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ATTEMPTS OF WHOLE-ROCK K/AR DATING OF MESOZOIC VOLCANIC AND HYPABISSAL IGNEOUS ROCKS FROM THE CENTRAL SUBBETIC (SOUTHERN SPAIN): A CASE OF DIFFERENTIAL ARGON LOSS RELATED TO VERY LOW-GRADE METAMORPHISM

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RESUMEN

Doce muestras de cuerpos básicos intrusivos en rocas triásicas («ofitas») y 11 muestras de volcanitas y rocas intrusivas asociadas en secuencias jurásico-cretáceas de la zona Subbética han sido objeto de datación radiométrica K/Ar (roca total) en combinación con análisis químico-petrográfico.

Las edades analíticas obtenidas son sólo satisfactorias en relación con un cierto número de muestras de rocas volcánicas, no obstante, con una concordancia respecto de las edades estratigráficas en el orden del 10% relativo; las del resto, fundamentalmente muestras de «ofitas», presentan una fuerte dispersión, con diferencias que pueden alcanzar valores superiores a los 30 Ma, incluso en conjuntos provinientes del mismo afloramiento o localidad.

Se concluye que las pérdidas de Ar causantes de los rejuvenecimientos de las edades analíticas observados son debidos a la existencia de transformaciones metamórficas alpinas, de muy bajo grado, que afectaron con mayor intensidad a las ofitas que a las rocas volcánicas presentes en niveles estratigráficos más altos. Otros cambios posteriores al emplazamiento magmático, tales como el grado de oxidación secundaria, son así mismo distintivos en ambos grupos de muestras al tiempo que proveen de soporte adicional al concepto de que el medio de alteración de las «ofitas» debió haber producido condiciones favorables a una interacción roca/fluidos más penetrativa y, por tanto, una recristalización más homogénea. En conjunto, la actividad magmática de la que derivaron las «ofitas» podría haber comenzado en el Trias terminal y continuado en el Jurásico Inferior.

Tanto las «ofitas» como las volcanitas se consideran el resultado de eventos magmáticos ligados a movimientos de distensivos a transtensivos que afectaron a las cuencas externas de las Cordilleras Béticas desde el Trías terminal hasta el Cretáceo inferior.

Palabras clave: *Datación K/Ar de rocas básicas, «ofitas», pérdida de Ar, metamorfismo de muy bajo grado, Cordilleras Béticas, Zona Subbética.*

ABSTRACT

12 samples of basic intrusives within Triassic rocks («ophites») and 11 samples of volcanic and associated intrusives within Jurassic to Early Cretaceous sequences of the Subbetic Zone were subjected to whole-rock K/Ar dating in combination with chemical/petrological analysis.

Satisfactory results were obtained only from a number of samples of volcanic rocks, however, analytical ages commonly agree, within about 10 relative percent, with those deduced from stratigraphic location. «Ophite» samples, on the other hand, may reveal considerably lower analytic ages than the volcanics and show much stronger scattering, even among samples collected within a small area.

It is argued that the inferred loss of Ar results from very-low-grade alpine metamorphic alteration, which affected the «ophites» more intensely than the higher volcanic rocks. Other post-emplacement chemical changes, such as the degree of secondary oxidation of Fe, are also distintive among the two

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groups of samples, and are to some extent consistent with the above view in that the alteration environment of the ophites should have produced conditions for more penetrative fluid-rock interactions and homogeneous recrystallization. Overall, the magmatic activity from which the ophitic rocks originated might have started in the Late Triassic and continued in the Lower Jurassic.

Both, the «ophites» and the volcanics are though to be the result of magmatic events following tensional to transtensive crustal movements affecting the external basins of the Betic Cordilleras from Late Triassic to Early Cretaceous times.

Key words: *K/Ar dating of basic rocks, «ophites», Argon loss, very-low-grade metamorphism, Betic Cordilleras, Subbetic Zone.*

Introduction

The external zones of the Betic Cordilleras represent various sedimentary realms of rocks that accumulated in basins adjacent to the Iberian subplate from Triassic to Miocene times. A bipartite subdivision is usually made on the basis of the inferred relative location of the depositional areas: the Prebetic series (corresponding to the Prebetic Zone) were deposited directly adjacent to the Iberic (continental) margin and the Subbetic series (in the Subbetic Zone)more to the S or SW, farther away from the former Iberic coastline.

During the alpine tectogenesis (with important deformational events up to the Middle —and even Late— Miocene) most of this ensemble of Mesozoic or younger sedimentary sequences was detached from its Paleozoic to Lower (most) Triassic substratum. The ensemble was then broken up into a great number of tectonic elements that, according to classical concepts, resulted essentially or at least primarily from thrusting towards the N or NW (e.g.: Durand-Delga, 1980; Durand-Delga and Fontboté, 1980; García-Hernández, *et al.,* 1980), or otherwise intrincately mixed (e.g.: Bourgois, 1978; Hermes, 1978; van de Fliert *et al.,* 1980; de Smet, 1984). The extreme structural complexity has led to considerable difficulty in attempts at paleogeographic and evolutionary reconstruction of the original areas of deposition, particularly of the subbetic sequences. In the central segment of the subbetic belt (between the meridians of Antequera and Pozo Alcón, fig. 1) an «external», «median» and «internal» subdomain were distinguished (cf. García-Dueñas, 1967). These subdomains can be partly extrapolated to adjacent segments where similar subdivisions have been proposed.

The differentiation of and within the Subbetic domain originated in the Early Jurassic, at the end of Carixian and beginning of Domerian times (about 200 Ma ago) and was caused by the development of a differential bathimetry, related to basement fracturing. That event is now generally interpreted as marking the onset of an extensional to trascurrent regime, in connection with the separation of Laurasia and Gondwanaland. Stratigraphic development indicates a possible continuation of this regime into the latest Early Cretaceous (Aptian-Albian).

The Early Jurassic breakup of the subbetic basins was accompanied by magmatic activity, particularly by recurrent extrusion of basic lavas, as described, e.g., by Fontboté and Quintero (1960), Busnardo and Chenevoy (1962), García-Dueñas (1967), Comas *et al.,* (1969), Vera (1969), García Yebra *et al.* (1972), García-Cervigón et al., (1976), Comas (1978), Golz (1978), van de Fliert *et al.,* (1979), Puga and Ruiz-Cruz (1980) and Comas *et al.,* (1986). Associated with these volcanics, especially within the «median» Subbetic, intrusive mafic bodies are also found as sills, dikes and small laccoliths. Many of these have a stratigraphic distribution similar to that of neigh-boring pillow-lavas, and hence have been assumed to bear a similar origin and age (Puga and Ruiz-Cruz, 1980; Comas *et al.,* 1986).

Apart from the above-mentioned lavas and spatially associated intrusives, frequent bodies of dolerite (the so-called «ophites» (1) are also found as more or less isolated masses within (often chaotic) Triassic sediments of germano-andalusian facies, either when they form the stratigraphic basis of the Subbetic units or within independent tectonic elements dominated by this type of facies (e.g., the so-called «Trias de Antequera» and the «Unidad de Cambil».

Because the «ophites» appear to have been intrusive and have not so far been found accompanied by indisputable extrusives within the Triassic rocks, their interpretation in terms both of age and possible genetic relationship with the volcanites and other magmatic bodies located at higher levels has remained uncertain. On the basis of their remarkable local abundance and quite uniform mode of appearance in the field, these «ophitic» bodies have often been interpreted as resulting from an older and distinct magmatic event, possibly connected with precursory tectonic instability within the corresponding Triassic basins.

Preliminary K/Ar dating of several samples and field observations in the Cantar area (see fig. 1), however, led van de Fliert *et al.* (1979) to discuss the alleged Triassic age and distinct origin and to conclude that most

(1) The term «ophite», introduced for comparabale rocks in the Pyrenean mountains by the Rev. Father Palassou as far back as 1798, has since been defined in various ways. As a rock name it did not receive general acceptance, in contrast with the concept of ophitic texture (Rinne, 1921). In the Western Mediterranean area (Pyrenean mountains, Spain, Morocco, Algeria and Tunisia) the term «ophite» is still commonly used for blocks and larger bodies of basic rocks of varying composition and texture encountered in —mostly diapiric— Triassic sediments.

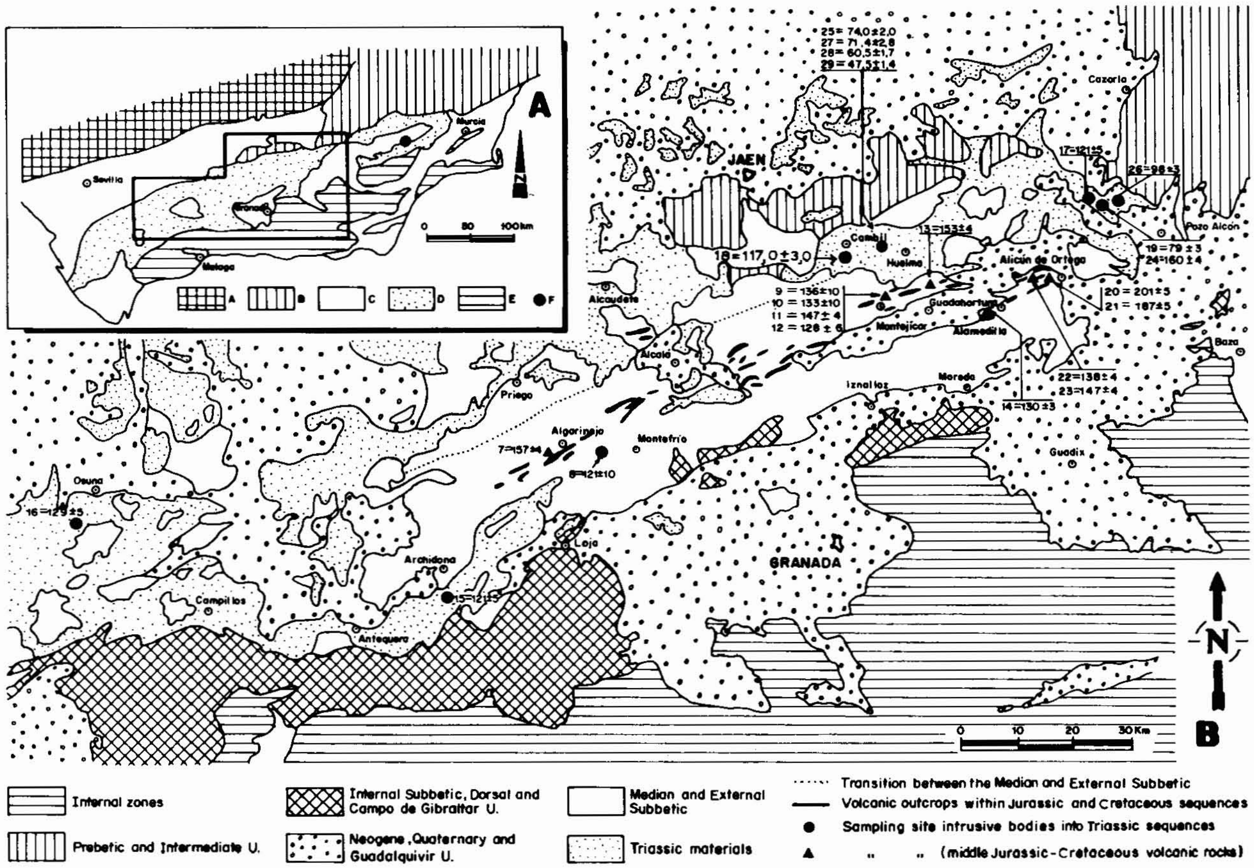

Fig. 1.—Geologic sketch map of the Subbetic Zone in the central segment of the Betic Cordilleras, showing locations of the sampled outcrops. Sample numbers are indicated, together with their respective analytic K/Ar ages in Ma. *Insect legend:* A: Iberic Borderland. B: Prebetic and Intermediate (Prebetic-Subbetic) Units; C: Neogene, Guadalquivir Units, and Quaternary of Depressions; D: Subbetic Units; E: Betic (or intenal) Zone; F: Cantar area (referred to in text).

«ophites» could in fact be nearly contemporaneous (within about 10-20 Ma) with the Jurassic and younger lavas.

In the Archidona region, on the other hand, the K/Ar dating of amphiboles from similar «ophitic» bodies resulted in apparent ages between 78 and 90 Ma, interpreted by Puga *et al.* (1983) as an indication of post-emplacement metamorphic recrystallisation.

On the present paper we report the results of attempts of K/Ar dating of an additional set of samples of volcanic and intrusive rocks (including «ophites») from the Subbetic series of the western and central segments of the Subbetic Belt, and discuss their significance as regards true ages of emplacement and possible later changes, in connection with some aspects of the evolution of the Subbetic realm and of the External Zone of the Betic Cordillera in general.

Field setting and description of the investigated samples

The hypabyssal dolerites («ophites») intruded into sedimentary rocks of Triassic age (plotted as squares in figs. 2-4) do mostly form small stocks with diameters of up to several hundred metres. The original relation with the enclosing strata is usually obscured as a result of secondary tectonic disturbance. Less frequently they form sills and discordant dikes with thicknesses up to some tens of metres. In most instances these outcrops do not reveal any clear spatial realtionship with the volcanics of Jurassic or younger age, even when corresponding tectonic units bear complete Mesozoic sequences.

The volcanic and hypabyssal rocks that appear in sediments of Jurassic of Early Cretaceous age (circles in figs. 2-4), on the other hand, consist essentially of lave flows with thicknesses of up to several hundred metres, whose outcrops are aligned roughly ENE-WSW along a band that stretches 300 km within the «median» Subbetic (fig. 1). Pillow lavas, with pillow diameter ranging from centimetres to some metres, and pillow basalt breccias are common in these lava flows. Other rocks belonging to this group appear as sills, dikes and small laccoliths (with thicknesses of up to several tens of metres) that

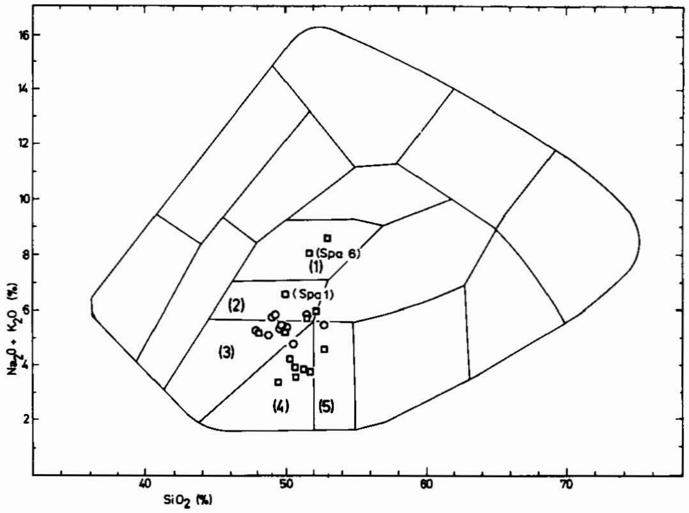

Fig. 2.—Silica/Alkali diagram after Cox *et al.* (1979), showing the relative position of the dated samples (except Spa 20, for which no major-element analysis is available). Squares: «ophites»; Circles: Jurassic volcanics and associated intrusives. *Key to pertinent compositional fields:* (1) Mugearites-trachybasalts, (2) Hawaiites, (3) Alkali-olivine basalts, (4) Tholeiitic subalkaline basalts, (5) Basaltic andesites. The boundary between fields 3 and 4 is after Irvine and Baragar (1971). Two samples from the Cantar area were also plotted in this figure (Spa 1 and 6).

intrude either the lava flows or the sedimentary strata alternating with these.

The more remarkable petrographic features of the dated samples have been summarized in tables 1-4, whilst major-element analyses are given in tables 5-6. From these data, as well as from a study of other samples from the same outcrops, it might be concluded that both groups are made essentially of similar basic rocks, in the range of alkali or tholeiitic basalt/dolerite (plus hawaiite, mugearite or basaltic andesite) (fig. 2); although a note of caution should be made about some samples whose original mineralogy, and hence possibly overall chemistry, might have been modified by secondary recrystallisation. As a whole, nonetheless, both chemical and primary mineralogical compositions might be regarded as transitional between the tholeiitic and alkaline sodic magmatic series. Apart from indicating a mantle origin, the petrographic and chemical characters of these rocks are consistent with the view that their emplacement or extrusion should have taken place under a relatively extensional crustal regime. In this regard these data agree well with existing interpretations in which the contemporaneous crustal dynamics are connected with the operation of deep NNE-SSW directed faults, whose mechanism woud have been mostly transtensive (Hermes, 1978; Comas *et al.,* 1986).

Table 1.—«Ophites». Mineralogy and modal estimates of the samples dated.

Sample	8	15	16	17	18	19	24	25	26	27	28	29
Original igneous assemblage												
Plagioclase	S(A)	A	A	A	S(A)	A	A	A	A	A	M(A)	A
Augite	(A)	M	A	A	S(A)	A	A	A	A	A	M(A)	A
Olivine	S	M	S	M	—	S	M	S	S	M	S	M
Opaque ore	(M)	M	S	M	(A)	M	M	M	M	M	(S)	M
Amphibole	—	—	S	S	—	S	S	S	S	S	—	S
Biotite	—	S	S	S	—	S	S	—	—	S	—	S
Quartz	—	—	S	S	—	S	S	S	S	S	—	S

Key for symbols: A=Abundant (>30%), M=Minor (10%-30%), S=Scarce (<10%). Porphyritic samples bear two symbols, the one between parentheses indicating the amount of crystals within the groundmass (e.g., S(A) would mean that the species forms scarce phenocrysts but is a abundant in the groundmass).

Secondary mineral assemblage (presence is indicated by a plus «+» sign)	8	15	16	17	18	19	24	25	26	27	28	29
Chlorite	+	+	+	+		+	+	+	+	+	+	+
Sericite (*)	+	+	+	+	+	+	+	+	+	+	+	+
Talc			+				+			+		+
Prehnite	+			+	+	+	+	+		+	+	+
Green Biotite	+			+	+	+	+	+		+	+	+
Pumpellyite	+	+	+	+		+	+	+	+	+	+	+
Jad. Pyroxene		+				+		+		+		+
Actinolite		+		+			+		+	+		
Crossite		+										
Epidote		+										

(*) Sericite usually replaces plagioclase. Degree of such replacement ranges from 10% to 70% in most «ophites».

Table 2.—**Volcanics and associated intrusives within Jurassic-Cretaceous sequences. Mineralogy and modal estimates of the samples dated.**

Sample	7	9	10	11	12	13	14	21	22	23
Original igneous assemblage										
Plagioclase	S(A)	A(M)	(A)	(A)	(A)	(A)	S(A)	(A)	S(A)	S(A)
Augite	S(A)	A	S(A)	(A)	(S)	S(A)	(A)	A	(M)	(A)
Olivine	—	M	S	S	M	S	S	A	S	S
Opaque ore	(A)	M(S)	(M)	(M)	(A)	(M)	(A)	M(S)	(A)	(M)
Biotite	—	—	—	—	—	—	—	(S)	—	—
Key for symbols: see Table 1										
Secondary mineral assemblage										
Clay minerals	+			+	+		+	+	+	+
Chlorite		+	+	+	+	+	+	+	+	
Analcime		+	+	+		+				
Zeolites	+	+						+		
Stilpnomelane		+	+	+		+				
Jad. Pyroxene		+	+	+						
Actinolite		+	+							

Table 3.—**«Ophites». Location and main features of the sampled outcrops.**

Sample	Utm local coordinates	Geologic setting	Structure of outcrop	Mesoscopic structure of sample	Type of rock
8	VG045312 (7 km E of Algarinejo)	Trias. Median Subbetic	Sill	Microporphyritic with fine intergranular matrix	Basalt porphyry
15	UG776056 (road Archidona-Villanueva del Trabuco, km 2)	Trias of Antequera	Stock or small laccolith	Intergranular to subophitic with medium grain size	Dolerite
16	UG112196 (road Osuna-Puerto de la Encina, km. 3)	Allochtonous Trias, similar or equivalent to that of Antequera.	Sill (lensoid body)	Subophitic. Medium grain size	Dolerite
17	VG944764 (road Huesa-Pozo Alcón)	Trias of Cambil/Guadiana Menor	Stock	Subophitic. Medium grain size	Dolerite
18	VG6505701 (road Cambil-Albuniel, near Cambil)	Trias of Cambil	Stock	Microporphyritic, with very fine intergranular matrix	«Chilled» dolerite
19	VG956754 (Ceal, W of Pozo Alcón)	Trias of Cambil/Guadiana Menor	Stock?	Subophitic. Medium grain size	Dolerite
24	VG956754 (same as 19)	(same as 19)	Stock?	Subophitic. Medium grain size	Dolerite
25	VG585705 (road Huelma-Cambil)	Trias of Cambil	Stock	Subophitic. Medium grain size	Dolerite
26	VG963754 (Ceal, W of Pozo Alcón)	Trias of Cambil/Guadiana Menor	Stock	Subophitic. Medium grain size	Dolerite
27	VG585705 (same as 25)	(same as 25)	Stock	Subophitic. Medium grain size	Dolerite
28	VG585705 (same as 25)	(same as 25)	Stock	Microglomeruloporphyritic, with fine intergranular matrix	«Chilled» dolerite
29	VG585705 (same as 25)	(same as 25)	Stock	Subophitic. Medium grain size	Dolerite

Table 4.—**Volcanics and associated intrusives within Jurassic-Cretaceous sequences. Location and main features of the sampled outcrops.**

Sample	Utm local coordinates	Geologic setting	Structure of outcrop	Mesoscopic structure of sample	Type of rock
7	UG964314 (2 km W of Algarinejo)	Median Subetic	Pillow-lava flow	Intergranular to intersertal, with medium grain size and vesicles	Alkali basalt
9	VG558588 (road Montejícar-Huelma, near Montejícar)	Median Subbetic	Massive to pillowed lava flow	Intersertal to subophitic, with fine grain size	Olivine hawaiite
10	VG558588 (same as 9)	Median Subbetic	(same as 9)	(same as 9)	Basaltic andesite
11	VG558588 (same as 9)	Median Subbetic	Interior of lava flow, with spherical parting	Intersertal and subophitic, with fine grain size	Tholeiitic basalt
12	VG558588 (same as 9)	Median Subbetic	(same as 11)	Microporphyritic, with very fine intersertal matrix and vesicles	Olivine hawaiite
13	VG653637 (road to Huelma Station, km 3)	Median Subbetic	Lava flow, with spherical parting	Intersertal and subophitic, with medium grain size.	Olivine hawaiite
14	VG758604 (3 km W of Alamedilla)	Median Subbetic	Pillow-lavas, with diameters up to 3 m	Fine sized intergranular, with vesicles	Alkali basalt
21	VG861622 (2 km W of Alicún de Ortega)	Median Subbetic	Sill, with spherical parting	Porphyritic, with medium sized intergranular matrix	Olivine dolerite
22	VG84a2623 (4.5 km W of Alicún de Ortega)	Median Subbetic	Xenolith-bearing and vesicular non-pillowed lava flow	Fine sized intersertal, with vesicles	Alkali basalt
23	VG842623 (same as 22)	Median Subbetic	Flattened pillow lavas up to 1 m in diameter	Fine sized intergranular, with vesicles	Alkali basalt

Besides these similarities, however, there are also some differential features between the rocks from each group of outcrops that must be taken into account when interpreting the results of K/Ar analysis. Many of these distinctive features, part of which are reflected in tables 1-4 and figs. 2-3, were already pointed out by Puga and Ruiz-Cruz (1980). For each group of samples they may be summarized as follows:

«Ophites», intruded within Triassic sediments

Although, as in the case of the Jurassic lavas, these rocks appear to have been derived mostly from transitional magmas, their chemistry bear a definite tendency towards tholeiitic rather than alkaline (see fig. 2 and table 5). Normative hypersthene (with or without quartz) is more frequent than nepheline, and there is also a nearly ubiquitous presence of small proportions of modal quartz, in some instance forming granophyric intergrowths with alkali feldspar (table 1). Another primary mineralogic feature of this group of samples is the presence of a titanium-poor augite as the more common pyroxene, while plagioclases are in the range of labradorite to oligoclase.

Medium sized subophitic textures are prevalent in these rocks. Olivine usually appears as inclusions within augite crystals and is systematically replaced by chlorite pseudomorphs. Common secondary assemblages include chlorite, sericite, prehnite and pumpellyite (table 1), that in some instances are accompanied by a slightly jadeitic pyroxene (Jd $< 20\%$), actinolite, crossite ($Gl_{38}Rieb_{62}$) and epidotes. The samples of this group are also characterized by more homogeneous and lower total volatile

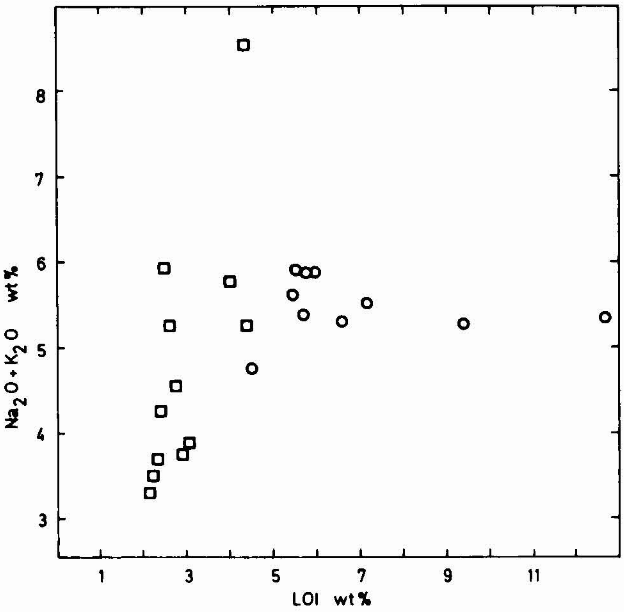

Fig. 3.—Plot of the sum of alkalis against total volatile content of the sample dated, showing the more significant major-element differences between «ophites» and jurassic volcanics and associated intrusives. Symbols as in figure 2.

contents, as well as by relatively moderate degrees of secondary oxidization (figs. 3-4).

Volcanic and intrusive rocks within Jurassic to Cretaceous strata

Their chemistry has a tendency towards alkaline sodic rather than tholeiitic, in contrast with «ophite» samples, as reflected in the more common appearance of nepheline instead of hypersthene when norms are calculated (see fig. 2 and table 6). In good agreement with this, no modal quartz is present and the more abundant primary pyroxene is a titaniferous augite. Plagioclase, moreover, is generally more calcic, in the range of bitownite to andesine.

The volcanic varieties within this group have a smaller grain size, vesicles, and common intersertal to intergranular textures, and hence bear considerable petrographic differences as compared with the «ophites». Nonetheless, the hypabissal varieties of this group also differ from their «ophitic» counterparts, including the prevalence of ophitic or porphyritic rather than subophitic textures. Additionally, olivine crystals may show only partial replacement by smectite-chlorite assemblages and are less frequently found as inclusions in the pyroxene. Plagioclases sometimes have a «cloudy» appearance (due to incipient alteration to clay minerals), but no sericite is seen to replace them as in the case of most «ophites». In general, the more significant secondary mineral assemblages include saponite, mixed-layer smectite-chlorite, zeolites and stilpnomelane, although these may in some instances be also accompanied by jadeite-bearing clinopyroxene (Jd $<$ 20%), actinolite and biotite (table 2). Overall, both volatile contents and degree of secondary oxidization are higher in this group of samples than in most «ophites» and associated intrusives within Triassic sediments (figs. 3-4).

Interpretation of the chemical and petrographic differences between the two groups of mafic rocks

The observed differences concern either chemical trends (major elements), mineralogy and textures, and might receive diverse explanations depending on the accepted relationship between their respective primary magmas. As regards primary chemical trends, however, our major-element data deserve further scrutiny in the light of a more comprehensive trace-element data set, especially if it is taken into account the noticeable degree of secondary alterations of some samples.

Table 5.—**Major-element analyses «Ophites»**

Sample	8	15	16	17	18	19	24	25	26	27	28	29
SiO_2	46.07	49.48	48.45	49.85	50.72	50.81	49.68	48.34	48.80	50.56	50.55	48.97
TiO_2	1.33	1.69	1.21	1.15	1.86	1.24	1.35	1.37	1.24	1.39	1.25	1.16
Al_2O_3	17.15	17.06	15.09	15.18	13.71	14.54	13.51	13.89	14.01	12.89	13.84	14.06
Fe_2O_3	2.86	5.02	2.72	2.86	8.36	2.32	5.31	5.72	5.10	5.01	5.77	5.66
FeO	7.58	5.86	8.16	7.21	4.81	7.53	8.54	7.16	7.55	7.65	6.95	6.06
MnO	.18	.14	.19	.17	.22	.17	.21	.17	.17	.16	.24	.16
MgO	6.46	6.11	8.67	6.95	3.53	6.62	6.48	6.13	6.64	6.58	5.26	7.63
CaO	9.13	5.60	10.09	10.36	4.47	8.74	9.47	9.10	9.40	10.27	7.49	9.96
Na_2O	3.40	4.64	2.29	2.78	4.56	3.06	2.53	4.33	2.76	3.10	4.73	3.11
K_2O	1.65	.91	.95	1.00	3.58	1.35	.92	.78	.99	.55	1.04	.79
P_2O_5	.30	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
L.O.I.	4.34	3.98	2.13	2.88	4.32	2.72	2.18	2.53	3.03	2.30	2.47	2.32
Total	100.45	100.49	99.95	100.39	100.14	99.10	100.36	99.52	99.69	100.46	99.59	99.88

L.O.I.=Loss on ignition; nd= not determined.

Table 6.—**Major-element analyses. Volcanics and associated intrusives within Jurassic to Cretaceous sequences.**

Sample	7	9	10	11	12	13	14	21	22	23
SiO_2	44.17	46.32	49.65	48.14	46.04	48.57	45.98	46.89	41.61	46.57
TiO_2	2.23	1.77	1.55	1.82	1.01	1.51	1.49	1.44	.88	1.01
Al_2O_3	14.84	17.21	17.19	16.35	15.21	17.27	16.32	16.14	17.46	16.65
Fe_2O_3	3.55	5.48	4.01	3.12	6.95	3.95	5.77	5.62	2.10	6.81
FeO	3.24	4.34	3.53	6.35	2.40	5.52	2.34	4.40	1.87	1.91
MnO	.26	.17	.18	.18	.19	.15	.12	.19	.11	.12
MgO	5.31	6.92	7.72	8.13	4.53	7.25	5.41	8.12	1.96	1.68
CaO	12.24	6.04	5.75	6.39	12.48	4.15	10.41	6.42	16.09	13.31
Na_2O	3.27	4.56	4.25	4.03	3.53	3.59	2.93	4.75	2.89	3.12
K_2O	1.52	1.00	.69	.53	2.22	1.94	2.20	.32	1.75	1.80
P_2O_5	.30	.29	nd	.26	nd	.21	.15	.24	.20	.24
L.O.I.	9.35	5.46	5.42	4.46	5.96	5.72	7.13	5.67	12.64	6.54
Total	100.28	99.56	99.44	99.76	100.52	99.83	100.25	100.20	99.56	99.76

L.O.I.=Loss on ignition; nd=not determined.

Other chemical and mineralogical distinctive features between the two groups, on the other hand, such as the different —or inequally developed— secondary assemblages, degree of secondary oxidization and total volatile content merit some special consideration, particularly with regard to the occurrence of low-, to very-low «burial» metamorphic recrystallisation. Thus, the comparatively higher degrees of recrystallisation found in most «ophites» would suggest the deeper burial of these bodies, as compared with the Jurassic and younger lavas. This would also agree with their more homogeneous and moderate degrees of secondary oxidization, inasmuch as recrystallisation under somewhat higher temperatures and/or within better confined systems should have resulted in improved internal buffering of oxigen fugacity, and, in general, in a more advanced condition of chemical equilibrium. In our samples, the resulting metamorphic assemblages do generally belong to the prehnite-pumpellyite (in some instances to the actinolite-pumpellyite) facies, in the case of the «ophites», and to the zeolite facies in the case of the Jurassic or younger lavas and associated intrusives. This agrees with previous observations by Puga *et al.*, (1983), whose estimates suggest conditions up to 3 kbar and 300°C for the prehnite-pumpellyite assemblage (somewhat higher for the actinolite-pumpellyite assemblages found in some «ophites»). For additional details and discussion of these metamorphic assemblages see Puga *et al.* (1983) and Morten and Puga (1983).

K/Ar Data

Experimental procedures and constants

Sieve fractions (125-250 μ) of the whole rocks were analysed. Potassium was analysed by flame photometry with lithium internal stantard and CsAl buffer. Argon was extracted in a glass vacuum apparatus and determined by stable isotope dilution techniques, using ^{38}Ar as a tracer with a Varian GD-150 mass spectrometer. All measurements were made by static mode. Analytical errors are estimated to be within 1% for K and 2% for Ar. The following constants were used for age calculations: L_e=0.581·10^{-10} a $^{-1}$, L_β=4.962·10^{-10} a^{-1}, and the abundance for ^{40}Ar=0.01167 atom percent of total K.

Analytical results

The results of K/Ar analysis of 23 samples are presented in table 7 and fig. 4. In order to stress that the calculated dates do not necessarily correspond with true age of rocks, the term «analytic age» is used.

Regarding these data, it should be remarked first that attempts of whole-rock K/Ar dating of basic intrusive and extrusive rocks in the external realm of the Betic Cordilleras meet with serious difficulties, the causes of which are only partly understood so far. When this program was initiated, however, more hopeful results were to be expected, the zone being considered to be composed of completely unmetamorphosed rocks. A first attempt was reported from the Cantar area (Van de Fliert *et al.*, 1979), based on the analysis of 6 samples: two from extrusive rocks containing fragments of Tithonian limestone and covered by Lower Cretaceous strata, and 4 from dolerites in the surrounding Trias. In that case the analytic age of the pillow-lavas corresponded closely with stratigraphic location, although the dolerites produced somewhat younger analytic ages in the range of 120 to 100 Ma. Some indications of metamorphism in the dolerites raised a problem in an admitted non metamorphic zone, at that time, so that the interpretation then advanced regarded comagmatic alteration (deuteresis) as the cause of the observed discrepancies. The origin of the pillow-lavas and dolerites was thus hypothetically attributed to the same magmatic activity in the Latest Jurassic to Early Cretaceous times.

At present, however, the analysis of additional samples

Table 7.—**Analytic results. Whole-rock K/Ar dating.**

Sample	K(%)	$^{40}Ar_{rad}$(ppb)	$\frac{^{40}Ar_{rad}}{Ar_{tot}}$ (%)	Analytic age T (Ma)	Sample	K(%)	$^{40}Ar_{rad}$(ppb)	$\frac{^{40}Ar_{air}}{Ar_{tot}}$ (%)	Analytic age T (Ma)
7	1.52	17.2	37.1	157±4	18	2.82	23.8	23,9	117±3
	1.52	17.3	15.5			2.82	23.6	30.7	
8	1.65	14.4	49.8	121±10	19	1.04	5 .73	48.8	79±3
	1,65	15.5	16,5			1.05	5 .99	50.6	
		13.7	22.8						
		14.1	24.4						
		14.1	45.5						
9	1.00	10.4	26.9	136±10	20	0.302	4 .50	32.5	201±5
	1.00	9,7	22.7			0.302	4 .41	41.4	
		9.4	20.8						
10	1.10	10.4	37.0	133±3	21	0.321	3 .93	64.5	187±5
	1.10	10.6	17.9			0.322	3 .94	61.6	
11	0.527	5.56	17.4	147±4	22	1.757	17.2	35.2	138±4
	0.527	5.61	22.2			1.757	17.7	31.7	
		5.57	27.3				17.3	41.2	
12	1.98	18.8	10.5	128±6	23	1.804	19.1	14.8	147±4
	1.98	17.9	14.7			1.806	19.6	30.9	
		17.8	11.1				19.4	27.8	
		18.3	12.1						
13	1.94	21.3	15.6	153±4	24	0.915	10.6	49.7	160±4
	1.94	21.6	10.7			0.915	10.5	39.5	
						0.920			
						0.915			
						0.914			
14	2.20	20.6	16.4	130±3	25	0.776	4 .14	47.3	74±2
	2.20	20.6	14.5			0.781	4 .04	51.5	
15	0.592	5.01	61.5	121±5	26	0.990	7 .03	53.4	98±3
	0.592	5.26	46.9			0.991	6 .81	42.9	
16	0.747	6.71	45.3	129±5	27	0.546	2 .70	76.8	71.4±2,8
	0.747	7.10	43.4			0.545	2 .80	76.9	
17	0.649	5.75	48.5	121±5	28	1.031	4 .39	62.3	60.6±1,7
	0.648	5.47	55.9			1.038	4 .42	52.6	
					29	0.791	2..67	60.3	47.5±1,4
						0.791	2 .61	61.6	

over a much wider area within the Subbetic Zone, as here reported, with much greater discrepancies between the analytical ages given by the two groups of basic rocks, as well as the description of unmistakebly metamorphosed «ophites» in the Archidona region (Puga *et al.*, 1983), suggest that the occurrence of a post-emplacement very-low-grade metamorphism should instead be taken into consideration. This means that the hypothesis of one and the same magmatic event for both groups of rocks is to be reappraised, as far as the analytic ages obtained, even in the case of apparently unweathered fresh rock samples, cannot be safely regarded as directly related to true emplacement age.

Contrary to the excess Ar (or loss of K?) encountered in some metamorphosed basic rocks from the Betic Zone (see Hebeda *et al.*, 1980), hence, we seem to meet here with a more or less pronounced but general loss of radiogenic Ar, affecting especially the «ophites». Effectively, the analytic ages of most «ophites», with the only exception of sample SPA-24, are systematically lower, often considerably, than those of the volcanics and associated intrusives, while their strong scattering makes them obviously more suspect of having suffered partial isotopic resetting. The analytic ages of the volcanic and associated intrusive rocks, on the other hand, can be evaluated much more precisely because of stratigraphic control. In table 8 they are compared with the values of the Harland *et al.* (1982) time scale, as appropiate for each stratigraphic location. Looking table 8, it can be seen that the analytic ages of three samples lie within the accuracy limits of Harland's time scale (SPA 11, 13 and 23; the same appears to hold for samples SPA 20 and 21, but the exact stratigraphic location of these is more uncertain). The other six samples show deviations from 8 to 15 relative percent, an average of about 10% too low when compared with the time scale.

Discussion and conclusions

Volcanic and associated intrusives in Jurassic-Cretaceous strata

As follows from table 8, the analytic ages of some of the submarine lavas agree within reasonable limits (i.e., less than about 10 relative percent) with estimates based on their stratigraphic location. The remaining appear to have been somewhat rejuvenated, in the range of 10-20 Ma, most probably as the result of the comparatively higher degree of wheathering of the corresponding samples. This is well illustrated, for instance, by the different analytic ages obtained from samples SPA 9, 10, 11 and 12, in spite of the fact that these were taken at the same locality and within as approximately 20 m thick lava pile near Montejícar (see fig. 1). In this respect it may be remarked that the oldest estimate obtained from this particular lava flow is given by sample 11, which also bears the lowermost modal percentage of secondary minerals within the group. Moreover, considering the whole set of samples this time, it seems not a coincidence that the two samples giving the lowest analytic ages (SPA 12 and 14) have rather high potassium contents (table 6), reflecting probably a more advanced degree of secondary clay formation from the primary assemblage. The samples giving the oldest analytic ages, on the other hand (SPA 20-21) are exceptionally fresh subvolcanic rocks (from a sill-like body), whose estimated K/Ar ages are quite consistent (within the limits of analytic error) both mutually and with the minimum given by stratigraphic location.

Table 8.—**Volcanics and associated intrusives within Jurassic-Cretaceous sequences. Comparison of radiometric results with values deduced from stratigraphic location.**

Sample	K/Ar age (in Ma)	Stratigraphic location	Minimum stratigraphic estimate*	Relative age difference (%)
20	201±5	Aalenian**	188 or younger	—
21	187±5	Aalenian**	188 or younger	—
7	157±4	Bajocian	175	10±2
13	153±4	Early Tithonian	150	2±3
23	147±4	Early Tithonian	150	2±3
11	147±4	Early Tithonian	150	2±3
9	136±10	Early Tithonian	150	9±7
10	133±3	Early Tithonian	150	11±2
12	128±6	Early Tithonian	150	15±4
22	138±4	Early Tithonian	150	8±3
14	130±3	Late Tithonian	144	10±2

(*) According to Harland *et al.* (1982) time scale.
(**) Samples 20 and 21 were taken from a sill-like body, so that only an upper limit can be given on the basis of stratigraphic location.

Intrusive rocks in Triassic sediments («ophites»)

The analytic ages obtained from this group of samples are much more scattered, with differences that may exceed 100 Ma. Marked age discrepancies are also obtained from samples that were collected at the same locality or outcrop. One extreme example is given by SPA 19 and 24, from the Trias of the Guadiana Menor, near Ceal, whose K/Ar ages differ by about 80 Ma, althought it should be noted that this case might no be representative as far as they were collected from a sedimentary accumulation rich in blocks of dolerite that permitted the sampling of particularly fresh-looking pieces of rock, but that might not have originated from the same body. The samples from the Cambil area, midway between Cambil and Huelma (SPA 25 and 27-29, with a maximum internal discrepancy of about 27 Ma), do belong to the same intrusive body.

Thus, and especially taking into account that no stratigraphic control on these samples can be made other than their being Triassic or younger, any definitive conclusion regarding the true age of the related magmatic event (or events) is precluded on the basis of our K/Ar data alone. The only significant constraint in this regard is perhaps that such true ages should have been older than the highest analytic estimate for each outcrop or locality (about 160 Ma and 74 Ma, respectively, in the examples discussed above; the same reasoning might be applied to other single-sample outcrops as summarized in fig. 1, with «minimum» ages in the range of 98 to 129 Ma).

The strong scattering of the analytic ages obtained with this group of samples is nonetheless consistent with the already noted higher degree of metamorphic recrystallization in most «ophites», and more particularly with the great extent to which primary plagioclases of these rocks have been replaced by sericite (cf. table 1). This observation might be taken as an additional indication in the sense that, regarded as very-low-grade metamorphic rocks, the «ophites» probably attained a higher —altough still variable— degree of chemical equilibrium with conditions prevailing during deep burial, as evidenced by secondary mineralogy. From this standpoint, our K/Ar data would suggest that such metamorphic event should have taken place during the Late Eocene or younger times, as indicated by the minimum 47 Ma datum obtained from sample SPA 29.

Relation of analytic age and rock alteration

Our interpretation of the discordant ages given by the samples of ophitic rocks, in terms of a partial isotopic resetting by a Late Eocene or younger metamorphic

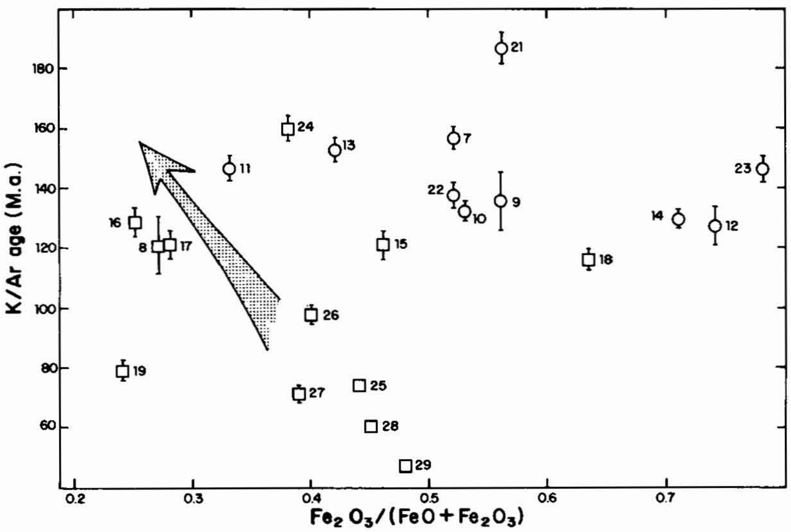

Fig. 4.—Plot of K/Ar ages versus degree of secondary oxidization of the dated samples, the latter taken as an indicator of secondary alteration environment. See text for implications and explanation. Symbols as in figure 2. Sample numbers correspond to those of plotted samples.

event, is perhaps best illustrated —and to some extent also supported— by plotting radiometric age versus a convenient index of secondary alteration. For most of the samples investigated the best general index is perhaps the degree of secondary oxidization of iron (expressed as the $Fe_2O_3/[Fe_2O_3+Feo]$ ratio) due to the fact that high oxigen fugacities were in all probability prevalent during their alteration/metamorphism, either in contact with sea water (volcanics) or within a red-bed sedimentary sequences («ophites» intruded into Trias of the Germano-Andalusian facies). This is done in fig. 4. As it can be seen in this plot, both groups of mafic rocks present rather high secondary oxidization ratios, even higher in the case of the volcanics, but rather different relationships to K/Ar analytic age.

On one hand the volcanics show poor or no relationship at all, which is interpreted as an indication in the sense that their secondary oxidization took place more or less contemporaneously with underwater extrusion, as expected from the fact that their analytic ages do closely match stratigraphic location. «Ophite» points, on the other hand, present a much different general pattern. First, they bear both more moderate and somewhat less scattered oxidization ratios which, in turn, show a noticeable overall negative correlation with analytic age (notice that such correlation would even be good if samples SPA 18 and 19 are taken apart). The meaning of this «ophite» pattern concerns the environment under which these rocks were altered, particularly when it is remembered that these intrusive bodies were in all probability subjected to very-low-grade burial metamorphism. Under these conditions, the process of secondary oxidization would not be expected to have taken place at the moment of intrusion (as in the case of the volcanics), but instead have run more or less in parelle with metamorphic recrystallization, particularly in parallel with plagioclase unstabilization and its replacement by sericitic aggregates. Hence, in a very general way, it should be no surprise that resetting of K/Ar systems in these rocks (mostly in plagioclase) and oxidization of mafic phases (as represented by the oxidization index) show the rough negative correlation as seen in the diagram.

An interesting feature of the «ophite» negative correlation to analytic age is that, in spite of the great uncertainty about the exact position of the regression line (the one shown in Fig. 4 was estimated visually), it points to the possibility that the intrusion of at least some «ophite» bodies preceded the oldest presently dated lava flow (around 200 Ma ago; samples SPA 20-21). This follows from the observation, in fig. 4, that the extrapolation of the «regression line» up to a point with an oxidization ratio of about 0.2, taken as representative of many fresh basaltic rocks (cf. e.g., Irvine and Baragar, 1971; see also some additional analyses of unaltered volcanic rocks from the Subbetic Zone in Puga and Ruiz-Cruz, 1980), would suggest an initial magmatic emplacement around 190 Ma (or even earlier) on the time scale. Hence, if the assumptions underlying this plot are indeed approximately correct, one could speculate with the possibility that magmatic activity within the Subbetic basins had started early, in the Lias and perhaps even in the Late Triassic («ophites»), reaching a maximum development later in Late Jurassic to Early Cretaceous times (volcanics and associated intrusives). Such possibility would agree with field observations by García-Cervigón *et al.,* (1976), in relation with «ophite» outcrops some 150 km to the E, near Cehegin. There, a Late Triassic age of magmatic emplacement was suggested on the basis of the interbedding, within Upper Triassic rocks, of placer magnetite deposits supposedly derived from an already weathered «ophitic» body. Although outside the Subbetic realm, it is interesting to note also that the existence of pillow-breccias within Triassic sediments was also reported by Soediono (1971), in the malaguide sequence outcropping near Ciudad Granada (W of Vélez-Rubio).

Metamorphism in the External Zone of the Betic Cordilleras

Until recently, hardly anything was known about metamorphism in the Subbetic Zone. Helmers (1978) reported in the Explanatory text of the Metamorphic Map of Europe (p. 152): «Apart from prehnitization or pumpellyitization of a few basic igneous rocks no metamorphic recrystallization has been reported from the Subbetic Zone». After the recent confirmation of the presence of true metamorphic assemblages in «ophites» from the Archidona region, near the boundary with the Betic Zone (Puga *et al.,* 1983), further petrologic research now reveals that very-low-grade metamorphic transformations affect also basic rocks over a much wider zone, including, although to a lesser extent, some volcanites and associated intrusives. In the case of the «ophites», this metamorphic event is now additionally revealed by the more or less pronounced occurrence of Argon loss within those systems, affecting the results of K/Ar dating attempts.

As mentioned before, the related assemblage are thought to be indicative of pressures in the range of 3 Kbar and temperatures around 300°C at the climax. Conditions may have been somewhat higher in the Archidona region. The causes of this metamorphism are still to be completely elucidated but, in the case of the «ophites», the neccesary conditions might have been easily reached taking into account that the original stratigraphic overburden can be estimated in the range of 3000 m. From this, any further burial might have been related to the ocurrence of deep going transpressive faultzones and associated tectonic loading, perhaps as one result of over-/under-thrusting related to them. Additional research is undoubtely needed to, for instance, confirm the presumable existence of metamorphic transformations within the enclosing sedimentary rock suites but, anyhow, our data do already suggest that the metamorphic event must have taken place in relatively recent times, perhaps during the Middle Tertiary, when the southern margin of the Iberic subplate collided with the Alboran Block. Thus the external Zone of the Betic Cordilleras should no longer be regarded as strictly non-metamorphic, just the same as the External Zones of the Alps where regional metamorphism, also for very-low-grade, was first demonstrated by Niggli *et al.,* (1956) and specified in numerous subsequent studies as those of Martini and Vuagnat (1965), Kübler *et al.,* (1975) or Frey *et al.* (1980).

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