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*Frau Prof. Dr. Emilie Jäger gewidmet*

## **Sr–Nd–Pb isotope data for Fuerteventura (Canary Islands) basal complex and subaerial volcanics: applications to magma genesis and evolution**

by *Kaj Alexander Hoernle<sup>1</sup>* and *George Robert Tilton<sup>1</sup>*

### **Abstract**

We report Sr, Nd and Pb isotopic compositions and concentration data for 35 igneous rocks and O and C isotopic compositions for six carbonatites from Fuerteventura (Canary Islands). The 24 samples from the basal complex (70–25 Ma) include tholeiitic and alkalic gabbro, basanite through nepheline benmoreite, nepheline, ijolite, syenite, fenite and sövitic carbonatite. The alkalic rocks yield very similar Sr, Nd and Pb isotope ratios, suggesting a close genetic relationship between these rock types. The isotopes of the 11 Miocene to Recent subaerial volcanic samples, which include basanite, alkali basalt, tholeiite and hawaiite, have less radiogenic Sr and Pb isotopes and more radiogenic Nd isotopes. Compared to the more undersaturated samples, the more  $\text{SiO}_2$ -saturated samples from each unit have lower  $^{143}\text{Nd}/^{144}\text{Nd}$ . Comparison of the Fuerteventura data with that from the neighboring island of Gran Canaria and from the westernmost islands of La Palma and Hierro suggest a model in which the magmas of both series originate from a mantle plume. Melts from the plume (HIMU) interact with asthenospheric and lithospheric mantle containing recycled enriched continental lithospheric mantle (EM) from beneath the West African Craton. The earlier, basal complex magmas, presumably erupted directly over the plume, reflect a mix between plume and lithospheric mantle. Since the plume was located to the west of the island during Miocene–Recent times, the subaerial magmas had to travel additional distance through the upper asthenosphere before eruption, leading to a higher level of asthenospheric (DM + EM) contamination. This model implies a plume origin for the Fuerteventura carbonatites. The data yield no evidence for contamination of magmas with sialic continental crustal material.

**Keywords:** Fuerteventura, Canary Islands; Sr, Nd, Pb, C, O isotopes; magma genesis; alkalic and tholeiitic volcanism; carbonatites.

### **List of abbreviations**

HIMU: mantle material with high time-integrated  $\mu$  ( $^{238}\text{U}/^{204}\text{Pb}$ ) ratios  
DM: mantle material with a time-integrated depletion in large ion lithophile elements  
EM: mantle material with a time-integrated enrichment in large ion lithophile elements;  
EM1 is characterized by a strong time-integrated enrichment of Nd relative to Sm and EM2 by a strong time-integrated enrichment of Rb relative to Sr  
MORB: mid ocean ridge basalt; two types E (enriched) and N (normal)

### **Introduction**

Fuerteventura, which has been active for ca. the last 80 Ma, is the oldest known ocean island volcano (LE BAS et al., 1986). The age span of this island covers the entire age span of the Hawaiian island – Emperor seamount chain. Unlike most ocean island volcanoes, the entire history of the volcano is subaerially exposed. These factors result from a combination of unique circumstances:

(1) the volcano formed in very shallow water on the edge of a continental rise, (2) the very slow rate of motion of the plate kept the volcano from being cut off from its supply of plume material, (3) the very low average eruption rate kept the base from being completely covered by later eruptives and allowed erosion to keep pace with volcanism once it was subaerially exposed, and (4) more than a kilometer of vertical uplift has exposed the basal portion of the volcano, reveal-

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ing the transition from ocean floor sedimentation at a continental rise to the submarine build-up of an ocean island volcano (LE BAS et al., 1986). Therefore isotopic studies of Fuerteventura should provide important insights into the initial stages of ocean island volcanism, as well as yield a coherent picture of the long term evolution of an ocean island volcano.

Except for the Cape Verde Islands, Fuerteventura is the only other known ocean island with subaerially-exposed carbonatites. A geochemical study of the basal complex on Fuerteventura can therefore also provide important insights into the origin of carbonatites. Although there have been a number of major and trace element studies on volcanic and plutonic rocks from Fuerteventura, Sr-Nd-Pb isotopic studies are rare. To date, only five Pb isotopic analyses (LANCELOT and ALLÈGRE, 1974; SUN, 1980) have been published. Stable-isotope data is included in PINEAU et al. (1973), JAVOY and STILLMAN (1981) and JAVOY et al. (1986). In this study of the evolution of Fuerteventura, which concentrates on the basal complex, we present Sr, Nd and Pb isotope results for 35 samples as well as O and C isotope results for six carbonatites. A more detailed study of the Miocene-Recent volcanics is presently underway (THIRLWALL, 1990).

### General geology

Fuerteventura is the second largest (1731 km<sup>2</sup>, 807 m maximum elevation above sea level) of the Canary Islands (SCHMINCKE, 1976). A number of major geologic studies have been conducted on the island (see FUSTER et al., 1968; SCHMINCKE, 1976; LE BAS et al., 1986; STILLMAN, 1987 for summaries). Two main geological units are present on Fuerteventura: the basal complex, consisting of submarine volcanics and plutonics, and the later subaerially-erupted volcanic group, primarily basaltic lava flows and dikes.

Albian-Cenomanian pelagic chalks interbedded with alkaline volcanics provide evidence that alkaline volcanism on Fuerteventura began in the Upper Cretaceous. Contemporaneous sedimentation and submarine volcanism continued until Oligocene times. Alkali basalt and ankaramite dikes, ultramafic plutons, tholeiitic and alkalic gabbros, syenites and the Ajui-Solapa carbonatite-ijolite-syenite intrusive (~ 60 Ma) extensively intrude the lower bedded sequence (ROBERTSON and STILLMAN, 1979; LE BAS et al., 1986; STILLMAN, 1987). These are in turn extensively intruded by dikes and high-level plutons, which range in age from 48 to 12 Ma. A second ijolite-

syenite-carbonatite complex (~ 30 Ma; LE BAS et al., 1986, Tab. 4) is exposed in the Esquinzo-Tindaya area 30 km north of the Ajui-Solapa carbonatite complex (BARRERA et al., 1981). Dikes also extensively intrude this complex. Both the dikes and host rocks of the basal complex are metamorphosed to the albite-epidote greenschist facies (LE BAS et al., 1986; STILLMAN, 1987). Stable-isotope data suggest that the dikes may have acted as pathways for the circulating waters, which were predominantly meteoric (JAVOY et al., 1986).

The oldest age from the overlying subaerial volcanics is 20.6 Ma (ABDEL-MONEM et al., 1971). FUSTER et al. (1968) has divided the subaerially-erupted volcanics into four Basaltic Series: I (Miocene), II (Pliocene-Quaternary), III (Quaternary ?) and IV (Subrecent). For further discussion and dates from the subaerial volcanics see SCHMINCKE (1976), ABDEL-MONEM et al. (1971) and FERAUD et al. (1985).

### Sampling and analytical methods

#### SAMPLING

Twenty-four samples in this study come from the basal complex on Fuerteventura (25–70? Ma), predominantly from the Ajui-Solapa and the Esquinzo ijolite-syenite-carbonatite complexes. These samples include tholeiitic and alkalic gabbro, basanite through nepheline benmoreite, nephelinite, ijolite, syenite, fenite and carbonatite. The 11 samples from Basalt Series I–IV (0–21 Ma) include basanite, alkali basalt, tholeiite and hawaiite and are primarily from the northern half of the island. Stratigraphic position, a brief petrographic description and location of the samples are given in Appendix 1. More detailed petrographic descriptions, as well as XRF and INAA data for these samples will be presented in HOERNLE and LE BAS (1991).

#### ANALYTICAL METHODS

Sr-Nd-Pb isotope analyses from rock powders and mineral separates and O-C isotope analyses for six carbonatites are listed in Tab. 1. For whole rock samples, approximately 100 g of rock was ground to flour in an agate mill. For isotopic compositions, 100–200 mg of powder was acid washed for ~ 45 minutes in a mixture of 50 °C 6N HCl and 7N HNO<sub>3</sub> to remove alteration products. In order to remove secondary calcite without fractionating the parent-daughter ratios, the pow-

ders for elemental concentrations of the six pre-21 Ma dikes were soaked for 15 minutes with cold 2N HCl. The other whole rock powders used to determine elemental concentrations were not acid washed. For mineral concentrates, we separated euhedral grains of feldspar, nepheline or calcite. Calcite separates are estimated to be > 99% pure. The calcite samples were rinsed with cold 2N HCl for 30–60 seconds to remove any surface contaminants, then dissolved in 2N HCl and split into two aliquots: one for isotopic composition and one for elemental concentrations. The silicate mineral separates were crushed to a flour to avoid problems with precipitates and to assure that all trace element and isotope analyses were from homogeneous sample material. The powders used to determine the isotope composition were soaked for 15 minutes in a dilute solution of cold HF + HCl to remove surface contamination; the powders for isotope dilution were not acid washed.

The splits for elemental concentrations were total-spiked with three mixed spikes:  $^{208}\text{Pb}$ – $^{235}\text{U}$ – $^{230}\text{Th}$ ,  $^{87}\text{Rb}$ – $^{84}\text{Sr}$  and  $^{150}\text{Nd}$ – $^{149}\text{Sm}$ . All silicate samples were then dissolved with hot HF +  $\text{HClO}_4$  in teflon screwcap vials. The pertinent elements from each split were separated by column chemistry in the following sequence: Pb, U–Th, Rb, Sr, Nd, Sm. Blank amounts for Sr, Nd and Pb, on the order of 0.3, < 1.0 and 0.3 nanograms respectively, were negligible. Isotope ratios were measured on a multiple collector mass spectrometer (Finnigan MAT 261) operating in the static mode. For consistency, the Pb, Sr and Nd isotopic ratios in this study were normalized to the same values as those used for two recent isotope studies of Gran Canaria, which were performed in the same laboratory and measured on the same mass spectrometer (COUSENS et al., 1990; HOERNLE et al., 1991a).

The  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio was normalized within-run to  $^{86}\text{Sr}/^{88}\text{Sr} = 0.1194$ , and then adjusted to a  $^{87}\text{Sr}/^{86}\text{Sr}$  value of 0.710250 for NBS 987. The  $^{143}\text{Nd}/^{144}\text{Nd}$  ratio was normalized within-run to  $^{146}\text{Nd}/^{144}\text{Nd} = 0.721900$ , and then adjusted to a  $^{143}\text{Nd}/^{144}\text{Nd}$  value of 0.511850 for the La Jolla standard or 0.511890 for the Ames standard (Note: the La Jolla and Ames standards were used at different times). Replicate analyses over a three year period of NBS 987 Sr (29 analyses) yielded  $0.710199 \pm 0.000023$  (2 sigma), of La Jolla Nd (8 analyses) yielded  $0.511866 \pm 0.000019$  (2 sigma), and of Ames Nd (21 analyses) yielded  $0.511946 \pm 0.000020$  (2 sigma). All Pb runs were normalized to TODT et al. (1984) values for NBS 981. Replicate analyses of Pb standard NBS 981 (10) run with the samples over a period of three years and with different Si gels gave the following average

values:  $^{206}\text{Pb}/^{204}\text{Pb} = 16.902 \pm 0.008$  (2 sigma),  $^{207}\text{Pb}/^{204}\text{Pb} = 15.449 \pm 0.014$  (2 sigma), and  $^{208}\text{Pb}/^{204}\text{Pb} = 36.562 \pm 0.046$  (2 sigma). The mass-spectrometric precision of all concentrations determined by isotope dilution are better than 1%. The O and C isotopes were measured on a Finnigan MAT 251 mass spectrometer at Santa Barbara. The uncertainties in  $^{18}\text{O}$  and  $^{13}\text{C}$  values were  $\pm 0.04$  to 0.06 per mil (2 sigma).

Because of the high degree of alteration (to the albite-epidote greenschist facies) of the basal complex (LE BAS et al., 1986; JAVOY et al., 1986; STILLMAN, 1987), great care was taken in collecting and preparing the freshest possible samples, which in most cases involved handpicking mineral separates under a binocular microscope. Nevertheless, we conducted detailed leaching studies on 13 samples from whole rock powders and mineral separates to determine the reproducibility of the isotopic composition of the samples (Tab. 2A). Acid washing affected the Sr and Pb isotopic ratios of about 50% of the samples. In most cases, the acid washed whole rock powders have lower  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios. The Pb isotopic ratios, however, showed no systematic variation with acid washing, although the Pb isotopic ratio for sample CF5 was raised significantly (see discussion below). The estimated two sigma reproducibility of different acid washed samples is  $\pm 0.000025$  for Sr and Nd isotope ratios, < 0.05% per a.m.u. for the  $^{206}\text{Pb}/^{204}\text{Pb}$  and  $^{207}\text{Pb}/^{204}\text{Pb}$ , and < 0.07% per a.m.u. for  $^{208}\text{Pb}/^{204}\text{Pb}$ . Multiple analyses of the same sample powders (flours) shows that Pb and U concentrations can be reproduced to 2% and Th to 6% (Tab. 2B). Differences in the concentrations of these elements in different pieces of the same sample illustrate sample heterogeneity (Tab. 2B). The initial isotope ratios for samples CF3 and CF4, which were collected 50 cm apart from the same intrusive body (see Appendix 1), are essentially within the two sigma analytical precision (Tab. 1). The initial  $^{87}\text{Sr}/^{86}\text{Sr}$ ,  $^{143}\text{Nd}/^{144}\text{Nd}$  and  $^{207}\text{Pb}/^{204}\text{Pb}$  ratios for samples CF1 and CF2, collected 2 m apart from the same intrusive body but separated by two 0.5 m dikes, are also within the two sigma analytical precision. The difference in the  $^{206}\text{Pb}/^{204}\text{Pb}$  and the  $^{208}\text{Pb}/^{204}\text{Pb}$  ratios are due either to improper corrections for *in situ* radiogenic Pb, or to alteration associated with dike injection. Samples CF1 and CF2 were collected 0.5 km up canyon from samples CF3 and CF4 and appear to be from the same intrusive complex. The initial  $^{87}\text{Sr}/^{86}\text{Sr}$ ,  $^{143}\text{Nd}/^{144}\text{Nd}$  and  $^{207}\text{Pb}/^{204}\text{Pb}$  ratios for these four samples are within the analytical precision, and the  $^{206}\text{Pb}/^{204}\text{Pb}$  and the  $^{208}\text{Pb}/^{204}\text{Pb}$  ratios for samples CF3 and CF4 fall within the range for samples CF1 and CF2.

Tab. 1 1) MG# and SiO<sub>2</sub> are from whole rock powders, not mineral separates.

2) The values preceded by an \* are from XRF (MG#, SiO<sub>2</sub>, Rb, Sr) and INAA (Sm, Nd, Th) (STILLMAN, 1987; LE BAS, unpubl data; HOERNLE and SCHMINCKE, unpub. data). All other concentrations are from isotope dilution.

3) Within run statistical errors for Sr and Nd isotope ratios not in table 2A are < ± 0.000021 (2 sigma).

Sample Number	Rock Type	Analyzed	Age Ma	MG#	SiO <sub>2</sub> wt. %	Rb ppm	Sr ppm measured	87Sr/86Sr	87Rb/86Sr	Sm ppm	Nd ppm measured	143/144Nd	147Sm/144Nd initial
SUBAERIAL VOLCANICS													
KFS240	Basanite	whole rock	0	69.9	42.0	*32	*929	0.703025	0.10	0.703025	0.512949	0.512949	
KFS96	Basanite	whole rock	0	70.5	43.0	13.7	892.06	0.703156	0.04	0.703156	0.512948	0.512948	
KFS82	Basanite	whole rock	0	69.7	44.9	*23	*611	0.703035	0.11	0.703035	0.512979	0.512979	
KFS69	Tholeiite	whole rock	1	62.3	49.6	13.6	488.58	0.703196	0.08	0.703195	0.512912	0.512911	
KFS110	Basanite	whole rock	4	66.3	44.5	27.1	800.81	0.702998	0.10	0.702992	0.512970	0.512967	
KFS140	Alkali Basalt	whole rock	12	64.9	45.5	*28	*668	0.703011	0.12	0.702991	*8.25	*41.1	
KFS34a	Hawaiite	whole rock	16	42.5	48.2	*66	*721	0.703051	0.26	0.702991	0.512944	0.512943	
KFS46	Alkali Basalt	whole rock	16	67.4	45.6	*28	*465	0.703129	0.17	0.703089	0.512913		
KFS53	Alkali Basalt	whole rock	16	60.8	47.2	*24	*712	0.703123	0.10	0.703101	0.512914		
KFS54	Alkali Basalt	whole rock	16	58.6	48.7	*44	*570	0.703096	0.22	0.703045	0.512907		
KFS55	Hawaiite	whole rock	16	46.3	49.8	*45	*661	0.703293	0.20	0.703249	0.512903		
BASAL COMPLEX													
F122	Tholeiitic Gabbro	whole rock	25	72.9	46.6	*9	*502	0.703252	0.05	0.703233	4.31	*8.3	
CF17	Basanite	whole rock	26	50.3	43.3	33.4	1080.2	0.703333	0.09	0.703300	*14.36	*73.1	
CF16	Tephrite	whole rock	27	51.1	47.8	48.6	1312.6	0.703318	0.11	0.703277	28.46	153.9	
CF15	Tephriphonolite	whole rock	28	29.5	52.0	60.1	3322.4	0.703318	0.05	0.703297	2.43	11.96	
68/SC/72	Carbonatite	calcite	30	48.7	0.3	0.05	18428	0.703312	<0.01	0.703312	23.31	160.4	
68/SC/73	Carbonatite	calcite	30	27.7	5.9	<0.01	14281	0.703244	<0.01	0.703244	22.55	158.6	
CF3	Ijolite	nepheline	30	72.6	47.1	83.5	1761.3	0.703391	0.14	0.703333	6.33	42.41	
CF1	Ijolite	nepheline	30	65.8	49.3	47.2	2233	0.703321	0.06	0.703295	4.08	27.56	
CF12	Ijolite	nepheline	30	64.7	41.9	16.2	2268.2	0.703375	0.02	0.703367	0.03	0.32	
CF4	Ijolite	nepheline	30	53.9	41.3	46.3	2281	0.703321	0.06	0.703296	7.66	44.13	
CF2	Syenite	nepheline	30	27.7	57.1	16.6	1527	0.703297	0.03	0.703283	1.63	8.47	
CF10	Albitite	feldspar	30	18.7	63.9	0.54	976.0	0.703281	<0.01	0.703280	0.22	1.44	
CF5	Nepheline	whole rock	45	51.9	43.7	72.1	1543.4	0.703296	0.14	0.703209	*19.1	*10.8	
CF10b	Nepheline	whole rock	45	45.7	46.1	37.7	1117.1	0.703297	0.10	0.703234	8.69	46.73	
CF11b	Nepheline	whole rock	45	49.8	44.3	42.2	1345.1	0.703299	0.09	0.703241	21.10	115.1	
LFU75/203	Tholeiitic Gabbro	whole rock	50	73.0	41.8	*9	*388	0.703296	0.07	0.703249	6.12	*30.5	
F/75/148	Carbonatite	calcite	60	49.0	2.5	0.17	17708	0.703214	<0.01	0.703214	40.04	286.4	
F/75/153	Carbonatite	calcite	60	36	36001	0.703224	<0.01	0.703224	0.08	0.703250	3.58	32.86	
F/75/158	Carbonatite	calcite	60	42.8	0.9	0.08	19967	0.703191	<0.01	0.703191	49.63	353.0	
F/75/165	Carbonatite	calcite	60	10.9	65.5	0.60	297.2	0.703293	0.01	0.703288	0.96	6.54	
CF6	Albitite	feldspar	60	5.9	60.9	*237	*3943	0.703505	0.17	0.703357	7.28	39.02	
CF9	Orthoclase	feldspar	60	1.5	62.5	*259	*1647	0.703637	0.45	0.703250	0.08	0.512866	
CF7	Orthoclase	feldspar	70	61.6	46.4	*45	*1554	0.703335	0.08	0.703251	*9.63	*44.2	
F2	Alkali Gabbro	whole rock	70	61.6	46.4						0.512885	0.13	0.512825

Sample Number	Pb ppm	U ppm	T h	206Pb/204Pb measured	207Pb/204Pb measured	208Pb/204Pb measured	$\mu$	K	206Pb/204Pb Initial	207Pb/204Pb Initial	208Pb/204Pb Initial	$\delta^{180}\text{SMOW}$	$\delta^{133}\text{Pb}$ PDB
<b>SUBAERIAL VOLCANICS</b>													
KFS240	3.03	1.58	6.41	19.326	15.553	39.033	33.82	4.18	19.326	15.553	39.033		
KFS96	3.10	1.19	6.19	19.330	15.548	39.042	24.81	5.39	19.330	15.548	39.042		
KFS82		2.9	19.105	15.555	38.872	39.057	24.44	3.70	19.206	15.566	38.872		
KFS69	1.48	0.56	2.00	19.210	15.566	39.046	22.36	4.64	19.341	15.556	39.025		
KFS110	2.58	0.89	3.99	19.355	15.557	38.941	33.19	4.17	19.193	15.542	38.860		
KFS140	1.98	1.02	4.12	19.253	15.545	39.039	25.53	4.56	19.237	15.553	38.947		
KFS94a	2.15	0.85	3.74	19.300	15.556	39.059	26.05	4.20	19.119	15.563	38.872		
KFS46	1.39	0.56	2.27	19.184	15.566	39.251	30.46	3.45	19.499	15.569	39.168		
KFS53	2.36	1.10	3.68	19.574	15.573	39.138	30.67	4.45	19.297	15.557	39.030		
KFS54	2.02	0.95	4.10	19.373	15.561	39.095	20.78	4.07	19.246	15.581	39.028		
KFS55	3.01	0.97	3.80	19.297	15.583								
<b>BASEAL COMPLEX</b>													
F122	0.31	0.04	0.11	19.624	15.592	39.425	7.83	3.11	19.598	15.590	39.398		
CF17	2.48	3.44	6.02	20.205	15.625	39.760	9.165	1.81	19.838	15.608	39.549		
CF16	2.72	1.73	5.13	19.816	15.602	39.673	41.68	3.07	19.643	15.594	39.504		
CF15	14.97	0.51	0.42	19.819	15.599	39.611	2.23	0.85	19.809	15.599	39.609		
68/SC/72	9.93	0.05	0.73	19.674	15.594	39.578	0.34	14.64	19.674	15.594	39.572	6.99	-5.43
68/SC/73	2.74	<0.01	1.00	19.625	15.578	39.483	0.05	457.2	19.625	15.578	39.447	6.81	-5.64
CF3	11.13	0.64	1.90	19.726	15.581	39.566	3.79	3.06	19.708	15.580	39.550		
CF1	1.58	0.13	0.13	19.761	15.607	39.646	5.45	1.03	19.739	15.606	39.641		
CF12	1.49	0.09	0.07	19.641	15.582	39.485	3.86	0.81	19.626	15.581	39.483		
CF4	1.77	0.93	0.58	19.845	15.619	39.663	34.70	0.64	19.687	15.611	39.633		
CF2	1.23	0.23	0.15	19.692	15.608	39.548	12.13	0.66	19.639	15.605	39.539		
CF10	0.43	0.21	0.17	19.797	15.625	39.530	32.86	0.81	19.657	15.618	39.501		
CF5b	8.14	2.51	6.56	19.798	15.588	39.551	20.25	2.70	19.656	15.581	39.430		
CF10b	3.77	1.11	3.86	19.748	15.575	39.576	19.22	3.61	19.614	15.569	39.422		
CF11b	3.03	1.00	4.63	19.884	15.578	39.759	21.79	4.77	19.733	15.571	39.529		
LFU75/203	2.55	0.65	2.11	19.982	15.599	39.713	16.91	3.33	19.851	15.593	39.574		
F75/148	3.35	0.22	0.89	19.659	15.570	39.451	4.32	4.15	19.622	15.568	39.400	7.84	-5.79
F75/153	3.42	0.07	0.55	19.660	15.583	39.482	1.29	8.39	19.651	15.582	39.452	7.39	-5.15
F75/158	8.59	0.07	1.27	19.658	15.574	39.464	0.55	18.12	19.655	15.574	39.436	6.78	-6.27
F75/165	7.11	1.08	3.78	19.677	15.588	39.517	9.95	3.61	19.586	15.584	39.411	7.22	-5.63
CF6	1.12	0.27	0.31	19.702	15.593	39.424	15.85	1.20	19.559	15.586	39.371		
CF9	2.40	1.46	5.09	19.995	15.609	39.739	39.98	3.61	19.624	15.591	39.312		
CF7	1.91	0.08	0.81	19.796	15.601	39.584	2.74	10.50	19.772	15.600	39.501		
F2	2.59	0.92	3.65	19.794	15.603	39.518	23.16	4.12	19.542	15.591	39.188		

Tab. 2A 1) The numbers at the end of each sample refer to the following: #1) not acid washed split of sample, #2) acid washed split (see analytical methods section for acid washing procedures), #3) second acid washed split; .1 and .2 refer two separate loads after column chemistry of split #3.

2) (Staudigel) refers to the samples analyzed at Lamont-Doherty by Hubert Staudigel.

3) All within run statistical errors are two sigma.

Sample Number	Analyzed	87Sr/86Sr	143Nd/144Nd	206Pb/204Pb	207Pb/204Pb	208Pb/204Pb
CF2#1	nepheline	0.703317(11)	0.512855(11)	19.765(3)	15.601(2)	39.568(5)
CF2#2	nepheline	0.703275(6)	0.512837(11)	19.680(3)	15.595(2)	39.501(6)
CF2#3.1	nepheline	0.703317(15)	0.512865(8)	19.703(4)	15.619(3)	39.579(8)
CF2#3.2	nepheline	0.703320(15)		19.705(5)	15.623(4)	39.608(11)
AVERAGE		0.703297	0.512851	19.692	15.608	39.548
CF5#1	whole rock	0.703321(14)	0.512841(9)	18.582(2)	15.548(2)	38.282(4)
CF5#2(5Min)	whole rock	0.703306(18)	0.512841(8)	19.550(28)	15.585(25)	39.465(77)
CF5#3(45Min)	whole rock	0.703296(15)	0.512880(10)	19.798(3)	15.588(3)	39.551(7)
CF6#1	feldspar	0.703326(14)	0.512918(17)	19.753(2)	15.605(2)	39.440(4)
CF6#2	feldspar	0.703297(15)	0.512923(21)	19.702(4)	15.593(3)	39.423(8)
CF6#3.1	feldspar	0.703291(17)	0.512945(11)	19.700(6)	15.589(5)	39.409(12)
CF6#3.2	feldspar	0.703288(19)		19.707(3)	15.598(2)	39.441(6)
AVERAGE		0.703293	0.512934	19.702	15.593	39.424
CF9#1	feldspar	0.703495(16)	0.512880(9)	20.028(7)	15.644(6)	39.858(17)
CF9#2	feldspar	0.703514(15)	0.512879(9)	19.981(4)	15.594(3)	39.688(7)
CF9#3.1	feldspar	0.703495(17)	0.512879(5)	20.008(5)	15.622(4)	39.779(11)
CF9#3.2	feldspar	0.703497(14)	0.512876(8)	20.010(4)	15.626(3)	39.803(8)
AVERAGE		0.703505	0.512878	19.995	15.609	39.739
CF12#1	nepheline	0.703349(17)	0.512905(33)	19.630(3)	15.571(3)	39.446(6)
CF12#2	nepheline	0.703379(16)	0.512870(33)	19.632(5)	15.572(5)	39.450(14)
CF12#3.1	nepheline	0.703388(15)	0.512886(23)	19.641(6)	15.584(5)	39.491(12)
CF12#3.2	nepheline	0.703355(14)		19.656(5)	15.599(4)	39.547(12)
AVERAGE		0.703375	0.512878	19.641	15.582	39.485
CF15#1	whole rock	0.703401(13)	0.512874(11)	19.773(1)	15.587(1)	39.605(2)
CF15#2	whole rock	0.703336(17)	0.512881(7)	19.819(2)	15.599(2)	39.608(5)
CF15#3.1	whole rock	0.703300(14)	0.512886(8)	19.819(5)	15.599(4)	39.608(11)
CF15#3.2	whole rock	0.703299(15)	0.512898(8)	19.820(2)	15.600(2)	39.619(5)
AVERAGE		0.703318	0.512887	19.819	15.599	39.611
CF16#1	whole rock	0.703390(13)	0.512824(13)	19.839(2)	15.615(2)	39.766(6)
CF16#2	whole rock	0.703328(15)	0.512861(9)	19.814(3)	15.599(2)	39.663(6)
CF16#3.1	whole rock	0.703320(19)	0.512851(8)	19.819(4)	15.605(4)	39.680(11)
CF16#3.2	whole rock	0.703294(17)	0.512858(6)	19.818(2)	15.605(2)	39.689(5)
AVERAGE		0.703318	0.512858	19.816	15.602	39.673
CF17#1	whole rock	0.703422(11)	0.512830(16)	20.042(2)	15.622(1)	39.843(4)
CF17#2	whole rock	0.703333(17)	0.512831(6)	20.201(5)	15.621(4)	39.745(12)
CF17#3.1	whole rock	0.703352(9)	0.512849(6)	20.206(6)	15.627(5)	39.768(14)
CF17#3.2	whole rock	0.703316(13)	0.512845(4)	20.211(2)	15.631(1)	39.783(4)
AVERAGE		0.703333	0.512839	20.205	15.625	39.760
F68/SC/73#1	calcite	0.703305(18)	0.512831(8)	19.611(3)	15.562(3)	39.434(8)
F68/SC/73#2	calcite	0.703257(13)	0.512867(7)	19.630(6)	15.582(5)	39.499(14)
F68/SC/73#3.1	calcite	0.703222(19)	0.512873(5)	19.617(9)	15.571(7)	39.462(18)
F68/SC/73#3.2	calcite	0.703238(11)	0.512879(6)	19.622(6)	15.576(5)	39.473(14)
AVERAGE		0.703244	0.512872	19.625	15.578	39.483
F/75/158#1	calcite	0.703248(12)	0.512879(5)	19.659(2)	15.575(2)	39.464(5)
F/75/158#2	calcite	0.703202(9)	0.512871(7)	19.653(3)	15.572(3)	39.461(7)
F/75/158#3.1	calcite	0.703231(16)	0.512845(6)	19.661(6)	15.575(5)	39.464(13)
F/75/158#3.2	calcite	0.703259(13)	0.512844(6)	19.663(3)	15.576(2)	39.469(7)
AVERAGE		0.703224	0.512858	19.658	15.574	39.464
KFS69(Staudigel)	whole rock	0.703270				
KFS69#2	whole rock	0.703196(13)	0.512912(8)	19.210(12)	15.566(10)	39.057(28)

Sample Number	Analyzed	87Sr/86Sr	143Nd/144Nd	206Pb/204Pb	207Pb/204Pb	208Pb/204Pb
KFS82(Staudigel)	whole rock	0.703080(40)				
KFS82#2	whole rock	0.703052(19)	0.512976(6)	19.102(4)	15.554(4)	38.863(8)
KFS82#3.1	whole rock	0.703025(15)	0.512985(5)	19.098(3)	15.545(3)	38.840(9)
KFS82#3.2	whole rock	0.703012(13)	0.512979(7)	19.119(2)	15.569(2)	38.922(6)
AVERAGE		0.703035	0.512979	19.105	15.555	38.872
KFS96(Staudigel)	whole rock	0.703200(13)				
KFS96#3.1	whole rock	0.703147(9)	0.512948(4)	19.330(10)	15.548(8)	39.042(23)
KFS96#3.2	whole rock	0.703166(14)				
AVERAGE		0.703156				
KFS110(Staudigel)	whole rock	0.703120(50)				
KFS110#2	whole rock	0.703010(16)	0.512958(5)	19.350(4)	15.552(3)	39.031(9)
KFS110#3.1	whole rock	0.702997(15)	0.512961(9)	19.358(7)	15.560(5)	39.054(14)
KFS110#3.2	whole rock	0.702974(16)	0.512982(8)	19.361(3)	15.563(3)	39.068(7)
AVERAGE		0.702998	0.512965	19.355	15.557	39.046
KFS140(Staudigel)	whole rock	0.703210(40)				
KFS140#2	whole rock	0.703032(14)	0.512944(5)	19.251(6)	15.544(5)	38.936(13)
KFS140#3.1	whole rock	0.702986(13)	0.512959(5)	19.252(4)	15.542(3)	38.929(8)
KFS140#3.2	whole rock	0.702995(13)	0.512962(5)	19.260(2)	15.552(2)	38.963(5)
AVERAGE		0.703011	0.512952	19.253	15.545	38.941

An additional source of error for the basal complex samples is the uncertainty in their ages (see LE BAS et al., 1986, for a detailed discussion). This uncertainty is most extreme in the nephelinite dikes. Sample CF5 could be anywhere between 25–60 Ma, and samples CF10b and CF11b between 30–70(?) Ma. Nonetheless, the initial isotopic ratios for the nephelinite dikes are similar to the other samples from the basal complex, such as the carbonatites (Tab. 1). The carbonatites have very small parent daughter ratios for all isotopic systems and therefore their initial ratios vary only slightly from their measured ratios. Also, note the close agreement in  $^{207}\text{Pb}/^{204}\text{Pb}$  and  $^{143}\text{Nd}/^{144}\text{Nd}$  ratios for multiple analyses of the acid-washed samples and for different samples from the same intrusive. These ratios are less affected by age corrections and alteration than the other isotope ratios. Although we do not have Sm and Nd concentration data for several of the subaerial volcanics, the corrections for the decay of  $^{147}\text{Sm}$  to  $^{143}\text{Nd}$  are negligible (between 0.000012–15), using the range in  $^{147}\text{Sm}/^{144}\text{Nd}$  ratios determined for the other subaerial volcanics.

### Results and observations

The samples from the basal complex (> 21 Ma) fall in a restricted field on isotope correlation diagrams (Figs 1–4). The initial  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios range from 0.70319 to 0.70337, the initial  $^{143}\text{Nd}/^{144}\text{Nd}$  ratios from 0.51274 to 0.51290, and the initial  $^{206}\text{Pb}/^{204}\text{Pb}$  ratios from 19.54 to 19.85. The O and C isotope ratios of the carbonatite samples, which are all sôvites, range from  $\delta = 6.8$  to 7.8 and  $-5.2$  to

$-6.3$  respectively, and fall within the range of "mantle fields" for carbonatites as defined in TAYLOR et al. (1967), DEINES and GOLD (1973) and DEINES (1989). The Fuerteventura values also fall within the range of mantle values based on studies of MORB (DES MARAIS and MOORE, 1984; KYSER et al., 1982). The  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  values argue against significant crustal or seawater interaction for the Fuerteventura carbonatite magmas. Furthermore, the isotopic composition of radiogenic elements in the carbonatites are the least likely to have been affected by crustal contamination, due to their extremely high concentrations of Sr and Nd and reasonably high concentrations of Pb (Tab. 1).

From the basal complex, only carbonatites have been previously analyzed for Pb isotopes (2 samples) in LANCELOT and ALLÈGRE, 1974). These samples have also been analyzed for O and C isotopes (3 analyses in PINEAU et al., 1973). The Pb isotope ratios for their sample P62 (19.69, 15.57, 39.37) agree well with the samples we analyzed. This sample also had mantle O and C values. The Pb ratios for their sample P58 (18.71, 15.51, 38.11) are much lower than all of the samples we analyzed after acid washing. This sample, which comes from a calcite dike in a syenite (PINEAU et al., 1973), also has anomalously high  $\delta^{18}\text{O}$  (17.0) and  $\delta^{13}\text{C}$  (-3.5) values, possibly reflecting crustal interaction. Our sample CF5, from a nephelinite dike, had nearly identical Pb isotope ratios to P58 before we acid washed it (Tab. 2). This sample contains ca. 15% calcite. After acid washing the sample for five minutes with 1N HCl, the  $^{206}\text{Pb}/^{204}\text{Pb}$  value increased from 18.6 to 19.6.

Tab. 2B 1) Capital letters (A, B) after the sample number = different dissolutions of the same powder; number after the decimal (1, 2) = different pieces of the same sample; AW = acid washed with 2N HCl for 15 minutes (cold).

Sample Number	Analyzed	Method	P b	U	T h	$\mu$	$\omega$
KFS69A	whole rock	ID	1.48	0.56	1.94	24.76	87.72
KFS69B	whole rock	ID	1.48	0.55	2.06	24.13	93.13
KFS140A	whole rock	ID	1.98	1.02	3.99	33.14	134.47
KFS140B	whole rock	ID	1.99	1.02	4.25	33.24	142.65
KFS240A	whole rock	ID	3.02	1.57	6.39	33.71	141.39
KFS240B	whole rock	ID	3.04	1.59	6.43	33.93	141.63
F122A	whole rock	ID	0.31	0.04	0.11	7.89	23.17
F122B	whole rock	ID	0.31	0.04	0.12	7.78	25.55
LFU75/203.1A	whole rock	ID	2.54	0.65	2.08	16.96	55.67
LFU75/203.1B	whole rock	ID	2.56	0.66	2.14	16.86	56.92
LFU75/203.2	whole rock	ID	2.69	0.69	2.10	17.00	53.04
F2.1A	whole rock	ID	2.59	0.92	3.60	23.24	94.26
F2.1B	whole rock	ID	2.60	0.91	3.70	23.08	96.62
F2.2	whole rock	ID	2.50	0.88	3.38	23.02	91.43
F68/SC/72.1	calcite	ID	9.93	0.05	0.73	0.34	4.96
F68/SC/72.2	calcite	ID	9.29	0.08	1.11	0.55	8.10
CF10.1	feldspar	ID	0.43	0.21	0.17	32.86	26.69
CF10.2	feldspar	ID	0.79	0.62	0.16	51.71	13.55
CF5bAW	whole rock	ID	8.14	2.51	6.56	20.25	54.60
CF5b	whole rock	INAA		2.6	8.3		
CF11bAW	whole rock	ID	3.03	1.00	4.63	21.79	103.90
CF11b	whole rock	INAA		1.1	5.0		
CF17bAW	whole rock	ID	2.48	3.44	6.02	91.65	165.81
CF17b	whole rock	INAA		3.5	6.7		

After acid washing for 45 minutes with a mixture of 50 °C 6N HCl and 7N HNO<sub>3</sub>, the value increased to 19.8, similar to that of other samples from the Ajui-Solapa complex. The Sr and Nd isotopic ratios for the unwashed and acid washed splits of CF5 are within the  $\pm 0.000025$  reproducibility of the other samples in table 2. In conclu-

sion, the anomalously low Pb and high O and C isotope ratios for P58 and the leaching results for sample CF5 suggest that the carbonate in samples P58 and CF5 have a surficial origin (i.e. is secondary) or re-equilibrated with fluids derived either from MORB-like oceanic crust or from sedimentary carbonate.

The Sr, Nd and Pb isotope ratios for the carbonatites with mantle O and C isotopic compositions fall within the field formed by the other rocks in the basal complex (Figs 1–4). The isotopic similarity between the carbonatites, ijolites, syenites, fenites and nephelinites is consistent with these rocks being genetically related. The Ajui-Solapa and the Esquinzo complexes have similar ranges in Nd and Pb isotope ratios, but the Esquinzo complex has slightly higher Sr isotope ratios overall.

The subaerial volcanic samples (< 21 Ma) analyzed in this study have initial  $^{87}\text{Sr}/^{86}\text{Sr} = 0.70299$ –0.70325,  $^{143}\text{Nd}/^{144}\text{Nd} = 0.51290$ –0.51298, and initial  $^{206}\text{Pb}/^{204}\text{Pb} = 19.10$ –19.50. Compared to the basal complex, the younger basalts have lower Sr and Pb but higher Nd isotope ratios, and are shifted towards mid-ocean ridge basalt (MORB) field in the isotope correlation diagrams (Figs 1–4). If we combine our data with those of SUN (1980; see Fig. 2), the Pliocene-Recent (< 4.5 Ma) volcanics are shifted towards the least radiogenic Pb, whereas the Miocene (12–21 Ma) volcanics have Pb isotopic ratios which completely overlap both the basal complex and the Pliocene-Recent basalt

fields. In summary, the isotopic composition of the volcanics on Fuerteventura are shifted towards DM (or MORB) with decreasing age.

Similar to what has been observed on the neighboring islands of Gran Canaria (HOERNLE et al., 1991) and Lanzarote (ARMIENTI et al., 1990), the more  $\text{SiO}_2$ -saturated compositions from both the basal complex and the subaerial volcanics are shifted to lower Nd isotope ratios. Interestingly, the Fuerteventura data fall below the Northern Hemisphere Reference Line (NHRL; HART, 1984) in the  $^{207}\text{Pb}/^{204}\text{Pb}$  versus  $^{206}\text{Pb}/^{204}\text{Pb}$  isotope correlation diagram, but the data lie above the NHRL in the  $^{208}\text{Pb}/^{204}\text{Pb}$  versus  $^{206}\text{Pb}/^{204}\text{Pb}$  diagram (Fig. 2).

#### Identification of mantle sources for Fuerteventura magmas

If we use the endmembers proposed by ZINDLER and HART (1986) and WÖRNER et al. (1986), then the basal complex has a composition between the HIMU and EM endmembers, whereas the subaerial volcanics are shifted towards the DM end-

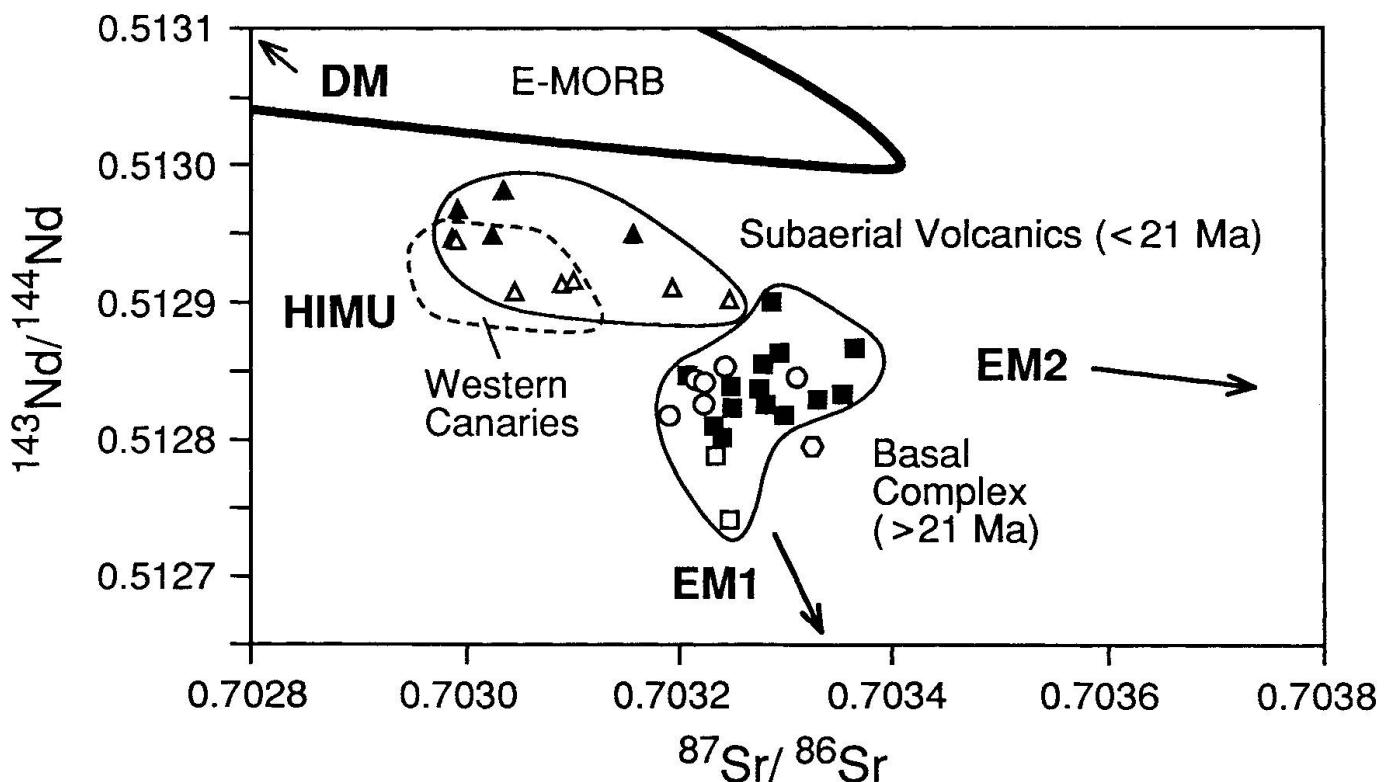


Fig. 1 Nd-Sr isotope ratio correlation diagram for Fuerteventura volcanic and plutonic rocks. Basal complex (> 21 Ma): Solid square =  $\text{SiO}_2$ -undersaturated silicate samples; open square = tholeiitic gabbros; open circles = carbonatites. Subaerial volcanics (< 21 Ma): solid triangle =  $\text{SiO}_2$ -undersaturated sample (basanite); open triangle = more  $\text{SiO}_2$ -saturated sample (alkali basalt, tholeiite and hawaiite). Hexagon designates initial ratios for the Oka carbonatite from BELL and BLENKINSOP (1987). Field for the westernmost Canary Islands (La Palma and Hierro) is from HOERNLE et al. (1991b). E-MORB field designates Atlantic Ocean enriched mid-ocean ridge basalt. DM, HIMU, EM1 and EM2 (see list of abbreviations) are from ZINDLER and HART (1986).

member (Figs 1-4). The simplest model for explaining these isotopic variations involves the mixing of two heterogeneous components. Accordingly, the basal complex plutonics would reflect the composition of the plume; and the sub-aerial basalts would reflect interaction of the plume with DM-like lithosphere/asthenosphere, after the volcano (island) has moved away from

the plume (for example, CHEN and FREY, 1983, 1985; WYLLIE, 1988). Comparison of the Fuerteventura data with data from other Canary Islands, however, suggests that this model is too simple.

Based on the east to west age progression and the abundant historic activity as recent as 1971, SCHMINCKE (1982) proposes that the Canary

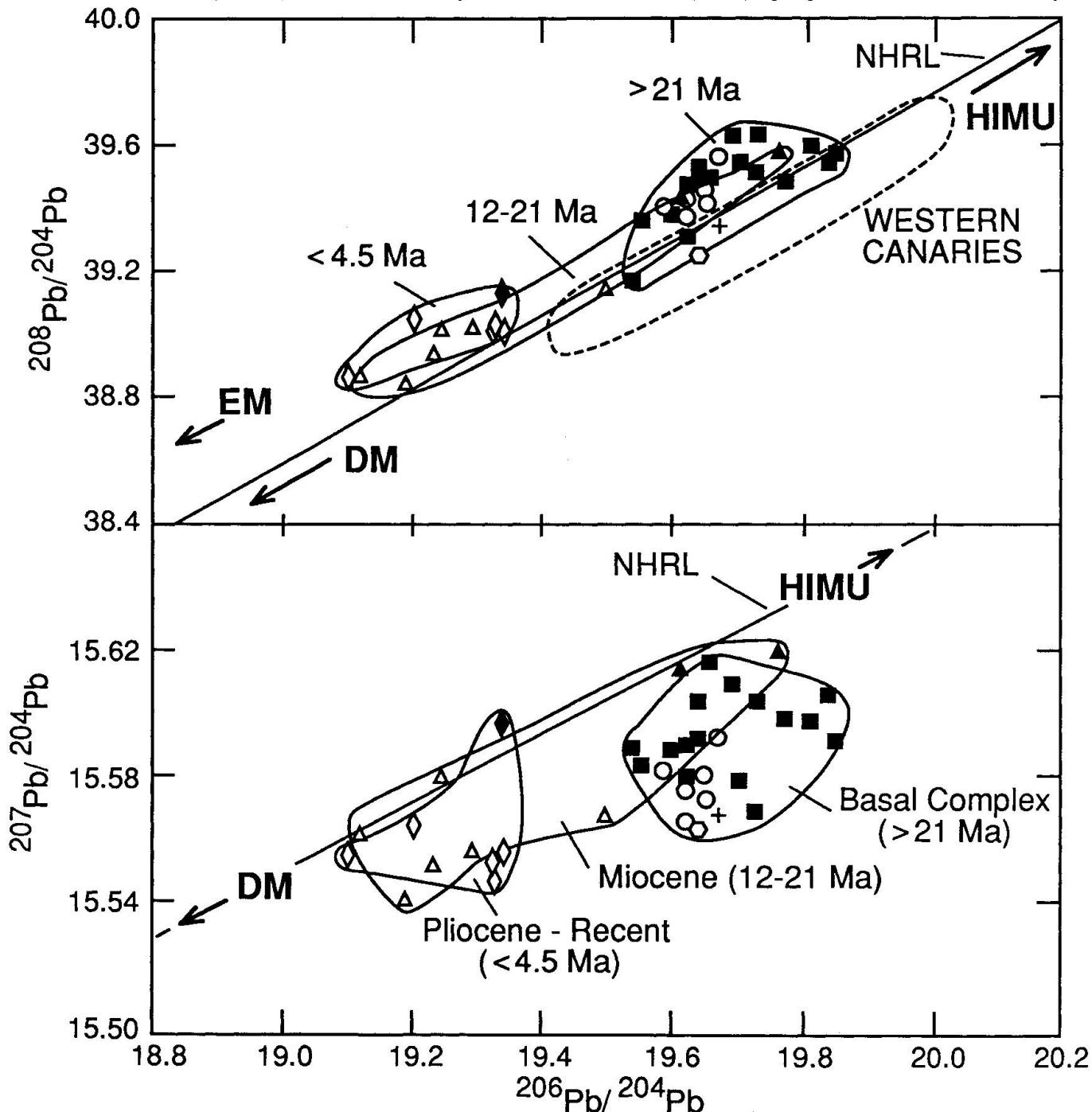


Fig. 2 Pb isotope correlation diagrams for Fuerteventura volcanic and plutonic rocks. Basal complex (> 21 Ma): solid squares = silicate sample; open circles = carbonatite. Miocene volcanics (12-21 Ma): open triangle = this study; solid triangle = SUN (1980). Pliocene-Recent basalts (< 4.5 Ma): open diamond = this study; solid diamond = SUN (1980). NHRL = northern hemisphere reference line of HART (1984). Field for the westernmost Canary Islands (La Palma and Hierro) is from HOERNLE et al. (1991b). Oka Pb data from GRÜNENFELDER et al. (1986). Cross designates carbonatite sample P62 from LANCELOT and ALLÈGRE (1974).

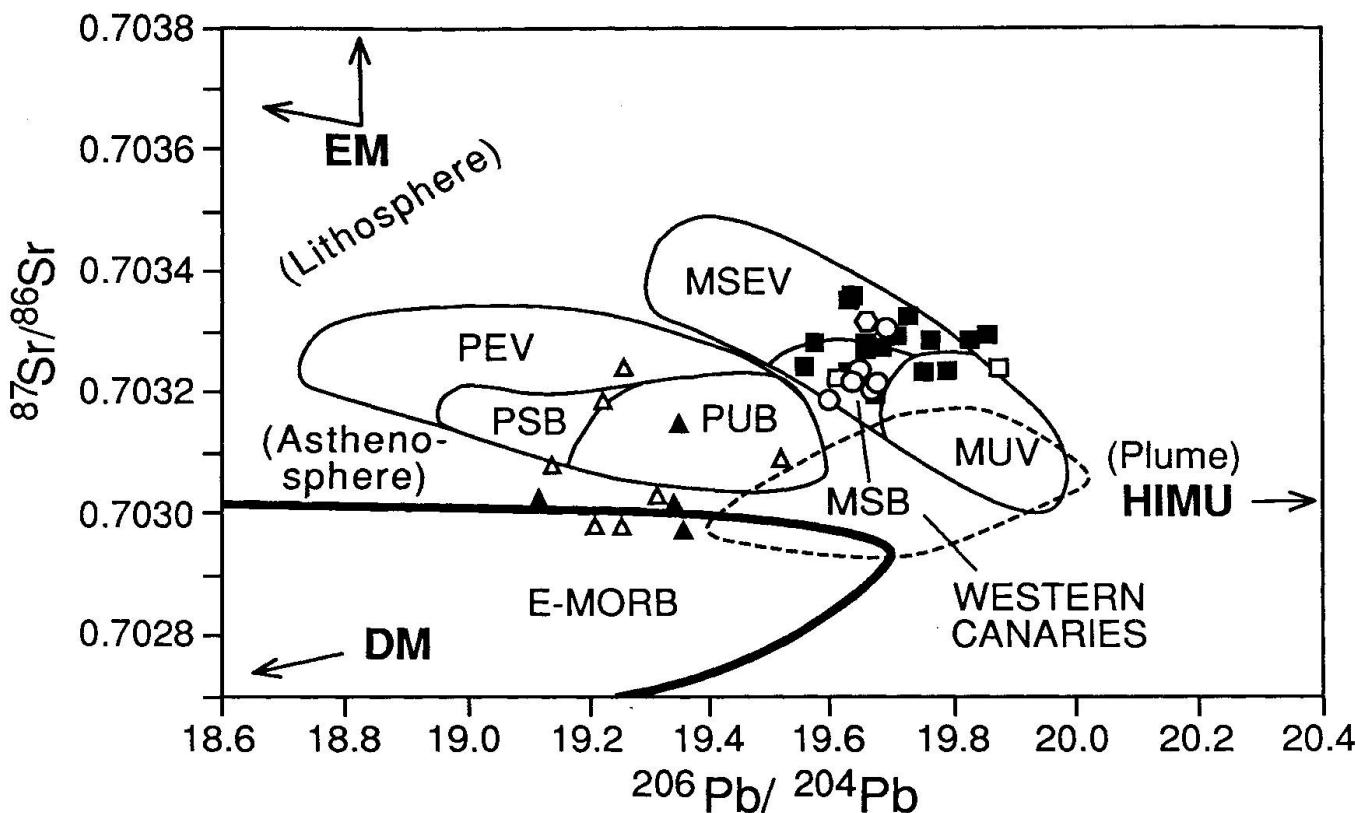


Fig. 3 Sr-Pb isotope ratio correlation diagram for Fuerteventura, Gran Canaria, Hierro and La Palma volcanic and plutonic rocks. Abbreviations for fields of Gran Canaria data from COUSENS et al. (1990) and HOERNLE et al. (1991a): MUV = Miocene undersaturated volcanics (nephelinites and trachyphonolites); MSB = Miocene saturated basalt (alkali basalts and tholeiites with MG#  $\geq$  62); MSEV = Miocene saturated evolved volcanics (alkali basalts-tholeiites through peralkaline rhyolites with MG#  $<$  62); PUB = Pliocene-Recent undersaturated basalt ( $\text{SiO}_2$   $<$  44; MG#  $\geq$  62); PSB = Pliocene-Recent saturated basalt ( $\text{SiO}_2$   $>$  44; MG#  $>$  62); PEV = Pliocene-Recent evolved volcanics (alkali basalt-basanite through trachyte-phonolite with MG#  $<$  62). Also shown are possible compositions for the lithosphere and asthenosphere beneath the eastern Canary Islands and for the Canary plume. See figure 1 for symbols and additional abbreviations and references not given above.

Plume is presently situated beneath La Palma, one of the two westernmost islands. Holocene activity on each of the other islands, except Gomera, may result from the spreading of plume material through the upper asthenosphere beneath the older islands (HOERNLE and SCHMINCKE, 1991). Compared to the Pliocene to Recent data from the eastern islands of Gran Canaria, Fuerteventura and Lanzarote, the volcanics from the westernmost islands of La Palma and Hierro have a very restricted range in isotopic composition, especially in Sr and Nd isotope ratios (see Figs 1-4) (SUN, 1980; COUSENS et al., 1990; ARMIENTI et al., 1990; HOERNLE et al., 1991 a, b). The data for the western islands is consistent with the Pliocene-Recent Canary Plume having a HIMU-like composition (HOERNLE et al., 1991b). The trend towards DM on the Pb isotope correlation diagrams (see Fig. 2) of these more oceanic islands is interpreted to reflect interaction of the plume melts (HIMU) with small-degree melts from the lithosphere/asthenosphere (DM), as

proposed for Hawaii (CHEN and FREY, 1983, 1985; FEIGENSON, 1986; WYLLIE, 1988).

The variation in the isotope data from the Miocene volcanics on Gran Canaria suggest that the Miocene Canary Plume also had a HIMU-like composition (HOERNLE et al., 1991a). The most  $\text{SiO}_2$ -undersaturated Miocene volcanics, nephelinites and trachyphonolites, have the lowest Sr and highest Pb isotope ratios and have the most HIMU-like compositions (Fig. 3). The more saturated volcanic suite (alkali basalt-tholeiite through peralkaline rhyolite) is shifted towards more radiogenic Sr and less radiogenic Pb isotopes and has more EM-like compositions. Based on mineralogical evidence that these volcanics cooled and fractionated in the mantle and on the absence of evidence for sediment contamination in the  $^{207}\text{Pb}/^{204}\text{Pb}$  ratios (SUN, 1980; COUSENS et al., 1990), HOERNLE et al. (1991a) propose that the more saturated volcanics assimilated enriched (EM-like) lithospheric mantle. The interpretation implies a HIMU-like composition for the Mio-

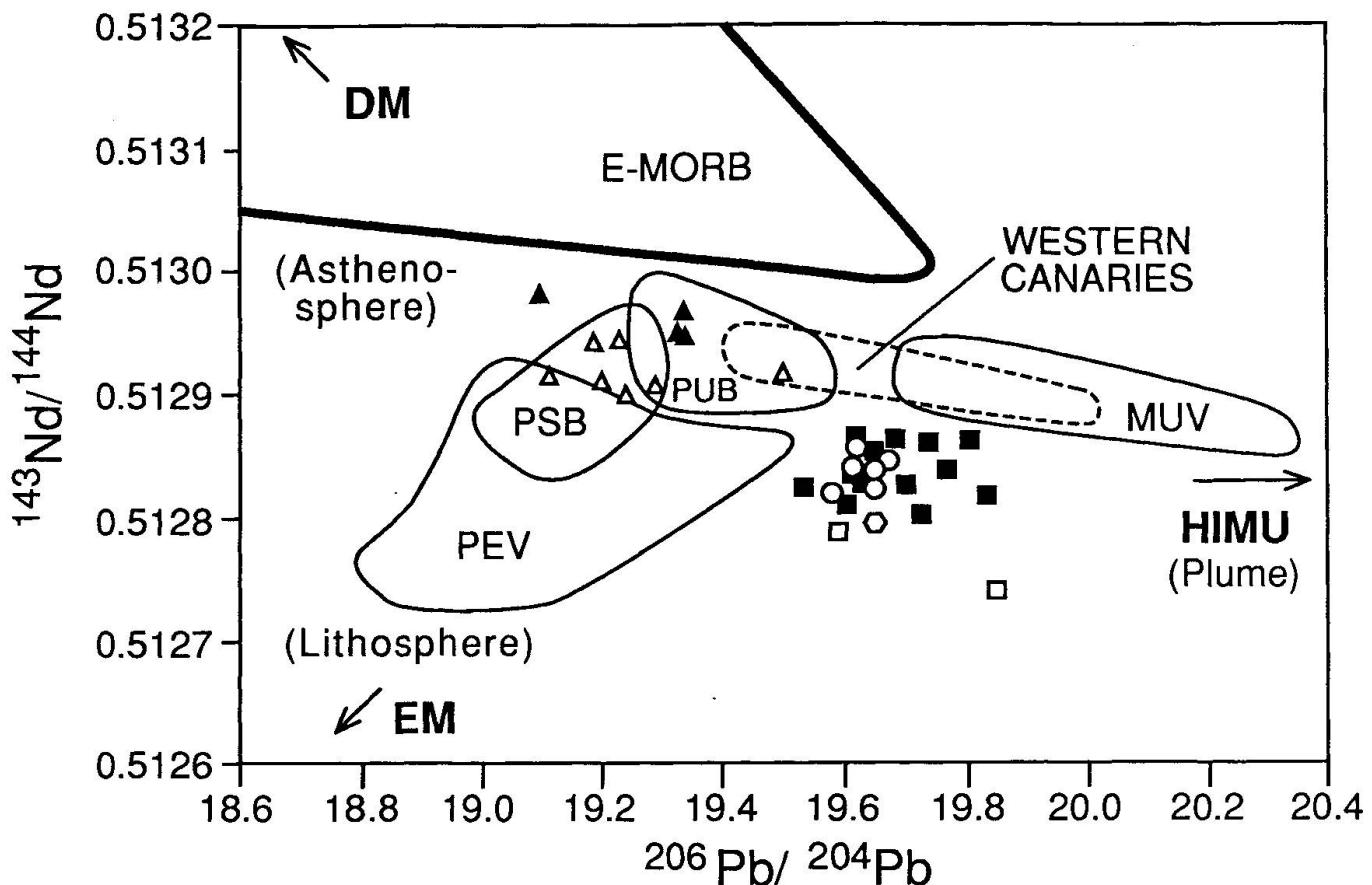


Fig. 4 Nd-Pb isotope correlation diagram for Fuerteventura, Gran Canaria, Hierro and La Palma volcanic and plutonic rocks. Abbreviations, symbols and references are the same as in figure 3.

cene Canary plume. The enriched material in the lithospheric mantle beneath Gran Canaria may be recycled continental lithospheric mantle from beneath the West African Craton (1.8–3.4 Ga), which was thermally eroded or delaminated during rifting of Pangaea. Chemical and thermal equilibrium of the plumbing system wall rocks beneath Gran Canaria could explain why the younger, more undersaturated Miocene magmas experienced less lithospheric contamination than the older, more saturated magmas.

Compared to the undersaturated Miocene volcanics on Gran Canaria and to all the volcanics on the westernmost islands, the basal complex plutonics on Fuerteventura have higher  $^{87}\text{Sr}/^{86}\text{Sr}$  and  $^{208}\text{Pb}/^{204}\text{Pb}$  ratios (at a given  $^{206}\text{Pb}/^{204}\text{Pb}$  ratio) but lower  $^{143}\text{Nd}/^{144}\text{Nd}$  ratios and are shifted towards enriched mantle (Figs 1–4). In figure 3, they have compositions similar to the saturated Miocene volcanics. Two possible explanations for these isotopic differences are the following: (1) the isotopic composition of the plume was different in pre-Miocene than in Miocene-Recent Epochs; or (2) melts from the pre-Miocene plume, which had a similar composition to the Miocene-Recent plume, interacted with enriched material in the lithospheric mantle beneath Fuerteventura. Two

arguments favor the second hypothesis. First, since Fuerteventura is between Gran Canaria and West Africa, one might also expect to find recycled continental lithospheric mantle beneath Fuerteventura, if it is beneath Gran Canaria. Second, on the Nd-Pb isotope correlation diagram (Fig. 4), the two tholeiitic gabbros from the basal complex have the lowest Nd isotope ratios and are shifted towards enriched (EM1-like) mantle in relation to the more undersaturated volcanics (Fig. 1). For these reasons, we propose that the basal complex magmas originated from a HIMU-like plume but assimilated enriched lithospheric mantle as they ascended through the lithosphere. This interpretation implies a plume origin for the Fuerteventura carbonatites, providing some of the most direct evidence to date that at least some carbonatites are plume derived.

The subaerial volcanics have similar Sr and Nd but generally lower Pb isotope ratios than the undersaturated Miocene volcanics and the volcanics from the western islands (Figs 1–4). At a given  $^{206}\text{Pb}/^{204}\text{Pb}$  ratio, however, they have higher  $^{208}\text{Pb}/^{204}\text{Pb}$  than the western islands, suggesting the presence of enriched mantle in these volcanics (Fig. 2). On the Sr-Pb and Nd-Pb isotope correlation diagrams (Figs 3 and 4), the subaerial volca-

nics are shifted towards a composition between depleted and enriched mantle (just above the field for E-MORB) and overlap the fields for the Pliocene-Recent basalts on Gran Canaria. During the Miocene-Recent on Fuerteventura and the Pliocene-Recent on Gran Canaria, the plume was presumably situated to the west of each island. The plume material that reached these islands had to travel diagonally or horizontally through the upper asthenosphere from the plume to the base of the lithosphere beneath the islands. Therefore, interaction between plume material/melts with upper asthenospheric material/melts is our preferred explanation for the shift towards a composition between the DM and EM end-members of the Miocene-Recent volcanics on Fuerteventura and the Pliocene-Recent volcanics on Gran Canaria (HOERNLE et al., 1991a). This interpretation implies that the upper asthenosphere, at least beneath the eastern Canary Islands, contains some enriched mantle, which is also possibly recycled West African continental lithospheric mantle. The more saturated subaerial volcanics have lower Nd isotopic compositions and are shifted towards enriched (EM-like) mantle (Figs 1 and 4). Variations with degree of  $\text{SiO}_2$ -saturation have also been observed in the basal complex plutonics, the Miocene and Pliocene-Recent basalts on Gran Canaria (COUSENS et al., 1990; HOERNLE et al., 1991a) and the Miocene-Recent basalts on Lanzarote (ARMIENTI et al., 1990). These differences are consistent with the interaction of the more  $\text{SiO}_2$ -saturated basalts from each of the eastern islands with enriched lithospheric mantle beneath these islands.

### Comparison with other young carbonatites

Detailed discussion of isotope relationships in young carbonatites is beyond the scope of this study. Here we briefly compare the Fuerteventura data with four other carbonatites – Cape Verde Islands, < 7 Ma (GERLACH et al., 1988); Oka, 110 Ma (GRÜNENFELDER et al., 1986; BELL and BLENKINSOP, 1987); Kaiserstuhl, 18 Ma (NELSON et al., 1987); and Magnet Cove, 97 Ma (TILTON et al., 1987). The tectonic setting of the Cape Verde carbonatites most closely resembles that at Fuerteventura. GERLACH et al. (1988) present Sr and Nd isotope data for four carbonatites and a microsövite from two islands, Fogo and São Vicente. The  $^{143}\text{Nd}/^{144}\text{Nd}$  ratios are ca. 0.51297 for Fogo and 0.51292 for São Vicente, with  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios ranging between 0.70312 to 0.70360. Assuming that the higher Sr ratios represent contamination, a reasonable value for the São

Vicente carbonatite initial ratios is  $^{87}\text{Sr}/^{86}\text{Sr} = 0.70312$  and  $^{143}\text{Nd}/^{144}\text{Nd} = 0.51292$ , which fall within the HIMU field of ZINDLER and HART (1986). A HIMU composition for the Cape Verde carbonatites is consistent with a plume origin, as has been suggested by GERLACH et al. (1988). The single Pb isotope analysis for a carbonatite from the Cape Verde Islands (LANCELLOT and ALLÈGRE, 1974) is from a different island (Brava) than the Sr and Nd isotope analysis, hence cannot be used for comparison with those data.

The Oka initial Pb, Sr and Nd ratios plot within or close to the basal complex fields shown in figures 1–4. The Kaiserstuhl und Magnet Cove ratios (not shown) are displaced from the basal complex fields towards EM, with Magnet Cove being more displaced than Kaiserstuhl. In a general sense, one can say that the Oka-Kaiserstuhl-Magnet Cove trend resembles that seen in the Fuerteventura volcanics, and that the variations could thus indicate varying degrees of interaction between asthenospheric plume and lithospheric components, as suggested in KWON et al. (1989). Based on the HIMU-like composition of many continental carbonatites, NELSON et al. (1988) have also proposed an asthenospheric mantle plume origin for carbonatites. It is interesting, and possibly significant that the Oka carbonatite, which formed in a rift tectonic environment, has Pb, Sr and Nd isotope ratios almost identical to those in the Fuerteventura carbonatite, which formed in a hot spot tectonic environment.

### Conclusions

The Fuerteventura volcanic and plutonic rocks analyzed in this study define two separate fields in isotope correlation diagrams. The older basal complex rocks (> 21 Ma) fall between HIMU and EM endmembers. The younger subaerial basalts (< 21 Ma) are shifted towards DM. We propose that the Fuerteventura magmas originated in a mantle plume in the asthenosphere but interacted with the lithosphere and/or asthenosphere as they ascended to the surface. The basal complex magmas, which were emplaced when Fuerteventura was above the plume, reflect mixing between plume material (HIMU) and lithospheric mantle (EM  $\pm$  DM). The Miocene-Recent subaerial volcanics were formed when the plume was beneath the more westerly islands. Studies of the more westerly islands (HOERNLE et al., 1991 a, b) indicate that the Canary Plume probably had a HIMU-like composition from the Miocene to Recent. Compared to the proposed Miocene-Recent plume composition, the subaerial volcanics on Fuerteventura are shifted

towards compositions between the DM and EM endmembers in isotope correlation diagrams. This shift may reflect contamination of plume material or melt as it was transported through the upper asthenosphere from the plume to the base of the lithosphere beneath Fuerteventura. The isotope patterns on Fuerteventura resemble the more completely defined trends from the neighboring island of Gran Canaria.

Pb, Sr and Nd isotope ratios from the associated syenites, ijolites, fenites, nephelinites, basanite-nepheline benmoreite, alkali gabbros and sōvitic carbonatites in the basal complex are similar, suggesting a close genetic relationship between all rock types. This study provides some of the most direct evidence to date for a plume origin of at least some carbonatites.

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## Appendix 1

Stratigraphic position, brief petrographic descriptions and locations of samples (more detailed petrographic descriptions, and XRF and INAA data from these samples will be presented in HOERNLE and LE BAS, 1991).

### *I. Basal complex*

#### *Pre-Ajui-Solapa Complex*

F2 Tierra Mala alkali gabbro pluton north of Pajera (see STILLMAN, 1987).

#### *Ajui-Solapa (Ijolite-Syenite-Carbonatite) Complex*

CF6 12 cm thick, coarse albitite fenite. Punta de la Nao (10°28'00" W, 28°23'00" N).

CF7 35 cm thick, coarse orthoclase-albitite fenite, 10 m from CF6.

CF9 20 cm thick, coarse orthoclase fenite cutting CF7.

F/75/148 Apatite-titanite coarse calcite carbonatite. Cliff face of Punta de la Nao.

F/75/153 Coarse calcite carbonatite with scattered crystals of albite. Cliff face of Punta de la Nao.

F/75/158 Coarse calcite carbonatite. Punta de la Nao.

F/75/165 Coarse calcite carbonatite intruding albitite. Punta de la Nao.

#### *Post-Ajui-Solapa Complex*

CF5 Nephelinite dike, with secondary calcite, cuts fenites and carbonatites. Punta de la Nao.

LFU75/203 Tholeiitic (orthopyroxene-bearing) gabbro pluton (PX1) near Mesquer (see LE BAS et al., 1986).

*Pre-Esquinzo Complex*

CF10b Aphanitic nephelinite dike trending E-W. In surf zone, 100 m from mouth of Barranco de Esquinzo (10°20'00" W, 28°37'30" N).  
 CF11b Aphanitic nephelinite dike trending E-W. 5 m from CF10b.

*Esquinzo (Ijolite-Syenite-Carbonatite) Complex*

CF10 10 cm thick, coarse albitite fenite trending N-S. Cuts CF10b.  
 CF12 25 cm thick, coarse ijolite dike which cuts fenites. On cliff face, 100 m south from mouth of Barranco de Esquinzo.  
 CF1 Coarse ijolite from pluton (?) heavily intrudes by mafic to intermediate dikes. 25 m below small dam in Barranco de Esquinzo (10°18'00" W, 28°36'30" N). See BARRERA et al. (1981) for detailed description of this locality.  
 CF2 Coarse syenite. 2 m from CF1 but separated by two mafic dikes.  
 CF3 Coarse ijolite from same or associated intrusive body as CF1 and CF2. Body is heavily intruded by mafic to intermediate dikes. Sample taken from bottom of Barranco de Esquinzo, 0.5 km downstream from CF1 and CF2.  
 CF4 Coarse ijolite. 50 cm from CF3.  
 68/SC/72 Coarse calcite carbonatite. Esquinzo.  
 68/SC/73 Coarse calcite carbonatite. Esquinzo.

*Post-Esquinzo Complex*

CF15 50 cm thick, nepheline benmoreite dike which cuts CF1 and CF2 pluton(s).  
 CF16 1 m thick, carbonate-rich, aphanitic tephrite dike which cuts CF15.  
 CF17 1 m thick, clinopyroxene basanite (with rare olivine) which cuts CF16.  
 F122 Tholeiitic (orthopyroxene-bearing) gabbro pluton (PX2) (see STILLMAN, 1987).

*II. Subaerial volcanics**Basaltic series I (Miocene)*

KFS46 Allkali basalt lava flow. West wall of Montaña Aceitunal (10°16'30" W, 28°32'15" N). Aceitunal lavas are stratigraphically beneath flows dated at 11.8 Ma (sample FV30; ABDEL-MONEM et al., 1971).  
 KFS53 Olivine-phyric alkali basalt lava flow. Same location as KFS46.  
 KFS54 Alkali basalt lava flow. East wall of Montaña Aceitunal.  
 KFS55 Hawaite lava flow. Same location as KFS54.  
 KFS34a Plagioclase-phyric hawaite dike. South wall of Montaña Fortaleza.  
 KFS140 Alkali basalt lava flow. Barranco de Jarubio (10°19'00" W, 28°33'45" N). Same unit as dated at 11.8 Ma (FV30; ABDEL-MONEM et al., 1971).

*Basaltic series II (Pliocene)*

KFS110 Basanite lava flow. Barranco de los Molinos (10°21'30" W, 28°18'00" N). Dated at 4.25 Ma (FV18; ABDEL-MONEM et al., 1971).

*Basaltic series III (Quaternary)*

KFS69 Tholeiite lava flow. On beach, east of La Oliva, near Tarajalito.

*Basaltic series IV (Subrecent)*

KFS96 Basanite lava flow. West side of Montaña Quemada (10°18'00" W, 28°33'45" N).  
 KFS240 Basanite lava flow. Caldera de Gairia (10°19'30" W, 28°21'00" N).  
 KFS82 Basanite lava flow. NW of La Oliva, about 25 km west of Pozo Negro.