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^{3}He/^{4}He isotopic ratio characterization of the Polynesian region: The Society and upper Cook-Austral chains

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Summary. — We report the result of a systematic survey of the helium isotopic composition for basaltic rocks from the Polynesian region. The database covering the Society chain lists 79 entries deriving from experiments carried out at SIO (Scripps Institution of Oceanography, University of California San Diego, CA, USA) following the procedure of crushing on-line with an 8 minute single step; data for the Cook-Austral islands are taken from the literature. The ^{3}He/^{4}He value distribution shows an intrinsic dispersion s between 1.1 and 1.4 times RA (RA= ^{3}He/^{4}He in Air = 1.39×10^{-6}) and appears sensibly uniform over the area explored, clearly independent from the variation of age (0 to 20 My) along the dorsal of the island chains. The difference appearing between the mean value obtained for the Society (R/RA = 6.3 ± 1) and the Cook-Austral (R/RA = 7.3 ± 1.4) is not appreciable within the "natural" dispersion. The values obtained are substantially lower than the Pacific MORB (R/RA ~ 8.7 RA). No evident correlation appears in the general picture between the helium data and the other radiogenic isotopes interpreted as tracers for possible heterogeneity in the mantle.

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PACS 32.10.Bi – Atomic masses, mass spectra, abundances and isotopes.
PACS 67.55 – Normal phase of liquid ^{3}He.

1. – Introduction

The occurrence of systematic differences in the chemical and isotopic characteristics between the Ocean Islands Basalts (OIB) and those continuously erupted along the mid-ocean spreading ridges (MORB) supports the evidence of an heterogeneous mantle as a general worldwide feature. The classification of the basalts based on their Sr, Nd and Pb isotopic composition has allowed to infer the existence

of a number of distinct reservoirs: DMM, HIMU, EM1, EM2, BSE [1]; the nature, development and scale of this heterogeneity is a matter of investigation.

In this regard, attempts have been made to use the noble gas data to explore the nature of the mantle (*e.g.*, [2]); the presently accepted conclusion is of a variability domain of the helium isotopic composition explained with the presence of two distinct types of mantle helium: the MORB-type, rather uniform in isotopic composition ($^3He/^4He$=(7–9)RA, RA=1.39×10^{-6}, in air) assumed to be typical of a depleted upper mantle, and the OIBs-type, with $^3He/^4He$ ranging from $\sim$4 to $\sim$32 times RA associated with a deeper portion of the mantle (see [3] for a review). In the presence of the wide range of variation observed in the OIBs, a central issue in considering the helium isotopic ratio for constraining mantle models is to understand to which extent the noble gas isotopes in igneous rocks are representative of the underlying mantle. The question arises whether they reflect the existence of real heterogeneous reservoirs, as inferred from the other radiogenic isotopes, or instead the U-Th-He system must be considered "decoupled" from the other radiogenic systems. Should this be the case, the heterogeneity of OIBs could be the result of modifications (atmospheric contamination, differential degassing, metasomatism, etc.) of a uniform deep mantle reservoir occurring as the magma rises to and it is exposed at the surface.

In this paper data on the helium isotopic composition and concentration are reported for basaltic rocks from two Polynesian islands volcanic chains (Society and Upper Cook-Austral) with the aim to investigate quantitatively the characteristics of the mantle beneath the South Pacific Ocean, in a typical setting of hotspot volcanism.

Because of its large geographic extension, the presence of two relevant fracture zones, the reported wide diversity of radiogenic signature for the basalts and the fact that magmatism continued in this region over a long period of time (20 My to present) as well as simultaneously in different islands or island groups, the Polynesian province appears as a unique natural laboratory for the investigation of the mantle helium in both time and space.

2. – Tectonic and geological background. The radiogenic setting

Figure 1 shows the large scale cartography of the Polynesian province, from 130° long. W to 160° long. W and from 7° lat. S to 30° lat. S. The islands form four major volcanic chains, identified with the name of their administrative grouping: Marquesas, Society, Cook-Austral and Gambier-Pitcairn (the group of the Tuamotus is all composed of coral atolls); these chains stretch along parallel line segments which extend North-West from their South-East extreme, almost perpendicularly to the East Pacific Rise, where the present sea-floor spreading in the eastern Pacific is occurring. Two major fracture zones, the Marquesas and the Austral, cross the area [4, 5]

Literature data [1, 6, 7] show that the Society Islands and the Marquesas are characteristic of EM2 (radiogenic Sr), while Mangaia and Tubuai in the Austral correspond to the HIMU composition (very radiogenic Pb), Pitcairn island has EM1 characteristic (low Pb isotopic ratios) and Fangataufa (Gambier) displays the lowest Sr isotopic composition. Moreover, when considering the Marquesas [6] samples from Nuku Hiva alone cover half the observed Sr-Nd isotopic variation in the oceanic islands and, together with Ua Pou and Ua Huka, they cover almost the entire range observed worldwide.

Along each island chain, the age increases to the northwest (fig. 2a: Society, 2b: Cook-Austral, 2c: Marquesas). The distance of each island from the youngest one is

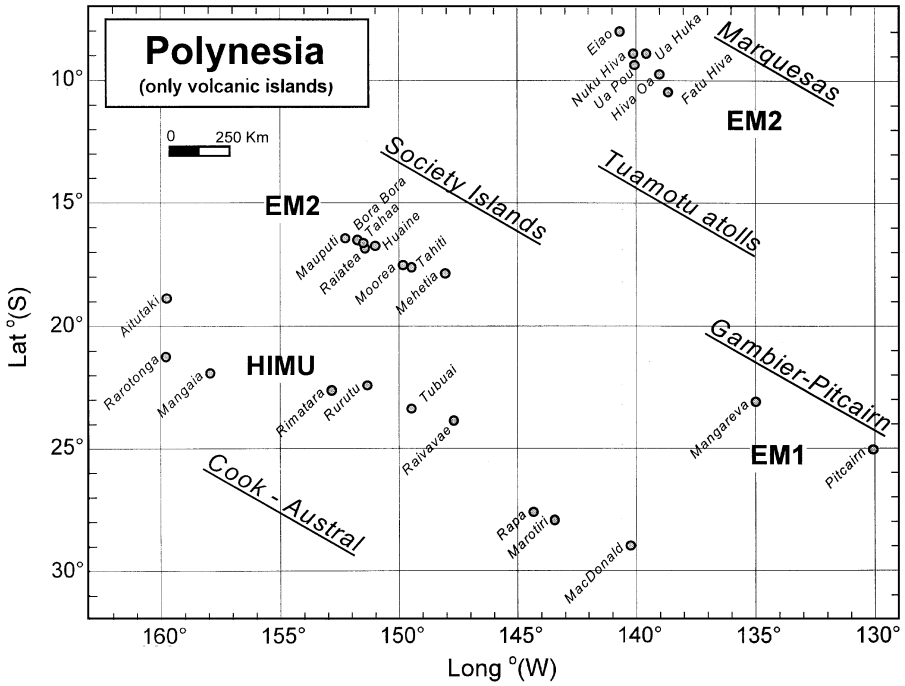

Fig. 1. – The Polynesian region. The fracture zone locations are taken from Dupuis *et al.*,1989 and Hemond *et al.*, 1994. The indicative identifications EM1, EM2, HIMU are taken from [1] and [7].

calculated as the interval between the projections of the island location on the dorsal defined as best fit taken along the chain. The age database derives from the literature [8-17]. The rate of migration of volcanism, as calculated from the nearly linear relationship between average island ages and distance from the southeast ends of the four alignments, is of about 11 cm/y [11].

The relationship between age and geographical location along the island chains is broadly consistent with classical hotspot models: the dispersion observed for the age of the volcanic activity and for the isotopic data spreads over almost the entire range of variations recorded for OIB.

3. – Analytical method

The database used for the He analysis in the Polynesian region derives from a series of measurements carried out at the Isotope Laboratory of SIO [18]; when appropriate we have complemented the information with data coming from the literature. The procedure of helium extraction from the phenocrysts of the basalts has been described in [18]. When the crushing time is prolonged above a minimum threshold value, the helium content of the fluid inclusions could be contaminated with other components present in the phenocrysts, inducing possible distortions in the measured value of the $^3He/^4He$ isotopic ratio characteristic of the primitive magma. This alteration of the sought-after isotopic value of the primary fluid inclusions can be

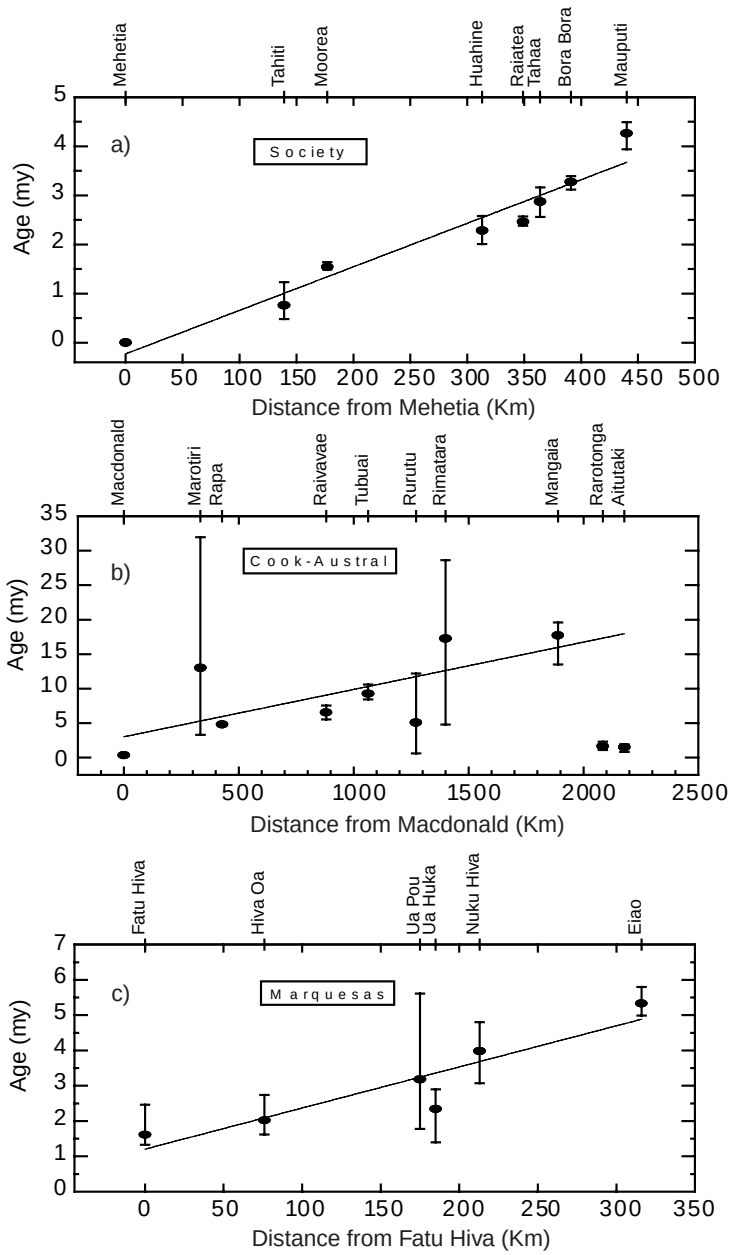

Fig. 2. – a) Society Islands. Age *vs.* distance from Mehetia along the dorsal of the chain. Dots represent average values; bars connect extreme values reported. b) Cook-Austral Islands. Age *vs.* distance from Macdonald seamount along the dorsal of the chain. Dots represent average values; bars connect extreme values reported. c) Marquesas Islands. Age *vs.* distance from Fatu Hiva along the dorsal of the chain. Dots represent average values; bars connect extreme values reported.

controlled and corrected for by adopting a procedure of "crushing by steps" or in general by keeping the total crushing time at a minimum, irrespective of the goal of obtaining a complete gas extraction. It is however difficult to establish a standard recipe for an optimum crushing time value which in general results to be dependent on the specific sample analyzed. For the experiments reported here we have adopted a single crushing step with $t = 8$ minutes; we should expect therefore occasionally a possible contamination effect for the primary fluid inclusion, although of relatively minor importance and varying from sample to sample.

The He concentration and the ^{3}He/^{4}He ratio have been measured following the standard procedure adopted at the SIO Isotope Lab. The gas extracted by crushing under vacuum was transferred into the inlet system of the mass spectrometer, removing the Ne cryogenically in a charcoal trap at 34 K; the ^{3}He/^{4}He ratio and He concentrations were measured statically on the double-collecting split-tube mass spectrometer GAD using the methodology described in [19]. ^{3}He was measured by ion counting with a Johnston electron multiplier and ^{4}He by collection in a Faraday cup. The measured isotope ratio was normalized to aliquots of a high ^{3}He/^{4}He (R/RA = 16.45) standard gas (MM). A measure of the blank has been carried out systematically before each experiment; after each measurement the system was pumped out for a sufficient time to minimize possible memory effects in the following runs. The error budget for the ^{3}He/^{4}He ratio is obtained by adding the instrumental errors on the measurement of ^{3}He and ^{4}He, provided that the contribution of the blank can be neglected; we have placed at 10% the maximum level of blank to consider the measured value suitable for further analysis. For higher blank values, corresponding in general to a measured He concentration in the sample of the order of 1 ncc/g or less, the calculated ^{3}He/^{4}He is affected in fact by large systematic errors, introducing a biased distortion in the isotopic ratio distributions or simulating the existence of apparent singularities with abnormally low/high values [18]. Normally the instrumental error is small ($< 10\%$) with respect to the natural dispersion for the measured values. The contribution of different components superimposed to the primary fluid inclusion will produce a systematic shift on the correct helium isotopic value representative of the primitive magma, introducing a skewing effect on the distribution of the values measured.

4. – ^{3}He/^{4}He results

4·1. *Society Islands.* – The complete database is given in table I: 79 measurements derive from the present work, 15 from [20] and 1 from [21].

The helium isotopic ratio value distribution for each island in the Society chain is given in fig. 3; average values range from $\langle R/RA \rangle = 4.8$ for Tahaa to $\langle R/RA \rangle = 7.7$ for Raiatea.

The means for the individual islands in the chain are compatible with the overall distribution, supporting the conclusion of a unique population with respect to the ^{3}He/^{4}He isotopic ratio. The $\langle R/RA \rangle$ for the entire Society chain is 6.3 with $\sigma = 1.1$; the distribution is well represented by a Gaussian as shown in fig. 3.

The single entry R/RA = 17 for Moorea reported [20], lies outside the general distribution ($\sim 10\sigma$); we have no direct explanation, if not a comment about the low value (1.3 ncc/g) reported for the He concentration and a possible distortion introduced by the correction for the blank. Because of its singularity, we limit ourselves to notice its presence, while we neglect its relevance in the general conclusions.

TABLE I. – $^{3}He/^{4}He$ *database for the Polynesian Region.*

Chain/Island	Sample	Ref.	[^{4}He] (ncc/g)	Blk (%)	$(R/R_A)_{BC}$	$(R/R_A)_{BC}$ mean	$(R/R_A)_{BC}$ min	$(R/R_A)_{BC}$ max
Society						**6.26**	**2.35**	**10.40**
Tahiti	T-85-109		2.96	0.49	7.04	6.84	5.28	10.40
	T-85-141		3.24	1.39	5.71			
	TAH-01		3.14	1.67	5.93			
	TAH-02		10.51	1.13	6.00			
	TAH-04(I)		10.96	2.47	7.18			
	TAH-04(II)		3.31	1.97	6.94			
	TAH-04(III)		0.54	12.82	*4.70* *			
	TAH-04(PR)		3.12	12.20	7.00 *			
	TAH-05(II)		0.43	15.70	*7.00* *			
	TAH-06(I)		0.62	11.75	*5.28* *			
	TAH-06(II)		7.63	1.27	6.71			
	TAH-06(III)		28.17	0.24	6.11			
	TAH-06(IV)		9.14	0.55	6.66			
	TAH-06(V)a		0.67	11.17	*8.43* *			
	TAH-06(V)b		0.94	4.74	7.79			
	TAH-06(V)		0.90	11.57	*7.23* *			
	TAH-06-VA-I		1.75	1.85	6.30			
	TAH-08b		7.39	0.69	6.55			
	TAH-09		0.49	1.19	5.89			
	TA01-02	[20]	1.60		10.40			
Moorea	MOR-01		0.85	6.69	7.52	6.54	5.15	7.52
	MOR-02b		12.33	1.56	7.02			
	MOR-03		2.25	6.96	6.72			
	MOR-05		2.18	4.06	5.83			
	MOR-06		1.21	6.66	5.15			
	MOR-08		6.47	1.35	6.98			
	MO01-01	[20]	1.30		*17.00* *			
Huaine	HUA-01		8.21	0.97	5.61	5.94	5.61	6.91
	HUA-02		0.19	54.28	*1.53* *			
	HUA-06		1.32	12.27	*6.91* *			
	HUA-07		0.53	12.13	*1.00* *			
	HUA-08		1.90	3.73	5.61			
	HUA-10		1.51	3.84	5.62			
Raiatea	RAI-01		36.82	1.27	7.94	7.66	6.79	8.73
	RAI-08		0.14	36.06	*4.18* *			
	RAI-08bis		0.08	38.21	*4.19* *			
	RAI-09		3.48	2.06	7.13			
	RAI-10		3.59	4.38	6.79			
	RAI-12		2.28	4.59	7.71			
	RAI-15		1.29	6.87	7.48			
	RAI-38		1.01	16.95	*7.02* *			
	RAI-17		19.77	1.15	7.68			
	RAI-18		6.16	1.63	7.31			
	RAI-18bis		6.78	2.33	6.49			

TABLE I. – (*Continued*).

Chain/Island	Sample	Ref.	[^{4}He] (ncc/g)	Blk (%)	$(R/R_A)_{BC}$	$(R/R_A)_{BC}$ mean	$(R/R_A)_{BC}$ min	$(R/R_A)_{BC}$ max
Raiatea	RAI-18 ol+		5.04	2.37	7.10			
	RAI-20		3.74	5.27	8.73			
	RAI-20 bis		2.00	2.51	*8.95*			
	RAI-23		3.33	2.95	7.60			
	RAI-24		1.23	4.87	8.12			
	RAI-25		3.90	0.80	7.50			
	RAI-29		2.98	4.41	8.23			
	RAI-31		41.75	0.45	8.32			
	RAI-33		4.49	2.80	7.73			
	RAI-34		1.75	7.17	8.17			
	RAI-35		5.15	1.45	7.01			
	RAI-39		6.53	1.56	7.26			
Tahaa	TAA-01		0.63	16.55	*1.86* *	4.80	3.34	5.72
	TAA-02		1.85	2.92	4.22			
	TAA-05		7.27	3.66	5.33			
	TAA-06		0.68	37.04	*4.55* *			
	TAA-07		5.04	0.53	4.96			
	TAA-08		6.87	0.82	5.72			
	TAA-11		2.54	10.72	*3.34* *			
	TAA-12		4.98	2.58	5.22			
Bora Bora	BB-01		1.08	10.87	*6.18* *	6.93	6.18	8.31
	BB-02		1.77	2.40	6.29			
	BB-03		1.46	5.53	6.56			
	BB-04		0.65	8.30	8.31			
	BB-11		0.74	13.71	*7.73* *			
	BB-12		1.64	12.28	*7.81* *			
	BB-15		1.86	8.72	7.05			
	BB-16		17.68	0.82	6.27			
	BB-17		3.60	7.48	6.18			
Mauputi	MAU-01		0.23	40.94	*−4.26* *	5.15	2.35	8.23
	MAU-02		0.66	14.23	*2.35* *			
	MAU-04a		1.16	6.88	3.57			
	MAU-04b		8.78	7.12	4.43			
	MAU-06a		13.26	2.09	8.04			
	MAU-06b		7.77	1.29	8.23			
	MAU-07		0.09	46.45	*−3.08* *			
	MAU-11		0.10	55.05	*2.51* *			
	MAU-12		0.98	6.44	4.27			
-Cook-Austral						**7.35**	**5.40**	**9.50**
Rarotonga	RTG-C4	[20]	3.60		9.30	9.30		
Mangaia	MGA-C8	[20]	5.60		6.80	6.33	5.40	7.00
	MGAC12	[20]	8.00		6.10			
	MGA-C23	[20]	3.60		7.00			
	MGA-C29	[20]	12.10		5.40			

TABLE I. – (*Continued*).

Chain/Island	Sample	Ref.	[^{4}He] (ncc/g)	Blk (%)	$(R/R_A)_{BC}$	$(R/R_A)_{BC}$ mean	$(R/R_A)_{BC}$ min	$(R/R_A)_{BC}$ max
Rurutu	RU01-01 ancient	[20]	16.20		6.80	7.92	6.80	9.50
	RU02-01 ancient	[20]	8.60		6.80			
	RU09-01 ancient	[20]	37.80		7.60			
	RRT-C31 recent	[20]	4.30		9.50			
	RRT-C33 recent	[20]	2.20		8.90			
Tubuai	TU01-01	[20]	13.90		6.90	7.19	6.90	7.50
	TU09-01	[20]	2.70		7.50			
	TU12-01	[20]	189.20		7.20			
	TU-21	[21]	115.00		7.15			

Notes:
– In Italics (marked with *): value not considered for the calculation of the average (see text).
– References:
[20]: Hanyiu & Kaneoka, 1997.
[21]: Graham *et al.*, 1992.
All other values (reference nb. not indicated) from this work.
– BC: corrected for blank.

The database is sufficiently rich to consent in two cases (Tahiti and Raiatea) a check of the ^{3}He/^{4}He distribution at the level of a single island in addition to the overview of the Society chain as a whole and the comparison of the global dispersion σ for the chain with that of a single island. For Tahiti: $\langle R/RA\rangle = 6.8$ with $\sigma = 1.2$; for Raiatea: $\langle R/RA\rangle = 7.7$ with $\sigma = 0.5$. In both cases the results substantially confirm that the dispersion σ for the overall chain is intrinsic and not resulting by the spread of isotopic values characterizing each single island.

To assure the homogeneity of the sampling *vs.* the location of the sampling site, fig. 4 shows, *e.g.*, the sample location for Raiatea and Bora Bora: no evident correlation appears to exist between the site location and the ^{3}He/^{4}He value in the distribution.

Figure 5 plots R/RA *vs.* distance (km) from Mehetia; the gray band represents the dispersion at 1σ level and the light gray that at 2σ level. Comparing this figure with fig. 2a, definitely no dependence on age is be observed for the ^{3}He/^{4}He isotopic ratio.

4·2. *Cook-Austral.* – The helium isotopic ratio data reported here are those available from the literature and refer to the North-West section of the chain (lat. $< 25°$S), north of the Austral Fracture Zone. The data for Rarotonga, Mangaia, Rurutu derive from [20]; those for Tubuai from [20] and [21]. Like for the Society chain, the global distribution is coherent with a uniform situation over the region considered with a mean ^{3}He/^{4}He=7.3 RA and $\sigma \pm 1.4$ to be compared with $\langle R/RA\rangle = 6.3 \pm 1.1$ of the Society (fig. 6). The values for the two chains are consistent within 1σ. When ^{3}He/^{4}He is plotted as a function of age (fig. 7), also in this case no dependence of the isotopic ratio with age is emerging.

An additional data-set for the Cook-Austral is available from measurements carried out at SIO. by P. Scarsi, but is not reported here because waiting for formal publication

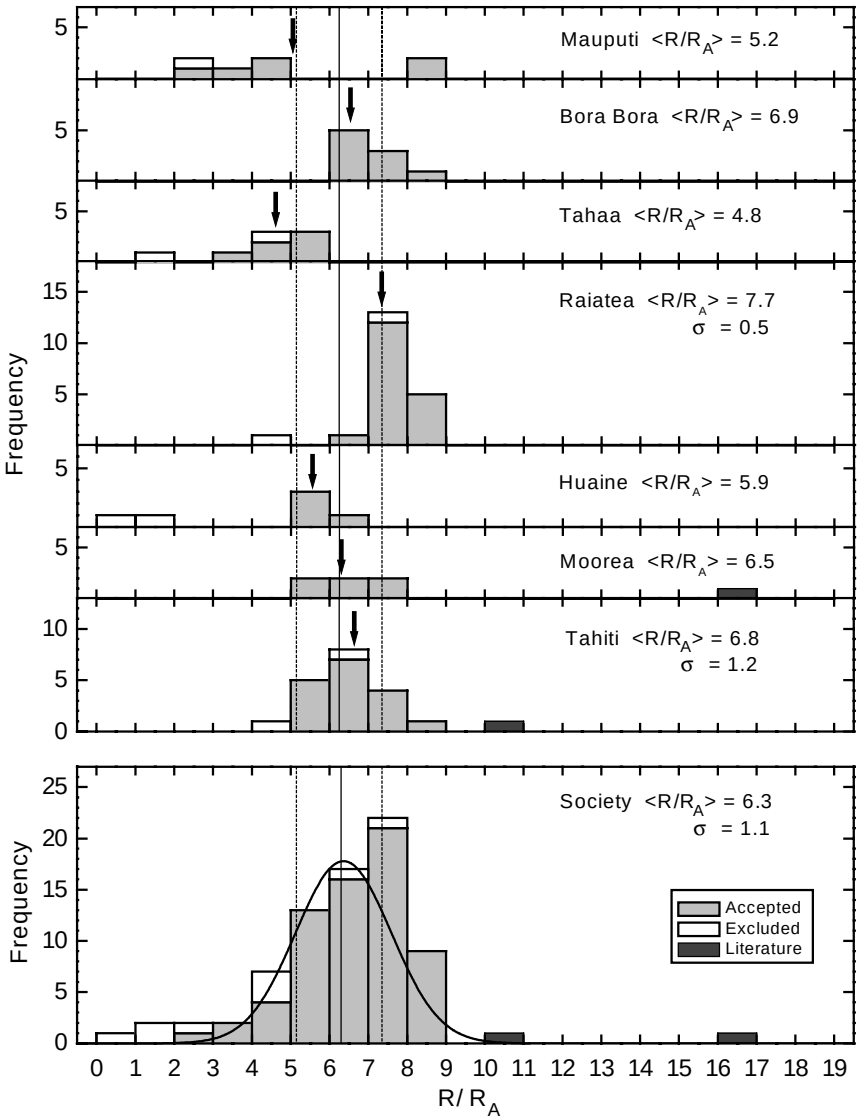

Fig. 3. – Frequency of ^{3}He/^{4}He in basalt samples for islands of the Society chain. The isotopic ratio is expressed in unit RA of the ^{3}He/^{4}He in atmosphere (RA=1.4×10^{-6}. All values from this work, except those marked with a black box coming from Hanyu and Kaneoka, 1992. Values marked with a white box are samples with blank $> 10\%$ and/or helium concentration lower than 0.5 ncc/g. The curve represents the Gaussian with $\langle R/RA \rangle = 6.3$ (solid line along the figure) and $\sigma = 1.1$ (dashed lines). The arrows represent the mean value for each island.

referred to specific experiments. The data-set, for a total of 19 entries refers to Mangaia, Tubuai and Raivavae: its introduction on the analysis reported above, leaves the panorama substantially unchanged.

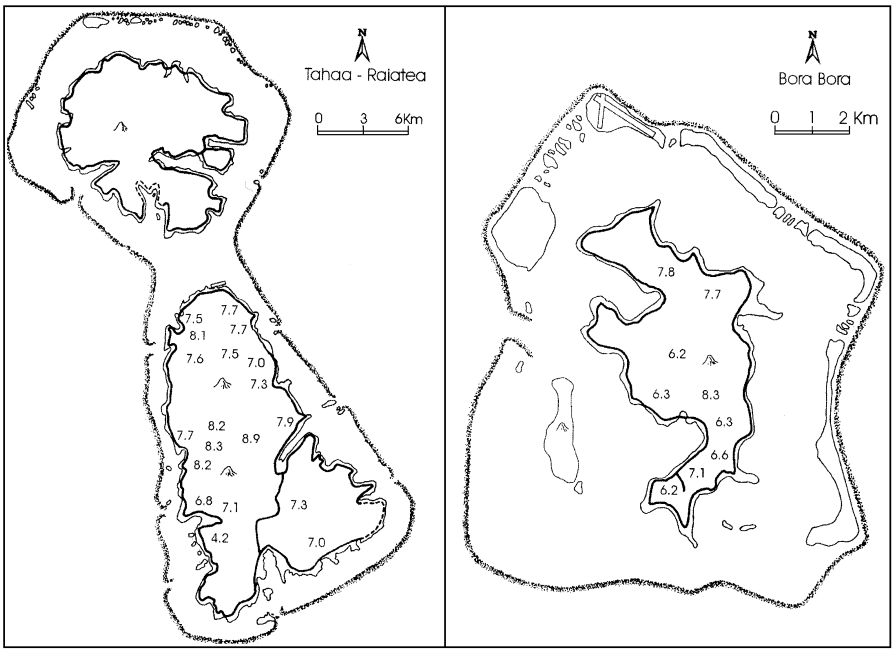

Fig. 4. – $^{3}He/^{4}He$ in basaltic rocks from the Island of Raiatea (left panel) and from Bora Bora (right panel).

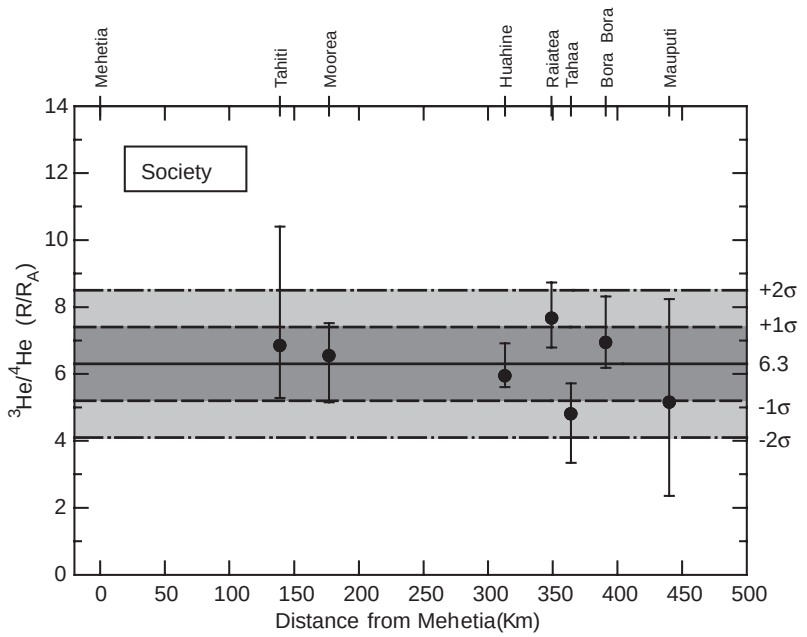

Fig. 5. – Society Islands. $^{3}He/^{4}He$ *vs.* distance from Mehetia along the dorsal of the chain. Dots represent average values; bars connect extreme values reported. The horizontal solid line represents $\langle R/RA \rangle = 6.3$.

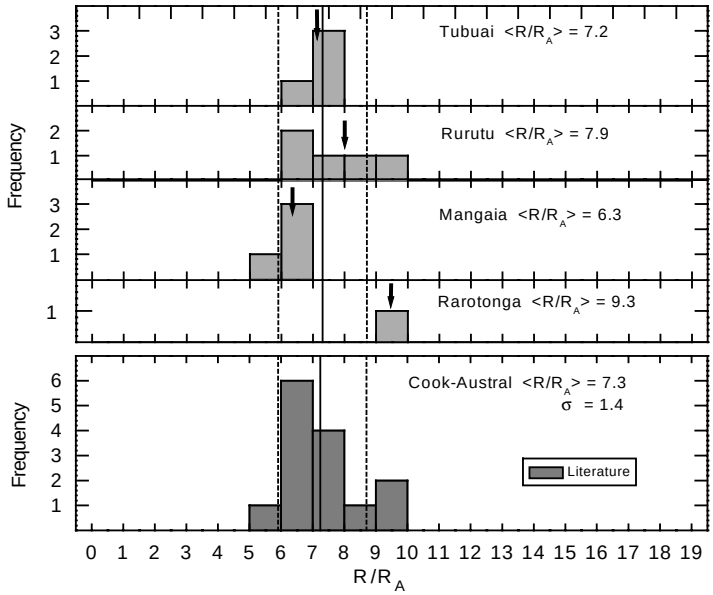

Fig. 6. – Frequency of ^{3}He/^{4}He in basalt samples for the Cook-Austral. The isotopic ratio is expressed in unit RA of the ^{3}He/^{4}He in atmosphere (RA=1. 4×10^{-6}). All values from this work, except those marked with a black box coming from Literature (see table I). Values marked with a white box are samples with blank $> 10\%$ and/or helium concentration lower than 0.5 ncc/g. The solid line represents the average $\langle$R/RA$\rangle$ value, the dashed lines $\langle$R/RA$\rangle \pm |\sigma|$. The arrows represent the mean value for each island.

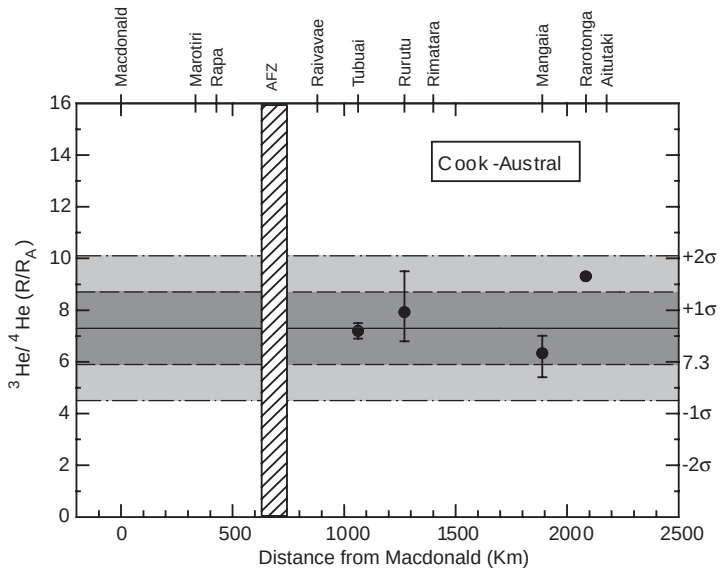

Fig. 7. – Cook-Austral Islands. ^{3}He/^{4}He *vs.* distance from Macdonald seamount along the dorsal of the chain. Dots represent average values; bars connect extreme values reported. Horizontal solid line represents $\langle$R/RA$\rangle$; the dashed lines represent respectively 1σ and 2σ variations.

5. – Discussion and conclusions

The relevant observational points can be summarized as follows:

a) The $^3He/^4He$ measured ratio distribution, when analyzed at the level of sampling a single island (*e.g.*, Raiatea and Bora Bora), shows a dispersion $\sigma \sim 1$ much higher than that expected by considering only the spread introduced by the propagation of experimental errors in the measurements and therefore must be be attributed to an "intrinsic variability" of the $^3He/^4He$ value in the basalts.

b) The distribution of the $^3He/^4He$ values observed in each individual island forming the volcanic chain is coherent with a unique mean value characterizing the whole chain; the dispersion σ is of the same order of that found for the individual elements in the chain.

c) In the Polynesian region (fig. 1) the $^3He/^4He$ panorama, as presented by the Society Islands and the upper North-West section (lat. $< 25°$S) of the Cook-Austral chain appears sustantially uniform. When comparing the two $\langle^3He/^4He\rangle$ mean values obtained, (R/RA)=(6.3 ± 1) for the Society Chain, (R/RA)=(7.3 ± 1.4) for the upper Cook-Austral, the difference is of the order of 1σ and therefore of scarce significance. A value of (R/RA)=(6.0–7.5) can be taken as representative for the geographical region defined by the islands considered (15°–25° lat. S; 145°–160° long. W); this is appreciably lower than the value commonly accepted for the Pacific MORB: (R/RA)$\sim$8.7.

d) The $^3He/^4He$ appears independent of the "age" defined for the island along the chain (fig. 2).

e) When comparing the helium isotopic value distribution with those of the other radiogenic isotopes (Sr, Nd, Pb) we observe that:

– Both for the Cook-Austral and the Society Islands, the $^{87}Sr/^{86}Sr$ isotopic ratio, similarly to the $^3He/^4He$ ratio remains constant along the dorsal chain (fig. 8a and fig. 8b).

– Considering the conventional Pb-Pb plots and Sr-Nd plot used to define the end-members, the helium panorama appears to be substantially uniform and not dependent from the geographical location. Possible explanations could be put forward: a weak dependence of the helium isotopic ratio from the mantle heterogeneity or in case of an existing dependence, this could be masked by high efficiency in the homogenization occurring during the rise of the magma to the surface.

The main outcomes of the analysis can be synthetized as follows: As a general conclusion, when asking if helium can be considered as a convenient tracer for mantle heterogeneity, we are confronted with the problem of the quantitative evaluation of the mixing occurring between possible different reservoirs in the mantle, together with that of the effects deriving from the interaction with the overlying crust during the magma ascent to surface.

In order to explain the "natural" dispersion ($\sigma \sim 1$) of the $^3He/^4He$ observed at the level of individual island and of the island chain, we have to consider the following processes which superimpose to a possible original heterogeneity of the mantle itself and modify the isotopic ratio either pre- or post-eruption:

i) isotope fractionation because of the diffusion or degassing,

ii) production of radiogenic helium,

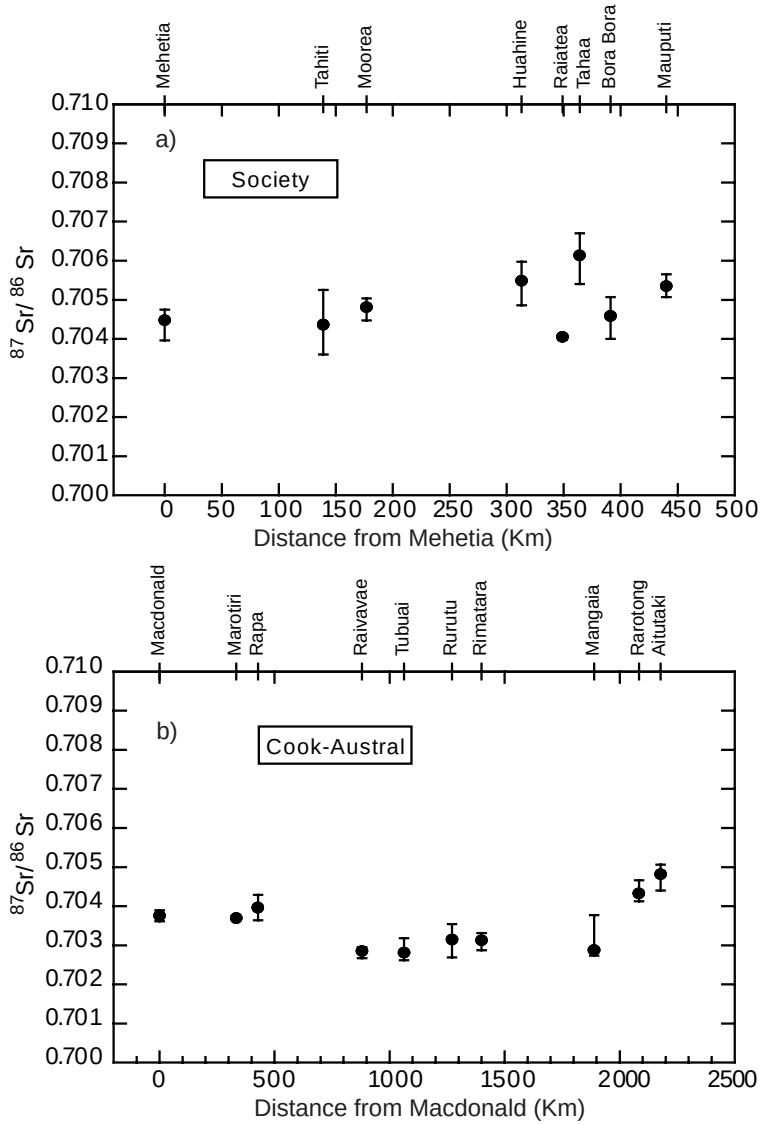

Fig. 8. – a) Society Islands. $^{87}Sr/^{86}Sr$ *vs.* distance from Mehetia along the dorsal of the chain. Dots represent average values; bars connect extreme values reported. Data from the literature. b) Cook-Austral Islands. $^{87}Sr/^{86}Sr$ *vs.* distance from Macdonald Seamount along the dorsal of the chain. Dots represent average values; bars connect extreme values reported. Data from the literature.

iii) contamination by helium of different sources.

The dispersion observed at the surface can then be accounted for by appropriate modeling introducing "convenient" boundary conditions for the ascent/residence phase of the magma at the surface without necessarily ask for the existence of a small scale heterogeneity present in the mantle.

When we refer to the large scale heterogeneity observed at surface for Polynesia in the context of a worldwide feature, the presence of intrinsic dispersions as that observed for the small scale, has to be taken into account as a scale factor.

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