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Caracterización del vulcanismo carbonatítico de Catanda (Angola)

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Publicaciones originales

9.4. Publicación IV

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Incipient continental rifting in SW Africa manifested by recent carbonatitic volcanism in Angola

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Abstract

The continental lithosphere thinning generate elongated depressions known as continental rifts, those are instability regions where continents can be pulled apart. Incipient rifting stages are represented by the emplacement of alkaline magmas, such as carbonatites – composed of >50% of carbonates. Carbonatitic volcanism was reported in the Catanda area (Angola). Their age was estimated to be Cretaceous, i.e. similar to other magmatic activity of kimberlites and carbonatites in central and eastern. The Angolan carbonatites and kimberlites are distributed along a narrow (1000 km wide) SW-NE trending depression, the Lucapa corridor. Here we report new $^{40}\text{Ar}/^{39}\text{Ar}$ and (U-Th-Sm)/He geochronology results on phlogopite and fluorapatite, which demonstrate that the Catanda carbonatites were emplaced at 0.65 ± 0.05 Ma. Seismic tomography evidences a low-velocity zone beneath Catanda and extending towards inland Angola, proving the occurrence of upper-mantle magmatism beneath this area. $\epsilon\text{Hf}-\epsilon\text{Nd}$ isotopic values obtained in Catanda are similar to those reported for mantle-derived melts (i.e. OIB's and Group I Kimberlites) and Sr-Nd isotopes present similitudes to carbonatites from continental rifting areas worldwide. Our dating and isotopic data, combined with the geophysical evidence suggest that the Catanda volcanism was inextricably linked to the present-day re-activation of the Lucapa rift. Lucapa were relevant in the break-up of Gondwana during the Cretaceous so it is not discernable that Africa can break up along this rifting structure in the future. At last, considering the young age of the Catanda volcanism, the occurrence of upcoming carbonatitic eruptions in this region of SW Africa is also plausible.

Keywords: continental rifting, carbonatites, Lucapa, Catanda, Angola

1. Introduction

Rifting events are extensional processes associated to asthenosphere rising and the corresponding thinning of the overlying lithosphere. In continental areas, these processes may create instability regions where continents can be pulled apart and even generate new plate boundaries, in the last stages of rifting evolution (Fourel et al., 2013). The incipient stages of rifting are associated with the emplacement of alkaline and carbonatite magmas in the crust (Pirajno, 2015). Several examples of incipient rifting areas with associated alkaline-carbonatite magmatism have been reported worldwide as, for example, the Rio Grande rise (Brasil) (O'Connor & Duncan, 1990), the Cenozoic European Rift System (CERS) (Lustrino & Wilson, 2007) or the East African Rift (EAR) (Chorowicz, 2005).

In the west margin of Africa is located the Lucapa corridor (Fig.1), a >1000 km-long NE-SW graben defined by a set of discontinuous fractures along. The Lucapa structure is located along the suture of Pan-African belts; those were originated during Neoproterozoic orogenic events in relation to the formation of the Gondwana supercontinent (McKenzie, 2015). Magmatism in Lucapa has been intermittent, occurring in the Neoproterozoic and the Permian (Sykes, 1978) and latter in the Cretaceous, when kimberlites, carbonatites and related magmas emplaced in the upper crust, which is probably best represented by the age of several kimberlite localities such as Catoca (117.9 ± 0.7 Ma) (Robles-Cruz et al., 2012), Val do Queve (133.4 ± 11.5 Ma) (Haggerty et al., 1983) or Luxinga clusters (from 145 to 113 Ma) (Eley et al., 2008). During the Cretaceous, Lucapa structures also played a relevant role in the break-up of Gondwana and the corresponding opening of the Atlantic Ocean. Nowadays, the Lucapa corridor is approximately aligned to the Rio Grande Atlantic fracture zone (Fig.1), which is considered the boundary between the Central and the Southern segments of the Atlantic Ocean (Moulin et al., 2010), so, now, the main question is if Western Africa can break up along this seemingly inter-continental structure.

Volcanic activity in the Lucapa corridor is well represented in the northern border of the area by the Catanda extrusive carbonatites (Fig.1). The Catanda carbonatite complex consists of a cluster of small volcanic edifices with maar and tuff ring morphologies that outcrop over a 50-km² area hosted in Archaean granites (Campeny et al., 2014). The volcanic materials are mainly pyroclastic rocks but also minor carbonatitic lavas are found, which include altered natrocarbonatites (Campeny et al., 2015), similar to those reported in few localities from the EAR such as the Oldoinyo Lengai, Tinderet or Kerimasi (Hay, 1983; Deans & Roberts, 1984; Dawson, 1993; Zaitsev et al., 2013). Some nephelinitic dykes are also present in the Catanda area and a poorly constrained K-Ar age of 92 ± 7 Ma was reported for one of these dykes (Torquato & Amaral, 1973). A similar age was also proposed for the carbonatite rocks (Silva & Pereira, 1973). However, the well-preserved morphology of the volcanic edifices and present-day hydrothermal activity (i.e. travertine deposits, mud-spots) in the area suggest a younger age for the carbonatites (Fig. 2). Here, we present the first direct dating of the Catanda carbonatites, which indicate a Middle Pleistocene age for this volcanism. This new dating argues for the present-day magmatic re-activation of rifting structures from the Lucapa corridor. The general implications of this new finding are discussed below.

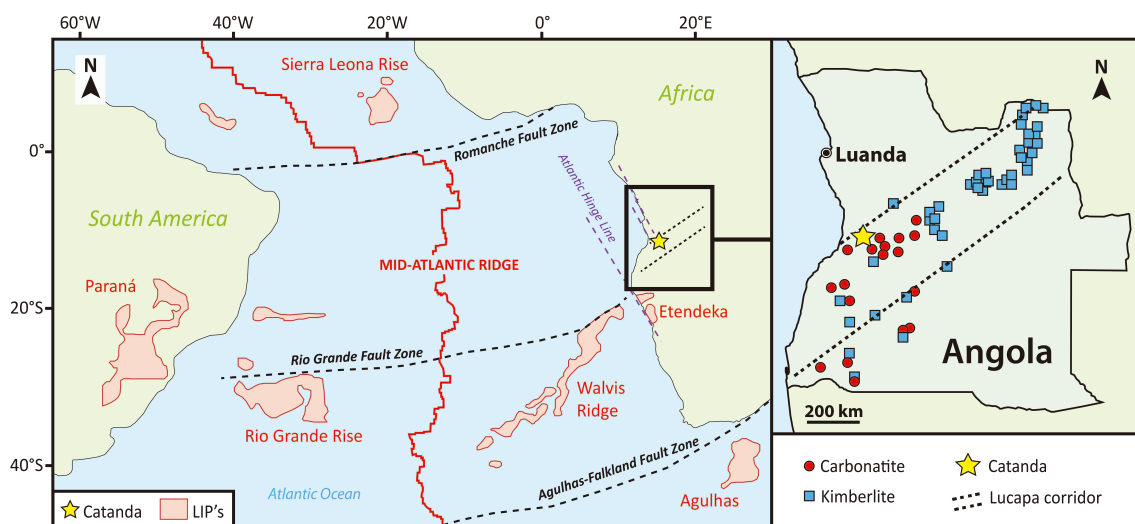


Figure 1. Synthetic map of the Mid-Atlantic Ridge. Location of the Catanda volcanic carbonatites and the Lucapa rift domain in relation to the tectonic structures and magmatic regions of the Mid-Atlantic Ridge area. Map of distribution of main carbonatites and kimberlites located in Angola.

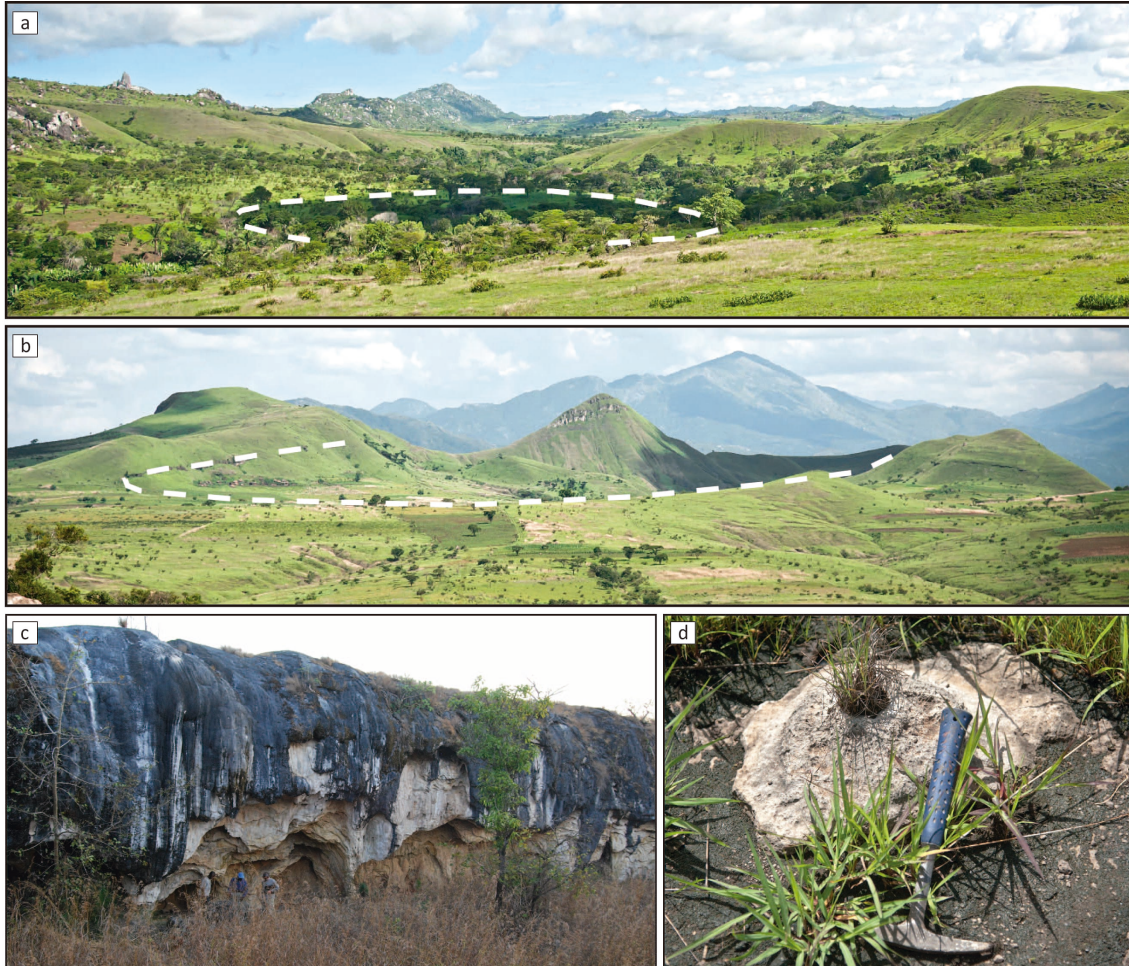


Figure 2. Detailed images from the Catanda area outcrops. (a), (b) General view of Catanda volcanic edifices in which is possible to distinguish a well-preserved morphology of the eruptive centres. **(c)** Travertine deposits up to 30 m thick, associated to present-day hydrothermal systems located in the Catanda area. **(d)** Recent carbonated mud pots in the carbonatite outcrops from Catanda.

2. Results

Catanda volcanic series mainly consist of pyroclastic rocks, those are generated during explosive eruptive episodes and contain carbonatitic minerals but also several grains coming from the hosted Archaean granites (Campeny et al., 2014). Given this consideration, our work has been focused in the study of the minor Catanda carbonatitic lavas, generated during more effusive episodes and majorly composed by primary carbonatitic minerals without a significant percentage xenolithic material. Catanda lavas generally consist of variable proportions of microphenocrysts of calcite, fluorapatite, magnetite, clinopyroxene and phlogopite hosted in calcite-rich groundmass also composed by variable proportion of accessory minerals such as

pyrochlore, perovskite, cuspidine and periclase (Campeny et al., 2015). We calculated the age of the Catanda carbonatites through ^{40}Ar - ^{39}Ar dating of phlogopite (556 ± 21 ka) and (U-Th-Sm)/He dating of fluorapatite (660 ± 90 ka) at the University of Melbourne (see Methods). The Sr-Nd-Hf-Pb isotopic compositions of fluorapatite and clinopyroxene grains from lava samples of three distinct units were also measured at the University of Melbourne (see Methods) (Table. A6). Catanda isotopic values are similar to those described in other present-day volcanic carbonatites associated to continental rift areas worldwide (Fig.3), such as the Quaternary carbonatites from the EAR (Bell & Blenkinsop, 1987) and the Eifel volcanoes, those are located in the CERS (Riley et al., 1996).

3. Methods

3.1. U-Pb dating of fluorapatite

Fluorapatite is one of the most abundant minerals in the Catanda rocks, but attempts to date fluorapatite by laser ablation ICP-MS were unsuccessful. We analysed 60 fluorapatite grains, and despite promising U and Th concentrations (1.8 to 14.6 ppm of U and 16.9 to 232.3 ppm of Th; Table. A1), $^{207}/^{206}\text{Pb}$ ratios are high (0.78 to 1.02; Table. A2) and dominated by “common Pb” (i.e. non-radiogenic Pb incorporated in the mineral lattice during crystallisation) and do not show clear correlations with $^{238}\text{U}/^{206}\text{Pb}$ ratios in the Tera-Wasserburg diagram. Pb isotope data for one fluorapatite (#21) and the groundmass samples for 3 samples (#21, #24, #25) acquired by MC-ICPMS (with U/Pb and Th/Pb from trace element data for the same sample solutions; Table. A1), also failed to provide unequivocal age information. Despite high and variable $^{238}\text{U}/^{204}\text{Pb}$ (120-314) and $^{232}\text{Th}/^{204}\text{Pb}$ (354-3585), measured $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$ ratios are similarly low in all 4 fractions (20.09-20.58, 39.87-40.18) (Table. A2). In the Th-Pb isochron diagram, the data points for the groundmass samples define a well-correlated line (MSWD 0.67, 2σ input errors of $x=1\%$, $y=0.1\%$, $\rho=0.6$) with an apparent age of 10.3 ± 1.8 Ma ($^{208}\text{Pb}/^{204}\text{Pb}_i=39.69 \pm 6$). By contrast, the Th-Pb data for fluorapatite and groundmass in sample #21 yield an apparent age of 1.26 ± 0.36 Ma

($^{208}\text{Pb}/^{204}\text{Pb}=39.96\pm 5$). In summary, the ^{238}U - ^{206}Pb system does not yield interpretable age constraints.

3.2. (U-Th-Sm)/He dating of fluorapatite

Nine different grains of fluorapatite from two different carbonatitic lava samples were used for (U-Th-Sm)/He (AHe) analysis. The method used followed an established laboratory routine for laser He extraction (House et al., 2000). Whereas clear euhedral and non-fractured grains are usually sought for such analysis, in this case all crystals were markedly anhedral and fractured. Grains chosen for analysis were hand picked under an Olympus SZX12 binocular microscope and subsequently immersed in ethanol and checked under polarised light to detect possible mineral inclusions. As it was not possible to accurately estimate the grain geometry for applying the α -ejection correction (Farley et al., 1996), grains selected were subjected to mechanical air abrasion. This was achieved by using silicon carbide grit (300-425 mm) to remove at least the outer ~ 25 - $30\ \mu\text{m}$ of the apatite ($> \alpha$ -ejection distance) in a cell similar to that described by Krogh (1982). This approach has previously been applied to (U-Th)/He dating of Late Tertiary to Quaternary volcanic samples (Spiegel et al., 2009). Abrasion was halted periodically and grain sizes and shapes were monitored using digital image capture. Using this approach makes it unnecessary to apply the α -ejection correction, and can also potentially overcome any influence of He implantation into the apatite from surrounding minerals.

In order to extract sufficient ^4He gas for measurement for most analyses more than one grain was required and these were loaded into small, acid-treated platinum capsules. Grains were then outgassed under vacuum at $\sim 900^\circ\text{C}$ for 5 minutes, using a semiconductor diode Coherent Quattro FAP laser, set on a wavelength of 820 nm with fibre-optic coupling to the sample chamber (to provide optimal coupling with samples and heating without melting, ablation or fusion). ^4He content was determined by isotope dilution using a pure ^3He spike calibrated against an independent ^4He standard and measured using a Balzers quadrupole (QMS 200–Prisma) mass spectrometer. A hot blank was run after each gas extraction to verify complete outgassing of the apatite grains. Most samples yielded negligible amounts of gas even after the first re-

extract, and for all samples the second re-extract contributed less than 0.5% of the total measured ^4He .

Samples were removed from the laser chamber and ^{238}U , ^{235}U , ^{232}Th and ^{147}Sm concentrations obtained by total dissolution of outgassed fluorapatite (still in their Pt capsules) in HNO_3 and analysed using an Agilent 7700x inductively coupled plasma mass spectrometer (ICP-MS). Analyses were calibrated using the reference material BHVO-1, with Mud Tank apatite and international rock standard BCR-2 used as check standards and run together with each batch of samples analysed. Analytical uncertainties for the University of Melbourne He facility for abraded samples (where uncertainties in grain size measurements do not need to be taken into account) are estimated at 3% ($\pm 1\sigma$), which incorporates gas analysis and ICP-MS analytical uncertainties. Accuracy and precision of U, Th and Sm content ranges up to 2% (at $\pm 2\sigma$), but is typically better than 1%. With each batch of samples analysed Durango apatite was also run as an internal standard and served as a further check on accuracy. The weighted mean of 4 Durango apatite measurements carried out for this study was 31.2 ± 1.9 Ma (uncertainty at 95% confidence level). This compares favourably (within error uncertainties) with a (U-Th-Sm)/He age of 31.02 ± 1.01 Ma ($\pm 1s$) reported for a set of 24 Durango apatite analyses carried in the Caltech He laboratory. The results obtained for the two samples yield grand weighted apparent ages of 650 ± 130 ka and 660 ± 90 ka ($\pm 2\sigma$), respectively (Table. A3).

3.3. Rb-Sr dating of phlogopite

Phlogopite is also a common microphenocryst in all Catanda carbonatite lavas. Preliminary trace element data for phlogopite from 3 samples (PHL-21, PHL-24, PHL-25) indicated high Sr contents (200-4000 ppm) and $\text{Rb}/\text{Sr} < 1$, presumably related to Sr-rich impurities (fluorapatite, carbonate) (Table. A4). Two splits of each separate were therefore briefly leached with warm 0.5M and 2M nitric acid, respectively, to gently remove easily soluble impurities and generate higher Rb/Sr ratios – more suitable for Rb-Sr dating - in the residual phlogopite (Maas, 2003). This treatment reduced Sr contents to 115-227 ppm and raised Rb/Sr to 1.79-4.48. The complementary 2M nitric acid leachates were high in Sr and had low Rb/Sr (0.05-0.28). Measured $^{87}\text{Sr}/^{86}\text{Sr}$ in the

phlogopite residues is low (0.70331-0.70397; Table. A4), irrespective of Rb/Sr, and similar to measured $^{87}\text{Sr}/^{86}\text{Sr}$ in the leachates (0.70346-0.70348; Table. A4) and in coexisting fluorapatite and clinopyroxene (0.70309-0.70354; Table. A4). This suggests that the Rb-Sr systems are very young. Various combinations of data points yield apparent ages in the range 0-4 Ma but no firm conclusions can be drawn because the data do not produce clear isochronous arrays.

3.4. ^{40}Ar - ^{39}Ar dating of phlogopite

Five phlogopite grains from samples PHL-21, PHL-24 and PHL-25 were also analysed for $^{40}\text{Ar}/^{39}\text{Ar}$ dating with a new generation ARGUSVI mass spectrometer (Phillips & Matchan, 2014) Samples PHL-24 and PHL-25 behaved quite similarly to one another, and contained a higher proportion of $^{40}\text{Ar}^*$ (~15% of total ^{40}Ar) (Table. A5). Total gas ages ranged from 582 ± 26 ka to 797 ± 80 ka. Data points were combined for inverse isochron analysis, which reveals the presence of some excess argon in these grains ($^{40}\text{Ar}/^{36}\text{Ar} = 302.2 \pm 1.1$ during 2σ). The 6-pt inverse isochrone age yield 556 ± 21 ka (2σ), derived from combining high-T data from PHL-24 and PHL-25. On the other hand, sample PHL-21 was collected from underlying stratigraphic compared to samples PHL-24 and PHL-25, and this fact is also reflected in the significant older age. Calculating a weighted mean age from concordant $^{40}\text{Ar}^*/^{39}\text{Ar}$ values from high-T heating steps (from all five grains, n=7 steps), sample PHL-21 yields an age of 741 ± 44 ka (6% 2σ ; MSWD = 1.3, p=0.23; Table. A5).

3.5. Sr-Nd-Pb-Hf isotopes

Fluorapatite and clinopyroxene from samples 21, 24 and 25 show variable Sr contents (3539-4274 ppm in fluorapatite, 147-2861 ppm in clinopyroxene), low Rb/Sr ($^{87}\text{Rb}/^{86}\text{Sr}$ 0.00003-0.00045 in fluorapatite, 0.0059-0.096 in clinopyroxene) and a narrow range of measured $^{87}\text{Sr}/^{86}\text{Sr}$ (0.70309-0.70354) (Table. A6). Nd concentrations are similarly diverse (536-1155 ppm in fluorapatite, 16.3-40.6 ppm in clinopyroxene, 183-220 ppm in groundmass) but measured $^{143}\text{Nd}/^{144}\text{Nd}$ ratios show little range (0.512782-0.512855, eNd +2.1 to +4.2, average $+3.0 \pm 0.6$, 1s). $^{176}\text{Hf}/^{177}\text{Hf}$ ratios for groundmass and

clinopyroxene also show a narrow range (0.282752-0.282827, eHf -0.7 to +1.9), as do the Pb isotope ratios for the groundmass and one of the fluorapatite fractions (Table. A6). Given the young age of the carbonatite, age corrections are trivial in almost all cases ($^{208}\text{Pb}/^{204}\text{Pb}$ in 21ap shifts from 40.18 to 40.06).

4. Discussion

The Middle Pleistocene age obtained for the Catanda carbonatites indicates active volcanism in SW Angola. Recent low magnitude earthquakes (4.2 to 5.1 M; <http://www.earthquake.usgs.gov>) of unresolved focal mechanism in the area also points to active tectonism along this region. Modern tectonics is also represented by a Quaternary transform faults system known as the Atlantic Hinge Line (Guiraud et al., 2010), which is sub-parallel to the Angolan coastline and the Mid-Atlantic Ridge (Fig.1). So, the main question is whether this volcanic and tectonic activity at Catanda is due to a local anomaly or can be linked to a broader-scale tectonic process.

The broad-scale option is supported by seismic tomography studies; those reported a low-velocity region at the lithosphere-asthenosphere boundary beneath the Catanda area and extending towards inland Angola (Fishwick, 2010; Hansen 2012). This mantle anomaly is also complemented by the detection of anomalous positive topography in the same area (Moucha & Forte, 2011). The ϵ Hf- ϵ Nd isotopic relation obtained for the Catanda lavas agree with the lithosphere-asthenosphere origin for the Catanda parental melts, plotting well below the global Hf-Nd isotope array and being also similar to geochemical signature of mantle-derived magmas such as the OIB's and the Group I kimberlites (Fig. 3a).

Similar low velocity regions and topographic anomalies as detected in SW Angola have been reported in incipient continental rift areas worldwide, such as the EAR (Pik, 2011; Civiero, 2015) or the CERS (Ritter et al., 2001; Wüllner et al., 2006), where the occurrence of volcanic events of carbonatitic composition is also well known (Woolley & Church, 2005).

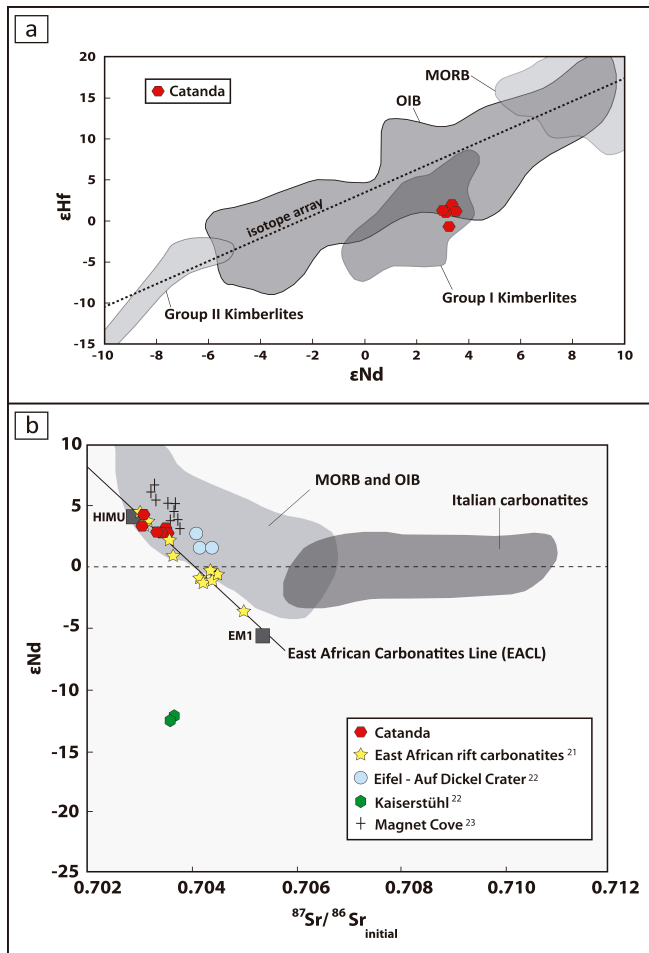


Figure 3. Covariation of Sr-Nd and Nd-Hf isotopic compositions. (a) Comparison of the Catanda carbonatites Sr-Nd isotope composition between global data set from carbonatites worldwide. (b) Nd-Hf composition of Catanda carbonatites compared to the oceanic basalts composition and to the Group I and Group II kimberlites.

The similitudes of Catanda with worldwide incipient continental rift areas is also supported by the occurrence of altered natrocarbonatite lavas (Campeny et al., 2015), similar to those described in a few localities from the EAR (i.e. Kerimasi and Tinderet: Hay, 1983; Deans & Roberts, 1984; Zaitsev & Keller, 2006; Zaitsev et al., 2013) and the CERS (i.e. Rockeskyll complex; Keller, 1989; Riley et al., 1996). The Sr-Nd isotopic features of the Catanda lavas confirm this resemblance. Catanda data follow the trend marked by the volcanic carbonatite localities from the EAR and also present like values to those reported in the Eifel carbonatites (Fig. 3b).

In our opinion, the occurrence of mantle geophysical anomalies in the area, the isotopic and compositional features of the Catanda lavas and the general similitudes between Catanda and incipient continental rift areas with associated carbonatitic

volcanism worldwide (i.e. the EAR and the CERS) argue for the occurrence of a broad-scale process of embryonic rifting in SW Angola.

The more plausible option to explain the origin of this process is the re-activation of the Lucapa rift structures, where the majority of the Angolan kimberlites and carbonatites, including Catanda, stand out (Fig.1). The Lucapa corridor was formed with the Pan-African orogen (at about 500-550 Ma) and the corridor experienced intermittent periods of extensional tectonism and anorogenic magmatism since the Neoproterozoic and later at the Permian and Cretaceous (Sykes, 1978; Jelsma et al., 2009). Anorogenic magmatism is well characterized by the intermittence of tectonic relaxed periods and apparent quiescence (Martin et al., 2012) as seems that occurred in Lucapa and also in several localities worldwide, those are associated with alkaline or carbonatitic magmatism such as in Chilwa (Malawi), Gardar (Greenland), Kola (Russia), or Grenville (Canada) (Martin et al., 2012). Following the intermittence of these cycles, it seems that Lucapa corridor is nowadays suffering a new period of magmatic re-activation, but the main issue is to understand why this process is occurring in this region at present-day.

A very plausible answer is the existence of a deep mantle superplume beneath Southern Africa (Gurnis, 2000), which has continuity to the upper mantle and contributes to the generation of shallow magmatic events (Al Hajri et al., 2009). The interaction of this superplume is broadly accepted to explain the magmatism of the EAR (Ritsema et al., 1999; Behn 2004; Civiero, 2015), but recent works argue for its displacement towards western Africa (Conrad, 2003). Then, would be not discernable the connection of this lower mantle superplume with the occurrence of embryonic continental rifting in SW Africa, which would be exemplified by the Pleistocene carbonatitic volcanism at the Catanda area.

In summary, our general interpretation is that present-day embryonic sub-lithospheric rifting is nowadays occurring in SW Africa. This process would be related with tectonic and magmatic re-activation of the Lucapa rift structures, generated by the interaction of the southern African superplume with the upper mantle beneath western Angola.

This general setting is exemplified by the occurrence of carbonatitic volcanism in the Catanda region.

The Lucapa rift structures were relevant in the break-up of Gondwana and the corresponding opening of the Atlantic Ocean during the Cretaceous so should not be discarded that western Africa can break up along this inter-continental structure if the rifting process continues active in the future.

At last, considering the young age of the Catanda volcanism, and the profusion of carbonatite and kimberlite outcrops in the Lucapa corridor, the occurrence of future alkaline-carbonatitic or kimberlitic eruptions in this portion of SW Africa is also plausible.

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Table A2

Fluorapatite																																		
Sample	AP-01	AP-02	AP-03	AP-04	AP-05	AP-06	AP-07	AP-08	AP-09	AP-10	AP-11	AP-12	AP-13	AP-14	AP-15	AP-16	AP-17	AP-18	AP-19	AP-20	AP-21	AP-22	AP-23	AP-24	AP-25	AP-26	AP-27	AP-28	AP-29	AP-30	AP-31	AP-32	AP-33	AP-34
²⁰⁶ Pb/ ²³⁸ U	0,021	0,021	0,016	0,022	0,028	0,030	0,015	0,014	0,020	0,019	0,029	0,028	0,027	0,023	0,024	0,031	0,020	0,016	0,015	0,015	0,016	0,036	0,029	0,032	0,017	0,020	0,032	0,030	0,030	0,030	0,029	0,055	0,016	0,035
± 1 RSE	4,2%	4,2%	3,9%	4,0%	3,9%	5,5%	4,5%	4,9%	3,9%	4,0%	3,6%	4,2%	4,7%	4,2%	4,2%	4,1%	4,3%	4,4%	4,4%	4,0%	4,7%	4,3%	4,3%	6,1%	6,2%	4,3%	3,3%	3,5%	3,5%	3,5%	3,2%	3,9%	4,4%	
²³⁰ Th/ ²³² Th	0,008	0,009	0,005	0,014	0,008	0,004	0,005	0,002	0,010	0,006	0,010	0,009	0,012	0,008	0,009	0,010	0,009	0,008	0,007	0,006	0,007	0,021	0,014	0,017	0,002	0,003	0,019	0,011	0,009	0,013	0,012	0,016	0,007	0,005
± 1 RSE	23,4%	30,0%	22,4%	38,0%	21,9%	3,3%	21,8%	3,3%	33,6%	20,2%	17,1%	15,1%	19,9%	18,0%	22,2%	25,9%	33,3%	32,5%	30,8%	22,3%	28,6%	31,0%	31,8%	30,3%	4,0%	4,0%	37,6%	32,0%	19,3%	31,2%	18,1%	15,3%	37,1%	2,6%
²⁰⁷ Pb/ ²⁰⁶ Pb	0,963	0,864	0,906	0,920	0,857	0,859	0,888	0,904	0,827	0,872	0,884	0,863	0,936	0,998	0,916	0,909	1,021	0,885	0,937	0,990	0,855	1,000	0,913	0,915	0,924	0,983	0,909	0,822	0,860	0,802	0,833	0,787	0,910	0,840
± 1 RSE	4,6%	4,6%	4,0%	4,3%	4,0%	5,8%	4,1%	5,1%	3,9%	4,2%	3,9%	4,7%	5,7%	6,5%	4,4%	4,5%	4,0%	4,6%	4,2%	5,2%	4,3%	5,0%	4,0%	4,7%	5,9%	6,9%	4,4%	3,5%	4,3%	3,7%	4,1%	3,5%	4,6%	4,5%

Table A3

Sample no.	Lab. no.	No. of crystals analysed	He no.	⁴ He (ncc)	Th/U ratio	^a Mean F _T	Age (Ma)	Error ($\pm 2\sigma$) (Ma)
21	8971	3	27059	0,047	11,86	1,00	0,69	0,04
21	9009	4	27145	0,078	12,88	1,00	0,89	0,05
21	9069	7	27193	0,166	12,26	1,00	0,58	0,03
21	9070	6	27195	0,208	13,29	1,00	0,57	0,03
21	11669	4	36352	0,035	15,75	1,00	0,65	0,04
							<i>b</i>0.65	0,13
25	8989	1	27083	0,017	13,34	1,00	0,64	0,04
25	9012	6	27156	0,044	8,82	1,00	<i>c</i>1.33	0,08
25	11673	4	36364	0,075	11,60	1,00	0,63	0,04
25	11674	6	36367	0,029	11,39	1,00	0,76	0,05
25	9072	5	27199	0,068	11,35	1,00	0,62	0,04
							<i>b</i>0.66	0,09
Durango apatite - standard								
Durango	9074	1	27204	1,308	17,32	1,00	32,4	2,0
Durango	11658	1	36180	5,357	15,27	1,00	31,6	2,0
Durango	11675	1	36289	3,867	15,18	1,00	31,7	2,0
Durango	11684	1	36400	21,672	17,25	1,00	29,7	1,8
							<i>b</i>31.3	1,9

^a FT is the a-ejection correction after Farley et al. (1996).

^b Weighted mean ages (95% confidence level) calculated using Isoplot v. 3.0 (Ludwig, 2003).

^c Analysis excluded from calculation of weighted mean.

Table A4

Sample	Phlogopite									Fluorapatite			Clinopyroxene		
	Initial (2M)			Separated-1 (0.5M)			Separated-2 (2M)			AC-21	AC-24	AC-25	AC-21	AC-24	AC-25
	AC-21	AC-24	AC-25	AC-21	AC-24	AC-25	AC-21	AC-24	AC-25						
Rb	431	169	66	513	475	409	210	378	459	0,3	0,4	2,6	4,2	0,1	11
Sr	1672	3748	236	115	227	196	118	174	169	5830	6335	3114	469	203	452
Rb/Sr	0.26	0.05	0.28	4.48	2.09	2.08	1.79	2.18	2.72	0	0	0.001	0.009	0	0.024
⁸⁷ Rb/ ⁸⁶ Sr	0.7458	0.1301	0.8143	12.9521	6.0468	6.0261	5.1638	6.2915	7.8585	0	0	0.002	0.026	0.001	0.068
⁸⁷ Sr/ ⁸⁶ Sr	0.703471	0.703463	0.703475	0.70397	0.70338	0.70343	0.70346	0.70345	0.70331	0.70337	0.70346	0.70354	0.70353	0.70311	0.70309

Table A6

Sample	Groundmass			Clinopyroxene			Fluorapatite		
	AC-21	AC-24	AC-25	AC-21	AC-24	AC-25	AC-21	AC-24	AC-25
<i>ppm</i>									
Rb	4.17	5.05	8.75	6.2	0.3	95.2	0.04	0.18	0.6
Sr	2495	2442	1036	601	146.6	2861	3539	4274	3996
Nd	220	211	183	40.6	21.4	16.27	536	1155	839
Sm	28	27.1	22.3	11.3	6.06	37.97	163	169	123.4
Lu	0.32	0.32	0.24	0.18	0.08	0.42	1.08	1.08	0.8
Hf	2.94	3.1	2.95	20.35	17.11	61.86	0.09	0.29	0.16
Pb	2.34	1.37	2.74	0.48	0.36	1.75	0.97	221.2	0.97
Th	18.5	18.4	14.1	0.68	0.23	1.18	50.62	92.9	54.91
U	6.77	6.43	4.97	0.13	0.04	0.31	3.88	6.53	4.59
⁸⁷ Rb/ ⁸⁶ Sr	0.00482	0.00597	0.02441	0.02987	0.0059	0.09618	0.00003	0.00012	0.00045
⁸⁷ Sr/ ⁸⁶ Sr	-	-	-	0.70353	0.70310	0.70309	0.70336	0.70346	0.70354
¹⁴⁷ Sm/ ¹⁴⁴ Nd	0.07708	0.07762	0.07388	0.10131	0.10911	0.12269	0.08968	0.08851	0.08868
¹⁴³ Nd/ ¹⁴⁴ Nd	0.51279	0.51282	0.51280	0.51280	0.51286	0.51281	0.51278	0.51278	0.51278
εNd	2.96	3.47	3.08	3.22	4.23	3.36	2.81	2.85	2.83
¹⁷⁶ Lu/ ¹⁷⁷ Hf	0.01546	0.01466	0.01155	0.00090	-	0.00081	-	-	-
¹⁷⁶ Hf/ ¹⁷⁷ Hf	0.28280	0.28281	0.282802	0.28275	-	0.28283	-	-	-
εHf	1.20	1.24	1.06	-0.71	-	1.95	-	-	-
²³⁸ U/ ²⁰⁴ Pb	193	314.24	120.3	-	-	-	261.17	-	-
²³² Th/ ²⁰⁴ Pb	547	930.66	353.64	-	-	-	3584.62	-	-
²⁰⁶ Pb/ ²⁰⁴ Pb	20.58	20.5	20.09	-	-	-	20.5	-	-
²⁰⁷ Pb/ ²⁰⁴ Pb	15.79	15.81	15.78	-	-	-	15.81	-	-
²⁰⁸ Pb/ ²⁰⁴ Pb	39.99	40.17	39.87	-	-	-	40.18	-	-