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Helium isotopes in some historical lavas from Mount Vesuvius

D.W. Graham[a,1], P. Allard[b], C.R.J. Kilburn[c], F.J. Spera[a] and J.E. Lupton[a,2]
[a]*Department of Geological Sciences, University of California, Santa Barbara, CA 93106, USA*
[b]*Centre des Faibles Radioactivités, Laboratoire mixte CNRS-CEA, 91190 Gif sur Yvette, France*
[c]*Osservatorio Vesuviano, Via A. Manzoni 249, 80123 Napoli, Italy*

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ABSTRACT

$^3He/^4He$ ratios in lavas erupted during the last 360 years at Mt. Vesuvius are between 2.2 and 2.7 R_A (R_A = atmospheric ratio of 1.39×10^{-6}), and are among the lowest values measured in young volcanic rocks. They are also identical to values measured in summit crater fumaroles sampled during 1987–1991. This agreement indicates that the $^3He/^4He$ ratio in the crater fumaroles faithfully tracks the magmatic value. The relatively low and uniform $^3He/^4He$ ratio in the lavas reflects either a mantle source enriched in $(U+Th)/^3He$, or a mixture of magmatic and crustal components.

Introduction

Mount Vesuvius is well known for its explosive eruption in 79 A.D. and the consequent violent destruction of the surrounding cities of Pompeii and Herculaneum. Over the last 400 years it has erupted frequently. During the repose period following its most recent eruption in 1944, the population in the surrounding Naples area has increased considerably, and is presently about 3 million people. Concerns for geochemical and geophysical monitoring of the volcano have also increased, since the potential for a volcanic catastrophe increases with longer repose times. One current monitoring effort involves the chemical analysis of volcanic gases sampled from fumaroles, and of diffuse soil emissions around the flanks of the volcano (Baubron et al., 1987; Allard et al., 1988; Tedesco et al., 1991). In particular, the isotopic composition of helium has been measured (in conjunction with other parameters), because an increase in the $^3He/^4He$ ratio is diagnostic of an increased contribution from magmatic gases, and hence may signal the onset of magma chamber recharge. However, studies of helium isotopes in lavas from Mt. Vesuvius and other volcanoes in Central Italy have never been performed. Therefore, the objective of this work is to provide a baseline of $^3He/^4He$ measurements in young lavas from Mt. Vesuvius, with which to compare monitoring efforts of the gas emissions.

Background

Previous work on helium isotopes in fumaroles and groundwaters from Central Italy have found low $^3He/^4He$ ratios ($\sim$0.03–3.0 R_A; Polyak et al., 1979; Hooker et al., 1985; Sano et al., 1989; Tedesco et al., 1990). Nevertheless, some mantle contribution is present even in many of these samples, because the radiogenic $^3He/^4He$ production ratio is <0.1 R_A. The previous results have generally been interpreted to indicate widespread interaction be-

[1]Present address: College of Oceanography, Oregon State University, Corvallis, OR 97331-5503, USA
[2]Present address: NOAA, Hatfield Marine Science Center, Newport, OR 97365, USA

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tween magmas and the local continental crust. In the Neapolitan area, Sano et al. (1989) and Tedesco et al. (1990) measured $^3He/^4He$ ratios between 2.0 and 3.2 R_A for the Campi Flegrei caldera, in both subaerial fumaroles from Solfatara and submarine fumaroles from Pozzuoli. Comparable $^3He/^4He$ ratios were found for summit crater fumaroles at nearby Mt. Vesuvius (2.2–2.7 R_A; Allard et al., 1988; Tedesco et al., 1991).

Samples analyzed in this study include clinopyroxene, olivine and leucite phenocrysts in a suite of historical lavas from Mt. Vesuvius (1631, 1714, 1855, 1906 and 1944) and clinopyroxenes from a cumulate nodule sampled from the surface of the 1944 lava flow. The young historical lavas at Mt. Vesuvius are the most undersaturated types erupted during its history (Joron et al., 1987). They form a homogeneous group of lavas with a relatively small range in MgO, mostly between ~3.0 and 6.0 wt.% in the whole rocks (Joron et al., 1987). They are often highly porphyritic, and clinopyroxene is always present. They generally contain abundant phenocrysts of leucite and clinopyroxene, and a groundmass comprised principally of leucite, clinopyroxene, oxides and minor plagioclase. Rarely, olivine is present as a microphenocryst (1631, 1714, 1855 and 1944) or in the groundmass. Clinopyroxenes characteristically show sector and oscillatory zoning, indicating several stages of crystallization. Olivine is also sometimes zoned, ranging from Fo_{78}–Fo_{60} as microphenocrysts, to Fo_{66}–Fo_{48} in the groundmass (Joron et al., 1987). Joron et al. (1987) argued that the systematically higher TiO_2 contents of the groundmass clinopyroxenes compared to coexisting clinopyroxene phenocrysts, but their similar ratios of Al^{IV}/Al^{VI}, indicate changing crystallization conditions primarily due to magmatic temperature variations.

$^{87}Sr/^{86}Sr$ ratios in the lavas erupted over the last 360 years range between 0.7072 and 0.7079, and display significant short-term variations (Cortini and Hermes, 1981; Caprarelli et al., 1993). $\delta^{18}O$ values are between 7.2 and 8.2‰ (Turi and Taylor, 1976), higher than values generally expected for a mantle source that remained unmodified by enrichment processes or fluid metasomatism (~5.5‰). Some leucite-bearing lavas in Italy have primary magmatic values of 5.5–8.0‰ and $^{87}Sr/^{86}Sr \cong 0.710$ (Cox et al., 1976; Holm and Munskgaard, 1982; Taylor et al., 1987). This range in $\delta^{18}O$ is similar to mantle phlogopites and amphiboles, and to peridotite xenoliths which display ^{18}O disequilibrium between coexisting olivine and pyroxene due to open system exchange with fluids (Taylor et al., 1987). Thus, the potassic parental magmas in Italy appear to originate from source regions that were metasomatized by K-, ^{18}O- and ^{87}Sr-rich fluids. The fluids themselves may be derived by dehydration and melting of subducted sediments (Rogers et al., 1985; 1987) or from oceanic crust transformed to eclogite (Taylor et al., 1987).

Several types of xenolith ejecta are also found at Mt. Vesuvius. We have studied one pyroxenitic nodule with accumulative texture, collected from the 1944 lava flow at Atrio del Cavallo. Pyroxenitic nodules from the 1944 eruption have been interpreted by Hermes and Cornell (1981) to be part of a crystal mush that was disrupted and ejected during eruption. However, whether these nodules are cumulate products related to the 1944 lava or to previous eruptions remains a point of debate. Trapping of melt and fluid inclusions in this nodule type suggests a multistage *P-T* history. Most of the minerals give trapping temperatures in the range of 1170–1240°C (Belkin et al., 1985; Cortini et al., 1985), while the density distribution of CO_2 inclusions shows several discrete stages, corresponding to depths between ~4.5 and 11 km (Belkin et al., 1985).

An important conclusion resulting from all the above studies is that hot, basic magma has periodically been injected into the Vesuvius magma chamber, where mixing with more evolved magmas has occurred throughout the course of the volcano's history (Cortini and Scandone, 1982; Joron et al., 1987; Civetta et al., 1991).

Methods and results

Rock samples were broken into cm size chunks, then crushed in a tungsten carbide jaw crusher and sieved into several size fractions. Pieces > 1.7 mm were further crushed in a steel mortar and pestle, and resieved. Minerals were then hand-picked from the 0.85–1.70 mm size fraction by observation through a binocular microscope. Crystals with more than ~ 10% of their surface covered by adhering groundmass or other crystal types, or with any signs of alteration were rejected. (In the case of the 1631 lava, where olivine was in sufficient abundance to be analyzed, some surfaces of the analyzed grains may have been partially altered to iddingsite.) Picked samples were ultrasonically cleaned in acetone and dried in air before weighing, and typically 500–800 mg of sample was analyzed. Trapped gases were extracted by in vacuo crushing, and helium isotope analyses followed methods described previously (Graham et al., 1990). Neon abundances were also measured, by peak height determination of the sample neon (using voltage switching) which had been cryogenically separated from the other rare gases.

Helium isotope results, and He and Ne abundances are reported in Table 1. $^3He/^4He$ ratios in all the clinopyroxenes and the olivine from 1631 are similar, and between 2.2 and 2.7 R_A. These values are identical to those measured in the summit crater fumaroles between 1987 and 1991, as well as in the submarine fumarole at Torre del Greco. Based on the limited number of lava analyses reported here, there has been no discernible change in $^3He/^4He$ ratio over the last 360 years (Fig. 1).

The helium concentrations of the clinopyroxenes from the lavas range between 1.7 and 18×10^{-9} cm^3 STP/g (Table 1 and Fig. 2). The olivine from 1631, and the clinopyroxene from

TABLE 1

Helium isotopes in historical lavas of Mt. Vesuvius

Sample	Date/Location/ Distance from summit crater	Phase	$^3He/^4He$ (R/R_A)	±	[He] (10^{-9} cm^3STP/g)	He/Ne:$(He/Ne)_{air}$
V4	1631/Torre del Greco	ol	2.42	0.06	76.7	>313
		cpx	2.23	0.08	9.23	48.5
V17	1714/ Massa del Carceriere/3.7 km SE	lc	0.88	0.44	0.70	1.14
		cpx	2.72	0.10	8.87	>101
V74	1855/S. Sebastiano/ 5.9 km SSE	cpx	2.48	0.18	1.68	12.7
V150	1906/Molara/ 4.7 km SE	lc	1.07	0.54	0.43	1.45
		cpx	2.60	0.08	17.7	158
V135b	1944/main flow/ 4.4 km NW	lc	0.76	0.46	0.55	1.00
		cpx	2.42	0.14	4.89	46.9
VN1	1944/Atrio del Cavallo/	cpx	2.65	0.04	92.9	811

cpx = clinopyroxene, lc = leucite, ol = olivine.
VN1 is a cumulate nodule: all other samples are lava flows.
All analyses are by crushing in vacuo of hand-picked mineral separates from the 0.85–1.70 mm size fraction (10–20 mesh), and weighing 500–800 mg (except for V4 ol, which was ~ 150 mg due to its scarcity).

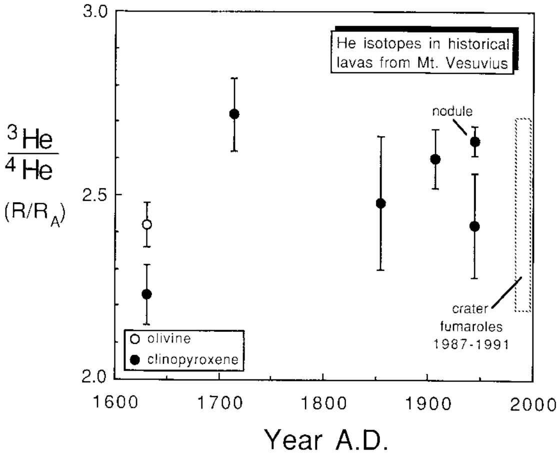

Fig. 1. $^3He/^4He$ ratio vs. date of eruption for Vesuvius lavas. The range of values for crater fumaroles sampled during 1987–1991 (Tedesco et al., 1991) is also shown. Error bars are ± 2 standard errors, and the shaded band shows the mean of 7 analyses $\pm$ one standard deviation ($^3He/^4He = 2.50 \pm 0.17\ R_A$).

the cumulate nodule have higher helium concentrations, between 77 and 93×10^{-9} cm^3 STP/g. Helium isotopes in the leucites (from 1714, 1906 and 1944) have been compromised by atmospheric contamination, attested to by their low [He], and the similarity of their $^3He/^4He$ and He/Ne ratios to atmospheric values.

Discussion

The similarity of $^3He/^4He$ in clinopyroxenes and olivines to the summit crater fumaroles studied by Allard et al. (1988) and Tedesco et al. (1991) demonstrates that the low ratios measured in the summit fumaroles are not modified significantly from magmatic values by hydrologic effects or by shallow crustal contamination; rather, they track the magmatic value. Olivines and pyroxenes in the lavas clearly record the magmatic value, because their $^3He/^4He$ ratios corrected for any possible air contamination effects (by assuming that all the Ne in the sample is derived from air and is accompanied by atmospheric He) are all within the stated uncertainty of the measured values reported in Table 1.

The mecahanism of atmospheric contamination for the leucites is not clear. It may occur during cooling of the lava flow, when the crystal undergoes inversion from a cubic to a tetragonal structure near ~625°C (Deer et al., 1966). Alternatively, gas exchange between lava and atmospheric gases (or those dissolved in groundwater) takes place at shallower depths in the crust where leucite crystallizes, while olivine and pyroxene retain their magmatic helium signatures because they crystallized deeper. (The occurrence of phreatomagmatic eruptions at Mt. Vesuvius is evidence for significant magma/water interaction, and the possible addition of an atmospheric component to magmatic volatiles; e.g., Bertagnini et al., 1991.) It is also possible that leucite is less retentive of its trapped gases simply because its crystalline structure is more easily fractured by fluid inclusion overpressures. Previous studies showed that high-density fluid inclusions are preserved only in high-strength minerals such as spinel, olivine and pyroxene (Belkin et al., 1985; Cortini et al., 1985). Also, clinopyroxenes in the lava samples studied here have lower helium contents than clinopyroxenes in the cumulate nodule, indicating that some magmatic degassing may have taken place after the initial stages of crystallization. The single olivine analysis gives a similar helium content to clinopyroxene in the cumulate nodule (Table 1; Fig. 2). Therefore, the relative efficiency of volatile trapping for mineral phases in these lavas appears to be olivine > clinopyroxene > leucite. In a qualitative sense this order reflects either the relative susceptibilities to gas loss from inclusions during magma ascent, eruption and cooling, or the sequence of crystallization/trapping in a degassing magma.

$^3He/^4He$ and $^{87}Sr/^{86}Sr$ ratios for volcanic rocks from Mt. Vesuvius and Mt. Etna are compared to some volcanic rocks from mid-ocean ridges, ocean islands and island arcs in Figure 3. Because the He isotope compositions for Vesuvius and Etna volcanics are each sim-

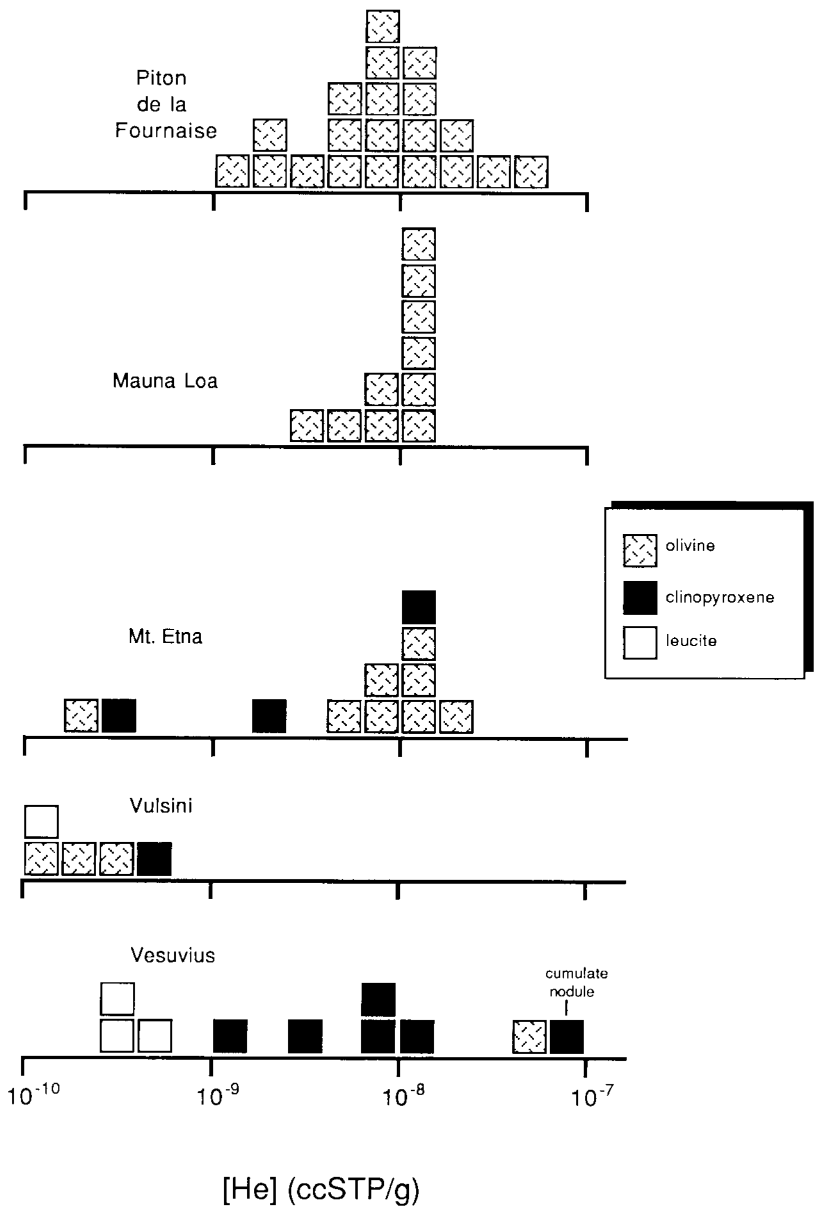

Fig. 2. Histogram of He concentrations trapped in mineral phases of historical lavas from Vesuvius. He contents for phenocrysts from the oceanic islands of Réunion (Piton de la Fournaise; Graham et al., 1990) and Hawaii (Mauna Loa; Kurz et al., 1987), and for some Italian volcanics from Vulsini in northern Italy (Graham, unpubl. data), and for Mt. Etna (Graham et al., 1991) are shown for comparison.

ilar to their associated fluids (Tedesco et al., 1991; Allard et al., 1991), we have also included fields for $^3He/^4He$ ratios measured in fluids from some other Italian provinces where helium isotope analyses of the rocks have not yet been performed (Vulsini, Roccamonfina, Mt. Amiata, and the Aeolian Islands of Vulcano and Salina), and compared them to $^{87}Sr/^{86}Sr$ for the associated volcanic rocks. The helium isotope compositions of recent lavas from Mt. Vesuvius are among some of the lowest values measured for young volcanic rocks. In

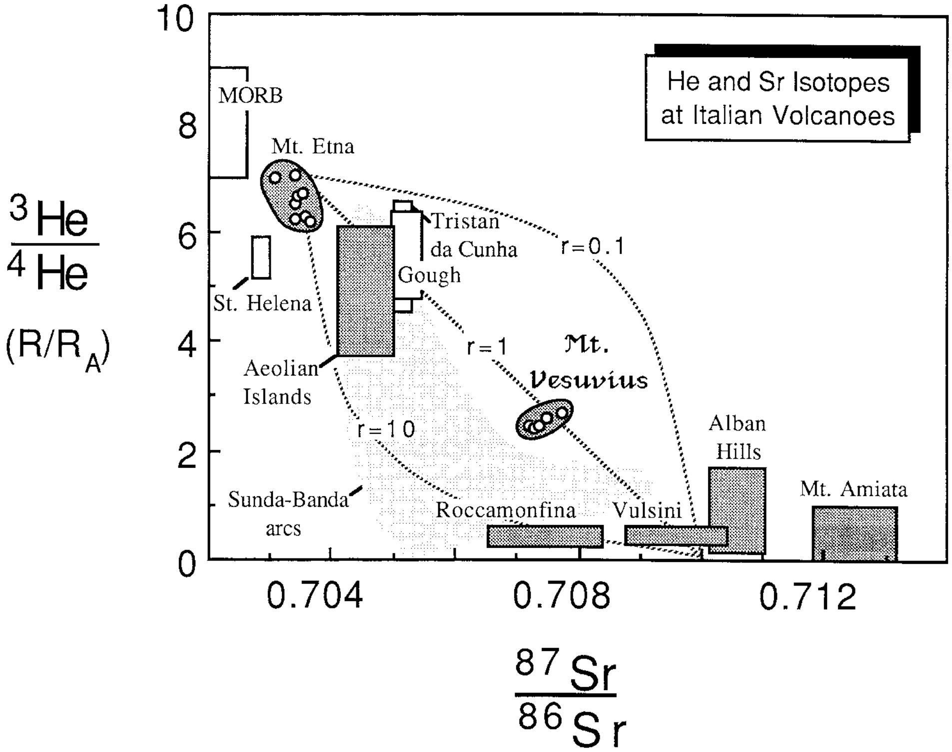

Fig. 3. $^3He/^4He$ vs. $^{87}Sr/^{86}Sr$ in volcanic rocks from some mid-ocean ridges, ocean islands and island arcs compared to values for Italian volcanoes. Helium and strontium data for Mt. Etna lavas are from Graham et al. (1991) and for Mt. Vesuvius from this work and Caprarelli et al. (1992). Other Italian volcanic data for $^3He/^4He$ are for fluids, analyzed by Hooker et al. (1985) and Sano et al. (1989); for $^{87}Sr/^{86}Sr$, data are for volcanic rocks analyzed by Poli et al. (1984), Ferrara et al. (1985), Rogers et al. (1985; 1987), Vollmer (1976), Hawkesworth and Vollmer (1979) and Ellam et al. (1988; 1989). Shaded field for the east Sunda–Banda arcs from Hilton et al. (1992) is also shown for comparison. Dashed curves are shown for hypothetical, binary mixing of an enriched-mantle end-member (component 1 with $^3He/^4He=0.1$ R_A, and $^{87}Sr/^{86}Sr=0.710$ as suggested by Taylor et al., 1987 for the primitive magmas from Central Italy) with a mantle end-member similar to that found at Mt. Etna (component 2 with $^3He/^4He=7.0$ R_A, $^{87}Sr/^{86}Sr=0.7035$). Values of r ($=([He/Sr]_1/[He/Sr]_2)$) are given along the curves.

conjunction with their relatively radiogenic $^{87}Sr/^{86}Sr$ and Pb isotope ratios (Vollmer, 1976; Cortini and Hermes, 1981; Civetta et al., 1991; Caprarelli et al., 1993), the helium isotopes at Mt. Vesuvius are consistent with either of two hypotheses for the origin and history of Italian potassic volcanics. These hypotheses are (1) derivation from a mantle source anomalously enriched by a crustal-derived component; or (2) assimilation of crustal material by mantle-derived magma during ascent and eruption. These contrasting scenarios have been debated in the literature on the basis of major elements, trace element patterns, and Sr-Nd-Pb-O isotope relationships (e.g., Cox et al., 1976; Turi and Taylor, 1976; Hawkesworth and Vollmer, 1979; Holm and Munksgaard, 1982; Rogers et al., 1985, 1987; Vollmer, 1989; Beccaluva et al., 1991). If mixing has occurred between an enriched component (having radiogenic $^3He/^4He\leqslant0.1$ R_A and $^{87}Sr/^{86}Sr=0.710$) and a mantle component beneath the Italian province that has Pb-Sr-Nd isotope compositions similar to those found at Mt. Etna (as suggested from the Pb-Sr-Nd isotope data of Ellam et al., 1989), then the He-Sr isotope relationships for Mt. Vesuvius and the Aeolian Islands suggest an equivalent or slightly higher He/Sr ratio in the enriched component (Fig. 3). A higher value is consistent with mantle metasomatism involving a fluid derived by dehydration and/or partial melting. This process has been suggested to explain the different $\delta^{18}O$-$^{87}Sr/^{86}Sr$ relationships for mafic lavas of the high- and low-potassic series in the Roman Magmatic Province (Rogers et al., 1987; Taylor et al., 1987), while the volcanic rocks with $^{87}Sr/^{86}Sr > 0.710$ are produced by interaction with the crust. According to this explanation, the similar He/Sr ratio for the end-members implied by the Vesuvius data would indicate that mixing took place at subcrustal depths, before crystal fractionation or magmatic outgassing could produce dispersion of the He/Sr ratios. Tedesco et al. (1990) also suggested that the low $^3He/^4He$ ratios measured in fumaroles from nearby Campi Flegrei reflect an enriched mantle signature. The alternative explanation is that the He-Sr relationships for Central Italian volcanoes are all produced by assimilation during passage of magma through the crust, e.g., by partial melting of granulite facies rocks in the lower crust. In this case the crust must have retained a large proportion of the radiogenic He generated in situ, despite continued volcanism in Central Italy for the past one million years. In addition, the relatively uniform He, Sr, Nd and Pb isotope compositions at Mt. Vesuvius would require a reproducible mixture of mantle and crustal components during relatively large-scale interaction of magma with the (isotopically heterogeneous?) crust. Although we cannot rule out this possibility, we favor the enriched mantle hypothesis.

Summary

Helium isotope compositions in historical lavas from Mt. Vesuvius are between 2.2 and 2.7 R_A. These values are identical to recent measurements of summit crater fumaroles, indicating that fumarolic helium at the summit is essentially all derived from a magma. The low $^3He/^4He$ ratios may be due to assimilation of a crustal component during magma transport and storage, or they may represent an anomalous mantle signature. Further helium isotope work on the prehistoric lavas of Mt. Vesuvius, and on several well characterized suites of potassic volcanic rocks from Central Italy are needed to resolve this issue.

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