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GEOCHEMISTRY AND AGE RELATIONSHIPS OF METAMORPHOSED MAFIC SILLS FROM SIERRA DE ENMEDIO AND SIERRA DE CARRASCOY (EASTERN BETIC ZONE, SOUTHEASTERN SPAIN)

E. Puga* and R. L. Torres-Roldán*

ABSTRACT

The presence of fairly abundant shallow-intrusive mafic bodies is a common feature of the almagride units, a recently defined group of tectonic elements of the Eastern Betic Zone whose paleogeographic and tectonic interpretation is particularly controversial. In this paper we focuse on the bulk geochemistry (including K/Ar data) and possible age relationships of these rocks, and discuss them in view of their significance regarding possible tectonic framework of emplacement and subsequent crustal evolution.

The analyses (49-55% SiO_2) point to a derivation from tholeiitic magmas that interacted with continental crust, as indicated by enrichment in the less compatible elements, such as Ba, Rb, Th and K, whose amounts are similar to those of well known continental tholeiitic provinces. Thus, the magmatic event is inferred to have been generated in a tectonic environment comparable to that of continental rifts. Emplacement may have taken place in Upper Triassic to Middle Jurassic times, as bracketed by their intrusion within Triassic beds and one whole-rock K/Ar date of 178±4 Ma from a less altered sample. Much younger analytical K/Ar ages, scattering between 41±5 and 57±2 Ma, are obtained from common samples, however, reflecting an Eocene or younger metamorphic event that caused partial recrystallisation under low-grade greenchist, to actinolite-pumpellyite facies conditions. As compared to other mafic complexes in the Betics, the observed chemical evidence for crustal contamination makes the almagride metabasites more similar to those in the external zona (e.g. the so-called «ophites») than in the Nevado-Filábride Ensemble, thus being consistent with proposals that correlate these units with the Subbetic in the Murcia area.

Key words: *bulk-rock geochemistry, K/Ar dating, mafic intrusives, almagride complex, eastern Betic zone.*

RESUMEN

La frecuente presencia de cuerpos de metabasitas es una característica común de las unidades almágrides, un grupo de unidades tectónicas de la Zona Bética Oriental, de reciente definición, cuya interpretación paleogeográfica es particularmente controvertida. El presente artículo hace especial referencia a la geoquímica (incluyendo datos K/Ar) y relaciones de edad de estas rocas, que se discuten en función de su significado como indicadores del contexto estructural de emplazamiento y evolución post-intrusión.

Los análisis (49-55% SiO_2) indican una derivación a partir de magmas toleíticos contaminados en medio continental, lo cual viene sugerido por un enriquecimiento en elementos incompatibles tales como Ba, Rb, Th y K, cuyas abundancias son análogas a las que presentan series bien conocidas de toleítas continentales. En consecuencia, el evento magmático debió originarse en un contexto estructural comparable al de un rift continental. El emplazamiento magmático pudo tener lugar entre el Trías Superior y el Jurásico Medio, estimación que viene limitada por su localización entre capas triásicas y una datación (roca total) K/Ar de 178±4 Ma obtenida sobre una muestra menos alterada. No obstante, edades K/Ar mucho más recientes se obtienen a partir de muestras comunes, reflejando la existencia de un evento metamórfico de edad eocena (o posterior), que fue causante de la recristalización parcial de estas rocas bajo condiciones propias de

(*) Instituto Andaluz de Geología Mediterránea and Dpto. de Mineralogía y Petrología, C.S.I.C.-Univ. de Granadaa. Fuentenueva, s/n. 18002 Granada, Spain.

las facies de esquistos verdes y/o de actinolita-pumpellyita. Frente a otros complejos máficos existentes en las Cordilleras Béticas, la evidencia composicional indicativa de contaminación continental hace a estas metabasitas más comparables a las de las zonas externas (e. g., las llamadas «ofitas») que a las del Conjunto Nevado-Filábride, lo cual es consistente con propuestas en las que se correlaciona a las unidades almágrides con el Subbético de la provincia de Murcia.

Palabras clave: *geoquímica de roca total, datación K/Ar, intrusiones máficas, unidades almágrides, zona Bética Oriental.*

Introduction

The presence of fairly abundant metabasite bodies is a conspicuous feature of a number of tectonic units of the Eastern Betic Zone forming the massives of Sierra de Almagro, Sierra de Enmedio and Sierra de Carrascoy. The classification of these elements and their paleogeographic interpretation within classical schemes of the Betic Cordilleras have had a particularly controversial development. Until recently, these units were thought to form part of the so-called Ballabona-Cucharon Complex (Egeler and Simón, 1969), which would include units with seemingly intermediate lithostratisgraphic and tectono-metamorphic development as compared with neighbouring Nevado-Filabride or Alpujarride sequences (see also Simon 1963; Simon *et al.,* 1976; Kozur *et al.,* 1974).

However, the distinction of the Ballabona-Cucharón Complex as a major ensemble within the Betic Zone (in addition to the three classical Nevado-Filabride, Alpujarride and Malaguide Ensembles), as proposed by Egeler and Simon (1969), has been a matter of disagreement. Aldaya *et al.* (1979), for instance, suggested instead its adscription to the Alpujarride Ensemble (i. e., within their Lújar Group of alpujárride nappes). Still more recently, Simon and Visscher (1983) dropped the mere notion of the Ballabona-Cucharón Complex, and regrouped its elements into a newly proposed «Almagride Complex» and the Alpujarride Ensemble. In doing so, they also emphasized that the new group of «almagride» units (always tectonically underlying the alpujarrides but with an uncertain structural relationship to the Nevado-Filábrides) bear marked lithostratigraphic affinities with Triassic sequences belonging to the Subbetic of the province of Murcia (see also Besems and Simon, 1982 and Kozur *et al.,* 1985). In consequence, two largely contrasting hypotheses on the paleogreographic provenance of these units (i.e. the part of the previous Ballabona-Cucharón group not reassigned to The Alpujarride Ensemble) would now coexist, involving implicit interpretations that regard them either as a southern prolongation of the Subbetic (external) realm, or as a part of the northern margin of the Alpujarride crustal domain.

With regard to these problems, a study of the mafic bodies present in these units was deemed promising, to compare with other well-hnown occurrences of mafic rocks within the Betic Cordilleras, i.e., in the Subbetic and in the Nevado-Filabride Ensemble. The purpose of the present paper is to discuss the tectonic framework of emplacement of these mafic intrusives, as inferred from their major and trace-element geochemistry, as well as age relationships based on field evidence and four whole-rock K/Ar determinations.

The mafic bodies

Field Setting

Figure 1 shows the location of the two selected study areas in Sierra de Enmedio and Sierra de Carrascoy, respectively. The sampled mafic bodies are intercalated in the Sierra de Enmedio Unit (Espinosa *et al., 1974*; Kozur *et al.,* 1974) of the Sierra de Enmedio (fig. 2), and within the Romero and Carrascoy Units (Kampschuur, 1972) of the Sierra de Carrascoy (fig. 3).

The field appearance of the mafic bodies in both areas is analogous. Most of these do probably represent the remains of discrete sill-like intrusions, with thicknesses that range from metres up to more than 100 metres. Their location in the respective stratigraphic columns (composed basically of Permian-(?) (1). Triassic suites with a predominantly quartzopelitic lower formation and a predominantly carbonatic upper formation; see references above) is variable, although commonly coincides with the occurrence of vertical lithologic discontinuities such as transitions from carbonatic to pelitic members. In fact, only one body was found to be emplaced within a relatively homogeneous sequence of presumable Early Triassic quartzites and phyllitic schists of the S. de Enmedio Unit (fig. 2).

In all instances, the Permian (?)-Triassic sequences enclosing the mafic intrusives bear the imprint of deformation (often complex) and low-grade metamorphic recrystallisation, both of which obviously postdate magmatic emplacement. With regard to deformation, most of the bodies seem to have acted as essentially competent blocks, in comparison with host metasediments, which explains the common disturbance

(1) The question mark refers to the fact that the presence of Permian metasediments is currently regarded as unlikely (cf. Simon and Visscher, 1983).

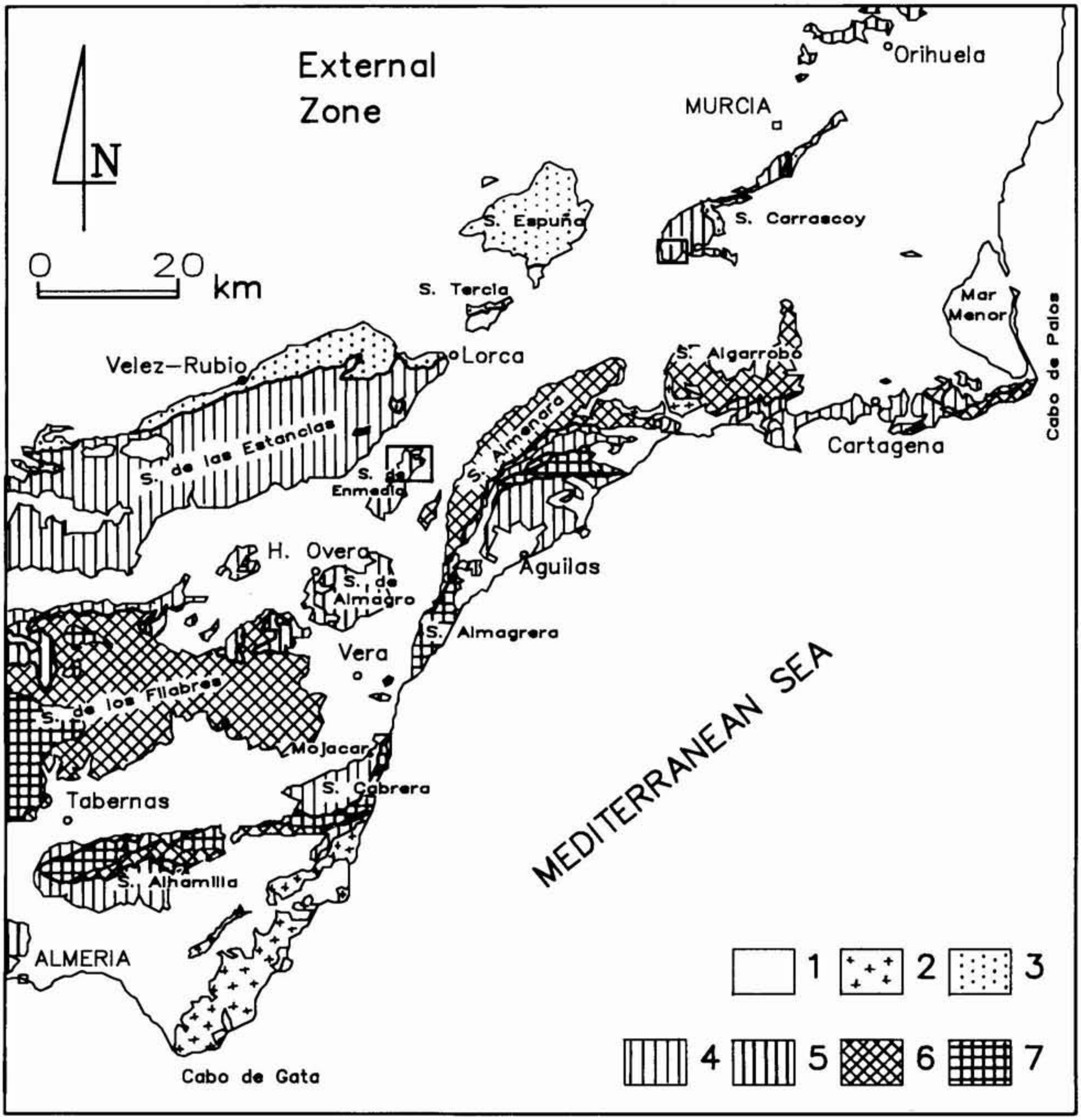

Fig. 1.—Generalized tectonic sketch map of the Eastern Betic Zone, showing the locations of the sampled areas in Sierra de Enmedio and Sierra de Carrascoy (indicated as small rectangles; see enlarged details in figures 2 and 3). Key to ornamentation: 1, post-nappe deposits; 2, Neogene volcanics; 3, malaguide units; 4, median-high alpujarride units; 5, lower alpujarride units (including «almagride» units); 6, Mulhacén Group (Nevado-Filábride Ensemble); 7, Veleta Group (N-F Ensemble). Modified after the compilation of Aldaya *et al.*, (1979; see references therein), with additional data from Díaz de Federico (umpublished), Navarro-Vilá *et al.*, (1984), and Alvarez & Aldaya (1985).

of original contact relationships. One notable exception is a rather large sill (now forming several discrete outcrops) located within the Romero Unit in the Sierra de Carrascoy (fig. 3), whose emplacement produced well preserved small-scale contact effects (porphyritic «chilled» borders, baking of host pelitic rock, local Na-metasomatism, etc. (see Kampschuur, 1972, for more details).

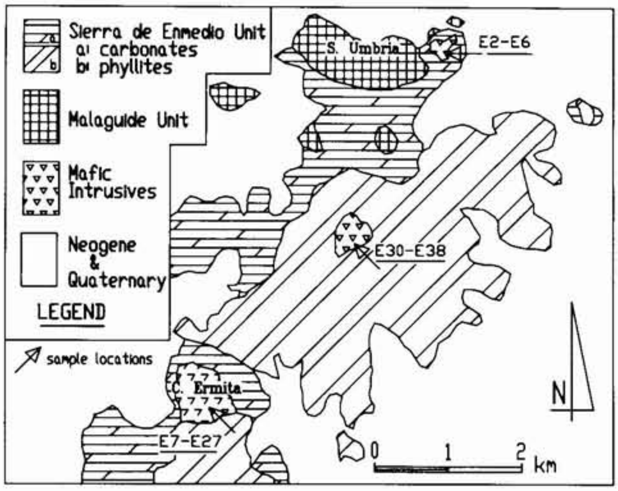

Fig. 2.—Geologic map of the northern half of Sierra de Enmedio (adapted from Espinosa *et al.,* 1974). Sampling localities are indicated by the underlined sample notations (e.g. E2-E6).

Mineral Assemblages

The most abundant type of rock forming the mafic bodies in both Sierra de Enmedio and Sierra de Carrascoy is fine, to coarse-grained dolerite, with textures ranging from doleritic to ophitic or subophitic. In these rocks the main igneous mineralogical constituents are plagioclase (andesine-labradorite) and augite, in some instances accompanied by bronzite. Interstitial micrographic intergrowths of quartz and alkali feldspar are also present, especially in the more differentiated lithotypes where local granophyric textures may develop. Apatite is always present as an accessory constituent. Near intrusive contacts, however, the samples show porphyritic to glomeroporphyritic textures, with olivine and orthopyroxene phenocrysts within a microcrystalline matrix of plagioclase, augite and Fe-Ti oxides.

As a rule, the above mentioned igneous assemblages are partly replaced by metamorphic minerals of different nature, although in most cases the original magmatic texture is well preserved. Thus, serpentine and chlorite pseudomorphs formed after olivine, which in turn have later been replaced by epidote and actinolite. Orthopyroxene shows nearly complete replacement by talc and serpentine. Augite is transformed into variable proportions of hornblendic and actinolitic amphiboles, with exsolution of rutile needles, and/or may be rimmed by a metamorphic greenish clinopyroxene. Most plagioclases have been nearly completely altered and replaced by assemblages of sericitic micas, prehnite, clinozoisite and/or pumpellyite. These metamorphic assemblages are also found within small veinlets, associated with sphene, quartz, calcite and albite. A stronger degree of textural change is shown by some dolerites, grading into decussate amphibolite. In such cases neoformation of albite is common, associated to epidote and actinolitee and, less frequently, to crossite.

Although it is not the purpose of this report to discuss the petrogenesis of the above mentioned secondary assemblages, it is to be noted that the coexistence of actinolite and epidote with pumpellyite indicates metamorphic conditions near the boundary of the greenchist facies with Hashimoto's (1966) actinolite-

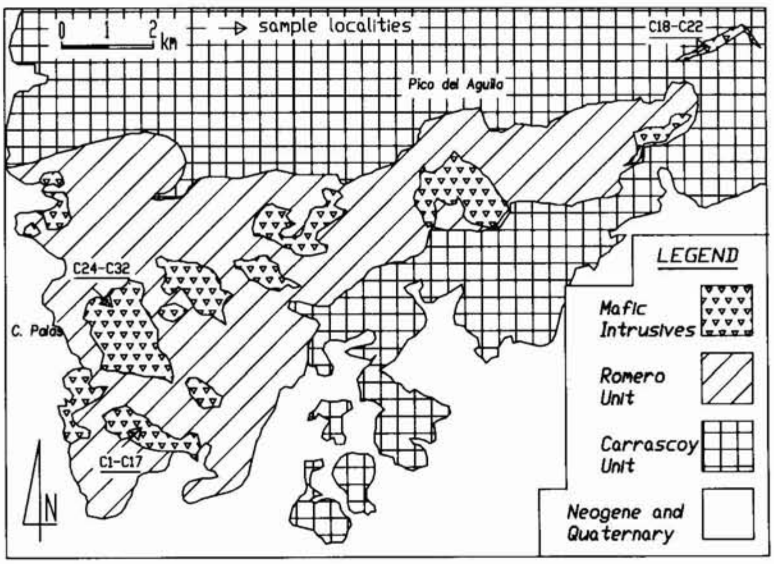

Fig. 3.—Geologic map of the southwestern part of Sierra de Carrascoy (simplified from Kampschuur, 1972). Sampling localities are designated as in figure 2.

pumpellyite subfacies. The generation of this assemblage, together with the occasional presence of crossite (cf. also Wood, 1979), would point to environmental pressures between 3.5 and 5.5 kbar, and temperatures around 350°C. In Sierra de Enmedio the temperature range might have been somewhat higher, as far as in these samples greenchist facies assemblages predominate (devoid of or with scarce pumpellyite), and metamorphic textures are also better developed.

Whole-rock geochemistry

The data corresponding to 19 samples from the Sierra de Enmedio and 16 samples from the Sierra de Carrascoy have been plotted in figures 5, 6, 8 and 12. From these, a selection of 15 major and trace-element analyses, together with their corresponding CIPW norms, are given in table 1. The analyses suggest a moderate range of differentiation for the

Table 1.—**Selected major, and trace-element analyses of mafic intrusives in Sierra de Enmedio and Sierra de Carrascoy**

Locality/sample	Sierra de Enmedio						Sierra de Carrascoy								
	E6	E30	E21	E36	E37	E9*	C12A	C14	C10	C11	C5	C9	C16	C13	C3
SiO_2	49.05	52.11	50.68	51.65	52.59	52.91	51.46	51.30	50.69	50.66	50.40	50.67	49.91	49.38	50.35
TiO_2	0.97	1.04	1.17	1.16	1.91	2.25	1.16	1.15	1.08	0.98	1.20	1.07	1.10	1.07	1.48
Al_2O_3	13.46	12.62	12.94	13.20	12.17	11.53	13.94	13.56	13.94	13.25	13.15	13.87	13.84	13.42	12.78
Fe_2O_3*	11.54	10.18	12.65	12.04	15.78	16.46	9.88	10.66	11.62	11.78	12.13	12.24	12.07	11.51	14.80
MnO	0.18	0.08	0.18	0.15	0.13	0.20	0.13	0.12	0.16	0.19	0.17	0.17	0.19	0.15	0.26
MgO	9.23	7.62	7.61	6.36	4.51	4.03	7.51	8.05	7.35	7.55	7.14	6.46	7.47	7.87	6.64
CaO	8.06	9.30	9.37	9.38	7.66	7.44	8.15	6.02	9.54	8.19	9.82	9.11	8.64	9.10	8.16
Na_2O	3.45	4.54	2.72	2.41	3.34	3.42	4.28	4.04	3.25	2.20	2.64	2.88	2.93	3.64	2.19
K_2O	0.64	0.58	0.85	0.75	0.88	0.79	0.86	1.40	0.74	1.89	0.95	1.66	1.80	0.63	1.10
P_2O_5	0.13	0.12	0.14	0.15	0.25	0.26	0.12	0.12	0.13	0.13	0.14	0.15	0.12	0.11	0.15
L.O.I.	3.29	2.75	2.34	2.24	1.33	1.88	2.63	2.49	2.66	2.56	2.79	2.69	2.05	2.68	2.11
Total	99.26	100.04	99.16	98.56	100.05	99.70	99.66	98.47	100.85	98.66	99.16	99.62	98.35	98.45	98.93
CIPW Norms:															
Q	—	—	—	4.17	3.46	4.40	—	—	—	—	3.46	2.57	1.67	0.38	6.04
Or	3.95	1.10	4.28	4.76	4.79	2.72	4.46	7.38	4.48	14.10	7.74	7.79	10.96	2.92	5.56
Ab	30.47	35.16	19.43	21.66	28.98	29.63	37.47	34.01	28.18	19.23	18.55	20.20	19.80	31.76	15.31
An	20.20	14.78	24.08	22.35	13.60	15.13	17.25	20.55	21.79	23.99	26.12	24.67	24.91	20.18	25.58
Di	16.67	25.96	18.83	21.12	23.08	20.75	19.17	7.85	21.05	13.82	16.06	17.41	15.03	22.94	13.95
Hy	8.51	14.46	23.53	19.14	17.18	17.15	6.33	21.46	13.38	20.20	21.81	21.03	21.25	15.55	25.83
Ol	14.23	2.03	—	—	—	—	8.75	2.39	4.89	2.72	—	—	—	—	—
Mt	2.73	3.97	4.01	4.07	4.89	5.42	3.99	3.91	3.83	3.72	3.86	3.87	3.89	3.84	4.47
Il	1.90	2.24	2.30	2.39	2.45	4.18	2.28	2.16	2.10	1.92	2.09	2.11	2.15	2.10	2.91
Ap	0.34	0.29	0.34	0.34	0.60	0.62	0.29	0.29	0.31	0.29	0.31	0.36	0.34	0.34	0.36
[Mg]	63.3	60.7	53.9	52.5	38.5	36.0	59.6	58.3	55.1	53.9	51.1	50.6	50.4	50.1	46.6
Selected trace-element contents** (ppm):															
Rb	23	—	30	24	50	13	16	38	28	56	31	23	55	13	45
Ba	209	180	224	259	289	296	1.416	976	373	522	250	422	314	265	309
Pb	30	41	31	20	21	135	22	27	50	34	33	57	41	221	26
Sr	447	689	549	363	376	862	733	830	499	358	812	539	431	1.328	457
La	—	12	12	7	17	10	—	9	5	5	17	5	10	10	12
Ce	—	16	—	12	43	—	16	—	—	5	—	—	—	—	—
Y	18	26	22	24	31	32	18	22	22	25	19	30	22	20	27
Th	—	23	9	17	6	7	—	—	1	—	11	4	—	2	16
Zr	103	97	110	109	149	176	92	104	106	89	109	120	110	107	151
Cu	18	—	114	68	332	151	—	44	202	110	91	71	115	40	156
Co	37	20	46	36	43	36	29	47	38	39	43	32	47	33	45
Ni	104	85	85	82	48	35	—	77	91	110	78	82	78	76	64
V	230	259	271	268	839	554	234	292	261	247	298	267	186	295	319
Cr	357	318	257	78	23	66	190	191	287	373	215	159	176	75	70

* Total Fe as Fe_2O_3; ** Determinations by XRF; L.O.I.=Loss on ignition.

rocks of the Sierra de Carrascoy (with [Mg] values between 60 and 46), and a somewhat wider one for those of the Sierra de Enmedio ([Mg] between 64 and 30). Overall, however, both groups of samples have similar chemical compositions and differentiation trends, as it is briefly discussed in next paragraphs.

Figure 4 is a silica versus Zr/TiO_2 diagram, which allows classifying the whole group of rocks as belonging to the family of subalkaline basalts. Individual lithotypes, as defined in the silica versus alkalies diagram (figure 5), may nevertheless range compositionally from subalkaline basalt to basaltic andesite and andesite. Differentiation trends appear to have been clearly tholeiitic (i.e., with strong iron enrichment in the more differentiated rocks; see figure 6) in both series of samples, and was in all probability connected to the early crystallisation of both olivine and bronzite. These are found as phenocrysts in the porphyritic samples found along well preserved intrusive contacts of some bodies. Strong Cr and Ni depletion accompanied the segregation of these early crystallizing phases (figure 7), which was coupled with enrichment in some elements like Cu and V. The latter observation, particularly the «incompatible» behaviour of Cu, are presently regarded as an exclusive feature of continental tholeiites (Dupuy and Dostal, 1984).

Other compositional features point to minor differential aspects between the rocks from Sierra de Enmedio and Sierra de Carrascoy, notably the fact that, for a given silica range, the rocks from S. de Carrascoy have somewhat higher Al_2O_3, K_2O and

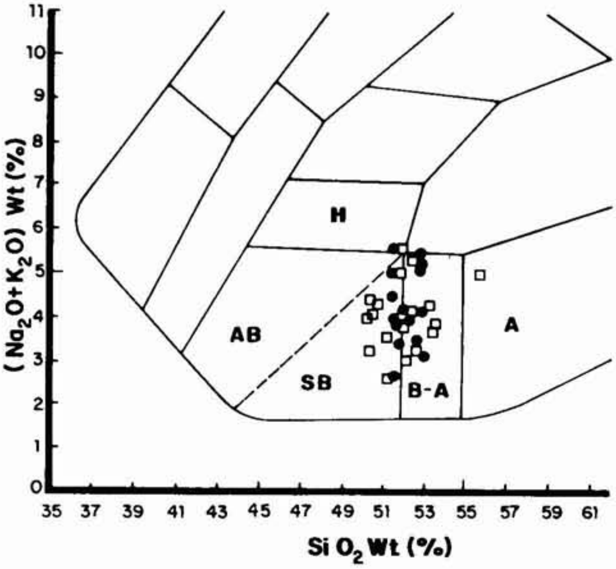

Fig. 5.—Silica versus alkalies diagram (Cox *et al.,* 1979). Plotting symbols as in figure 4. Boundary line between AB (alkali basalt) and SB (subalkali basalt) from Irvine and Baragar (1971). Key to other abbreviations: H=hawaiite; A=andesite; B-A=basaltic andesite.

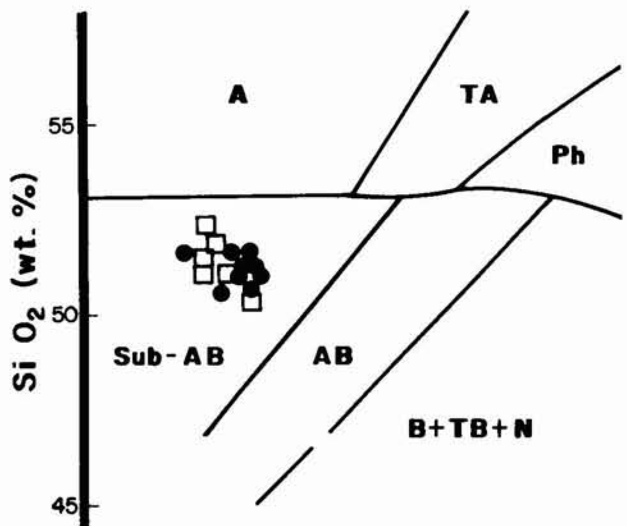

Fig. 4.—SiO_2 versus Zr/TiO_2 plot of the samples from Sierra de Enmedio (open squares and Sierra de Carrascoy (solid circles), indicating their overall subalkaline character. Fields after Winchester and Floyd (1977): Sub-AB=subalkali basalt; AB=alkali basalt; A=andesite; TA=trachyandesite; Ph=phonolite; B=basanite; TB=trachybasanite; N=nephelinite.

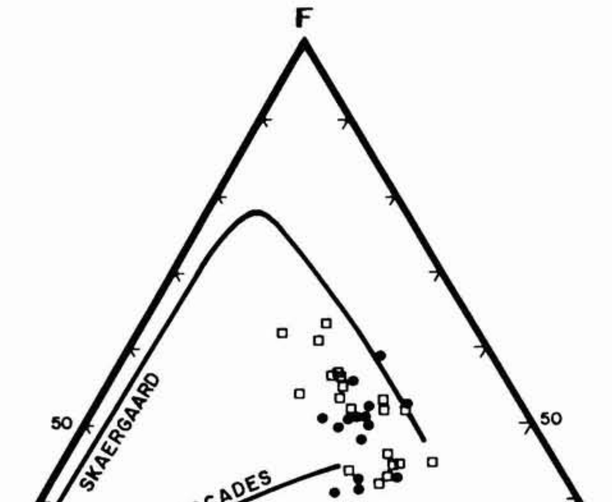

Fig. 6.—AFM plot (An=Na_2O+K_2O; F=FeO_{tot}; M=MgO), showing the overall iron-enrichment (tholeiitic) trend of the mafic suites from Sierra de Enmedio and Sierra de Carrascoy. The noticeable scattering of points towards the A apex is thougth to be at least partly related to heterogenous assimilation of crustal material and/or syn-metamorphic element mobilisation. Note also the wider range of differentiation of the rocks from S. de Enmedio, Symbols as in figure 4.

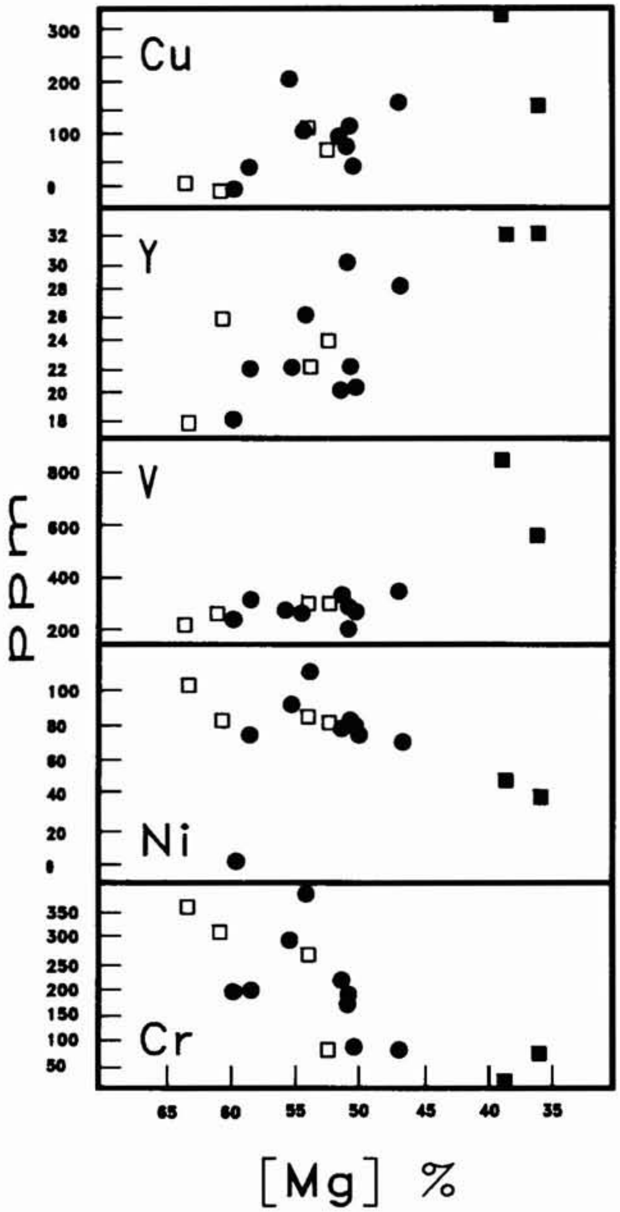

Fig. 7.—Cr, Ni, V, Y and Cu versus [Mg] variation diagrams of the investigated mafic complexes. [Mg] (magnesium number) is calculated as Mg/(Mg+Fe^{2+}), with Fe^{2+} standardized to Fe^{3+}/Fe^{2+}=0.15. Key to symbols: squares: S. de Enmedio (solid squares represent granophyric differentiates); solid circles: S. de Carrascoy.

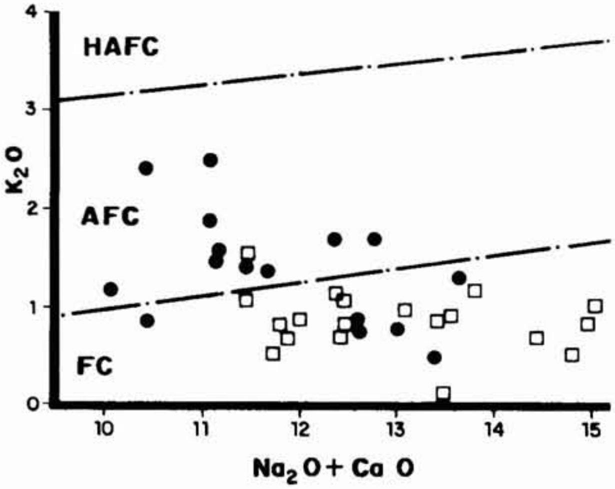

Fig. 8.—K_2O versus $Na_2O + CaO$ plot of the investigated rocks. This diagram separates suites with varying degrees of assimilation versus fractional crystallisation as componental mechanisms of chemical differentiation. Fields after Puga and Portugal (1989). Key to abbreviations refer to inferred main differentiation mechanisms: FC = fractional crystallisation; AFC = fractional crystallisation, plus assimilation; HAFC=high assimilation, plus fractional crystallisation. Symbols as in figure 4.

CaO contents and lower TiO_2 than those from S. de Enmedio. These differences are more clearly illustrated in a plot of K_2O versus Na_2O+CaO (fig. 8). Within this diagram, according to the models of differentiation proposed by Puga and Portugal (1989) for Mesozoic magmatic rocks in the Subbetic Zone, the compositions plotting in the FC field (see fig. 8; in our case most of the samples from S. de Enmedio and less than a half of those from S. de Carrascoy) would have followed mainly a trend of differentiation by fractionated crystal settling. On the other hand, those within the AFC field would also have differentiated mainly through fractionated crystallisation but accompanied by noticeable crustal contamination. In particular, assimilation of pelitic rock is thought to explain the relatively high K_2O, SiO_2 and Al_2O_3 contents in many of the sample, whereas that of small proportions of carbonates and/or gypsum should result in the observed less pronounced decrease of CaO, with differentiation, especially in the rocks from S. de Carrascoy.

Tectonic environment of magma generation and emplacement

The pattern of normalized abundances of incompatible elements is analogous to that of well known continental tholeiitic provinces (figure 9), whose magmas are often enriched in the more incompatible elements (e.g. Ba, Rb, Rb, Th and K; see Dupuy and Dostal, 1984). The Th maximum is particularly typical of these tectonic settings, due to Th leaching from deep crustal rocks while magma is transported towards the surface (cf. Thompson *et al.*, 1982). For comparison purposes, figure 9 also includes the corresponding patterns of mafic rocks («ophites») from the Subbetic Zone, also belonging to a continental province and that of eclogites from the Nevado-Filabride Ensemble

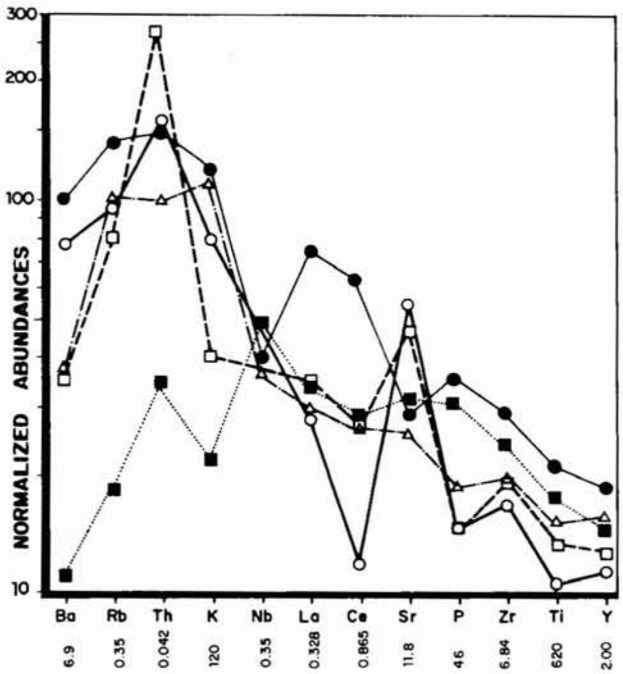

Fig. 9.—Mean normalized incompatible-element abundances of the investigated rocks from S. de Enmedio (open squares) and S. de Carrascoy (open circles), compared to those of a continental tholeiite from the Columbia River province (solid circles), «ophites» from the subbetic (triangles) and eclogitized basalts from the Nevado-Filábride Ensemble (solid squares). Values for the Columbia River basalt were computed after the international standard BCR-1 (Govindaraju, 1984), and those of the subbetic «ophites» and nevado-filábride eclogites after Puga and Díaz de Federico (1988). Normalizing factors used, according to Thompson (1982), are given below each element symbol.

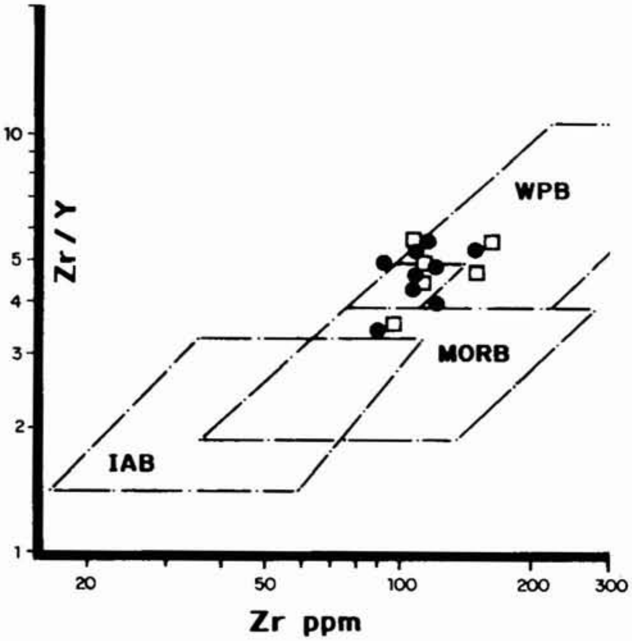

Fig. 10.—Plot of the investigated rocks within the Zr versus Zr/Y diagram, proposed by Pearce and Norry (1979) as indicative of tectonic environment of generation of basalts. Key to abbreviations: WPB = within-plate basalts; MORB = mid-oceanic ridge basalts; IAB=island arc basalts. Symbols as in figure 4.

of the Betic Zone, having a more plain oceanic character (Puga *et al.,* 1988). A further indication of overall intraplate tectonic environment is given by the Zr/Y versus Zr plot (figure 10). As seen, only two (non cumulitic) samples plot outside the within-plate (WPB) field, due to particularly low Zr contents.

Another useful elemental index of tectonic setting is the V/Ti ratio, whose value does not change easily as the result of either alteration or metamorphism (Shervais, 1982). V/Ti ratios of the rocks investigated are rather homogenous in both Sierras (all values comprised between 20 and 40), and are in the range found in both mid-ocean and flood continental tholeiites (figure 11), hence proper of crustal extensional environments. Furthermore, the presence of high absolute amounts of V and Ti as found in one of our samples (a coarser differentiate from S. de Enmedio, with interstitial granophyric intergrowths) appear to be exclusive of continental basalts, such as those of the Columbia River Province.

K/Ar data

In a preliminary attempt to assess age relationships, four total-rock samples from Sierra de Enmedio have been subjected to K/Ar analysis, the data being summarized in table 2. Highly discordant results were obtained, with apparent ages ranging from about 178 Ma (sample E9) to 59-40 Ma (samples E37, E21 and E11).

For one interpretation of these discordant ages, however, it is important to remark that K/Ar results appear to be correlated to the degree of replacement of plagioclases by sericite. Thus, the oldest result is given by sample E9 (178±4 Ma), which consists of an andesine-clinopyroxene coarse-grained differentiate, with granophyric interstitial intergrowths and abundant ilmenite. In this rock the pyroxene appears extensively replaced by actinolite, but plagioclases and K-feldspar granophyric intergrowths are to a large extent well preserved. This contrasts with the other three dated samples where plagioclases show rather advanced degrees of replacement by sericite. Hence, and opposite to the obvious alternative explanation involving possible radiogenic Ar enrichment (e.g., Hebeda *et al.,* 1980), we think that recrystallisation accompanying low-grade metamorphism was in all probability responsible for the observed discrepancies among the four samples dated, via differential argon loss and the concomitant

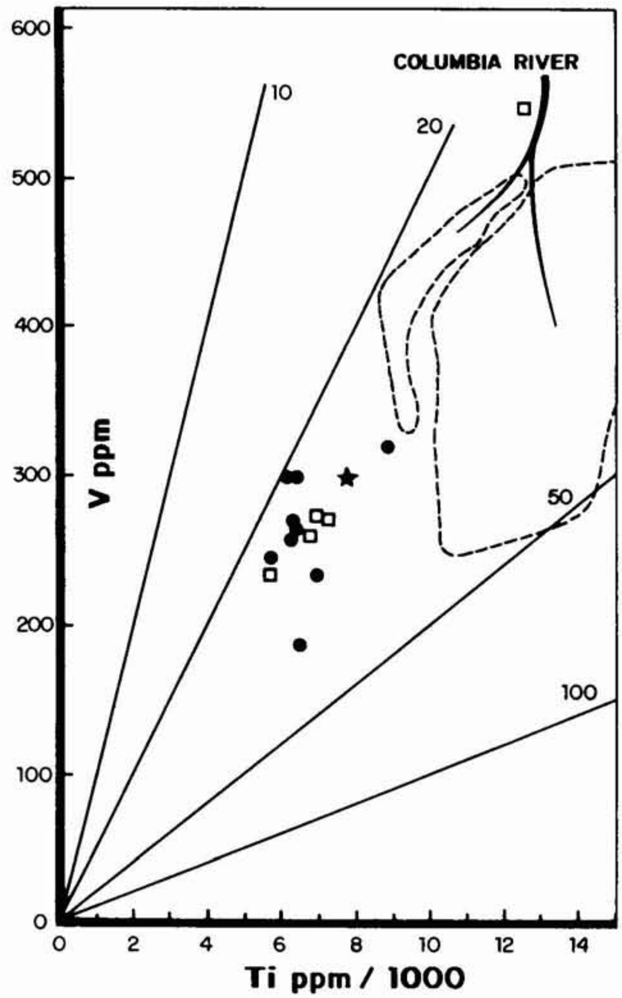

Fig. 11.—V/Ti diagram (after Shervais, 1982), showing the plotting of the investigated metabasics with that of subbetic «ophites» and continental and mid-ocean ridge tholeiites. See text for additional comment. Fields for rocks from the Columbia River province are indicated, as well as for average basalt from the Red Sea axis (asterisk; see sources in Shervais, 1982). Other symbols as in figure 4.

rejuvenation of radiometric dates. The degree to which radiogenic argon was liberated from these systems would hence be related to the intensity of recrystallisation, which we have noted is fairly variable even for samples coming from one and the same outcrop.

The 178±4 Ma datum might thus be taken as a minimum estimate for magmatic emplacement, indicating that intrusion of these bodies took place during Early Middle Jurassic or somewhat older times. A maximum bracket is given by stratigraphic location, within Upper Triassic beds. This interpretation, as opossed to any hypothesis involving Ar enrichment, is also consistent with field evidence as summarized by Kampschuur (1972, p. 43), and interpreted in the

Table 2.—**Analytic results of K/Ar dating (*)**

Sample	K (%)	$^{40}Ar_{rad}$ (ppb)	$\frac{^{40}Ar_{air}}{^{40}Ar_{tot}}$ (%)	Analytic age (Ma)
E9	0.399	5.11	33.4	178 ± 4
	0.394	5.15	33.2	
E11	0.742	2.49	52.9	41.2 ± 5.1
	0.735	1.84	57.4	
		2.07	43.4	
		2.13	56.4	
E21	0.636	2.08	50.3	44.4 ± 2.2
	0.631	1.91	60.8	
		1.92	49.6	
E37	0.587	2.29	44.8	57.9 ± 2.1
	0.586	2.46	51.9	
		2.42	51.5	

(*) Details on the analytical procedures and constants used are given in Puga *et al.* (1988b).

sense that their intrusion affected not yet completely lithified sediments of Upper Triassic age.

The true significance of the remaining much younger estimates is more difficult to assess without additional evidence. The relatively fair concordance among the remaining three dates would however suggest that the metamorphic event(s) (and associated deformation) affecting these units might have taken place during the Middle Eocene, but also in younger times if Ar loss was incomplete during low-grade metamorphism. An Eocene event might be better correlated with similar alpine metamorphic ages from nevado-filabride sequences (cf. Portugal Ferreira *et al.*, 1988; «eoalpine event»), as well as with possible significant tectonic activity in the area (cf. Paquet, 1966, 1974), but again younger metamorphic ages and strong tectonicism are also well known to have taken place in the Betic Zone up to the Early Miocene.

Comparison with other mafic complexes in the Betic Cordilleras

Evidence of significant Mesozoic basaltic activity is known from several places within the Betic Cordilleras, notably in the Subbetic Zone and the Nevado-Filábride Ensemble (see Puga *et al.*, 1988a, b, and references therein). A comparison with these instances is made in figure 12. This plot further illustrates the already noted general trend of potassium enrichment of the rocks investigated (that is even more pronounced in samples from S. de Carrascoy; cf. also figure 8), which we relate to the occurrence of assimilation of pelitic rock. This enrichment in K (and other lithophile elements; see fig. 9) is hence regarded as evidence in the sense that the corresponding magmas must have traversed some extent of continental crust while in their way to final emplacement. These chemical indices of assimilation make these rocks comparable to some of the mafic intrusives (the so-called «ophites») from the Subbetic Zone, whose magmas, also tholeiitic in nature, do bear similar chemical signatures of contamination by continental crustal material. As shown in figure 12, however, this was not the case with meta-

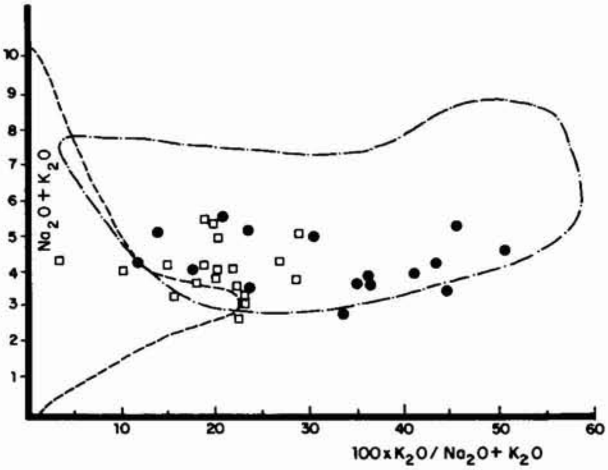

Fig. 12.—Comparison of the alkali ratio versus total alkali content of the investigated metabasics with that of subbetic «ophites» and nevado-filabride eclogites (data from Puga and Díaz de Federico, 1988). Key to fields: discontinuous line=nevado-filabride eclogites; lines and dots=subbetic «ophites». Plotting symbols as in figure 4. See text for additional comments.

basites from the Nevado-Filabride Ensemble, whose generally lower lithophile-element contents are more consistent with an emplacement within an open oceanic environment (Puga and Díaz de Federico, 1988).

Concluding remarks

The study of the mafic complex in the almagride units of the Eastern Betic Zone reveals a two-stage history, related to original igneous emplacement and subsequent metamorphism, respectively.

During the Early Mesozoic, i.e., within a period stretching from the Late Trias to the Early Middle Jurassic, the paleogeographic site of these units was the locus of crustal extension and subcrustal magma generation. The geochemical characters of the ensuing mafic intrusives, especially their relatively high lithophile-element contents, point to some kind of aborted or limited continental rifting as the more probable tectonic scenario of magmatic emplacement. Also, the existence of differences in the degree of ensialic contamination between the two groups of outcrops investigated might be interpreted in terms of variations in the degree of attenuation of continental crust in the corresponding domains. Crustal thinning (related to the extensional event) could have been less pronounced under the depositional area of the Romero unit (S. de Carrascoy) than under the one of the S. de Enmedio Unit, possibly meaning that the two domains were not arranged parallel to the rifting axis.

With regard to the problem of the provenance of the enclosing almagride units (refer to the introductory section), one significant point to be remarked is that these mafic intrusives bear much rassemblance with known hypabissal metabasites from the external zone of the Betic Cordilleras (see above), which is consistent with proposals that correlate these units with the Subbetic in the Murcia area. As a note of caution, nonetheless, it should be remembered that within the subbetic realm submarine volcanics played a significant role, that is absent here, and that the alternative possibility that the mafic bodies investigated could witness either (a) the existence of an independent zone of aborted rifting in the surroundings of the inferred oceanic gap associated to the Nevado-Filabride Ensemble, or (b) the remains of an initial stage of opening of the latter, preserved within one of the separating thinned and faulted continental margins, cannot be completely discarded. The latter hypotheses implying a closer plaleogeographic relationship to the Alpujarride or Nevado-Filabride crustal realms, would in turn be supported by the relatively older time of emplacement of the investigated mafic bodies, as compared with inferred maximum extensional dynamics in the western Tethys during the Middle Jurassic to the Early Cretaceous (cf., e.g., Lemoine *et al.*, 1987).

During the Early Tertiary, both the mafic intrusions and host sedimentary sequences were affected by low grade metamorphism, whose characteristics are not easily explained unless some kind of underthrusting, or analogous process causing deep burial under a moderate temperature regime, is invoked. Torres-Roldán (1979, p. 38) suggested that one possible explanation might be their dragging down (or underplating) in relation with one possible Late Cretaceous to Early Tertiary subduction event, that was postulated responsible for the eoalpine high-pressure assemblages in the Nevado-Filabride Ensemble (cf. also Díaz de Federico *et al.*, 1979). This notion would appear consistent with our metamorphic K/Ar dates, although the precise tectonic setting of the metamorphism remains now more open given the fact that LT-HP assemblages are presently known to occurr also in both the subbetic (Puga *et al.*, 1983, 1988b) and alpujarride (Goffé *et al.*, 1988) sequences.

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