

# Cretaceous Alkaline Magmatism in Algarve Littoral (South Portugal): a Basanite–Lamprophyre Rock Suite

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**ABSTRACT.** The Cretaceous alkaline magmatism in Algarve Littoral is represented by a basanite–lamprophyre rock suite predominantly occurring west of Algarve, geographically associated with the Serra de Monchique. This rock suite is characterized by the simultaneous occurrence of brown salitic and green fassaitic clinopyroxene cores, showing different optical and chemical characteristics than those corresponding to the host rock. The same phenomenon is also observed on amphibole cores. Both the pyroxenes and amphiboles show inverse zoning. The compositional diversity of the mineral assemblage is attributed to a variable magma mixing process, acting in a polycyclic magmatic chamber, where recharge, residence time and extraction parameters control the mineralogical transition from basanites to lamprophyres. The Algarve Littoral alkaline magmatism is correlated geographically, chronologically, geochemically and petrogenetically with the Monchique subvolcanic massif. The Algarve Littoral basanite–lamprophyre rock suite is considered as a precursor of the Monchique magmatism. These alkaline, basic and undersaturated melts of mantle origin, showing no evidence of crustal contamination, isotopically depleted and simultaneously enriched in high incompatible trace elements, were derived from an asthenospheric component probably rising as a result of a plume effect and subjected to a previous metasomatic event.

**KEY WORDS:** alkaline magmatism, basanite, lamprophyre, clinopyroxene chemistry, Portugal, Monchique, Algarve Littoral.

## Introduction

Since the 19th century (Blum 1861), the igneous body topographically corresponding to the Serra de Monchique, located in Algarve (South Portugal), has drawn attention of the geological scientific community. The previous works, among which Ribeiro dos Santos (1973) and Rock (1978) constitute essential references, focused on the main Monchique massif and only reported the Algarve Littoral occurrences. This work comprises a petrographic, mineralogical, geochemical and petrogenetic characteristics of the Cretaceous alkaline magmatism in Algarve Littoral. Particularly, a petrogenetic model for the exotic mineralogical assemblage and a cogenetic relation to the subvolcanic alkaline massif of Monchique are proposed.

## Geological setting

The alkaline magmatism in Algarve Littoral is mainly represented by a basanite–lamprophyre rock suite that intruded Late Jurassic limestones and rarely the scarce and discontinuous Early Cretaceous sedimentary rocks.

This magmatism is represented by numerous and multiple igneous bodies: dykes, sills, domes, small flows and breccias. The latter are related to fault zones and occur (predominantly) in the eastern part of the Algarve Littoral (orientated E–W). The other types (although scattered from E to W) occur predominantly to the west of Algarve, being geographically associated with Serra de Monchique, the topographic expression of the subvolcanic alkaline complex of Monchique (Fig. 1).

The Monchique alkaline massif, located in southern Portugal, is an E–W elongated body, emplaced into Carboniferous pelites overlying the Hercynian basement of the Iberian Peninsula. The massif is lithologically characterized by chemically, mineralogically and texturally different rocks, by the presence of breccias, schlieren, basic segregations, dykes of tinguaites, lamprophyres and dykes of foyaitic rocks, which represent the dominant lithotype of the massif (Ribeiro dos Santos 1973; Rock 1978). The emplacement age of this massif is well constrained to  $72 \pm 2$  Ma by several whole rock K–Ar and Rb–Sr

data (Mendes 1968; Rock 1976; McIntyre and Berger 1982; Bernard-Griffiths et al. 1997).

The Algarve Littoral basanite–lamprophyre rock suite, in spite of being external to the main massif, is geographically, geochemically and chronologically ( $72 \pm 2$  to  $75 \pm 2$  Ma; Martins, 1991) related to the Monchique alkaline complex; thus, it must be considered an integral part of this complex.

Besides the Monchique alkaline massif and the Algarve Littoral basanite–lamprophyre rock suite the Portuguese Late Cretaceous alkaline magmatism comprises the correlative Sintra massif (75–90 Ma; Mendes 1968; Storetved et al. 1987) and Sines massif (72–75 Ma; Canilho and Abranches 1982; Storetved et al. 1987) and the Lisbon Volcanic complex (72–75 Ma; Ferreira and Macedo 1979; Storetved et al. 1987).

The emplacement of these alkaline magmas is linked with the conjunctural process of the North Atlantic opening and rotation of the Iberian Peninsula. The latter process paleomagnetically constrained to 70–90 Ma (Galdeano et al. 1989; Platzman and Lowrie 1992) closely confines the emplacement time of the three massifs. Related dykes striking NNW–SSE were subsequently emplaced using a deep fracture zone in the crust as a pathway for mantle-derived magma ascent (Terrinha and Kullberg 1998).

The Portuguese Late Cretaceous alkaline magmatism is part of the Iberian to central European alkaline mega-province of Late Cretaceous to Palaeocene–Oligocene age, extending from the Western point, Portugal, to the Eastern Bohemian Massif (Oyarzun et al. 1997; Wilson and Downes 1991).

## Samples and analytical techniques

An extensive and exhaustive sampling from West to East Algarve Littoral led to the collection of a sample set ( $n = 70$ ), which allowed a complete view of the subject and careful sample selection.

All the occurrences produced fresh rock samples, only the fault-associated breccias display a high degree of alteration. Whole rock samples were crushed and then powdered in agate mill.

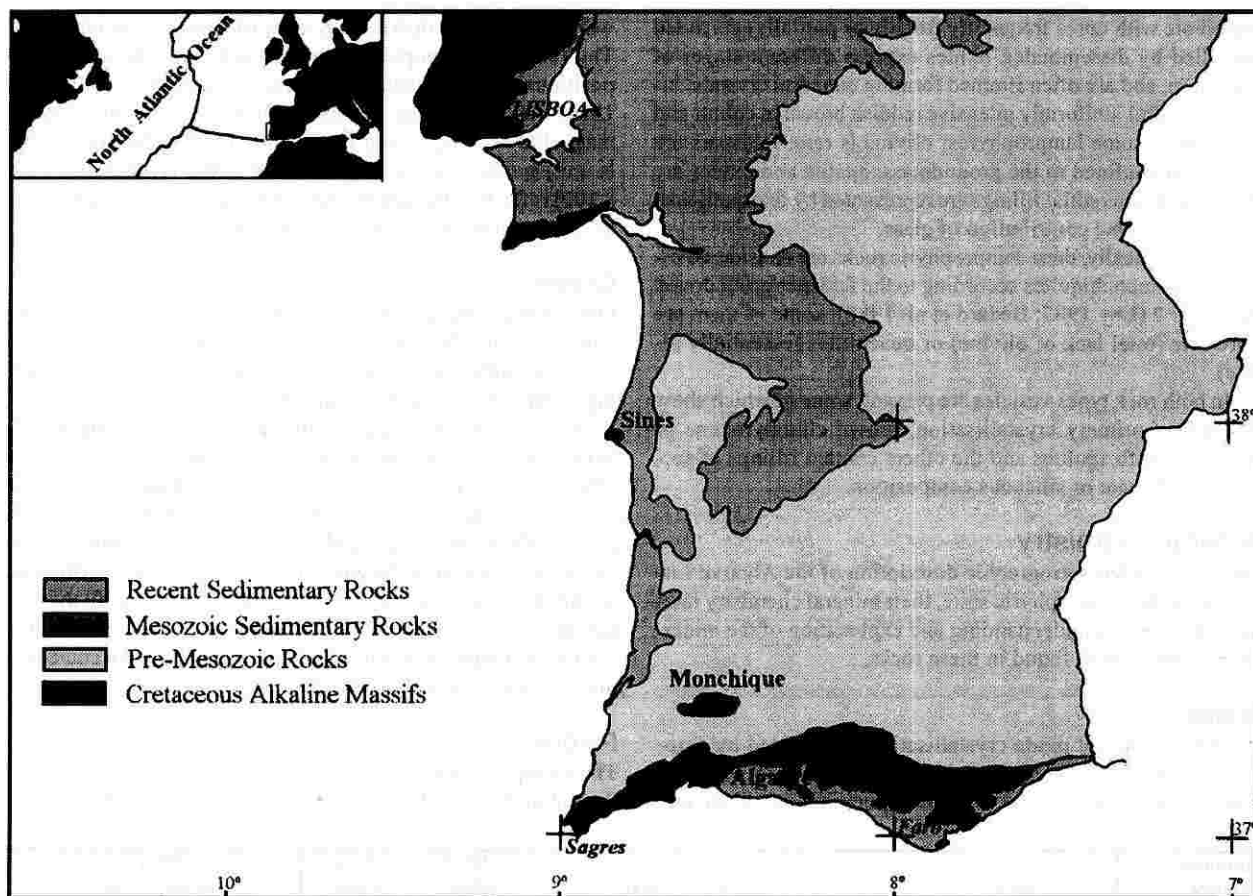


Fig. 1. A simplified geological sketch showing the location of Algarve Littoral in South Portugal and in North Atlantic area. Adapted from Mendes (1968).

Except for gravimetrically analysed  $\text{SiO}_2$  content, concentrations of major elements were determined by atomic absorption spectrometry. Total iron is reported as  $\text{Fe}_2\text{O}_3$ .

Trace elements Sc, V, Cr, Ni, Rb, Sr, Y, Zr, Nb and Ba, Ti and P were determined by XRF.

This work was performed in the Rock Analysis Laboratory at the Geological Department of the University of Lisbon. The analytical precision, better than 10% and 5% for major and trace elements, respectively, was controlled using international reference samples such as: BHVO-1, JB-1, W-1, MRG-1, BR, AGV-1.

Analyses of REE (La, Ce, Nd, Sm, Eu, Tb, Lu), Cs, Th and Hf were performed by Nuclear Activation Services Limited, Canada.

Isotopic data: Sr analyses were carried out by Prof. Cecilia Abranches at Leeds University; whole rock K-Ar ages were determined by Prof. Regencio Macedo, after the methodology described by Macedo et al. (1977), by the Laboratory of Geochronology of the Earth Sciences Department at Coimbra University.

Mineral analyses were performed under the supervision of Prof. José Munhá, Microprobe Laboratory of the Centro de Geologia, University of Lisbon, using homogeneous minerals as reference samples (Si – wollastonite and olivine; Ca – wollastonite; Ti and Na – kaersutite; Ti – ilmenite; Al – kyanite; Fe and Mg – olivine; Mn – rhodonite; K – adularia) and pure synthetic metals (Cr, V and Ni). The analytical precision was better than 2% for major elements.

## Petrography

Petrographically this rock suite ranges from basanites to lamprophyres; indeed, among all studied samples only a few of them correspond to a different lithology (limburgites, ankaramites, a tephrite and a trachyte found in the eastern part of Algarve Littoral, Fig. 1). In this context, the Algarve alkaline magmatic province is considered to be a representative of basanitic to lamprophyric suites.

The basanites have aphanitic to (mostly) porphyritic textures. Their mineral assemblage is characterized by an initial phase of oxide precipitation (included in olivine and clinopyroxene cores) followed by a continuous silicate crystallization episode; olivine is a common mineral also forming zoned phenocrysts; the clinopyroxene group, showing spectacular optical characteristics, occurs in the form of markedly zoned phenocrysts with brown and green cores genetically either associated or not associated with the parental rock; the green phenocrysts expressing either resorption or euhedral shape with sector zoning, both core types are light brown followed by a euhedral dark brown rim similar or equal to microphenocrysts and groundmass clinopyroxenes in composition; feldspar group, mainly plagioclase in composition, is confined to groundmass; apatite and interstitial feldspar–feldspathoidal mesostasis represent the final crystallisation products.

The lamprophyres are markedly porphyritic, characterized by the coexistence of brown and green clinopyroxene cores, similar to those known from basanites; however, green cores may contain inclusions of apatite and oxides; abundant red brown

amphibole with cores frequently (totally or partially) corroded and filled by disseminated oxides express different stages of resorption, and are often rimmed forming euhedral crystals; biotite is euhedral, uniformly intensive reddish brown in colour and abundant in some lamprophyres; olivine is rare; feldspars are scarce and confined to the groundmass; apatite and oxides are also present; interstitial fillings are represented by feldspathoids, zeolites and some contribution of glass.

Systematically, these lamprophyric rocks are considered essentially as monchiquites according to the feldspar/groundmass ratio of 1: 2 (Eby 1987; Bédard et al. 1988); some of them are fourchites (total lack of olivine) or ouachitites (essentially biotite).

In both rock types vesicles are present, some of which show products of primary crystallisation, brown clinopyroxene or amphibole with zeolites and the others contain fillings of secondary carbonate or siliceous composition.

### Mineral chemistry

After the detailed petrographic description of the Algarve Littoral basanite-lamprophyric suite, their mineral chemistry is an important tool for understanding and explanation of the mineralogical association found in these rocks.

### Oxides

The initial phase of oxide crystallisation represented by chromian ( $\text{Cr}_2\text{O}_3 = 23.71$  wt.%) and aluminian ( $\text{Al}_2\text{O}_3 = 38.41$  wt.%) spinels was limited by the intensive precipitation of olivine,

which controls Cr distribution in silicate liquids (Munhá 1982; Thy 1983), and clinopyroxene which is responsible for the compositional zoning of spinels in basaltic liquids (Hill and Roeder 1974). After this stage, the oxide phase corresponds to titanomagnetite with increasing Ti contents (1 to 6 cations per formula unit) and decreasing #Mg of 40–10 [#Mg =  $(\text{Mg} / \text{Mg} + \text{Fe}^{2+}) \times 100$ ] reflecting the compositional evolution of the melt during the crystallisation of clinopyroxene rims/groundmass.

### Olivine

Olivine is an abundant mineral in basanites, and shows compositions varying between  $\text{Fo}_{85-78}$ ,  $\text{Fo}_{80-69}$  and  $\text{Fo}_{76-59}$  in phenocrysts, microphenocrysts and groundmass, respectively, according to the liquid evolution (Martins 1991).

Olivines, when zoned, usually show normal zoning ( $\text{Fo}_{85-68}$  from core to rim) but some examples of inverse zoning were also observed (e.g.,  $\text{Fo}_{82-87}$  from core to rim). Although the inverse zoning of olivine can be explained by several hypotheses (Khon et al. 1989; Schwindinger and Anderson 1989), in this case it is explained by the simultaneous precipitation of olivine rims and abundant titanomagnetite (as observed in thin section); the titanomagnetite is selective for FeO, promoting the decrease of the FeO/MgO liquid ratio, which, in turn, controls the Fo content in olivine (Roeder and Emslie 1970).

### Pyroxenes

The clinopyroxenes are by far the most important, not only by their abundance and diversity but (mainly) because their chem-

Samples Crystals Site	R1-26			Phenocryst 1			R1-7 Mph 3	R1-4 Grdm 3	R1-1** Phenocryst 1		
	core	mantle	rim	core*	mantle	rim			core*	core	rim
$\text{SiO}_2$ (wt%)	45.62	46.57	45.35	44.29	48.31	46.15	48.05	45.32	43.06	44.37	47.37
$\text{TiO}_2$	2.61	2.52	3.75	2.57	2.18	2.96	2.27	3.02	2.13	2.75	2.22
$\text{Al}_2\text{O}_3$	7.67	7.99	8.18	9.21	6.09	7.18	5.83	6.98	9.27	8.04	5.34
$\text{Cr}_2\text{O}_3$	0.00	0.46	0.00	0.00	0.35	0.02	0.06	0.02	0.01	0.00	0.00
$\text{Fe}_2\text{O}_3$	4.33	1.48	1.85	10.65	1.97	1.63	2.36	4012	9.73	6.54	2.26
FeO	4.60	4.76	5.01	2.24	4.17	5.55	4.54	3.87	5.39	4.37	5.56
MnO	0.11	0.03	0.12	0.31	0.03	0.10	0.15	0.11	0.47	0.22	0.14
MgO	11.05	12.93	11.72	8.36	13.71	12.40	12.52	11.74	7.14	9.39	12.10
CaO	22.10	22.53	22.61	21.34	22.86	22.29	22.83	22.65	21.43	22.65	22.92
$\text{Na}_2\text{O}$	0.90	0.27	0.55	2.26	0.39	0.33	0.66	0.63	1.58	1.11	0.40
$\text{K}_2\text{O}$	0.00	0.00	0.02	0.00	0.00	0.00	0.06	0.02	0.01	0.01	0.05
Total	98.99	99.54	99.17	101.23	100.06	98.61	99.33	98.48	100.23	99.46	98.36
Si	1.726	1.736	1.707	1.657	1.788	1.745	1.799	1.722	1.648	1.689	1.801
Al (IV)	0.274	0.264	0.293	0.343	0.212	0.255	0.201	0.278	0.352	0.311	0.199
Al (VI)	0.068	0.087	0.070	0.063	0.054	0.064	0.056	0.034	0.066	0.049	0.040
Ti	0.074	0.071	0.106	0.072	0.061	0.084	0.064	0.086	0.061	0.079	0.063
Cr	0.000	0.014	0.000	0.000	0.010	0.001	0.002	0.001	0.000	0.000	0.000
$\text{Fe}^{3+}$	0.123	0.041	0.053	0.300	0.055	0.046	0.06	0.118	0.280	0.187	0.065
$\text{Fe}^{2+}$	0.146	0.148	0.158	0.070	0.129	0.176	0.142	0.123	0.173	0.139	0.177
Mn	0.004	0.001	0.004	0.010	0.001	0.003	0.005	0.004	0.015	0.007	0.005
Mg	0.623	0.718	0.657	0.466	0.756	0.699	0.699	0.665	0.407	0.533	0.686
Ca	0.896	0.900	0.912	0.855	0.906	0.903	0.916	0.922	0.879	0.924	0.933
Na	0.066	0.020	0.040	0.164	0.028	0.024	0.048	0.046	0.117	0.082	0.029
K	0.000	0.000	0.001	0.000	0.000	0.000	0.003	0.001	0.000	0.000	0.002
Wo	50.00	49.78	51.12	50.26	49.05	49.42	50.11	50.33	50.12	51.62	50.00
En	34.77	39.71	36.83	27.40	40.93	38.26	38.24	36.30	23.20	29.78	36.76
Fs	15.23	10.51	12.05	22.34	10.02	12.32	11.65	13.37	26.68	18.60	13.24

**Table 1.** Representative microprobe analyses of clinopyroxenes. Formula unit calculated on basis of 6 oxygens and 4 cations (Morimoto et al. 1988). Samples R1-26, R1-4 and R1-7 are basanites; R1-21 is a lamprophyre. Mph – microphenocryst; Gdm – groundmass; \* – green fassaitic cores; \*\* – core with salitic and fassaitic zones showing variable resorption. Wo, En, Fs, molecular proportions of wollastonite, enstatite and ferrosilite.

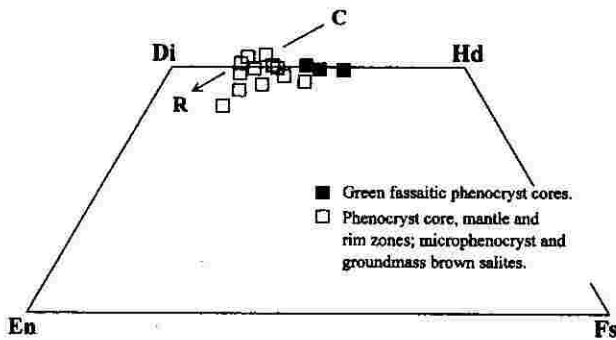


Fig. 2. Clinopyroxenes of Algarve Littoral basanite-lamprophyre rock suite. Their compositional field in the Wo-En-Fs system. Arrow indicates the evolution trend from core (C) to rim (R).

istry reflects the petrogenetic history of the host rock (Le Bas 1962).

Chemically these clinopyroxenes correspond to salites (Fig. 2) with a significant "non-quad" (Tab. I) component as is characteristic of alkaline undersaturated rocks (Carmichael et al. 1974; Duda and Schmincke 1985; Bédard et al. 1988) where the low silica activity allows for the Al enrichment of the Ca-clinopyroxenes.

Groundmass clinopyroxenes and microphenocrysts are similar and correspond to brown coloured salites (50Wo:36En:14Fs) and (52Wo:34En:14Fs), respectively, for basanites and (50Wo:37En:13Fs) and (49Wo:37En:14Fs) for lamprophyres. On the contrary, phenocrysts display a spectacular and complex chemical zoning reflecting the observed optical characteristics. In fact, the brown core phenocrysts are salites while green cores are fassaitic salites, always mantled and rimmed by clinopyroxene of salitic composition. Mantle and rim zones are more primitive (higher Mg and Cr) than cores and similar to microphenocrysts and groundmass clinopyroxenes (Fig. 2), suggesting common crystallisation conditions and a normal evolution of the melt. However, a different composition separates salitic and fassaitic cores expressing the lower  $Ti/Al_{(tot)} \sim 1/8$  and the higher  $Fe^{3+}$  (0.1–0.25), # Fe (0.2–0.3), Na (0.05–0.15) of the fassaitic cores relatively to salitic (Figs. 3 and 4).

So, the green core clinopyroxenes represent an inverse zoning. These distinctive characteristics associated with the different projection fields in the diagrams of Aoki and Shiba (1973) and Wass (1979), Fig. 5, clearly show that the crystallising conditions were very different for the two clinopyroxene cores, suggesting that although coexisting in the same host rock these nuclei cannot be cogenetic.

**Amphibole and biotite**

These two minerals are present mainly in the lamprophyres. The amphibole, kaersutitic in composition, has been frequently totally or partially absorbed giving rise to cores filled with disseminated oxides, expressing different resorption features, in contrast with the euhedral rims. Inverse zoning occurs with the mantle zone being more primitive (higher Mg and  $Fe^{2+}$ ) – Fig. 6.

Like the coexisting green core clinopyroxenes, the instability characteristics of the amphibole cores suggest their crystallisation from magma different from that represented by the host rock chemistry.

Biotites are always euhedral with a uniform phlogopitic composition (61–67Phl).

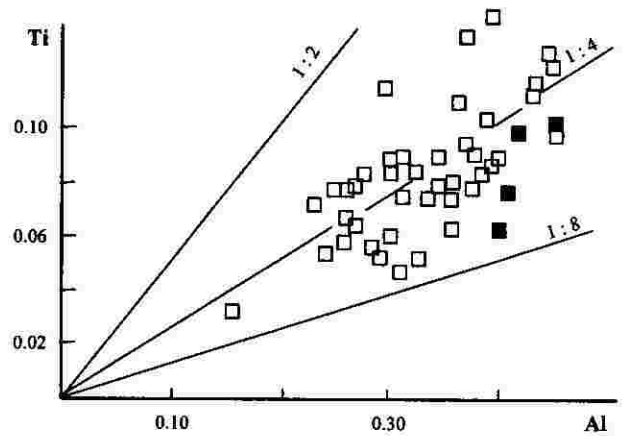


Fig. 3. Variation in Ti/Al (tot) ratio in clinopyroxenes. Symbols as in Fig. 2.

**Feldspars**

These minerals are restricted mainly to the groundmass of basanites and show a compositional range from plagioclase ( $An_{10-70}$ ) to interstitial potassic feldspar ( $Or_{40-97}$ ). The appearance of this late potassic feldspar, after nepheline (some nepheline crystals are rimmed by potassic feldspar), is attributed to the previous crystallisation of amphibole, biotite and nepheline, which leads to the silica enrichment of the residual liquid.

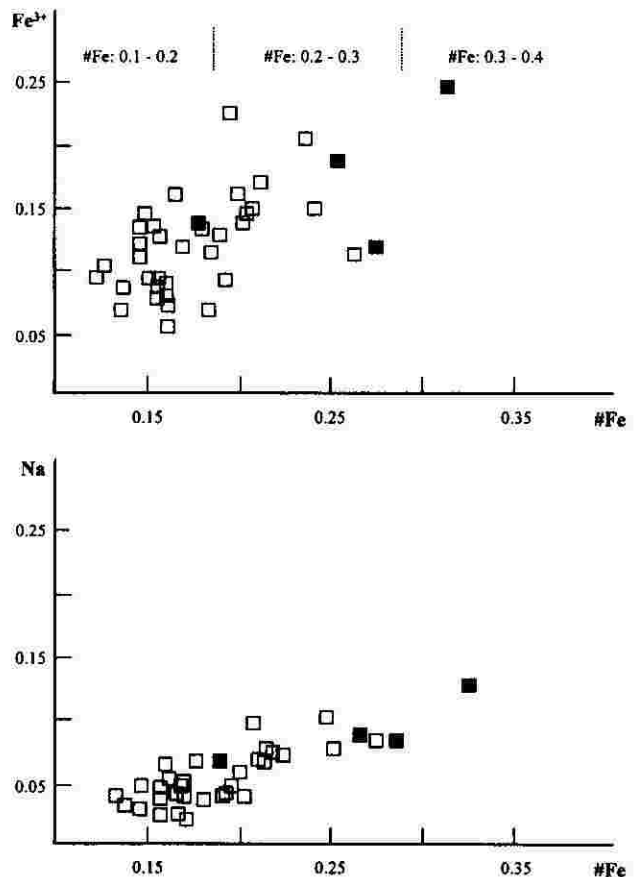


Fig. 4. Compositional variation of  $Fe^{3+}$  and Na in clinopyroxenes with its fractionation index, # Fe =  $Fe^{2+}/Fe^{2+} + Mg$ . Symbols as in Fig. 2.



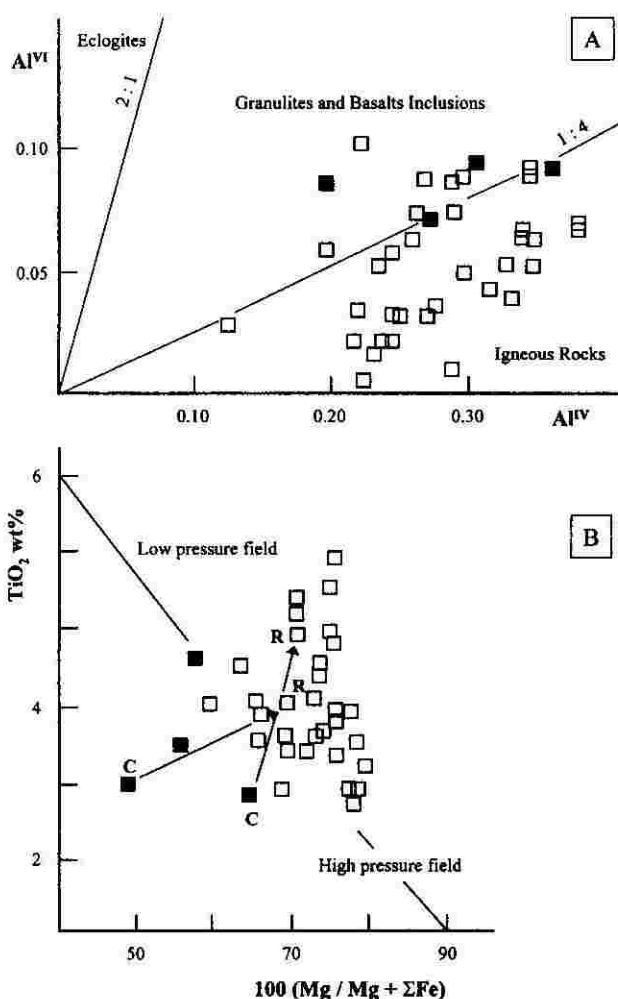


Fig. 5. Aoki and Shiba (1973) – A and Wass (1979) – B diagrams expressing clinopyroxene crystallisation conditions. Symbols as in Fig. 2.

Whole rock geochemistry

The mineralogical features that allow establishment of the Algarve Littoral basanite–lamprophyre rock suite express an alkaline, basic and undersaturated whole rock chemistry (Fig. 7); lamprophyric rocks represent volatile-enriched basanite rock

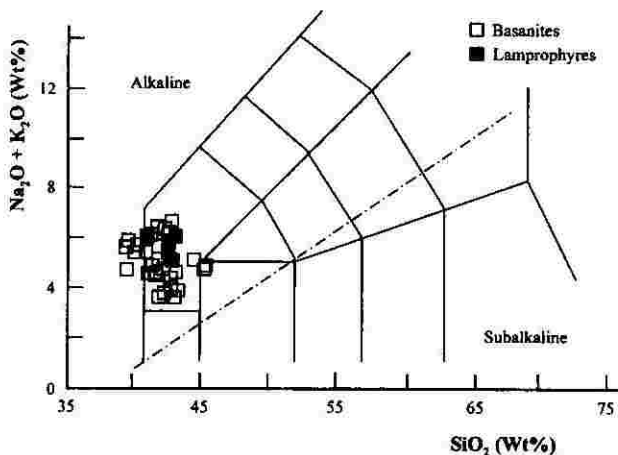


Fig. 7. TAS diagram for the Algarve Littoral rock suite, illustrating the overlap of basanites and lamprophyres in their composition (Le Bas et al. 1986).

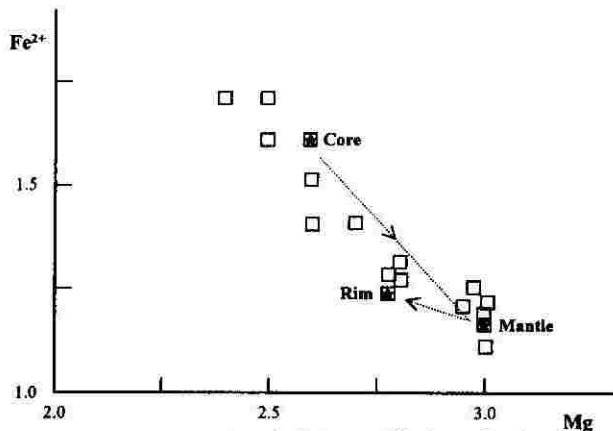


Fig. 6. Substitution of Mg/Fe<sup>2+</sup> in amphiboles reflecting inverse zoning.

magmas (Table 2) and overlap the narrow compositional range of the basanitic liquids.

Basanitic rocks correspond to more primitive liquids #Mg: 68–70; MgO: 12–13 wt.%; Ni: 210–344 ppm; Cr: 350–600 ppm relative to lamprophyres: #Mg: 47–63; MgO: 6–9 wt.%; Ni: 21–97 ppm; Cr: 20–154 ppm. Compositional grading between them is observed both in chemistry and mineralogy.

The similar geochemical behaviour of this basanite–lamprophyre suite is reflected by the REE (Fig. 8) and incompatible trace element (Fig. 9) patterns.

The corresponding profiles express an enrichment character in LREE, and in highly incompatible trace elements, corroborated by the mean values of the following ratios: (La/Yb)<sub>N</sub>: 25.50 and 23.82; Ti/Zr: 71.97 and 69.59; Zr/Nb: 3.16 and 2.81; Rb/Sr: 0.029 and 0.046; La/Ba: 0.125 and 0.064; La/Nb: 0.87 and 0.89 for basanites and lamprophyres, respectively.

With the exception of the enrichment of rocks in incompatible trace elements, their patterns do not show any signs of crustal contamination, i.e., no negative anomalies in Nb, P and Ti were observed. This lack of crustal “fingerprint” is confirmed by the low values of initial Sr isotope ratios (<sup>87</sup>Sr/<sup>86</sup>Sr)<sub>0</sub>: 0.70276–0.70385 (Martins 1991).

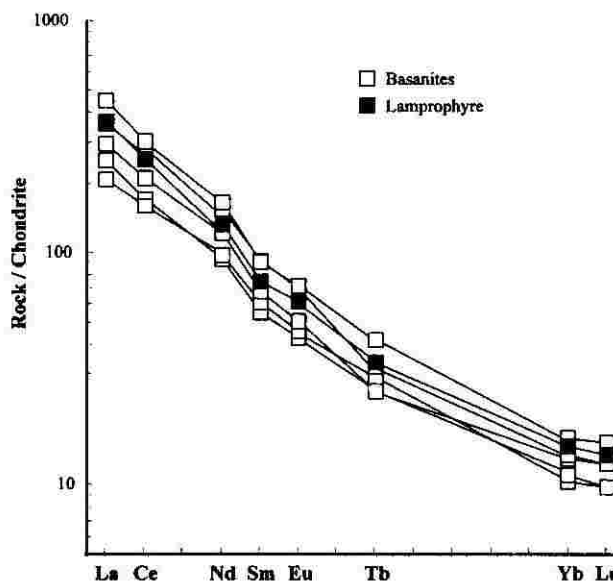


Fig. 8. Representative chondrite-normalized (after McDonough and Sun 1995) REE patterns for the Algarve Littoral rock suite.

As the geochemical patterns express petrogenetic properties of the corresponding melts (Thompson et al. 1984), the inferred properties are attributed to mantle source, reflecting an Sr-isotopically depleted mantle and simultaneously enriched in highly incompatible elements (Ba, Th, Nb, La). These contradictory characteristics have been attributed (Lloyd and Bailey 1975; Bailey 1987) to an enrichment by metasomatism that shortly preceded melt extraction from the mantle. An asthenospheric mantle plume may provide the explanation for the geochemical characteristics of the Algarve Littoral basanite–lamprophyre rock suite (Martins and Munhá 1993).

As it has been initially pointed out the Algarve Littoral Cretaceous magmatic activity is linked to the Monchique alkaline complex. This connection is also evident from their geochemical features, as confirmed by the similarity of the incompatible trace element patterns (Fig. 10) and Sr-isotope ratios (Table 3), suggesting a “consanguinity” between these products of Late Cretaceous magmatism in Algarve (South Portugal).

**Discussion and conclusions**

The most important characteristic of the Algarve Littoral basanite–lamprophyre rock suite is the petrogenetic history expressed

by its mineralogy, particularly by the clinopyroxene petrography and chemistry:

- \* basanites with only brown salitic clinopyroxene;
- \* basanites where brown salitic and the green fassaitic cores coexist, both of them mantled by a more primitive light brown salite and subsequently rimmed by dark brown salite similar to microphenocrysts and groundmass clinopyroxenes in composition;
- \* basanites where, besides the two clinopyroxenes, kaersutitic amphibole is present;
- \* lamprophyres where again the two types of clinopyroxene cores are present but only the fassaitic ones possess apatite and oxide inclusions and amphibole cores show obvious aspects of their disequilibrium with the host rock liquid, expressing a transition between basanites and lamprophyres.

The distinct chemical and physical features of the coexisting clinopyroxene cores clearly point to their non-cogenetic character; fassaitic cores represent more evolved clinopyroxenes crystallising at relatively higher pressure conditions and from a more evolved magma than the salitic cores. These cores crystallized from different liquids were connected with a more primi-

Samples	R1-30	R1-53	R1-36	R1-25	R1-1	R1-4	R1-7	607-3	R1-9*	R1-1*	R1-5*	R1-8*
SiO <sub>2</sub> wt%	41.72	42.79	38.89	40.86	40.32	40.93	40.61	40.03	40.68	40.47	41.59	41.77
TiO <sub>2</sub>	3.11	2.47	3.01	3.49	3.27	3.27	3.34	4.69	3.30	3.16	3.61	4.27
Al <sub>2</sub> O <sub>3</sub>	15.68	12.32	14.85	14.83	13.03	14.83	15.68	12.74	14.36	14.83	12.09	12.75
Fe <sub>2</sub> O <sub>3</sub>	11.87	12.15	12.44	11.65	13.08	12.08	9.87	12.58	11.15	11.87	13.44	13.16
MnO	0.20	0.19	0.21	0.17	0.15	0.18	0.13	0.20	0.15	0.22	0.19	0.18
MgO	6.79	12.67	7.88	9.53	9.25	9.11	9.78	8.12	7.62	5.55	8.65	7.95
CaO	11.06	12.04	13.20	11.55	12.71	10.15	12.04	13.15	8.46	11.06	11.26	10.77
Na <sub>2</sub> O	4.58	3.03	4.04	2.56	3.77	4.31	4.04	3.30	2.51	3.91	3.50	3.64
K <sub>2</sub> O	1.99	1.66	2.20	1.45	1.25	1.63	0.72	2.10	2.65	2.23	2.05	1.74
P <sub>2</sub> O <sub>5</sub>	1.12	0.72	1.38	0.61	0.61	0.76	0.96	1.09	0.82	1.09	0.87	0.90
LOI	2.37	1.19	1.51	3.61	3.52	3.23	1.89	1.85	6.89	5.90	2.87	3.25
Total	100.49	101.23	99.61	100.31	100.96	100.48	99.06	99.85	98.59	100.29	100.12	100.38
#Mg	56.82	70.57	59.30	65.29	61.93	63.43	69.50	59.75	61.12	51.82	59.68	58.15
Sc (ppm)	19	25	19	29	24	22	22	29	19	16	24	22
V	259	250	268	318	269	260	276	338	237	251	273	270
Cr	37	533	65	186	151	102	97	104	41	20	104	154
Ni	49	210	53	124	91	87	84	79	38	21	79	97
Rb	56	46	30	35	28	20	34	27	62	72	49	44
Sr	1355	825	1424	835	1178	1443	1445	1510	1376	1639	1079	942
Y	35	25	33	27	28	24	25	33	29	33	31	31
Zr	350	233	335	197	261	285	289	362	272	355	289	272
Nb	120	69	117	63	77	106	102	91	96	141	102	95
Ba	777	614	745	484	426	665	680	607	1344	1015	608	570
Th	9.90	6.50		4.70	7.11	8.90		8.10	8.30			
Hf	7.60	5.40		5.00	6.40	6.50		7.60	7.30			
La	160.00	59.00		49.00	69.00	90.00		84.00	86.00			
Ce	184.00	103.00		97.00	128.00	15.00		161.00	153.00			
Nd	75.00	42.00		44.00	55.00	76.00		70.00	60.00			
Sm	13.40	8.06		8.91	9.92	12.00		13.50	11.00			
Eu	3.98	2.37		2.55	2.82	3.27		3.92	3.43			
Tb	1.50	0.90		1.00	0.90	1.40		1.10	1.20			
Yb	2.54	1.76		1.66	2.08	1.55		2.14	2.36			
Lu	0.37	0.24		0.24	0.30	0.23		0.30	0.33			
<sup>87</sup> Sr/ <sup>86</sup> Sr	0.70301 ±0.00005		0.70283 ±0.00004	0.70390 ±0.00004			0.70292 ±0.00005					

**Table 2.** Representative analyses of the Algarve Littoral basanite–lamprophyre rock suite. \* Lamprophyric rocks. Fe<sub>2</sub>O<sub>3</sub> as Fe total. #Mg = 100 (Mg/Mg + Fe<sup>2+</sup>); Fe<sup>3+</sup>/Fe<sup>2+</sup> = 0.15.

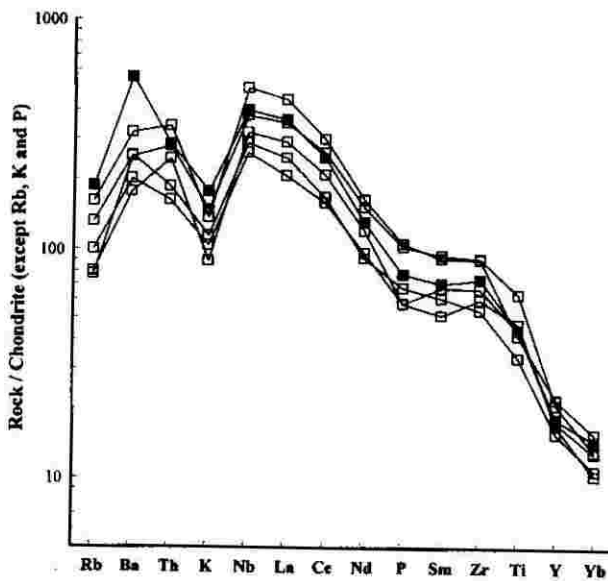


Fig. 9. Representative chondrite-normalized geochemical patterns for the Algarve Littoral rock suite. Normalization values after McDonough and Sun (1995), except for Rb, K and P (PM values after Sun 1982).

tive magma batch and the residual liquid proceeding their normal evolution represented by phenocryst rims, microphenocrysts and groundmass clinopyroxenes. There does not exist any chemical difference between basanite and lamprophyre clinopyroxenes.

The conjugation of salitic and fassaitic cores expresses a complex process of polybaric crystallisation as pointed by Duda and Schmincke (1985) and Bédard et al. (1988) for very similar cases in basanites of West Eifel (Germany) and alkali basalts and lamprophyres of Monteregeian dykes, respectively.

The fassaitic cores represent relics of an early crystallisation episode in the host magma; however, they correspond to a more evolved stage of differentiation, which has been explained by magma mixing process in upper mantle/crust magma chambers (Duda and Schmincke 1985).

For the Algarve Littoral rock suite, Martins and Munhá

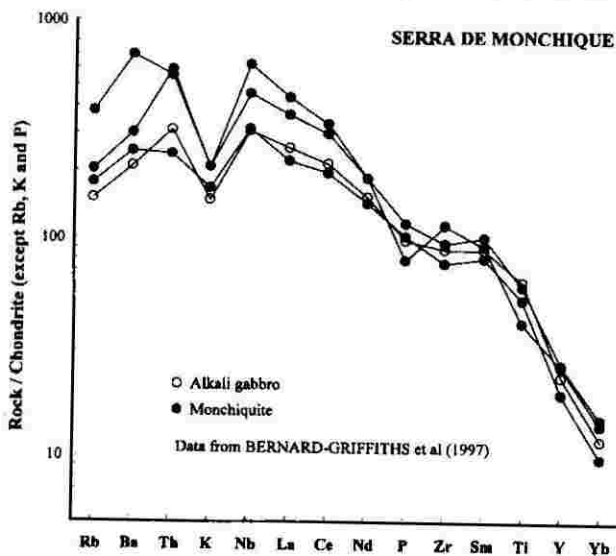


Fig. 10. Representative chondrite-normalized geochemical patterns for Monchique rocks.

Sample	$(^{87}\text{Sr} / ^{86}\text{Sr})_0$
Algarve Littoral basanite (R1-30)	0.70288*
Algarve Littoral basanite (R1-36)	0.70276*
Algarve Littoral basanite (R1-25)	0.70385*
Algarve Littoral basanite (R1-7)	0.70287*
Monchique basic rocks	0.7030 - 0.7044**
Monchique lamprophyric rocks	0.7026 - 0.7035**
Monchique main syenitic rocks	0.7040 - 0.7049**
Serra de Monchique samples	0.7032 ± 1***

Table 3. Sr-isotope ratio values. Initial Sr ratios calculated for: \* – 75 Ma (Martins 1991); \*\* – 72 Ma (Rock 1982); \*\*\* – 72 Ma (Bernard-Griffiths et al. 1997).

(1993) proposed variable degrees of magma mixing, acting in a polycyclic magma chamber, to explain the clinopyroxene compositional diversity.

In this model, the mineralogical assemblage that express the transition from basanites to lamprophyres is a function of variable parameters, such as recharge, residence time and extraction, which control the dynamic evolution of the magma chambers. Consequently, the basanites express a longer residence time, relative to extraction, leading to a total mixing process, whereas the lamprophyres correspond to a partial mixing reflecting an extraction subsequent to the recharge and promoting the coexistence of the corroded and oxide-filled amphibole cores, the more evolved green fassaitic cores with apatite and oxide inclusions showing variable degrees of resorption, and brown salitic cores. Variable degrees of mixing were registered between these two extremes as expressed by the mineralogy of the Algarve Littoral basanite–lamprophyre rock suite.

As concerns the whole rock geochemistry and petrogenesis the most relevant aspect is the genetic correlation between the Algarve Littoral rock suite and the alkaline massif of Serra de Monchique; this implies that the Algarve Littoral rock suite (although external to the main massif), is an integral part of the Monchique alkaline complex and a precursor of the Monchique melts. These alkaline, basic and undersaturated melts were derived from mantle sources, with no crustal influence, and have chemical characteristics (Sr-isotopically depleted and simultaneously enriched in highly incompatible trace elements) that suggest the presence of asthenospheric component, probably ascendant by a plume effect, which was subjected to a metasomatic event that shortly preceded melt extraction.

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