A late Archean origin for Guyania followed by one billion years of pervasive intra-crustal recycling

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April 12, 2016

ABSTRACT

The combined U-Pb-Hf-O isotope systematics of zircon from several Proterozoic granitoids of the Guyana Shield, northern South America, allow to infer that their preceding magmas were dominantly crustally-derived and sampled a source that separated from the mantle in the Neo-Archean. The Hf isotopic evolution of their possible crustal predecessor (herein referred to as Guyana Primordial Crust, or GPC) is revealed by the alignment of granitoid mean $^{176}Hf/^{177}Hf_{(t)}$ values in isotope vs. age space. The slope of this trend yields a time-integrated $^{176}Lu/^{177}Hf \approx 0.021$, which indicates the

GPC was likely mafic in composition. We suggest this crustal reservoir was the major mass contributor (as traced by Hf) to the ca. 2.2 to 1.4 Ga plutons exposed in the northern Guyana Shield, attesting to the importance of intra-crustal reworking for nearly 1.0 Gy of magmatic history in this major Precambrian crustal nucleus. The zircon U-Pb ages of the studied plutons indicate that these were themselves constructed by relatively short-lived felsic magmatic events at ca. 2.0, 1.8, 1.5 and 1.4 Ga, which are in cases geographically and temporally associated with the emplacement of mafic magmas occurring nearby or represented elsewhere in the shield. However, since no resolvable Hf contributions from these (presumably) more radiogenic mantle melts can be discerned from the granitoid data, the exposed felsic plutonic archive of the Guyana Shield gives the impression that no significant crustal addition took place in over one billion year timescales. In light of these new results, we suggest that the widely accepted model for the growth of northern Amazonia by lateral accretion of dominantly juvenile Paleo- to Mesoproterozoic intra-oceanic arcs is unsupported, and therefore fundamental aspects of its tectonic evolution will need revision.

INTRODUCTION

End-member models used to explain the origin and growth mechanisms of Earth's continental lithosphere postulate that: a) growth was dominantly episodic in nature, commonly associated with superplume events or mantle overturns (e.g., Stein and Hofmann, 1994; Condie, 1998; Arndt and Davaille, 2013); or b) growth was a steady-state process on average, mostly controlled by the continuous extraction of juvenile melts from the mantle along convergent plate margins in a scenario that resembles modern-day plate tectonics (e.g., Belousova et al., 2010; Dhuime et al., 2012). Distinguishing between these processes and resolving their net contribution to continental growth through time has proven difficult, as direct access to samples of mafic lower-crust is limited (Vervoort et al., 2000), and because intra-crustal distillation and contamination of mantle-derived melts typically causes mixed isotopic arrays that further conceal the evidences of primary crust-forming processes (Kemp et al., 2007).

The combined application of U-Pb, Lu-Hf and $\delta^{18}O$ in zircon has emerged as a powerful tool to unveil many issues associated with crust generation, and has sparked renewed interest in understanding the modes and rates of crustal growth throughout Earth's history (Cawood et al., 2013; Roberts and Spencer, 2015). However, despite these improved techniques, the dichotomy of episodic vs. continuous generation mechanisms still persists as evidences for growth along ancient active continental margins (e.g., Kemp et al., 2009; Collins et al., 2011) but also episodic generation (e.g., Kemp et al., 2006; Wang et al., 2009) can arguably be identified in the geologic record. Nevertheless, indications of the latter have mostly been inferred from the modern and ancient detrital zircon (DZ) record, while direct evidences from bedrock samples for the episodic formation and long-term survival/reworking of ancient crust at cratonic scales have remained scarce (e.g., Laurent and Zeh, 2015).

The Guyana Shield (Fig. 1) composes the northern half of the Amazon Craton (herein referred to as Amazonia), one of Earth's largest Precambrian nuclei (>4.4×10^6 km^2). The long-term evolution of Amazonia has been attributed to the progressive lateral growth by accretion of Proterozoic mobile belts around an ancient Archean core (Tassinari and Macambira, 1999; Cordani and Teixeira, 2007), much as the successive accretion of the Yavapai, Mazatzal, and Granite-Rhyolite provinces against the margins of the older (i.e., >1.8 Ga) core of North America are considered to progressively increase the crustal volume of Laurentia during the late Paleo- and Mesoproterozoic (Whitmeyer and Karlstrom, 2007). In this progressive growth scenario, distinct basement provinces and their isotopic compositions should each reveal the net addition of juvenile crust to a growing cratonic nuclei, thus attesting to the quasi-continuous nature of crustal generation and accretion as opposed to episodic formation and subsequent intra-crustal reworking. Given the still scarce isotopic constraints on the crustal growth history of northern Amazonia, and the relevance of this craton for Precambrian tectonics and supercontinents (Cordani et al., 2009), we aimed to test this accretionary model in order to better understand its growth within the context of global Proterozoic crust-generation processes.

SAMPLING AND METHODS

Samples were collected along a ~1000 km-long transect in the N Guyana Shield, covering most of the length of the Orinoco River in central Venezuela and segments of the Inírida and Atabapo Rivers near the Colombia-Venezuela border (Fig. 1). Plutonic rock samples were collected from the Imataca Complex (IC), the Cuchivero Group (CG), the Parguaza Rapakivi Granite (PRG), and the poorly studied Inírida/Atabapo granitoids of the Mitú Migmatitic Complex (MMC). Additionally, two metasedimentary migmatite samples from the IC and one paragneiss from a klippe of the Pastora allochthon (PA) overlying the IC were also collected. This sampling transect is perpendicular to the strike of the major basement provinces thought to constitute Amazonia, which are generally postulated to be dominantly accretionary in nature; these are the Maroni-Itacaiunas (MI), Ventuari-Tapajos (VT), and Rio Negro-Juruena (RNJ) provinces (Fig. 1).

Zircon from twenty-two granitoids and three paragneiss samples were analyzed for U-Pb and Lu-Hf isotopes by laser ablation – multicollector – inductively coupled plasma – mass spectrometry (LA-MC-ICP-MS) at the Arizona LaserChron (ALC) facility. Twenty-one intrusive rock samples were analyzed for $\delta^{18}O_{(zrn)}$ using a CAMECA 1280 ion microprobe at the WiscSIMS facility. Analytical results, methods, sampling coordinates and petrographic classifications of studied samples are included in the online Data Repository (DR1-DR6 Tables).

RESULTS

Cathodoluminescence imaging revealed that zircon crystals from all our plutonic samples have oscillatory zoning patterns consistent with a magmatic origin. Excluding the results from samples of the Imataca Complex, which is regarded as an exotic block to the Guyana Shield (Tassinari et al., 2004), the obtained ages of igneous crystallization for all other plutons range between ca. 1390 and 2140 Ma, and yield mean $\varepsilon Hf_{(t)}$ compositions in the range from -5.6 to +3.5; no isotopically juvenile (i.e., depleted mantle-like) compositions in terms of $^{176}Hf/^{177}Hf_{(t)}$ were measured for any of our samples. Additionally, despite the significant distance in between all sampling locations (>1000 km, Fig. 1), the U-Pb ages and $^{176}Hf/^{177}Hf_{(t)}$ values obtained for each geologic unit define tight clusters around a narrow age and Hf isotope compositional range (Fig. 2). This suggests that the magmatic systems that constructed these plutons were relatively short-lived in nature and likely sampled a source with relatively homogeneous Hf isotope compositions (e.g., Andersen et al., 2009). The $\delta^{18}O_{(zrn)}$ results are variable between units but also fairly consistent for different samples within the same unit (Fig. 3). The PRG and CG yield $\delta^{18}O_{(zrn)}$ that either resemble or deviate slightly from mantle-like zircon compositions; mean values between 5.7 and 6.5 ‰ for the PRG may indicate a limited degree of supracrustal contamination whereas samples from the CG, although all within uncertainty of mantle-like compositions, display some low values below 5.0 ‰ that could be indicative of hydrothermal alteration of their source. Granitoids from the MMC on the other hand, have a clear supracrustal signature, many of them displaying elevated mean values above 7.5 ‰ and thus indicating a significant contribution of supracrustally altered (e.g., sedimentary) material in their source region (Valley et al., 2005).

Results from the IC and the PA show that these domains have a much older ancestry with respect to all other samples studied here, indicated by the significantly lower $^{176}Hf/^{177}Hf_{(t)}$ compositions measured both from protolith zircon cores of orthogneisses and detrital zircon cores in metasedimentary gneisses (Fig. 2). This corroborates the previously inferred exotic nature for these units with respect to the main Guyana basement (Tassinari et al., 2004; Hildebrand et al., 2014; DR7 figure).

EPISODIC NEOARCHEAN CRUST GENERATION

The Paleo- to Mesoproterozoic granitoids of the northwestern Guyana Shield define a conspicuous linear array in Hf isotope vs. crystallization age space (Fig. 2), strongly suggestive of an origin dominated by intra-crustal reworking of an ancient and isotopically closed crustal reservoir with respect to Hf (e.g., Kemp et al., 2006). A linear regression through the $^{176}Hf/^{177}Hf_{(t)}$ values obtained for granites that display mantle-like or only moderately elevated $\delta^{18}O_{(zrn)}$ compositions (i.e., between 5.0 and 6.5 ‰) delineates the evolution of their crustal predecessor, herein referred to as Guyana Primordial Crust (GPC). This regression defines an array with a modeled depleted mantle (DM) intercept near 2.6 Ga (assuming a juvenile-crust-like mantle model; Vervoort and Blichert-Toft, 1999) while its slope constrains a source $^{176}Lu/^{177}Hf \approx 0.021$, suggesting that the GPC was likely mafic in composition (e.g., Pietranik et al., 2008). Remarkably, granitoids found to have elevated $\delta^{18}O_{(zrn)} > 7.5$ ‰ and thus indicative of the involvement of surficially-altered supracrustal material in their source region, do not significantly deviate from the regressed relation shown in Fig. 2; this makes the selection of the $\delta^{18}O_{(zrn)}$ cutoff used for defining the GPC rather unimportant for the regressed array. The elevated $\delta^{18}O_{(zrn)}$ compositions of the MMC samples, which were obtained from either two-mica or garnet-bearing granitoids, suggest that sediment reworking constituted an important component in the source during their generation. However, the general agreement in Hf isotopic signatures between the ~1.8 Ga MMC granites and the GPC suggests that sediment reworking took place rapidly and also within a relatively closed-system (with respect to Hf), possibly within an isolated Paleo- Mesoproterozoic Amazonia (or Guyania?) proto-craton (e.g., Pisarevski et al., 2014). The slightly less radiogenic $^{176}Hf/^{177}Hf_{(t)}$ values obtained from the ~1.5 Ga granites of the MMC with respect to the main GPC trend could be a result of supra-crustal Lu-Hf decoupling during older erosion and sedimentation (i.e., 'zircon effect'; Vervoort et al., 1999), or also by mass contribution from older, possibly IC-like material to their sources (Fig. 2).

Our inferences about the GPC composition described above are not exclusively supported from the new data presented here. Mesoproterozoic (ca. 1.5 Ga) anorthosites and granitoids of the Mucujaí complex in the south central part of the Guyana shield (Heinonen et al., 2011), approximately 700 km away from our study area (Fig. 1), yield Hf isotope compositions that fit well with our model (Fig. 2). Additionally, the Paleoproterozoic (ca. 1.99 Ga) Kabalebo charnockites from the Bakhuis Mountains UHT terrane in western Suriname (>1000 km away from our study area; Klaver et al., 2015a) also have Hf isotope compositions consistent with derivation from a GPC-like reservoir (Fig. 2). These observations further support the idea that the shared crustal ancestry of Guyania could indeed be cratonic in scale and not only a fortuitous localized phenomenon.

Zircon U-Pb ages in the range from 2.5 to 2.8 Ga, around the inferred extraction timing of the GPC, are mostly absent from the U-Pb detrital zircon record of the Guyana Shield (Goldstein et al., 1997). This is not a surprising result, as would be expected from a crustal predecessor that was dominantly mafic in composition and thus had low fertility to form this phase. However, we note that this inferred extraction interval coincides with a major pulse of juvenile magmatism known to have taken place between 2.5 and 2.8 Ga in other cratons (McCulloch and Bennett, 1994; Condie, 2005) but that, thus far, had been notably under-represented in the global zircon Hf record (Kemp and Hawkesworth, 2014). The new zircon Hf data from the Guyana shield presented here fill this apparent gap in the episodicity of crustal-generation observed for the late Archean (Pietranik et al., 2008; Kemp and Hawkesworth, 2014; DR7).

INTRACRUSTAL RECYCLING AND APPARENT NO GROWTH

Source hybridization and resulting mixed isotopic arrays are not exclusively related to the incorporation of supracrustal material to a dominantly juvenile magma, but can also develop via addition of younger, and thus more radiogenic, juvenile material to a crustally-derived melt (e.g., by mafic underplating and mixing in sub-arc or mantle plume systems). The addition of contemporaneous juvenile mantle material to an ancient mantle-derived reservoir, however, would not be identifiable from the $\delta^{18}O_{(zrn)}$ data if the older crust has not experienced significant hydrothermal or sub-aerial weathering, as no significant contrast in the $^{18}O/^{16}O$ ratios of these two mantle-derived mixing components (regardless of the age of mantle extraction) would exist. Nevertheless, such a process would result in a positive deflection of the $^{176}Hf/^{177}Hf$ compositions of hybrid magmas towards more radiogenic values (see Fig. 4 of Ibanez-Mejia et al., 2015), shifted by a magnitude that positively correlates with the mass of Hf contributed by the modern juvenile end-member (e.g., Xu et al., 2008). Although the geochronological database for the Guyana shield is still limited, particularly regarding its mafic magmatic 'barcode' (Ernst et al., 2013), recent geochronologic results have shown that regional mafic magmatism occurred throughout the shield contemporaneously (within uncertainties) with respect to the granitoids studied here. For instance, gabbros are known to occur in association with charnockitic intrusives of the Serra da Prata suite, emplaced in the south-central part of the shield at ca. 1.94 Ga (Fraga et al., 2009). The Avanavero Large Igneous Province, emplaced at 1.79 Ga, is widespread in the central part of the shield and consists of thick dykes and sills of tholeiitic affinity (Reis et al., 2013). Furthermore, mafic dyke swarms of possible Paleoproterozoic age are known to intrude the IC and the CG near our study area (Onstott et al., 1984; Gibbs, 1987), and also known to occur in association with the UHT basement of the Bakhuis Mountains (Klaver et al., 2015b). However, since no noticeable positive deviations or clear vertical mixing trends in $^{176}Hf/^{177}Hf$ values are observed for the Guyana Shield plutons reported here (Fig. 2), and the time-integrated $^{176}Lu/^{177}Hf$ slope regressed for the GPC resembles that typical of mafic crust (e.g., Kemp et al., 2006; Pietranik et al., 2008), we suggest that no voluminous additions of contemporaneous mantle material to the source of the studied granitoids can be discerned from the Hf data. This pattern gives the apparent impression that no juvenile crustal additions occurred during the ca. 2.6 to 1.4 Ga time interval.

The results described above are puzzling, and stimulate additional questions regarding the possible tectonic scenario(s) and the mechanisms responsible for generating the punctuated episodes of magma emplacement evidenced by the new Guyana Shield U-Pb data. Although a full discussion of the tectonics associated with each magmatic pulse is beyond the scope of this paper, we briefly speculate that a possible mechanism to generate repeated crustally-derived magmatism with no apparent rejuvenation could be by extensive underplating of mafic magmas providing enough heat and/or water to melt the lower crust (e.g., Petford and Gallagher, 2001; Collins et al., 2016) but without significant transfer of mass –or at least HFSE– from contemporaneous mantle to the evolved mid- to upper-crustal felsic plutons. A similar generation model has been proposed for the crustally-derived anorogenic granites of Laurentia (Goodge and Vervoort, 2006), Paleoproterozoic granitic intrusives of the Transscandinavian Igneous Belt in Sweden (Andersen et al., 2009) and the classic Rapakivi granites of Finland (Heinonen et al., 2010). In the Fennoscandian scenarios, geophysical (Korja and Heikkinen, 2005) and geochronologic (Söderlund et al., 2005) evidence exists to support the emplacement of large volumes of mafic magma in close spatial and temporal association with the generation of isotopically homogeneous crustal melts. This analog could be particularly meaningful for understanding the new data from the Guyana Shield, considering the possible close paleogeographic relation between these two shields during parts of the Paleo- Mesoproterozoic (Pisarevski et al., 2014; D'Agrella-Filho et al., 2016; and references therein).

AMAZONIA OR GUYANIA?

The crustal generation and evolution scenario for the Guyana shield described herein is in stark contrast with the generally accepted models for the development of Amazonia, which postulate that growth took place progressively throughout the Proterozoic via lateral accretion of dominantly juvenile arc-like terranes around an older Archean nucleus (Tassinari and Macambira, 1999; Santos et al., 2000). Our results suggest that a major episode of crustal growth took place rapidly near the Archean-Proterozoic boundary, and that this material was later re-melted during successive intra-crustal reworking episodes to generate the plutons that dominate the exposed magmatic archive of the shield.

Due to the paucity of comparable U-Pb-Hf-O data from the southern portion of Amazonia, it is yet unclear if this same period of episodic generation is also representative of the crust south of the Amazon River graben (i.e., the Central Brazilian shield, CBS). However, the large number and wide distribution of samples from which Nd isotopic results have been obtained in the CBS (Tassinari and Macambira, 1999; Santos et al., 2000; Cordani and Teixeira, 2007; and references therein) suggest that the traditional accretionary model might be more applicable to the southern fragment of Amazonia's basement. Based on these apparent differences, we speculate that the Guyana Shield and CBS might represent crustal fragments with contrasting origins and growth histories that were amalgamated to form a composite Amazon Craton prior to its incorporation to the Rodinia supercontinent. Although more data are needed in order to validate these differences, recent paleomagnetic results from ca. 1.8 Ga units in the Guyana Shield and the CBS (i.e., Colider and Avanavero poles; Bispo-Santos et al., 2008, 2013) are consistent with the viability of a 'composite Amazonia' hypothesis.

ACKNOWLEDGEMENTS

We thank P.J. Patchett and M.P Eddy for discussions on data interpretation, Z. Amaya and D. Mendi for their help during fieldwork, M. Baquero for access to borehole sample CNX-1, and A. Strickland, K. Kitajima, and N. Kita for assistance with the CAMECA 1280 at the WiscSIMS facility. The ICP-MS and SEM facilities at the ALC are partially funded by NSF-EAR-1338583 and EAR-0732436 awards. WiscSIMS is partially supported by NSF-EAR-1053466, -1355590. This research also benefited from NSF-EAR-1118525.

REFERENCES

Andersen, T., Andersson, U.B., Graham, S., Aberg, G., and Simonsen, S.L., 2009, Granitic magmatism by melting of juvenile continental crust: new constraints on the source of Palaeoproterozoic granitoids in Fennoscandia from Hf isotopes in zircon: *Journal of The Geological Society*, v. 166, p. 233–247.

Arndt, N., and Davaille, A., 2013, Episodic Earth evolution: *Tectonophysics*, v. 609, p. 661–674, doi: 10.1016/j.tecto.2013.07.002.

Belousova, E.A., Kostitsyn, Y.A., Griffin, W.L., Begg, G.C., O'Reilly, S.Y., and Pearson, N.J., 2010, The growth of the continental crust: Constraints from zircon Hf-isotope data: *Lithos*, v. 119, no. 3-4, p. 457–466, doi: 10.1016/j.lithos.2010.07.024.

Bispo-Santos, F., D'Agrella-Filho, M. S., Pacca, I. I. G., Janikian, L., Trindade, R. I. F., Elming, S.-A., et al. (2008). Columbia revisited: Paleomagnetic results from the 1790 Ma Colider volcanics (SW Amazonian Craton, Brazil). *Precambrian Research*, *164*(1-2), 40–49.

Bispo-Santos, F., D'Agrella-Filho, M. S., Trindade, R. I. F., Janikian, L., & Reis, N. J., 2013, Was there SAMBA in Columbia? Paleomagnetic evidence from 1790Ma Avanavero mafic sills (northern Amazonian Craton). *Precambrian Research*, *244*, 139–155. http://doi.org/10.1016/j.precamres.2013.11.002

Bouvier, A., Vervoort, J. D., & Patchett, P. J., 2008, The Lu-Hf and Sm-Nd isotopic composition of CHUR: Constraints from unequilibrated chondrites and implications for the bulk composition of terrestrial planets. *Earth and Planetary Science Letters*, *273*(1-2), 48–57.

Cawood, P.A., Hawkesworth, C.J., and Dhuime, B., 2013, The continental record and the generation of continental crust: *Geological Society Of America Bulletin*, v. 125, no. 1-2, p. 14–32.

Collins, W. J., Belousova, E. A., Kemp, A. I. S., & Murphy, J. B. (2011). Two contrasting Phanerozoic orogenic systems revealed by hafnium isotope data. *Nature Geoscience*, *4*(5), 333–337.

Collins, W. J., Huang, H.-Q., & Jiang, X. (2016). Water-fluxed crustal melting produces Cordilleran batholiths. *Geology*, *44*(2), 143–146.

Condie, K.C., 2005, Crustal and Mantle Evolution, in Earth as an Evolving Planetary System, Elsevier, Amsterdam, p. 265–314.

Condie, K.C., 1998, Episodic continental growth and supercontinents: a mantle avalanche connection?: *Earth And Planetary Science Letters*, v. 163, no. 1-4, p. 97–108.

Cordani, U.G., and Teixeira, W., 2007, Proterozoic accretionary belts in the Amazonian Craton : *The Geological Society of America, Special Publications*, v. 200, p. 297–320.

Cordani, U. G., Teixeira, W., D'agrella-Filho, M. S., & Trindade, R. I. (2009). The position of the Amazonian Craton in supercontinents. *Gondwana Research*, *15*(3-4), 396–407.

D'Agrella-Filho, M. S., Trindade, R. I. F., Queiroz, M. V. B., Meira, V. T., Janikian, L., Ruiz, A. S., & Bispo-Santos, F. (2016). Reassessment of Aguapeí (Salto do Céu) paleomagnetic pole, Amazonian Craton and implications for Proterozoic supercontinents. *Precambrian Research*, *272*, 1–17.

Dhuime, B., Hawkesworth, C., and Cawood, P., 2011, When Continents Formed: *Science*, v. 331, no. 6014, p. 154–155.

Dhuime, B., Hawkesworth, C.J., Cawood, P.A., and Storey, C.D., 2012, A Change in the

Geodynamics of Continental Growth 3 Billion Years Ago: *Science*, v. 335, no. 6074, p. 1334–1336.

Ernst, R.E., Bleeker, W., Soderlund, U., and Kerr, A.C., 2013, Large Igneous Provinces and supercontinents: Toward completing the plate tectonic revolution: Lithos, v. 174, p. 1–14.

Fraga, L.M., Macambira, M.J.B., Dall'Agnol, R., and Costa, J.B.S., 2009, 1.94–1.93 Ga charnockitic magmatism from the central part of the Guyana Shield, Roraima, Brazil: Single-zircon evaporation data and tectonic implications: Journal Of South American Earth Sciences, v. 27, no. 4, p. 247–257.

Gibbs, A.K., 1987, Contrasting Styles of Continental Mafic Intrusions in the Guiana Shield, in Halls, H.C. and Fahrig, W.F. eds., Mafic Dyke Swarms, Geological Association of Canada Special Papers, p. 457–465.

Goldstein, S., Arndt, N., and Stallard, R., 1997, The history of a continent from U-Pb ages of zircons from Orinoco River sand and Sm-Nd isotopes in Orinoco basin river sediments: Chemical Geology, v. 139, no. 1-4, p. 271–286.

Goodge, J., & Vervoort, J., 2006, Origin of Mesoproterozoic A-type granites in Laurentia: Hf isotope evidence. *Earth and Planetary Science Letters*, *243*, 711–731.

Heinonen, A.P., Andersen, T., and Ramo, O.T., 2010, Re-evaluation of Rapakivi Petrogenesis: Source Constraints from the Hf Isotope Composition of Zircon in the Rapakivi Granites and Associated Mafic Rocks of Southern Finland: Journal Of Petrology, v. 51, no. 8, p. 1687–1709.

Heinonen, A.P., Fraga, L.M., Ramo, O.T., Dall'Agnol, R., Mänttäri, I., and Andersen, T., 2011, Petrogenesis of the igneous Mucajaí AMG complex: Lithos,, p. 1–18.

Hildebrand, R. S., Buchwaldt, R., & Bowring, S. A. (2014). On the allochthonous nature of auriferous greenstones, Guayana shield, Venezuela. *Gondwana Research*, *26*(3-4), 1129–1140.

Ibanez-Mejia, M., Pullen, A., Arenstein, J., Gehrels, G. E., Valley, J. W., Ducea, M. N., et al. (2015). Unraveling crustal growth and reworking processes in complex zircons from orogenic lower-crust: The Proterozoic Putumayo Orogen of Amazonia. *Precambrian Research*, *267*, 285–310.

Kemp, A.I.S., and Hawkesworth, C.J., 2014, Growth and Differentiation of the Continental Crust from Isotope Studies of Accessory Minerals: Elsevier Ltd. pages?

Kemp, A.I.S., Hawkesworth, C.J., Collins, W.J., Gray, C.M., Blevin, P.L., EIMF, 2009, Isotopic evidence for rapid continental growth in an extensional accretionary orogen: The Tasmanides, eastern Australia: Earth And Planetary Science Letters, v. 284, p. 455–466.

Kemp, A.I.S., Hawkesworth, C.J., Foster, G.L., Paterson, B.A., Woodhead, J.D., Hergt, J.M., Gray, C.M., and Whitehouse, M.J., 2007, Magmatic and crustal differentiation history of granitic rocks from Hf-O isotopes in zircon: Science, v. 315, no. 5814, p. 980–983.

Kemp, A.I.S., Hawkesworth, C.J., Paterson, B.A., and Kinny, P.D., 2006, Episodic growth of the Gondwana supercontinent from hafnium and oxygen isotopes in zircon:

Nature, v. 439, no. 7076, p. 580–583.

Klaver, M., de Roever, E. W. F., Nanne, J. A. M., & Mason, P. R. D., 2015a, Charnockites and UHT metamorphism in the Bakhuis Granulite Belt, western Suriname: Evidence for two separate UHT events. *Precambrian Research*, *262*, 1–19.

Klaver, M., de Roever, E. W. F., Thijssen, A. C. D., Bleeker, W., Soderlund, U., Chamberlain, K., Ernst, R., Berndt, J., Zeh, A., 2015b, Mafic magmatism in the Bakhuis Granulite Belt (western Suriname): relationship with charnockite magmatism and UHT metamorphism. *Gff*, 1–16.

Korja, A., and Heikkinen, P., 2005, The accretionary Svecofennian orogen—insight from the BABEL profiles: Precambrian Research, v. 136, no. 3-4, p. 241–268.

Laurent, O., & Zeh, A., 2015, A linear Hf isotope-age array despite different granitoid sources and complex Archean geodynamics: Example from the Pietersburg block (South Africa). *Earth and Planetary Science Letters*, *430*, 326–338.

McCulloch, M.T., and Bennett, V.C., 1994, Progressive growth of the Earth's continental crust and depleted mantle: geochemical constraints: Geochimica Et Cosmochimica Acta, v. 58, no. 21, p. 4717–4738.

Onstott, T. C., Hargraves, R. B., & York, D., 1984, Dating of Precambrian diabase dikes of Venezuela using paleomagnetic and $^{40}Ar/^{39}Ar$ methods (Vol. 2, pp. 513–518). Presented at the Anais II Symposium Amazônico, Manaus, Brazil.

Petford, N., and Gallagher, K., 2001, Partial melting of mafic (amphibolitic) lower crust by periodic influx of basaltic magma: Earth And Planetary Science Letters, v. 193, p. 483–499.

Pietranik, A.B., Hawkesworth, C.J., Storey, C.D., Kemp, A.I.S., Sircombe, K.N., Whitehouse, M.J., and Bleeker, W., 2008, Episodic, mafic crust formation from 4.5 to 2.8 Ga: New evidence from detrital zircons, Slave craton, Canada: Geology, v. 36, no. 11, p. 875.

Pisarevsky, S. A., Elming, S.-A., Pesonen, L. J., & Li, Z.-X. (2014). Mesoproterozoic paleogeography: Supercontinent and beyond. *Precambrian Research*, *244*, 207–225.

Reis, N.J., Teixeira, W., Hamilton, M.A., Bispo-Santos, F., Almeida, M.E., and D'Agrella-Filho, M.S., 2013, Avanavero mafic magmatism, a late Paleoproterozoic LIP in the Guiana Shield, Amazonian Craton: U–Pb ID-TIMS baddeleyite, geochemical and paleomagnetic evidence: Lithos, v. 174, p. 175–195.

Roberts, N. M. W., and Spencer, C. J., 2015, The zircon archive of continent formation through time. *Geological Society, London, Special Publications*, *389*(1), 197–225.

Santos, J., Hartmann, L., Gaudette, H., Groves, D., McNaughton, N., and Fletcher, I., 2000, A new understanding of the provinces of the Amazon craton based on integration of field mapping and U-Pb and Sm-Nd geochronology: Gondwana Research, v. 3, no. 4, p. 453–488.

Söderlund, U., Isachsen, C., Bylund, G., Heaman, L., Patchett, J.P., Vervoort, J., and Andersson, U., 2005, U-Pb baddeleyite ages and Hf, Nd isotope chemistry constraining repeated mafic magmatism in the Fennoscandian Shield from 1.6 to 0.9 Ga:

Contributions To Mineralogy And Petrology, v. 150, no. 2, p. 174–194.

Stein, M., and Hofmann, A.W., 1994, Mantle plumes and episodic crustal growth: Nature, v. 372, no. 6501, p. 63–68.

Tassinari, C., and Macambira, M., 1999, Geochronological provinces of the Amazonian Craton: Episodes, v. 22, no. 3, p. 174–182.

Tassinari, C., Munha, J., Teixeira, W., Palacios, T., Nutman, A., S, C., Santos, A., and Calado, B., 2004, The imataca complex, NW Amazonian craton, Venezuela: Crustal evolution and integration of geochronological and petrological cooling histories: Episodes, v. 27, no. 1, p. 3–12.

Valley, J. W., Lackey, J., Cavosie, A., Clechenko, C., Spicuzza, M., Basei, M., Bindeman, I., Ferreira, V., Sial, A., King, E., Peck, W., Sinha, A.K., and Wei, C., 2005, 4.4 billion years of crustal maturation: oxygen isotope ratios of magmatic zircon: *Contributions To Mineralogy And Petrology*, v. 150, no. 6, p. 561–580.

Vervoort, J.D., and Blichert-Toft, J., 1999, Evolution of the depleted mantle: Hf isotope evidence from juvenile rocks through time: *Geochimica Et Cosmochimica Acta*, v. 63, no. 3, p. 533–556.

Vervoort, J., Patchett, P., Albarede, F., Blichert-Toft, J., Rudnick, R., and Downes, H., 2000, Hf-Nd isotopic evolution of the lower crust: *Earth And Planetary Science Letters*, v. 181, no. 1-2, p. 115–129.

Vervoort, J., Patchett, P., Blichert-Toft, J., & Albarede, F., 1999, Relationships between

Lu-Hf and Sm-Nd isotopic systems in the global sedimentary system. *Earth and Planetary Science Letters*, *168*, 79–99.

Wang, C.Y., Campbell, I.H., Allen, C.M., Williams, I.S., and Eggins, S.M., 2009, Rate of growth of the preserved North American continental crust: Evidence from Hf and O isotopes in Mississippi detrital zircons: Geochimica Et Cosmochimica Acta, v. 73, no. 3, p. 712–728.

Whitmeyer, S.J., and Karlstrom, K.E., 2007, Tectonic model for the Proterozoic growth of North America: Geosphere, v. 3, no. 4, p. 220–259.

Xu, Y.-G., Luo, Z.-Y., Huang, X.-L., He, B., Xiao, L., Xie, L.-W., and Shi, Y.-R., 2008, Zircon U–Pb and Hf isotope constraints on crustal melting associated with the Emeishan mantle plume: Geochimica Et Cosmochimica Acta, v. 72, no. 13, p. 3084–3104.

FIGURE CAPTIONS

Figure 1. Simplified maps of northern South America showing: a) the location and outline of the exposed Guyana Shield, with internal traces denoting the approximate boundaries of Amazonia's geochronological provinces, their names and inferred ages of crust generation (after Tassinari and Macambira, 2009; Cordani and Teixeira, 2007); and b) outline of relevant geological units and location of samples analyzed during this study. GS - Guyana Shield; BM – Bakhuis Mountains; CA – Central Amazonia Province; MI – Maroni-Itacaiunas province; VT – Ventuari-Tapajos province; RNJ: Rio Negro-Juruena province; IC – Imataca Complex; SC & PA; Supamo Complex & Pastora Allochthon;

CG – Cuchivero Group; PRG – Parguaza Rapakivi Granites; MMC – undifferentiated Mitú Migmatitic Complex; MC – Mucujaí Complex. Solid blue lines denote national borders.

Figure 2. Initial $^{176}Hf/^{177}Hf$ compositions of zircon from granitoids of the Guyana Shield at their respective mean U-Pb crystallization ages. Black dashed line represents a regression using only granitoids with mean $\delta^{18}O_{(zrn)}$ values between 5.0 and 6.5 ‰ (fig. DR 7); this yields an array with a time-integrated $^{176}Lu/^{177}Hf \approx 0.021$, typical of mafic crust, and an approximate mantle 'extraction' time ca. 2.64 Ga assuming a juvenile crust-like depleted mantle model (DM; Vervoort and Blichert-Toft, 1999) or ca. 2.52 Ga assuming a 'New Crust' model (NC; Dhuime et al., 2011). Samples of the Imataca complex and Pastora allochthon plot significantly below the GPC model, indicating their derivation from a much older crustal ancestor. The age range indicated for the Transamazonian orogeny is the mean U-Pb age obtained for zircon rims from a migmatite leucosome in the Imataca complex (sample 10MIGU18, see DR). Data from the Mucujaí complex are after Heinonen et al. (2011); Kabalebo charnockites of the Bakhuis Mountains after Klaver et al. (2015a). CHUR – chondritic uniform reservoir model after Bouvier et al., (2008).

Figure 3. Values of $\delta^{18}O_{(zrn)}$ vs. mean zircon U-Pb age from granitoids of the Guyana Shield. Symbols are the same as in Figures 1 and 2. Error bars shown as 2 SD. Mantle-derived zircon envelope after Valley et al. (2005), also shown at 2 SD.

SUPPLEMENTARY MATERIAL

DR1 Table. Instrumental parameters for LA-MC-ICP-MS U-Pb and Yb-Lu-Hf measurements

DR2 Table. Sampling coordinates and petrographic/macroscopic rock type descriptions

Table DR2 would be a good place for a table listing and defining ALL abbreviations from this paper.

DR3 Table. Summary of U-Pb ages and Hf-O isotope compositions of zircons obtained in this study

DR4 Table. Tabulated analytical data – U-Pb analysis of zircon by LA-MC-ICP-MS

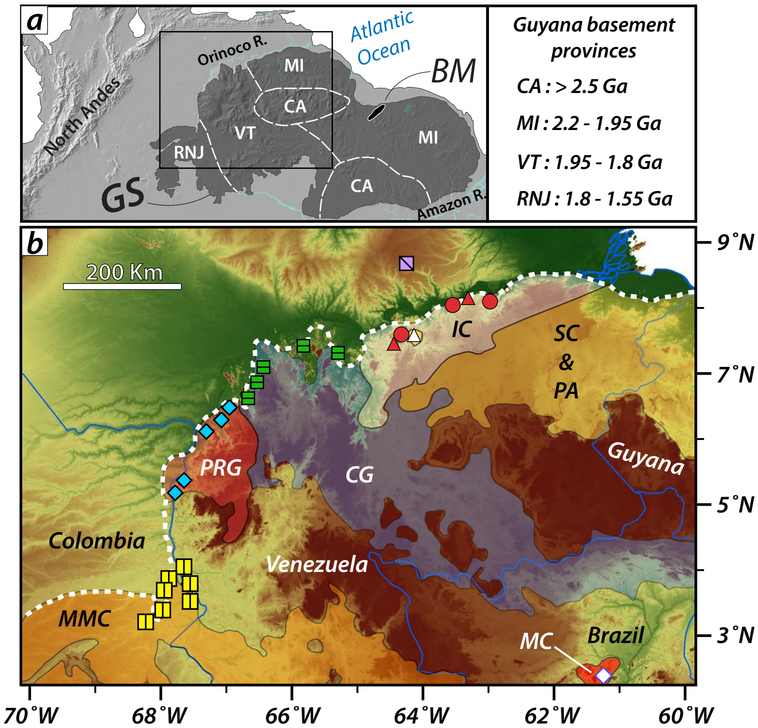
DR5 Table. Tabulated analytical data – Yb-Lu-Hf analysis of zircon by LA-MC-ICP-MS and results from secondary reference materials

DR6 Table. Tabulated analytical data – $\delta^{18}O$ analysis of zircon by SIMS

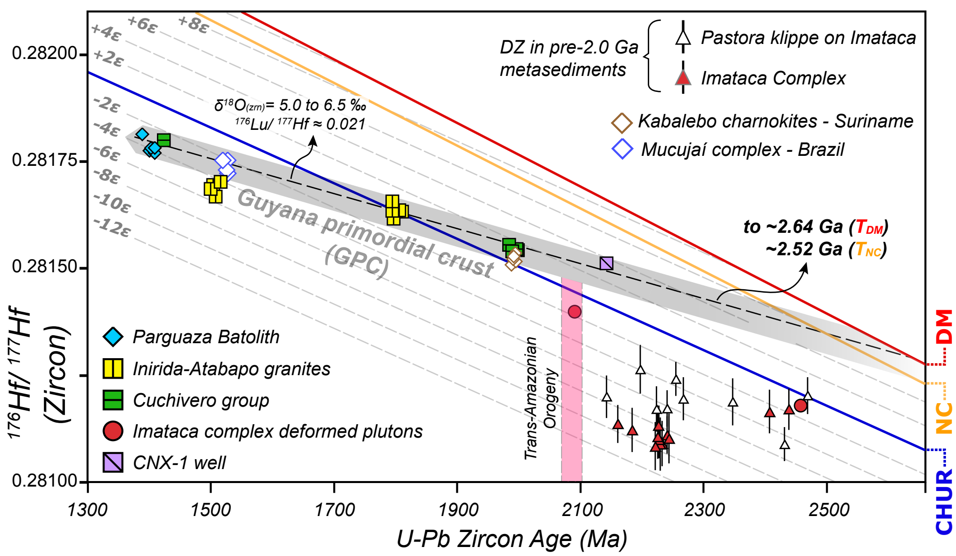
DR7 Figure. Figure of Guyana Shield U-Pb-Hf data within a global context of Archean crust growth

[1]GSA Data Repository item 201Xxxx, including instrument operating parameters (DR1), sample coordinates (DR2), U-Pb, Lu-Hf and O analytical data (DR3-DR6), and other diagrams supporting points made in the text (DR7), is available online at www.geosociety.org/pubs/ft20XX.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

FIGURE 1


a
Orinoco R.
Atlantic
Ocean
BM
North Andes
MI
CA
VT
RNJ
GS
CA
MI
Amazon R.
Guyana basement
provinces
CA : > 2.5 Ga
MI : 2.2 - 1.95 Ga
VT : 1.95 - 1.8 Ga
RNJ : 1.8 - 1.55 Ga
b
200 Km
IC
SC
&
PA
PRG
CG
Guyana
Colombia
Venezuela
MMC
MC
Brazil
9˚N
7˚N
5˚N
3˚N
70˚W
68˚W
66˚W
64˚W
62˚W
60˚W

FIGURE



DZ in pre-2.0 Ga metasediments
Pastora klippe on Imataca
Imataca Complex
Kabalebo charnokites - Suriname
Mucujaí complex - Brazil
δ18O(zrn)= 5.0 to 6.5 ‰
176Lu/ 177Hf ≈ 0.021
Guyana primordial crust (GPC)
to ~2.64 Ga (TDM)
~2.52 Ga (TNC)
Trans-Amazonian Orogeny
Parguaza Batolith
Inirida-Atabapo granites
Cuchivero group
Imataca complex deformed plutons
CNX-1 well
+4ε
+6ε
+8ε
+2ε
-2ε
-4ε
-6ε
-8ε
-10ε
-12ε
176Hf/177Hf (Zircon)
0.28200
0.28175
0.28150
0.28100
1300
1500
1700
1900
2100
2300
2500
U-Pb Zircon Age (Ma)
DM
NC
CHUR