

RARE EARTHS AND SOME OTHER TRACE ELEMENTS IN AN IGNEOUS ROCK SUITE FROM FUERTEVENTURA (CANARY ISLANDS)

P. DE PAEPE

Geological Institute, State University of Ghent (Belgium)

R. GIJBELS* & J. HERTOGEN**

Institute of Nuclear Sciences, State University of Ghent (Belgium)

1. Introduction

Fuerteventura is located in the eastern part of the Canarian archipelago (Fig. 1). The greater part of the island is covered by Tertiary (probably Miocene) and Quaternary volcanic rocks of basaltic composition. Near the west coast, in the surroundings of Betancuria and Pájara, these volcanic series overlie unconformably a relatively old massif called Betancuria Massif. The core of this massif is formed by a large stratiform complex with rocks ranging in composition from peridotites to gabbros. Moreover younger siliceous sediments and submarine volcanic series are outcropping. The several ring dykes with syenitic-trachytic composition that appear near Vega de Río de Palmas and Toto, and that gave rise to important contamination phenomena in the host rocks (e.g. alkalization), are probably the youngest formations of the Betancuria Massif. Similar alkaline intrusions are also present in other parts of Fuerteventura where they cut through the base of the Miocene (?) basalts.

Our present knowledge of the geology of Fuerteventura is mainly based upon the recent publications of the Department of Petrology of the University of Madrid. For general information about geology, stratigraphy and

petrography we refer to the memoir of FUSTER *et al.* (1968). More detailed studies have been published by CENDRERO (1966), MUÑOZ (1969), GASTESI (1969), IBARROLA (1969) and LOPEZ RUIZ (1970).

The present study was undertaken because of the great lack of information on REE* and other trace elements in the rocks from this island. This paper deals only with the preliminary results of this investigation.

Twelve whole-rock samples were analyzed for Sc, La, Ce, Sm, Eu, Tb, Dy, Yb, Lu, Hf, Ta, Th and U by means of neutron activation. Rocks from different parts of the island (fig. 1) and belonging to the main geological units as described by FUSTER *et al.* (1968) have been selected. Sample description and location are given in table 1. Petrographical description of the rocks is added to the text as appendix. Chemical analyses of rock samples from the same localities are available in literature (see references above). In addition the results of four new analyses are given in table 2. The alkali content of the different rocks studied is listed in table 3.

Rocks were collected by the senior author during the summer of 1966. Sample numbers are those of the collections of the Laboratory of Geology, State University of Ghent (Belgium).

* Research associate I.I.K.W.

** Navorsingsstagiair N.F.W.O.

* Rare earth elements.

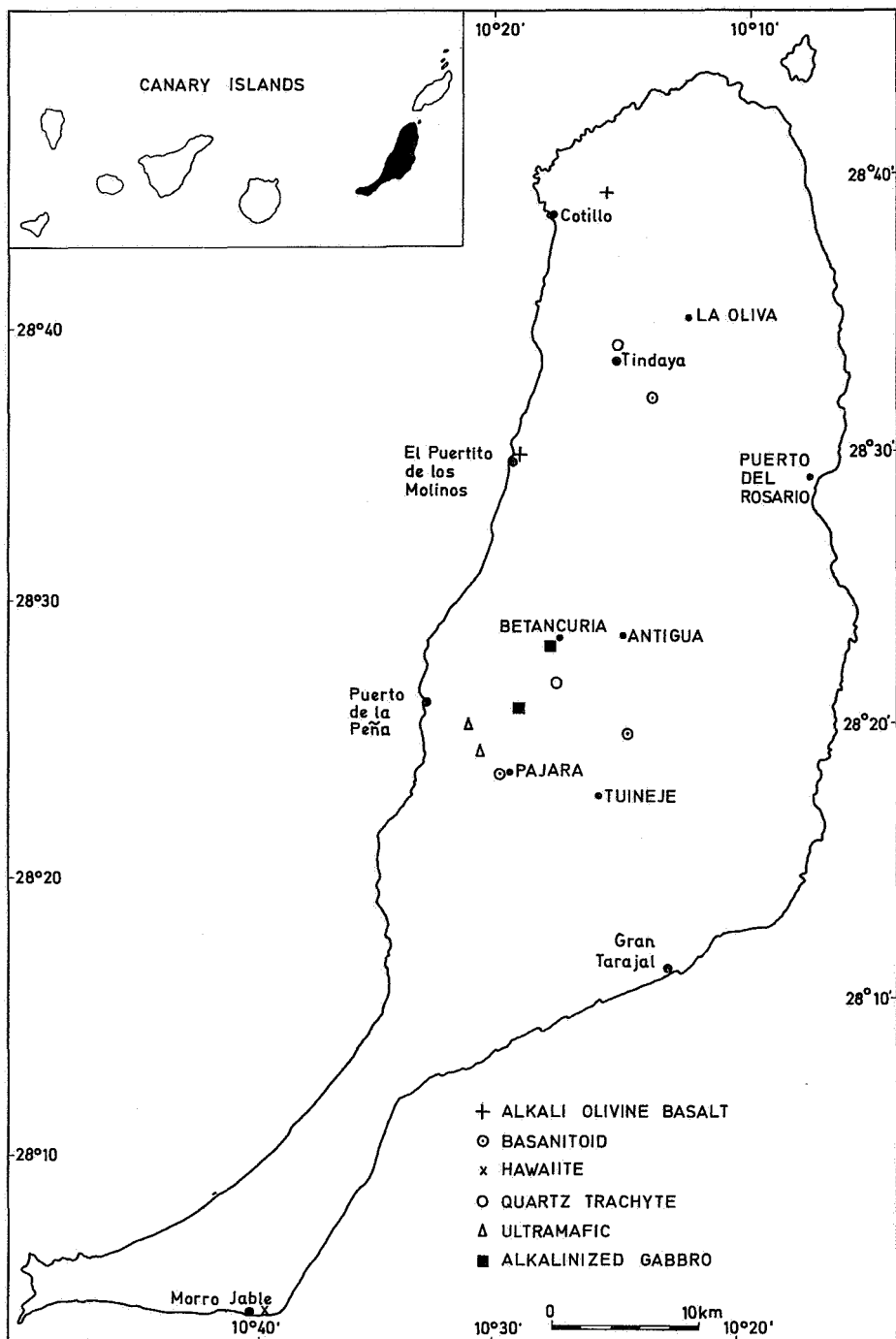


Fig. 1. Location of rocks studied from Fuerteventura.

TABLE 1. *Sample description and locality**

Rock type	Sample no.	Locality
alkali olivine basalt (B.S.II)	FU 64	El Puertito de los Molinos (Puerto del Rosario)
alkali olivine basalt (B.S.IV)	FU 98	Along the road from Cotillo to Lajares, near Casa de la Costilla (La Oliva)
basanitoid (B.S.II)	FU 90	Barranco del Risco, La Matilla (Puerto del Rosario)
basanitoid (B.S.IV)	FU 41	Barranco de Pájara, along the road from the village of Pájara to Puerto de la Peña (Pájara)
basanitoid (B.S.IV)	FU 185	Southwest slope of Caldera de Gairía (Antigua)
hawaiite (B.S.I)	FU 128	Playa del Matorral, along the road from Gran Tarajal to Morro Jable (Pájara)
quartz trachyte	FU 70	West slope of Montaña Tindaya (La Oliva)
quartz trachyte	FU 14	South of El Facarón, along the road from Betancuria to Pájara (Betancuria)
clinopyroxenite	FU 1	Barranco de Pájara, Los Huertos de Mesquer (Pájara)
wehrlite	FU 31	Barranco de Pájara, half-way between Ternemoy and Los Huertos de Mesquer (Pájara)
(weakly) alkalinized gabbro	FU 11	Barranco de Betancuria, south of the village of Betancuria (Betancuria)
(strongly) alkalinized gabbro	FU 179	Along the road from Betancuria to Pájara, ca. km 31.3 (Betancuria)

* B.S. = Basaltic Series

TABLE 2. *Chemical composition of different rock types from Fuerteventura**

	(a)	(b)	(c)	(d)
SiO ₂	43.85 %	50.56 %	46.40 %	42.14 %
TiO ₂	2.86	2.25	2.20	2.80
Al ₂ O ₃	7.50	17.34	13.04	11.03
Fe ₂ O ₃	8.17	3.66	7.14	3.82
FeO	5.53	5.00	5.13	8.91
MnO	0.16	0.21	0.14	0.16
MgO	11.84	4.26	8.95	14.66
CaO	17.71	6.52	10.57	10.80
Na ₂ O	1.27	6.02	3.01	2.89
K ₂ O	0.37	2.44	0.92	1.25
H ₂ O ⁺	0.36	0.29	0.88	0.38
H ₂ O ⁻	0.14	0.10	0.43	0.23
P ₂ O ₅	0.25	0.90	0.41	0.68

(a) clinopyroxenite FU 1

(c) alkali olivine basalt FU 64

(b) (strongly) alkalinized gabbro FU 179

(d) basanitoid FU 185

* Anal. I. ROELANDTS and G. BOLOGNE. Laboratory of Geology and Petrology, State University of Liège (Dir. Prof. Dr. P. MICHOT)

TABLE 3. Alkali content of all rocks investigated*

Rock type	Sample no.	Na ₂ O + K ₂ O (%)
alkali olivine basalt	FU 64	3.93
	FU 98	3.83
basanitoid	FU 90	4.32
	FU 41	4.55
	FU 185	4.14
hawaiite	FU 128	5.17
quartz trachyte	FU 70	11.07
	FU 14	9.07
clinopyroxenite	FU 1	1.64
	FU 31	0.99
wehrlite	FU 11	4.23
(weakly) alkalinized gabbro	FU 179	8.46
(strongly) alkalinized gabbro		

* Anal. C. CAMMAERTS. Geological Institute, State University of Ghent

2. Experimental methods

Radiochemical thermal neutron activation has been in use since several years for the determination of a large number of trace elements in geological specimens, such as igneous rocks, as appears from a recent bibliography (LUTZ *et al.*, 1968 and 1969). It is relatively easy to obtain information on Sc, Hf, Ta, Th and most of the REE without recourse to chemical separations, by counting the activated sample with a high-resolution Ge(Li) detector (GORDON *et al.*, 1968).

2.1. Detector and electronics

The coaxial germanium detector used in this study was made in the Institute for Nuclear Sciences, State University of Ghent (Belgium). The active volume is approximately 18 cc. The detector was operated in a vacuum at a temperature of about 80°K with a bias voltage of 1000 V. The output signal from the detector was fed into an *Ortec* Model 118A preamplifier, an *Ortec* Model 440A amplifier with an *Ortec* Model 438 base line restorer or an *Ortec* Model 450A research amplifier. The

resultant pulse was then analyzed by an *Inter-technique* 4000-channel analyzer Model *Didac*. An interface allowed direct transfer of the data to a *Digital* Model PDP-9 computer. Alternatively, the spectra could also be stored on magnetic tape, using the *Inter-technique* Model RG-23 tape recorder. The computer was programmed for automatic (Calcomp) plotting of the spectra and other reduction of raw data. Resolution of the system was 3.5keV for the ⁶⁰Co 1332 keV peak, with a peak to Compton ratio of 7. For the determination of the Dy and U abundances, a small "low energy photon detector" (Ge-Li LEPD) was used; the resolution of the actual measuring chain was ~ 480 eV at 100 keV. This type of Ge(Li)-detector and its characteristics have been described in detail by PALMS *et al.* (1968), and by HERTOGEN and GIJBELS (1971).

2.2. Standard and irradiations

The rock samples were powdered and the sample size was 2 × 1 g. These were weighed in small polyethylene vials (8 mm diameter × 32 mm height) for irradiation. As a standard we used the U.S.G.S. standard rock BCR-1,

TABLE 4. Average element content of BCR-1 (in ppm)
 [(after FLANAGAN, 1969, except for La, Sm, Yb and U)]

Sc	36.5	Yb	3.1 (b, c)
La	22.9 (a, b, c)	Lu	0.60
Ce	49	Hf	4.4
Sm	6.2 (a, b, c)	Ta	0.88
Eu	2.2	Th	6.82
Tb	1.0	U	1.80 (d)
Dy	6.0		

(a) BRUNFELT & STEINNES (1966)

(b) GORDON *et al.* (1968)

(c) MORRISON *et al.* (1969)

(d) BRUNFELT & STEINNES (1969)

a basalt from the Columbia River Group (Yakima type), described by FLANAGAN (1967). The average element contents used are shown in table 4 and are based mainly on the calculations by FLANAGAN (1969).

Most irradiations were carried out for 6h at a thermal neutron flux of $5.5 \times 10^{10} \text{n.cm}^{-2} \text{sec}^{-1}$ in the research reactor Thetis of the University of Ghent. The thermal to fast neutron flux ratio was *ca.* 15. Samples and monitors were positioned in the irradiation containers in such a way that the vertical and horizontal flux gradient effects were minimized.

For counting, the vials were placed in a plastic holder on top of the detector. Small differences in geometry were corrected for. A typical spectrum is shown in fig. 2. As is generally the case for siliceous rocks, the spectrum contains a great number of lines, many of them from the lanthanides. The spectra of basic rocks are much more strongly dominated by γ -rays from ^{46}Sc , ^{59}Fe and ^{60}Co (after decay of 15-h ^{24}Na); lines from lanthanides and most other species are much less prominent.

2.3. Identification of species

Identification of the observed γ -rays was based largely on the energies of the lines as

listed by GORDON *et al.* (1968) and by ADAMS & DAMS (1969). Since most of the active species emit more than one strong line, the relative intensity ratios in the sample spectra can be checked against known values for each species. A final test was to determine the half-life.

2.4. Abundance determinations

Each sample was observed at four different times after irradiation to optimize determinations for species of various half-lives, nl. after *ca.* 20h (during 30m: ^{153}Sm , $^{152\text{m}}\text{Eu}$), after *ca.* 5d (during 90m: ^{239}Np , ^{140}La), after *ca.* 14d (during 3h: ^{177}Lu , ^{141}Ce , ^{46}Sc , ^{181}Hf) and after 30 to 40d (during 12h: ^{46}Sc , ^{181}Hf , ^{182}Ta , ^{141}Ce , ^{160}Tb , ^{152}Eu , ^{169}Yb , ^{233}Pa). For the latter counting 2g of sample was used instead of 1g. Dysprosium was determined *via* 2.36-h ^{165}Dy after a separate irradiation.

The amount of a given element in a sample was computed from the ratio of the peak areas in the sample to the areas of corresponding peaks in the BCR-1 standard. Corrections were applied for decay between sample and monitor counts, for decay during the counting if required, for different counting times and geometry differences. The peak areas were determined using the PDP-9 computer, with a program written by OP DE BEECK (1970).

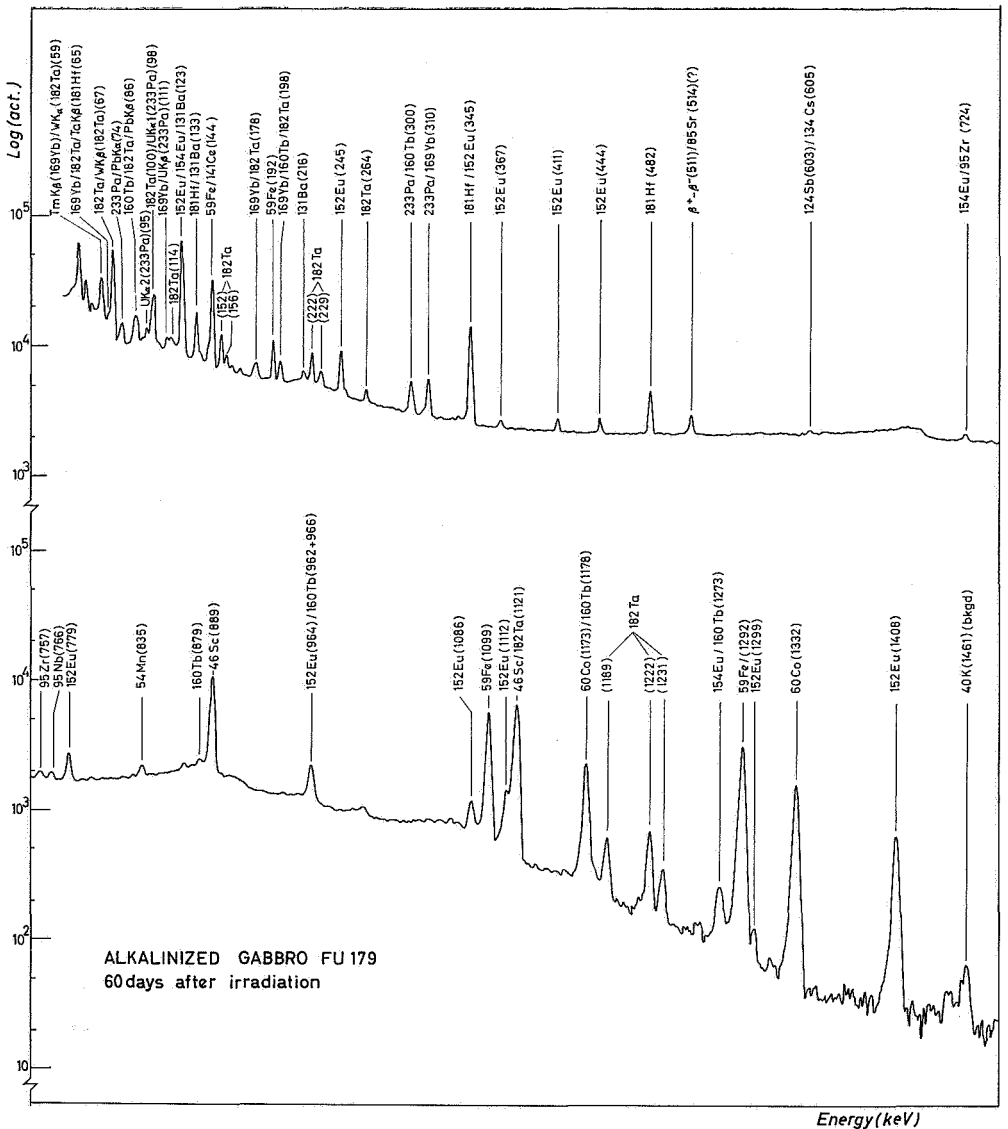


Fig. 2. Spectrum of γ -rays from FU 179 observed with Ge(Li) detector 60 days after neutron irradiation.

Even with the reasonably good resolution of our Ge(Li) detector, there are some multiple peaks that could not be resolved into their components such as ^{59}Fe 142.5keV and ^{141}Ce 145.5keV. Since cerium cannot be determined *via* another photopeak, the net contribution had to be determined by comparison with the γ -ray spectra of the pure radionuclides. There is also complicated interference between ^{182}Ta , ^{169}Yb , ^{160}Tb and ^{233}Pa .

Table 5 shows the photopeaks that were used for the analysis. Several of the above spectral interferences can be avoided when using the LEPD.

3. Results and discussion

3.1. Scandium

In igneous rocks scandium is mostly dispersed in pyroxenes, amphiboles and dark micas.

TABLE 5. Information on radionuclides and counting conditions

Element	Radionuclide and half-life	Photopeak used in determination (keV)	Time after irradiation	Interference in these conditions
Sc	83.9-d ⁴⁶ Sc	889.4; (1120.3)	14-40d	—
Co	5.24-y ⁶⁰ Co	(1173.1); 1332.4	30-40d	(a)
La	40.27-h ¹⁴⁰ La	328.6; 1595.4	5d	—
Ce	32.5-d ¹⁴¹ Ce	145.4	14-40d	⁵⁹ Fe(b)
Sm	47-h ¹⁵³ Sm	103.2	1d	—
Eu	9.37-h ^{152m} Eu	121.8	1d	—
	12.2-y ¹⁵² Eu	1407.5	30-40d	—
Tb	73-d ¹⁶⁰ Tb	298.6	30-40d	²³³ Pa
Dy	2.36-h ¹⁶⁵ Dy	94.6	2h	—(c)
Yb	30.6-d ¹⁶⁹ Yb	63.5; 177.0; 307.5	30-40d	¹⁸² Ta; ²³³ Pa
Lu	6.75-d ¹⁷⁷ Lu	208.4	14d	—
Hf	44.6-d ¹⁸¹ Hf	482.2	14-40d	—
Ta	115.1-d ¹⁸² Ta	67.7; 179.5	30-40d	¹⁶⁹ Yb
Th	27-d ²³³ Pa	311.8	30-40d	¹⁶⁹ Yb
U	2.35-d ²³⁹ Np	106.1	7d	—(c)

(a) the samples were contaminated with cobalt during grinding, hence the results are not included in this paper

(b) the ⁵⁹Fe contribution varies from ~ 5 % for quartz trachytes to ~ 50 % for basalts

(c) if measured with low energy photon detector

According to FRONDEL (1970) these mafic minerals of complex composition easily allow that trivalent and quadrivalent elements, such as Sc³⁺, Fe³⁺, V³⁺, Ti⁴⁺, Zr⁴⁺, etc., enter into their structure and there is no evidence for a crystallochemical relation between Sc³⁺ and (Mg²⁺, Fe²⁺) as supported by several authors.

Data obtained for the rock samples of the volcanic sequence from Fuerteventura show a decreasing Sc content from the basic to the acid rock types (table 6). Although there is a tendency to somewhat higher concentrations in the basanitoids, all basic rocks have Sc abundances within a very narrow range (24-28 ppm). The figures correspond well with the averages given by ENGEL *et al.* (1965), PRINZ (1967) and NORMAN & HASKIN (1968) for rocks with similar composition. PRINZ (1967) suggested that nepheline-normative basalts are especially poor in scandium but our values do not confirm this statement.

Scandium concentrations in both quartz trachytes investigated differ by a factor of 15. While rock sample FU 14 has a Sc content that is quite in line with values found in trachytes and rhyolites from other volcanic provinces (e.g. Ascension Island), the value of 0.4 ppm noted for the rock from Montaña Tindaya is extremely low. It is noteworthy that, according to BORISENKO & RODIONOV (1961) and NORMAN & HASKIN (1968), syenites and nepheline syenites are characterized by Sc contents of the same magnitude as sample FU 70.

As expected the ultramafic rocks have by far the highest concentrations. Difference in concentration between the clinopyroxenite FU 1 and the wehrlite FU 31 can easily be explained by the presence of *ca.* 25 % modal olivine in the latter, the Sc content of olivine always being very low (VLASOV, 1966). BORISENKO (1969) found averages of 77.3 ppm Sc in ten

TABLE 6. *Sc, Hf and Ta abundances in rocks from Fuerteventura (in ppm)*

Rock type	Sample no.	Sc	Hf	Ta
alkali olivine basalt	FU 64	24.1	5.3	3.1
	FU 98	24.1	5.0	2.5
basanitoid	FU 90	26.4	5.9	5.3
	FU 41	25.9	5.7	3.9
	FU 185	27.7	5.7	6.2
	FU 128	14.4	11.8	6.9
hawaiite	FU 70	0.4	9.1	8.3
quartz trachyte	FU 14	6.6	27.4	17.9
	FU 1	81.8	3.6	1.2
clinopyroxenite	FU 31	57.4	3.6	1.3
wehrlite	FU 11	17.3	2.2	1.2
(weakly) alkalized/gabbro	FU 179	6.1	9.1	6.7
(strongly) alkalized/gabbro				

clinopyroxenites from Khabarninsk Massif and 88.0 ppm Sc in two ultrabasic rocks, with similar mineralogical composition, from Kempirsay Massif. The average Sc content of 239 pyroxenites from the Urals is 82.0 ppm according to the same author.

The alkalized gabbros are hybrid rocks and yielded quite different values. This is not astonishing if we take into account that both rocks have undergone alkalization at different degree. This is clearly indicated by their strongly divergent alkali content (table 3). Rock sample FU 179, with the highest alkali content, has chemically a nepheline monzonite composition. Sample FU 11, on the other hand, can still be considered as a normal gabbroic rock. Hence Sc concentrations obtained agree well with the values reported by VLASOV (1966) respectively for gabbroic and monzonitic rock types.

3.2. Hafnium

Owing to the strong geochemical affinity that exists between Zr and Hf, zirconium minerals (principally zircon) are the most important hafnium carriers in igneous rocks. For the same reason both elements behave in the same way during magmatic processes showing in-

creasing concentrations from ultrabasic and basic to more siliceous rocks. In contrast with zirconium, results of direct hafnium determinations in rocks and minerals are rather limited in literature. Therefore comparison of abundances found in Canarian samples (table 6) with data for similar rock types from other regions is quite difficult.

Recently BROOKS (1970) published Hf concentrations of a few rock samples from the Hawaiian archipelago. He reported 2.9 ppm Hf for an alkali olivine basalt, 10.1 ppm for a hawaiite and 17.7 ppm for a trachyte. The hafnium content found by this author in a nepheline basalt from the same area was 3.5 ppm. As compared with the data obtained for Hawaiian samples with the same composition, alkali olivine basalts from Fuerteventura contain appreciably more hafnium. Their content is rather constant and this is also true for the basanitoids. The latter however yielded somewhat higher values and the same phenomenon was observed in rocks with modal nepheline from Hawaii. In line with our results for scandium, quartz trachytes FU 14 and FU 70 differ also greatly in their Hf abundances. Considering the general trend in the alkali rock suite from Hawaii, sample FU 70 has a very low content of this element.

Recent investigations have demonstrated

that the bulk of the hafnium present in ultrabasic and basic igneous rocks is concentrated in pyroxenes and in amphiboles. In spite of their divergent mineralogical composition the clinopyroxenite FU 1 and the wehrlite FU 31 contain equal amounts of this element. The average Hf content of all ultrabasic rocks (largely dominated by the olivine-rich classes) given by TUREKIAN & WEDEPOHL (1961) and by TAYLOR (1965) is respectively 0.6 ppm and 0.5 ppm. The abundance of 2.2 ppm found in the alkalinized gabbro FU 11 agrees well with the average Hf value for all gabbros given by the former authors (2 ppm). This shows once again the unimportant contamination undergone by this rock during the syenitic-trachytic intrusions. Sample FU 179 tends to the average Hf content of syenitic rocks (TUREKIAN & WEDEPOHL, 1961).

3.3. Tantalum

In most magmatic rocks tantalum occurs in dispersed state (PARKER & FLEISCHER, 1968; VLASOV, 1966). This behavior results from the crystallochemical similarity between this element and others such as Ti, Fe, Zr, Nb, W and Sn. Therefore, among the common rock-forming minerals, ilmenite, sphene, perovskite, zircon and to less extent pyroxenes, amphiboles and biotite carry the highest concentrations of this element.

The distribution of tantalum in all analyzed volcanic rocks from Fuerteventura shows a gradual increase from the basic samples to the more alkaline and siliceous members of the series (table 6). The content ranges from an average of 2.8 ppm in alkali olivine basalts to 17.9 ppm in quartz trachyte FU 14. On the average basanitoids contain twice as much tantalum as the alkali olivine basalts (5.1 ppm).

As pointed out by PARKER & FLEISCHER (1968) in their review on the geochemistry of niobium and tantalum only few data of Ta analyses for alkaline basaltic rocks are available. GLADKIKH & VIKTOROVA (1967) published data about the distribution of tantalum in two basalt-trachyte series of the Kuznetskiy Alatau Range and the Maymecha-Kotuy pro-

vince (USSR). In both series investigated by the latter the Ta content of the olivine basalts is below 4 ppm (the detection limit of the method used). In the Kuznetskiy Alatau Range the amount of tantalum passes through a maximum of 21 ppm in the andesitic rocks before falling to 15 ppm in trachytes. In the Maymecha-Kotuy province on the other hand the Ta concentration is constant (8 ppm) from the basaltic andesites to trachytes. Basanites and tephrites from the same regions contain respectively 8 ppm and 5 ppm of this element.

The average tantalum contents compiled by VINOGRADOV (1956) and by TUREKIAN & WEDEPOHL (1961) for ultramafic rocks are 0.75 ppm and 1 ppm. Abundances found in ultramafics from Fuerteventura correspond well with these figures. The degree of alkalinization of the gabbros is reflected by the Ta values, the most transformed rock containing approximately five to six times more tantalum than the other specimen. Gabbros investigated by ATKINS & SMALES (1960), GOTTFRIED (1965) and GERASIMOVSKII & KARPUSHINA (1965) have 0.19 to 1.0 ppm of this element. Four syenites from USSR and from Greenland yielded values in the range of 8.7 to 18 ppm.

3.4. Thorium and uranium (table 7)

As thorium and uranium show strong chemical and geochemical similarities they will be discussed here together. In igneous rocks both elements are mainly concentrated in accessory minerals such as monazite, allanite, xenotime, zircon, sphene, apatite and epidote. In most of these minerals Th and U are isomorphously substituting for Zr, Ca, Hf, Ce and other elements with similar properties. They can also be fixed in small quantities in more abundant rock-forming minerals (quartz, feldspars, pyroxenes) but here their mode of occurrence is uncertain. Possibilities suggested by ROGERS & ADAMS (1969a and 1969b) are: concentration in lattice defects, adsorption along crystal imperfections or along grain boundaries, inclusions, etc.

The volcanic rock suite from Fuerteventura is characterized by a very strong increase in

TABLE 7. *Th, U and K abundances and the Th/K and Th/U ratios in rocks from Fuerteventura**

Rock type	Sample no.	Th	U	K	Th/K.10 ⁴	Th/U
alkali olivine basalt	FU 64	2.3	0.80	0.764	3.0	2.9
	FU 98	3.3	0.74	0.614	5.4	4.5
basanitoid	FU 90	5.9	1.34	0.921	6.4	4.4
	FU 41	4.1	nd	1.046	3.9	nd
	FU 185	6.5	1.23	1.038	6.3	5.3
hawaiite	FU 128	9.4	2.23	1.436	6.5	4.2
quartz trachyte	FU 70	46.0	8.89	4.068	11.4	5.2
	FU 14	36.4	6.56	2.656	13.7	5.5
clinopyroxenite	FU 1	1.0	—	0.307	3.3	nd
wehrlite	FU 31	—	—	0.149	nd	nd
(weakly) alkalinized gabbro	FU 11	3.3	nd	0.539	6.1	nd
(strongly) alkalinized gabbro	FU 179	6.7	2.18	2.026	3.3	3.1

* Th and U concentrations in ppm; K concentrations in %

nd: not determined

—: value below detection limit

thorium and uranium from the mafic towards the more felsic members of the series. Alkali olivine basalts contain on the average 2.8 ppm Th and 0.77 ppm U. These values are in agreement with the ranges given by HEIER & CARTER (1964) for alkali olivine basalts from different volcanic provinces, namely 2.0-8.8 ppm Th and 0.44-1.4 ppm for U. Th and U abundances of both quartz trachytes analyzed are exceptionally high as compared e.g. with data available for Hawaiian trachytes (HEIER *et al.*, 1964; SOMAYAJULU *et al.*, 1966). A similar enrichment was reported in trachytes belonging to several alkaline rock suites studied by LARSEN & GOTTFRIED (1960) and by GOTTFRIED *et al.* (1962).

For the ultramafic rocks only Th abundances are available. Both samples are very poor in thorium and the figures obtained are in complete agreement with data published by other authors for similar rock types (HEIER & CARTER, 1964). Difference in concentration between clinopyroxenite FU 1 and wehrlite FU 31 can only be explained by an even lower Th content in olivine as compared with clinopyroxene.

Concentrations of thorium in various rock-forming minerals given by ADAMS *et al.* (1959) and by ROGERS & ADAMS (1969a) confirm this statement. As it was the case for scandium, hafnium and tantalum the two alkalinized gabbros differ also in their thorium content. Sample FU 179 contains twice as much of this element as gabbro FU 11. It is probable that a large part of the thorium present in the former is enclosed in the abundant apatite crystals.

Investigations on thorium, uranium and potassium in several rock types by HEIER & ROGERS (1963), HEIER (1964) and HEIER *et al.* (1964) led to the following conclusions concerning the behavior of these elements in igneous rocks:

- (1) there exists a strong coherence between Th, U and K in most rock types;
- (2) Th, U and K abundances increase with igneous differentiation and the relative enrichment is Th > U > K; for this reason the Th/K, U/K and Th/U ratios also increase with the petrogenetic evolution;
- (3) the variation in the Th/K, U/K and Th/U

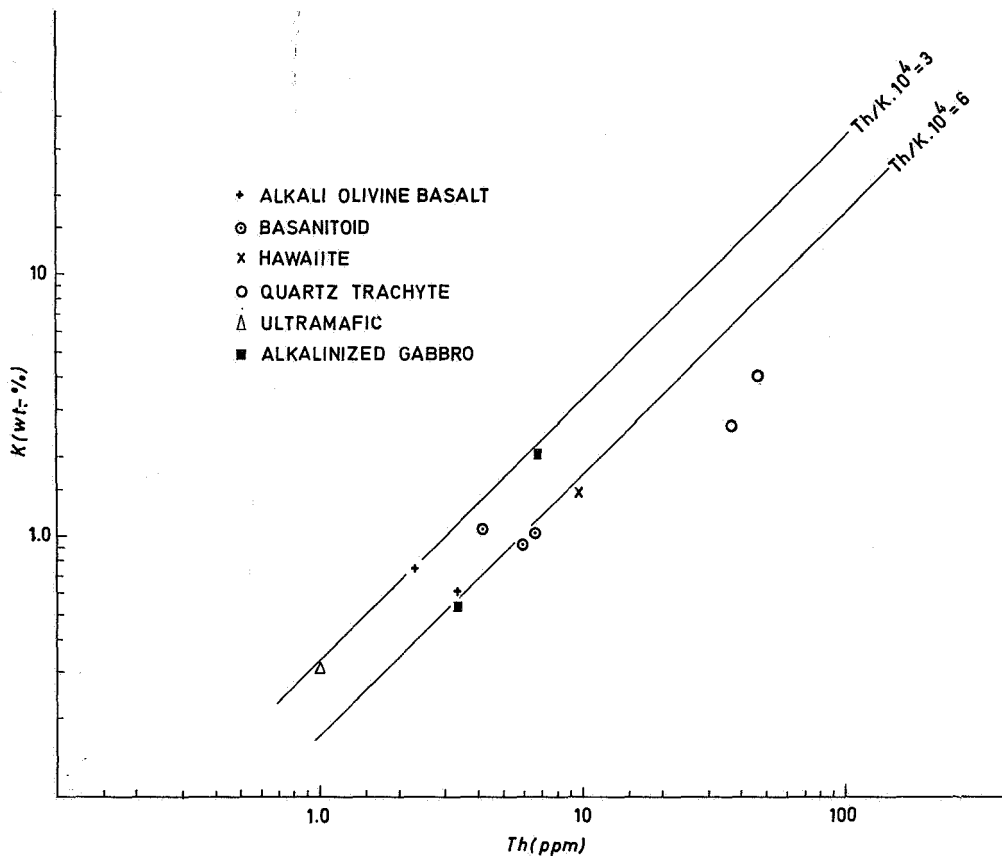


Fig. 3. Plots of thorium versus potassium in rocks from Fuerteventura (symbols as for Fig. 1).

ratios do not exceed one order of magnitude during normal magmatic fractionation.

The increase in thorium and uranium content from alkali olivine basalts to quartz trachytes in rocks collected at Fuerteventura was discussed before. Fig. 3 shows a plot of thorium versus potassium for all studied samples. The average $\text{Th}/\text{K} \cdot 10^4$ ratio is 4.2 for alkali olivine basalts, 5.5 for basanitoids, 6.5 for the hawaiiite and 12.6 for the quartz trachytes. As far as we know the average ratio found for the trachytic rocks is exceptional as compared with results available for other volcanic regions of the world.

As the uranium concentrations show the same increase in abundance towards the more differentiated rock types as the thorium concentrations, the Th/U ratios of all rocks from

Fuerteventura vary only little (fig. 4). The average ratio is about 4.4. ROGERS & ADAMS (1969a) believe that the general Th/U ratio of all igneous rocks is in the range of 3.5 to 4. Only in rocks directly derived from the upper mantle this ratio is considerably lower. Oceanic tholeiitic basalts e.g. have ratios between 1 and 2.

3.5. Rare earth elements

The present method permitted the determination of only eight out of the fourteen REE. The position of these eight elements in the lanthanide group is however so that it is possible to establish the geochemical behavior of all REE with the obtained values. Only in the group of the heavy lanthanides there can

- | | |
|-------------------------|----------------------|
| + ALKALI OLIVINE BASALT | ○ QUARTZ TRACHYTE |
| ⊙ BASANITOID | △ ULTRAMAFIC |
| x HAWAIIITE | ■ ALKALINIZED GABBRO |

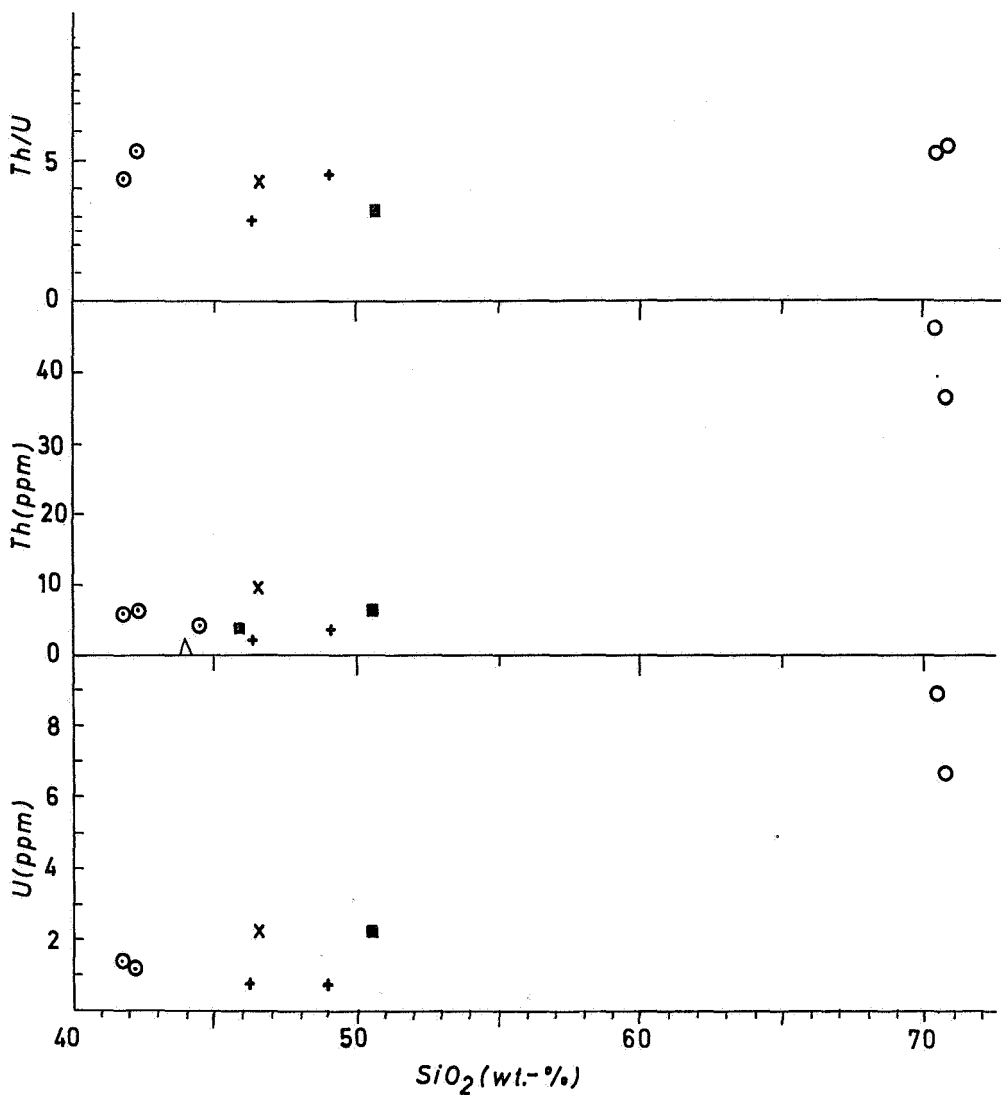


Fig. 4. Variation of thorium and uranium concentrations and Th/U ratios in rocks from Fuerteventura (symbols as for Fig. 1).

be some uncertainty if we consider the difficulties of the Yb determination owing to the interference from other radionuclides such as ^{182}Ta , ^{160}Tb and ^{233}Pa in the γ -ray spectra and the low Lu abundance.

The absolute abundances of La, Ce, Sm, Eu, Tb, Dy, Yb and Lu in the various rocks from Fuerteventura are given in table 8. The average concentration of the two alkali olivine basalts, the three basanitoids together with the

TABLE 8. Absolute abundances of some REE in rocks from Fuerteventura and in a composite of nine chondrites (in ppm)

	clinopyroxenite FU 1	weirite FU 31	alkali ol. basalt FU 64	alkali ol. basalt FU 98	basanitoid FU 90	basanitoid FU 41	basanitoid FU 185	hawaiite FU 128	quartz trachyte FU 14	quartz trachyte FU 70	(weakly) alkalinized gabbro FU 11	(strongly) alkalinized gabbro FU 179	composite of 9 chondrites*
La	11.5	12	29	48	63	54	51	90	223	76	19	102	0.330
Ce	28	29	44	55	96	66	95	142	292	99	34	166	0.88
Sm	5.0	6.7	8.9	8.8	12.4	7.8	9.5	19.4	28.5	4.2	4.3	20.7	0.181
Eu	2.1	2.0	2.8	2.9	3.9	2.7	3.5	6.0	6.2	1.4	2.3	5.5	0.069
Tb	0.6	1.1	0.7	0.9	1.0	1.0	1.0	1.8	3.2	0.5	0.2	2.0	0.047
Dy	3.5	3.6	4.6	5.0	5.9	4.7	4.6	9.0	18.5	2.9	3.0	8.6	
Yb	—	—	2.1	2.1	1.9	3.9	2.0	2.5	3.1	2.9	1.3	23.0	0.200
Lu	—	—	0.27	0.19	0.23	0.23	0.20	0.37	1.63	0.33	—	0.73	0.034

* after HASKIN, HASKIN, FREY & WILDEMAN (1968) as Dy was not calculated by HASKIN *et al.* (1968) we used the average Dy value given by HASKIN *et al.* (1966) for 20 chondrites (Dy: 0.31 ppm)

values obtained for the hawaiite and the quartz trachyte FU 14 are plotted normalized to a composite of 9 chondrites in fig. 5. The resulting diagram shows clearly the behavior of the REE in the different rock types of the volcanic series.

All rock types are enriched in light REE relative to the chondritic meteorites and the relative enrichment decreases gradually with increasing atomic number. Moreover the light rare earth enrichment undeniably depends on the alkalinity of the investigated rocks (table 3). Similar REE patterns were found in related rocks from other volcanic provinces in the world, e.g. Hawaii (SCHILLING & WINCHESTER, 1966 and 1969), N.W. Germany (HERRMANN, 1968), Gough Island (ZIELINSKI & FREY, 1970) and in Japan (MASUDA, 1968).

The much higher absolute concentration of REE in rocks from the earth's crust in comparison with chondrites and the mantle is the result of the structure of the minerals building up the latter. Substitution of REE for magnesium and iron is largely prevented by the ionic

radii. As the radius of the REE is decreasing with increasing atomic number (lanthanide contraction) the discrimination will be the strongest for the cerium group (light lanthanides). For the same reason other elements with large ionic size (K, Th and Ba) are concentrated in more differentiated magma types. Within the group of the alkali olivine basalts, on the one hand, and in rocks of the basanitoid group, on the other hand, absolute concentrations of the different REE vary only little as compared with the mutual differences found in the trachytic rocks. Although both quartz trachytes show the same enrichment towards the La end of the lanthanide series (fig. 6) the absolute abundances in sample FU 70 from Montaña Tindaya are on the average 4 to 5 times lower than those noted in the rock originating from the ring dyke complex. FU 70 is also the only rock from the volcanic suite of Fuerteventura in which the heavy lanthanides have been uniformly fractionated relative to the chondrites.

In spite of a different mineralogical com-

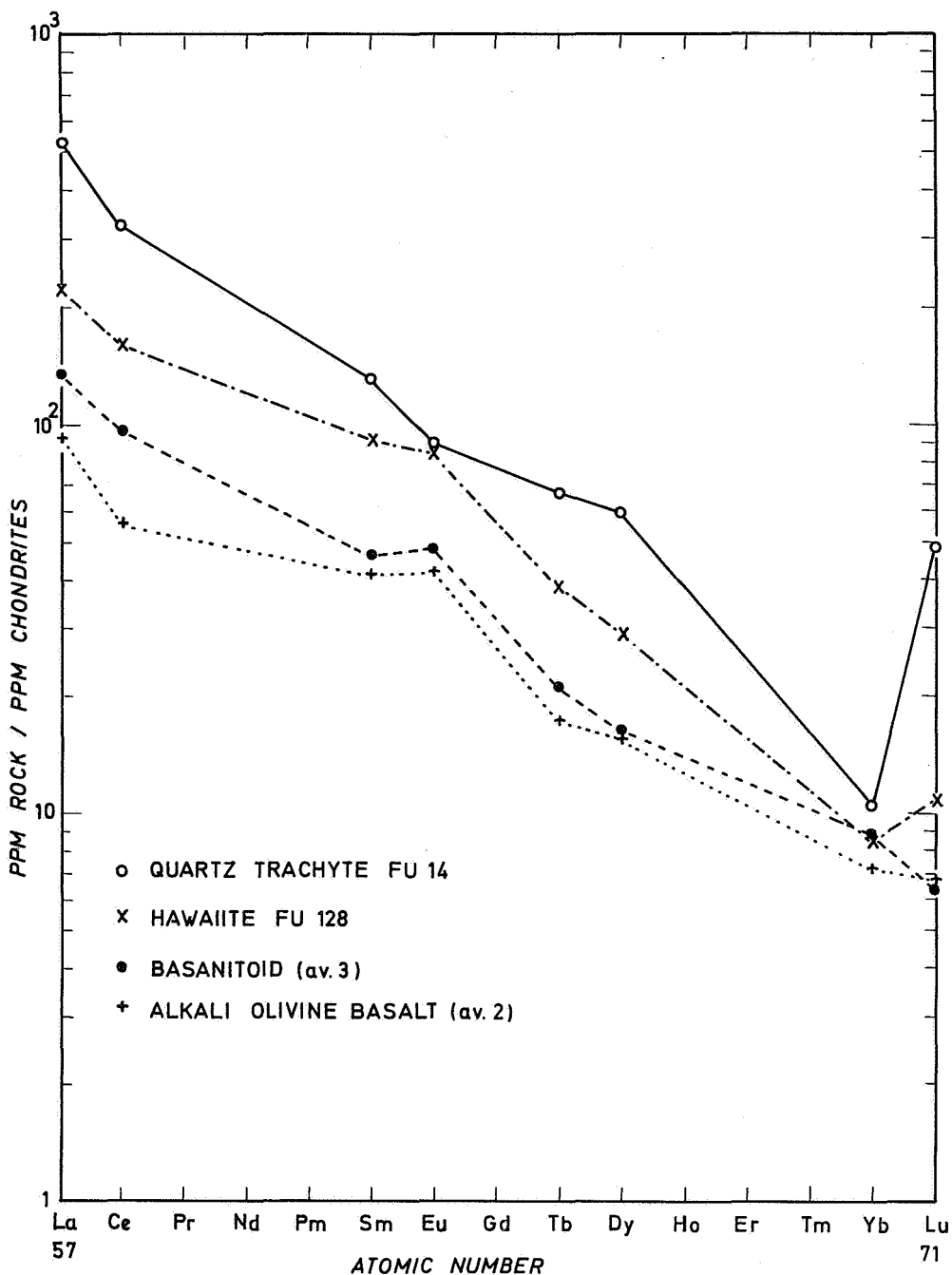


Fig. 5. Abundances of REE relative to nine chondrites in volcanic rocks from Fuerteventura.

position the two ultramafic rocks investigated have about the same absolute concentration for the different REE. As shown in fig. 7 they

are slightly enriched in light lanthanides as compared with the composite of nine chondrites and, unlike the volcanic suite, the en-

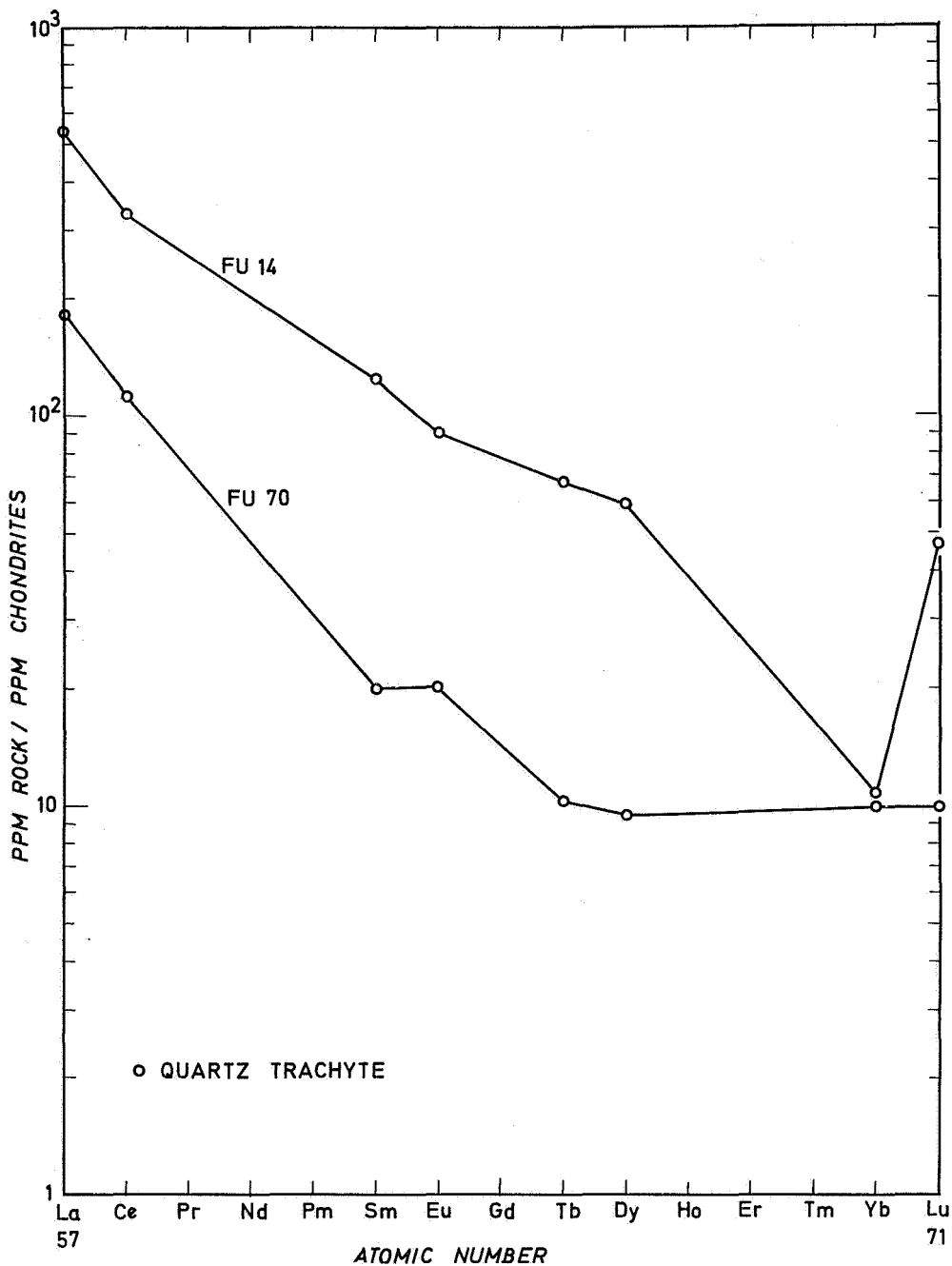


Fig. 6. Abundances of REE relative to nine chondrites in quartz trachytes from Fuerteventura.

richment is rather constant from La to Eu. In the middle of the series (near Gd) the pattern shows a break and progressively decreases towards the Lu end. As both rocks contain

very low amounts of Yb and Lu it was impossible to obtain quantitative data with the method used.

During alkalinization of the gabbros belong-

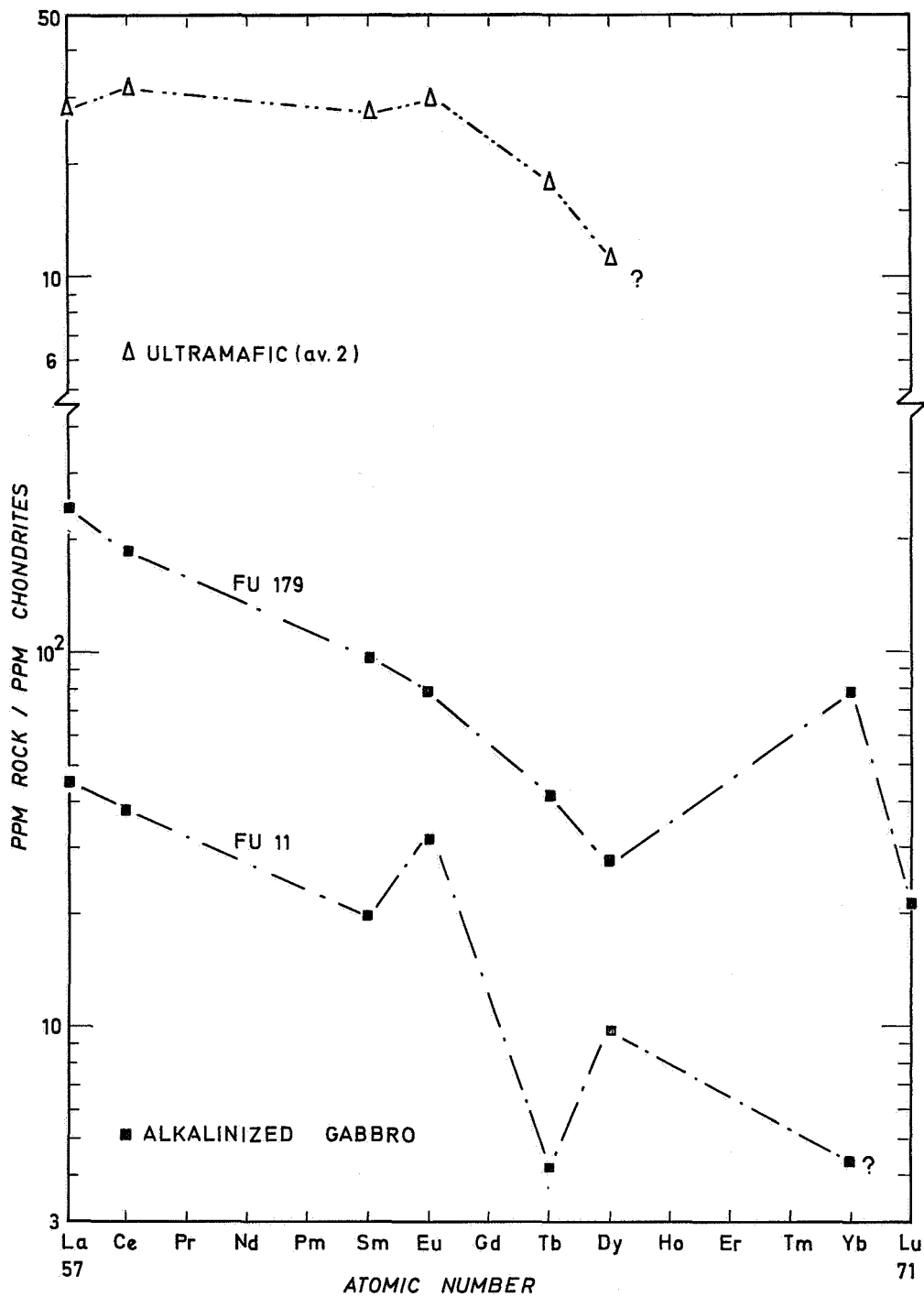


Fig. 7. Abundances of REE relative to nine chondrites in alkalinized gabbros and ultramafic rocks from Fuerteventura.

ing to the Betancuria Massif, resulting from the emplacement of the trachytic-syenitic ring dykes, the original rocks were not only enriched in Hf, Ta and Th but also in REE (fig. 7). The absolute REE abundances in gabbro FU 11 are systematically lower than in the alkali olivine basalts but the general trend is the same relative to chondrites as in the other rock samples. The REE pattern for the strongly alkalinized gabbro FU 179 on the other hand is comparable with that of the hawaiite except for the heavy lanthanides.

4. Conclusions

The study of the Sc, Hf, Ta, Th, U and REE abundances in different rock types from Fuerteventura led to several conclusions regarding the origin and the geochemistry of the island of Fuerteventura:

- The data suggest that most of the rocks belonging to Basaltic Series I, II, III and IV, and erupted from Miocene until Recent times, are derived from a common source.
- Relative RE patterns of rocks from the same series show trends that are similar to those noted in related rocks from other volcanic provinces. Light RE enrichment increases with increasing alkali content of the rock. Absolute RE abundances may differ considerably as compared with similar rock types from other parts of the world.
- The great discrepancy between the two quartz trachytes intruding the base of basaltic series I is difficult to understand if the hypothesis is admitted that the syenitic-trachytic ring dyke complexes and other trachytic dykes and plugs on the island have a comagmatic origin (FUSTER *et al.*, 1968; MUÑOZ, 1969). More detailed study of these intrusions is therefore desirable.
- Behavior of Sc, Hf, Ta, Th and U during magmatic processes is in good agreement with data reported in literature.
- The average Th/U ratio for all investigated rock samples is 4.4.
- Th/K ratios diverge more than Th/U ratios do. As compared with other rocks both

quartz trachytes are characterized by very high Th/K ratios.

- The gabbros of the basement complex were alkalinized by the later syenitic-trachytic intrusions. The alkalinization was attended by a change of trace element content in the host rocks. The importance of the latter phenomenon seems to a certain extent proportional with the degree of alkalinization.

Appendix: Petrographical description

- FU 64: Massive lava with scattered small olivine phenocrysts in an intergranular groundmass of plagioclase, augite, olivine, iron ore and interstitial carbonates. Most of the olivine crystals are altered to iddingsite.
- FU 98: Moderately vesicular pahoehoe with doleritic texture mainly composed of plagioclase, olivine, augite and iron ore. The ore minerals often show skeletal growth.
- FU 90: Rather massive porphyritic lava containing abundant phenocrysts of olivine (up to 3 mm across) in an intergranular groundmass of titanite, plagioclase, olivine and iron ore. Olivine microlites, as well as phenocrysts, are partly iddingsitized.
- FU 41: Slightly vesicular lava with abundant phenocrysts of olivine and less abundant augite phenocrysts in a pilotaxitic textured matrix of plagioclase, augite, olivine, iron ore and some glass.
- FU 185: Highly vesicular lapilli and ashes consisting mostly of volcanic glass. The pyroclasts contain abundant olivine phenocrysts. Augite phenocrysts are rare.
- FU 128: Glomeroporphyritic lava rich in plagioclase, augite and olivine phenocrysts. The plagioclase and augite phenocrysts are large (up to 8 mm long) as compared with the olivine phenocrysts (on average 1 mm across). The fine-grained groundmass is built by plagioclase, augite

- and ore minerals. Vesicles in the rock are filled by zeolites, carbonates and chloritic material.
- FU 70: Dense lava with small anorthoclase phenocrysts (up to 2 mm) in a groundmass of anorthoclase, some quartz and interstitial iron ore. Biotite is rather exceptional. The constituents of the matrix are disposed in a sub-parallel manner.
- FU 14: Slightly porphyritic lava with scattered perthitic alkali feldspar phenocrysts, up to 3 mm long, in a randomly oriented matrix of alkali feldspar, quartz and iron ore. Some feldspars show incipient alteration to muscovite.
- FU 1: Coarse allotriomorphic-granular rock consisting mainly of clinopyroxene and ore minerals with minor amounts of oxyhornblende (formed at the expense of the clinopyroxene) and biotite. Small irregular veins are present in the rock and contain plagioclase, carbonates, epidote minerals and chlorites.
- FU 31: Medium-grained rock with hypidiomorphic to allotriomorphic-granular texture and built up principally by clinopyroxene (greatly transformed to oxyhornblende), olivine and iron ore. Plagioclase is the most important accessory mineral. Many olivines are rimmed by serpentine.
- FU 11: Medium-grained hypidiomorphic-granular rock with plagioclase as main constituent but also containing considerable amount of augite, amphibole (kaersutite), biotite, iron ore and some apatite. Spherulites of chlorite and radial aggregates of clinozoisite occur in several inter-spaces of the rock.
- FU 179: Fine to medium-grained, hypidiomorphic-granular rock built by plagioclase, alkali feldspar, augite, amphibole (kaersutite?), biotite and iron ore. Accessories are apatite (abundant and up to 1.5 mm long) and some sphene.

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