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Research Paper

Crustal reworking and orogenic styles inferred from zircon Hf isotopes: Proterozoic examples from the North Atlantic region

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ABSTRACT

Zircon Hf evolutionary patterns are powerful tools to investiage magma petrogenesis and crustal evolution. The ^{176}Hf/^{177}Hf isotopic signature of a rock is particularly informative and can be used to derive an estimation of the time when mantle extraction and diagnose closed system reworking where successive samples through time define an Hf evolution array dependant on the source Lu/Hf ratio. However, many magmatic events require new mantle addition as the thermal impetus for melting pre-existing crust. In this situation, rather than simply reflecting reworking, the isotopic signature indicates mixing with contributions from both reworked crust and new radiogenic input. Different geodynamic settings have different propensities for either reworking or addition of new mantle-derived magma. Hence, Hf-time trends carry within them a record, albeit cryptic, of the evolving geodynamic environment as different tectonic configurations recycle and add new crust at different rates, magnitudes, and from different sources. As an example of the difference in apparent Hf evolution slopes, we present Hf-time compilations from three geographically distinct Meso- to Neoproterozoic orogenic belts in the North Atlantic Region whose geodynamic configurations remain a subject of debate. We use the εHf/Ma trajectory to assist in understanding their evolution. The εHf/Ma trajectory of the Sveconorwegian Orogen corresponds to a ^{176}Lu/^{177}Hf ratio of 0.012, which implies a process driven primarily by reworking of pre-existing crust that is balanced with input from the depleted mantle resulting in a relatively shallow εHf/Ma slope. The Valhalla Orogen reveals a similar comparatively shallow εHf/Ma path. In stark contrast to these patterns is the steep εHf/Ma trajectory of the Grenville Orogen that requires a mixing process involving a greater contribution of old crust of at least ~1.8 Ga age. The degree of reworking required to produce the εHf/Ma trend of the Grenville Orogen is consistent with a continent–continent collisional orogeny whereas both Sveconorwegian and Valhalla orogens appear more consistent with accretionary margins.

1. Introduction

The age and ^{176}Hf/^{177}Hf ratio of igneous zircon allow geochemists to track magmatic source characteristics of an orogenic system in both space and time. A range of different isotopic mixing processes can be recognized through Hf (or Nd) isotopes in magmatic systems, from those operating on time scales of 10^{6-7} years (such as plutonic systems; e.g. Goodge and Vervoort, 2006) to the longer-term evolution (10^{8-9} yrs) of continental crust (e.g. Hawkesworth and Kemp, 2006). Hf isotopes, in particular, enable interrogation of the source history of a rock, including assessing previous isotopic fractionation events and possible radiogenic depletion or enrichment of magmatic sources (e.g. reworking of pre-existing crust versus new addition from the depleted mantle). Theoretically, distinctive Hf evolution patterns may be expected for specific tectonic environments, reflecting juvenile input, reworking of an older continent, or a combination of these processes (Collins et al., 2011; Spencer et al., 2013).

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We present zircon Hf isotopic signatures from three spatially and temporally distinct Meso- to Neoproterozoic tectonic systems in the North Atlantic Region: ~1085–985 Ma (meta)sedimentary successions in Labrador and Scotland, ~1140–900 Ma Sveconorwegian igneous and sedimentary rocks in southern Norway and southern Sweden, and ~980–910 Ma and 840–680 Ma sedimentary successions and granitoid intrusions in the Norwegian Caledonides, Greenland and Svalbard. The geodynamic settings (whether dominated by collision or subduction) for each of these orogens are contested. Through a combination of previously published and new data, we show that it is possible to differentiate ε_{Hf}-time trends and use those to inform on the style of orogenesis.

2. Geological setting

Within the circum-North Atlantic region, thick sequences of Meso- to Neoproterozoic sedimentary and igneous rocks are preserved within the Meso- to Neoproterozoic Grenville, Sveconorwegian and Valhalla orogens (Fig. 1; Bingen et al., 2008, Cawood et al., 2010, 2011; Rivers et al., 2012).

2.1. Grenville orogen

The Grenville Orogeny (sensustricto, i.e. the 1.2–1.0 Ga orogeny in eastern Laurentia as defined locally within the Grenville Province and surrounding environs) is characterized by initial crustal thickening and upper-amphibolite to granulite-facies metamorphism (Bickford et al., 2008; Hynes and Rivers, 2010) and subsequent syn-collisional magmatism (Rivers et al., 2012) attributed to collision between the south-eastern margin of Laurentia and, most likely, the Amazonia craton (Ibanez-Mejia et al., 2011) from ~1085 Ma to 985 Ma (Gower and Krogh, 2002). However, Evans (2009) proposed a palaeogeography that places the locus of Grenville orogenesis outboard of the Laurentian margin implying a margin characterized by a subduction zone. Currently, there are no published zircon U–Pb/Hf data for the igneous rocks of the Grenville Orogen but detrital zircon U–Pb/Hf data are available for many of the sedimentary successions that flank the Grenville orogenic belt; these include the (from oldest to youngest) Siamarnekh Formation, Sleat Group, Battle Harbour Psammite, Stoer Group, Applecross and Aultbea formations, Morar Group, Glenfinnan and Loch Eil groups and Double Mer and Bradore formations (see Supplementary information for new sample locations; additional data from Lancaster et al., 2011; Spencer et al., 2015).

2.2. Sveconorwegian orogen

The ~1140–900 Ma Sveconorwegian orogen is preserved along the southwest margin of the Fennoscandian craton (Bingen et al., 2008; Slagstad et al., 2013; Roberts and Slagstad, 2014). Two contrasting interpretations have been advanced for this orogen. One consists of four phases (Bingen et al., 2008): an initial accretion of the Idefjorden and Telemarkia terranes and granulite-facies metamorphism (Arendal phase, 1140–1080 Ma); subsequent oblique collision and associated magmatism (Agder phase, 1050–980 Ma); collisional culmination with eclogite-facies metamorphism (Falkenberg phase, 980–970 Ma); and, lastly, gravitational collapse (Dalane phase, 970–900 Ma). In contrast, Slagstad et al. (2013, 2017) interpreted the period from 1050 Ma to 1020 Ma to record subduction-related magmatism (the Sirdal Magmatic Belt), followed by an amagmatic period of metamorphism from 1035 Ma to 970 Ma attributed to flat slab subduction and associated crustal thickening, and then a second phase of subduction-related magmatism from 990 Ma to 920 Ma. The sedimentary record consists of the pre-orogenic Vindeggen Group and the syn-orogenic Oftefjell, Høydalsmo, Lifjell, Heddal and Kalhovd groups, and the Brukeberg and Eidsborg formations; all of these were deposited during Sveconorwegian orogenesis (Slagstad et al., 2017). No post-orogenic Proterozoic sedimentary successions have been documented. Zircon U–Pb/Hf data from the Sveconorwegian Orogen are

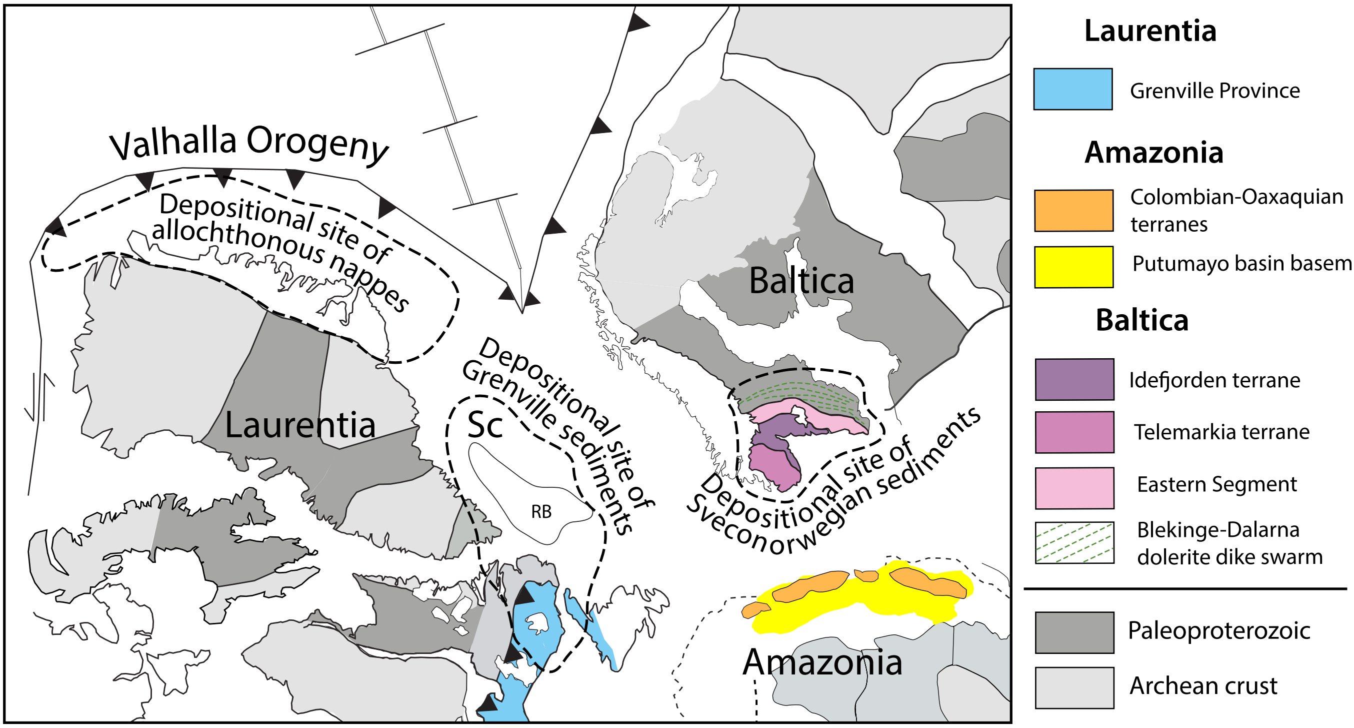

Figure 1. Palaeogeographic map of the North Atlantic region circa 1.0 Ga (after Cawood et al., 2010; Ibanez-Mejia et al., 2011). Outlined are the depo-centers for sediments derived from the Grenville, Sveconorwegian, and Valhalla orogens. Sc: Scotland, RB: Rockall Bank.

compiled from both igneous and sedimentary samples (data from Andersen et al., 2002, 2004, 2009a, 2009b, 2011; Andersen and Griffin, 2004; Pozer, 2008; Pedersen et al., 2009; Kurhila et al., 2010; Lamminen and Köykkä, 2010; Andersson et al., 2011; Brander et al., 2012; Roberts et al., 2013; Roberts unpublished).

2.3. Valhalla orogen

Meso- to Neoproterozoic sedimentary and magmatic rocks in Ellesmere Island, East Greenland, Scotland, Norway, the North Sea, and Svalbard (Strachan et al., 1995, 2010; Kirkland et al., 2006; Myhre et al., 2008; Malone et al., 2014, 2017; Cawood et al., 2014; Gee et al., 2015; Spencer and Kirkland, 2016) have been interpreted as defining the Valhalla Orogen, an external orogen formed during the time interval associated with the collision of Laurentia, Baltica and Amazonia (Cawood et al., 2010, 2014). A major clockwise rotation of Baltica after ca. 1250 Ma is viewed as having produced the oceanic depocentre in which these units were deposited along the periphery of Rodinia (Cawood et al., 2010; Cawood and Pisarevsky, 2017). This orogen is characterized by calc-alkaline magmatism and high-grade metamorphism with clockwise PT paths (Cutts et al., 2009; Pettersson et al., 2010). The magmatic rocks are grouped into two broad episodes: the ~980–910 Ma Renlandian and ~840–680 Ma Knoydartian events (Kirkland et al., 2006; Cawood et al., 2010, 2014; Walker et al., 2015; Bird et al., 2018). It is noteworthy that the sedimentary rocks deposited during the inferred Valhalla orogenic cycle have detrital age spectra and associated isotopic signatures that have been interpreted to reflect derivation from the Grenville Orogen (sensustricto) in eastern Canada (Spencer et al., 2015). Following on from the convergent-style processes, there was likely substantial lateral translation of crustal fragments (Pettersson et al., 2010 and references therein), a scenario similar to that inferred for the Cordilleran margin of North America (Hildebrand, 2015 and references therein).

Zircon U–Pb/Hf data are combined with data from metasedimentary and igneous rocks in the Caledonian nappes of Norway and Greenland, the Kalak and Gaissa nappes, and the Northwestern Terrane of Svalbard (see Supplementary information for new sample locations; additional data from Bingen et al., 2005, 2011; Lamminen et al., 2011). Rocks that are derived from a Laurentian provenance and from geographically more proximal locations to the Grenville front (e.g. Moine metasediments of Scotland) are used as a proxy for the Grenville Orogen whereas those with disputed provenance (e.g. formations of the Caledonide Nappes; cf. Gee et al., 2015) are assigned to the Valhalla Orogen in order to avoid an explicit assignment to either Baltica or Laurentia.

3. Hafnium isotopes in zircon

Linear εHf–time arrays of zircon (Figs. 2 and 3) are typically interpreted to represent long-term evolution trends of reworking from a singular isotopic source (Kemp et al., 2007; Laurent and Zeh, 2015). These trends may be attributed to the ^{176}Lu/^{177}Hf ratio of the reservoir from which the zircon crystallized, such that a shallow slope (e.g. ^{176}Lu/^{177}Hf $= \sim 0.02$) is often associated with reworking of a mafic parent rock whereas a steeper slope (e.g. ^{176}Lu/^{177}Hf $= \sim 0.01$) is generally attributed to reworking of a felsic parent rock (Griffin et al., 2000; Hawkesworth et al., 2010a,b; Payne et al., 2016) (Table 1 for further information). Nevertheless, evolution arrays should be interpreted with caution as they may reflect complex mixing processes. In addition, arrays can be modified when zircon is altered by isotopic mobility such as Pb-loss; e.g. Hf isotopic composition remains unchanged whereas the U–Pb age may be younger than the true age (e.g. Guitreau and Blichert-Toft, 2014; Vervoort and Kemp, 2016). For this reason, in this work only ^{207}Pb/^{206}Pb ages are used, a ratio that is insensitive to recent radiogenic-Pb loss, and furthermore those analyses with >10% discordance are not considered.

4. Zircon Hf from the orogens of the North Atlantic region

Sample descriptions/locations, analytical methods, and new data presented herein are provided in the supplementary materials (S1, S2, S3). In the following descriptions of data (Fig. 2), we calculate the εHf arrays following the onset of crustal reworking related to orogenesis. Defining the timing of the onset of crustal reworking is not trivial (Fig. 2). The onset of true continent–continent collision in the Grenville is suggested at ~1090–1020 Ma by regional metamorphism of rocks on the Laurentian margin, and cessation of extension in the Mid-continent rift at ca. 1.105 Ga (Rivers et al., 2012). In the Sveconorwegian Orogen, the timing for commencement of collision may be somewhat different as there is no clear change in tectonic regime (Bingen et al., 2008). A time of 1.14 Ga has been considered to equate to collision, based on high-grade metamorphism in the Bamble sector (Johansson et al., 1991). Much of the evidence of the Valhalla Orogen is cryptic as it is mainly preserved through the deposition of sedimentary successions (in Scotland, Greenland and Norway), with intermittent deformation, metamorphism and magmatism in these same sedimentary rocks (Kirkland et al., 2011). All the Valhalla Orogen rocks are now in allochthonous terranes. The Valhalla orogeny as typically defined is considered to have started <0.98 Ga (Cawood et al., 2010).

We evaluate the slope of the εHf array from a variety of common time points for each of these orogens (1200 Ma, 1100 Ma and 1000 Ma). These time points represent an estimate of the age of the basement-cover contact for the Sveconorwegian and Grenville orogens (Gower, 1996; Åhäll and Connelly, 1998; Brewer et al., 2002; Kamo et al., 2011; Spencer et al., 2014, 2015). Regressions were fitted to the <1200 Ma, <1100 Ma, and <1000 Ma components of the evolution arrays for each orogenic system using the software Past v. 3.10 (Hammer et al., 2013). Least trimmed squares regression was used to find the relationship between ^{176}Hf/^{177}Hf and age. As the U–Pb data has less scatter at any point in time compared to Hf data, which may include mantle to crustal sources as well as compositional mixtures, a robust regression model that sought to minimize variation on the Y-axis was employed (Rousseeuw and Driessen, 1999; Mount et al., 2014). Pearson's *r* correlation and the probability that εHf and age are uncorrelated are presented in Table 2. In all cases, *r*-values are positive indicating that, generally, as age increases so too does εHf. In the following text we discuss in detail the results for the <1200 Ma regression as similar relationships are apparent when other starting times are chosen (Table 2).

203 analyses from the Grenville Orogen (see references listed in Geologic Setting) yield U–Pb ages less than the 1200 Ma inflection point (where the εHf slope changes from negative – toward the depleted mantle – to positive – away from the deplete mantle). εHf values range from −37 to +10 (median value of +1). The Grenville Orogen data show similar patterns to the reported isotopic evolution of western Laurentia (Goodge and Vervoort, 2006; Spencer et al., 2012) in that the post-1200 Ma data show a steeply sloping trajectory (εHf/Ma = ~0.04). This corresponds to an equivalent ^{176}Lu/^{177}Hf slope of −0.22, which cannot be attributed to enrichment via radiogenic decay and remelting of a single source and instead must be explained by the mixing of at least two isotopically distinct end members. Although in all likelihood many more components were involved.

502 analyses from the Sveconorwegian Orogen (see references listed in Geologic Setting) yield U–Pb ages less than the 1200 Ma Hf inflection point. εHf values range from −21 to +15, with a median

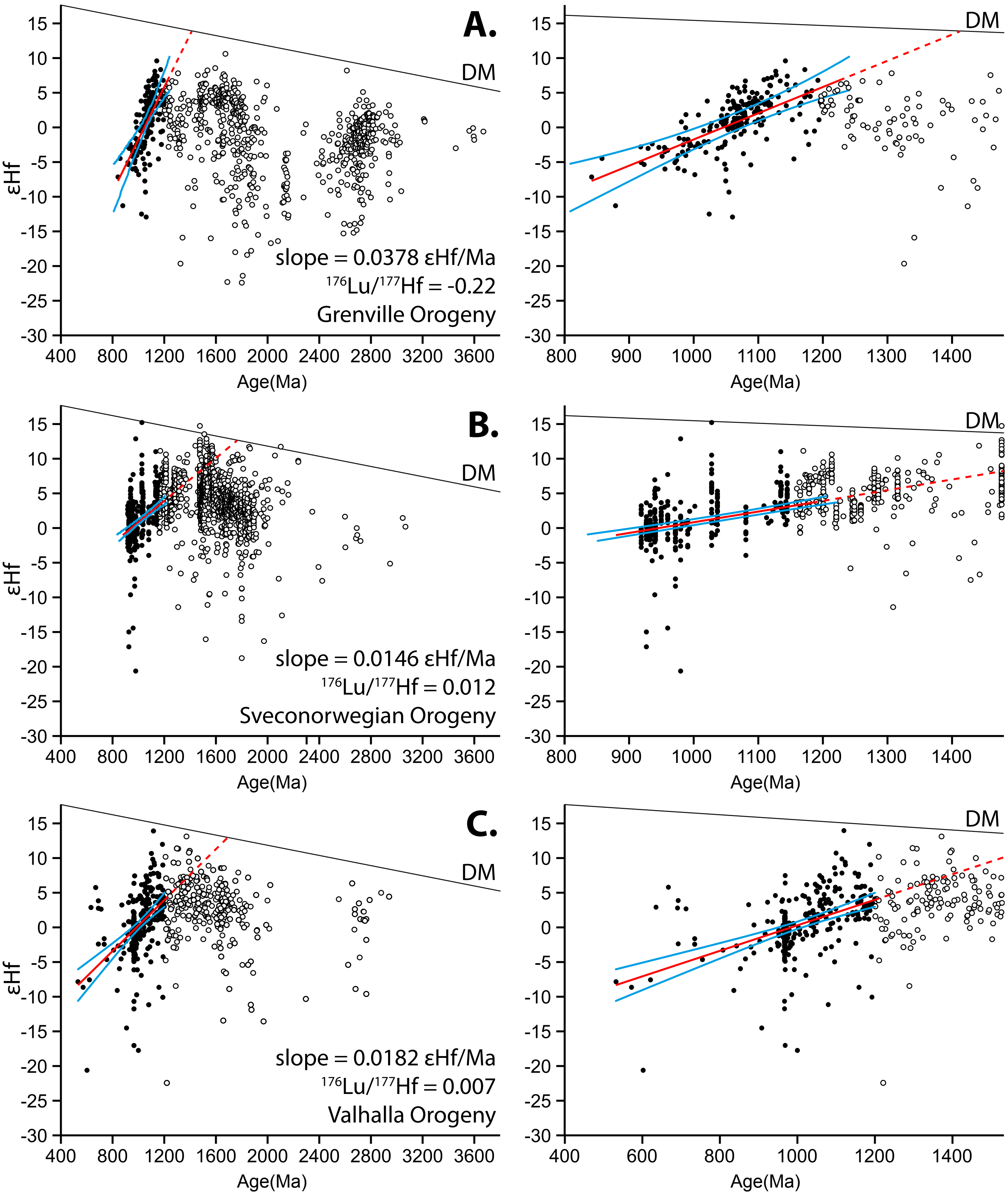

Figure 2. Zircon Hf data from the (A) Grenville Orogen, (B) Sveconorwegian Orogen, and (C) Valhalla Orogen (left panels are all of the data, right panels are subset focused on the data included in the regression). The regression line is calculated using only the filled symbols (those after the onset of reworking) and extrapolated to the depleted mantle. Average uncertainties are 2% for U–Pb (see Horstwood et al., 2016) and ∼1σ unit for Hf (see Supplementary information for more information).

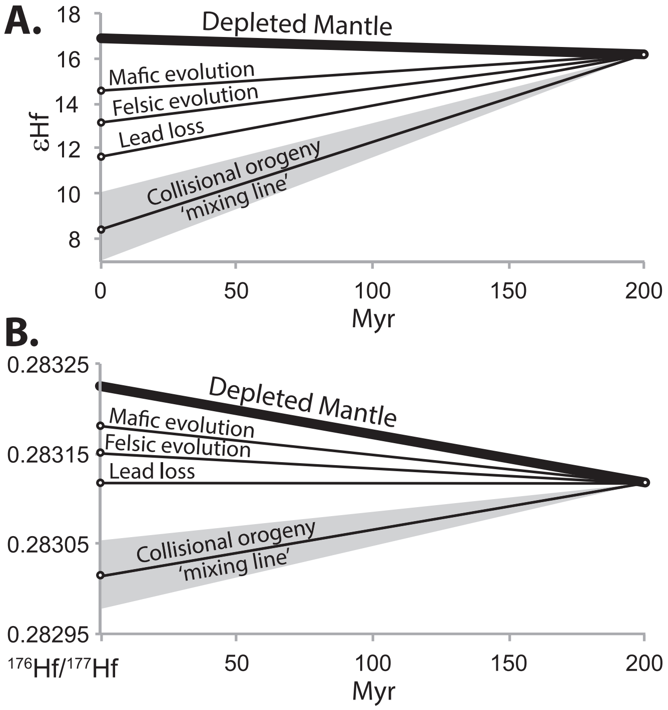

Figure 3. Schematic illustration of typical interpretations of ^{176}Lu/^{177}Hf ratios in zircon (A) εHf and (B) ^{176}Hf/^{177}Hf time arrays. The mafic, felsic, and lead loss evolution lines correspond to ^{176}Lu/^{177}Hf ratios of 0.022, 0.012, and 0, respectively. The evolution array corresponding to collisional orogeny (in this case, the Grenville Orogen) has an apparent ^{176}Lu/^{177}Hf ratio much lower than the lead loss trajectory and hence a steeper slope. This is caused by the incorporation of an already radiogenically enriched source faster than the radiogenic decay of ^{176}Lu to ^{176}Hf, regardless of initial ^{176}Lu/^{177}Hf of the source.

value of +3. Both Hf and age values are non-normally distributed. The pre-Sveconorwegian Orogen data show similar patterns to the reported isotopic evolution of Baltica (Andersen et al., 2002, 2009a,b) such that a linear regression of the post-1200 Ma data (selected from the latest steep inflection of the moving mean) provides a εHf/Ma slope of ~0.01; this corresponds to an equivalent ^{176}Lu/^{177}Hf slope of 0.012. This slope is consistent with radiogenic enrichment of a felsic crustal source.

Table 1
Summary of ^{176}Lu/^{177}Hf of selected geologic units and rock types.

	^{176}Lu/^{177}Hf
Continental crust[a]	
Bulk	0.0130
Lower	0.0212
Upper	0.0093
Cratonic shales[b,c]	
Archaean	0.0140
Proterozoic	0.0148
Phanerozoic	0.0164
PAAS	0.0138
NASC	0.0117
GLOSS[d]	0.0164
Island arcs[e]	0.0261
LIPs and Oceanic Plateaux[e]	0.0182
Granitoids[f]	0.0180

PAAS, post-Archaean Australian Shale; NASC, North American Shale composite; GLOSS, global subducting sediment.
[a] Rudnick and Gao (2003).
[b] Condie (1993).
[c] Nance and Taylor (1976).
[d] Plank and Langmuir (1998).
[e] Payne et al. (2016).
[f] Hawkesworth et al. (2010a,b).

Table 2
Values of the least trimmed squares robust regression as calculated by Past3 (Hammer et al., 2013) for the Grenville, Sveconorwegian, and Valhalla Orogenies.

	Grenville	Sveconorwegian	Valhalla
Least trimmed squares robust regression			
Slope < 1200 Ma	0.0378	0.0146	0.0182
Intercept at 0 Ma with <1200 Ma data	−39.56	−13.74	−18.31
Slope < 1100 Ma	0.0439	0.0217	0.0162
Slope < 1000 Ma	0.0338	−0.0064	0.007
95% bootstrapped regression (<1200 Ma; $N = 1999$)			
Slope	0.04672	0.0168	0.011661
Zero-intercept	−49.32	−16.24	−23.46
Correlation (<1200 Ma)			
r	0.39583	0.52436	0.42445
r^2	0.15668	0.27496	0.18016
t	6.111	13.77	7.872
p (uncorr.)	5.05E−09	8.34E−37	7.55E−14
Permutation p	0.0001	0.0001	0.0001

167 analyses from rocks assigned to the Valhalla Orogen (see references listed in Geologic Setting) yield U–Pb ages less than the 1200 Ma inflection point. εHf values range from −21 to +12, with a median value of +1. Both Hf and age values are non-normally distributed. A linear regression of the post-1200 Ma data provides a εHf/Ma slope of ~0.02. Similar to the Sveconorwegian data, this corresponds to a nearly equivalent ^{176}Lu/^{177}Hf slope of 0.007. This slope is slightly steeper than that which would be expected from solely radiogenic enrichment of a felsic crustal source although it is within the 95% confidence envelope of the Sveconorwegian array (see Table 2) and does not require significant input of other crustal reservoirs. Furthermore, although the εHf/Ma slope of the Valhalla and Sveconorwegian orogens are equivalent, the former post-dated the latter by nearly 100 million years. Therefore the 1200–1000 Ma detritus deposited in basins related to the Valhalla Orogen may have been derived from the earlier Sveconorwegian Orogen. Nevertheless, the εHf/Ma slope of the post-1000 Ma detrital zircons (i.e. those exclusively related to the magmatism of the Valhalla Orogen) has an equivalent slope to that inclusive of the 1200–900 Ma detrital zircons. Lastly, the εHf signature of the 1200–1000 Ma detritus ascribed to the Valhalla and Sveconorwegian orogens is distinct from the Grenville Orogen, further supporting separation of these orogenic events in space and time.

5. A geodynamic driver for Hf isotopic trajectory

The steep εHf/Ma trajectory of the Grenville Orogen implies greater contribution of an evolved component of >~1.8 Ga (Spencer et al., 2014). We interpret the steep trend as primarily a function of the quantity of evolved material in the magmas. Greater evolved contributions into magmatic systems are consistent with orogenic episodes due to continent–continent collisions in which magmatism is influenced by thickened crust including components of significantly older age than the orogeny itself (Hopkinson et al., 2017). Such a scenario is compatible with the perceived history of the Grenville Orogen with tectonothermal overprinting of the Laurentian margin by Grenville age magmatism, indentor tectonism, and high-grade metamorphism (Gower et al., 2008; Rivers et al., 2012 and references therein) (Fig. 4). Furthermore, it is important to note that altering the start point for the regression analysis (e.g. 1200 Ma through to 900 Ma) does not result in a significant difference beyond the uncertainty bounds to the observed evolutionary slopes (Table 2).

If Himalayan-style orogenesis is an appropriate analogue for the Grenville Orogen (as proposed by Gower et al., 2008; Rivers et al., 2012), then the predicted isotopic character would commence

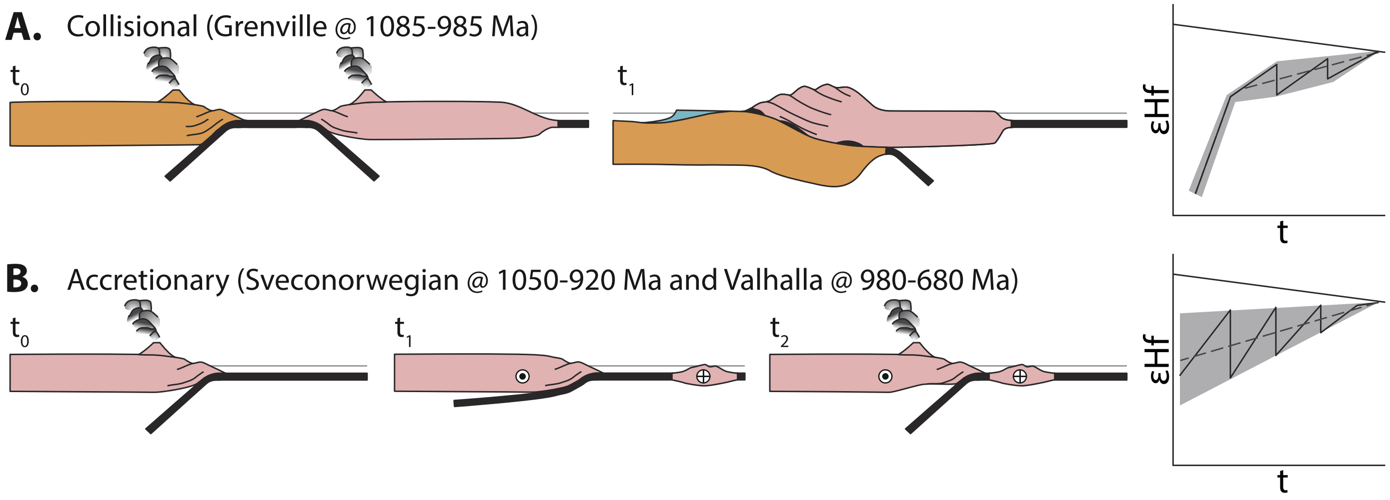

Figure 4. (A) Schematic cross-section of the Grenville collisional orogen (opposing dual subduction zones after Spencer et al., 2013) and predicted εHf/Ma trajectory. (B) Schematic cross-section of the Sveconorwegian and Valhalla collisional orogens and predicted εHf/Ma trajectory representing variable mixtures of reworked crust and depleted mantle. Translation of the continent and accreted terrane speculative after Bingen et al. (2008) for the Sveconorwegian Orogeny and Pettersson et al. (2010) for the Valhalla Orogeny.

with magmatism of a relatively depleted character during arc production prior to collision, followed by rapid input of an unradiogenic component due to reworking of an older enriched collider (e.g. Wu et al., 2007). This isotopic pattern is observed for the Grenville Orogen (Fig. 3) and supports the hypothesis that the Grenville Orogeny was collisional in nature. Evans (2009) proposed an alternative palaeogeographic model that implies the Grenville Orogen was not collisional, but rather was part of a long-lived accretionary orogen; however, this model does not account for high-grade metamorphism accompanied by significant reworking of an evolved crustal reservoir.

The εHf/Ma trajectory of the Sveconorwegian Orogen corresponds to a ^{176}Lu/^{177}Hf ratio of 0.012. The isotopic pattern from the Valhalla Orogen reveals a similar and comparatively shallow εHf/Ma path. Such shallow εHf/Ma trends can be explained through the predominant reworking of an evolved crustal component with little need to invoke mixing between isotopically enriched and depleted end members. This scenario is applicable to subduction zone settings (Fig. 4).

Of the two geodynamic models proposed for the Sveconorwegian Orogen, an accretionary margin culminating with continental collision (Bingen et al., 2008) versus a long-lived accretionary margin dominated by subduction processes (Slagstad et al., 2013, 2017), the currently complied Hf data would appear most consistent with an accretionary margin model. The crustal reworking trajectory in Hf evolution space for this orogenic episode remains broadly constant for ~700 Myr (900–1600 Ma) and corresponds to the expected evolution trend for reworking predominantly felsic crust. This pattern is inconsistent with a collisional orogeny as described above (c.f. Bingen et al., 2008). Rather, an accretionary model driven primarily by subduction and minor accretion/translation of relatively young crustal fragments predicts isotopic patterns akin to an alternating advancing or retreating subduction zone (Kemp et al., 2009; Boekhout et al., 2015), wherein long term radiogenic enrichment is driven by the average composition of arc magmatism and hence the continental crust (i.e. a ^{176}Lu/^{177}Hf ratio of ~0.012). Examples of this process are seen in the Andean Orogen (DeCelles et al., 2009; Boekhout et al., 2015) and the Tasmanide Orogen (Kemp et al., 2009). Although some unradiogenic outliers also imply reworking of Archaean components (Bingen et al., 2011), the majority of the dataset is consistent with a long-lived accretionary margin.

The isotopic pattern from the Valhalla Orogen reveals a comparatively shallow εHf/Ma path relative to the Grenville Orogen. Although existing geodynamic models for the Valhalla Orogen lack consensus, the isotopic signature presented herein is comparable to that from the Sveconorwegian Orogen. The geodynamic model of Lorenz et al. (2012) implies the equivalence of the Grenville, Sveconorwegian, and Valhalla orogens extending this belt into the high Arctic and suggesting that its entire length was collisional. Conversely, Cawood et al. (2010) defined the Valhalla Orogen as a discrete orogenic system both in space and time and argue that the post-1.0 Ga clockwise rotation of Baltica set the stage for an accretionary orogenic system with successor basins along the margin of Rodinia. The εHf/Ma trend of the Valhalla Orogen (Fig. 3) is similar to (and within uncertainty of) the trend of the Sveconorwegian Orogen. This provides further evidence that the geodynamics associated with the Valhalla Orogen were similar to, and perhaps a continuation of, those associated with the Sveconorwegian Orogen, from which some of the sediment of the Valhalla Orogen may have been ultimately sourced. It is important to note, however, that the similarity is in Hf isotopic pattern only as these two orogenic systems occurred in different geographic locations and are temporally distinct. Hence, this similarity should not be taken as evidence that sediments within allochthonous nappes of Valhalla were situated directly on top of Baltica during their depositional timeframe.

6. Conclusions

Using zircon Hf data from three distinct orogenic belts, we propose that εHf/Ma trends can be used broadly to distinguish different styles of orogenesis. Subduction systems will generally develop shallower ^{176}Lu/^{177}Hf slopes than full continental collision systems due to source magmas being dominantly arc related. In the case of the Sveconorwegian and Valhalla orogens, their shallow ^{176}Lu/^{177}Hf slopes maintained over several hundreds of millions of years is compatible with reworking evolution trends in accretionary orogens. Conversely, steeper mixing trends can be explained by crustal reworking in a continental–continental collisional system where greater evolved material is incorporated into melts over time due to melt penetration into thickened crust. Such a steep εHf/Ma array is the case for the Grenville Orogen, where the quantity of evolved material incorporated into the magmatic system is on average greater than that observed in the Sveconorwegian and Valhalla orogens.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gsf.2018.09.008.

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