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Not all supercontinents are created equal: Gondwana-Rodinia case study

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ABSTRACT

The geologic records associated with the formation of the supercontinents Rodinia and Gondwana have markedly different seawater Sr and zircon Hf isotopic signatures. Rodinia-related (Grenville-Sveconorwegian-Sunsas) orogens display significantly less enriched crustal signatures than Gondwana-related (Pan-African) orogens. Seawater Sr isotope ratios also exhibit a more pronounced crustal signal during the span of the Gondwana supercontinent than at the time of Rodinia. Such isotopic differences are attributed to the age and nature of the continental margins involved in the collisional assembly, and specifically to the depleted mantle model ages, and hence the isotope ratios of the material weathered into the oceans. In our preferred model the isotopic signatures of Rodinia-suturing orogens reflect the closure of ocean basins with dual subduction zones verging in opposite directions, analogous to the modern Pacific basin. This would have resulted in the juxtaposition of juvenile continental and island arc terrains on both margins of the colliding plates, thus further reworking juvenile crust. Conversely, the assembly of Gondwana was accomplished primarily via a number of single-sided subduction zones that involved greater reworking of ancient cratonic lithologies within the collisional sutures. The proposed geodynamic models of the assembly of Rodinia and Gondwana provide a connection between the geodynamic configuration of supercontinent assembly and its resulting isotopic signature.

INTRODUCTION

Secular trends of geologic features such as U-Pb detrital zircon ages, abundance of passive margins, and Sr isotopes in seawater vary with the cycle of assembly and dispersal of supercontinents (Fig. 1; Hawkesworth et al., 2010; Bradley, 2011; Cawood et al., 2013). The running average of epsilon (ε) Hf in zircon has similar secular trends with peaks and troughs of positive and negative values (Fig. 1; e.g., Belousova et al., 2010; Roberts, 2012; Cawood et al., 2013). Specifically, the running average of εHf analyses from a worldwide database of ~7000 U-Pb and Hf analyses of zircons from Phanerozoic sediments (from Dhuime et al., 2012) shows the most negative trough of −12 at 550 Ma (Fig. 1), corresponding to the timing of the Gondwana-forming orogenies. These strongly negative values associated with Gondwana assembly contrast with those at the time of the Rodinia-forming orogenies (1250–980 Ma), when the εHf running mean remains near the chondritic uniform reservoir (Fig. 1).

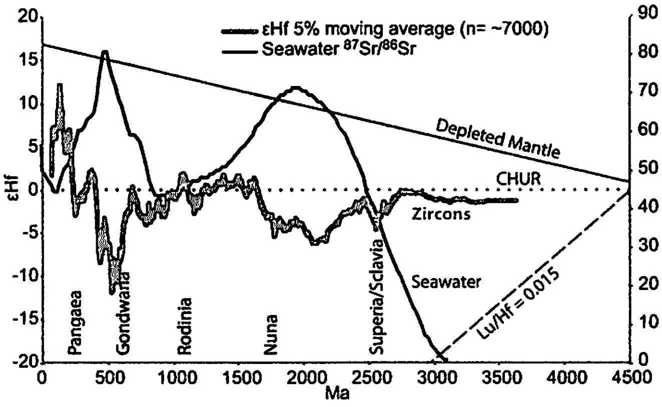

Figure 1. Normalized seawater $^{87}Sr/^{86}Sr$ curve (Shields, 2007) plotted with 5% running average of initial zircon εHf (i.e., 5% of total number, n, in database is used for period of running average) from global database of modern and recent river sediments (see Dhuime et al., 2012, for references). Time periods of Grenville and Pan-African orogenic events (Bradley, 2011) are outlined (CHUR—chondrite uniform reservoir).

We argue that the Sr and Hf isotopic characteristics of material formed during the assembly of supercontinents (specifically Rodinia and Gondwana), and consequently the Sr isotope ratios of seawater, are consequences of the age and isotope composition of the margins associated with the assembly of each supercontinent. We relate these isotopic features to differing models of supercontinent assembly.

RODINIA AND GONDWANA CONTINENTAL MARGINS

The ages of preserved continental margins involved in the assembly of Rodinia and Gondwana differ significantly in age and isotopic character. Relatively young, isotopically juvenile rock units dominate the continental margins incorporated into Rodinia, whereas the Gondwanan margins are significantly older and more evolved. Prior to the Rodinia-forming orogenies, the early Mesoproterozoic crust of the 1.5–1.3 Ga Granite-Rhyolite (USA), 1.51–1.45 Ga Pinwarian (Canada), 1.56–1.3 Ga Rondonian (Brazil), and 1.52–1.48 Ga Idefjorden, Bamble, and Telemark (Norway) provinces (Whitmeyer and Karlstrom, 2007; Bettencourt et al., 2010; Bingen et al., 2008) dominated the colliding margins of Laurentia, Amazonia, and Baltica. The rocks on these margins were <400 m.y. old at the time of collisional assembly. Other end-Mesoproterozoic orogenic events are also found in Australia, Antarctica, India, and north China; however, the assembly of these blocks resulted in geographically restricted episodes of magmatism (e.g., Kröner et al., 2003; Collins and Pisarevsky, 2005; Cawood and Kosch, 2008; Zhao and Cawood, 2012) (Fig. 2B). In contrast, Archean and Paleoproterozoic crust dominates the continental margins associated with the assembly of Gondwana. The Damara-Zambezi belt juxtaposes the northern Archean–Paleoproterozoic margins of the Kalahari craton and Rayner-Rauer complex with the southern Archean margins of the Congo and Dharwar cratons (Gray et al., 2008, and references therein; de Waele et al., 2008). The Dahomeyide, Pinjarra, and Brasiliano collisional orogens share similar relationships (e.g., Cawood, 2005; Rapela et al., 2011). These margins were significantly older at the onset of the amalgamation of Gondwana than those involved in the formation of Rodinia.

Using geologic maps and ArcGIS the present-day lengths of the margins were measured for the Rodinia- and Gondwana-forming orogens and the adjacent geologic provinces. This indicates that 63% of the Grenville-Sunsas-Sveconorwegian orogenies were juxtaposed with 1.3–1.5 Ga crust, the remaining comprising ca. 1.7–1.9 Ga crust (e.g., Labradorian and Yavapai provinces) (Fig. 2B). This is in stark contrast to the Gondwana-forming (Pan-African) orogenies, in which 58% of the margins involved are adjacent to Archean cratons and the remaining are comprised of Neoproterozoic and Mesoproterozoic crust and minor Paleoproterozoic crust (Fig. 2A).

Assuming that the present distribution of exposed rock units is representative of the relations at the time of syncollisional erosion, we

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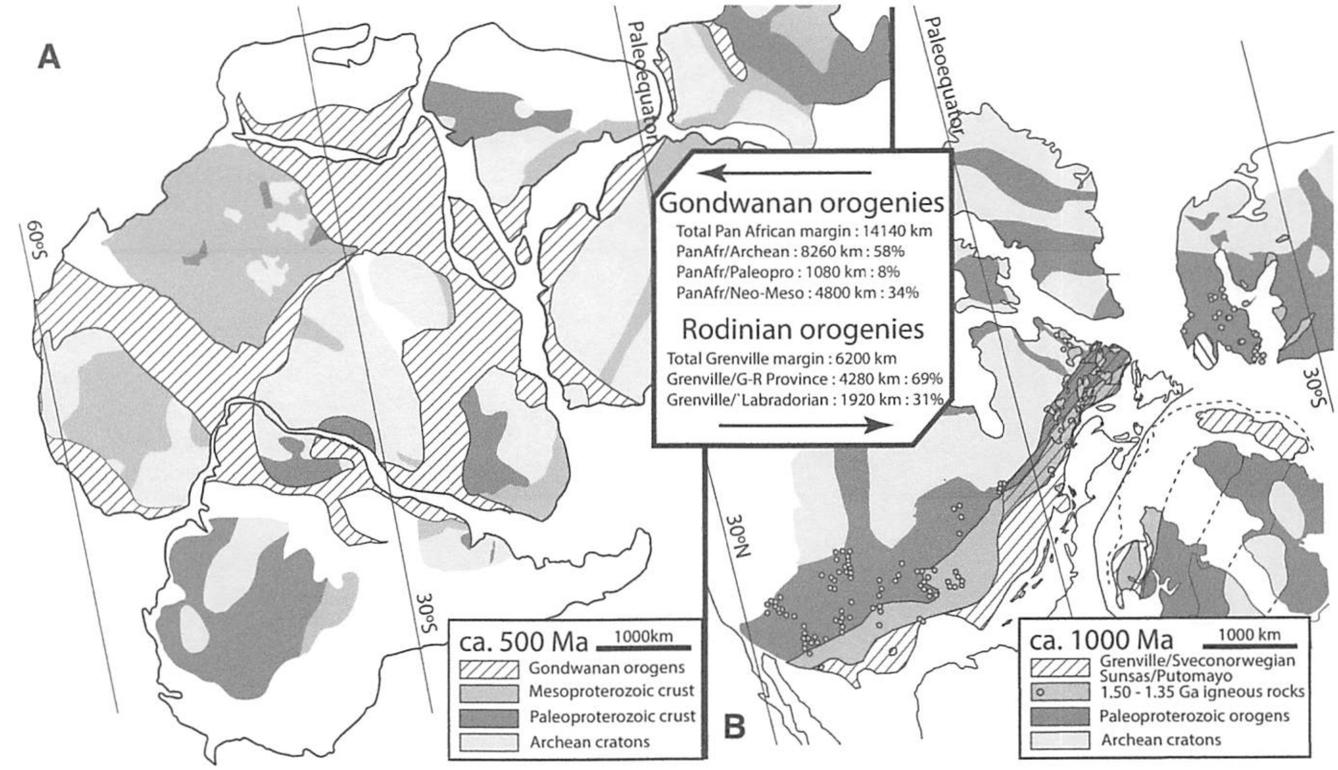

Figure 2. A: Map of Gondwana (ca. 500 Ma) showing extent of Gondwana-forming orogenies and distribution of Precambrian provinces (modified from Li et al., 2008; Cawood and Buchan, 2007; Torsvik and Cocks, 2009, and references therein). B: Map of Laurentia (ca. 1.3 Ga), with Paleozoic and younger geology omitted, showing extent of Rodinia-forming orogenies (modified from Tohver et al., 2002; Cawood and Buchan, 2007; Jacobs et al., 2008). PanAfr—Pan African; Paleopro—Paleoproterozoic; Meso—Mesoproterozoic; Neo—Neoproterozoic; G-R—Granite-Rhyolite.

compared the relative proportions of juvenile versus evolved crust associated with orogenesis during assembly of Rodinia and Gondwana. The compiled U-Pb and Hf analyses from Phanerozoic sediments (from Dhuime et al., 2012) were used to evaluate initial Hf isotope ratios in zircon and Hf depleted mantle model ages for zircons that crystallized in the periods associated with the assemblies of Gondwana and Rodinia in the Pan-African and Grenville orogenies, respectively.

Zircons with U-Pb crystallization ages of 520–650 Ma were selected to represent the isotope compositions of the rocks associated with the formation of Gondwana, and those with ages of 980–1250 Ma represent the assembly of Rodinia (Cawood and Buchan, 2007; Bradley, 2011). Depleted mantle model ages were then normalized to ages of 900 and 480 Ma, which broadly represent the end of the Rodinia- and Gondwana-forming orogenies, respectively (i.e., 480 and 900 Ma were subtracted from the present-day depleted mantle model ages of zircons that crystallized in the time periods identified, using an average crustal Lu/Hf = 0.15). Integration of probability density plots highlights that Rodinia-forming orogenies incorporate significantly more material with relatively young model ages, whereas Gondwana-forming orogens have a greater proportion of relative old model ages (Fig. 3).

The average depleted mantle model Hf ages from the Gondwana- and Rodinia-forming orogenies were in turn used to calculate the bulk Sr isotopic composition of the eroded margins at 900 Ma for Rodinia and 480 Ma for Gondwana assuming an average upper crustal Rb/Sr ratio of 0.256 (Rudnick and Gao, 2003). The Sr isotope ratio of seawater is ~0.7053 at 900 Ma and ~0.7082 at 480 Ma (from Shields, 2007), and the calculated average Sr isotope ratios of the active margins at those times were 0.709 and 0.711, respectively. Thus the Sr isotope ratio of seawater increased by 0.0029 between 900 Ma and 480 Ma, and the runoff from the active margins increased by 0.0019. Assuming that the Sr abundances in the fluxes from the mantle and crustal end members are similar to those of the present day, much of the difference between the Sr isotope signals for the Rodinia- and Gondwana-forming orogenies can therefore be attributed to the differences in the ages of the preexisting rocks reworked along those margins, and the rest may largely reflect the Sr isotope ratios of continental runoff from areas not involved in these two orogenic systems.

The different zircon Hf and seawater Sr isotope signatures of the Grenville and Pan-African orogenic systems is readily explained by contrasting geodynamic scenarios. The assembly of Rodinia (ca. 1250–1140 Ma) was primarily accomplished through dual opposing subduction zones beneath the Kalahari-Amazonia on one side (Ibanez-Mejia et al., 2011, and references therein; Jacobs et al., 2008) and Laurentia-Baltica on the other (Cawood et al., 2007; Rivers and Corrigan, 2000, and references therein; Bingen et al., 2008) (Fig. 4). This dual-sided subduction system juxtaposed juvenile continental arcs on the colliding continental margins. Several previously accreted island arc terranes are also found throughout the Grenville and related orogens (Rivers and Corrigan, 2000; Bingen et al., 2008), adding to the juvenile component of the continental margins. Compiled zircon Hf isotopes from Grenville-derived sedimentary rocks in Laurentia and Baltica (Fig. DR1 in the GSA Data Repository[1]) show an increasingly juvenile signature with time just prior to the collisional assembly of Amazonia, Laurentia, and Baltica (i.e., the ca. 1.5–1.3 Ga Granite-Rhyolite, Pinwarian, Labradorian, and Gothian provinces),

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[1] GSA Data Repository item 2013219, compiled zircon Hf isotopes from sedimentary rocks derived from the Grenville/Sveconorwegian and Pan-African orogenies (*sensu stricto*), is available online at www.geosociety.org/pubs/ft2013.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

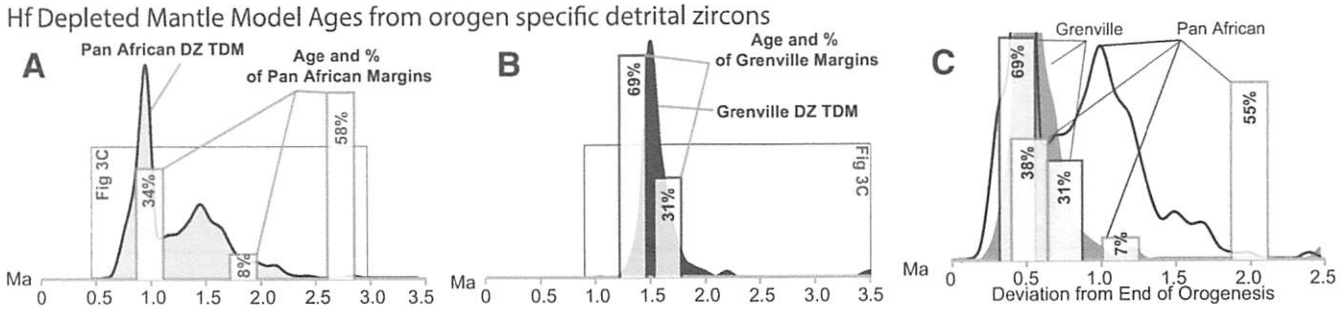

Figure 3. Relative probability of zircon Hf-depleted mantle model ages (TDM) of Grenville and Pan-African orogenies and percentage of pre–1.0 Ga and post–1.0 Ga analyses (shaded probability density plot). Percentage and age of continental margins involved in assembly of Rodinia and Gondwana are superimposed on TDM distributions (spaced histogram). Ages of margins are generalized average not representing exact span of time. A: Pan-African. B: Grenville. C: Closeup of left side of TDM distributions. Ages of margins and TDM ages are normalized to end of respective collisional orogenies.

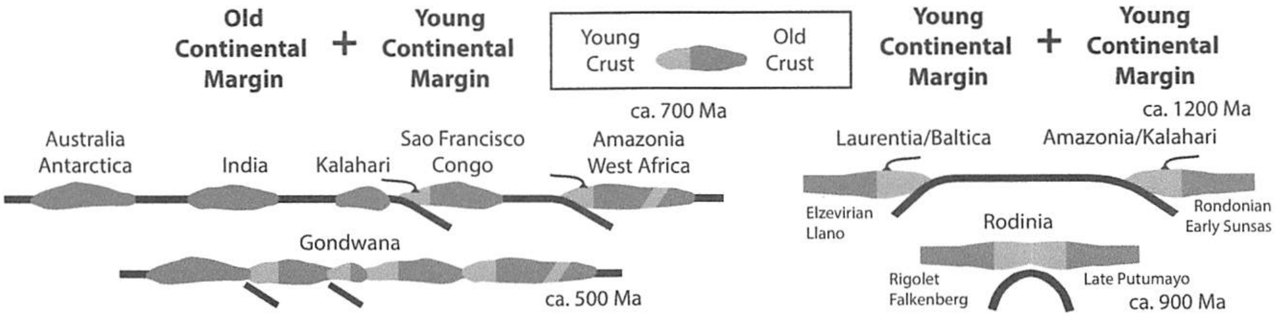

Figure 4. Contrasting supercontinent geodynamic models of Rodinia and Gondwana (modified from the modern circum-Pacific and Eurasian orogenic models of Collins et al., 2011).

consistent with a dual-opposing subduction model, and analogous to the modern Pacific (Fig. 4; see also Collins et al., 2011). Following the initial stages of collision (ca. 1.25 Ga), zircon Hf isotopes became increasingly isotopically enriched with a greater degree of crustal reworking (Fig. DR1).

The assembly of Gondwana was primarily accomplished through collision between the Amazonian–West African, Sao Francisco–Congo, Kalahari, India, and Australia-Antarctica cratons between 650 and 520 Ma (Collins and Pisarevsky, 2005; Cawood and Buchan, 2007) (Fig. 4). In contrast to the assembly of Rodinia, the isotopic data associated with the assembly of Gondwana require the incorporation of greater proportions of older crustal material (Avigad et al., 2012). We infer that the assembly of Gondwana was dominated by single-sided subduction, which allowed for the juxtaposition of juvenile continental arcs with passive margins (see also Meert, 2003; Gray et al., 2008). Although the Pan-African and other orogens associated with the assembly of Gondwana have a significant juvenile component in some areas (e.g., accreted island arcs and ophiolites of the Arabian-Nubian shield) (Stern, 2002; Johnson et al., 2011), Hf isotopic signatures indicate that an evolved continental signature dominated the orogenic system (Fig. 4). This is similar to the long-lived unidirectional subduction systems of Eurasia (Fig. DR1; see also Collins et al., 2011).

The observed isotopic patterns associated with the assembly of Gondwana and Rodinia reflect the ages of the contemporaneous continental margins and different styles of subduction and subsequent collision. These patterns can aid in the discrimination of various geodynamic styles of continental collision (e.g., single versus dual-sided assembly; Collins et al., 2011). Further work is needed along the margins of the other ancient supercontinents to assess the geodynamic configuration of supercontinent assembly and associated isotopic characteristics.

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