Earth's new tectonic regime at the dawn of the Paleoproterozoic: Hf isotope evidence for efficient crustal growth and reworking in the São Francisco Craton, Brazil

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ABSTRACT

A zircon Hf isotopes dataset of Archean and Paleoproterozoic magmatic and metasedimentary rocks of southern São Francisco Craton is interpreted as evidence of accretionary and collisional plate tectonics at least since the Archean-Proterozoic boundary. During the Phanerozoic, accretionary and collisional orogenies are considered the end members of different plate tectonic settings, both involving pre-existing stable continental lithosphere and consumption of oceanic crust. However, mechanisms for the formation of continental crust during the Archean and Paleoproterozoic are still debated with the addition of magmatic rocks to the crust being explained by different geodynamic models. Hf isotopes can be used to quantify the proportion of magmatic addition into the crust: positive εHf values are usually interpreted as indications of magmatic input from the mantle, whereas crust-derived rocks show more negative εHf. We show that the crust of the amalgamated Paleoproterozoic tectonostratigraphic terranes that make up the southern São Francisco craton were generated from different proportions of mantle and crustal isotopic reservoirs. Plate tectonic processes are implied by a consistent sequence of events involving the generation of juvenile subduction-related magmatic arc rocks,

followed by collisional orogenesis and re-melting of older crust, and post-collisional bimodal magmatism.

INTRODUCTION

Whether plate tectonic processes initiated around the Archean-Paleoproterozoic boundary or at a different point in Earth's evolution is intensely debated (e.g., Dhuime et al., 2012; Windley et al., 2020; Palin and Santosh, 2020). Hf isotopes provide an important tool for understanding tectonic processes through time because magmatic sources can be identified by the contrasting isotopic behaviour of Hf between the mantle and the crust (Griffin et al. 2000). Secular changes in orogenic processes can be traced by Hf isotope variations, as the isotopic signature of magmatic zircon crystals is usually related to their petrogenesis, thereby indicating degrees of mantle contributions and crustal sources and thus constraining the predominant magmatic and tectonic style (e.g., Goodge and Vervoort, 2006; Belousova et al., 2010; Dhuime et al., 2012; Spencer et al., 2019, 2020).

Different εHf/Ma trajectories and $^{176}Lu/^{177}Hf$ ratios are key in determining changes in tectonic environment (Kemp et al., 2007; Laurent and Zeh, 2015; Spencer et al., 2019). Two end members of orogenic cycles can be distinguished by their contrasting Hf evolution patterns: 1) collisional orogens arising from the collision of two or more continental blocks and resulting in reworking of crustal material, and 2) accretionary orogens containing a high component of juvenile material related to the amalgamation of island arcs (eg. Belousova et al., 2010; Collins et al., 2011; Spencer et al., 2019, 2020).

We use Hf isotopes in zircon grains to determine the proportion of juvenile and reworked material in the studied samples and to interpret the tectonic framework of a Paleoproterozoic orogenic system in southeastern Brazil (the Minas Segment of the

Minas-Bahia Orogenic System). The variations in the dataset show an intense reworking of older continental fragments as well as major input of mantle-derived magmas comparable with the isotopic evolutionary trend of Neoproterozoic and Phanerozoic orogenic systems. The resemblance with modern-style plate tectonic processes indicate that similar mixing mechanisms have operated throughout the last 2.4 billion years of Earth's history.

TECTONIC FRAMEWORK OF A PALEOPROTEROZOIC OROGENIC SYSTEM

The Precambrian basement of Brazil comprises Archean-Paleoproterozoic cratons that were amalgamated during the ca. 0.6-0.5 Ga Brasiliano-Pan African orogeny and later covered by Phanerozoic intracontinental basins (Figure 1a) (e.g., Heilbron et al., 2017). The São Francisco Craton (SFC) mainly composed of Archean blocks and Paleoproterozoic arc-related rocks, and its reworked inliers within the Neoproterozoic belts, formed during one of the most important periods of juvenile crust addition and reworking, expressed by Siderian to Rhyacian accretional to collisional episodes. On the eastern side of the SFC, the Paleoproterozoic orogenic belt known as the Minas-Bahia Orogenic System (MBOS) is subdivided into two segments: the northern (Bahia) segment, which outcrops in the interior of the cratonic area, and the southern (Minas) segment, exposed on the southern tip of the SFC as well as in reworked basement inliers occurring in the Neoproterozoic orogenic systems (e.g., Alkmim and Teixeira, 2017; Teixeira et al., 2017) (Figure 1b).

The Minas segment of the MBOS (ca. 2.47-2.05 Ga) represents a myriad of microcontinents and magmatic arcs, including mainly intra-oceanic, largely juvenile accretionary arcs that were diachronously amalgamated between ca. 2.1 and 2.05 Ga (e.g., Heilbron et al., 2010; Ávila et al., 2014; Alkmim and Teixeira, 2017; Araújo, 2020; Bruno et al., 2020, 2021; Cutts, et al., 2020). From west to east they are regarded as (Figure 1c): 1) Archean complexes encompassing Paleo- to Neoarchean tonalite-trondhjemite-granodiorite (TTG), migmatites, high-K meta-granitoids, greenstone belt sequences (e.g., Rio das Velhas Supergroup) of ca. 2.9 to 2.65 Ma and Archean-Paleoproterozoic supracrustal units of the passive to active margin type of the Minas Supergroup; 2) the Mineiro magmatic arc comprising Siderian to Rhyacian juvenile to crust-contaminated magmatic arc granitoid rocks including high Ba-Sr, TTGs, sanukitoids and hybrid granitoids and related supracrustal units; 3) the Archean Piedade microcontinent, with Neoarchean TTG and sanukitoids intruded by ca. 2.5 Ga intraplate alkaline basic rocks; 4) ca. 2.05 Ga post-collisional granitoids and associated tholeiitic metabasics; and 5) the Mantiqueira, ca. 2.2 Ga to ca. 2.0 Ga, and Juiz de Fora magmatic arcs, ca. 2.4 to 2.07 Ga, which are represented by juvenile to crustal contaminated TTGs, sanukitoids, post-collisional alkaline, within-plate tholeiitic basic rocks and peraluminous granitoid rocks (e.g. Heilbron et al., 2010; Ávila et al., 2014; Alkmim and Teixeira, 2017; Teixeira et al., 2017; Degler et al., 2018; Moreira et al., 2018; Bruno et al., 2020, b; Cutts et al., 2020; Araújo, 2020).

LU-HF SIGNATURES OF THE MINAS SEGMENT OF THE MBO

Analytical methods, sample descriptions/locations, U-Pb and new Lu-Hf isotope data are presented in Supplementary Materials A and B. Fifteen samples that represent the chemical diversity of the Paleoproterozoic magmatic arcs and Archean microcontinent were chosen for Hf isotopic analysis (Figure 2). The Lu-Hf analyses were performed on concordant to sub-concordant zircon grains directly on U-Pb spots (when possible). Analyses were performed using an ASI Resolution SE 193 excimer laser connected to a Nu Plasma I MC-ICP-MS. For old and complex terranes, such as the São

Francisco Craton, model ages values (TDM) have been used in a rather qualitative way to support geological interpretation (eg. Vervoort and Kemp, 2016; Spencer et al., 2020).

Lu-Hf analyses of Neoarchean rocks of the Piedade microcontinent (Samples 50, 66A and 66B) show a range of εHf (crystallization age) from approximately chondritic (-0.65) to crustal (-8.70) values, suggesting an even older Archean substratum into which these rocks were intruded or derivation from a source of that age within the crust (Figure 2). Paleoproterozoic metamorphic rims were also analyzed and yield εHf (at metamorphic age) of -12.23 and -22.10 further suggesting crustal reworking (Figure 2). The $^{176}Hf/^{177}Hf$ ratios versus the crystallization age of the zircon grains display values ranging ranging from 0.28089 ± 0.00003 to 0.28114 ± 0.00003 for the magmatic cores and for the metamorphic rims, which are coincident within uncertainty and thus likely represent simple recrystallisation under metamorphic conditions or new zircon with more negative εHf reflecting the increase of $^{176}Hf/^{177}Hf$ in CHUR (Figure 2). TDM values vary from Paleo- to Mesoarchean ages ca. 3.55 to 3.01 Ga.

The Rhyacian (ca. 2.152 to 2.114 Ga) arc-related granitoids of the Mineiro magmatic arc (Samples 42, 51B and 52B) show $^{176}Hf/^{177}Hf$ values of 0.28128 ± 0.00002 and 0.28159 ± 0.00002 with juvenile and crustal εHf (crystallization age) values of +5.84 and – 5.52 and TDM of ca. 2.81 and 2.16 Ga, that together with the presence of Archean zircon inheritance in Sample 51B, indicate a mixed mantle-crust evolution of this Paleoproterozoic magmatic arc.

Sample 67, from the Mantiqueira magmatic arc, yields chondritic to juvenile εHf (crystallization age) of +1.68 to +0.57 whereas samples 8 and 64 B yield more evolved, and therefore crust-contaminated values of εHf (crystallization age) between -3.40 and -8.68 (Figure 2). The $^{176}Hf/^{177}Hf$ values of the samples vary between 0.28117 ± 0.00003 and 0.28149 ± 0.00003, with TDM varying from 3.25 to 2.32 Ga, also indicating a complex evolutionary history (Figure 2).

The Paleoproterozoic samples of the Piedade microcontinent (Samples 58A, 58B, 65, 68A and 70B), related to the post-collisional setting of the Minas segment of the MBOS yield negative values of εHf values (at crystallization age) between -7.21 and -20.92, implying reworking of older continental crust. Inherited zircon grains were also analyzed showing an evolutionary trend of the isotopic reservoir of the Piedade microcontinent from the Archean towards the Paleoproterozoic (Figure 2). The model ages show Archean signatures varying from ca. 3.52 to 2.82 Ga and $^{176}Hf/^{177}Hf$ ratios from 0.28083 ± 0.00003 to 0.28128 ± 0.00002. Sample 70A, a tholeiitic metabasic rock, of ca. 2.05 Ga displays variable εHf (crystallization age) of -17.63 to +2.63 implying a juvenile addition with crustal reworking related to an extensional setting, indicating the mixed crustal-mantle sources for the post-collisional bimodal magmatism (Figure 2).

A PROTRACTED MIXED ACCRETIONARY TO COLLISIONAL OROGENIC CYCLE

Linear εHf–time arrays can be indicative of long-term evolution trends from a singular isotopic source (e.g., Rudnick and Gao, 2003; Laurent and Zeh, 2015; Spencer et al., 2019). With reference to the time intervals of ca. 2.5 - 2.4 Ga, 2.4 -2.3 Ga, 2.2 - 2.1 Ga and 2.1-2.0 Ga, the values of εHf/Ma trajectories and $^{176}Lu/^{177}Hf$ are regarded as reflecting the main periods of juvenile input and reworking, marked by collisional episodes, as shown by the probability regressive line of juvenile and crust-contaminated samples (Figure 3a).

The interval of ca. 2.5 – 2.4 Ga, represents the initial stages of magmatic arc granitoid rocks generation in the MBOS with mainly crust-contaminated isotopic signatures (εHf/Ma = 0.00793). The ca. 2.4 – 2.3 Ga interval (εHf/Ma = -0.05784), reflects the onset of juvenile magmatism in the Mineiro and in the Juiz de Fora magmatic arcs. The interval of ca. 2.2 - 2.1 Ga (εHf/Ma = 0.00752) reflects the main period magmatic arc granitoid rocks generation in the MBOS whereas ca. 2.1-2.0 Ga (εHf/Ma = 0.13384) reflects the collisional episodes of MBOS with mostly crustal recycling (Figure 3 a). For the whole Paleoproterozoic continental crust evolution of the MBOS, analyses of igneous magmatic zircon grains of the Mineiro, Mantiqueira and Juiz de Fora magmatic arcs, including the results from this study, show a trajectory of εHf/Ma = 0.0232 and ^{176}Lu/^{177}Hf = -0.0014 (Figure 3a). Values of the least trimmed squares robust regression as calculated can be found in Supplementary Material A.

In comparison with other Proterozoic orogenies such as the collisional Grenville (εHf/Ma = 0.0378 and ^{176}Lu/^{177}Hf = -0.22), and accretionary Sveconorwegian (εHf/Ma = 0.0146 and ^{176}Lu/^{177}Hf = 0.012) and Valhalla (εHf/Ma = ~0.0182 and ^{176}Lu/^{177}Hf =0.007), the Minas segment evolution arrays reflects a mixed collisional and accretionary process in a collisional setting (e.g., Spencer et al., 2019).

SIMILAR PHANEROZOIC HF MODEL RECORDED IN A PALEOPROTEROZOIC OROGEN

Two thousand four hundred and sixty-eight (n=2468) Hf analyses for the São Francisco Craton, including the results from this work, were compiled in order to better constrain the evolutionary trend of the Hf isotopic array of the Minas segment of the Minas-Bahia Orogenic System.

Regarding the Archean complexes and associated passive margin Minas Supergroup, in addition to the Piedade microcontinent, there are zircon grains in magmatic rocks as old as ca. 3.2 Ga with positive to negative εHf values, and up to ca.

3.9 Ga detrital zircons with mainly negative εHf values suggesting the presence of an even older crust segment in this area. The Siderian to Rhyacian Mineiro and Juiz de Fora and the Rhyacian Mantiqueira magmatic arcs display the isotopic trend array of a mixed crustal-mantle signature, suggesting some degree of magmatic addition from the mantle to the crust in the time span between ca. 2.4 Ga and 2.0 Ga with εHf/Ma between 3.0 and 2.0 Ga of ~0.00255 (Figure 4a).

Accretionary episodes are characterized mostly by juvenile additions, whereas collisional episodes of internal orogens lead to high reworking rates and large variation in the negative εHf values (Roberts and Spencer, 2015). Together, they are markers of modern tectonic settings and depict how efficient mixing processes govern crustal balance on Earth. Nonetheless, the variation with higher proportions of juvenile signatures in the dataset present here, alongside a regional εHf-time reworking array of the regional Archaean rocks suggests that there was a change in between these periods that is comparable to modern-tectonics, as shown by the εHf/Ma trajectory of Archean and Paleoproterozoic rocks (Figure 4a).

The assembly of the Minas segment of the MBO resembles the Hf isotopic array of the Phanerozoic internal orogenic systems of North China, South China and the Himalayas with an εHf/Ma trajectory of 0.00767 (collisional - Figure 4b) in contrast to external orogenic systems of East Australia, Gondwana, Japan, New Zealand, South America and Europe with εHf/Ma trajectory of -0.0027 (accretionary – Figure 4c) (Collins et al., 2011). Successive collisional orogenies of the Minas segment are progressively younger towards the east (Figure 3), with subduction related magmatism restricted to periods of ocean closure. The onset of accretionary and collisional episodes throughout Earth history, from the Archean-Proterozoic boundary, suggests the opening and closure of oceans and provides important information regarding the formation of supercontinent cycles (eg. Belousova et al., 2010; Collins et al., 2011; Hawkesworth et al., 2016).

The increasing reworking rates and juvenile magmatic contributions at the boundary between the Archaean and Paleoproterozoic marks a turning point in Earth geodynamics. In the Archean, the lower contribution of juvenile magmatism, testified by the less proportions of overall εHf values, forms a dominant crustal reworking array. In the Paleoproterozoic, the proportion of juvenile magmas is enhanced in comparison to the magmas derived from crustal reworking, which is analogous to the geodynamics of modern plate tectonics.

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FIGURE CAPTIONS

Figure 1: A) Tectonic Framework of Brazil (Modified after Heilbron et al., 2017); B) Basement (Archean blocks and Paleoproterozoic magmatic arcs) of the São Francisco Craton. (Modified from Alkmin and Teixeira, 2017; Barbosa and Barbosa, 2017; Degler et al., 2018; Bruno et al., 2020); C) Geological map and location of studied samples (Modified from Alkmin and Teixeira 2017; Bruno et al., 2021).

Figure 2: εHf vs. $^{207}Pb/^{206}Pb$ ages of analyzed magmatic zircon grain and metamorphic rims; b)$^{176}Hf/^{177}Hft$ versus vs. $^{207}Pb/^{206}Pb$ ages of analyzed magmatic zircon grains and metamorphic rims. Depleted Mantle area (DM) after Albert et al., (2016). All these

samples were previously dated via (LA-ICP-MS) U-Pb in zircon by Bruno et al. (2020) and Bruno et al. (2021). CHUR constants of Bouvier et al. (2008) $^{176}Hf/^{177}Hf$ = 0.282785 and $^{176}Lu/^{177}Hf$ = 0.0336). Classifying fields of juvenile, moderately juvenile and evolved from Bahlburg et. al., (2011).

Figure 3: Integrated tectonic evolution model for the Minas segment of the MBOS as envisaged for the period between a) ca. 2.4 to 2.1 Ga and b) ca. 2.1 to 2.0 Ga (Modified after Bruno et al., 2021) c) Zircon Hf data from the Paleoproterozoic rocks and trajectory of εHf/Ma (Data from this study, Barbosa et al., 2015, 2019; Teixeira et al., 2015; Degler et al., 2018; Moreira et al., 2018; Kuribara et al., 2019; Araújo, 2020). Depleted Mantle area (DM) after Albert et al., (2016).

Figure 4: A) Hafnium isotopic signature of the Minas segment. (Data from this study, Barbosa et al., 2015,2019; Teixeira et al., 2015; Albert et al., 2016; Moreira et al., 2016; Martinez-Dopico et al., 2017; Degler et al., 2018; Moreira et al., 2018; Kuribara et al., 2019; Cutts et al., 2020; Araújo, 2020). Samples from the Acaiaca, Pedra Dourada and Minas Supergroup metasedimentary sequences are not considered for calculations of trajectory of εHf/Ma; B) Hafnium isotopic signature of Phanerozoic internal orogenic systems (Collins et al., 2011 and references therein); C) Hafnium isotopic signature of Phanerozoic external orogenic systems (Collins et al., 2011 and references therein. Depleted Mantle area (DM) after Albert et al., (2016).

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Figure 1

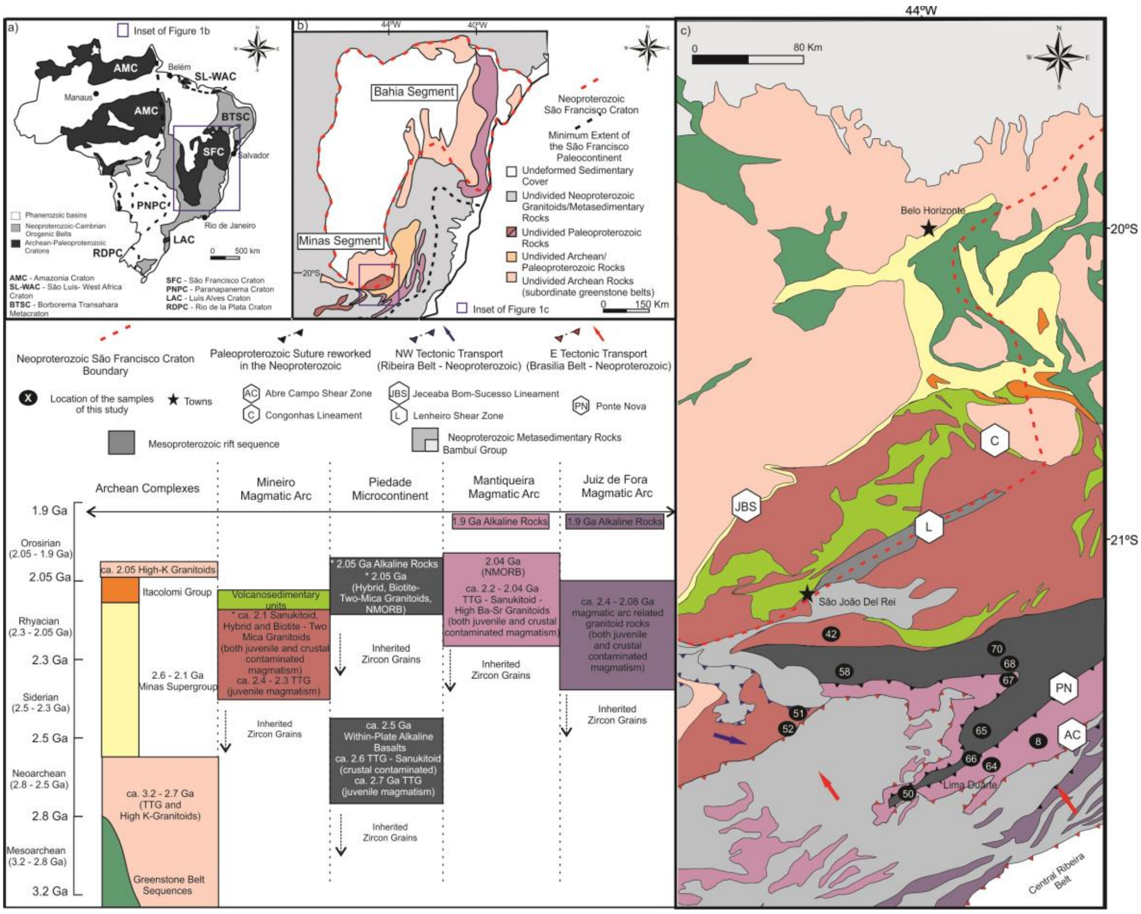


Figure 2

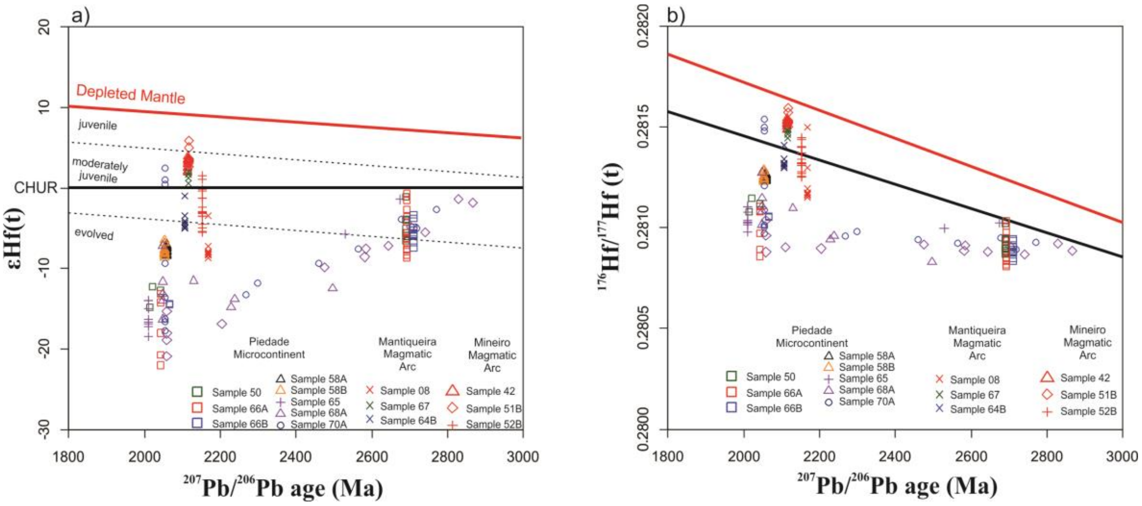


Figure 3

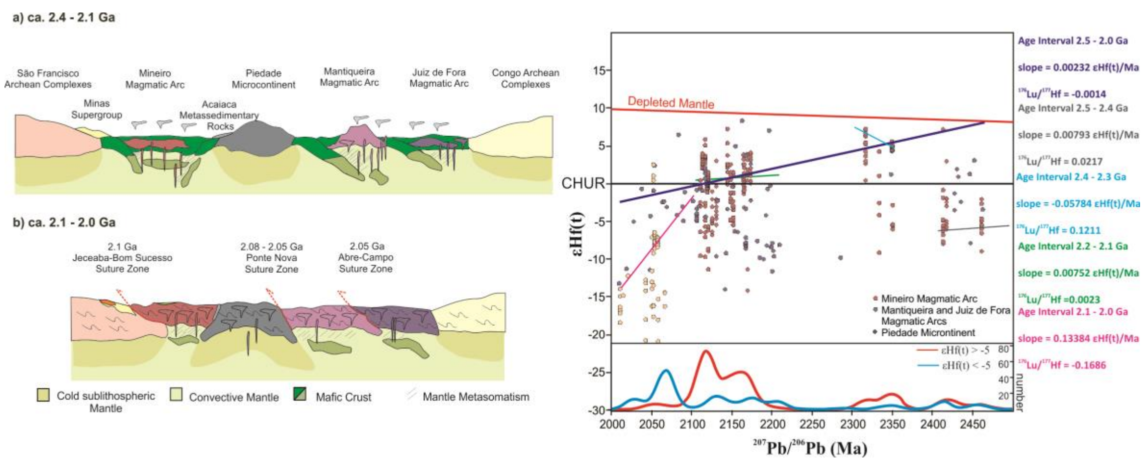
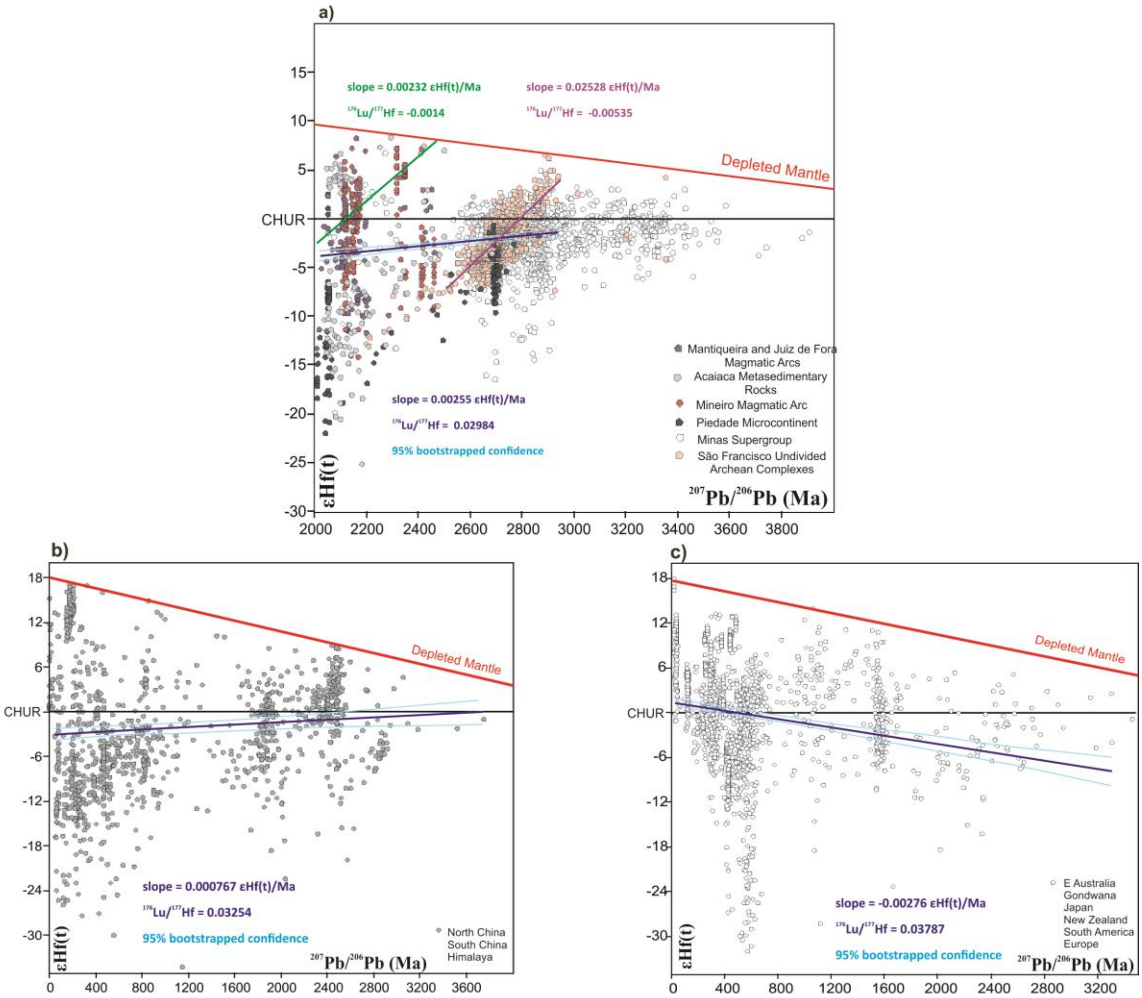


Figure 4


a)
slope = 0.00232 εHf(t)/Ma
176Lu/177Hf = -0.0014
slope = 0.02528 εHf(t)/Ma
176Lu/177Hf = -0.00535
Depleted Mantle
CHUR
Mantiqueira and Juiz de Fora Magmatic Arcs
Acaiaca Metasedimentary Rocks
Mineiro Magmatic Arc
Piedade Microcontinent
Minas Supergroup
São Francisco Undivided Archean Complexes
slope = 0.00255 εHf(t)/Ma
176Lu/177Hf = 0.02984
95% bootstrapped confidence
εHf(t)
207Pb/206Pb (Ma)
b)
Depleted Mantle
CHUR
slope = 0.000767 εHf(t)/Ma
176Lu/177Hf = 0.03254
95% bootstrapped confidence
North China
South China
Himalaya
εHf(t)
207Pb/206Pb (Ma)
c)
Depleted Mantle
CHUR
slope = -0.00276 εHf(t)/Ma
176Lu/177Hf = 0.03787
95% bootstrapped confidence
E Australia
Gondwana
Japan
New Zealand
South America
Europe
εHf(t)
207Pb/206Pb (Ma)