The 1.23 Ga Fjellhovdane rhyolite, Grøssæ-Totak; a new age within the Telemark supracrustals, southern Norway

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Abstract

The Grøssæ-Totak supracrustal belt is part of the several-kilometre thick Telemark supracrustal sequences that are exposed in southern Norway. Deposition of the Telemark supracrustals spans the period between Telemarkian continental growth at ~1.52-1.48 Ga and Sveconorwegian orogenesis associated with continental collision at ~1.1-0.9 Ga. The timing of deposition is largely constrained by U-Pb geochronology of detrital zircons in sedimentary units, and igneous zircons within felsic volcanics. A younger Supergroup that has been referred to as the Sveconorwegian Supergroup comprises depositional ages younger than 1.16 Ga; units of the Grøssae-Totak belt have been mapped as part of this Supergroup. This study presents a new U-Pb age of 1233 ± 29 Ma for the Fjellhovdane rhyolite, one of the lowermost units within the Grøssæ-

Totak belt; this age suggests that at least the lower part of this sequence is not part of the Sveconorwegian Supergroup, but formed in an earlier volcano-sedimentary basin that is correlative in age to the Sæsvatn-Valldal and Setesdal supracrustal belts that occur to the west and south respectively. The geochemistry of the Fjellhovdane rhyolite is compatible with crustal melting of previously-formed supra-subduction rocks, as has been advocated for the Sæsvatn-Valldal rhyolites.

Introduction

From ~1.8 to ~1.5 Ga Fennoscandia is considered to have grown along its southwestern margin via oceanward migration of a long-lived subduction zone (Åhäll & Connelly, 2008), i.e. in a retreating accretionary orogen (Cawood et al., 2009). The Telemarkia block (terminology of Bingen et al., 2005) is suggested to represent a continuation of this south-westerly growth, thereby extending continental growth via arc magmatism to at least ~1460 Ma (Roberts, 2009; Slagstad et al., 2008). Alternatively, the Telemarkia block may have an exotic origin to Fennoscandia, with amalgamation with the craton occurring during the Sveconorwegian orogeny (e.g. Cornell & Austin Hegardt, 2004; Bingen et al., 2005). Following the 1.8-1.46 Ga growth of SW Fennoscandia, and before the onset of the Sveconorwegian orogeny at ~1.1 Ga, the crustal domains were subject to repeated episodes of magmatism. These have previously been referred to as interorogenic events (Åhäll & Connelly, 1998; Bingen et al., 2003); however, it is now increasingly recognised that these magmatic events likely occurred in response to convergent-margin processes on the SW margin of Fennoscandia (Brewer et al., 2004; Söderlund et al., 2005; Söderlund & Ask, 2006).

Extensional basins that formed in the Telemarkia block are typically not correlated across the Mandal-Ustaoset Shear Zone which separates the Suldal and Rogaland Sectors from the Telemark Sector (Figure 1). In the original mapping of this region (Sigmond, 1975; 1978), the Grøssæ-Totak supracrustal belt in Telemark was speculatively correlated with the Sæsvatn-Valldal supracrustal belt in Suldal. Since then, this correlation has not existed in the published literature; the belt is not included in published map and tectonostratigraphic figures (e.g. Corfu & Laajoki, 2008), but according to mapping by the Norwegian Geological Survey is inferred to correlate with the Ofte Formation of the younger 1.16-1.10 Ga 'Sveconorwegian' Supergroup (Sigmond et al., 2009; terminology of Laajoki et al., 2002). A new U-Pb age of 1233 ± 29 Ma for the Fjellhovdane rhyolite that falls within the lower part of the Grøssæ-Totak belt is presented here, indicating that this belt does not fall within the 1.16-1.1 Ga 'Sveconorwegian' Supergroup. Rather than suggesting a revision to the current stratigraphy, this paper aims to highlight that further complexities remain in the relatively well-studied Telemark supracrustals.

Geological Setting

The Telemarkia block comprises four sectors; the Telemark Sector in the east, and the Rogaland, Suldal and Hardangervidda Sectors in the west (Bingen et al., 2005; Bingen et al., 2008). In Hardangervidda, the oldest outcropping rocks may be as old as 1.65 Ga (Ragnhildsveit et al. 1994), however gneisses with >1.5 Ga zircon ages have since been interpreted as paragneiss units (Bingen et al., 2005). In all of the sectors the basement comprises volcanic-plutonic gneisses and granitoids that are 1.55-1.46 Ga in age and likely formed in a continental arc setting (Bingen et al., 2005; Pedersen et al., 2009;

Roberts & Brewer, 2008; Roberts, 2010). The Sæsvatn-Valldal supracrustal belt formed within the Suldal Sector at 1.26-1.21 Ga (Bingen et al., 2002; Brewer et al., 2004). At 1.22-1.16 Ga, a minor suite of orthopyroxene-bearing granitoids intruded the Rogaland Sector (Zhou et al., 1995; Slagstad et al., 2008). Intruding both the Rogaland and Suldal sectors are ~1.06 to 1.02 Ga porphyritic granitoids and leucogranites that formed either as a result of convergent-margin magmatism (Bingen & van Breemen, 1998; Slagstad et al., 2008; Slagstad et al., in review), or from partial-melting of continental crust after thickening during the early stage of the Sveconorwegian orogeny (Bingen et al., 2008). Late-Sveconorwegian granites (0.98-0.93 Ga; Andersen et al., 2002; 2007a) and a 0.93 Ga Anorthosite-Mangerite-Charnockite complex (Schärer et al., 1996; Vander Auwera et al., 2011) are interpreted to be post-collisional in relation to the Sveconorwegian orogeny (e.g. Andersen et al., 2001; Bolle et al., 2003; Vander Auwera et al., 2003).

The Telemark Sector features a ~10km thick succession of supracrustals that comprises the 1.51 to >1.35 Ga 'Vestfjorddalen' and 1.16 to 1.10 Ga 'Sveconorwegian' Supergroups (according to terminology of Laajoki et al., 2002). The 'Vestfjorddalen' Supergroup was deposited in a continental rift basin that started forming at ~1.51 Ga and by ~1.35 Ga had extended into an epicontinental sea (Lamminen & Köykkä, 2010); voluminous felsic volcanism (Tuddal Fm.) was associated with extension and followed by voluminous basic magmatism (Vemork Fm.). Continental extension may have occurred inboard of a subduction zone in a setting similar to the Granite-Rhyolite provinces in the mid-continental US (Slagstad et al., 2009). A cross-cutting diabase intrusion dated at 1347 ± 4 Ma (Corfu & Laajoki, 2008) places a minimum age constraint on sedimentary deposition within the 'Vestfjorddalen' Supergroup. The

‘Sveconorwegian’ Supergroup comprises bimodal volcanic and sedimentary sequences deposited between ~1.16 and 1.10 Ga (de Haas et al., 1999; Laajoki et al., 2002; Bingen et al., 2003), that are interpreted to have formed in extensional basins inboard of a continental arc (Brewer et al., 2004), or in a ‘basin and range’ type extensional setting (Bingen et al., 2003). The Grøssæ-Totak belt in the west of the Telemark Sector is included within the ‘Sveconorwegian’ Supergroup, but is not defined within maps in recent publications (e.g. Laajoki et al., 2002; Bingen et al., 2003; Corfu & Laajoki, 2008; Lamminen & Köykkä, 2010). In the Setesdal region in the south of the Telemark Sector, supracrustal deposition and calc-alkaline plutonism occurred between 1.32 and 1.20 Ga (Pedersen et al., 2009); the exact tectonic setting during this period is not constrained, but the geochemistry points to a supra-subduction zone setting. Other intrusions in the Telemark Sector include 1.22-1.20 Ga juvenile granitoids (Andersen et al., 2007b), 1.19-1.13 Ga A-type plutons (Bingen et al., 2003), and a 1.03 Ga suite transitional between calc-alkaline and A-type (Bingen & van Breemen, 1998).

In the eastern parts of the Southwest Sveconorwegian Domain (SSD) the magmatic record for the ~1.3-1.2 Ga time period is dominated by mafic magmatism in localised extensional settings. This includes the 1.3 Ga Vastergotland dolerite suite in the ‘Idefjorden’ block, the 1.27-1.26 Ga Central Scandinavian Dolerite Group across central Scandinavia, and the 1.22-1.20 Ga Protogine Zone dolerites in the Eastern Segment/Idefjorden boundary zone (Söderlund et al., 2005). The latter features granite and syenite intrusions as well as mafic magmatism (Johansson, 1990).

Analytical Methods

Zircon U-Pb geochronology was performed by laser ablation multi-collector inductively coupled plasma mass spectrometry (LA-MC-ICP-MS) at the NERC Isotope Geosciences Laboratory, Nottingham, UK. Zircons were separated using standard techniques (Wilfley table, heavy liquid, Frantz magnetic separation). Zircons from the non-magnetic fraction were picked under alcohol, mounted in 1 inch diameter epoxy resin mounts and polished to expose an equatorial section through the grains.

The analytical protocol was similar to that outlined in Horstwood et al. (2003). The analyses used a Nu Plasma HR (Nu Instruments, Wrexham) multi-collector inductively coupled plasma mass spectrometer, coupled to a 193 nm solid state (UP193SS, New Wave Research) Nd:YAG laser ablation system, and an in-house designed low volume 'zircon ablation cell' based on the design principles of Bleiner & Gunther (2001). Helium gas was introduced to the ablation cell to transport the ablated sample material. A Tl-U solution was aspirated using a Nu Instruments DSN-100 de-solvating nebulizer using an ESI PFA-50 nebuliser.

The collector array measured ^{238}U, ^{235}U, ^{205}Tl, ^{203}Pb, and ^{202}Hg on Faraday cups, and ^{207}Pb, ^{206}Pb, and ^{204}Pb/Hg on discrete dynode ion-counting detectors. Tuning of the MC-ICP-MS at the start of each analytical session was achieved with the aspiration of a 500ppt solution of ^{203,205}Tl-^{235}U. Ion-counter to Faraday gains were determined using a 100ppt $^{203-205}$Tl-^{235}U solution by jumping the ^{205}Tl peak through each ion counter and comparing the equivalent Faraday signal. During the ablation analyses a Tl/^{235}U solution was simultaneously aspirated, facilitating correction for drift of instrumental mass bias (Tl) and plasma induced inter-element fractionation (Tl-U). The isobaric interference of

^{204}Hg on ^{204}Pb was corrected by simultaneous measurement of ^{202}Hg (assuming $^{204/202}Hg$ = 0.229887).

Ablation was conducted with 25µm x 25µm rasters, thereby ablating a 40 x 40 µm area, and made with a 15µm spot scanned at 15µm per second; 8 passes gave 40 seconds of analysis. The laser was warmed-up for 15 seconds prior to opening the shutter, and used at 70-80% power at 5Hz giving an average fluence of 2 J/cm^3.

The primary reference material was 91500 (Wiedenbeck et al., 1995). This matrix-matched reference was analysed at regular intervals during each analytical session. The deviation of the average daily $^{207}Pb/^{206}Pb$ and $^{206}Pb/^{238}U$ values of the reference material compared to the true value were used to normalise the sample data. The latter corrects for inter-element fractionation, whilst the former corrects for any drift or offset in the ion-counter gains recorded previously. To take account of the uncertainties associated with the normalisation process, the reproducibility of the primary standard ratios is propagated into the uncertainty of the sample ratios. The reference zircons GJ-1 (Jackson et al., 2004) and Plešovice (Sláma et al., 2008) were used as secondary references to monitor the precision and accuracy of each analytical session.

Data were reduced and uncertainties propagated using an in-house spreadsheet, with ages determined using Isoplot 3 (Ludwig, 2003). Analyses that recorded <<0.01mV ^{207}Pb were rejected as they were below detection limit. The common lead (^{204}Pb) signal of the samples was below detection (300 cps), thus, no correction was made for common lead.

The reproducibility of the reference zircons was 1.14, 1.36 and 1.22 (2σ %) for 91500, GJ-1 and Plešovice respectively for $^{207}Pb/^{206}Pb$, and 1.86, 2.46 and 2.74 (2σ %) for 91500, GJ-1 and Plešovice respectively for $^{206}Pb/^{238}U$. The secondary references gave mean $^{206}Pb/^{238}U$ ages of 601.0 ± 15.9 Ma (2σ) for GJ-1 (accepted $^{207}Pb/^{206}Pb$ age 609 Ma, but its $^{206}Pb/^{238}U$ age is accepted as ~602-604 Ma due to its slight normal discordance; Jackson et al., 2004), and 337.7 ± 14.0 Ma for Plešovice (accepted age 337.13 ± 0.37 Ma; Sláma et al., 2008).

Sample description and results

The sample that has been dated (F11) is a metarhyolite from the Fjellhovdane unit towards the base of the Grøssæ-Totak sequence, and formed part of the study of the Telemark supracrustals undertaken by Brewer (1985). A full description of the Grøssæ-Totak sequence is given in Sigmond (1978); the stratigraphy according to this previous work is shown in figure 3. The dated sample comprises fine-grained quartz and feldspar, with epidote, Fe-Ti oxides and rare muscovite; coarser quartz grains have developed into ribbons due to deformation. Zircon occurs as an accessory phase. Whole-rock geochemistry of the Fjellhovdane unit is reported in Brewer (1985).

Sixteen analyses provide a mean (average) $^{207}Pb/^{206}Pb$ age of 1233 ± 29 Ma (2s.d.)with an MSWD of 2.1; two slightly older analyses (but <1300 Ma) are rejected from this calculation, and may represent inheritance of slightly older material or a slight shift in age due to incorporation of common lead. This $^{207}Pb/^{206}Pb$ age of 1233 ± 29 Ma is interpreted to reflect crystallisation of the rhyolitic protolith.

Discussion

In regional maps, the Grøssæ-Totak supracrustal belt is grouped under the 'Sveconorwegian' Supergroup, and according to the Vinje mapsheet (Sigmond et al., 2009) is part of the Ofte Fm.; it is thus assumed to have a 1.17-1.14 Ga depositional age. The 1233 Ma age of the Fjellhovdane rhyolite shows that at least the lowermost part of the Grøssæ-Totak belt is older than the 'Sveconorwegian' Supergroup, and is in fact much closer in age to the Trossovdal rhyolite (1259 ± 2 Ma; Brewer et al. 2004) of the 1.26-1.21 Ga Sæsvatn-Valldal Belt (Bingen et al., 2002) in the Suldal Sector, and to the ~1.22 Ga Bygland Fm. rhyolites in the Setesdal region in the southwestern part of the Telemark Sector (Pedersen et al., 2009). There are no age constraints on younger parts of the Grøssæ-Totak belt, thus, there is potential that this belt spans a wide age range, with the upper sedimentary deposits being correlative to <1.16 Ga units elsewhere in Telemark, and only the lowermost units forming a distinct event at ~1.23 Ga. Future work that involves detrital zircon geochronology on the sedimentary units may aid correlation of the upper parts of the Grøssæ-Totak belt.

As well as a similar age, the Grøssæ-Totak and Sæsvatn-Valldal belts have similar characteristics that suggest they formed by similar tectonic and magmatic processes, namely, early rhyolitic volcanism followed by voluminous basaltic volcanism, with intercalated quartz-rich sediments (Sigmond, 1978; Brewer et al., 2004). The Setesdal region also features bimodal magmatism at ~1.2 Ga that is overlain by metasediments (Pedersen et al., 2009). The geochemistry and whole-rock Nd and Hf isotope systematics of the Sæsvatn-Valldal Belt are interpreted by Brewer et al. (2004) to represent rhyolite formation by crustal anatexis, early basaltic volcanism involving significant crustal contamination, and later basaltic volcanism tapping a mantle source and undergoing less crustal contamination. The initial crustal anatexis was hypothesised to have been produced by basalt intrusion into the crust as a consequence of lithospheric thinning (Brewer et al., 2004). The geochemistry of the Grøssæ-Totak rhyolites is near identical to that the Trossovdal rhyolites of the Sæsvatn-Valldal belt (Figure 5), indicating that the protoliths that underwent melting to form the rhyolites were also similar. Both suites feature highly enriched Large Ion Lithophile Elements (LILE), enriched High Field Strength Elements (HFSE), elevated LILE/HFSE ratios, and relative depletion in Nb, Sr, P and Ti. These features are indicative of a continental arc setting (Wilson, 1989; Pearce, 1982). In the Suldal Sector, ~1.5 Ga Telemarkian rocks have been interpreted as forming in a continental arc setting (Roberts & Brewer, 2008; Slagstad et al., 2008; Roberts, 2010), and thus provide a potential candidate for crustal protoliths that underwent melting to form the rhyolites in the Sæsvatn-Valldal belt. Assuming the Fjellhovdane rhyolite formed by the same tectonothermal process as for the formation of the Trossovdal rhyolite, the geochemistry indicates that continental arc rocks are also located at depth within the Telemark Sector. It may be that ~1.5 Ga gneisses exposed in the Suldal Sector underlie much of the Telemark Sector; however, the crustal protolith may also be much older (~1.7-1.9 Ga), according to isotope data on younger granites (e.g. Andersen et al., 2001, 2002; Andersen et al., 2007b).

Gneisses of the Vråvatn Complex in Telemark are slightly younger than the Grøssæ-Totak belt, with ages of ~1.22-1.20 Ga, and have Hf isotope signatures that suggest formation with a significant depleted mantle input (Andersen et al., 2007b). This juvenile magmatism is interpreted to reflect an episode of mafic underplating in the region (Andersen et al., 2007b). In the Setesdal region south of the Grøssæ-Totak belt, Hf isotopes from gneisses suggest that a change in magmatism from a dominantly older crustal input to a juvenile input occurred between 1220 and 1215 Ma (Pedersen et al. 2009); providing further support for a mafic underplating event at this time.

The deposition of volcanic and sedimentary rocks with associated juvenile mafic intrusions, spanning the period from 1.32 to 1.2 Ga, is probably linked to the same long-lived tectonic process. This involved mafic underplating and intrusion, crustal anatexis, and continental sedimentation in rift basins. As suggested by Brewer et al. (2004), the lithospheric extension that allowed for these processes can be linked to extension of the overriding plate in a subduction setting, i.e. the extensional basins are inboard expressions of a long-lived convergent margin in a continental setting; this is also similar to the 'basin and range' scenario advocated by Bingen et al. (2003). Except perhaps for the small 1.2 Ga Tromøy Block located off the southeast coast of Telemarkia that has a postulated island-arc origin (Knudsen & Andersen, 1999), continental arc rocks of ~1.3-1.2 Ga are not recorded in southern Norway. If a continental arc located to the west of Telemarkia did exist at 1.3-1.2 Ga, then this crust must have been recycled by subduction erosion, or translated to a different continental region during the Sveconorwegian orogeny.

The 1.3-1.2 Ga events in Telemarkia are distinct from those in the eastern part of the SSD, i.e. in the west there was basin formation with deposition of sediments and associated bimodal volcanism, and in the east there was localised mafic magmatism with minor felsic magmatism. This contrast lead Corfu & Laajoki (2008) to suggest a more outboard and exotic origin for the Telemarkia terrane, as similar characteristics are recorded in the Composite Arc Belt of the Grenville province in Laurentia (Carr et al., 2000). Detrital zircon populations from the 'Vestfjorddalen' Supergroup feature a major peak at 1730 Ma and a lack of peaks between 1650-1500 Ma, this contrasts to the age of the Fennoscandian basement, and may reflect Telemarkia's origin being closer to the Laurentian craton rather than Fennoscandinavia (Lamminen & Köykkä, 2010). However, the Dal Group in the Eastern Segment is an extensional basin that is interpreted to be a more distal equivalent of ~1.16 Ga supracrustals in the 'Sveconorwegian' Supergroup (Brewer et al., 2002). The Dal Group comprises quartzite, slate, mafic volcanics, and arkose that are interpreted as forming in a rift basin (Lundberg, 1973; Alm et al., 1997), with deposition bracketed between 1.33 and 1.05 Ga (Romer & Smeds, 1996; Piontek et al., 1998); thus, although the timing of Dal Group deposition is not well constrained, it provides a link between the western and eastern parts of the SSD.

At ~1.3-1.2 Ga, the contrast between extensional basin formation in Telemarkia and formation of discrete mafic intrusions in Idefjorden and further east, may be a consequence of the exotic origin of Telemarkia, or, if an indigenous origin is accepted, may be a difference in thermal properties of the crust. The Telemarkia block is younger, and therefore may have been a warmer, more mobile and thus weaker domain, whereas the Idefjorden and Eastern Segments were older and thus probably colder and stronger crustal domains. This difference may have aided the broad and widespread extension recorded in Telemarkia, and discrete more localized extension in the eastern domains.

Nonetheless, the origin of southern Norway remains enigmatic, with data from the deep crust being used in favour of an indigenous origin (e.g. Andersen et al., 2002; 2004; Andersen & Griffin, 2004), and data from the uppermost crust being used in favour of an exotic origin (e.g. Corfu & Laajoki, 2008; Lamminen & Köykkä, 2010). To be robust, future models of SW Fennoscandia's evolution need to encompass all of the available data, ranging from lower crustal isotope signatures, to supracrustal zircon populations.

Conclusions

A U-Pb zircon age of 1233 ± 29 Ma for the Fjellhovdane rhyolite indicates that the lowermost part of the Grøssæ-Totak supracrustal belt is older than the 1.16-1.14 Ga 'Sveconorwegian' Supergroup, and overlaps in age with the Sæsvatn-Valldal and Setesdal belts elsewhere in Telemarkia. The presented age widens the temporal and spatial extent of magmatism at 1.3-1.2 Ga, a period that saw a widespread extensional phase affecting southern Norway, and suggests that the tectonostratigraphy of the Telemark supracrustals is not wholly understood.

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Figures

Figure 1. Map of SW Fennoscandia highlighting post-1.5 Ga and pre-Sveconorwegian units. RVA = Rogaland Vest-Agder, MUSZ = Mandal-Ustaoset Shear Zone.

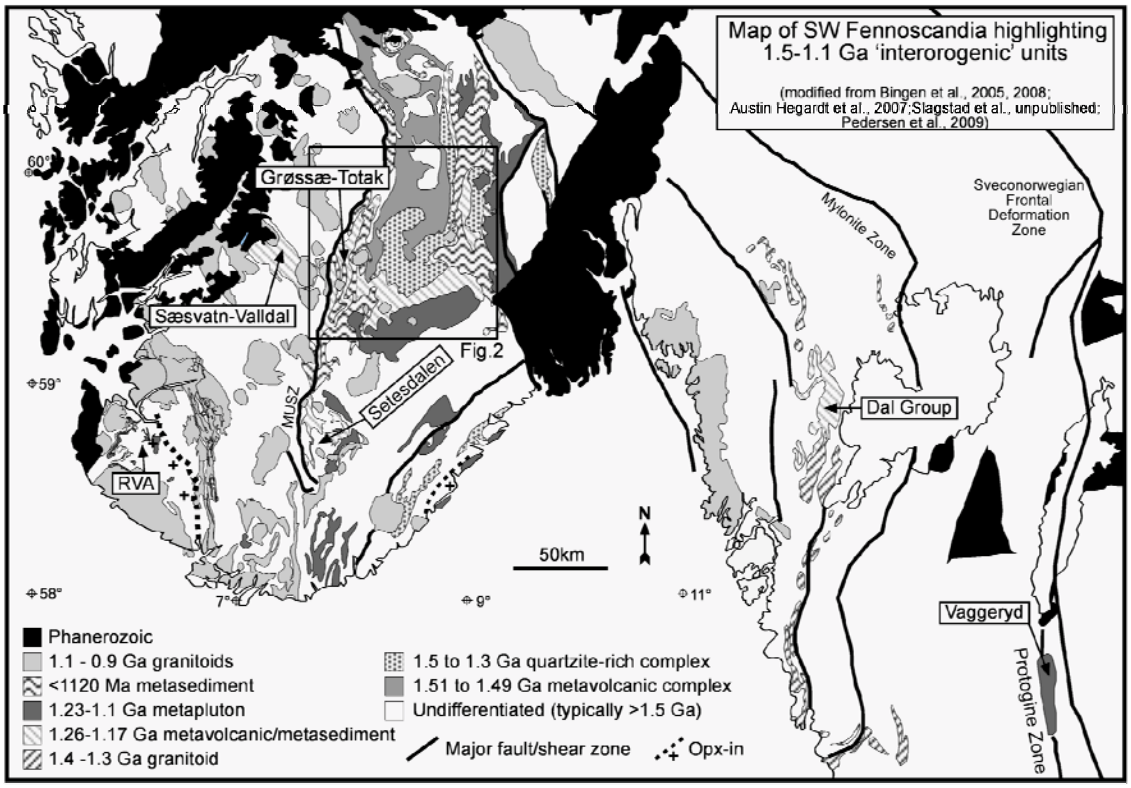

Figure 2. Map of the southern part of the Telemark supracrustals, showing the location of the dated Fjellhovdane metarhyolite (F11). Modified from Bingen et al. (2003) and Corfu & Laajoki (2008).

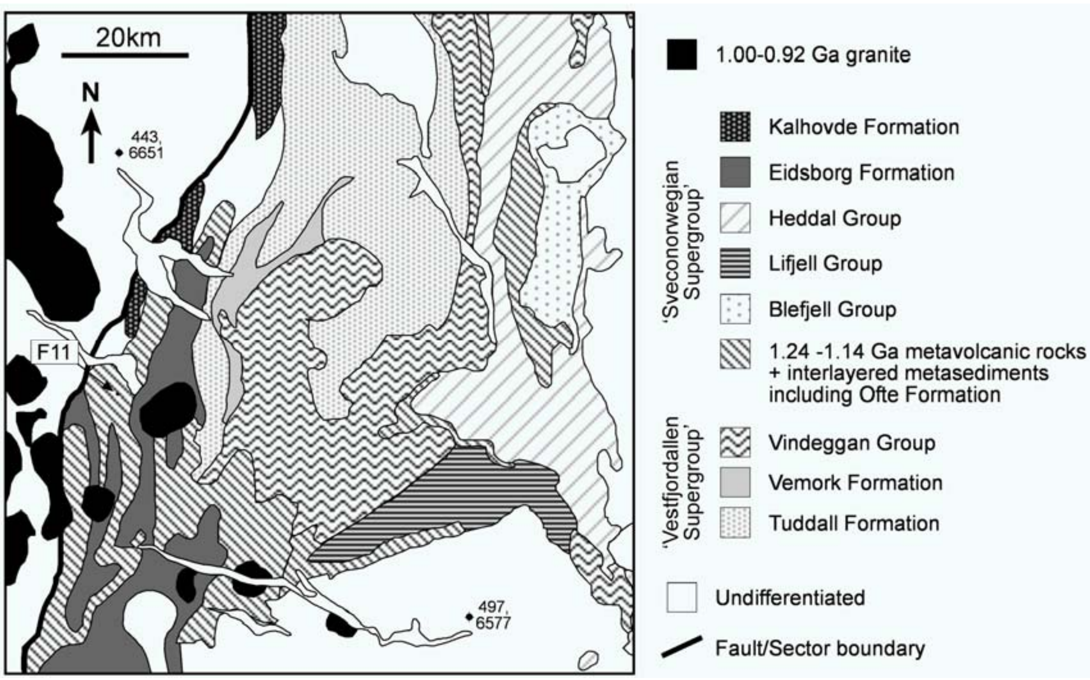

Figure 3. Stratigraphy of supracrustal belts within Telemarkia, based on Sigmond (1978), Bingen et al. (2002), Brewer et al. (2004) and Corfu & Laajoki (2008).

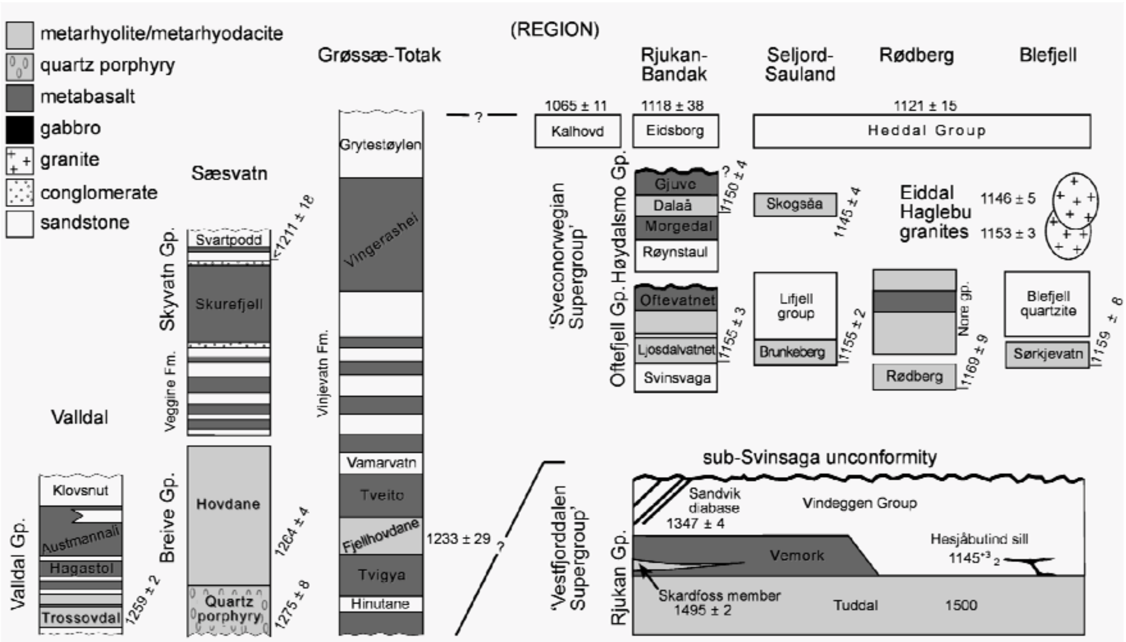

Figure 4. U-Pb concordia showing results of LA-ICP-MS dating of the Fjellhovdane rhyolite.

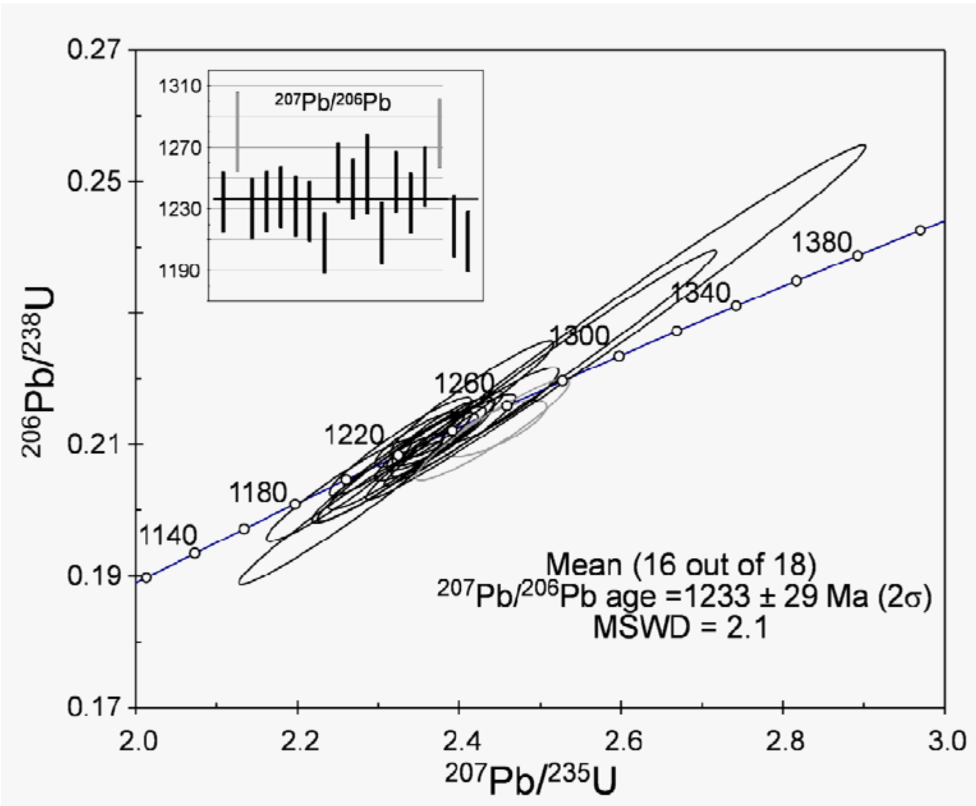

Figure 5. Primitive Mantle normalised (Sun & McDonough, 1989) plot for felsic units within the Sæsvatn-Valldal belt (Trossovdal), Grøssæ-Totak belt (Fjellhovdane) and metaplutonic/volcanic basement within the Suldal Sector (Sauda). Trossovdal data from Brewer et al. (2004); Suldal data from Slagstad (pers. comm.) and Roberts (2010).