What do epsilon hafnium isotopic arrays tell us about Wilson cycle tectonics? Implications for the type area in the Appalachian-Variscan Orogen

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Abstract

The Appalachian Orogen in Atlantic Canada, and its extension into the Variscan Orogen of Europe, are crucial locations for the development of some of the earliest ideas associated with plate tectonic theory. The recognition of a boundary that separated rocks of Gondwanan faunal affinity from those of Laurentian faunal affinity in the northern Appalachians was fundamental in defining a Wilson cycle; the process of opening and closing an oceanic basin that pre-dated the Atlantic Ocean. Tectonic models for the Appalachian Orogen have become increasingly complex as more geological data have become available resulting in the subdivision of distinct exotic terranes (Avalonia, Ganderia and Meguma) and putative multiple subduction/accretion events. These terranes, collectively referred to as “peri-Gondwanan”, are generally interpreted to have been rifted from the northern Gondwanan margin in the early Paleozoic and sequentially accreted to the Laurentian margin via the closure various oceans, thereby suggesting successive Wilson cycles during the mid-late Paleozoic. A viable method for testing the model of multiple Wilson cycles is to investigate the hafnium isotopic arrays from zircon grains, which are capable of recording the evolution of complex accretionary orogenic systems. This thesis presents a comprehensive hafnium data set from igneous and sedimentary rocks in the Appalachian and Variscan orogens to assess the isotopic signature of sequential Wilson cycle tectonics.

Hafnium isotopic (εHf) arrays allow the provenance of exotic terranes in the Appalachian-Variscan orogenic system to be established. Ganderia and Avalonia, and probably Meguma, were built on a Mesoproterozoic basement that must have formed along the former Grenvillian suture-zone. In Variscan Europe, εHf arrays show that Iberia was derived from the Saharan metacraton and Armorica from the West African Craton. The Upper Allochthon of Iberia is often linked to the West African Craton, but it is more similar to the εHf array of Avalonia. Hafnium isotopes of magmatic and detrital zircons from Ganderia indicate the terrane hosted a long-lived magmatic arc that began between 800-750 Ma and continued until 450 Ma. The arc initially formed on juvenile Grenvillian crust, but a transition toward more evolved Hf isotopic compositions between 650-600 Ma coincides with accretion of Ganderia to the Gondwanan margin. Increasing amounts of juvenile crustal inputs between ~550-500 Ma are interpreted to reflect subduction roll-back and eventual rifting of Ganderia from the margin, associated with opening of the Rheic Ocean. Juvenile zircons from the leading-edge arc system of Ganderia, the Penobscot-Popelogan-Victoria arcs, indicate that they were exclusively oceanic by ~500 Ma. By contrast, evolved Hf values confirm that the coeval Notre Dame arc developed on the Laurentian margin between ~515-430 Ma. The preservation of very evolved (εHf =-15 to -25) Notre Dame arc zircons in Ganderian overstep sequences confirm the arrival of the leading edge of Ganderia to Laurentia by ~450 Ma.

The Dover Fault separates Ganderia from Avalonia. Monazite geochronology and mineral phase equilibria modelling of amphibolite facies rocks from within the fault system help constrain the younger tectonic evolution of Ganderia. The metamorphic rocks record two major stages of Ganderia evolution: (1) a low pressure (P), high temperature (T) (3-4 kbar, 600°C) event recorded by 460 ± 7 Ma monazites, associated with formation of the adjacent Tetagouche-Exploits back-arc basin, and (2) a higher P, lower T event (5-6 kbar, ~600-650°C) characterised by migmatisation and formation of garnet-sillimanite bearing metamorphic assemblages at 409 ± 6 Ma, interpreted to reflect a short interval of compression associated with the widespread Acadian orogeny.

The Hf isotopic arrays show that Avalonia records a history of arc magmatism dating back to 800-750 Ma, when it formed on Grenvillian-aged crust. A shift to more juvenile (+εHf) values by 700 Ma indicates it had evolved to an oceanic terrane at that stage, but like Ganderia, it also records the transition toward more evolved Hf isotopic compositions between 650-600 Ma, coinciding with accretion onto the Gondwanan margin.

Thereafter, it also records the shift back toward juvenile values as the terrane rifted from Gondwana to open the Rheic Ocean. The isotopic array of Meguma overlaps with those of Ganderia and Avalonia, indicating that it travelled the same journey. Accordingly, the three terranes are combined and referred to as "composite Avalonia".

The characteristic Hf array of composite Avalonia, and comparison with Hf data compilations from cratonic Amazonia, Baltica and Laurentia, allow Neoproterozoic to Paleozoic paleogeographic models to be reassessed. Avalonian continental arc magmatism began at ~800 Ma near the former Grenville suture-zone, most likely along the Laurentian margin. It is proposed that arc magmatism is the southern extension of the Valhalla arc in east Greenland. Propagation of an ocean spreading ridge behind the developing Valhalla Orogen opened the Asgard Sea, separating Baltica and Amazonia from Laurentia, possibly as early as 900 Ma. Subduction was initiated along the Laurentian margin between ~800-750 Ma, and the uniform shift toward juvenile ε(Hf) values between 750-650 Ma suggests the arc retreated from Laurentia to form the microcontinental ribbon of composite Avalonia by 700 Ma, opening proto-Iapetus as a back-arc basin between the ribbon and Laurentia. Migration of the composite Avalonian ribbon and its accretion to Gondwana by 650 Ma closed the Asgard Sea, as shown by the reversal of εHf data to progressively negative values between 650-600 Ma.

Reversal of the isotopic trend to +εHf values between 600-450 Ma for composite Avalonia, along with the Iberian and Amorican terranes of Europe, shows that all developed as a retreating oceanic arc off the north Gondwanan margin. As the ribbon separated the Rheic Ocean formed, with Meguma as the trailing passive margin. Composite Avalonia migrated northward, initially closing the Tornquist Sea as it collided with Baltica, then closing Iapetus at ~450 Ma during protracted collision with Laurentia. Following the final accretion of composite Avalonia by ~440 Ma, subduction stepped outboard into the trailing Rheic Ocean, placing composite Avalonia in an upper plate, suprasubduction zone setting. The εHf array for the northern Appalachian Orogen shows a progressive homogenisation toward CHUR. This "arrow-head" εHf array is interpreted to indicate crustal reworking during tectonic switching, between retreating (e.g. Salinic and Neoacadian orogenies) and advancing (e.g. Acadian orogeny) subduction episodes, which exclusively reworked the juvenile (Late Neoproterozoic) and Grenvillian-type basement.

The Variscan European hafnium array is remarkably similar to the Appalachian array between ~600-450 Ma in that both transition towards increasingly radiogenic values, indicating all the terranes along the northern Gondwanan margin developed into retreating magmatic arcs during subduction rollback. After ~450 Ma, the European arrays also record continual recycling of the former Neoproterozoic arc basement along a typical crustal evolutionary path, with limited input from the depleted mantle and no recycling of ancient Gondwanan crust. Intermittent back-arc opening and closing events, including the Variscan orogeny at ~360 Ma, occurred throughout the Paleozoic and early Mesozoic of Europe. The Mesozoic-Cenozoic εHf array of Variscan Europe simply reflects ongoing subduction-related magmatic activity in Europe associated with opening and closing of basins in the Tethyan oceanic realm, following Pangean amalgamation. A strong negative εHf excursion at 30 Ma indicates subduction and melting of Gondwanan cratonic lithosphere for the first time since 600 Ma, suggesting the arrival of former Gondwana into the subduction zone.

Hf isotopic arrays indicates that the completion of the type-Wilson cycle in the northern Appalachians is marked only by termination of magmatism as the εHf array converged on CHUR at ~300 Ma. Similarly in Europe the collision of Gondwana with Laurentia to form Pangea is not reflected in the εHf array and also reflects only the reworking of composite Avalonia. Therefore, the assembly of Pangea could form only part of a larger, longer-term supercontinental cycle. Accordingly, Hf isotopic arrays provide an opportunity to reassess Precambrian supercontinent reconstructions at a cratonic scale, but are less likely to recognise individual Wilson cycles unless they involve reworking of cratonic crust at the beginning and end of each cycle.

Declaration

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Publications arising from this thesis

Journal articles

Bonnie Henderson, W. J. Collins, J. Brendan Murphy, Gabriel Gutierrez-Alonso, Martin Hand, (in press), *Gondwanan basement terranes of the Variscan-Appalachian orogen: Baltican, Saharan and West African hafnium isotopic fingerprints in Avalonia, Iberia and the Armorican Terranes,* Tectonophysics, DOI:10.1016/j.tecto.2015.11.020

Bonnie Henderson, W.J. Collins, J. Brendan Murphy, Martin Hand, *A hafnium isotopic record of magmatic arcs and continental growth in the Iapetus Ocean: the contrasting evolution of Ganderia and the peri-Laurentian margin,* (in review), Gondwana Research

Conference abstracts

Bonnie Henderson, W.J. Collins, J. Brendan Murphy, Martin Hand, *What can hafnium isotope ratio arrays tell us about orogenic processes? An insight into geodynamic processes operating in the Alpine/Mediterranean region*, AGU Fall meeting 2013

Bonnie Henderson, W.J Collins, J. Brendan Murphy, Martin Hand, Gabriel Gutierrez-Alonso, Tracking the Neoproterozoic-Permian tectonic evolution of Avalonia in the Canadian Appalachians: a combined U-Pb-Hf detrital zircon study, Gondwana15, Madrid, 2014

W.J Collins, **Bonnie Henderson**, J. Brendan Murphy, Martin Hand, Gabriel Gutierrez-Alonso, *Evolution of Phanerozoic Europe from an Hf isotope perspective: implications for supercontinental and Wilson cycles*, Gondwana15, Madrid, 2014

G. Gutierrez-Alonso, J. Fernandez-Suarez, **Bonnie Henderson,** Daniel Pastor-Galan, Alicia Lopez Carmona, J. Brendan Murphy, Arlo B Weil, M Francisco Pereira, Javier Fernandez-Lozano, *Another model for Western Europe Paleozoic Variscan evolution: questioning redundant subduction and oceans*, Variscan 2015

Erin Martin, W. J. Collins, **Bonnie Henderson**, *Neoproterozoic global geodynamic rearrangement recorded by Hf isotopes in zircon: Birth of the circum-Pacific and dawn of the Phanerozoic,* Australian Earth Science Convention 2014

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