L., Van Kranendonk, M.J., 2016. The juvenile hafnium isotope signal as a record of supercontinent cycles. Sci. Rep. 6, 1–10.

Granseth, A., Slagstad, T., Coint, N., Roberts, N.M.W., Røhr, T.S., Sørensen, B.E., 2020. Tectonomagmatic evolution of the Sveconorwegian Orogen recorded in the chemical and isotopic compositions of 1070–920 Ma granitoids. Precambrian Res. 340.

Griffin, W.L., Pearson, N.J., Belousova, E., Jackson, S.E., van Achterbergh, E., O'Reilly, S.Y., Shee, S.R., 2000. The Hf isotope composition of cratonic mantle: LAM-MC-ICPMS analysis of zircon megacrysts in kimberlites. Geochim. Cosmochim. Acta 64, 133–147.

Hawkesworth, C., Cawood, P.A., Dhuime, B., 2019. Rates of generation and growth of the continental crust. Geosci. Front. 10, 165–173.

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

Högdahl, K., Andersson, U.B., Eklund, O., 2004. The Transscandinavian Igneous Belt (TIB) in Sweden: A Review of its Character and Evolution (Geological survey of Finland Espoo).

Holland, M.E., Grambling, T.A., Karlstrom, K.E., Jones, J.V., Nagotko, K.N., Daniel, C.G., 2020. Geochronologic and Hf-isotope framework of Proterozoic rocks from Central New Mexico, USA: Formation of the Mazatzal crustal province in an extended continental margin arc. Precambrian Res. 347, 105820.

Kalsbeek, F., Higgins, A.K., Jepsen, H.F., Frei, R., Nutman, A.P., Higgins, A.K., Gilotti, J.A., Smith, M.P., 2008. Granites and granites in the East Greenland Caledonides. The Greenland Caledonides: Evolution of the Northeast Margin of Laurentia, pp. 227–249.

Karlstrom, K.E., Åhäll, K.-I., Harlan, S.S., Williams, M.L., McLelland, J., Geissman, J.W., 2001. Long-lived (1.8–1.0 Ga) convergent orogen in southern Laurentia, its extensions to Australia and Baltica, and implications for refining Rodinia. Precambrian Res. 111, 5–30.

Kemp, A.I.S., Hawkesworth, C.J., Collins, W.J., Gray, C.M., Blevin, P.L., 2009. Isotopic evidence for rapid continental growth in an extensional accretionary orogen: the Tasmanides, eastern Australia. Earth Planet. Sci. Lett. 284, 455–466.

Kirsch, M., Paterson, S.R., Wobbe, F., Ardila, A.M.M., Clausen, B.L., Alasino, P.H., 2016. Temporal histories of Cordilleran continental arcs: Testing models for magmatic episodicity. Am. Mineral. 101, 2133–2154.

Kohanpour, F., Kirkland, C.L., Gorczyk, W., Occhipinti, S., Lindsay, M.D., Mole, D., Le Vaillant, M., 2019. Hf isotopic fingerprinting of geodynamic settings: Integrating isotopes and numerical models. Gondwana Res. 73, 190–199.

Laajoki, K., Corfu, F., Andersen, T., 2002. Lithostratigraphy and U-Pb geochronology of the Telemark supracrustals in the Bandak-Sauland area, Telemark, South Norway. Norwegian J. Geol./Norsk Geologisk Forening 82.

Lamminen, J., Andersen, T., Nystuen, J.P., 2011. Zircon U-Pb ages and Lu-Hf isotopes from basement rocks associated with Neoproterozoic sedimentary successions in the Sparagmite Region and adjacent areas, South Norway: the crustal architecture of western Baltica. Norwegian J. Geol./Norsk Geologisk Forening 91.

Laurent, A.T., Bingen, B., Duchene, S., Whitehouse, M.J., Seydoux-Guillaume, A.-M., Bosse, V., 2018a. Decoding a protracted zircon geochronological record in ultrahigh temperature granulite, and persistence of partial melting in the crust, Rogaland, Norway. Contrib. Mineral. Petrol. 173, 29.

Laurent, A.T., Duchene, S., Bingen, B., Bosse, V., Seydoux-Guillaume, A.-M., 2018b. Two successive phases of ultrahigh temperature metamorphism in Rogaland, S. Norway: Evidence from Y-in-monazite thermometry. J. Metamorph. Geol. 36, 1009–1037.

Menuge, J.F., Brewer, T.S., 1996. Mesoproterozoic anorogenic magmatism in southern Norway. Geol. Soc. Lond., Spec. Publ. 112, 275–295.

Mitchell, R.N., Spencer, C.J., Kirscher, U., He, X.-F., Murphy, J.B., Li, Z.-X., Collins, W.J., 2019. Harmonic hierarchy of mantle and lithospheric convective cycles: Time series analysis of hafnium isotopes of zircon. Gondwana Res. 75, 239–248.

Møkkelgjerd, S.H.H., 2019. Metamorphic and Magmatic Evolution near Mandal, Vest-Agder; a Key Area for Elucidating Sveconorwegian Orogenesis. Institutt for Geovitenskap og Petroleum. Norges Teknisk-Naturvitenskapelig Universitet, Trondheim, p. 163.

Möller, C., Bingen, B., Andersson, J., Stephens, M.B., Viola, G., Scherstén, A., 2013. A non-collisional, accretionary Sveconorwegian orogen–comment. Terra Nova 25, 165–168.

Möller, C., Andersson, J., Dyck, B., Antal Lundin, I., 2015. Exhumation of an eclogite terrane as a hot migmatitic nappe, Sveconorwegian orogen. Lithos 226, 147–168.

Nance, R.D., Murphy, J.B., Santosh, M., 2014. The supercontinent cycle: a retrospective essay. 25, 4-29.

Nijland, T.G., Harlov, D.E., Andersen, T., 2014. The Bamble sector, South Norway: a review. Geosci. Front. 5, 635–658.

O'Brien, P.J., 2001. Subduction followed by collision: Alpine and Himalayan examples. Phys. Earth Planet. Inter. 127, 277–291.

Paterson, S.R., Ducea, M.N., 2015. Arc Magmatic Tempos: Gathering the evidence. Elements 11, 91–98.

Pedersen, S., Andersen, T., Konnerup-Madsen, J., Griffin, W.L., 2009. Recurrent Mesoproterozoic continental magmatism in south-Central Norway. Int. J. Earth Sci. 98, 1151–1171.

Petersson, A., Scherstén, A., Andersson, J., Möller, C., 2015a. Zircon U–Pb and Hf – isotopes from the eastern part of the Sveconorwegian Orogen, SW Sweden: implications for the growth of Fennoscandia. Geol. Soc. Lond., Spec. Publ. 389, 281–303.

Petersson, A., Scherstén, A., Bingen, B., Gerdes, A., Whitehouse, M.J., 2015b. Mesoproterozoic continental growth: U–Pb–Hf–O zircon record in the Idefjorden Terrane, Sveconorwegian Orogen. Precambrian Res. 261, 75–95.

Rivers, T., 2015. Tectonic setting and evolution of the Grenville Orogen: an assessment of progress over the last 40 years. Geosci. Can. 42, 77–124.

Rivers, T., Corrigan, D., 2000. Convergent margin on southeastern Laurentia during the Mesoproterozoic: tectonic implications. Can. J. Earth Sci. 37, 359–383.

Roberts, N.M., 2010. From Crystal to Crust: The Proterozoic Crustal Evolution of Southwest Norway. University of Leicester, Depart of Geology.

Roberts, N.M.W., Slagstad, T., 2015. Continental growth and reworking on the edge of the Columbia and Rodinia supercontinents; 1.86–0.9 Ga accretionary orogeny in southwest Fennoscandia. Int. Geol. Rev. 57, 1582–1606.

Roberts, N.M., Parrish, R.R., Horstwood, M.S., Brewer, T.S., 2011. The 1.23 Ga Fjellhovdane rhyolite, Grøssæ-Totak; a new age within the Telemark supracrustals, southern Norway. Nor. J. Geol. 91, 239–246.

Roberts, N.M.W., Slagstad, T., Parrish, R.R., Norry, M.J., Marker, M., Horstwood, M.S., 2013. Sedimentary recycling in arc magmas: geochemical and U–Pb–Hf–O constraints on the Mesoproterozoic Suldal Arc, SW Norway. Contrib. Mineral. Petrol. 165, 507–523.

Rollinson, H.R., 1993. Using geochemical data: evaluation, presentation, interpretation. Routledge.

Slagstad, T., Culshaw, N., Daly, J., Jamieson, R.A., 2009. Western Grenville Province holds key to midcontinental Granite-Rhyolite Province enigma. Terra Nova 21, 181–187.

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

Slagstad, T., Roberts, N.M., Kulakov, E., 2017. Linking orogenesis across a supercontinent; the Grenvillian and Sveconorwegian margins on Rodinia. Gondwana Res. 44, 109–115.

Slagstad, T., Roberts, N.M.W., Coint, N., Høy, I., Sauer, S., Kirkland, C.L., Marker, M., Røhr, T.S., Henderson, I.H.C., Stormoen, M.A., Skår, Ø., Sørensen, B.E., Bybee, G.M., 2018. Magma-driven, high-grade metamorphism in the Sveconorwegian Province, Southwest Norway, during the terminal stages of Fennoscandian Shield evolution. Geosphere 14, 861–882.

Slagstad, T., Kulakov, E., Kirkland, C.L., Roberts, N.M., Ganerød, M., 2019. Breaking the Grenville–Sveconorwegian link in Rodinia reconstructions. Terra Nova 00, 430–437.

Slagstad, T., Marker, M., Roberts, N.M.W., Saalmann, K., Kirkland, C.L., Kulakov, E., Ganerød, M., Røhr, T.S., Møkkelgjerd, S.H.H., Granseth, A., Sørensen, B.E., 2020. The Sveconorwegian orogeny – Reamalgamation of the fragmented southwestern margin of Fennoscandia. Precambrian Res. 350, 105877.

Söderlund, U., Elming, S.-Å., Ernst, R.E., Schissel, D., 2006. The Central Scandinavian Dolerite Group—Protracted hotspot activity or back-arc magmatism?: Constraints from U–Pb baddeleyite geochronology and Hf isotopic data. Precambrian Res. 150, 136–152.

Söderlund, U., Hellström, F.A., Kamo, S.L., 2008. Geochronology of high-pressure mafic granulite dykes in SW Sweden: tracking the P–T–t path of metamorphism using Hf isotopes in zircon and baddeleyite. J. Metamorph. Geol. 26, 539–560.

Spencer, C.J., Roberts, N.M., Cawood, P.A., Hawkesworth, C.J., Prave, A.R., Antonini, A.S., Horstwood, M.S., 2014. Intermontane basins and bimodal volcanism at the onset of the Sveconorwegian Orogeny, southern Norway. Precambrian Res. 252, 107–118.

Spencer, C., Kirkland, C., Prave, A., Strachan, R., Pease, V., 2019. Crustal reworking and orogenic styles inferred from zircon Hf isotopes: Proterozoic examples from the North Atlantic region. Geosci. Front. 10, 417–424.

Stormoen, M.A., 2015. Synkinematic Intrusion of Granitoid Sheets, with Implications for Molybdenite Deposits in the Knaben Zone, Institutt for Geologi Og Bergteknikk. Norges teknisk-naturvitenskapelige universitet, Trondheim.

Tual, L., Pitra, P., Möller, C., 2017. P–T evolution of Precambrian eclogite in the Sveconorwegian orogen, SW Sweden. J. Metamorph. Geol. 35, 493–515.

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 Res. 124, 107–148.

Whattam, S.A., 2018. Primitive Magmas in the Early Central American Volcanic Arc System Generated by Plume-Induced Subduction Initiation. Frontiers in Earth Science 6.