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A non-collisional, accretionary Sveconorwegian orogen

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ABSTRACT

The late Mesoproterozoic Sveconorwegian orogen in southwest Baltica is traditionally interpreted as the eastward continuation of the Grenville orogen in Canada, resulting from collision with Amazonia, forming a central part in the assembly of the Rodinia supercontinent. We challenge this conventional view based on results from recent work in southwest Norway demonstrating voluminous subduction-related magmatism in the period 1050–1020 Ma, followed by geographically restricted high-*T*/medium-*P* metamorphism between 1035 and 970 Ma, succeeded by ferroan magmatism over large parts of south Norway in the period 990–920 Ma. This magmatic and metamorphic evolution may be better understood as reflecting a long-lived accretionary margin, undergoing periodic compression and extension, than continent–continent collision. This study has implications for Grenville–Sveconorwegian correlations, comparisons with modern continental margins, Rodinia reconstructions and how we recognize geodynamic settings in ancient orogens.

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Introduction

Accretionary orogenesis, involving oceanic subduction and terrane accretion along a convergent margin, and continent–continent collision between two major land masses, represent two very different geodynamic regimes (Cawood *et al*., 2009). Nevertheless, orogen-scale cross-sections of the collisional Tibetan Plateau (Yin and Harrison, 2000; Searle *et al*., 2009) and the accretionary Altiplano–Puna Plateau (Elger *et al*., 2005; McQuarrie *et al*., 2005) show a number of similarities, including major crustal shortening, crustal-scale shear zones and high-grade metamorphism resulting in mid-crustal partial melting. Whereas, the geodynamic settings are relatively easy to determine in these modern orogens, distinguishing between them in ancient orogens, where causal relationships are generally obscured or removed by later geological processes, is far from straightforward. Continent–continent collision involves thrusting of a continent and its leading, passive margin beneath the overriding continental plate. Burial of the passive-margin sediments to mid-crustal levels results in radioactive self-heating and extensive dehydration melting typically within *c*. 20 million years of the onset of collision (Beaumont *et al*., 2010; Jamieson *et al*., 2010; Rivers, 2012). Evidence of this is seen in collisional orogens, such as the Himalayas and the Greenland Caledonides (e.g. Kalsbeek *et al*., 2001). In contrast, syn-orogenic magmatism in accretionary orogens is typically calc-alkaline with mixed crust-mantle sources (e.g. Ort *et al*., 1996; Davidson and Arculus, 2006), and may vary periodically in volume and composition if the orogen alternates between compression and extension (Kemp *et al*., 2009). The style of high-grade metamorphism and *P–T* conditions will also differ, with collisional orogens characterized by mid-crustal temperatures typically < 800 °C (e.g. Jamieson *et al*., 2004), whereas accretionary orogens undergoing periodic extension/compression may reach temperatures up to 900 °C at similar crustal levels, over comparatively geographically restricted areas (Collins, 2002). Thus, the timing and composition of pre-, syn- and post-orogenic magmatism and the style of high-grade metamorphism may be two of the most powerful ways of determining the geodynamic settings of ancient orogens.

The Sveconorwegian Province in southwest Baltica is commonly interpreted as the eastward continuation of the Grenville Province in Canada (e.g. Gower *et al*., 1990; Karlstrom *et al*., 2001), and the Grenville–Sveconorwegian orogenic belt is widely regarded as a Himalayan-type and -scale orogen (e.g. Bingen *et al*., 2008b; Hynes and Rivers, 2010) resulting from collision with an unknown continent, possibly Amazonia, to the south. This orogen is typically regarded as forming an integral part in the assembly of the Rodinia supercontinent (refs. in Fig. 1). The Li *et al*. (2008) Rodinia reconstruction is the most recent advocating this ‘classic’ Baltica–Laurentia–Amazonia configuration (Fig. 1A); however, other reconstructions exist that are incompatible with this classic interpretation. The most radical of these alternative reconstructions is that of Evans (2009), who suggested that the Baltica–Laurentia margin was external, facing a large ocean to the southwest, with Amazonia located north in Rodinia (Fig. 1B).

Modern orogenic systems commonly display significant along-strike variations in tectonic style. For example, the collisional Himalayan orogen continues south-eastwards to become the accretionary Indonesian arc, and westwards into the active arc in Makran, with a combined length of over 5000 km. The Grenville–Sveconorwegian orogenic belt is similar in scale and identifying variations of this type along the length of the orogen is essential for constraining the presently incompatible reconstructions of Rodinia. Here, we focus on the magmatic evolution of the Sveconorwegian

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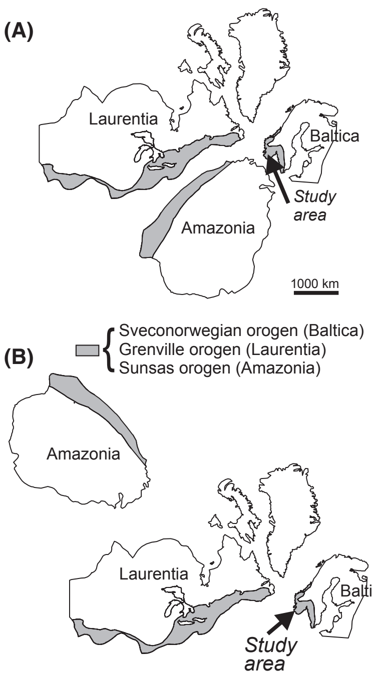

Fig. 1 Rodinia maps vary significantly, reflecting the difficulties in reconstructing Precambrian supercontinents where the palaeomagnetic record is sparse, palaeontological data are absent and geological information is commonly obscured by later geological events. (A) 'Classic' configuration with the Laurentia–Baltica margin facing Amazonia, roughly along the lines proposed by Cawood *et al.* (2007), Dalziel (1997), Pisarevsky *et al.* (2003), Li *et al.* (2008). (B) Alternative reconstruction with Amazonia located north of Laurentia, with the Laurentia–Baltica margin facing a Pacific-scale ocean, proposed by Evans (2009).

orogen, how it can be interpreted in terms of accretionary rather than collisional orogenesis, and its bearing on models of the Laurentia–Baltica margin and Rodinia reconstructions.

1050–1020 Ma pre- to syn-Sveconorwegian, arc-related magmatism in southwest Norway

Sveconorwegian-age calc-alkaline magmatism in southwest Norway was first documented by Bingen (1989), who identified a relatively narrow, N–S-trending belt of porphyritic granitoids referred to as the Feda augen gneiss. Later, dating by Bingen and van Breemen (1998) yielded an age of 1051 Ma for this augen gneiss, which they interpreted to reflect short-lived subduction of the southwest margin of Baltica prior to continent–continent collision. Figure 2 shows a new generalized regional map of south Norway based on several years of mapping, and indicates locations of new geochronological and geochemical data from pre- to syn-Sveconorwegian granitoid rocks. The prefixes pre-, syn-, late- and post- used in the text are used relative to the timing of high-grade Sveconorwegian metamorphism in southwest Baltica, defined by Bingen *et al.* (2008a) as between *c.* 1035 and 970 Ma (Fig. 3), with continent–continent collision believed to have initiated at *c.* 1050 Ma. Methods and data are presented in Electronic Supplements 1–4. These undeformed to weakly deformed pre-/syn-Sveconorwegian granitoids form a NNW-trending belt several tens of kilometres wide, i.e. significantly wider than the Feda augen gneiss (Fig. 2). We coin the term Sirdal Magmatic Belt (SMB) for this granitoid belt, of which the Feda augen gneiss is a constituent. Although granulite-facies conditions have been reached locally in the study area, the investigated granitoids generally reached only amphibolite facies. We therefore interpret our zircon U–Pb dates to reflect igneous crystallization rather than later metamorphic overprinting, in line with the textural and compositional data from the zircon grains. The age data show that magmatism in the SMB was continuous from *c.* 1050 to 1020 Ma, and overlapped early Sveconorwegian metamorphism by *c.* 15 Ma. Geochemically, the granites are calc-alkaline, magnesian and similar to 'Cordilleran' granites as defined by Frost *et al.* (2001) (Fig. 4A). Primitive mantle-normalized trace-element patterns (Fig. 4B inset) display enrichments in large ion lithophile elements, negative Nb–Ta anomalies and an overall negatively sloping trend with increasing compatibility, typical of subduction-zone magmas. This arc-like signature, as represented by a negative Nb–Ta anomaly, may be inherited during melting of pre-existing crust; however, both older and younger ferroan granitoids within the region that have a large crustal input (Andersen *et al.*, 2009) do not exhibit this anomaly (Fig. 4B), suggesting that an additional subduction-zone signature was imparted on the SMB. The main crust-forming event in south Norway was at *c.* 1500 Ma (Bingen *et al.*, 2005), and the available isotopic data (Fig. 4C) show that a simple remelting of this crust, as would be expected during a continent–continent collision, cannot account for the isotopic composition of SMB rocks. Nd–Sr mixing calculations by Andersen *et al.* (2001) suggest that the Feda augen gneiss has a 65–80% mantle-derived component. Moreover, the onset of SMB magmatism 15 Ma prior to high-grade metamorphism is inconsistent with crustal reworking. We therefore interpret the available geochemical and isotopic data to suggest formation of the SMB in a continental magmatic arc between *c.* 1050 and 1020 Ma. Contemporaneous magmatism with transitional calc-alkaline–anorogenic affinity in Vest-Agder (1035 ± 2 Ma Fennefoss augen gneiss, Bingen and van Breemen, 1998), and ferroan magmatism in Aust-Agder (1036 ± 23 Ma Rosskreppfjord granite, Andersen *et al.*, 2002) and Telemark (1024 ± 24 Ma Otternes granite, Andersen *et al.*, 2007), requires a heat source for crustal melting, and a degree of relatively juvenile mantle input to produce their isotopic signatures (Andersen *et al.*, 2009). This is compatible with lithospheric thinning and asthenospheric uprise, indicating an extensional setting at this time, i.e. intra- or back-arc, rather than compressional, and show that this magmatic phase affected a large portion of south Norway. This interpretation of the SMB is incompatible with collision at 1050 Ma, as proposed earlier, or at any time before 1020 Ma.

990–920 Ma late- to post-Sveconorwegian magmatism

Following and overlapping Sveconorwegian high-grade metamorphism, widespread ferroan ('A-type'), hornblende-biotite granite magmatism between 990 and 920 Ma (HBG suite of Vander Auwera *et al.*, 2003, 2011), and anorthosite-mangerite-charnockite (AMC) magmatism in the Rogaland Igneous Complex between 950 and 920 Ma (Schärer *et al.*, 1996; Andersen and Griffin, 2004; Vander Auwera *et al.*, 2011), is recorded in the Sveconorwegian Province (Figs 2, 3). For simplicity, we use the terms HBG

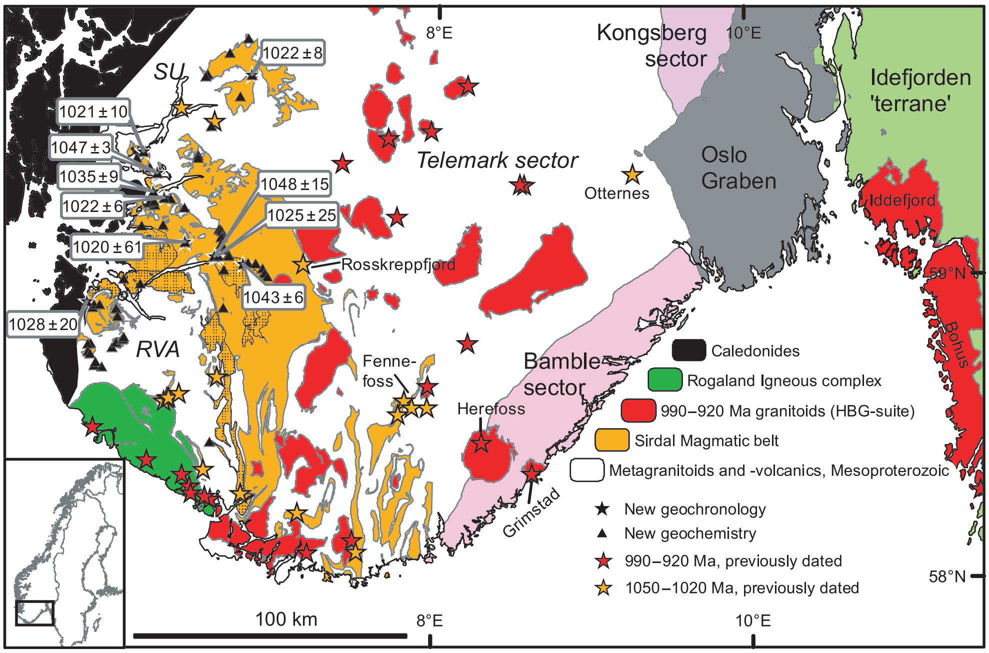

Fig. 2 Simplified geological map of the western and central Sveconorwegian Province based on previously published maps by the Geological Survey of Norway. The apostrophes in Idefjorden 'terrane' have been added because of uncertainties regarding the terrane status of this unit. The Sirdal Magmatic Belt is based on new, unpublished mapping. The dotted pattern indicates the previously inferred extent of Sveconorwegian-age magmatism in south Norway (Feda). The new mapping shows that Sveconorwegian magmatism was significantly more voluminous than previously thought. Published age data from compilation by Bingen and Solli (2009). RVA, Rogaland–Vest-Agder sector; SU, Suldal sector.

and AMC suite here, but acknowledge that this is a lumper's approach and that further work may warrant a different subdivision. Geochemical and isotopic data from the AMC and HBG suites indicate mixed lower crustal, juvenile and mature sources (Vander Auwera *et al.*, 2011 and refs. therein). Vander Auwera *et al.* (2011) recently suggested that the mafic constituents of the Feda suite (part of the SMB) were the most likely juvenile source of both the HBG and AMC suite. This interpretation is consistent with geographically widespread magmatism during formation of the SMB. A relatively dry, lower crustal source, possibly as a result of Sveconorwegian granulite facies metamorphism, appears to be required for the post-orogenic AMC magmatism, whereas a more hydrated lower to infra-crustal source is required for some of the earlier and contemporaneous ferroan granites (Vander Auwera *et al.*, 2003; Bogaerts *et al.*, 2006). HBG and AMC magmatism is generally interpreted to result from post-orogenic gravitational collapse (Bingen *et al.*, 2006). Evidence for collapse comes from Re–Os dating of molybdenite from quartz and pegmatite veins in southwest Norway, but large-scale extensional structures to support this interpretation have not been described. The duration of late-/post-orogenic magmatism is also significantly longer than that ascribed to late-/post-orogenic extension or slab break-off following continental collision in other orogens (Atherton and Ghani, 2002; Neilson *et al.*, 2009). Formation of the HBG and AMC suites therefore appear inconsistent with a short-lived 'collapse' event.

An accretionary Sveconorwegian orogen. A viable alternative to collision?

Figure 5 schematically presents an alternative tectonic model for the Sveconorwegian evolution of southwest Baltica. Formation of the SMB, interpreted to be subduction-related, started at *c.* 1050 Ma, well before the onset of high-grade metamorphism (Fig. 3), and was continuous until *c.* 1020 Ma. Transitional calc-alkaline/ferroan and ferroan magmatism inboard of, and partly within, the SMB between *c.* 1035 and 1025 Ma, may indicate an extensional convergent setting at least periodically during SMB arc magmatism, but the evidence for this is as yet weak. The cessation of magmatism at 1020 Ma, and onset of high-grade metamorphism slightly earlier at *c.* 1035 Ma, could reflect either continental collision as suggested by other workers in the Sveconorwegian orogen, or a flattening of the subducting slab, e.g. as a result of subduction of an oceanic plateau (Collins, 2002; Martinod *et al.*, 2010) or changes in convergence rate or geometry (Cawood and Buchan, 2007; Cawood *et al.*, 2011). For reasons outlined below, we prefer the non-collisional interpretation.

Magmatism in the SMB continued *c.* 15 Ma after the onset of high-grade metamorphism. This may be difficult to reconcile with a simple collision model in which arc magmatism ceases when one of the continents enters the subduction zone. In contrast, compression related to a change from steep- to flat-slab subduction may

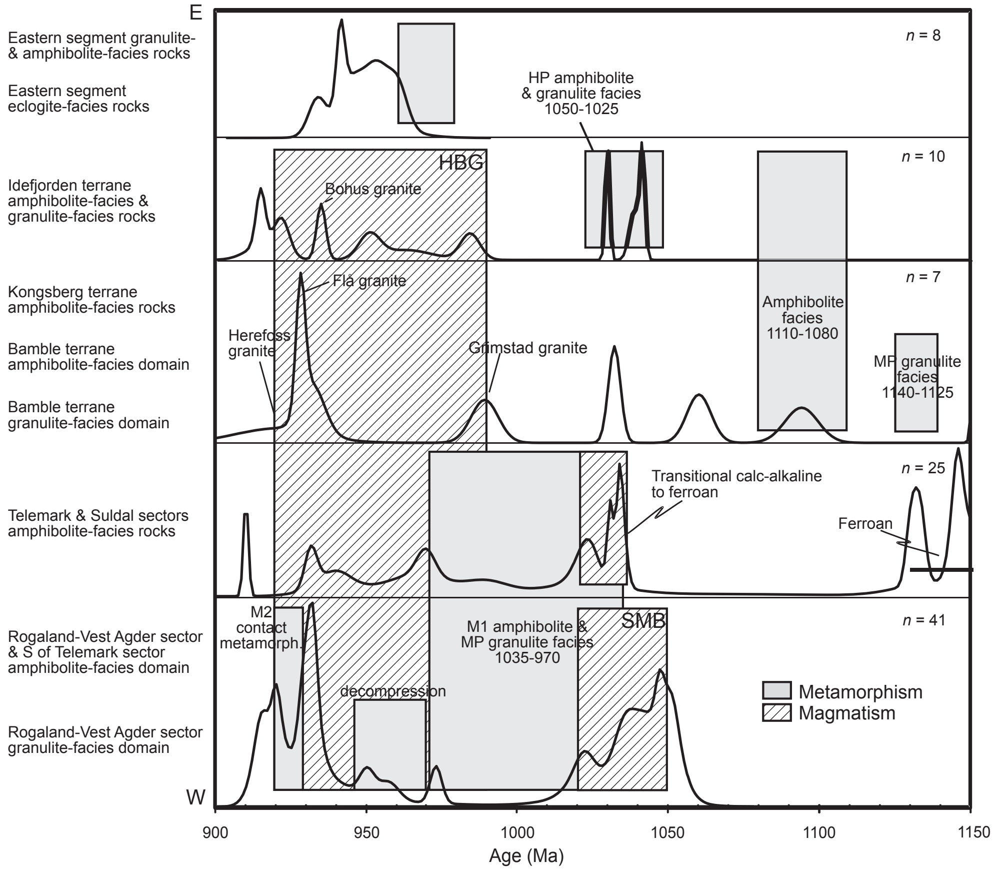

Fig. 3 Timing of high-grade metamorphism and magmatism in the Sveconorwegain Province, from Bingen *et al.* (2008a), compared with probability density distributions of published U–Pb ages from Sveconorwegian crustal sectors. All ages are plotted, including minor dykes and pegmatites. The age of major units are indicated in the plots showing the Kongsberg/Bamble- and Idefjorden data, due to limited overlap between these and the age of minor units. All ages from the Eastern Segment are from smaller dykes and pegmatites with unknown regional significance. Data from Bingen and Solli (2009) and this study. Original references and brief source descriptions are listed in Electronic Supplement 4.

temporally overlap arc magmatism for several million years (Espurt *et al.*, 2008). The area undergoing high-grade metamorphism at 1035–970 Ma was geographically restricted to the Rogaland–Vest-Agder sector (Figs 2, 3), with areas further east (Telemark sector) undergoing only low-grade metamorphism at this time (Bingen *et al.*, 2008a). Peak metamorphic temperatures at *c.* 1000–1010 Ma have been estimated at > 800–900 °C at mid-crustal levels (6–7 kbar) (Drueppel *et al.*, 2008; Elsaesser *et al.*, 2008), higher than those normally attained in collisional orogens (e.g. Jamieson *et al.*, 2004). Similar *P–T* conditions could potentially be attained following delamination of subcontinental lithospheric mantle under an orogenic plateau. However, the limited geographical distribution of high-grade Sveconorwegian metamorphism argues against the development of an orogenic plateau. Even if a plateau had formed in the Sveconorwegian Province at this time, it would in itself not constitute evidence of collision, as major plateaus may also form in accretionary settings (cf., Altiplano–Puna plateau). Thus, the timing, style and geographical distribution of Sveconorwegian high-grade metamorphism do not require continent collision, and are more in line with models of arc/back-arc extension and compression as a result of a periodically retreating and advancing subduction zone (Collins, 2002; Cawood *et al.*, 2009). If one accepts an arc setting for the SMB, Figure 3 shows that there is a lack of syn-collisional magmatism in the Sveconorwegian Province, which distinguishes the Sveconorwegian evolution from that of many other collisional orogenic belts, such as the Greenland Caledonides and the Himalayas, where such rocks are widespread.

High-grade metamorphism and magmatic quiescence in southwest Norway was succeeded by geographically widespread, ferroan granite magmatism between *c.* 990 and 920 Ma (Figs 2, 3), which requires a major, long-lived thermal event that can only be explained by invoking upwelling asthenosphere as a result of extension and/or lithospheric-mantle delamination. There is no evidence of large-scale extensional structures that would be expected if the orogen had undergone orogenic collapse, and the metamorphic evidence shows that most of south Norway was

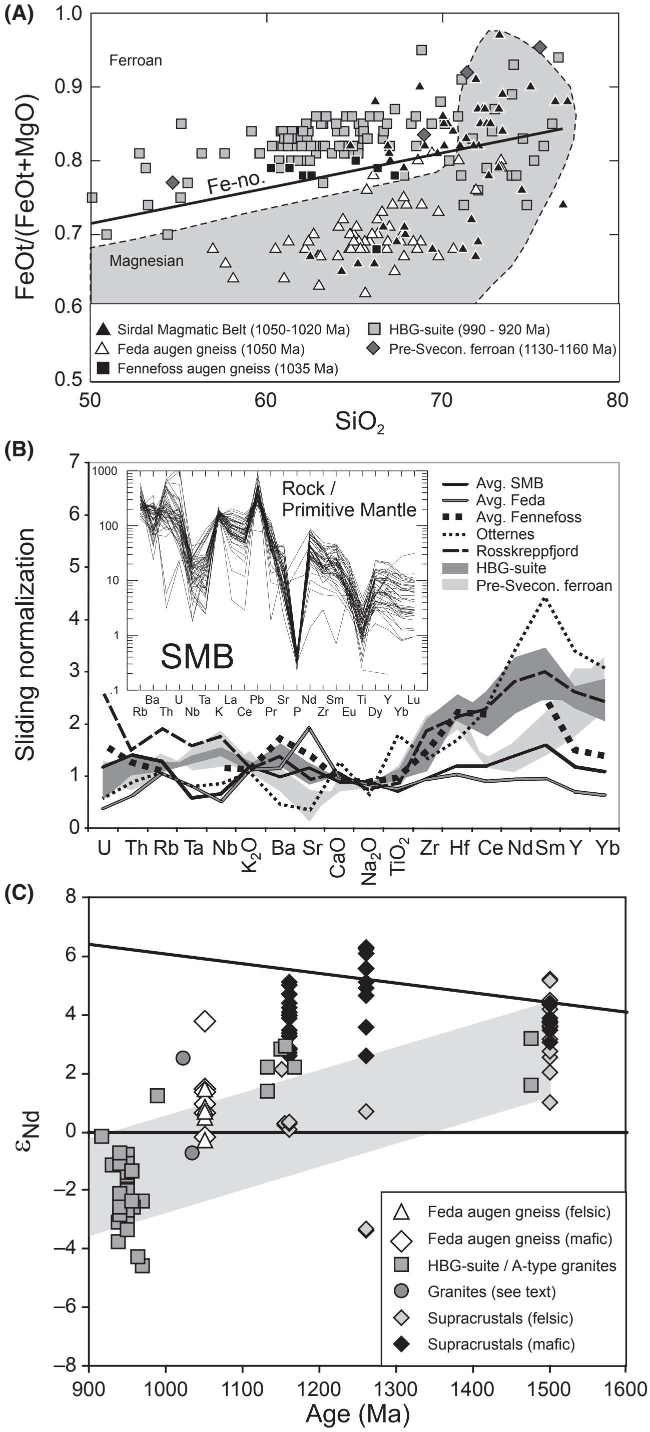

Fig. 4 Major and trace-element compositions of the SMB, the coeval Feda and Fennefoss augen gneisses, Rosskreppfjord and Otternes granites, the younger HBG suite and pre-Sveconorwegian (*c.* 1130–1160 Ma) ferroan granites. (A) SiO_2 vs. $FeO_t/(FeO_t + MgO)$ plot defined by Frost *et al.* (2001); the Fe-number line separates ferroan from magnesian granitoids. Dark grey field outlines Cordilleran granitoids defined by Frost *et al.* (2001). (B) Sliding normalization multi-element plot, following Liégeois *et al.* (1998) and Vander Auwera *et al.* (2011). Note the negative Nb–Ta anomaly in SMB and Feda. Inset: Primitive Mantle-normalized multi-element plot of SMB. Primitive Mantle values from Sun and McDonough (1989). Data for HBG suite from Bogaerts *et al.* (2003) and Vander Auwera *et al.* (2003), Feda from Bingen (1989), Fennefoss from Bingen and van Breemen (1998), Otternes, Rosskreppfjord and pre-Sveconorwegian ferroan granites from Andersen *et al.* (2009). (C) Nd vs. time for Mesoproterozoic magmatism in the Telemark/Rogaland-Vest-Agder sectors; the grey field shows the evolution of *c.* 1500 Ma crust (data from Vander Auwera *et al.* (2011) and refs. therein). The depleted mantle has been calculated with the model of DePaolo *et al.* (1991).

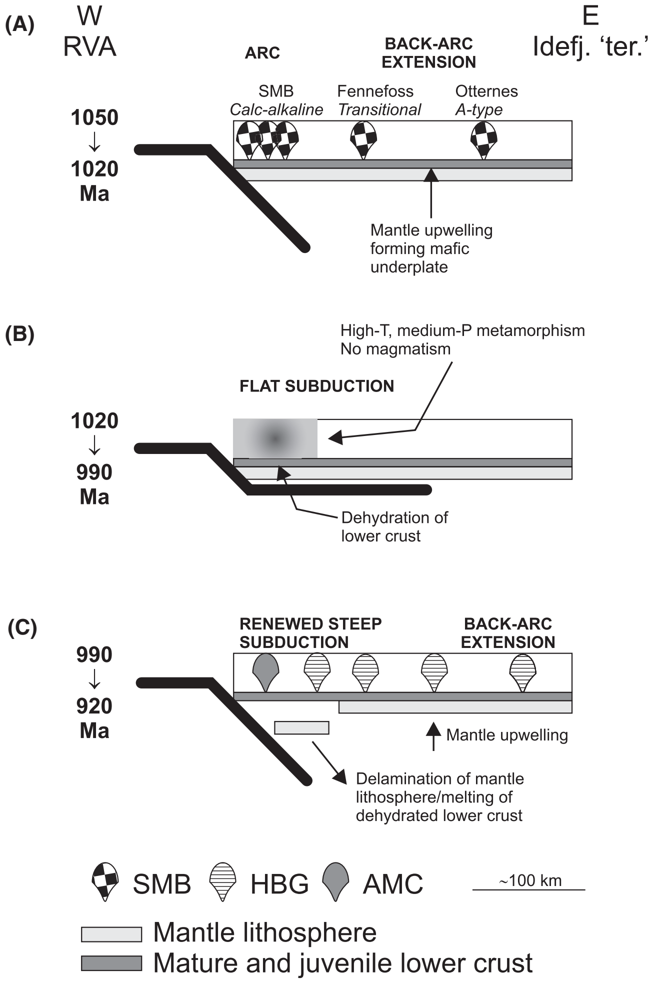

Fig. 5 Tectonic cartoon illustrating a possible non-collisional model for the magmatic and metamorphic evolution of the Sveconorwegian orogen from *c.* 1050 to 920 Ma. RVA, Rogaland–Vest-Agder sector; Idef. 'ter.', Idefjord 'terrane'.

at relatively low- to medium-grade, which probably means that the lithospheric thickness required for large-scale upper-mantle/lower-crustal delamination was too small. We cannot exclude the possibility that presently exposed rocks in south Norway were situated at high-crustal levels during Sveconorwegian metamorphism; but proponents of collision/delamination would then need to rely on an unobservable metamorphic event to explain the formation of the HBG suite. Alternative mechanisms for explaining this long-lived magmatic event, not requiring a significant preceding thickening of the continental lithosphere, are foundering of the flat slab at *c.* 990 Ma or a return to an extensional subduction regime with back-arc extension affecting most of south Norway. Foundering would probably produce a relatively short-lived magmatic pulse, akin to that expected from orogenic collapse, whereas back-arc extension and lower crustal melting can account for more protracted magmatism, and is the favoured mechanism here; however, an improved understanding of the post-orogenic magmatism in south Norway is required before this issue can be resolved. AMC magmatism between *c.* 950 and 920 Ma was most likely a result of delamination or convective thinning of the thickened mantle root to the SMB arc (cf., Corrigan and Hanmer, 1997), and partial melting of dehydrated lower crust, which may have resisted earlier eclogitization and delamination on account of its dry nature (Bjørnerud and Austrheim, 2004; Jackson *et al.*, 2004). This interpretation is consistent with that of Vander Auwera *et al.* (2011).

Implications for Rodinia reconstructions

Classic reconstructions of Rodinia involve collision between Laurentia, Baltica and Amazonia, forming the Grenville, Sveconorwegian and Sunsas orogenic belts respectively (Li *et al.*, 2008 and references therein). One notable exception to this interpretation is that of Evans (2009), who restored Amazonia to a more northerly position in Rodinia, adjacent to the West Africa and Congo cratons, leaving the late Mesoproterozoic Grenville–Sveconorwegian margin facing a large ocean to the southwest (Fig. 1B). A cordilleran-type accretionary margin is consistent with our interpretations from southwest Baltica. In contrast, the Grenville Province lacks the voluminous syn-collisional magmatism (e.g. Carr *et al.*, 2000) that we show characterizes the Sveconorwegian Province. Also, Grenville-age basement in the Appalachian orogen appears to be exotic to Laurentia, and was probably accreted during Rodinia assembly (Fisher *et al.*, 2010). It is possible that there were significant along-strike variations in tectonic style along the Grenville–Sveconorwegian margin, similar to those observed along the Himalayan–Indonesian system; that the evolution observed in the Sveconorwegian Province is a localized phenomenon in an overall collisional setting; or that models suggesting a correlation between the Grenville and Sveconorwegian Provinces may be incorrect (cf., Gower *et al.*, 2008). In any case, this study shows that the generally rather simplistic view of Grenville–Sveconorwegian orogenic processes and Rodinia assembly and reconstructions needs to be revised.

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Supporting Information

Additional Supporting Information and Data may be found in the online version of this article.

Data S1. Methods.

Data S2. U-Pb zircon data.

Data S3. Whole-rock geochemical data.

Data S4. List of ages used to plot Fig 3.