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Magma residence time beneath the Piton de la Fournaise Volcano, Reunion Island, from U-series disequilibria

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Abstract

The U, Th and Ba concentrations, ^{238}U–^{230}Th–^{226}Ra–^{210}Pb and ^{228}Ra –^{232}Th disequilibria have been measured in a suite of basalts and oceanites erupted during the last two millennia at Piton de la Fournaise (Réunion Island, Indian Ocean). Most of the variation in the concentration of all three incompatible elements is due to crystal fractionation or accumulation (and incorporation of olivine xenocrysts in the oceanites), but contamination by hydrothermally altered rocks or secondary minerals might explain significant variations in Ba/Th. Basalts with Th contents lower than 2.25 ppm have only been produced in eruptions outside the Enclos Fouqué caldera, whereas more evolved basalts are predominantly observed close to the summit craters, inside the Enclos caldera and the rift-zones. The samples have almost uniform Th/U of 3.95, identical Th isotope ratios (($^{230}Th/^{232}Th$)=0.934) and, therefore, approximately 20% excess of ^{230}Th over ^{238}U. All analysed samples are in ^{228}Ra–^{232}Th radioactive equilibrium, showing the absence of recent (<30 years) Ra–Th fractionation.

Lava flows erupted inside the Enclos caldera and the rift-zones have $(^{226}Ra/^{230}Th)_0$ varying from 1.18 to 1.34, whereas the basalts from craters outside the Enclos caldera and the rift-zones, in addition to the oceanites and the 1945 basalt, have higher $(^{226}Ra/^{230}Th)_0$ around 1.40. This value is assumed to represent that of the deep magma entering the central plumbing system, beneath the Enclos caldera. The evolution through time of $(^{226}Ra/^{230}Th)_0$ is attributed to alternating episodes of near closed-system evolution in one or several, poorly replenished, deep reservoirs, on timescales of the order of 1000 yr, and episodes of increased re-injection and mixing of the deep magma into older magmas of the previous period. Modelling of such a recent re-injection episode, from 1960 to 1998, suggests a short residence time of about 25 yr and a volume of 0.35 km^3 for the shallow reservoir.

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At the time of eruption, $(^{210}Pb/^{226}Ra)_0$ in both oceanites and basalts from the Enclos and rift-zones spans a narrow range with a mean value of 0.68, with the exception of the 1945 basalt which has an unusually low ratio of 0.20. The value of 0.68 can be explained by Rn degassing from the shallow magma chamber on a timescale comparable to that deduced from the evolution of $(^{226}Ra/^{230}Th)_0$ in the 1960–1998 period.

Keywords: U-series disequilibria; magma residence time; magma chamber; Piton de la Fournaise; Reunion Island

1. Introduction

The identification and location of magma chambers beneath active basaltic volcanoes is not always straightforward. Measurable deformation just before and during eruptions indicates a subterranean source of pressure changes, often interpreted to be magma chambers, whereas seismic tomography studies may fail to detect small magma reservoirs. When magma can be dated and transfer-time from the mantle source region to the surface estimated, older magmas must be inferred to have been stored in a magma chamber or pockets en route to the surface. The presence or absence of a magma chamber beneath an active volcano could, therefore, be indicated if magma transfer or residence times are obtainable.

According to the definitions in Condomines et al. [1], transfer time is defined here as the time it takes for a magma to move from a given locality at depth to the surface, whereas magma residence time only applies to the time spent in an open-system magma chamber or reservoir. An age derived from crystals either through trace element diffusion (e.g., [2]) or isochron relationships (e.g., [3]) can be much shorter (microlites) or longer (xenocrysts) than transfer or residence time. The residence times in magma chambers beneath Piton de la Fournaise and Kilauea volcanoes have been inferred from compositional variations in the young basaltic lavas [4,5]. However, the deeper structure of the plumbing system below these volcanoes still remains somewhat obscure. Radioactive disequilibria between short-lived nuclides of the ^{238}U-series can yield magma residence time if the composition of both the young magma and the older magma entering and leaving a reservoir respectively can be measured (e.g., [1,6–9]). Here, we present results on ^{230}Th–^{226}Ra–^{210}Pb and ^{232}Th–^{228}Ra systematics measured in historic and pre-historic lava flows from Piton de la Fournaise volcano on Réunion Island in the Indian Ocean. After a brief discussion about the origin of these disequilibria, it will be shown that the new results most likely indicate the presence of a deep magma chamber from which most magma is supplied to a shallow dyke-and-sill complex before being erupted. Estimates are given for the residence time and volume of the summit reservoir.

2. Short geological overview of Piton de la Fournaise

The structure of Piton de la Fournaise volcano has been thoroughly described by Bachèlery [10] and Lénat and Bachèlery [11]. Here, we only emphasise those structures that are pertinent to the interpretation and discussion of the present results. La Fournaise is a shield volcano with at least three major caldera rims decreasing in age from west to east [12]. The youngest one is the Enclos Fouqué (Fig. 1), a horseshoe-shaped depression open to the east and younger than 3.4 ± 1 ka [13]. The floor of the Enclos Fouqué depression is relatively flat west of a prominent central cone which has two summit craters, Dolomieu and Bory. To the east, the slope of the floor steepens abruptly towards the sea at the limit of the Grandes Pentes. Two rift-zones originate from the central cone, one to the north-east and the other to the south-east, and both of them extend outside the Enclos Fouqué depression down to sea level. A significantly older and most likely a deeper-seated fracture extends from the south-east towards the north-west across the island. This fracture may be a fault inherited from the Indian sea-floor [10]. The surface expression of this structure is characterised by numerous large Strombolian cones, or eccentric craters, of highly variable ages, such as Petit Cratère, Commerson, Piton sous le Gîte and Piton Chisny (Fig. 1).