Magmatic activity in incipient continental break-up as revealed by coupling melt and fluid inclusions

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ABSTRACT

Deciphering deep magmatic processes driving the onset of continental break-up is fundamental to constrain our understanding of plate tectonics. The East African Rift System (EARS) is the only currently active system on Earth to study distinct stages of rift evolution. We present a coupled analysis of melt and fluid inclusions in the Virunga Volcanic Province (VVP) offering an unprecedented insight into the dynamics of incipient rifting and its evolution. Our study highlights that melting of distinct metasomes in the deep lithosphere is a common feature of immature rifts. In the VVP, it leads to the emission of nephelinitic and basanitic melts at Nyiragongo and Nyamulagira volcanoes, respectively. Additionally, the chemical composition of melt and fluid inclusions supports the identification of another magmatic series in the area. Related alkali basaltic melts would be produced by contemporary melting of a less enriched domain in the upper lithosphere, more classically documented in mature rifts. Various extents of mixing and crystallisation of these three distinct magmatic series occur in the lower crust beneath

the VVP where the barometric estimates are consistent with the presence of a thick seismic low velocity zone (LVZ). The involvement of alkali basaltic melts in the regional magma production could be also detected in the spread of gas emissions in the rift valley and in the fumaroles of the main active volcanoes. Melting of the corresponding mantle domain is an added source of gas release that may largely contribute to CO_2 emissions along the EARS.

INTRODUCTION

Magmatic activity in continental rifting handles some of the most remarkable volcanic manifestations on Earth, including emission of hyperalkaline undersaturated and carbonatitic volcanism (Rooney et al., 2020a), and massive CO_2 degassing (Wong et al., 2019). However, the origin and evolution of the involved magmas as well as the architecture of associated magmatic systems (especially the depth of magma ponding zones) are still poorly understood with respect to other geodynamical contexts (Biggs et al., 2021).

The East African Rift System (EARS) is regarded as the current largest example of continental break-up on Earth with magmato-tectonic events starting about 45 Myr on the Eastern branch (Michon et al., 2022 and references therein). It evolved from trap-scale to plate-scale rifting under the combined effect of an overall complex mantle upwelling dynamics and of extensive stress acting on the African lithosphere (Michon et al., 2022). The origin of the large chemical variability of associated lavas erupted is still a matter of debate, and several models have been being formulated over the years, including various extents of mixing of distinct components (Rooney et al., 2020a) such as (1) a convecting mantle with different mantle plumes or thermal anomalies rooted in the African Large Low Shear Velocity Province, together with a depleted mantle endmember (DMM) and (2) a sub-continental lithospheric mantle (SCLM) with

both a common lithospheric mantle (CLM) component partially metasomatized by the agents extracted from the convecting mantle, and a Pan-African (PA) lithospheric domain that is enriched in metasomes likely deriving from previous subduction events.

Magmatic activity on the Western branch started about 25 Myr ago and concentrated in four main volcanic provinces, which are from North to South (Michon et al. (2022) and references therein): Toro Ankole, Virunga, Kivu, and Rungwe. Carbonatitic, silica undersaturated hyperalkaline and tholeiitic lavas are predominant with a prominent increase in SiO_2 and depletion in K_2O from Toro Ankole to Kivu, which reflects a progressive decrease of the melting depth towards the South (Furman and Graham, 1999; Rosenthal et al., 2009). The Virunga Volcanic Province (VVP) is currently the sole volcanic province of the Western branch characterized by ongoing eruptive activity. The VVP is characterized by a massive gas release from both volcanic gas plumes (CO_2, SO_2, and halogens) and soil degassing (CO_2) across the rift valley (Tedesco et al., 2010; Bobrowski et al., 2017; Fischer et al., 2019). The VVP is also known for its high potassic magmatism, making it one of the largest within-plate potassic provinces on Earth (Minissale et al., 2022). Two main magmatic series are coexisting (Pouclet et al., 2016): leucite bearing basanite and leucite-melilite bearing nephelinite. They are best represented by the eruptive activity that occurred over 12 ka at the Nyamulagira and Nyiragongo volcanoes, respectively. Previously, it has been proposed that those magmas were related to mantle plume sources (Chakrabarti et al., 2009; Castillo et al., 2014). Recent studies have rather supported the melting of a heterogeneous metasomatized SCLM by thinning-driven adiabatic decompression (Pouclet et al., 2016; Muravyeva et al., 2021; Pitcavage et al., 2021; Boudoire et al., 2022; Minissale et al., 2022). However, the reason for the slight enrichment in primordial helium (^3He), leading to $^3He/^4He$ values higher than those expected from SCLM melting, in

some gaseous emissions along the Western branch is still poorly understood (Tassi et al., 2009; Tedesco et al., 2010; Castillo et al., 2014; Boudoire et al., 2022).

Most studies that tried to elucidate the origin of the chemical variability of magmas in continental rifting were based either on a compilation of bulk rock analyses for the entire EARS or on the study of melt inclusions entrapped in crystals hosted by lavas from a single volcanic edifice (see **Appendix A** for references). In this study, we present the analyses of both melt and fluid inclusions from distinct eruptive centres in the VVP and discuss them in a global scheme including earlier analyses of mafic melt inclusions obtained for other volcanic edifices along the EARS (**Figure 1a**). This innovative approach of coupling information from melt (major, volatile, and trace elements) and fluid (noble gases, barometry) inclusions from the same products offer a unique opportunity to constrain magmatic processes in the VVP and more broadly those involved in continental rifting.

SAMPLING STRATEGY AND RESULTS

Lava flow samples

Lavas flows from five eruptive sites were collected in the VVP (**Figure 1b**): a melilite nephelinite from the Nyiragongo summit lava lake in 2020, a potassic basanite from the Nyamulagira summit eruption in 2020, as well as two olivine nephelinite or melilitites samples (Mudjoga, Kashaka), and an alkali basalt (Rumoka) from peripheral eruptive cones (<12 ka) in the rift valley (Pouclet et al., 2016; Pouclet and Bram, 2021; Minissale et al., 2022; Molendijk et al., 2024). The major element composition of the bulk rocks mostly overlaps within the chemical variability previously documented in the area (**Figure 1c**), in particular the two main nephelinitic and basanitic magmatic series reported in the VVP (Pouclet et al., 2016).

Composition of melt and fluid inclusions

Melt and fluid inclusions in olivine, clinopyroxene, and nepheline crystals from the collected lava flows were analysed (see **Appendix A** for the full methodology and **Appendix B** for the dataset). Melt and fluid inclusions in high (Fo_{87-90}; where Fo is the forsterite content in molar proportions), and low (Fo_{75-85}) magnesian olivine crystals were distinguished.

Three endmembers that frame the whole chemical variability in major, trace, and volatile elements were identified (**Figure 2**; **Appendixes B and C**). (1) The "Nyiragongo-type" nephelinitic melt exhibits the lowest Na_2O/K_2O (= 0.46), and the highest Cl (2352 ppm) and F (4866 ppm) contents. The enrichment in more incompatible elements with respect to less incompatible ones is significant (La/Yb = 59.1). Noble gases measurements are not reported due to the existence of a diffusive loss and isotopic fractionation involving especially ^3He and ^4He. (2) The "Nyamulagira-type" basanitic melt is characterized by Na_2O/K_2O = 1.1, high Cl (1249 ppm) and F (2145 ppm) contents as well as intermediate ratios between more incompatible and less incompatible trace elements (La/Yb = 37.1). Noble gases systematics show relatively low $^3He/^4He$ (Rc/Ra = 7.8), $^4He/^{40}Ar^*$ (= 0.2), but a high $CO_2/^3He$ (= 7.9×10^9). (3) The "Rumoka-type" basaltic melt (in primitive Fo_{89-90} olivine crystals) is characterized by the highest Na_2O/K_2O (= 1.4) and the lowest Cl (641 ppm) and F (1038 ppm) contents. The ratio between light (LREE) and heavy (HREE) rare earth elements is the lowest (La/Yb = 22.1). Noble gases show the highest $^3He/^4He$ (Rc/Ra = 8.1), $^4He/^{40}Ar^*$ (= 3.4), and lowest $CO_2/^3He$ (= 3.5×10^8). Strong variations of highly incompatible elements ratios (such as Ce/Pb, Nb/La, Th/U, Zr/Hf) are observed among these melts. The chemical composition of melt inclusions in olivine crystals from the Mudjoga and Kashaka lavas ranges between a "Nyiragongo-type" nephelinitic melt and

a "Rumoka-type" basaltic melt (**Figure 2c, d**; **Appendix C**). The chemical composition of melt and fluid inclusions in low magnesian olivine crystals from Rumoka lavas diverges from the composition of a "Rumoka-type" basaltic melt towards a "Nyamulagira-type" basanitic melt (Head et al., 2011).

Barometric estimates

The dissolved CO_2 content in melt inclusions ranges from 0.11-0.31 wt% in "Nyamulagira-type" basanitic melt to 0.28-0.35 wt% in "Nyiragongo-type" nephelinitic melt and up to 1.69 wt% in "Rumoka-type" basaltic melt. In melt inclusions from other peripheral products (Kashaka and Mudjoga), the dissolved CO_2 content shows intermediate values (0.13-0.77 wt%) like the ones (0.29-0.88 wt%) measured in the more evolved melt inclusions at Rumoka (Fo_{83} olivine crystal). The CO_2 density in fluid inclusions for these peripheral products ranges from 0.57 to 0.94 g/cc (**Appendix B**).

Corresponding barometric estimates allow us to define four pressure ranges (**Figure 3**). (1) The highest pressures (870-700 MPa) are recorded for Rumoka and Kashaka peripheral products. Intermediate pressures are centred on two modes at (2) 540-450 MPa and (3) 230-330 MPa for Nyamulagira products (mirroring a differentiation trend from $Fo_{79.6}$ to $Fo_{75.6}$) and for all peripheral products. (4) The lowest pressures (70-130 MPa) are recorded in melt inclusions from Nyiragongo (in nepheline crystals) and partially from Mudjoga. These barometric estimates agree with earlier results based on petrological, geochemical, and geophysical methods (Louaradi et al., 1993; Pouclet and Bram, 2021; Molendijk et al., 2024) which suggest at least three major magma ponding zones beneath the VVP in similar pressure ranges.

DISCUSSION

For a single eruptive centre, the decrease in MgO, CaO/Al_2O_3, and Sc correlated to an increase in incompatible elements such as K and Th suggest that olivine-clinopyroxene crystallisation accounts for most of the chemical evolution in major and trace elements from the primitive to the more evolved melt inclusions (**Figure 2a**; **Appendix C**). This predominant role of olivine-clinopyroxene crystallisation (followed by feldspathoids in shallower magma reservoirs) in the chemical variability was previously documented for lavas erupted in the surroundings of Nyiragongo (Pitcavage et al., 2021; Molendijk et al., 2024). However, the crystallisation of the main mineralogical phases reported in VVP magmas cannot explain the chemical variability observed between the chemical endmembers (Minissale et al., 2019), nor that observed on certain highly incompatible trace elements ratios (such as Th/U) between primitive and more evolved melt inclusions at Rumoka. Our data also confirm that a significant role of crustal contamination may be discarded consistently with the absence of Ce/Pb and Nb/La anomalies (**Figure 2b**; Chakrabarti et al., 2009; Minissale et al., 2022) and thus in favour of heterogenous mantle sources.

Melting of metasomes in the deep lithospheric mantle

The "Nyiragongo-type" nephelinitic melt has a clear affinity with a carbonatitic component (high Zr/Hf and low Th/U, Ti/Eu), as previously suggested in the area (Chakrabarti et al., 2009; Pouclet et al., 2016), and for nephelinitic melts emitted at Ol Doinyo Lengaï (**Figure 2c; Appendix C**). Lithium-enrichment in the "Nyamulagira-type" basanitic melt is consistent with a preferential affinity for the global average of subducted sediment (GLOSS-II component) as previously suggested also for the Bufumbira volcanic field in the VVP (**Figure 2d**; Hudgins et

al., 2015). While subducted sediments are thought to play a negligible role in the genesis of VVP magmas (Minissale et al., 2022), past episodes of mantle metasomatism by slab-derived fluids have led to preferential enrichment in some elements (Taniuchi et al., 2024), as attested by the elevated Li/Yb in the Bufumbira volcanic field (Hudgins et al., 2015), and the lower $\delta^{13}C$ values of CO_2 in gaseous emissions at Nyamulagira (Boudoire et al., 2022). The chemical composition of melt inclusions also highlights a preferential signature of garnet over spinel (enrichment in LREE and MREE with respect to HREE; **Figure 2e**) and of phlogopite over amphibole (low Ba/Rb, Na_2O/K_2O and high Rb/Sr; **Figure 2f**) in the mantle sources of the two related magmatic series (Chakrabarti et al., 2009; Condomine et al., 2015; Muravyeva et al., 2021; Minissale et al., 2022).

In summary, our new data from melt inclusions entirely agree with the melting of two distinct types of metasomatized lithologies in the mantle beneath the Nyiragongo and Nyamulagira volcanoes ("Type V magmas"; Rooney et al., 2020a). The generation of a Nyiragongo primary olivine melilitic melt (leading to present nephelinitic melt by differentiation) agrees with the melting of a carbonated metasome in the garnet-phlogopite-carbonate stability field at depth >100 km, close to the base of the lithosphere (140-160 km-depth; Chakrabarti et al., 2009; Muravyeva et al., 2021; Minissale et al., 2022). Conversely, a distinct metasome affected by old slab fluids is expected to be at the origin of the Nyamulagira primary basanitic melt (Chakrabarti et al., 2009; Minissale et al., 2022).

Contemporary melting of an upper lithospheric mantle domain

The chemical composition of melt inclusions analysed in this study also clearly highlights the contemporary production of a third magmatic series (the "Rumoka-type" basaltic melt) not yet

documented in the VVP but reminiscent of "Type IIb magmas" (Rooney et al., 2020a). The similarity of chemical compositions in trace elements between the related melt inclusions and those from the 2011 eruption at Nabro in the Afar region is striking (**Figure 2**; **Appendix C**). These melts are ubiquitous along the EARS and are considered to be produced at the beginning of the transition towards mature rifts by thermobaric destabilization of a thick lithosphere (Rooney et al., 2020a, 2020b; Chiasera et al., 2021). Along the Western branch, these melts would be produced by melting of a less enriched lithospheric mantle domain (Chakrabarti et al., 2009; Rosenthal et al., 2009; Pouclet et al., 2016).

The Na_2O/K_2O ratio above the unit in the primitive basaltic melt inclusions at Rumoka suggests the presence of amphibole (together with phlogopite) in the mantle source, a mineral characteristic of a shallower lithospheric melting domain (60-80 km-depth; Rosenthal et al., 2009; Muravyeva et al., 2021). The melting of a similar shallow mantle domain was consistently proposed for the genesis of alkali basalts of similar composition in the neighbouring Kivu volcanic province (Rosenthal et al., 2009) and in the genesis of Type IIb magmas (Rooney et al., 2020a). In the VVP, it supports the idea of contemporary melting of distinct lithospheric mantle domains involved in magma genesis. A heterogeneous SCLM with a deeper lithospheric mantle hosting metasomes (U-Th enriched lithologies) and a less enriched upper lithospheric mantle could be a reasonable explanation for the slight $^3He/^4He$ variability seen between Nyiragongo, Nyamulagira, and Rumoka ~~products~~. This hypothesis agrees with the observation that metasomatized lithologies are preferentially found near the base of the lithosphere along the EARS (Rooney et al., 2020a). Such vertical partition has also been suggested beneath the North Tanzanian Divergence (NTZ) of the Eastern branch, where a LVZ has been imaged at a mid-lithospheric depth (~60 km) separating the two mantle components (Plasman et al., 2017).

Whatever the case, the $^{3}He/^{4}He$ values remain within the range of values classically attributed to the DMM (8±1 Ra; Tedesco et al., 2010) and confirm the major contribution of the upper mantle in the genesis of the fluids under this part of the EARS (Aiuppa et al., 2021; Boudoire et al., 2022).

Magma mixing of distinct magmatic series

The primitive melt inclusions entrapped in the deepest roots of the magmatic systems beneath the VVP, i.e. at the crust-mantle transition zone (Muravyeva et al., 2021) (**Figure 3**), and those of Nyiragongo and Nyamulagira, better preserve the chemical signature of distinct magmatic series. Conversely, more evolved melt inclusions from peripheral eruptive vents have a hybrid chemical composition between these magmatic series (**Figure 2**). We suggest that this fingerprint results from variable mixing of the distinct identified magmatic series in intermediate crustal magma ponding zones. In fact, we document two intermediate crustal pressure modes (540-450 MPa and 230-330 MPa) for these peripheral products (**Figure 3**) that match with the top of the LVZs beneath the VVP (Mavonga et al., 2010; Pouclet and Bram, 2021) with the main one extending from 18 to 28 km depth (Muravyeva et al., 2021). These LVZs image magma reservoirs or several melt-rich sills where magma mixing is eased (Muravyeva et al., 2021). Complex crystal zoning and textures reported in some peripheral lavas (Molendijk et al., 2024) partially highlight this mixing process. A similar LVZ linked to magmatic processes has also been imaged in the lower crust (15-35 km depth) beneath the NTZ of the Eastern branch (Plasman et al., 2017).

Insights on current degassing processes

Nyiragongo and Nyamulagira are among the strongest volcanic gas emitters on Earth (Fischer et al., 2019). Degassing paths modelled from the initial composition of melt inclusions (see **Appendix A** for the methodology) were compared to the temporal evolution of CO_2/SO_2 and Cl/S from gas plumes composition reported in literature (Bobrowski et al., 2017; Boudoire et al., 2022). This period overlaps with the progressive replenishment of the Nyiragongo lava lake between the two flank eruptions in 2002 and 2021 (Burgi et al., 2020) and the renewal of lava lake activity at Nyamulagira since 2012 (Burgi et al., 2021). The increase in CO_2/SO_2 and Cl/S values suggests that magma arrival and degassing in the deeper crustal magmatic reservoirs (>250 MPa) prevail on magma degassing in the shallowest ones (<150 MPa; **Figure 4a, b**) over time. At Nyiragongo, the existence of various degassing magmatic sources involved in the outgassing of the lava lake was previously proposed (Bobrowski et al., 2017) and the exceptional occurrence of deep mush material in the 2021 lava from Nyiragongo (Molendijk et al., 2024) supports this hypothesis.

We also note that the $^3He/^4He$ values in Nyiragongo fumaroles may have been slightly lower in 2020 (Rc/Ra = 7.3±0.2) (Boudoire et al., 2022), preceding the 2021 flank eruption than during the 2003-2007 period (Rc/Ra = 7.8±0.8 and up to 8.7; Tedesco et al., 2010) (**Figure 4c**). This behaviour mirrors the increase of magma flux feeding the lava lake on the same time span (Burgi et al., 2020, 2021). This slight decrease in $^3He/^4He$ values over time, which does not depend on pressure (and is therefore not linked to the deepening of the degassing magmatic sources over time), highlights a potential ^4He-enrichment from 2003 to 2020. It could reflect an increase of the magma production (and influx) from the Nyiragongo deep metasomatized mantle source that is enriched in U-Th (and thus ^4He) with respect to the other endmembers described in this study. Conversely, it is worth noting the chemical affinity (higher Rc/Ra and $^4He/^{40}Ar^*$

coupled with low $CO_2/^3He$ and $\delta^{13}C$) of regional dry CO_2 gas emissions (e.g., mazuku on **Figure 4c**) from the rift valley with the isotopic signature of fluid inclusions in crystals from Rumoka products. High $^4He/^{40}Ar^*$ and low $CO_2/^3He$ and $\delta^{13}C$ are reminiscent of more degassed magmas (Boudoire et al., 2022) and may suggest that steady-state outgassing through the rift valley is mostly linked to magma storage and degassing in the LVZs that could be preferentially fed by the melting of the upper and less enriched lithospheric mantle domain (Tedesco et al., 2010; Boudoire et al., 2022).

CONCLUSIONS

Melt and fluid inclusions suggest that current magma production beneath the VVP is not solely linked to the melting of various mantle metasomes that preferentially feed the main volcanic edifices, as documented for immature rifts (Rooney et al., 2020a; Aiuppa et al., 2021). The contemporary melting of a less enriched lithospheric domain, isolated at a shallower level in the mantle, is shown by the composition of primitive melt inclusions from peripheral products erupted in the rift valley. This process is rather reminiscent of magmatic production at the beginning of the transition towards mature rifts. We propose that steady-state degassing associated with continental rifting in the area is preferentially triggered by magma production in the upper part of the lithosphere (at 60-80 km-depth), followed by mixing and storage of the melt in the lower crust (at 15-35 km-depth), where LVZs are imaged, rather than by the melting of isolated deep lithospheric metasomes (Muirhead et al., 2020; Aiuppa et al., 2021). This model would preferentially account for global CO_2 emissions along the EARS with respect to volcanic emissions (Wong et al., 2019) and for the large chemical variability of erupted melts (Rooney et al., 2020a).

SUPPLEMENTARY MATERIAL AND DATA AVAILABILITY STATEMENT

The Supplemental Material is composed of four appendixes. **Appendix A** describes the methodology used in this study. It provides details about the analytical conditions of measurements, data treatment, degassing models, and comparative data from literature. **Appendix B** is the complete dataset of measurements acquired for this study. **Appendix C** is composed of four complementary figures that sustain the discussion about the role of crystallisation, contamination, mixing processes, and mantle sources lithologies in the chemical variability of melt inclusions. **Appendix D** is the completed repository template available on a recognized domain repository of the GFZ Data Services through the link https://dataservices.gfz-potsdam.de/panmetaworks/review/0987bbb94d29daa7e406e048ef73614579375334e467578be75da9e606a69d78/ with a reserved (and not yet registered at this step) DOI (https://doi.org/10.5880/fidgeo.2024.029) (Boudoire, 2024) for accessing the dataset and the data description in accordance with the data availability statement.

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FIGURE CAPTIONS

Figure 1. (A) Location of the volcanoes of the East African Rift System (EARS) for which basic melt inclusions were documented and compiled in this study. Continuous lines show the main EARS active segments (Michon et al., 2022). (B) Location of the sampling sites in the Virunga Volcanic Province (VVP) for the melt and fluid inclusions investigation of this study. (C) Composition of the host lavas (coloured dots refer to the lava sampled in the VVP) and comparison with literature data (coloured fields refer to the lava sampled along the EARS, see **Appendix A** for references).

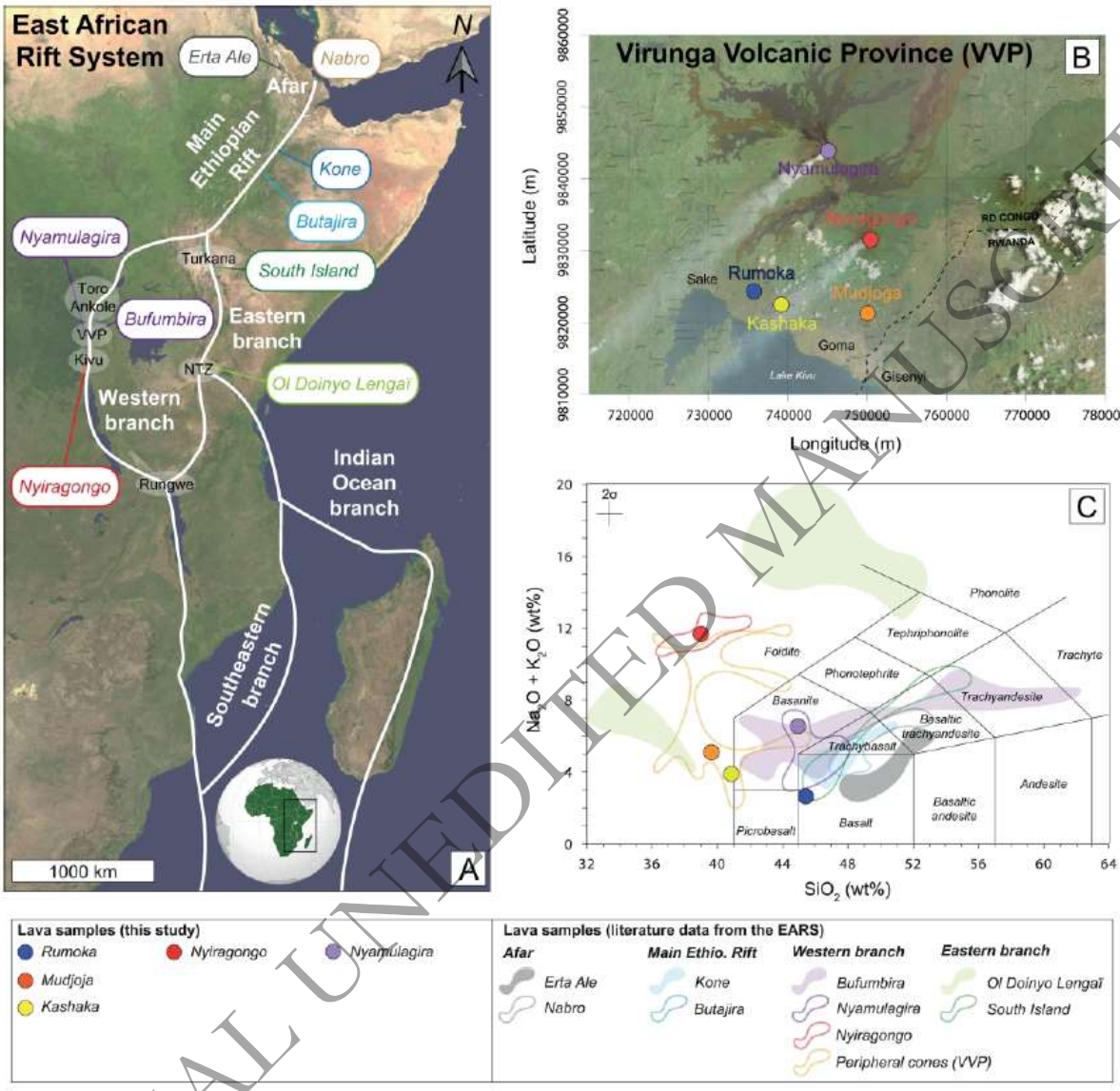
Figure 2. (A) SiO_2 vs. K_2O in melt inclusions with the composition of the main mineralogic phases in the VVP indicated with crosses (Cpx. stands for clinopyroxene). (B) Nb/La vs. Ce/Pb, (C) Zr/Hf vs. Th/U, and (D) Li/Yb vs. Nb/U in melt inclusions compared with the composition of global endmembers showed with squares (see **Appendix A** for references). (E) K/Yb vs. Dy/Yb and (F) Ba/Rb vs. Rb/Sr in melt inclusions with the expected effect of amphibole, phlogopite, garnet and spinel in the melted mantle source (Furman and Graham, 1999; Duggen et al., 2005). Numbers show the melting degree on the theorical mantle sources melting paths. Coloured fields refer to the composition of basic melt inclusions from the EARS documented in the literature (see **Appendix A** for references).

Figure 3. Pressure and depth estimates of magma ponding zones beneath the VVP from CO_2 densimetry in fluid inclusions (FI) and CO_2-H_2O equilibrium in melt inclusions (MI). Earlier data from literature (Lit.) for Nyamulagira and Nyiragongo about potential magma ponding

zones (shaded coloured ellipsoids) and the crust structure (low velocity zones, crust-mantle transition zone) are listed in **Appendix A**. The melt inclusions selected as chemical endmembers in this study are highlighted: *(1)* for Nyiragongo-type melt, *(2)* for Nyamulagira-type melt, and *(3)* for Rumoka-type melt.

Figure 4. Pressure-dependence of CO_2/SO_2 and Cl/S molar ratios in gas plumes emitted at (A) Nyiragongo and (B) Nyamulagira. Degassing paths were modelled using SulfurX (Ding et al., 2023) and SolEx (Witham et al., 2012) considering both Fractional Equilibrium Degassing (FED) and Batch Equilibrium Degassing (BED). See **Appendix A** for more details about starting conditions and parameters used in the modelling. Values framed on the x-axis highlight (i) averaged measurements made in volcanic gas plumes from 2005 to 2014 (Sawyer et al. 2008; Bobrowski et al., 2017a, b) and (ii) minimum and maximum values measured in 2020 (Boudoire et al., 2022). The theorical pressure ranges corresponding to these measurements are highlighted on the y-axis (shaded boxes) as well as the corresponding magma ponding zones (circles) from **Figure 2**. (C) $CO_2/^3He$ vs. Rc/Ra in fluid inclusions with dashed black lines evidencing mixing of a mantle endmember (Rumoka-type melt) and various crustal components (Barry et al., 2013). The stars show the average composition of the fumaroles at Nyiragongo and Nyamulagira (Tedesco et al., 2010; Boudoire et al., 2022). $CO_2/^3He$ vs. Th/U with dashed lines showing mixing between *(1)* a Nyiragongo-type melt and either *(2)* a Nyamulagira-type melt or *(3)* a Rumoka-type melt.

524 **Fig. 1.**



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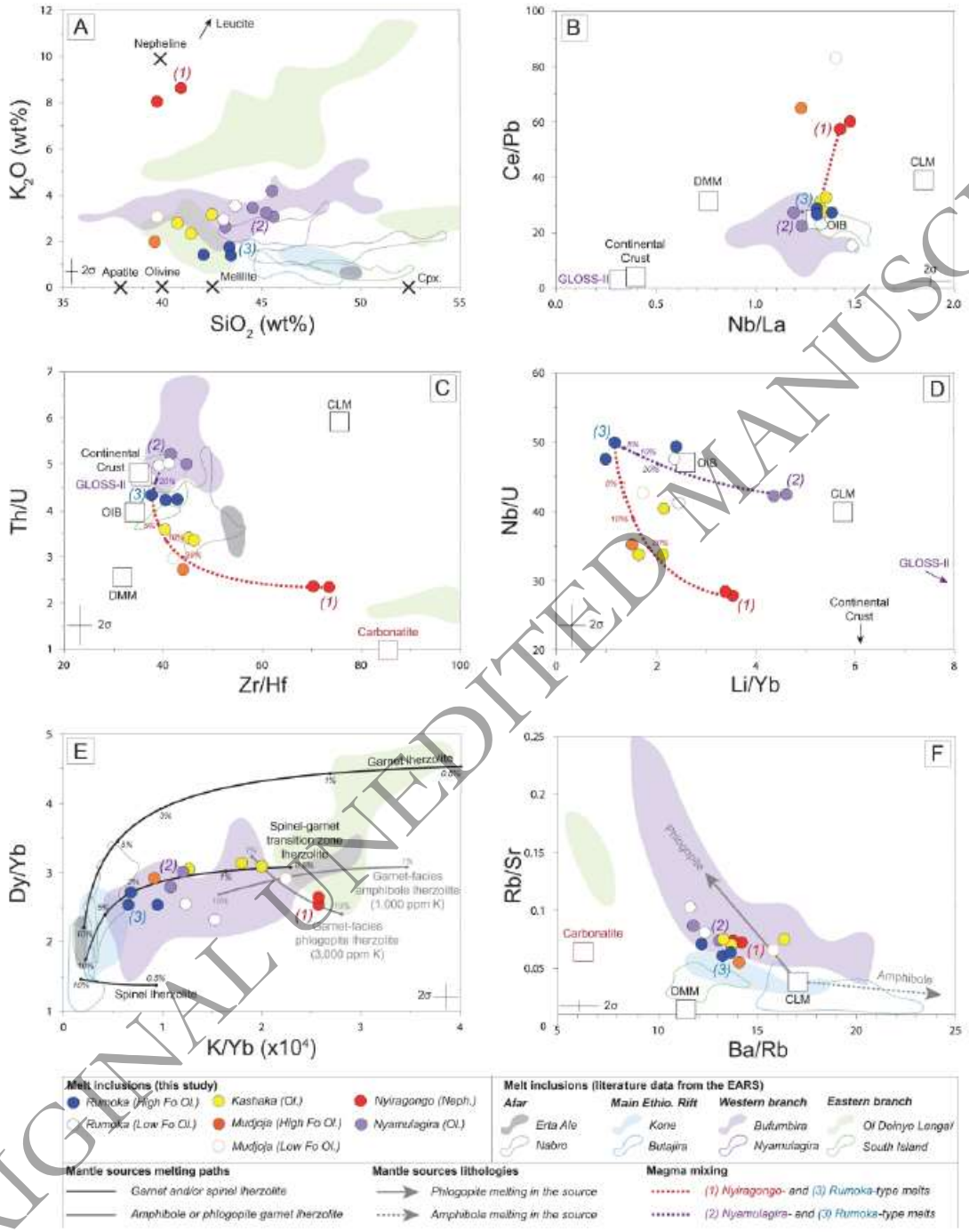
532 **Fig. 2.**



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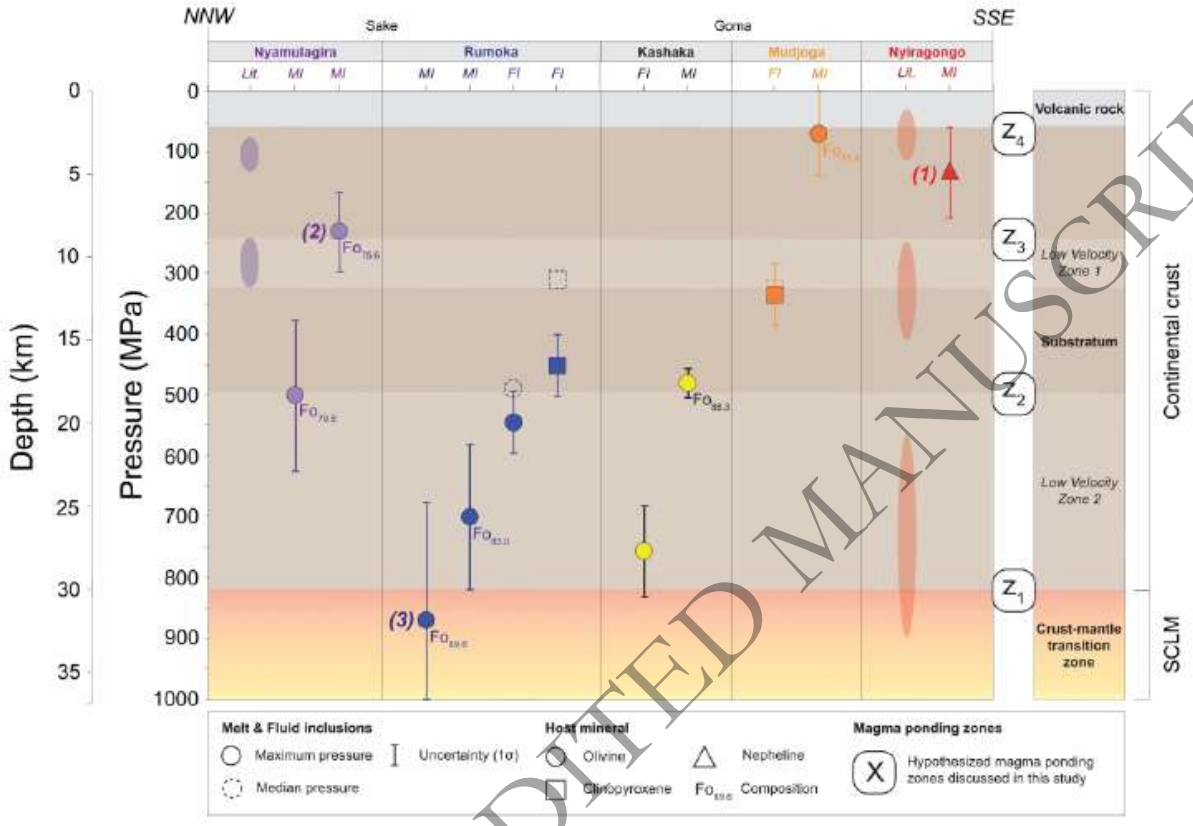
537 **Fig. 3.**



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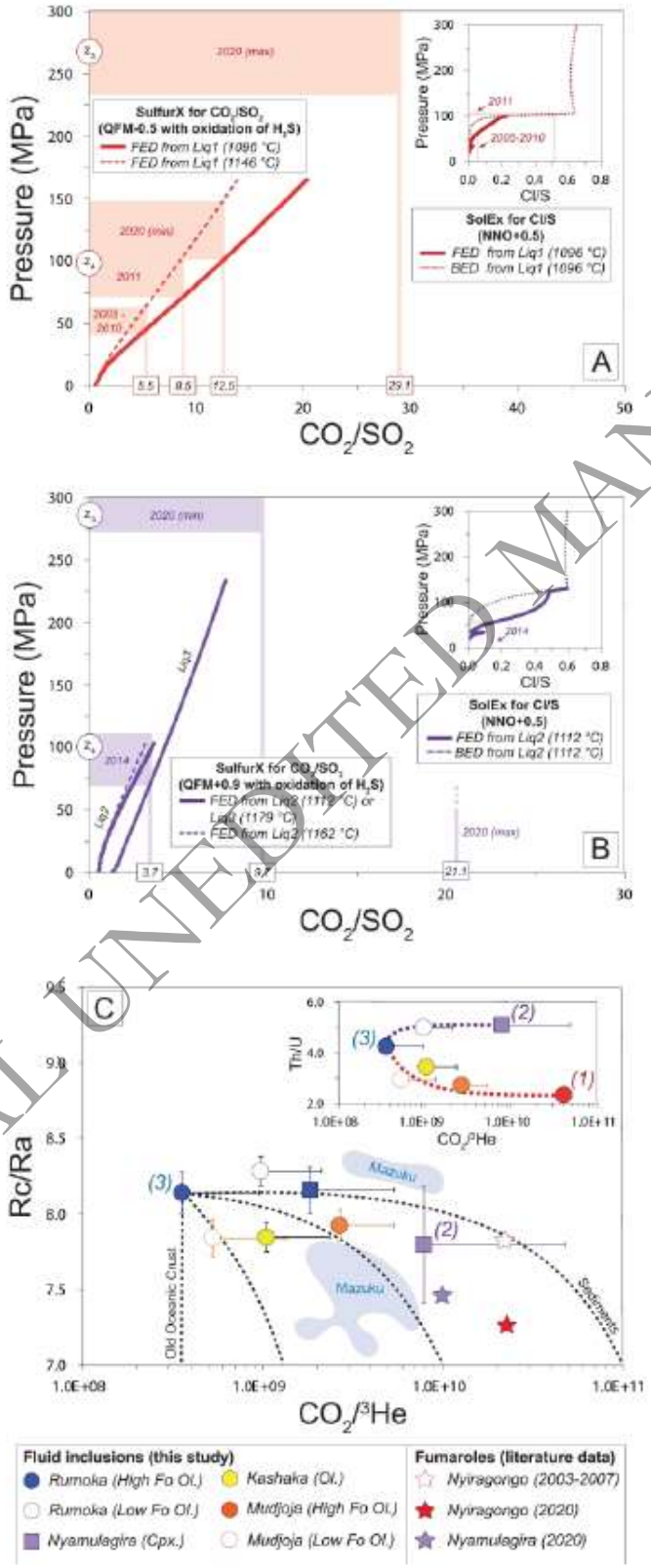
549 **Fig. 4.**



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