Zircon Hf and O-isotope constraints on the evolution of the Paleoproterozoic Baoulé-Mossi domain of the southern West African Craton

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Abstract

The use of zircon isotopic systems, such as Lu-Hf and O, has proven to be an invaluable tool for unraveling the evolution of the early Earth. In order to achieve a comprehensive understanding of the evolution of the southern West African Craton and, in particular, the Paleoproterozoic Baoulé-Mossi domain, zircon grains from 75 felsic intrusions were analyzed for Hf-isotopes; 22 of those samples were analyzed for O-isotopes covering an area that covers more than 1000 km², from southwest Burkina Faso across southern Mali and into eastern Guinea. The results of the study reveal that the Baoulé-Mossi domain comprises two magmatic regions that display broadly juvenile isotopic character, but with significant localized evidence of crustal contamination. The Hf model age data show that the crustal contaminant is potentially as old as ca. 2800 Ma and indicate that the two domains may have evolved slightly differently. In fact, the westernmost region presents a slightly older (or less radiogenic) Hf-isotope signature when compared to the easternmost region. Furthermore, the O isotopic data support the notion that the felsic magmas were subject to supra-crustal contamination, as $\delta^{18}\text{O}$ values range between 6 and 12 ‰. The data presented in this study provide robust evidence that the Baoulé-Mossi domain of the southern West African Craton evolved by accretionary processes between ca. 2250-2050 Ma.

Keywords

West African Craton, Paleoproterozoic Baoulé-Mossi domain, zircon Hf- O-isotopes, crustal evolution

1 Introduction

Zircon is a very resilient and chemically refractory mineral capable of retaining its original chemical and isotopic composition (e.g. trace elements, Hf- O- U-Pb isotopes) even through multiple episodes of sedimentary and magmatic recycling, metamorphic reworking, weathering and superficial transport processes. Its widespread occurrence in a variety of highly fractionated igneous rocks makes it ideal for isotope studies on felsic rocks (Belousova et al., 2002, 2006; Hawkesworth and Kemp, 2006; Scherer et al., 2007).

U-Pb, O and Hf isotopic systems in zircon are of great importance as they provide a geochronological and geochemical record of the source and crystallization time of their host rocks. U-Pb systematics supply a record of the crystallization intrusion age, whereas O- and Hf- isotope compositions provide a record of crustal and mantle processes. Their combination provides key information on the nature of the source rock and parent magmas (Belousova et al., 2006, 2010; Griffin et al., 2002; Hawkesworth and Kemp, 2006; Kemp and Hawkesworth, 2014; Kemp et al., 2007; O'Reilly et al., 2008). It has been recognized that $\epsilon\text{Hf}_{(T)}$ values that are positive reflect melts derived from depleted mantle associated with juvenile sources. Conversely, negative $\epsilon\text{Hf}_{(T)}$ represents rocks that incorporate melts that include recycling old crust (O'Reilly et al., 2008; Scherer et al., 2007).

The ability of zircon to retain undisturbed U-Pb and Hf isotopic information (Belousova et al., 2010a; O'Reilly et al., 2008) is complemented by the preservation of valuable information in the O-isotope system. This is usually presented as a ratio ($^{18}\text{O}/^{16}\text{O}$) relatively to the Vienna Standard Mean Ocean Water (SMOW) in the form of $\delta^{18}\text{O}$. The $\delta^{18}\text{O}$ can be used as a proxy to distinguish between mantle derived magmas with values around $5.3 \pm 0.6 \text{ ‰}$ (2σ) and rocks that underwent sedimentary (10-40 ‰) or

hydrothermal alteration processes, e.g. $\delta^{18}\text{O}$ of hydrothermally altered oceanic crust (10-20‰) (Hawkesworth and Kemp, 2006; Kemp et al., 2006, 2007; Pidgeon et al., 2013; Valley, 2003; Valley et al., 1994, 2005). Additionally, King et al. (1998) and Hawkesworth and Kemp (2006) have shown that the initial $\delta^{18}\text{O}$ ratio of igneous zircon can remain unchanged even after metamorphism and crustal partial melting. More recently Belousova et al. (2015) has shown that the O-isotope system can be disturbed, thus highlighting the importance of an integrated approach when performing zircon isotopic studies (e.g. Belousova et al., 2010a; Dhuime et al., 2012; Hawkesworth et al., 2010; Kemp et al., 2006; Wang et al., 2009).

Zircon is an ideal tool to provide insights into the evolution of the Paleoproterozoic Baoulé-Mossi domain between ca. 2300 and 2000 Ma (Abouchami et al., 1990; Boher et al., 1992; Taylor et al., 1992). The period between ca. 2300 and 2000 Ma is underrepresented in the global geochronological record (Parra-Avila et al., 2017 and references there in) and is considered a transition period between "hot" orogen, (Chardon et al., 2009) and "cold" orogen (Cagnard et al., 2011) tectonic regimes.. While many authors have regarded the West African Craton as the result of juvenile crust generation between ca. 2350 and 2050 Ma (e.g. Abouchami et al., 1990; Boher et al., 1992; Tapsoba et al., 2013; Taylor et al., 1992), others such as Begg et al. (2009) have suggested that the African continent, including the West African Craton is the result of accretion of Archean cratonic fragments with addition of a juvenile component, reworked during the Proterozoic time.

More recently, authors such as Abati et al. (2012), Block et al. (2016), Petersson et al. (2016) and Eglinger et al. (2017) have recognized the juvenile nature of the Baoulé-Mossi domain, but have also identified a greater crustal contamination than previously

reported. As the main geodynamic driver in the assembly of the West African Craton, some authors suggest that modern plate tectonics applied to the region (e.g. Allibone et al., 2002; Eglinger et al., 2017; Feybesse et al., 2006; Feybesse and Milési, 1994; Lambert-Smith et al., 2016; Petersson et al., 2016;), whereas others are in favor of vertical tectonics (e.g. plume mantle driven processes; Lompo, 2010; Pons et al., 1995; Vidal and Alric, 1994; Vidal et al., 1996, 2009).

Early isotopic characterization of the West African Craton included Sm-Nd systematics by Abouchami et al. (1990) and Boher et al. (1992). Abouchami et al. (1991) reported basalts with $\epsilon\text{Nd}_{(T)}$ values between +1.2 and + 4.9. The source of the $\epsilon\text{Nd}_{(T)}$ values was interpreted to be a depleted upper mantle. The previously mentioned authors suggested a juvenile nature for the Paleoproterozoic domains of the West African Craton. More recently Abati et al. (2012), Petersson et al. (2016) and Eglinger et al. (2017) have used the Lu-Hf systematics and identified model ages as old as ca. 2800, whereas Tapsoba et al. (2013) used whole rock Sm-Nd and identified model ages up to ca. 2600 Ma.

This study builds on the geochronological characterization of the Baoulé-Mossi domain of the southern West African Craton (Table 1) across Burkina Faso, Ghana, Guinea and Mali presented in Parra-Avila et al. (2015, 2017), by including new zircon Hf- and O-isotope data from felsic intrusions. Zircon grains from a total of 75 igneous samples were analyzed for Hf-isotope composition. In addition, zircon grains from 22 of the 75 samples were evaluated for their O-isotope composition. The geographic distribution of those samples across the studied region is shown in Figure 1. The present work identifies further interaction between juvenile magmas and crustal components, providing additional evidence of interaction between the Paleoproterozoic and Archean domains.

2 Geological Setting

2.1 The West African Craton

The West African Craton (Figure 1) stabilized at ca. 1900 Ma and comprises the northern Reguibat Rise, the southern Leo-Man Rise, as well as the Kédougou-Kéniéba and Kayes Inliers (Abouchami et al., 1990; Baratoux et al., 2011; Boher et al., 1992; Jessell et al., 2016; Taylor et al., 1992). These three provinces border the Taoudenni Basin, a Late Proterozoic to Phanerozoic cratonic platform of sediments. The Reguibat and Leo-Man Rise are composed of Archean nuclei in their western segments and Paleoproterozoic portions in their eastern regions, whereas the Kédougou-Kéniéba and Kayes Inliers are composed of Paleoproterozoic units (Abouchami et al., 1990; Baratoux et al., 2011; Boher et al., 1992; Parra-Avila et al., 2016).

The southern Leo-Man Rise comprises the western Archean Kénéma-Man and the eastern Paleoproterozoic Baoulé-Mossi domain. The Baoulé-Mossi domain includes the Birimian linear to arcuate volcanic belts and corresponding volcano-sedimentary basins (Abouchami et al., 1990; Boher et al., 1992; Junner, 1940, 1954; Taylor et al., 1992; Vidal and Alric, 1994). The Birimian units are commonly intruded by large granitic terranes (Abouchami et al., 1990; Boher et al., 1992; Parra-Avila et al., 2017). Birimian volcanic belts are characterized by tholeiitic and calc-alkaline rocks, whereas the basins are dominated by shales, grey-wackes and carbonates (Béziat et al., 2000, 2008; Block et al., 2016; Leube et al., 1990).

2.1.1 Felsic intrusions and isotopic characterization

Based on new and historical U-Pb data, Parra-Avila et al. (2017) have identified continuous magmatic activity between ca. 2300 and 2000 Ma, highlighting a diachronous

evolution across the Baoulé-Mossi domain. Parra-Avila et al. (2017) have also identified a retreat and migration of the magmatic front of approximately 35 km/Myr from east to west similar to migrating Phanerozoic magmatic arcs. In this context, the tectonic evolution of the Baoulé-Mossi domain is divided into two main periods, the Eoeburnean phase between ca. 2260 and 2150 Ma and the Eburnean phase between ca. 2140 and 2050 Ma. During the Eoeburnean period volcanic activity in the region occurred coeval with the emplacement of felsic intrusions across Burkina Faso and western Mali (Baratoux et al., 2011; de Kock et al., 2011; Feybesse et al., 2006; Hirdes and Davis, 1998; Lahondère et al., 2002; Tshibubudze et al., 2013). During the Eburnean phase Baratoux et al. (2011) established that mafic and felsic volcanisms occurred coevally with felsic granitoids.

Generally, felsic intrusions from across the Baoulé-Mossi domain (Figure 1) have been previously described as Paleoproterozoic chemical equivalents to Archean tonalite-trondhjemite-granodiorites (TTG) (Castaing et al., 2003; Doumbia et al., 1998; Egal et al., 2002; Gasquet et al., 2003; Hirdes et al., 1992, 1996; Liégeois et al., 1991; Lompo, 2009; Naba et al., 2004; Oberthür et al., 1998; Tapsoba et al., 2013; Vegas et al., 2008). They are broadly subdivided into three major groups: 1) usually hornblende-bearing; 2) biotite-bearing granitic rocks; and 3) potassic alkaline plutons (Castaing et al., 2003; de Kock et al., 2011, 2012; Doumbia et al., 1998; Egal et al., 2002; Gasquet et al., 2003; Hirdes et al., 1992; Kouamelan et al., 1997; Liégeois et al., 1991; Oberthür et al., 1998; Parra-Avila et al., 2017).

Eoeburnean intrusions dominate the eastern portion of the Baoulé-Mossi domain. Eoeburnean intrusions are mainly described as medium- to coarse-grained equigranular granodiorites, tonalites, quartz-diorites, quartz-monzodiorites and megacrystic granites (Castaing et al., 2003; Hein et al., 2004; 2010; Naba et al., 2004; Tapsoba et al., 2013;

Vegas et al., 2008; Parra-Avila et al., 2017). In addition to the medium- to coarse-grained intrusions a fine-grained generation has been identified. The fine-grained intrusions are predominately tonalities, trondhjemites, quartz-diorites, monzodiorites and granites, usually biotite-rich and occasionally hornblende-rich (Block et al., 2016).

During the Eburnean period, intrusions are mainly concentrated across the western portion of the Baoulé-Mossi domain. Liégeois et al. (1991) and McFarlane et al. (2011) have recognized: 1) plutons of intermediate composition, locally known as Sadiola type, mainly equigranular, fine-grained quartz-diorites, to quartz-monzodiorites to granodiorites; and 2) granites, monzogranites and potassic leucogranites locally known as Diele type. More recently Parra-Avila et al. (2017) have described these intrusions as: 1) one mica bearing, dominated by plagioclase, feldspar, quartz, hornblende, and biotite; 2) two mica bearing, characterized by plagioclase, feldspar, quartz, muscovite and biotite; and 3) porphyries, defined mainly by a very fine-grained recrystallized matrix rich in sericite and plagioclase phenocrysts. Finally, in the westernmost portion across the Siguiri Basin the intrusions are described as one or two mica bearing granodiorites and small granite plutons (Egal et al., 2002; Eglinger et al., 2017).

Lu-Hf isotopic studies across the Baoulé-Mossi domain indicate a predominately juvenile source for zircons dated between ca. 2300 and 2100 Ma. It is interpreted that these samples are the result of an accretionary process involving an oceanic environment, reworked in an arc type or oceanic plateau system later accreted due to continental terrane collision (Block et al., 2016; Eglinger et al., 2017; Petersson et al., 2016). The previously mentioned studies have identified a crustal component with Hf model ages ranging between ca. 2800 and 2400 Ma.

3 Samples and analytical methods

Samples for the present study were collected from across Burkina Faso, Ghana, Guinea and Mali. A total of 75 igneous rock samples were analyzed for Lu-Hf isotopes: 31 samples from Burkina Faso, 6 from Ghana, 3 from Guinea and 36 from across southern Mali (Table 1). Zircon concentrates and mount preparation were performed following the procedures described in Claoué-Long et al. (1995) and Compston et al. (1984), and summarized in Parra-Avila et al. (2017). Zircon imaging by BSE and CL techniques as well as the morphological characterization process are described in detail in Parra-Avila et al. (2017).

Oxygen isotope analyses were performed on 22 of the 75 samples characterized for Hf-isotopes. The samples chosen for O-isotopes cover an area that extends from the Banfora Belt (Burkina Faso), across southern Mali and into the Siguiri Basin (eastern Guinea). The Hf-isotope studies were carried out on zircons characterized for U-Pb geochronology previously presented in Parra-Avila et al. (2017). These samples were divided by geographical areas (Figure 1, Table 1). In addition, 7 felsic intrusions, mainly granites and granodiorites dated by O. Bruguier (West African Exploration Initiative – Stage 2 Final report, unpublished data) from across the Boromo-Hounde belts in Burkina Faso, were analyzed for zircon Hf-isotopes as part of the present study.

3.1 Lu-Hf isotope system determination

Griffin et al. (2000) and Belousova et al. (2006) have described in detail the methodology and analytical conditions for Lu-Hf isotope analysis, which are summarized in Parra-Avila et al. (2016). The analyses were performed *in situ* using a Photon Machines 193 Excimer laser-ablation microprobe, attached to a Nu Plasma multi-collector ICP-MS

at the ARC CCFS/GEMOC Centre, Macquarie University, Sydney (Australia). A complete summary of the analytical conditions is presented in Appendix A.

The reproducibility of the data can be evaluated by examining the uncertainty of the control standards GJ1, Temora2 (TEM2) and reference material Mud Tank zircon (MT). Because standards are meant to be homogeneous, large uncertainties in standard averages could signify instrument instability and possibly lack of precision. The $^{176}\text{Hf}/^{177}\text{Hf}$ values and associated 2σ uncertainties determined for the standard reference materials are: GJ1 0.282007 ± 0.000053 (0.282015 ± 0.00019 ; Elhlou et al., 2006), TEM2 0.282715 ± 0.000062 (0.282680 ± 0.000024 ; Woodhead et al., 2004) and MT 0.282509 ± 0.000057 (0.282506 ± 0.000026 ; Woodhead and Hergt, 2005).

3.2 O-isotope system determination

Analyses were performed using a Cameca IMS 1280 HR2 ion microprobe, following the protocol described in Martin et al. (2006; 2008). A Cs^+ primary ion beam of 5 to 7 nA was focussed on a 20 μm diameter area. An electron gun was used for charge compensation. Negative secondary ions were measured with a mass resolution of 3000 ($M/\Delta M$) and an energy slit of 35 eV. Before each measurement, the sample was pre-sputtered for 60 seconds with a beam rastering on an area of ca. 10 μm^2 to clean up the sample surface; secondary beam was automatically centered in the field aperture. Measurements were made on multi-collection mode with a counting time of 120 seconds. Instrumental mass fractionation was determined on the reference Zircon 91500 ($\delta^{18}\text{O} = 10.07 \pm 0.06 \text{ ‰}$, 2σ) and Temora2 ($8.2 \pm 0.02 \text{ ‰}$, 2σ), as discussed in Valley (2003). Each measurement consists of 15 counting cycles of 10 seconds. The uncertainties of the reference Zircon 91500 and standard Temora2 are equivalent to similar type of studies

(e.g. Gao et al., 2014; Hawkesworth and Kemp, 2006) and therefore are considered to reflect the nature of the studied samples.

4 Results

A summary of the information (e.g. rock type, basic mineral composition) available for the studied samples from the Baoulé-Mossi domain of the West African Craton is presented in Table 1; additional information is in Parra-Avila et al. (2017). Table 2 contains the mean values for zircon O- and Hf-isotope analyses for individual igneous samples. The complete dataset of O- and Hf-isotope data is provided in Supplementary Material A and B, respectively.

4.1 Hf-isotope data

For the purpose of evaluating the data, two age intervals were identified: 1) samples older than ca. 2130 Ma predominately Eoeburnean (ca. 2250 – 2150 Ma), and 2) samples younger than ca. 2130 Ma (Eburnean ca. 2150 – 2050 Ma). The 2130 Ma age boundary was established based on peak metamorphic age established by Block et al. (2015) and proposed in Parra-Avila et al. (2017) as an age boundary between magmatism in the east and west. Zircon Hf isotopic data show that within individual rock samples there is a relatively large variability in Hf-isotope composition (Table 2). This large variability is reflected in the relatively large uncertainty bars associated with the mean values calculated for each sample in the $\epsilon\text{Hf}_{(T)}$ vs U-Pb age plot (Figure 2).

Despite this variability, samples older than ca. 2130 Ma (predominately Eoeburnean phase) have a relatively narrow $\epsilon\text{Hf}_{(T)}$ range between +2 and +5. In contrast, samples belonging to the Eburnean period have a wider range of values from -2 to +9

$\epsilon\text{Hf}_{(T)}$ units (Figure 2). It is possible to observe that samples in the easternmost portion of Burkina Faso, across the Belahouro Belt, present slightly more radiogenic Hf-isotope composition (Figure 3). The zircon Hf-isotope data show little variability in the samples from the eastern and central parts of the Boromo-Hounde belts, but variability increases to the west of the Boromo-Hounde belts. This trend continues into the Banfora Belt, where the zircon grains with the most evolved Hf-isotope signatures (lower $\epsilon\text{Hf}_{(T)}$ values around 0) are found (Figure 3).

Farther to the west, epsilon Hf values appear to increase across the Bagoé and Morila belts. Zircon grains from the Morila Belt show a wider range in their Hf-isotope composition. In contrast, zircon grains from the Bougouni region show less variability and overall the $\epsilon\text{Hf}_{(T)}$ values appear to be slightly lower than the ones from the Morila Belt ($\epsilon\text{Hf}_{(T)}$, at the interpreted crystallization age, between +1 and +10). The Hf-isotope values across southern Mali within the Yanfolila Belt also show a large variability and overall slightly higher values (between 0 and +8) than the ones of the Bougouni area (between +1 and +3). Finally, zircon grains from the three samples of the Siguiri Basin in eastern Guinea show a wide range in their Hf-isotope composition, with ϵHf_t varying between +1 and +8 (Figure 3). To better visualize the Hf-isotope data, a map of the isotopic data distribution is presented in Figure 4. The distribution modeling of the Hf isotopic data is based on natural neighbor classification, using the natural neighbor interpolation tool within as described in Champion (2013) and Champion and Huston (2016).

4.2 O-isotope data

All but 3 samples analyzed for zircon O-isotopes were collected across and west

of the Banfora Belt in Burkina Faso, into Mali and Guinea and belong to the younger intrusions (< 2130 Ma) identified in Parra-Avila et al. (2017). The Banfora Belt samples show the greatest variability, with $\delta^{18}\text{O}$ values that range between 6 and 11 ‰ (Table 2; Figure 5). The sample from the Bagoé Belt shows the lowest $\delta^{18}\text{O}$ value around 6 ‰, close to the typical mantle range 5.3 ± 0.6 ‰, 2σ (Valley, 2003), whereas the samples analyzed from across the Morila Belt have $\delta^{18}\text{O}$ values that vary between 6 and 9 ‰ (Figure 5). Farther west, the intrusions from the Bougouni region show less variability, with $\delta^{18}\text{O}$ values ranging between 6.5 and 8 ‰. Finally, the samples from the Yanfolila Belt in Mali and the eastern portion of the Siguiri Basin (eastern Guinea) show $\delta^{18}\text{O}$ values that range between 6.5 and 8.5 ‰ (Figure 5).

When O-isotope data are plotted as a function of U-Pb age (Figure 5), a broad evolution trend is observed. Samples older than ca. 2100 Ma have a relatively low $\delta^{18}\text{O}$, between 6 and 7.5 ‰, while zircons with O-isotope composition that range between 6 and up to 10 ‰ belong predominately to the younger than ca. 2100 Ma age populations (Figure 5). One exception is recorded by a sample from the Banfora Belt with an age of ca. 2150 Ma, which displays the highest $\delta^{18}\text{O}$ value at around 11 ‰. There is no particular correlation found between O- and Hf- isotope data (Figure 6).

5 Discussion

The present study displays the largest and broadest O- and Hf-isotope dataset for the Baoulé-Mossi domain of the southern West African Craton. The tectonic and geodynamic implications will be explored in the following paragraphs keeping in mind the limitations imposed by the methodology and sample density. The variability observed within the Hf isotopic data will be discussed taking into account the different belts that

were part of the present study. The isotopic variability observed across the region can be attributed to source magma heterogeneity and/or crustal contamination or simply reflect different tectonic environments.

5.1 Hf-isotope variability across the Paleoproterozoic Baoulé-Mossi domain

The average epsilon Hf-isotope values for individual samples spread within the range between the model Depleted Mantle and CHUR reference lines between 0 and +9, with only one sample plotting below zero (Figure 2). A wide range of predominately positive $\epsilon\text{Hf}_{(T)}$ values indicates that the source of these intrusions is dominated by a mantle-derived component. However, an addition of reworked older crustal material or magma mixing would explain $\epsilon\text{Hf}_{(T)}$ values near or equal to 0 (or CHUR). The addition of reworked crustal material is an indicator of a collisional setting.

The Hf-isotope data trends could be interpreted in two ways: 1) the data form a broad downward band from older to younger samples (Figure 7-A), and 2) data plot along a pattern that is sinuously ascending and descending (Figure 7-B). Because of the relatively large variability of the measured Hf-isotope values within the individual samples and the relatively large uncertainty, the first approach in which the data form a downward band from older to younger samples is deemed more appropriate for the present data set.

Magmatism occurring within compressional geodynamic environments are usually associated with downward trends (e.g. Kemp et al., 2009) similar to the one observed in the present study. Abati et al. (2012) described a comparable trend in the Anti Atlas Belt, Morocco. Abati et al. (2012) interpreted this downward trend to represent juvenile crustal evolution within an arc-type system that evolved towards a continental

arc environment and later to a continent-continent collision.

Zircon Hf-isotope data show some difference between the eastern and western regions of the Baoulé-Mossi domain. The region in the east Banfora Belt is dominated by intrusions emplaced during the Eoeburnean period, which display an ϵHf variability of 4 ϵHf units between +2 and +6. The relatively small range of epsilon Hf values indicates that the entire block was subject to similar conditions and that the amount of mixing between juvenile and older crustal material remained relatively unchanged consistent with an accretionary setting. West of the Banfora Belt the variability is much greater, between 0 and +9: this range is not uniform across the entire western region, which is dominated by felsic intrusion from the Eburnean period. The Morila and Yanfolila belts show the greatest amount of variability, while the Bougouni region displays a very narrow range of just 2 ϵHf units. The variability observed in the Morila and Yanfolila belts could be the result of short and minor periods of extension tectonics driving the Hf-isotopes to more radiogenic composition. Alternatively, it could indicate greater and variable amounts of interaction between older crustal material and juvenile magmas typical of collisional environments.

The eastern and western blocks are separated by the Banfora Belt, which showcases the least radiogenic (or more evolved) zircon Hf-isotope signature for the entire study area (Figures 3 and 4). ϵHf for the Banfora Belt ranges between 0 and +2 recording the greatest amount of older crustal component. The Banfora Belt region in SW Burkina Faso, which separates two regions with a more juvenile signature, coincides with the boundary between the two Paleoproterozoic blocks proposed by Hirdes and Davis (2002) and Parra-Avila et al. (2017). The variability of the Hf-isotope signature within the two distinct blocks can be explained in two different ways, which might reflect

different tectonic settings across the region and that will be discussed in sections 5.4 and 5.5.

5.2 O-isotope variability

To complement the zircon Hf-isotope characterization made in this study, we measured the O-isotope composition of zircon grains from selected samples from the Banfora Belt (SW Burkina Faso); Bagoe, Morila, Bougouni, Yanfolila belts (southern Mali); and the easternmost portion of the Siguiri Basin (Guinea). The $\delta^{18}\text{O}$ values show a range between 6 and 11.5 ‰ (Figures 5 and 6). These values do not reflect the composition of zircons that formed in equilibrium with mantle oxygen values (5.3 ± 0.6 ‰, 2σ ; Valley, 2003) and thus suggest the involvement of a supracrustal component during petrogenesis of the felsic intrusions. Overall O-isotope values consistent with the suggestion that that samples were subject to crustal contamination either in the source or during emplacement.

5.3 Source of crustal contamination and tectonic implications

The determination of the crustal evolution reference lines is done by assessing the time that passed since the melt that crystallized the zircon was extracted from a Depleted Mantle reservoir (Scherer et al., 2007). With this method, it is possible to establish the minimum possible age at which any given melt was extracted from the Depleted Mantle reservoir. Figure 2 shows that the ϵ_{Hf} data fits the 2800-2400 Ma crustal evolution reference lines. These data suggest that the minimum possible age of the reworked crustal source is about 2800 Ma, assuming a Depleted Mantle for this source. The minimum age determined by this method does not imply that the sample was extracted from a 2800 Ma

source melt but that it potentially has a crustal component as old as 2800 Ma; alternatively, it is possible to hypothesize that the crust was extracted from a mantle source less depleted than the MORB source mantle.

These observations in conjunction with the findings of Parra-Avila et al. (2017) further support the case for convergent geodynamic setting evolving from an accretionary-type orogeny, mostly recorded in the eastern part of the West African Craton, during ca. 2250 and 2130 Ma to a collisional-type identified predominately in the western part of the West African Craton as reported by Eglinger et al (2017) during the period between ca, 2100 and 2050 Ma. Similar findings are presented by Petersson et al. (2017) across Ghana, where a large proportion of zircons with ages between ca. 2200 and 2130 Ma (Eoeburnean) show Archean crustal contamination. In Parra-Avila et al. (2017), the Baoulé-Mossi domain was split into two crustal blocks that were accreted to the Archean Kénéma-Man at ca. 2100-2080 (Eglinger et al., 2017), with the boundary between the two blocks across the Banfora and Bagoé belts. The more evolved isotopic expression found during this study between the Banfora and Bagoé belts could be the result of a sliver of older crust wedge between the two regions or an area where magma mixing and crustal contamination played a larger role.

The regions east and west of the proposed boundary are mostly juvenile in nature; however, the westernmost portion where many intrusions emplaced mainly during the Eburnean period can be found, appears to have undergone a slightly different evolution when compared to the easternmost portion, which is dominated by intrusions emplaced during the Eoeburnean period. The slightly more evolved ϵHf signature found in the westernmost portion of the study area might reflect a collisional-type setting while the more radiogenic ϵHf signature of the block east of the Banfora Belt could represent a

different tectonic setting, perhaps a back-arc-type. The back arc-type environment has been long debated and recently proposed in multiple studies across Mali, Ghana and Guinea (e.g. Block et al., 2016; Eglinger et al., 2017; Lambert-Smith et al., 2016; Petersson et al., 2016; 2017).

Proponents of the arc-type setting across the Baoulé-Mossi domain have identified whole rock elemental compositions which are commonly associated with modern arc environments. These include negative Nb and Ta anomalies along with positive Pb anomalies and variable degrees of enrichment of the LILE (Arculus et al., 1999). Recent studies have identified subduction-related geochemical signatures across Burkina Faso, Ghana, Guinea and Mali (Anum et al., 2015; Block et al., 2016; Eglinger et al., 2017; Fontaine et al., 2017; Lambert-Smith et al., 2016; Masurel et al., 2017; Petersson et al., 2016). The samples presented in this study are considered to be mineralogical equivalents to the samples studied in the previous mentioned studies. The samples are characterized as biotite-rich and in some cases hornblende-rich.

Petersson et al. (2016) related zircon Hf-isotope signatures similar to the ones presented here with assimilation of older crust during the process of juvenile crustal formation. Petersson et al. (2016) and Parra-Avila et al. (2017) have also documented the presence of coeval felsic and mafic magmatism as well as widespread occurrence of calc-alkaline rocks and Hf-isotope signature, giving further support for an arc-type setting. On the basis of careful analysis of zircon inheritance, Parra-Avila et al. (2017) have indicated that crustal thickening resulted from some underthrust process that occurred from east to west, allowing the entrapment of the inferred older crustal material from the easternmost portion of the craton into the younger westernmost portion. The large ϵ_{Hf} variability would explain a greater interaction between an older crustal component and the young

juvenile magmas of the different intrusions and give further support for crustal thickening due to an arc-type environment which later evolved into a collisional-type orogen between the Paleoproterozoic and Archean domains of the West African Craton. To the east, in the most probable back arc-type setting, the juvenile mantle-derived magmatism is older in age but less contaminated with pre-existing crustal component and overall presents more radiogenic Hf-isotope signature.

5.4 Geodynamic framework

Based on the scenario that the southern West African Craton formed as the result of accretionary orogenic processes consisting of at least two crustal blocks, it is possible to evaluate two of the models proposed in recent years to explain the geodynamic evolution of this region. Baratoux et al. (2011) have proposed two models for the geodynamic evolution of western Burkina Faso: 1) the occurrence of a single large arc system stretching over 400 km; and 2) a series of volcanic arc systems roughly corresponding to each belt. In addition, Baratoux et al. (2011) evaluated a third scenario proposed by Ama Salah et al. (1996) that involved a single arc that was dismembered due to an early deformation event. This last model was considered to be less likely based on the structural field relationships described by Baratoux et al. (2011). Moreover, the diachronous and isotopic characteristics summarized in the present study suggest that the arc system was accreted and not dismembered for the period between ca. 2250 and 2050 Ma, further precluding the model by Ama Salah et al. (1996). Furthermore, Eglinger et al. (2017) provide evidence of a collisional orogen between the Archean and Paleoproterozoic domains.

The first model proposed by Baratoux et al. (2011) envisages the presence of an

arc with the extension of the entire study area, stretching for over 1100 km. This would require a very shallow subduction. Furthermore, this model does not explain the presence of the two distinct regional isotopic domains and cannot explain the more evolved Hf-isotope signature in zircon grains from the samples along the Banfora Belt region. The second model suggests that during the accretionary orogeny a series of small arc fragments accreted to form the southern West African Craton, with thrusting resulting in a progressive thickening of the crust. Crustal thickening was further enhanced by the collisions of the Paleoproterozoic and Archean regions.

From the data presented in this study and the geochronology summary and interpretations in Parra-Avila et al. (2017), it is clear that two distinct blocks composed the Paleoproterozoic domain. Structural observations further support the existence of these crustal blocks based on the orientation of the different volcanic belts. In the easternmost block, in Burkina Faso, Ghana and portions of Côte d'Ivoire, they are oriented NE-SW. Conversely, in the westernmost block, mainly in Mali and western Côte d'Ivoire, the volcanic belts trend mostly N-S. This difference in orientation is another indication that eastern and western portions were subject to different tectonic regimes. An alternative explanation is that they were independent crustal blocks and the deformation events that affected one block did not affect the other.

The data presented in this study suggest that the Baoulé-Mossi domain of the West African Craton is of mostly juvenile character, supporting the conclusions of earlier isotopic studies (e.g. Abati et al., 2012). However, based on new zircon O- and Hf-isotope data, we argue that the amount of recycling and crustal reworking of older crust is greater than previously recognized and that it provides support for an accretionary/collisional-type environment. Furthermore, U-Pb ages of inherited zircons described in Parra-Avila

et al. (2017) are in agreement with older Hf model ages, indicating that the minimum age of crustal contamination is as old as 2800 Ma. Finally, the O-isotope data show that the melts that produced the felsic intrusions across the younger region (west of Banfora Belt) interacted with supracrustal material, strengthening the case for recycling and crustal contamination. The nature of the supracrustal materials can be evaluated from the O-isotopes and U-Pb ages. In the case of the westernmost regions the lack of widespread occurrence of inherited zircon grains could suggest that the recycled high $\delta^{18}\text{O}$ component consisted mostly of material that was deficient in older zircon populations, such as surficially altered mafic volcanic rocks.

6 Conclusions

The results of the new datasets presented in this study along with existing geochronological data show that the Baoulé-Mossi domain of the southern West African Craton is composed of two mainly juvenile regions, which are separated by a more crustal-contaminated domain across the Banfora-Bagoe belts. Although the studied felsic intrusions are of mostly juvenile origin, they have an older crustal component potentially as old as ca. 2800 Ma. Overall, the integration of the new data presented here with the geochronological information presented in Parra-Avila et al. (2017) sheds a new insight on the controversy over the crustal and architectonic evolution of the West African Craton and in particular the Baoulé-Mossi domain providing further support for an accretionary tectonic evolution under an arc-type setting that later evolved into a collisional-type setting.

Some noticeable differences in the Hf-isotope signatures of the two regions indicate that the westernmost part has a higher proportion of older crustal material in the

source than the easternmost area. The slightly more evolved signature is the result of the interaction between the western regions and the Archean Kénéma-Man domain, which indented the Paleoproterozoic regions between ca. 2100-2050 Ma under a collisional-type orogen. This finding reflects a greater interaction between the Paleoproterozoic and Archean domains than previously recognized. The zircon Hf-isotope data support the hypothesis that the felsic intrusions incorporate a crustal component potentially as old as 2800 Ma. The zircon O-isotope data confirm observations that the felsic magmas interacted with supracrustal materials, especially across the westernmost regions of the Baoulé-Mossi domain. Based on the paucity of inherited zircons, these supracrustal materials are considered to be altered mafic volcanics.

The isotopic data along with the geochronological results confirm that the southern West African Craton resulted from an accretionary process involving a series of arcs. These arcs accreted forming two regions that are separated by an isotopically less radiogenic (for Hf-isotopes) region across the Banfora Belt in southern Burkina Faso. Across the easternmost region the early felsic magmatic activity occurred syn-tectonically with the formation and accretion of the arc systems, subsequently evolving into a collisional orogeny, when the amalgamated arcs were indented by the Archean Kénéma-Man domain.

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8 Tables and supplementary materials

Table 1. Summary of studied samples showing the U-Pb age characterization and distribution by rock type and location.

Table 2. Summary of the Hf and O isotopic data.

Figure 1 A) Simplified map of the West Africa Craton, Boher et al. (1992) and B) Simplified geological map of the southern Leo-Man rise of the West African Craton, after Lebrun et al. (2016). The map shows the sample distribution across the study area (Burkina Faso, Mali and Guinea). Samples color-coded in bright pink are analyzed for Hf- and in green for both Hf- and O-isotopes.

Figure 2 Mean ϵ_{Hf} vs. U-Pb intrusion age for zircon grains from the West African Craton.

Figure 3 ϵ_{Hf} plotted as a function of longitude.

Figure 4. Hf-isotope distribution map modeled using natural neighbor interpolation as described in Champion and Huston (2016) and references therein, showing the isotopic variations across the southern West African Craton. Cold colors represent regions with lower zircon ϵHf and thus older crustal protoliths. Warm colors represent more juvenile Hf-isotopic signature.

Figure 5 $\delta^{18}\text{O}$ (‰) vs. longitude (A) and vs. U-Pb intrusion age (B).

Figure 6 $\delta^{18}\text{O}$ (‰) plotted as a function of the $\epsilon\text{Hf}_{(T)}$.

Figure 7 $\epsilon\text{Hf}_{(T)}$ vs age showing the interpreted evolution trend. A) Conservative interpretation in which samples form a “band”; and B) Evolution trend in which a change in the tectonic regime can be observed from extension to collision back to extension.

Supplementary Material A. Oxygen isotopes raw data.

Supplementary Material B. Lu-Hf isotopes raw data.

9 Appendix A - detail Hf isotope methodology

A.1 Lu-Hf isotope system determination

The procedure is described after Andersen (2002); Belousova et al. (2006); (2010); Griffin et al. (2000) and Pearson et al. (2008). The beam diameter to carry out the analyses was set up at 40 or 55 μm , with a 4 to 5 Hz repetition rate, depending on the individual grain size. Ablation times lasted between 100-120 seconds, producing pits 30-40 μm deep. The ablated material was transported using He gas from the laser-ablation cell, passing by a mixing chamber and into the ICPMS torch. The interference of ^{176}Lu on ^{176}Hf was corrected by measuring the intensity of the interference-free ^{175}Lu isotope and using $^{176}\text{Lu}/^{175}\text{Lu} = 0.02669$ (De Bièvre and Taylor, 1993) to determine the $^{176}\text{Lu}/^{177}\text{Hf}$. In the same way, the interference of ^{176}Yb on ^{176}Hf was corrected by measuring the

interference-free ^{172}Yb isotope and using the $^{176}\text{Yb}/^{172}\text{Yb}$ ratio to establish the $^{176}\text{Yb}/^{177}\text{Hf}$. The value of the $^{176}\text{Yb}/^{172}\text{Yb}$ ratio was found by spiking the JMC475 Hf standard with Yb; this produced a value for the $^{176}\text{Yb}/^{172}\text{Yb}$ of 0.58669 needed to yield the value of $^{176}\text{Hf}/^{177}\text{Hf}$ obtained on the pure Hf solution. A more detailed discussion of the overlap corrections for ^{176}Lu and ^{176}Yb can be found in Pearson et al. (2008). Although the severe corrections on ^{176}Hf , the 2SD internal precision is of 0.00002 for the $^{176}\text{Hf}/^{177}\text{Hf}$ ratio equivalent to 0.7 ϵ_{Hf} units analyses of standard zircons (Griffin et al., 2008; Pearson et al., 2008) .

Chondritic values of Bouvier et al. (2008) were adopted for the calculation of ϵ_{Hf} values, $^{176}\text{Lu}/^{177}\text{Hf}$ (CHUR, today) = 0.0336 ± 1 and $^{176}\text{Hf}/^{177}\text{Hf}$ (CHUR, today) = 0.282785 ± 11 . The adopted decay constant for ^{176}Lu is $1.867 \pm 0.008 \times 10^{-11}/\text{yr}$ proposed by Söderlund et al. (2004). In order to calculate the model ages (T_{DM}) based on a depleted-mantle source, it is necessary to assume that the depleted mantle (DM) reservoir had developed from an initially chondritic mantle, and that it is complementary to the crust extracted over time. The T_{DM} model ages for each zircon were calculated assuming that the parental magma originated from an average continental crust with $^{176}\text{Lu}/^{177}\text{Hf} = 0.015$ (Griffin et al., 2004).

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Inverse Distance Weighting Prediction Map