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Autor(en): **Morata, Diego / Puga, Encarnación**

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Aluminium silicate xenocrystals in the "Ophites" of the Subbetic Zone (Southern Spain)

by *Diego Morata*[1] and *Encarnación Puga*[1]

Abstract

In one of numerous basic intrusions in the Triassic Keuper facies of the Betic Cordilleras a picritic dolerite was found. Evidence of gravity accumulation processes could be observed in this outcrop showing rocks which commonly contain crystalline aggregates of corundum + green spinel + highly sericitized plagioclase. These are pseudomorphs after andalusite. The dolerite has a high content of incompatible elements.

The observations suggest a continental setting of the magmatism i.e. metapelites belonging to basement rocks (not found in the outcrops) have been assimilated by the magma.

Keywords: Continental magmatism, dolerites; crustal contamination, Al-rich xenocrystals, Betic Cordilleras, southern Spain.

Introduction

Small subvolcanic bodies of basic rocks, locally known as "ophites", crop out in the Triassic Keuper facies of the External Zones of the Betic Cordilleras (Southern Spain). The first studies carried out on this type of rocks were made by CARCIA-CERVIGON (1973) and GÖLZ (1978) in the eastern zone of the Betic Cordillera, Province of Murcia, and by PUGA and RUIZ-CRUZ (1980) in the central zone of the Betic Cordillera. More recently PUGA (1987), PUGA and DIAZ DE FEDERICO (1988) and PUGA et al. (1989b, 1989c) have provided sufficient analytical results which allow to procede with their petrological and geochemical characterization. The rocks show a tholeiitic-transitional affinity; they have been generated in an intracontinental distensive regime during the late Triassic–early Jurassic. In this article we provide the first data concerning an "ophite" outcrop of picritic dolerite containing Al-rich xenocrystal aggregates. The xenocrystals observed derive from metapelites, and they confirm the continental setting of the magmatism as, throughout the Subbetic Cordillera, indicated by chemical changes due to the assimilation of such rock types. The aim of this paper is to describe these xenocrystals together with the other phases formed during the endomorphic process, and to propose a genetic model.

Geological setting and lithology

The "ophites" are basic subvolcanic rocks which appear mainly as small intrusive bodies in the Triassic Keuper facies of the External Zones of the Betic Cordilleras (Southern Spain) (Fig. 1). The sediments consist principally of multicoloured, more-or-less carbonate bearing clays, containing frequent intercalations of gypsum, carbonate-lutites, ochre and grey carbonates, all of which represent an evaporitic, fluvial-coastal sequence (PEREZ-LOPEZ, 1991).

In the Subbetic Zone the morphology and contacts of the ophite bodies are masked by the effects of severe alteration and fracturing during Alpine tectonic events, which obliterated the primary igneous contacts. The "ophites" occur as stocks, sills and/or dykes of varying sizes, in which

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[1] Instituto Andaluz de Geología Mediterránea y Departamento de Mineralogía y Petrología (CSIC-Universidad de Granada), Avda. Fuentenueva s/n., E-18002 Granada, Spain.

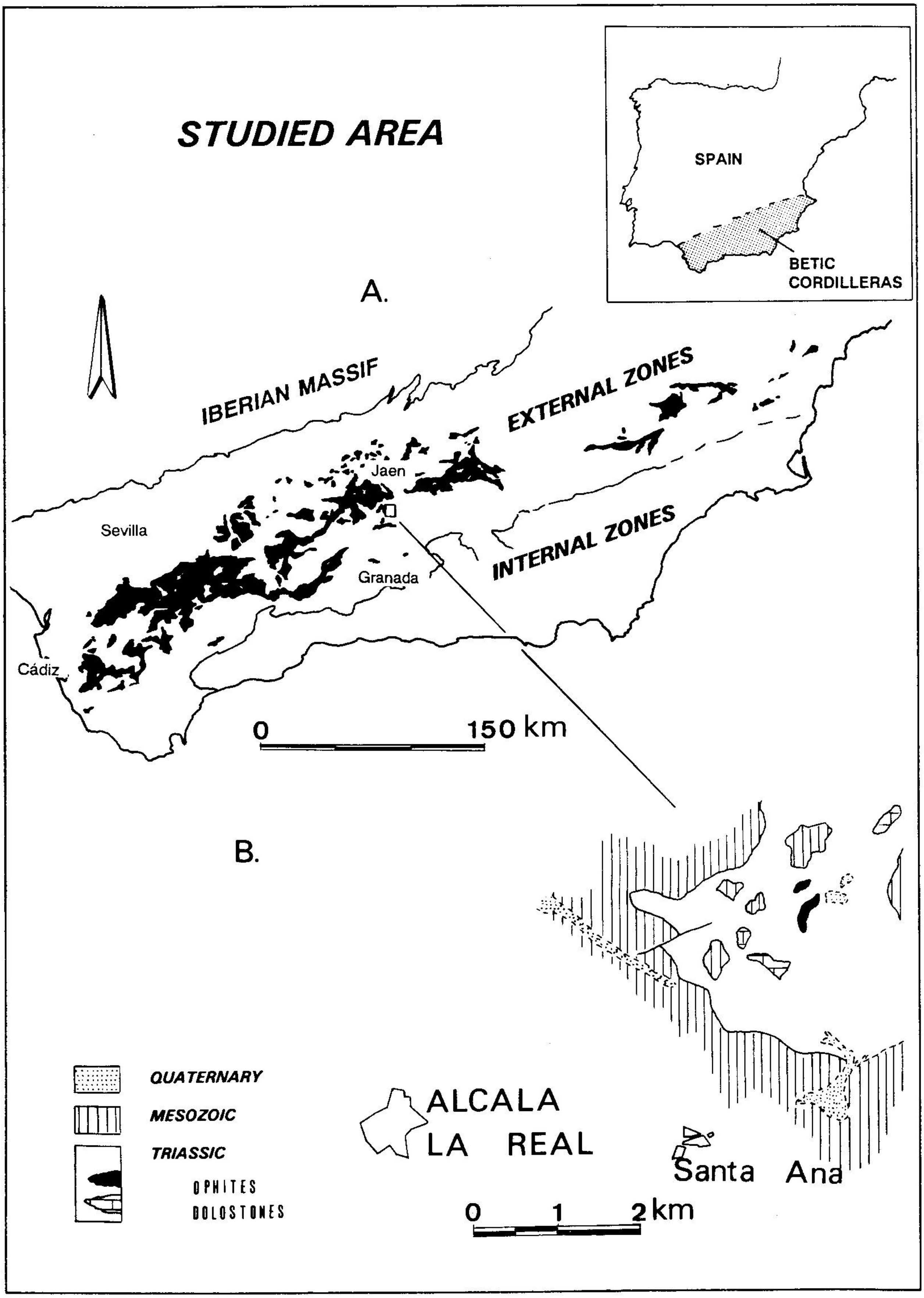

Fig. 1 Geological setting. A) Distribution of the Triassic Keuper facies in the External Zones of the Betic Cordilleras, modified after Lopez-Garrido and Vera (in AZEMA et al., 1979). B) Geological sketch map of the studied area.

the igneous contacts are locally preserved showing chilled margins. In some localities they show flow structures, as a result of magma intrusion into poorly consolidated sedimentary rocks, and locally of extrusion over them (Morata, 1990).

In general the mineralogy of the "ophites" is fairly homogeneous. However compositional and textural differences occur according to the position of the rocks between the border and the central part in each outcrop. These variations are more obvious in the larger bodies, where three facies types can be clearly distinguished:

Border facies: phenocrystals of plagioclase + clinopyroxene + orthopyroxene (+ olivine) within a groundmass which may vary from hypocrystalline to intergranular microcrystalline towards the centre of the body.

Central facies: idiomorphic plagioclase crystals partially surrounded by clinopyroxene, with ophitic or subophitic textures, or else aggregated with intergranular textures. Orthopyroxene crystals are subordinate. Amphibole, biotite and Fe–Ti oxides occur as interstitial phases.

Pegmatoid facies: crystals of more than 1 cm in size of plagioclase, clinopyroxene, amphibole, biotite and Fe–Ti oxides, with an interstitial development of micrographic intergrowths between quartz and sodic plagioclase. These facies appear in the form of decimetric droplet-shaped bodies in the larger outcrops.

Petrology and geochemistry of the dolerites containing xenocrystals

Close to Alcala la Real in Jaen (Fig. 1b) an "ophite" outcrop has been found with a cumulitic texture, composed of a picritic dolerite (after the proposed nomenclature of Le Maitre et al., 1989), with massive appearance and a grain size of less than 2 mm, varying towards the top to an olivine-depleted dolerite. The Al-rich xenocrystal aggregates are only present in the picritic dolerite. This dolerite contains about 45% in volume of cumulitic olivine, Fo$_{76-84}$, with Cr-rich spinel inclusions (Tab. 1). Plagioclase, An$_{55-64}$ and clinopyroxene are present as intercumulus phases (Fig. 2). A Ti-rich amphibole (edenite-kaersutite) and phlogopitic biotite showing very strong pleochroism from reddish-brown to pale-brown crystallized as tardive phases. Ni–Cu–Fe sulfide ores, pyrrhotine-pentlandite-chalcopirite, and magnetite-ilmenite are associated with these phases. In general the ores appear as small aggregates dispersed throughout the picritic dolerite, associated with interstitial amphibole and/or biotite. Table 2 shows selected microprobe analyses of the main igneous minerals.

Tab. 1 Comparison of the modal composition of the picritic dolerite with the central areas and the chilled margins of the "ophites".

Modal compositions			
	Picritic dolerite	Central areas	Chilled margins
Pl	19.5	44.4	67.4
Cpx	8.5	29.3	29.5
Pgt	–	1	–
Opx	–	4.6	3.1
Ol	46.5	–	–
Ores	2.7	3.2	–
Amph	2	3.2	–
Bt	8.5	2.8	
others	14.3	11.5	–

The bulk-rock chemical composition of the picritic dolerite compared to the extreme values of the "ophites" belonging to the border and central facies are shown in table 3. It can be seen that the cumulitic rocks are clearly enriched in MgO, Cr and Ni and depleted in SiO$_2$, Na$_2$O, K$_2$O, Ba, Th, Rb, Y and V, as expected from their differences in mineralogical composition (Tab. 1 and 3).

On the other hand, the relatively high content in Ba, Rb, Th, K and LREE and the high Rb/Sr, Ba/La, Th/La and low Nb/La ratios of the rock composition (Tab. 3), have been generally considered as typical characteristics of continental tholeiites in opposition to MORB chemistry (see Dupuy and Dostal, 1984; Thompson et al., 1984, among others). The high content of some incompatible elements may be interpreted as the result of variable degree of assimilation of continental material by mantle derived magmas during their ascent throughout the continental crust. If we consider a theoretical assimilation model like AFC (De Paolo, 1981), this incompatible element enrichement would be more evident in the most differentiated facies than in the cumulitic one. In our case, with the high contents of incompatible elements (Tab. 3), the chemistry of the dolerites affirms the existence of a crustal contaminant component of metapelitic nature, according to the relics of Al-silicate xenocrystals described in this paper. Other authors (Puga and Diaz de Federico, 1988 and Puga et al., 1989b) have indicated the probable existence of two contaminat types of rocks (granitic and metapelitic) in the magmatic evolution of the other vol-

Tab. 2 Microprobe analyses of representative minerals.

	1	2	3	4	5	6	7	8	9		10	11
SiO_2	39.766	38.722	52.112	54.376	49.308	52.100	46.010	43.510	38.767	**TiO_2**	0.473	0.225
TiO_2	0.017	0.029	0.096	0.136	0.072	1.286	2.870	4.560	4.363	**Al_2O_3**	44.762	63.251
Al_2O_3	0.043	0.004	31.073	29.624	32.729	2.277	8.040	9.820	14.587	**FeO(*)**	18.552	19.433
FeO(*)	14.667	21.651	0.360	0.432	0.332	6.310	11.280	10.610	10.592	**V_2O_3**	0.118	0.109
MnO	0.161	0.289	0.000	0.000	0.019	0.116	0.160	0.120	0.044	**Cr_2O_3**	19.050	0.111
MgO	44.322	39.071	0.035	0.038	0.018	15.152	14.890	13.970	18.160	**MnO**	0.111	0.132
CaO	0.246	0.190	13.027	11.228	15.466	22.266	10.850	11.180	0.014	**MgO**	15.338	15.754
Na_2O	0.042	0.024	4.035	4.957	2.730	0.375	3.040	3.110	1.448			
K_2O	0.004	0.000	0.075	0.085	0.039	0.000	0.340	0.480	6.979			
Total	99.268	99.980	100.813	100.876	100.713	99.882	97.480	97.360	94.954	**Total**	98.404	99.015
Si	1.004	1.002	9.391	9.741	8.958	1.926	6.831	6.401	5.621	**Ti**	0.080	0.035
Al	0.000	0.000	6.600	6.254	7.007	0.074	1.169	1.599	2.379	**Al**	11.861	15.593
										Fe^{3+}(1)	0.571	0.300
Ti	0.000	0.000	0.013	0.018	0.010	0.036	0.321	0.504	0.476	**Cr^{3+}**	3.387	0.018
Al	0.001	0.000	0.000	0.000	0.000	0.025	0.238	0.105	0.114	**V^{3+}**	0.021	0.018
Fe(*)	0.310	0.512	0.054	0.065	0.050	0.195	1.401	1.305	1.284	**Fe^{2+}**	2.949	3.116
Mn	0.003	0.007	0.000	0.000	0.003	0.004	0.020	0.015	0.005	**Mn**	0.021	0.023
Mg	1.668	1.468	0.009	0.010	0.005	0.835	3.294	3.064	3.926	**Mg**	5.141	4.913
Ca	0.007	0.008	2.515	2.155	3.010	0.882	1.726	1.762	0.002			
Na	0.002	0.002	1.410	1.722	0.961	0.027	0.876	0.888	0.407			
K	0.000	0.001	0.017	0.019	0.009	0.000	0.065	0.090	1.291			
	Fo 84.34	74.14	**An** 63.80	55.31	75.62	**En** 43.59						
	Fa 15.66	25.86	**Ab** 35.76	44.19	24.15	**Fs** 10.38						
			Or 0.44	0.50	0.23	**Wo** 46.03						

(*) FeO as total iron; (1) Fe^{2+}/Fe^{3+} oftcr Droop (1987).

1. Olivine core; 2. Olivine rim; 3. Plagioclase core; 4. Plagioclase rim; 5. Neoformated plagioclase; 6. Clinopyroxene core; 7. Edenitic amphibol; 8. Kaersutitic amphibol; 9. Biotite (phlogopite); 10. Brown spinel included in olivine; 11. Green spinel.

Analyses performed with an automatic (SX-50) Cameca microprobe at Granada University.
Operation conditions: 10 s. counting time. c. 30 nA beam current and 20 kV accelerating voltage.

canic and subvolcanic rocks from the External Zones of the Betic Cordilleras.

The characteristics of the xenocrystals and metacrystals

We have not found any xenoliths s.s. in the outcrop studied, such as those found in the Jurassic basalts, coming from the same Subbetic Zone, by Puga and Portugal (1989). Only crystalline aggregates (xenocrystals) derived from partly assimilated metamorphic rocks, and newly formed minerals (metacrystals) resulting from thermal transformations within the magma could be detected.

XENOCRYSTALS

They make up whitish crystalline aggregates, centimetre-sized (< 2 cm), generally rounded, and occasionally quadrangular. They are pseudomorphs after andalusite xenocrystals (Fig. 4), which are nearly completely substituted by corundum aggregates. In many cases they are surrounded by a greenish rim made up of green spinel (Fig. 5 and Tab. 2). A light-brown external corona, less than 1 mm thick, of highly sericitized plagioclase, separates these xenocrystals from the surrounding picritic dolerite. The composition of a plagioclase crystal preserved at the outer edge of one of these coronas is An$_{75}$ (Tab. 2). Very small rutile crystals are present in some aggregates; they may represent metamorphic inclusions in the andalusite crystals.

Similar xenocrystals have been described from other localities in the Betic Cordilleras in the External Zone (Puga, 1987 and Puga and Portugal, 1989) and in the Internal Zone (Puga et al., 1989a; Gomez-Pugnaire and Munoz, 1990, 1991; Castroviejo et al., 1991 and Puga and Diaz de Federico, in press).

Tab. 3 Chemical composition of the picritic dolerite compared with those of the central areas and the chilled margins of the "ophites".

Chemical comparison			
	Picritic dolerite	Central areas	Chilled margins
SiO_2	43.40	52.40–51.36	52.41–52.00
TiO_2	1.13	1.26–1.05	1.74–1.12
Al_2O_3	10.70	15.37–13.70	14.40–12.53
Fe_2O_3	12.80	12.30–10.48	13.57–10.20
MnO	0.18	0.22–0.13	0.19–0.15
MgO	19.00	6.83–5.42	6.42–4.75
CaO	6.02	10.00–7.56	9.45–6.05
Na_2O	1.64	4.66–1.98	5.42–2.77
K_2O	0.61	1.30–0.58	1.33–0.58
P_2O_5	0.17	0.16–0.13	0.23–0.12
LOI	3.77	2.85–0.55	2.39–0.47
[mg]	0.77	0.60–0.51	0.58–0.44
Ba	167	327–144	436–159
Rb	23	53–22	40–22
Th	1.4	7–2	6–2
Nb	22	19–7	18–16
La	10.2	14.8–10.1	18.0–11.8
Ce	20.5	36.8–25.3	36.0–25.9
Sr	304	391–213	278–139
Zr	84	125–74	165–92
Y	12	40–22	36–15
Yb	1.5	2.6–2.1	2.6–2.3
Cr	795	322–66	263–149
V	146	321–266	294–290
Ni	596	76–56	67–55

The analyses have been made in the X-Ray Assay Laboratoires (Ontario) using the following methods: XRF for majors, Zr, Rb, Nb, Ba and Sr; DCP for V; ICP for Ni, Cr and Y; ICP–MS for REE; and NA for Th.

METACRYSTALS

Two stages can be distinguished in the neoformation of these minerals developed during the temperature increase due to the endomorphic process.

a) Silicate-stage: Sillimanite, in the form of fibrolite, replaced the andalusite crystals at the beginning of the temperature increase (Fig. 4).

b) Oxide-stage: During this very-high-grade metamorphic stage the xenocrystals and the previously formed sillimanite, were desilicated and transformed into corundum + spinel. Corundum crystals appear as an acicular latticework or as a prismatic palmeate structure (Fig. 5). Sometimes the corundum crystals follow the direction of the fibrolite bunches which they are substituting (Fig. 4). The corundum crystals systematically present an anomalous positive elongation; they obviously retain the positive elongation of the fibrolite. According to this hypothesis, the corundum could be formed by *solid-state desilication reactions.* The excess silica reacted with the enclosing magma, to form the plagioclase coronas surrounding the xenocrystals.

The green spinels are also a product of endomorphic reactions during this stage, between xenoliths and the sourrounding magma. These spinels are rich in Fe (Tab. 2) and their frequent association with corundum indicates that both phases could well have been formed at the same time and represent the highest temperature mineral phases during the desilication processes. The sericitized plagioclase at the periphery of the pseudomorphs probably also originated from the reaction between the Al-silicates and the surrounding magma.

The origin of the xenocrystals

Crystalline aggregates similar to those described here have been interpreted by PUGA and PORTUGAL (1989) in the Jurassic volcanic rocks from Alicun de Ortega (Subbetic Cordillera) as resulting from the assimilation of metapelitic rocks containing aluminium silicates. It can be surmised that a similar process has taken place in a magmatic chamber placed at the basement level during an initial stage of the generation of the xenocrystals before the final emplacement of the magma into the Triassic sediments. In the dolerite outcrop dealed with here, the cumulitic host rock containing the xenocrystals, does not show an increase in Si, K and Rb characterising the assimilation of metapelitic rocks (Tab. 3). These chemical changes are however noteworthy in the olivine-depleted dolerite at the top of the stock. According to these facts, the aggregate xenocrystals might be formed by the following two-stage process:

1st stage: metapelites containing aluminium silicates were assimilated and aluminium silicates were transformed into corundum and spinel aggregates at the top of a magmatic reservoir;

2nd stage: because of their high density (more than 4 g/cm^3) these aggregates, together with olivine, descended to the bottom of the reservoir. A subsequent intrusion of this basaltic olivine bearing magma in the form of a small stock and the gravitational accumulation of the heaviest phases would have formed the picritic dolerite containing xenocrystals at the base of the outcrop, leaving in the topmost part an olivine-depleted magma.

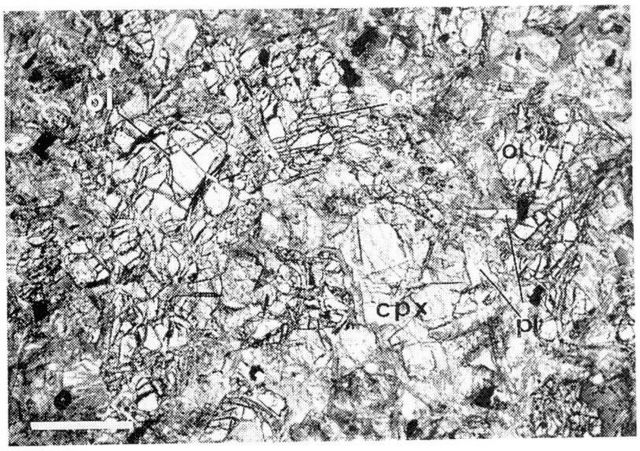

Fig. 2 Microphotography of picritic dolerite with cumulitic texture, within which the initial igneous paragenesis, formed by olivine (ol), plagioclase (pl) and clinopyroxene (cpx), can be seen. Scale bar = 0.5 mm. Abbreviations for all figures and table 1 following KRETZ (1983).

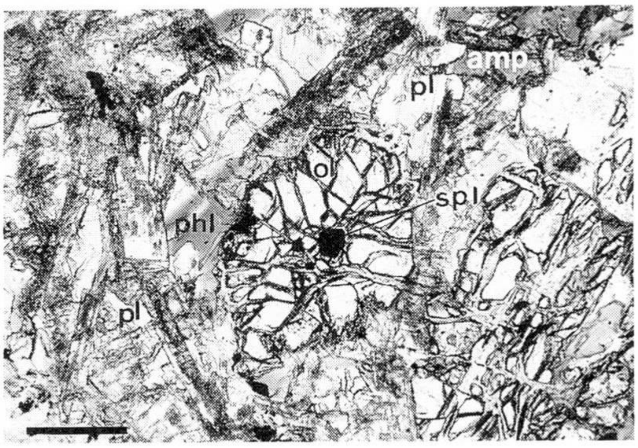

Fig. 3 Detail of Cr-rich spinel (spl) included in olivine crystals in the picritic dolerite, with intercumulitic amphibol (amp) and phlogopite (phl). Scale bar = 0.2 mm.

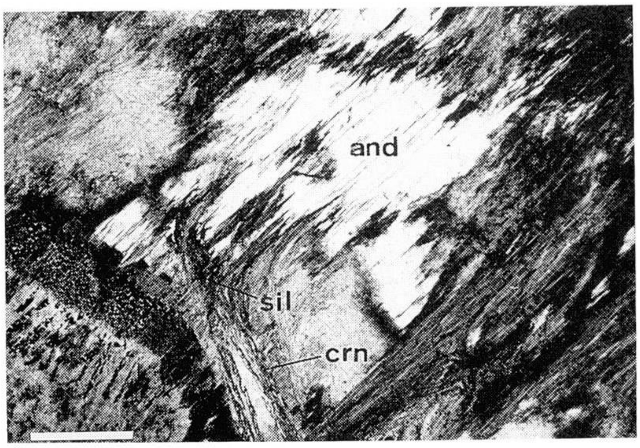

Fig. 4 Microphotography of Al-rich xenocrystals, containing remains of andalusite (and), partly transformed into fibrolite (sil). Detail of corundum needles (crn) substituting fibrolite bunches. Scale bar = 0.5 mm.

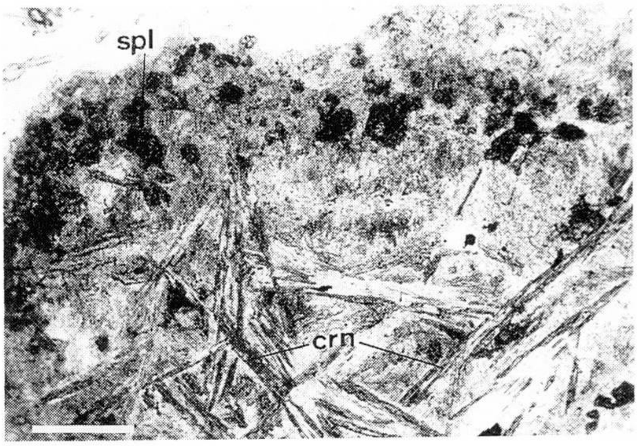

Fig. 5 Detail of an aluminium-oxide aggregate with a border of green-spinel and the bundled acicular habits of the corundum. Scale bar = 0.2 mm.

Genetic conditions of the xenocrystals

The proposed petrogenetic model includes the physical conditions necessary to explain the following processes:

– The dehydration and partial melting of pelitic rocks, followed by their assimilation by a basaltic magma.

– Metamorphic reactions that destroyed the pre-existing minerals, such as the fibrolitic-sillimanite formed during the initial stages of thermal metamorphism, to arrive at the metamorphic climax corundum and spinel were the only stable phases.

– The gravitational accumulation of these oxides in the picritic dolerite, thus separating themselves from the contaminated magma.

The most significant temperature differences between the magma and the surrounding rocks occur in the upper zone of the earth's crust when the magma, retaining its liquidus temperature, reaches superficial levels and there maximum assimilation takes place (CAMPBELL, 1985; CAMPBELL and TURNER, 1987; HUPPERT and SPARKS 1985). Under these circumstances it is possible that part of the country rocks, such as micaschists from the basement, might be stripped from the wall of the magmatic chamber by thermal erosion. Pre-exist-

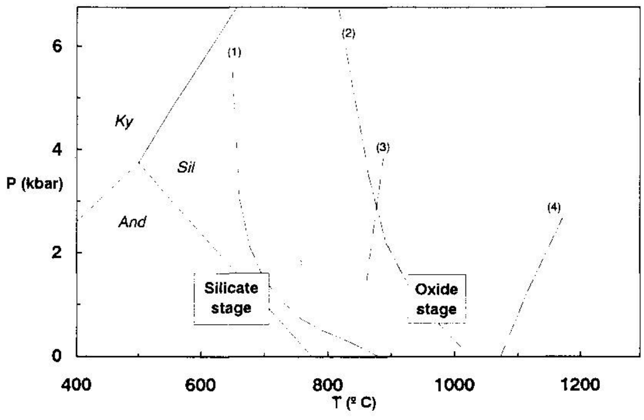

Fig. 6 Simplified petrogenetic grid for the thermometamorphic processes. $SiAl_2O_5$ polimorphs equilibrium after Holdaway (1971). The reaction (1) represents the initial granitic melt (in Yardley, 1989). The reactions (2), (3) and (4) showed are according to Schreyer (1976), and represent: (2) initial basaltic melt; (3) Sil + Bt <=> Crn + Spl + Qtz + V; (4) Sil + Mu <=> SiO_2. The arrow shows the tentative P-T evolution for the thermal metamorphism (see text for comments).

ing andalusite in these fragments would quickly become transformed into sillimanite at temperatures of around 650–700 °C (silicate-stage) (see Fig. 6). The destruction of the greater part of the minerals constituting the micaschists (quartz + muscovite + biotite, etc.) during the process of endomorphism, at temperatures of between 600 and 900 °C causes an enrichment in SiO_2, K_2O, Na_2O, Al_2O_3, H_2O and incompatible elements in the magma, together with the liberation of andalusite pseudomorphs, which, as a result of their high fusion temperature (approx. 1545 °C) would remain as restitic minerals (assimilation stage). At temperatures between 900 and 1000 °C (Fig. 6) sillimanite would be transformed into corundum aggregates, which would be segregate by their high density. SiO_2 would be released into the magma (oxide-stage). Probably, the decay of aluminium silicates (fibrolitic sillimanite) would be favourised by the existence of a gradient in the chemical potential of SiO_2 between the pelitic material and the basaltic magma. The hercynite rims and anorthite-rich plagioclase coronas (highly sericitized) around the xenocrystals can be explained by mass transfer processes in both directions, between the xenocrystals and the magma, involving the loss of SiO_2 and the gain in FeO, MgO and CaO in the resulting pseudomorphic aggregates. This mass transfer hypothesis is similar to that showed by Bergen (1983) from the Mt. Amiata metapelitic xenoliths. This migration of SiO_2 into the magma could be responsible for a decrease in solubility of the sulfur, thus provoking the separation of an immiscible sulfide melt, from which the sulfide ores precipitated and crystallized following a monosulfide solid solution type (mss) crystallization sequence.

The metamorphic and ultrametamorphic evolution described here may have been a continuous process, beginning at the same time as the magmatic differentiation produced by the assimilation within the magmatic chamber or its walls and continuing throughout the basalt crystallization.

The development of silica-undersaturated assemblages capable of generating minerals such as corundum and spinel has been interpreted by Pattison and Harte (1985) as the result of the thermal metamorphism of pelitic rocks at low pressures. On the other hand, the process of pseudomorphism after andalusite crystals by combinations of sillimanite, corundum, spinel and An-rich plagioclase is typical of interactions between metapelitic crustal xenoliths and relatively mafic magmas (Barker, 1964; Puga, 1987; Puga and Portugal, 1989; Gomez-Pugnaire and Munoz, 1991 and references therein) or even more siliceous magmas (Bergen, 1983; Bergen and Barton, 1984). Chemical studies of such assimilation processes at low pressures and also metamorphic transformations of the remains of pelitic materials would indicate that the pressure conditions for this metamorphism were 1 kbar at the most, coinciding with the physical conditions for the endomorphic processes in the Jurassic basaltic magmas at Alicun de Ortega (Fig. 7 in Puga and Portugal, 1989).

Concluding remarks

1) Within the "ophites" in the External Zones of the Betic Cordilleras we have identified an outcrop of picritic dolerite, cumulitic in texture and containing numerous xenocrystals of pseudomorphs of andalusite together with dispersed Ni–Cu–Fe sulfide ores.

2) These xenocrystals have undergone a series of endomorphic transformations, by reaction with the enclosing magma. A simplified reaction scheme would be:

andalusite → sillimanite + (Fe, Mg, Ca, Na) → corundum (+ spinel) ± plagioclase + SiO_2

3) The textures and parageneses of the sulfide ores result from a mss crystallization sequence, starting from an immiscible sulfide melt.

4) The presence of these xenocrystals confirms the hypothesis of crust assimilation put forward by Puga and Diaz de Federico (1988) and Puga et al. (1989b) for the "ophites" of the Subbetic Zone, based on their chemical characteristics, and

also the genesis of these tholeiitic magmas within an intracontinental distensive regime.

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