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The intra-orogenic Soportújar Formation of the Mulhacén Complex: Evidence for the polycyclic character of the Alpine orogeny in the Betic Cordilleras

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Key words: Betic Cordilleras, Mulhacén Complex, Soportújar Formation, Alpine orogeny, calc-alkalin magmatism, intra-orogenic sediments

ABSTRACT

The Soportújar Formation makes up part of the Mulhacén Complex, which crops out in southeastern Spain below the Alpujárride and Maláguide Complexes of the Betic Cordilleras. This formation constitutes a discontinuous level several metres to tens of metres thick, formed by continental and evaporitic metasediments and by calc-alkaline basaltic andesites, dated as Paleocene, intercalated between several tectonic units of the Mulhacén Complex. The deposition of this formation and the development of its calc-alkaline magmatism took place between the eo-Alpine (Upper Cretaceous) and the meso-Alpine (Oligocene) metamorphic events, as is evidenced by the character of its conglomeratic levels, which contain Mesozoic polymetamorphic clasts from different units of the Mulhacén Complex in a monometamorphic matrix, as well as by K-Ar dating of its meta-andesites.

RESUME

La formation Soportújar fait partie du Complexe du Mulhacén qui affleure au Sud-Est de l'Espagne sous les Complexes Alpujarride et Malaguide. Cette formation constitue un niveau discontinu, de quelques mètres à plusieurs dizaines de mètres d'épaisseur, formé par des métasédiments continentaux et évaporitiques, et par des andésites basaltiques calcoalcalines datées du paléocène. Il est intercalé entre plusieurs unités tectoniques du Complexe du Mulhacén. Le dépôt de cette formation et le développement de son magmatisme calco-alcalin eurent lieu entre les événements métamorphiques éo-alpin (Crétacé Supérieur) et méso-alpin (Oligocène), comme il est mis en évidence par le caractère de ses niveaux conglomératiques, qui contiennent des clasts Mésozoïques polymétamorphiques, venant de diverses unités du Complexe du Mulhacén, dans une matrice monométamorphique, et par la datation radiométrique de ses métaandésites.

Introduction and geological setting

The Soportújar Formation (SF) (Puga et al. 1984), also known as the Intraorogenic Formation (Puga & Díaz de Federico 1978), forms part of the Mulhacén Complex (MC) in

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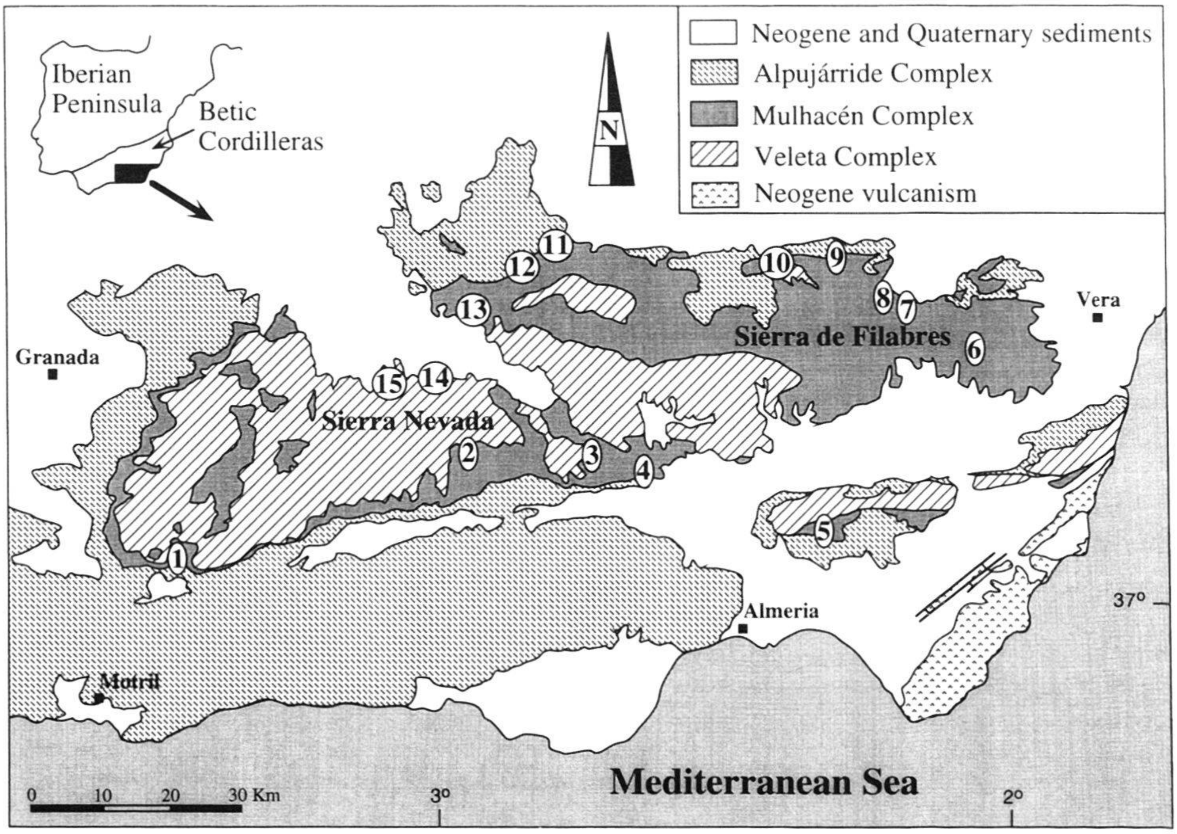


Fig. 1. Geological sketch map of the central-eastern sector of the Betic Cordilleras, showing the location of the following studied outcrops: 1 = Soportújar, 2 = Cerro del Almirez, 3 = Ohanes, 4 = Alboloduy, 5 = Baños de Sierra Alhamilla, 6 = Lubrin, 7 = Cóbdar, 8 = Lijar, 9 = Macael, 10 = Sierro, 11 = Bastidas, 12 = Fuente Fría, 13 = Las Piletas, 14 = Dólar and 15 = Cardal. Limits between complexes according to geological maps 1 : 50.000 of the MAGNA series and A. Diaz de Federico's unpublished data.

the Betic Cordillera. This complex and the underlying Veleta Complex are the deepest units of the Internal Zones of the Betic Cordilleras and crop out in a series of tectonic windows below the Alpujárride and Maláguide Complexes (Fig. 1). The geological characteristics of these complexes and their relative positions resemble the superposition of the Austroalpines over the Penninic nappes in the Tauern or Engadine windows of the central Alps, as was first suggested by Brouwer (1926).

The MC (Puga & Díaz de Federico 1978) is part of the previously named Nevado-Filábride Complex (Egeler 1963), and is formed by a pile of thrust nappes of crustal origin, composed of Paleozoic basements and Mesozoic covers, among which a Jurassic-Cretaceous nappe originating from an oceanic floor is intercalated (Hebeda et al. 1980; Portugal et al. 1988; Tendero et al. 1993). This nappe is made up of all the elements of a dismembered ophiolitic association, known as the Betic Ophiolitic Association (BOA) (Puga 1990; Puga et al. 1989a, 1995). The metamorphism of this complex took place in a convergent plate margin via two subduction processes, which affected the oceanic floor and its overlying sediments as well as the rocks of the contiguous continental margins. This metamorphism developed fundamentally during two events: the eo-Alpine (Late Cretaceous) and the meso-Alpine (Oligocene), which gave rise to the development of low and intermediate gradient facies respectively (Puga et al. 1989b, 1995). Between these two events, there was a relaxation period during which a quick exhumation of the previously subducted materials must have taken place to allow the good preservation of the high pressure (HP) paragenesis, especially in the basic and ultrabasic rocks making up the oceanic floor and in the metasediments with metabasite layers deposited on this floor. A similar relaxation period has been recorded in the Alps by Trümpy (1973), Hunziker & Martinotti (1984), Deville (1990), Steck & Hunziker (1992), Ballèvre & Merle (1993) and Froitzheim et al. (1995), among others.

The constitutive materials of the MC covers have usually been considered as belonging to the Permo-Triassic or Triassic, due to of a lithological similarity with stratigraphically dated series in the overlying Alpujárride and Maláguide Complexes, and also because a sedimentary hiatus between the Triassic and the Miocene has generally been presumed in this complex (Fallot 1948; Egeler & Simon 1969; Simon & Visscher 1983). Recently, however, remains of probable foraminifera of Cretaceous age have been identified in the metasedimentary sequence of the BOA (Tendero et al. 1993), which present similar lithological characteristics to the "schistes lustrés", overlying the Alpine ophiolites (Lagabrielle et al. 1984; Deville et al. 1992), dated as Late Cretaceous by Lemoine et al. (1984). Meanwhile, the underlying metabasites, some of which alternate as pyroclastic and volcanic levels intercalated in the metasedimentary sequence of the BOA, have been dated as Early to Late Jurassic (Hebeda et al. 1980; Portugal et al. 1988; Puga et al. 1995). Moreover, the SF constitutes a discontinuous level in the upper part of several MC tectonic units, formed by continental metasediments and andesitic *s.l.* metavolcanites, which have been dated by K/Ar as Paleocene (Tab. 3). A comparative study of the tectono-metamorphic evolution of this formation with that of other materials composing the MC covers, leads us to believe that the deposition of its sediments and the coeval magmatism took place between the eo-Alpine and meso-Alpine metamorphic events (Puga & Díaz de Federico 1978; Díaz de Federico 1980; Díaz de Federico et al. 1980, 1990). A pyroclastic, intra-orogenic volcanism of similar age to that present in the SF, accompanied by carbonate deposits and overlain by Eocene pelites, has been identified by Deville (1990) in the Grande Motte Unit in the French Alps and interpreted by this author as the consequence of a distensive stage in the Alps, which occurred between the eo-Alpine and the meso-Alpine metamorphic events.

The aim of this paper is to describe the lithological, geochemical and geochronological characteristics of the SF in the MC that have led us to consider it as an intra-orogenic formation (Puga & Díaz de Federico 1978; Puga et al. 1984) and to emphasize its great geological importance in the establishment of the polycyclic evolution of the Alpine orogeny in the Betic Cordilleras.

Field relations and lithological peculiarities

The SF constitutes a discontinuous guide level and is present throughout the entire extent of the MC (Fig. 1), with peculiar lithological features that allow us to differentiate it from the other formations in this complex. Figure 2 shows a synthetic lithological column of the SF composed from the different partial sequences of this fomation cropping out in the vicinity of the localities indicated in figure 1. The secondary thickness of this forma-

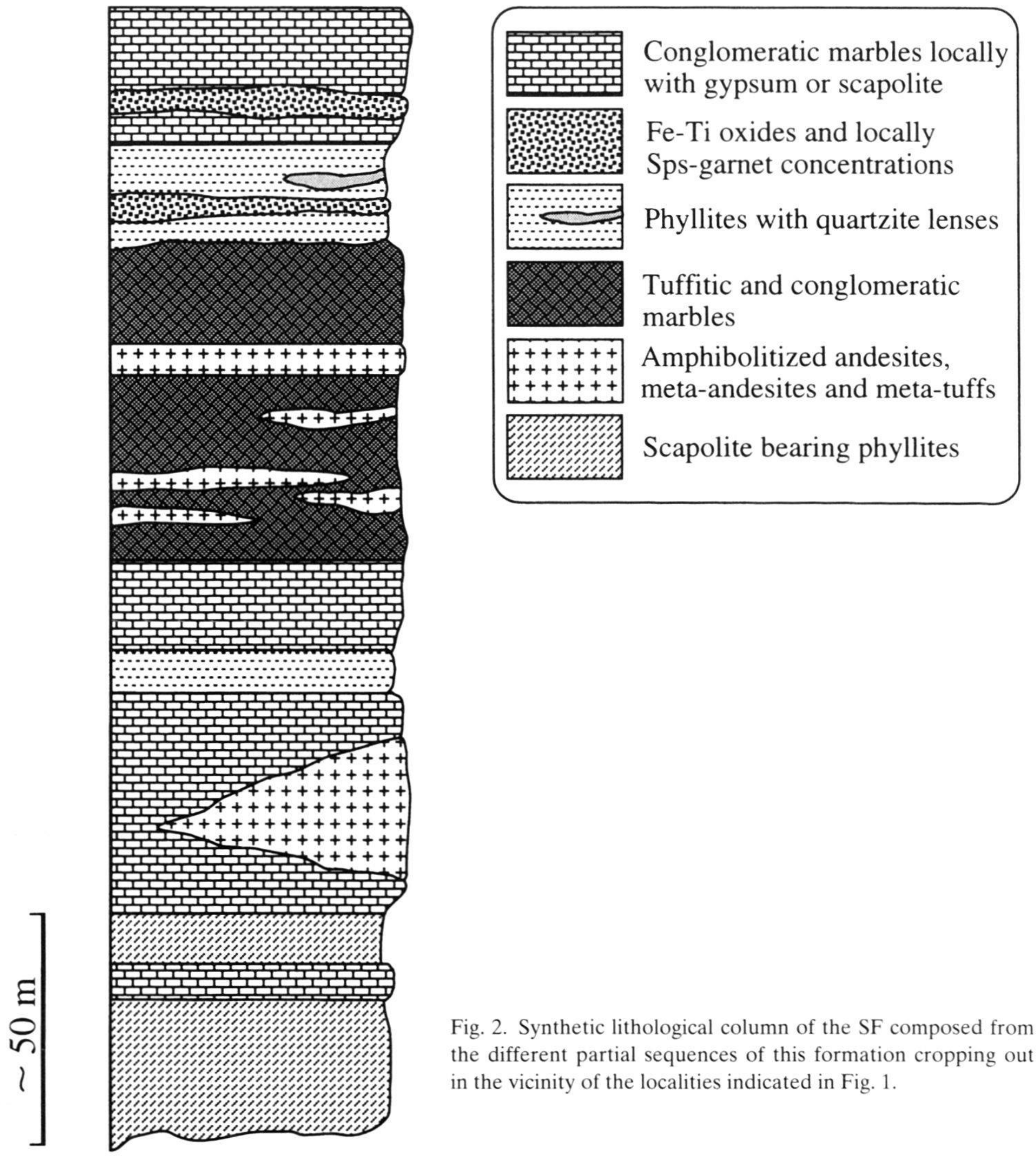


Fig. 2. Synthetic lithological column of the SF composed from the different partial sequences of this formation cropping out in the vicinity of the localities indicated in Fig. 1.

tion varies from several metres to tens of metres, although in some outcrops, such as Alboloduy, it can reach up to 200 m. This formation is found tectonically intercalated between different MC tectonic units and between the latter and the overlying Alpujárride Complex. It seems to have been unconformably deposited onto metamorphosed rocks (Fig. 3 top), either oceanic in origin (ophiolites) or constituent of the continental cover MC formations, though the primary contacts have very often been modified by the Tertiary meso-Alpine and neo-Alpine tectonic stages.

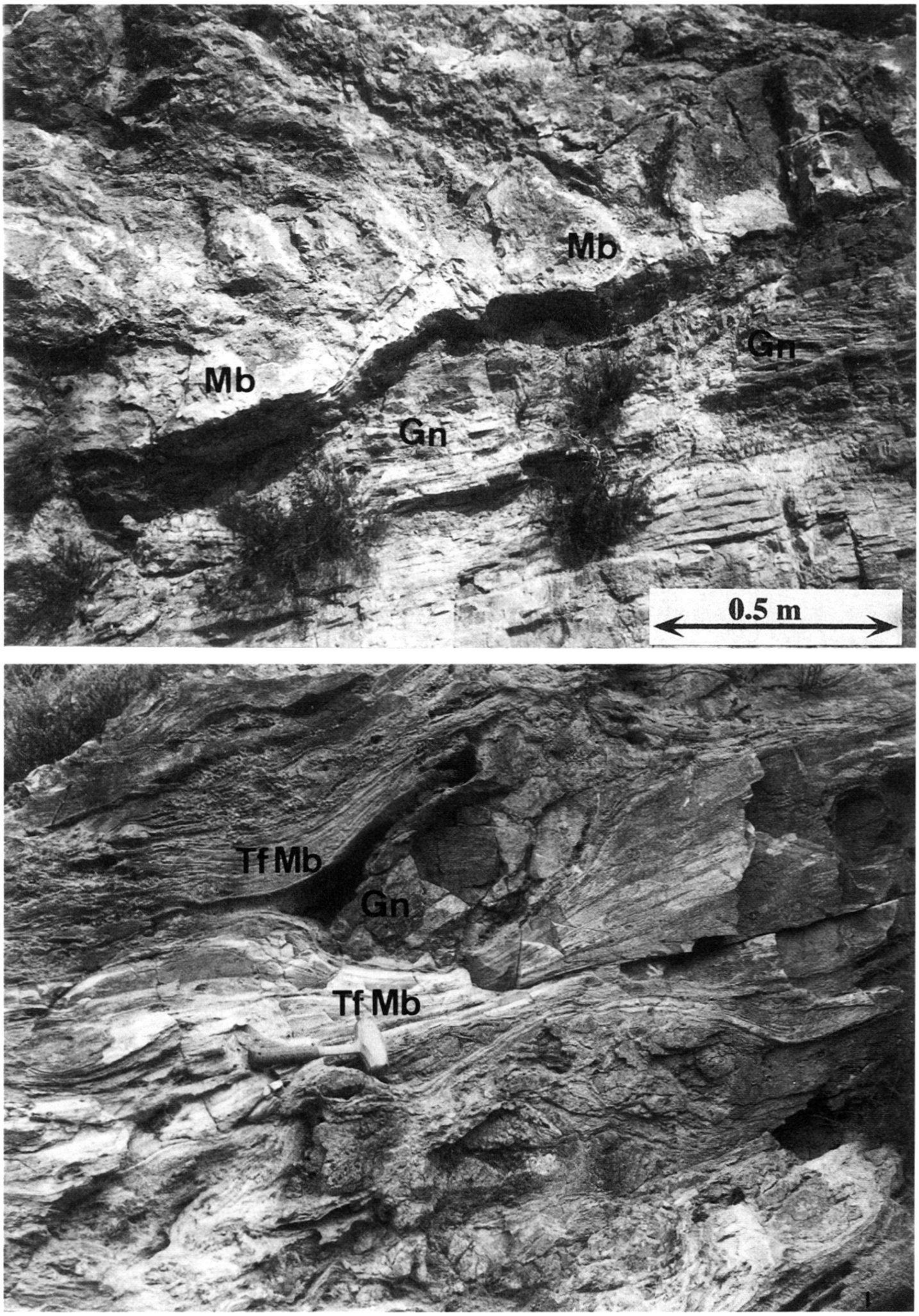


Fig. 3 top. Unconformity between the conglomeratic marbles (Mb) of the SF and Triassic ortho-gneisses (Gn) of the uppermost unit of the MC showing axial plane schistosity. Lijar outcrop. 3 bottom. Metric fragment of Triassic orthogneiss (Gn) embedded in a tuffitic marble (Tf Mb) showing isoclinal folds in the upper left adaptation zone of the host rock around the fragment. Soportújar outcrop.

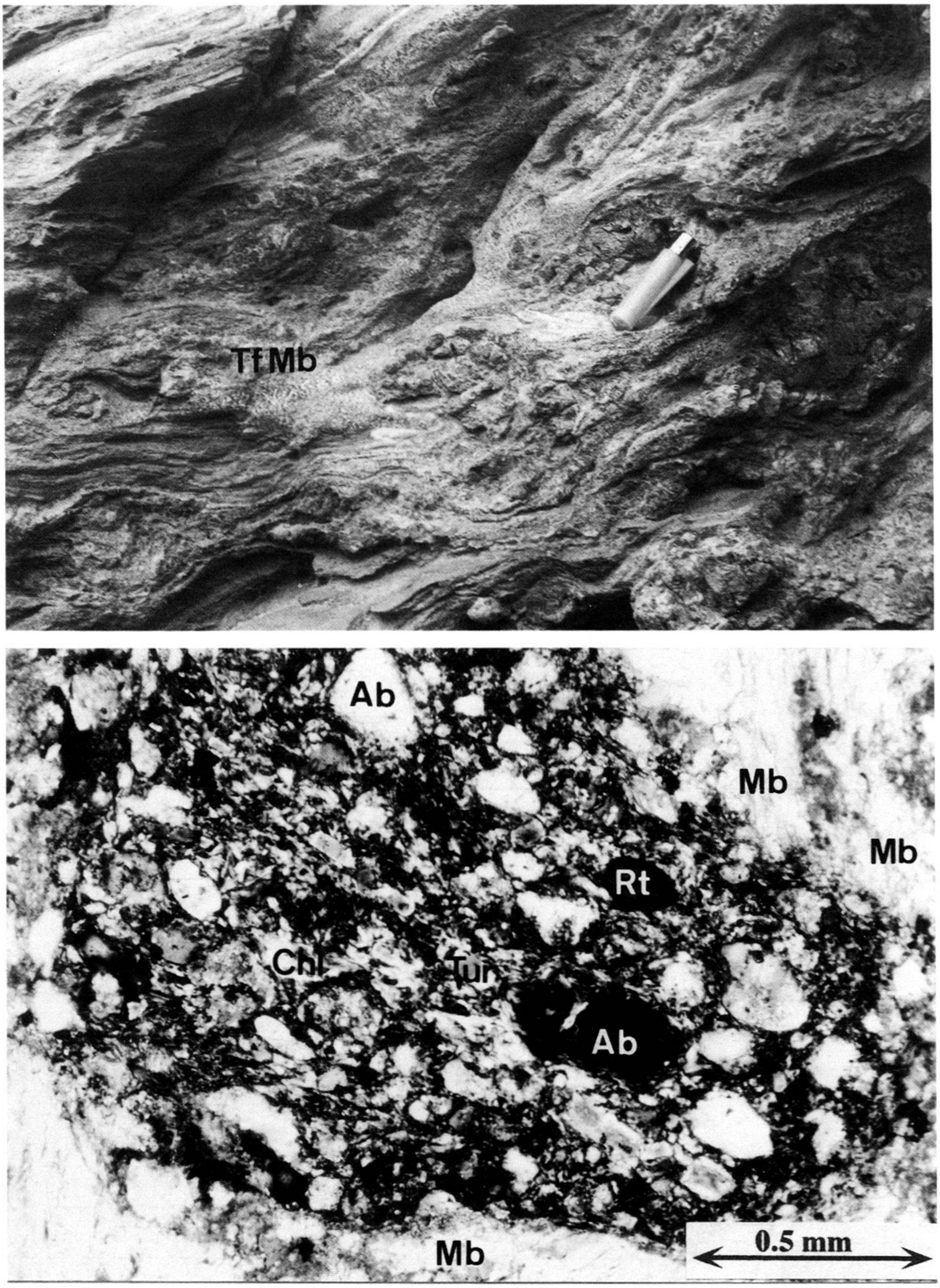
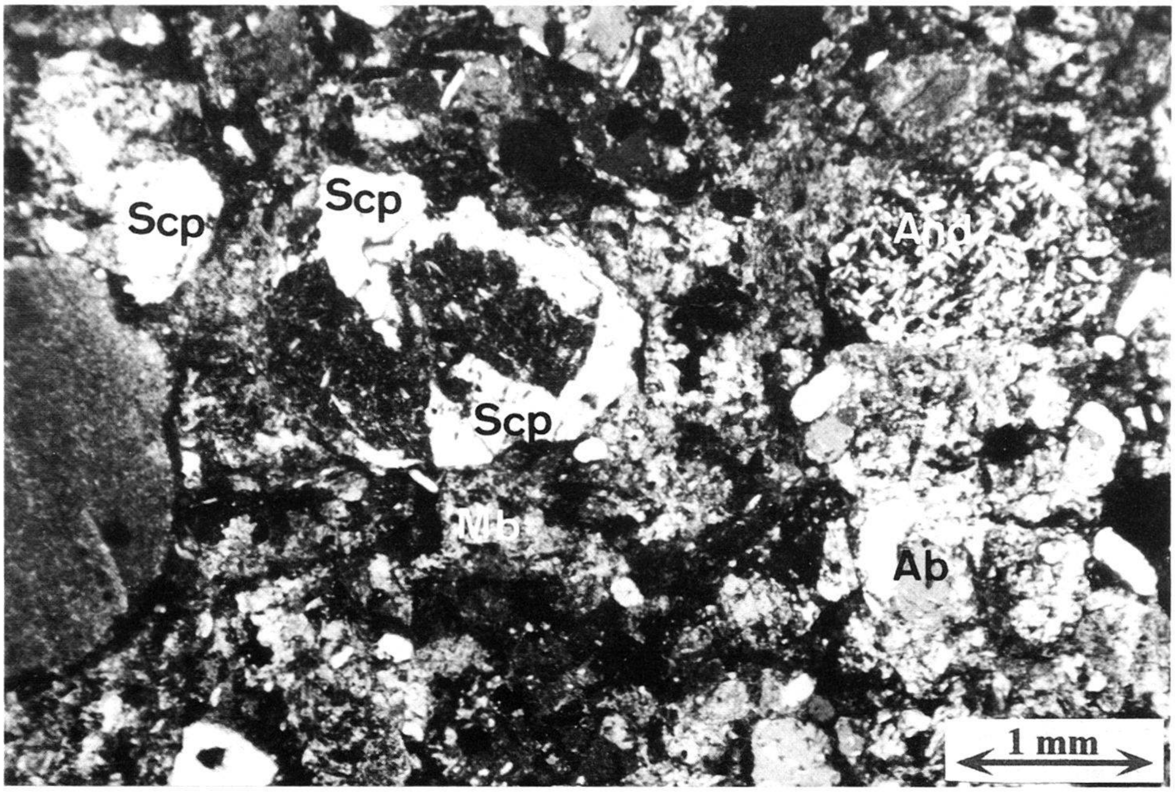


Fig. 4 top. Conglomeratic and tuffitic marble (Tf Mb) of the same outcrop as Fig. 3 bottom. The pyroclastic material forms abundant millimetric green pebbles (dark grey points in the photo), which are more concentrated at some levels indicating the original layering. 4 bottom. Albite-bearing, chlorite-schist pebble, rich in rutile and elbaite, surrounded by carbonate, resulting from the meso-Alpine metamorphism of the pyroclastic andesitic material scattered within the tuffitic marble shown in Fig. 4 top. Mineral abbreviations after Kretz (1983).



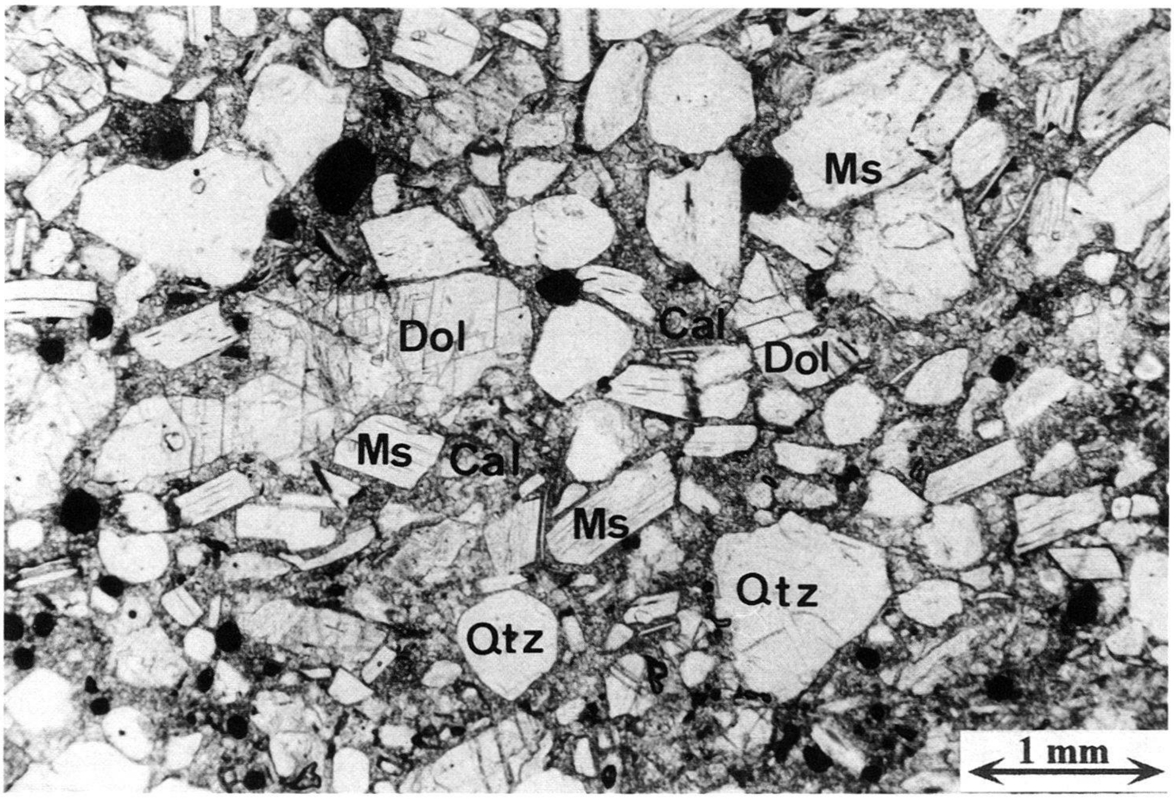
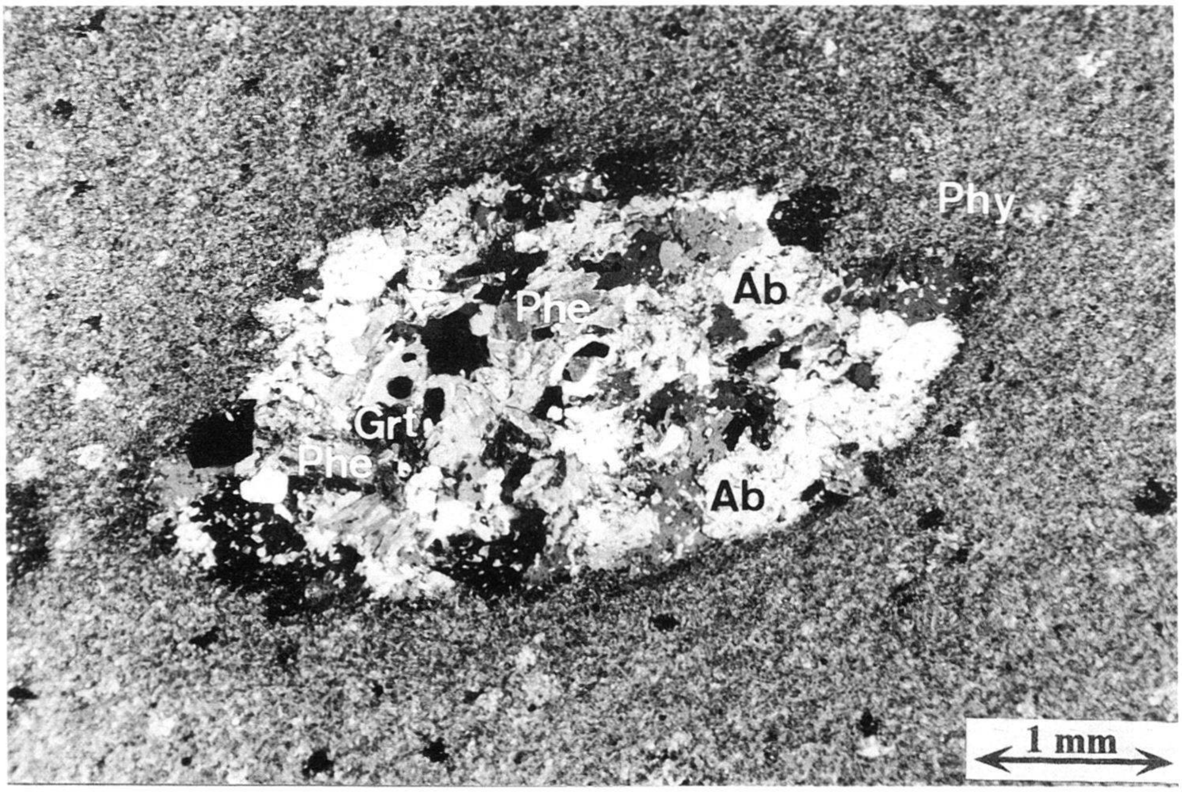


Fig. 5 top. Conglomeratic marble from the Lijar outcrop containing irregular millimetric clasts of meta-andesite (And, upper right corner) and very fine grained carbonate (Mb, centre and left) partially corroded by scapolite poeciloblasts. 6 bottom. Conglomeratic marble from the Cerro del Almirez outcrop made up of clasts of dolomite and other detrital millimetric minerals, coming from different MC units, in a much more fine-grained calcite matrix.



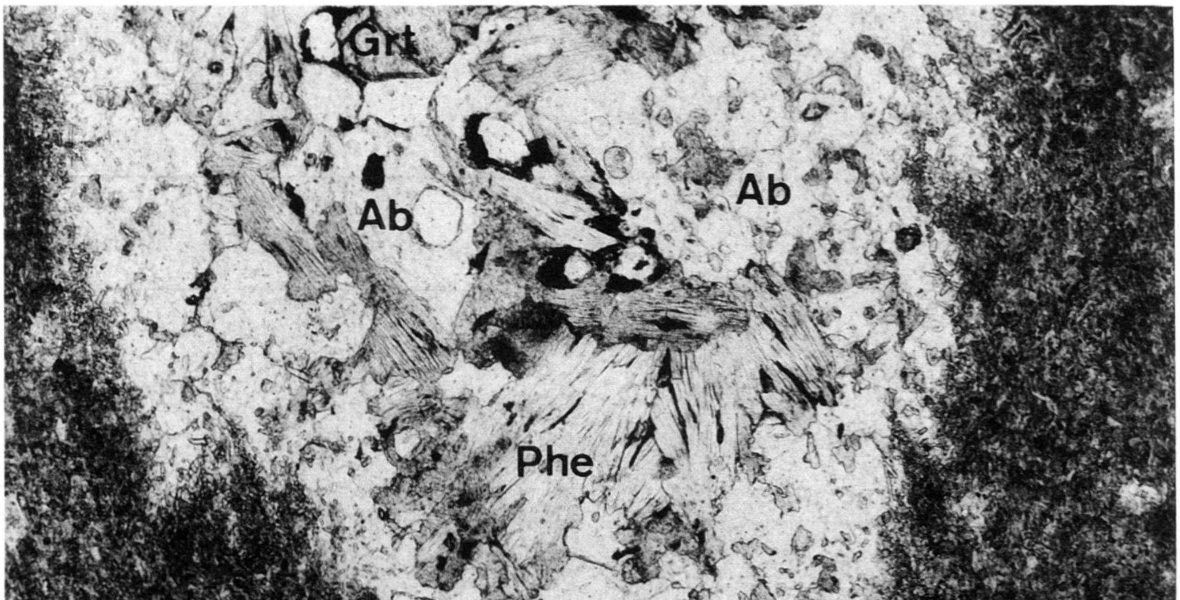


Fig. 6 top. Millimetric clasts of albite-garnet-bearing micaschists, coming from the sedimentary sequence of the BOA, dispersed in a fine-grained biotite-scapolite-bearing phyllite. Cóbdar outcrop. 7 bottom. Detail of Fig. 7 top showing the notable difference in grain size between the micaschist clast and the surrounding phyllite and the partial corrosion of the minerals around the border of the clast by the host rock during the meso-Alpine metamorphism.

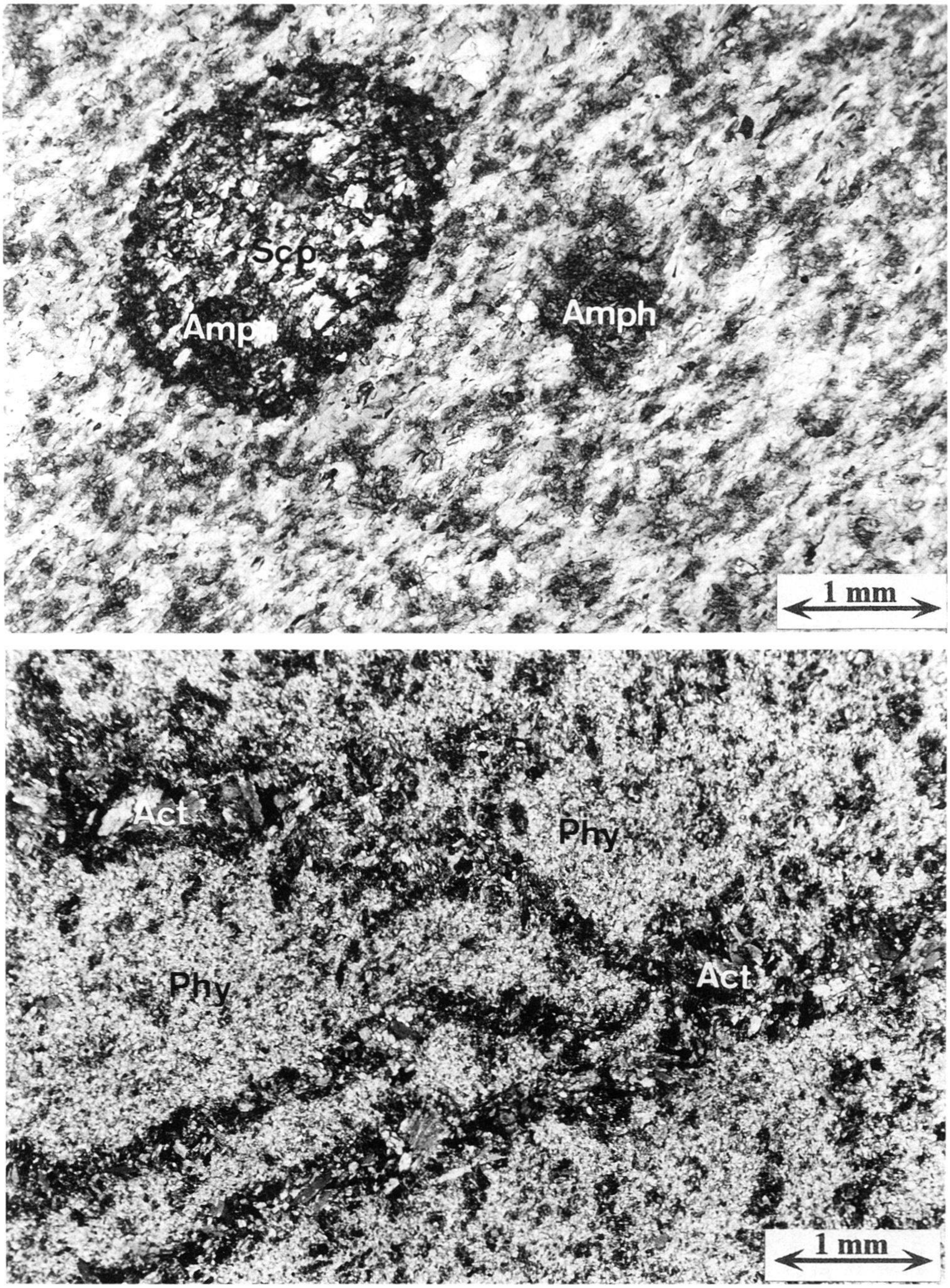


Fig. 7 top. Biotite – albite – Na-Ca amphibole bearing phyllite with phengite, rutile and elbaite in the matrix, containing millimetric scapolite poeciloblasts richer in meionite towards the rims. Cóbdar outcrop. 7 bottom. Paragonite-talc-bearing phyllite rich in actinolitic hornblende, showing irregular veins filled by the same matrix minerals recrystallized with larger grain size. Cóbdar outcrop.

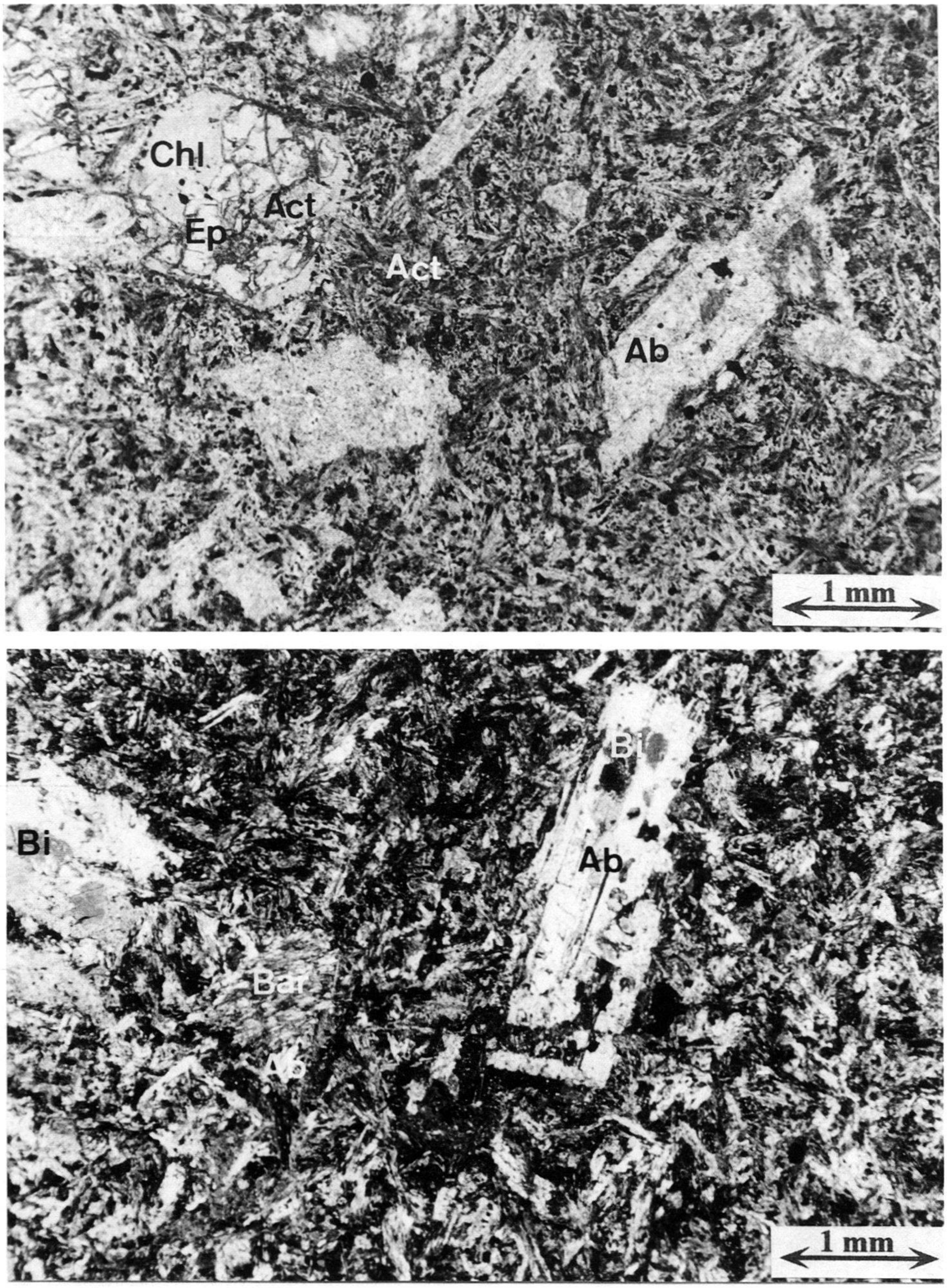


Fig. 8 top. Meta-andesite from Ohanes outcrop showing the preserved microporphyric texture with intergranular to variolitic matrix. The pyroxene phenocrysts are replaced by epidote, chlorite and minor actinolite and the plagioclase ones by albite, in a matrix made up of actinolite, albite and ore. 8 bottom. Amphibolitized andesite made up of Na-Ca amphibole paragenetic with albite, sphene, epidote and green biotite, replacing the igneous paragenesis and preserving the microporphyric texture with plagioclase phenocrysts. Bastidas outcrop.

The more distinctive peculiarities of the SF with respect to the other MC formations are illustrated in Figures 3 to 8, and may be summarized as follows:

1) The presence of conglomerates containing metamorphic detrital minerals and millimetric to decametric pebbles and/or boulders of metamorphic rocks, supplied from the covers of the other MC tectonic units (Fig. 3 bottom and 4 to 6).
2) The presence of phyllites instead of micaschists, originating from pelitic and tuffitic sediments, a consequence of the lesser metamorphic grade attained by all the lithotypes in this formation (Fig. 6, 7).
3) Its simpler metamorphic evolution, consisting of a unique metamorphic event with physical conditions similar to the Oligocene meso-Alpine event in the other MC units, with the exception of the conglomerate clasts in which relics of a high-pressure eo-Alpine event, dated as Late Cretaceous, are also preserved (Fig. 6).
4) The presence of gypsum and other evaporitic minerals, such as elbaite and scapolite, in its metasediments (Fig. 5 top and 7 top). Scapolite may also be present in the host rocks of this formation, although restricted to its contacts, indicating local metasomatism accompanying the metamorphic processes.
5) The andesitic s.l. composition of its ortho-derived rocks, which have been transformed into chlorite-schists, meta-andesites or amphibolites (Fig. 4 bottom and 8).

Depositional environment

The depositional environment of the SF is continental, throughout the extension of the MC, as suggested by the oxygen and carbon isotopic signature of its carbonatic rocks, with $\partial^{18}O_{PDB}$ values ranging from –6.32 to –12.16 and $\partial^{13}C_{PDB}$ values from –0.46 to –7.39 (Tab. 1a and Fig. 9). This isotopic signature is clearly different from those corresponding to the marbles coming from the other MC formations in which $\partial^{18}O_{PDB}$ vary from –3.3 to –13.4 and $\partial^{13}C_{PDB}$ from –1.19 to 3.1, values that indicate a marine origin (Tab. 1b and Fig. 9).

Some SF marbles, such as those shown in figure 5 bottom, contain, within a fine-grained calcitic matrix, detrital minerals with a higher grain size, similar to those making up the sedimentary sequence of the BOA underlying this formation in the Cerro del Almirez (Fig. 1). The dolomitic clasts, the calcitic matrix and the whole rocks from these conglomeratic marbles (ZM-49, 52 and 76, Tab. 1a) have been separately analyzed, and their isotopic values are plotted in Fig. 9, in which C_1, C_2, C_3 correspond to the dolomitic clasts, M_1, M_2, M_3 to their respective matrices, and points 1, 2, 3 (along the jointing lines C-M) represent mixed isotopic values for the whole rocks. This figure confirms the marine nature of the dolomitic clasts, which could proceed either from the underlying sedimentary sequence or from other MC units and the continental nature of the matrix of the conglomeratic marbles that make up part of the SF.

The relative depletion of the $\partial^{18}O$ values of the MC marbles, plotted in figure 9, with respect to the marine and continental carbonate fields used as references, which nevertheless do not prevent the recognition of their original environment, may be due to the metamorphic reequilibration of these carbonates under increasing temperature conditions, as has been suggested by Weissert & Bernoulli (1984) and Baker (1990) for other metamorphic regions.

Table 1a. Samples of carbonates coming from the SF. Abbreviations after Kretz (1983).
Table 1b. Samples of carbonates coming from the different MC tectonic units. Abbreviations after Kretz (1983), except for: Amph = amphibole and Fuchs = fuchsite.

Sample	Locality	Type of rock analyzed	Mineralogy	$\partial^{13}C$ PDB	$\partial^{18}O$ PDB
JAT-17	Alboloduy	Fine-grained marble with Gp	Dol matrix, scarce grains of Cal, Gp	**−3.84**	**−12.16**
JAT-64	Alboloduy	Fine-grained conglomeratic marble	16% Dol grains in a Cal matrix	**−4.45**	**−9.65**
JAT-77	Alboloduy	idem	Ank matrix with scarce Cal grains	**−5.37**	**−10.40**
JAT-79	Alboloduy	idem	23% Dol grains in a Cal matrix	**−0.46**	**−8.62**
ZM-49	Almirez	Fine-grained conglomeratic marble	71% Dol + Ank grains, Cal matrix	**−2.23**	**−8.46**
		Separated clasts from ZM-49	Dol + Ank	**−0.90**	**−9.08**
		Matrix of ZM-49	Cal	**−6.88**	**−7.79**
ZM-52	Almirez	Fine-grained conglomeratic marble	69% Dol grains in a Cal matrix	**−2.70**	**−10.01**
	Almirez	Separated clasts from ZM-52	Dol	**−0.85**	**−11.00**
	Almirez	Matrix of ZM-52	Cal	**−7.30**	**−7.80**
ZM-76	Almirez	Fine-grained conglomeratic marble	42% Dol grains in a Cal matrix	**−5.16**	**−10.31**
	Almirez	Separated clasts from ZM-79	Dol	**−2.43**	**−13.64**
	Almirez	Matrix of ZM-79	Cal	**−7.14**	**−7.90**
ZL-81	Almirez	Fine-grained calcitic marble with scarce clasts of Dol	Cal, Dol	**−6.67**	**−9.18**
7-CB	Cóbdar	Conglomeratic marble with phyllite fragments	Cal, Ms, Ky	**−7.39**	**−6.36**
PECO-109	Cóbdar	Fine-grained marble	Cal, Ms, Scp	**−4.88**	**−6.32**
SOP-1	Soportújar	Tuffitic marble with Cal matrix	Cal, Chl, Ab, Rt	**−5.81**	**−10.33**
C-35B	Ohanes	Fine-grained marble	Cal	**−2.5**	**−6.8**
FI-6	Soportújar	Tuffitic marble with Cal matrix	Cal, Chl, Ab, Rt	**−6.56**	**−9.17**

Sample	Locality	Tectonic Unit	Type of rock analyzed	Mineralogy	$\partial^{13}C$ PDB	$\partial^{18}O$ PDB
ZM-6	Almirez	BOA	Marble in serpentinites	Dol, Tr, Zo	**1.44**	**−8.56**
ZM-12	Almirez	BOA	idem	Dol, Ms, Qtz	**0.87**	**−5.42**
ZM-66	Almirez	BOA	idem	Dol, Tr, Fuchs	**0.36**	**−5.87**
ZM-93	Almirez	BOA	idem	$Dol_{20}Cal_{80}$, Ms, Qtz	**0.25**	**−6.82**
ZM-94	Almirez	BOA	idem	$Dol_{40}Cal_{60}$, Ms, Qtz	**0.52**	**−10.49**
ECO-74	Cóbdar	BOA	Marble in calc-schists	Cal, Ms, Qtz, Ab	**−0.41**	**−9.15**
COB-11	Cóbdar	BOA	idem	Dol, Ab, Ms	**−0.48**	**−5.18**
COB-1	Cóbdar	BOA	idem	Cal, Ms, Qtz, Ab	**2.28**	**−6.68**
AA-42	Cóbdar	BOA	idem	Cal, Ms, Ep, Qtz, Ttn	**0.92**	**−8.70**
FC-7A	Cóbdar	BOA	idem	Cal, Ms, Qtz	**0.92**	**−8.72**
DL-4	Lubrin	BOA	Marble in metabasites	Cal, Qtz, Amph	**−0.95**	**−11.56**
DL-11	Lubrín	BOA	idem	$Dol_{97}Cal_{3}$, Ab	**2.41**	**−13.06**
SM-9	Santillana	BOA	Marble in serpentinites	Dol, Tr	**2.03**	**−4.51**
CB	Cóbdar	Sabinas	Marble in metapelites	$Cal_{97}Dol_{3}$	**3**	**−3.3**
MC	Macael	Sabinas	idem	Cal	**2.5**	**−4.8**
C-43A	Lubrín	Caldera	idem	Cal	**3.1**	**−13.4**
MN-24	Montenegro	Caldera	idem	$(Ank + Dol)_{69}$, Cal_{31}	**−1.19**	**−11.77**

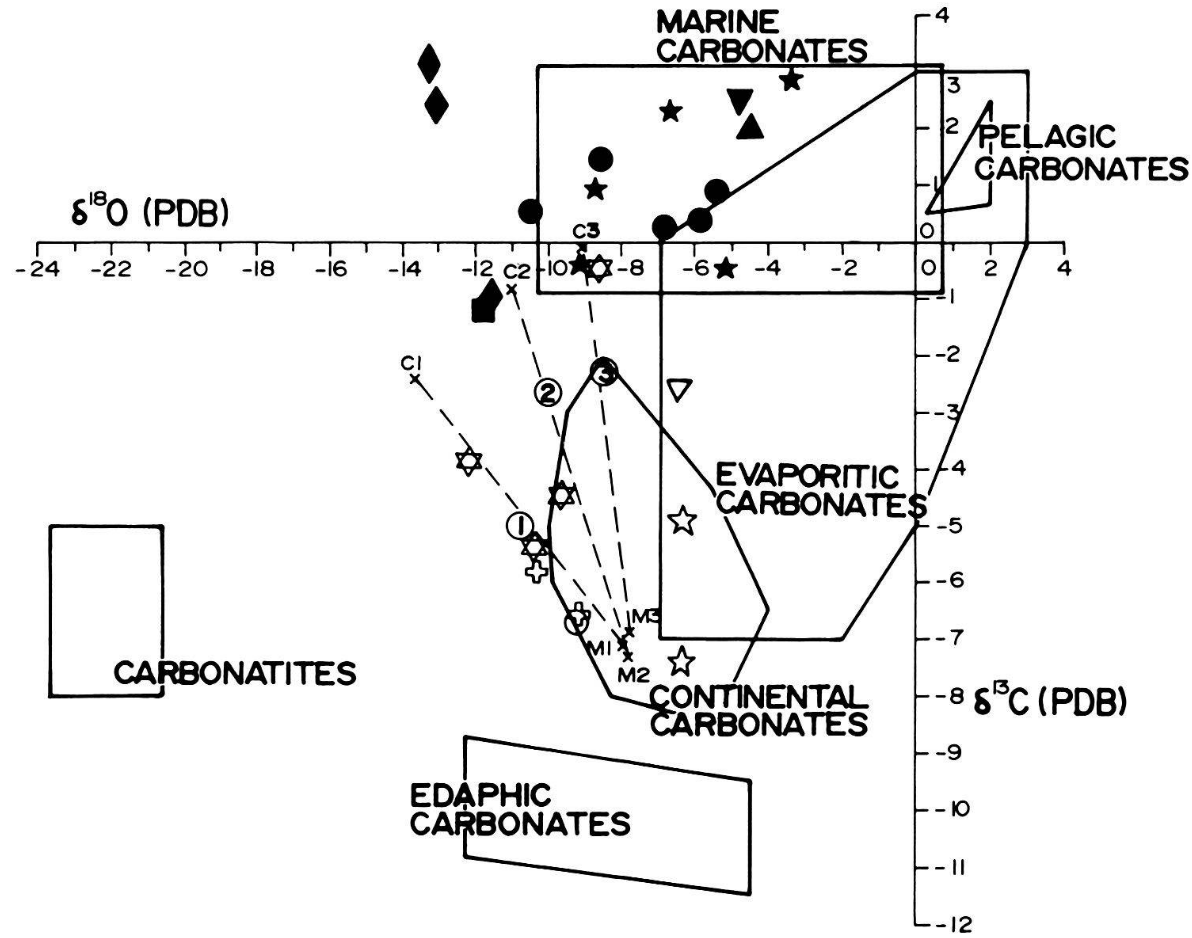


Fig. 9. Plot of the carbon and oxygen isotope values presented in Table 1a and 1b. Open symbols correspond to carbonates of the SF from the following localities: Albololoduy (six-pointed star), Almirez (circle), Cóbdar (five-pointed star), Soportújar (cross) and Ohanes (inverted triangle). Filled symbols correspond to carbonates of the other units of the Mulhacén Complex from: Almirez (filled circle), Cóbdar (five-pointed star), Lubrín (rhomb), Santillana (triangle), Montenegro (box) and Macael (inverted triangle). Comparative fields after Blattner & Cooper (1974), Faure (1986), Hudson (1977) and Salomons (1975). All the isotope analyses were done at the Stable Isotope Laboratory of the EEZ, CSIC-Granada (Spain), following the procedure described by McCrea (1950).

The evaporitic nature of the SF is also evident in the majority of its outcrops in the variable, and locally notable content of elbaite, gypsum, scapolite (marialite 60–75%) and/or apatite, among other minerals characteristic of such an environment (Fig. 5 top and 7 top). Scapolite, with the same chemical composition as in the phyllites, is also found in the rocks from other formations that were in contact with the SF sediments during the meso-Alpine and neo-Alpine metamorphism, such as some underlying ophiolitic outcrops of metabasites in the Cóbdar region. In these metabasites, scapolite replaces minerals of eclogitic and amphibolitic parageneses, mainly those filling the vesicles in metabasalts, and fills in later fractures with development of radial aggregates of well-

Table 2. Representative whole-rock analyses of meta-andesites, phyllites, metatuffs and marbles from the SF. The provenance localities, represented in Fig. 1, correspond with analysis numbers as follow: 1 = Ohanes, 2 = Bastidas, 3 = Fuente Fria, 4 = Soportújar, 5 = Cóbdar, 6 = Lubrín, 7 = Cardal, 8 = Cóbdar. The mean value of the metabasites of the BOA used in Figs. 8–11 is also set out. All the analyses were made at XRAL Assay Laboratories (Canada) following the analytical procedures described in Baedecker (1987).

Rock	Meta-andesites			Meta-tuff	Phyllites			Marble	BOA
Sample	B-11	DAA-44	DAA-47	SOP-1	ACB-2	C-79	F-2	7-CB	mean
number	1	2	3	4	5	6	7	8	9
SiO_2 (%)	51.90	48.20	40.20	54.13	57.27	54.12	55.13	16.10	47.92
TiO_2	1.08	1.30	2.17	0.75	0.93	0.97	0.93	0.18	1.53
Al_2O_3	14.10	16.60	14.60	15.40	15.70	20.05	23.72	4.45	16.59
Fe_2O_3	9.58	11.00	9.64	7.04	7.17	9.33	8.17	2.01	9.55
MgO	7.85	7.95	4.93	11.14	6.00	4.61	1.73	7.75	7.68
MnO	0.08	0.09	0.07	0.00	0.09	0.02	0.02	0.07	0.13
CaO	7.64	8.10	15.40	3.13	2.72	1.45	0.51	36.30	9.71
Na_2O	4.09	3.83	3.37	2.42	0.97	4.83	1.29	0.09	4.29
K_2O	0.62	1.16	1.09	1.90	5.13	2.01	5.32	0.48	0.31
P_2O_5	0.13	0.14	0.47	0.19	0.24	0.17	0.17	0.10	0.22
CO_2	ND	ND	ND	ND	ND	ND	ND	30	ND
LOI	3.16	1.85	8.39	3.58	2.39	3.02	3.45	31.90	1.26
Total	100.20	100.22	100.28	99.70	98.61	100.58	100.44	99.30	99.19
Li (ppm)	49	73	55	25	41	38	37	9	26
Rb	19	18	24	41	125	69	225	18	7
Be	3	2	4	2	ND	5	4	2	4
B	24	20	160	83	ND	192	ND	178	ND
Ba	153	106	10	92	720	565	773	102	78
Sr	542	292	517	259	313	250	144	104	176
Cr	380	346	100	45	98	102	102	31	508
Ni	74	106	39	23	53	83	53	12	111
Y	12	19	27	12	28	23	14	5	33
Nb	7	13	32	9	20	38	30	2	11
Zr	90	101	166	67	188	ND	133	19	134
Ta	1.0	1.0	1.0	1.0	1.3	5.5	4.8	1.0	0.7
Hf	2.4	2.5	4.2	2.6	4.0	ND	3.4	1.0	2.6
Th	2.2	1.5	2.6	5.7	11.3	9.3	17.0	2.3	0.7
La	7.8	8.9	24.1	16.5	35.1	17.9	26.1	9.0	7.7
Ce	17.4	17.7	48.9	30.6	74.1	46.4	57.6	14.1	18.4
Pr	2.3	2.4	6.5	3.9	ND	4.5	6.4	2.1	2.3
Nd	10.8	12.2	28.4	14.6	34.0	16.6	23.1	7.2	12.8
Sm	2.5	3.2	6.7	3.4	7.0	3.5	4.2	1.4	3.6
Eu	0.8	1.0	2.2	0.7	1.5	0.7	1.1	0.3	1.2
Gd	2.7	3.4	6.5	2.9	ND	4.5	4.6	1.1	4.2
Tb	0.4	0.6	1.0	0.4	0.9	0.6	0.6	0.2	0.7
Dy	2.9	4.2	6.6	2.4	ND	3.9	3.0	1.1	4.7
Ho	0.5	0.9	1.3	0.5	ND	0.8	0.5	0.2	1.0
Er	1.5	2.4	3.1	1.7	ND	2.5	1.5	0.7	2.6
Tm	0.2	0.3	0.4	0.3	ND	0.4	0.2	0.1	0.4
Yb	1.3	2.1	2.5	2.0	2.6	2.3	1.1	0.5	2.5
Lu	0.1	0.3	0.4	0.3	0.4	0.3	0.1	0.1	0.4

shaped crystals several centimetres in length (Portugal et al. 1987; Puga et al. 1989a). Nevertheless, scapolite is never present in the eclogitized metabasites, or any other type of MC rocks not in contact with the SF (Puga et al. 1989b, 1995).

The SF phyllites originated from continental clays, very rich in Al_2O_3 and locally in MgO (analyses 5 to 7, Tab. 2). The high Li content of some phengite- or chlorite-bearing phyllites in this formation explains their abundance in elbaite (Fig. 4 bottom). Some phyllite levels, such as those containing scapolite (Fig. 7 top), have a chemical composition that indicates an evaporitic origin, according to Moine et al. (1981) diagrams, similar to other lithotypes of the same formation (Gomez-Pugnaire & Cámara 1990; Gomez-Pugnaire et al. 1994).

Petrography, geochemistry and genetic environment of the metavolcanites

The most abundant lithotypes among the SF metavolcanites are the basaltic andesites, which, in some outcrops, may be associated to minor basalts or andesites *s.str.* These rocks constitute small subvolcanic bodies or thin lenses of pyroclastic origin, interlayered at different levels within the SF metasediments (Fig. 2). The pyroclastic material is also scattered within a carbonatic matrix forming tuffitic marbles, such as those in the Soportújar outcrop (Fig. 1), which also contain decimetric to metric boulders and rock fragments from the Triassic ortho-gneisses of the underlying formation (Figs. 3 bottom and 4 top). The pyroclastic rock mixed with the carbonate (dark-grey points in Fig. 4 top), forms abundant rounded millimetric fragments, which were transformed during the meso-Alpine metamorphic event into albite-bearing chlorite-schist, very rich in rutile and elbaite, preserving their andesitic chemical composition (Fig. 4 bottom and analysis 4, Tab. 2). Some more massive pyroclastic levels and the subvolcanic bodies, such as those from Ohanes or Bastidas (Fig. 1), become more or less amphibolitized meta-andesites, which preserve igneous textures (Fig. 8), or more often amphibolites in which the igneous textures have been more obliterated by metamorphism.

The SF amphibolites may be confused macroscopically with some fine-grained oceanic metabasites from the BOA with which they are in contact in some outcrops. Nevertheless, the andesitic *s.l.* amphibolites from the SF may be differentiated from the BOA basaltic amphibolites by their not containing either mineral or textural relics of the eo-Alpine eclogitic metamorphism, which are present in all BOA metabasite outcrops. Furthermore, these two types of amphibolites can be clearly distinguished by their different chemical compositions (Fig. 10 to 13).

Representative chemical analyses of metavolcanites from four SF outcrops are set out in table 2 (analyses 1 to 4), together with three representative analyses of phyllites and marbles from the same formation, and an average value for the BOA metabasites. Figures 8 and 9 show some compositional characteristics of the SF meta-andesites in comparison with those corresponding to the BOA metabasites and to other types of basalts or basaltic andesites that formed in different genetic environments. These diagrams show the calc-alkaline (Fig. 10) or the transitional from theoleiitic to calc-alkaline (Fig. 11) chemical affinity of the SF metavolcanites and indicate a continental environment for their magmas, as opposed to the oceanic environment corresponding to the BOA metabasites plotted in the MORB field. The enrichment in Th *vs.* Yb of the SF metavolcanites indicates, according to Pearce's (1982) diagram (Fig. 10), a crustal contamination of their

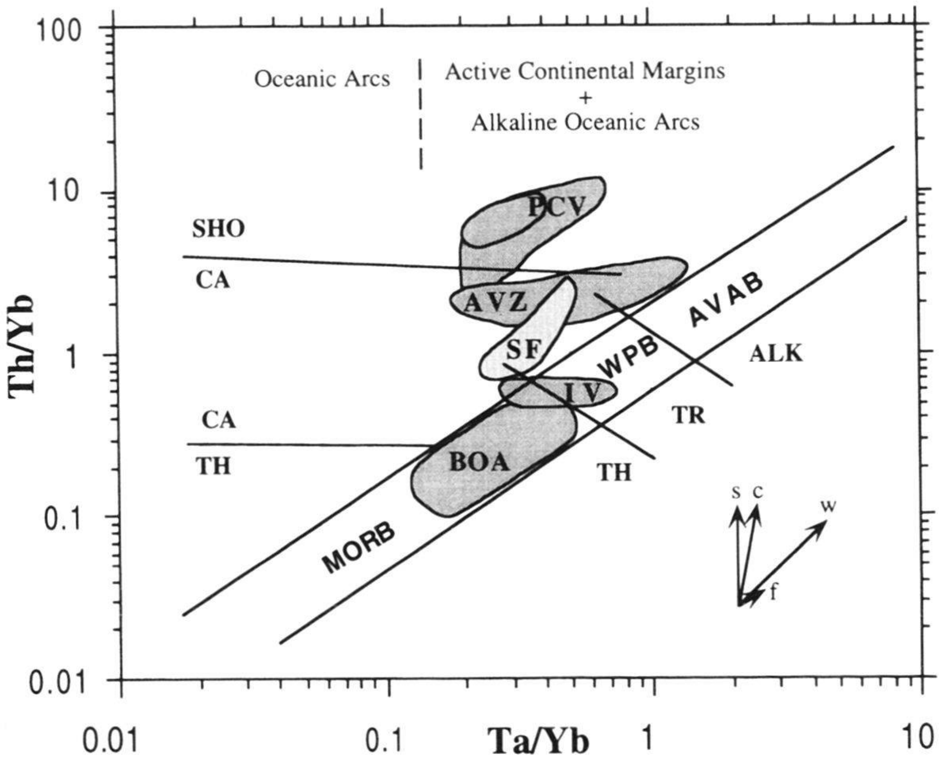


Fig. 10. Th/Yb versus Ta/Yb plot (Pearce 1982) of the meta-andesites of the SF showing a calc-alkaline character. Comparative fields: BOA = Betic Ophiolitic Association (Puga et al. 1989a, 1995); IV = Intraorogenic metavolcanics of whithin-plate affinity from the French Alps (Deville 1990); PCV = Post-Collisional Volcanism from the Italian Alps (Venturelli et al. 1984) and from the Balkans (Yanev et al. 1989); AVZ = Volcanites from the active continental margin of te Andean Volcanic Zone (in Wilson 1989, tables 7.3 and 7.4). The vectors represent enrichment by subduction (s), crustal contamination (c), within-plate (w) and fractional crystallization (f) processes.

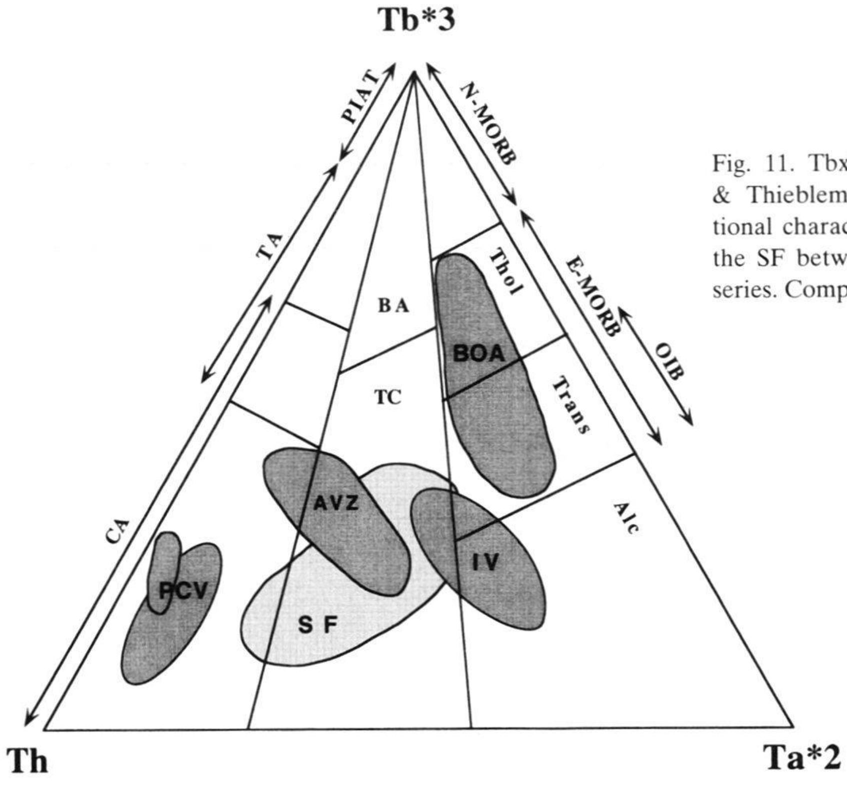


Fig. 11. Tbx3:Th:Tax2 diagram (Cabanis & Thieblemont 1988) showing a transitional character for the meta-andesites of the SF between tholeiitic to calc-alkaline series. Comparative fields as in Fig. 10.

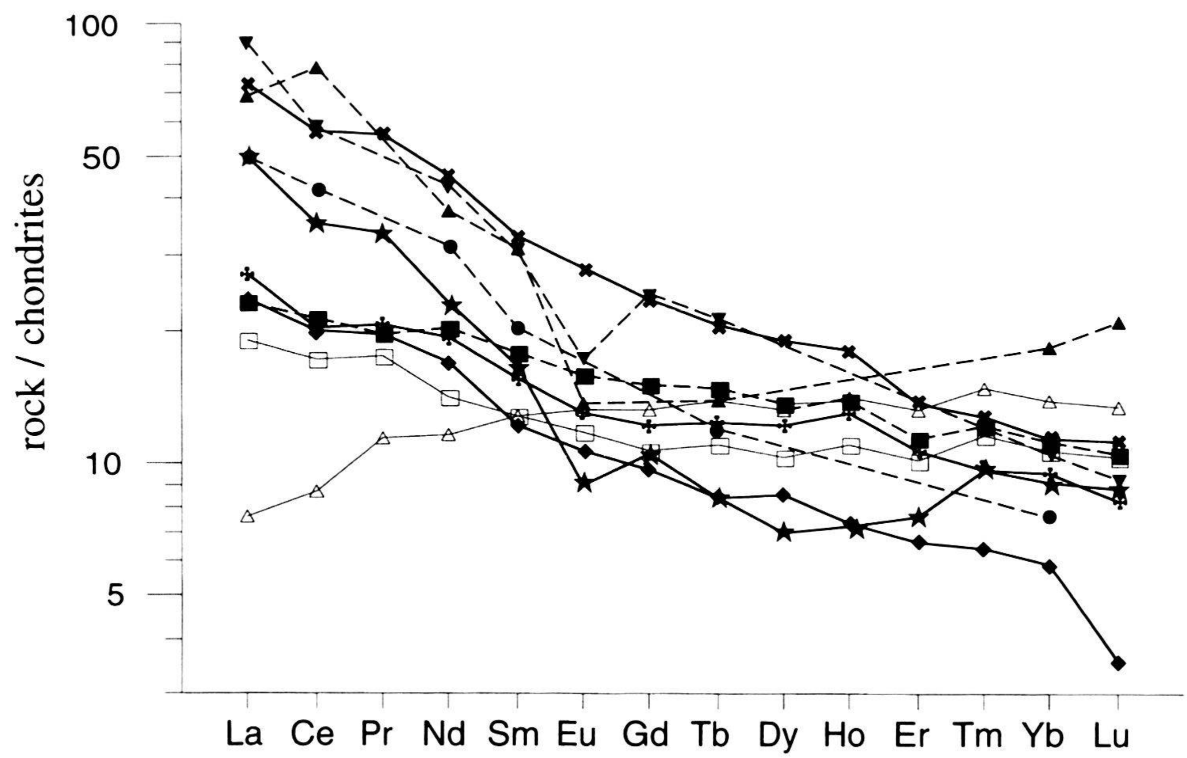


Fig. 12. Chondrite-normalized REE plot of representative samples of meta-andesites from the SF to which correspond the following analysis numbers in Table 2 and the symbols in this Figure: n° 1 = rhomb, thick line; n° 2 = cross, thick line; n° 3 = X-shaped cross, thick line; n° 4 = five-pointed star, thick line. Comparative patterns: N-MORB = open triangle and E-MORB = open box in Sun & McDonough (1989); mean value of the metabasites of the BOA in Puga et al. (1989, 1995) = filled box, thick-dashed line; intra-orogenic volcanism in Deville (1990) = upward filled triangle, thick-dashed line; post-collisional volcanism in Venturelli et al. (1984), Yanev et al. (1989) = downward filled triangle, thick-dashed line and the Andean volcanic zone in Wilson (1989) = filled circle, thick-dashed line.

magmas, which could have been generated in a suprasubduction zone. This environment is also suggested by the greater similarity of the SF metavolcanites with the field (AVZ) corresponding to basaltic andesites and basalts from the Andean continental margin, rather than to the intra-orogenic or post-collisional basalts from the Alps and Balkans, used for comparison in figures 10 and 11. The relationships between some compatible elements, such as Cr and Ni *vs.* Co, which differentiate post-collisional and continental margin volcanism (Yanev et al. 1989), also suggest that the genetic conditions of the SF metavolcanites correspond to an active continental margin environment.

Figure 12 shows the REE patterns normalized to chondrites of the representative analyses for the four SF metavolcanite outcrops shown in table 2, together with the average values for the volcanites of different continental environments from the Alps, Balkans and Andes (used for comparison in figures 10 and 11), so as the average values corresponding to oceanic ridges, both normal (N-MORB) and enriched in incompatible ele-

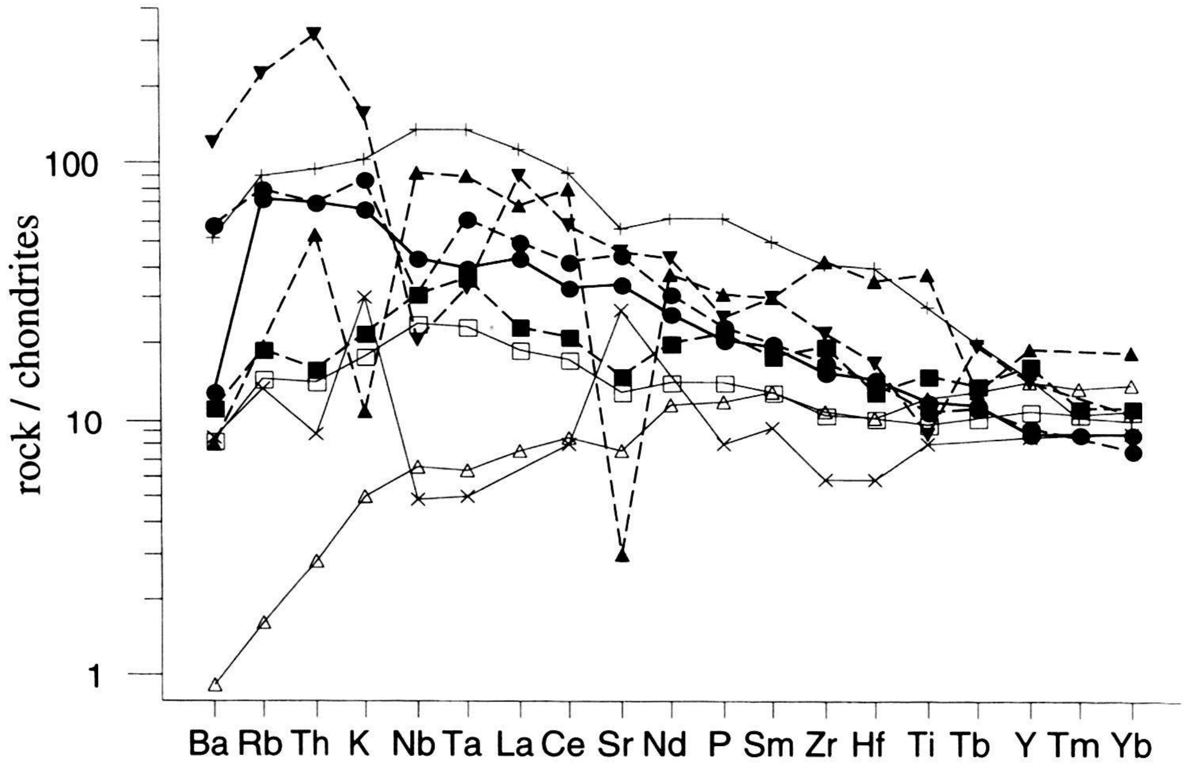


Fig. 13. Incompatible elements, chondrite-normalized spidergram of a mean value of the meta-andesites of the SF = filled circle and thick-continuous line, compared with N-MORB = open triangle, E-MORB = open box and OIB = cross in Sun McDonough (1989); IAT = X-shaped cross in Pearce (1982), and other comparative curves with the same symbols and references as in Fig. 12.

ments (E-MORB). The REE normalized patterns of the four SF metavolcanite samples correspond to basaltic andesites whose parental magmas retain records of a continental environment. The La content in the representative analysis from Ohanes is similar to that of the BOA and slightly higher than that in the E-MORB curves, although the slope of its REE pattern is much steeper, with $(La/Yb)_N$ ratio double than those in the BOA and E-MORB patterns. The other SF metavolcanites are richer in LREE than the BOA and the normal and enriched ridge magmas, and have also a higher LREE/HREE ratio than that found in these three types of oceanic magmas. The average REE pattern of the volcanites from the Andean continental margin are intermediate within the range of REE values for the SF metavolcanites, while the intra-orogenic and post-collisional magmas of the Alps and Balkans have REE contents similar to the highest values shown by the SF metavolcanites from Bastidas and Fuente Fría outcrops. Finally, the more irregular pattern of the volcanoclastic rocks from the Soportújar outcrop is more similar to that of the volcanoclastic intra-orogenic rocks from the Alps, probably due to their similar depositional environment and the mixing with sediments.

The spidergram (Fig. 13) shows the pattern of incompatible elements normalized to chondrites for the average values of the SF metavolcanites, together with the patterns of the average values corresponding to the different types of volcanites used for comparison in figures 10 to 13. Other mean patterns of incompatible elements, corresponding to different genetic environments such as oceanic island basalts (OIB), island arc tholeiites (IAT) and basalts from normal-type ridges (N-MORB) or from ridges enriched in incompatible elements (E-MORB), have also been plotted for comparison. This figure shows that the SF metavolcanites have both a high content for the more incompatible elements such as Rb, Th and K and a relative minimum for Nb and Ta, which is characteristic of magmas originated in continental environments. On the other hand, the average pattern of the BOA metabasites follows that of the E-MORB, and presents a maximum for Nb and Ta values, which is typical of oceanic-type magmas. Moreover, the SF magmas are chemically more similar to those originating in the Andean continental margin than for any other of the compared environments, including the intra-orogenic and post-collisional volcanism of the Alps and Balkans (Fig. 11). Therefore, their origin could be related, similarly to the magmas originating the Andean magmatism, to the subduction of an oceanic slab from which the BOA materials would have proceeded.

Relative to the magmas generated in the Andean continental margin, the SF metavolcanites are more similar, in their low SiO_2 and K_2O contents (Tab. 2) and their high $^{143}Nd/^{144}Nd$ isotopic ratio, to those originated at the southern zone of the Andes (SVZ). In fact, the $^{143}Nd/^{144}Nd_{(i)}$ ratio for the SF metavolcanites, measured in the better-preserved basaltic andesite from Ohanes, is 0.512449 ± 30 (2σ), which is within the range of values for this ratio in the SVZ (in Wilson 1989). These chemical similarities seem to indicate a rate of crustal influence for the SF magmas similar to that found in the SVZ magmas, which originated in a suprasubduction lithospheric zone with reduced crustal thickness (Wilson 1989).

Finally, the ε^{i}_{Nd} value of –2.22 for the Ohanes meta-andesites indicates a high crustal influence on the parental mantellic magmas of the SF metavolcanites, which allows them to be clearly distinguished from the parental magmas of the BOA metabasites, whose ε^{i}_{Nd} values vary between +8 and +9.8 corresponding to an oceanic-ridge environment.

Age of the metavolcanites

The volcanism of the SF could have occurred during the Paleocene, judging by the K/Ar whole rock radiometric datings of two meta-andesites from the Ohanes and Bastidas outcrops (Fig. 1), if an excess of Ar similar to that found in some MC metabasites (Hebeda et al. 1980; Portugal et al. 1987) does not affect these rocks. The radiometric ages obtained are: 67 ± 5 M.a. for the Ohanes sample and 43 ± 0.5 M.a. for the one from Bastidas (Tab. 3). The rock types dated are similar to those shown in Fig. 8 respectively. In both cases the rocks are basaltic meta-andesites that preserve the igneous texture, microporphyric with intergranular to variolitic matrix, indicative of rapid cooling, but the igneous minerals (andesine + augite + Fe oxides) have in large part been substituted by secondary parageneses. Some of these could have been hydrothermal late-magmatic in origin not changing, consequently, the radiometric ages corresponding to the igneous paragenesis. With respect to the Alpine metamorphism the one that affected the Ohanes outcrop was not very deformative and was low enough to explain the preservation, not only of the igneous textures in the meta-andesites, but even of the original andesine to bytownite composition of plagioclase in some phenocrysts. These compositional and textural evidences suggest that the K/Ar system might not have been opened locally during metamorphism and consequently the whole rock dating might represent the magmatic age. In the Bastidas outcrop, the metamorphic transformation was more pervasive and corresponding to a higher grade, for which reason the whole rock radiometric dating of 43 ± 0.5 M.a. may be interpreted as representing either an intermediate age due to partial resetting of the igneous system during metamorphism or, less probably, as the age of the metamorphic minerals making up this rock. The partial resetting of the igneous ages by differential Ar-loss during metamorphism is common in the Betic Cordilleras (Portugal et al. 1987; Puga et al. 1988; De Jong 1991).

Table 3. Geochronological data of the meta-andesites from the Ohanes (samples B-1 and B-11) and Bastidas (samples PDP-1 and PDP-9) outcrops. The K/Ar analyses were made in the Department of Earth Sciences at the University of Coimbra (Portugal), following the procedure described in Costa et al. (1974).

Sample	Weight (gr)	K (%)	Spike #	$^{40}Ar_{(rad)}$ ccSTP/g10^{-6}	$^{40}Ar_{(atm)}$ (%)	AGE
B-1 (WR)	0.27162	0.183	1100	0.4705	74	67 ± 5
B-11 (Amph)	0.20724	0.174	1101	0.1866	86	28 ± 3
B-11 (Plag)	0.31595	0.797	1099	0.8709	54	28 ± 4
PDP-1 (WR)	0.33276	0.370	7646	0.0063	46	43 ± 0.5
PDP-9 (Biot)	0.12520	5.830	7709	0.0605	25	26 ± 0.5

P-T conditions of the metamorphism

The most useful index minerals to evaluate the pressure and temperature of the metamorphism that affected the SF are found in their amphibolitized meta-andesites and phyllites. We have tried to use THERMOCALC (Powell & Holland 1988) to estimate the P-T conditions of the metamorphism without results, due to the existence of only local equilibria in the meta-andesites, and to the lack of an independent set of reactions among the paragenetic minerals in the phyllites. For this reason, we have used only conventional thermobarometric methods to estimate the P-T conditions of this metamorphism.

In the different lithotypes making up the SF (with the exception of gypsum) Na-Ca amphiboles are present, and their chemical composition, plotted in Brown's diagram (Fig. 14) allow us to approximately estimate their P conditions, directly related with their Na(M4) contents and their relative T, increasing with the Al(IV) content. Among the amphiboles found in the SF, those of actinolitic or tremolitic composition plott in the lower P and T field, and actinolitic Hornblende, Mg-Hornblende and Fe-Pargasite occur at higher conditions (Fig. 14). Mg-Kataphorite and Barroisite also formed under the metamorphic climax conditions. The presence in all the SF lithotypes of amphibole paragenetic with plagioclase has allowed us to establish the T of metamorphism more accu-

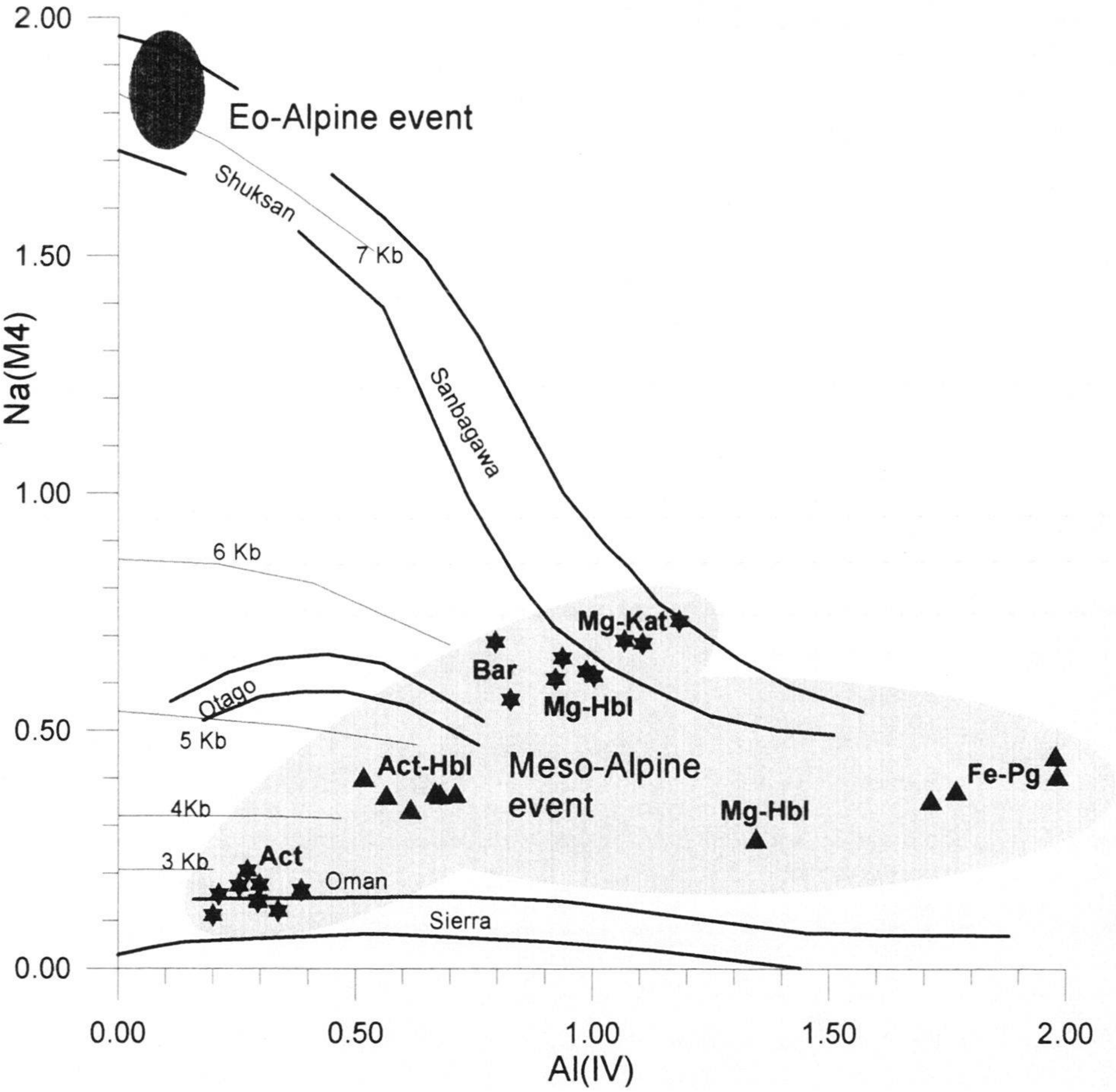


Fig. 14. Plot of amphiboles analyzed in the meta-andesites (six-pointed stars), and in the phyllites (triangles) of the SF in Brown's diagram (1977) with a tentative estimate of pressure and temperature according to Na(M4) versus Al(IV) atoms p.f.u. A field of the Eo-Alpine amphiboles (dark-shaded area) from the metabasites of the BOA is also plotted as a comparison. Minerals were analyzed with an automated Camebax SX50 (University of Granada) operated at 20 Kv and 20 nA, using simple oxides and silicates as calibration standards.

rately in this formation by applying the Holland & Blundy (1994) geothermometer. The minimum and maximum T values of this metamorphism calculated from the pairs actinolite-albite (analyses 1 and 2, Tab. 4a) and Mg-hornblende-albite (analyses 6 and 7, Tab. 4a) are represented in figure 15 by the Act-Pl and Mg Hbl-Pl curves, respectively. The green biotite, abundant in this formation, is stable within this T range, and even at lower temperatures for pressures lower than 5 Kb, according to the Bi-in curve (Fig. 15), but within the physical conditions characteristics of the greenschist facies, as the absence of pumpellyite in the amphibolites of this formation suggests.

Table 4a. Representative analyses of metamorphic minerals in meta-andesites from to Ohanes (# 1 to 5) and Bastidas (# 6 to 8) outcrops.

Point	B1195	B11102	B118	B813	B1116	E7569	E7771	E8377
Number	1	2	3	4	5	6	7	8
Mineral	Actinolite	Albite	Biotite	Chlorite	Epidote	Barroisite	Albite	Phengite
SiO_2	53.7	69.17	38.21	29.21	37.67	51.01	68.05	49.37
TiO_2	0.1	0	1.22	0.01	0.04	0.21	0	0.18
Cr_2O_3	0.2	0.01	0.1	0.07	0.11	0.06	0	0.02
Al_2O_3	3.69	20.3	14.8	18.22	23.43	9.15	19.79	29.29
FeO	12.66	0.05	17.05	20.44	11.93	10.39	0.05	2.88
MnO	0.11	0	0.03	0.08	0.06	0.11	0.01	0
MgO	14.37	0	13.73	19.42	0.01	14.73	0	2.65
CaO	11.62	0.3	0.01	0.11	23.5	8	0.39	0.02
Na_2O	0.91	11.56	0.07	0.05	0.02	3.58	11.53	0.41
K_2O	0.18	0.04	9.14	0.07	0	0.26	0.04	10.45
Total	97.54	101.43	94.36	87.682	96.769	97.516	100.32	95.28
# ox/cat	23	8	22	28	25	23	8	22
Si	7.726	2.978	5.789	5.968	6.188	7.262	2.984	6.611
Al	0.626	1.03	2.643	4.386	4.537	1.536	1.016	4.624
Fe_2	1.523	0.002	2.16	3.492	1.639	1.237	0.002	0.323
Mg	3.082	0	3.101	5.916	0.002	3.127	0	0.529
Ca	1.791	0.014	0.002	0.024	4.136	1.221	0.018	0.003
Na	0.254	0.965	0.021	0.022	0.006	0.989	0.973	0.108
K	0.033	0.002	1.767	0.017	0	0.048	0.002	1.785
Ti	0.011	0	0.139	0.002	0.004	0.023	0	0.018
Mn	0.013	0	0.004	0.013	0.008	0.014	0	0
Cr	0.023	0	0.012	0.011	0.014	0.006	0	0.003

Pressure conditions during the metamorphism of the SF have been estimated by application of the geobarometre of Massonne & Schreyer (1987) to the phengitic micas that exist in low proportions in the higher part of the lithotypes of this formation. The higher Si values in these micas generally vary between 3.2 and 3.3 in the meta-andesites and phyllites (analyses 8 and 13, Tab. 4). These rocks also show lower Si values in phengites of up to 3.15. The isopleths of Si = 3.15 and Si = 3.3 in figure 15 indicate (according to Massonne & Schreyer 1987) the range of minimum pressure values for the development of phengite, which is paragenetic with biotite but not with K-Feldspar in the rocks of this formation. This more probable pressure range for the SF metamorphism varies between approximately 4 and 9 Kb according to the T considered within the margins fixed by the stability conditions of the albite-amphibole paragenetic with the phengite. Other major minerals are present in different lithotypes of the SF, such as scapolite, biotite, chlorite, epidote and, more rarely, talc, whose representative analyses are set out in tables 4a and 4b. These minerals have blastesis conditions compatible with the P-T range established from the stability conditions corresponding to the phengitic micas paragenetic with Na-

Table 4b. Representative analyses of metamorphic minerals in phyllites from the Cóbdar outcrop. Two different parageneses are set out, the first one in the phyllite matrix (# 9 to 13), and the second one filling later veins (# 14 and 15).

Point	NCH6a7	NCH6a8	CB242	CB248	CB246	NCH3a9	NCH3a4
Number	9	10	11	12	13	14	15
Mineral	Mg-Hornb.	Albite	Scapolite	Biotite	Phengite	Act-Hornb	Talc
SiO_2	45.45	74.31	54.93	39.7	48.39	52.57	62.57
TiO_2	0.38	0.02	0.007	1.32	0.58	0.11	0.01
Cr_2O_3	0	0	0.009	0.01	0.03	0	0
Al_2O_3	12.11	15.93	23.48	15.99	27.05	7.92	0.47
FeO	14.67	0.09	0.048	12.14	3.64	6.47	3.2
MnO	0.12	0	0.019	0.08	0.01	0.11	0.03
MgO	11.48	0	0	16.29	4.46	17.96	29.2
CaO	10.38	0.78	9.691	0.03	0.03	10.53	0.05
Na_2O	1.89	9.34	8.291	0.08	0.37	2.05	0
K_2O	0.97	0.06	0.413	9.44	10.03	0.34	0.01
Total	97.43	100.52	96.88	95.068	94.59	98.05	95.53
# ox./cat	23	8	12	22	22	23	22
Si	6.705	3.182	7.98	5.812	6.572	7.325	7.991
Al	2.105	0.804	4.02	2.759	4.33	1.3	0.07
Fe_2	1.81	0.003	0.006	1.486	0.413	0.754	0.341
Mg	2.524	0	0	3.555	0.902	3.731	5.559
Ca	1.64	0.036	1.508	0.004	0.005	1.572	0.007
Na	0.541	0.775	2.336	0.022	0.097	0.554	0
K	0.183	0.003	0.077	1.762	1.739	0.061	0.002
Ti	0.042	0.001	0.001	0.145	0.059	0.011	0.001
Mn	0.014	0	0.002	0.01	0.001	0.013	0.003
Cr	0	0	0.001	0.001	0.003	0	0

Ca amphiboles and albite in these rocks. In addition to these minerals, small spessartite garnets (Sps 40–82%) can be found largely concentrated in certain phyllite beds enriched in Mn (Torres Ruiz et al. 1982). Other garnets richer in almandine and pyrope are locally found in low proportions, and very small size, in phyllites with high Mg content. Kyanite can be found in very small proportions in Al_2O_3-rich phyllites.

The absence of pumpellyite in the amphibolites and in the other types of rocks in this formation indicates a lower temperature limit within the greenschist facies conditions, while the upper temperature limit, characterized by albite paragenetic with Na-Ca amphibole and epidote, correspond to the Ab-Ep Amphibolite facies. Moreover, the generalized absence of high-pressure minerals such as lawsonite and glaucophane, besides omphacite and jadeite, in amphibolites and other SF lithotypes enable us to establish the upper pressure limit for the SF metamorphism, which would be confined to the physical conditions of the two mentioned facies. The more probable P-T range deduced for the SF metamorphism is represented in figure 15 by the light-grey shaded area. These conditions coincide with those characterising the meso-Alpine event in the other MC units and are

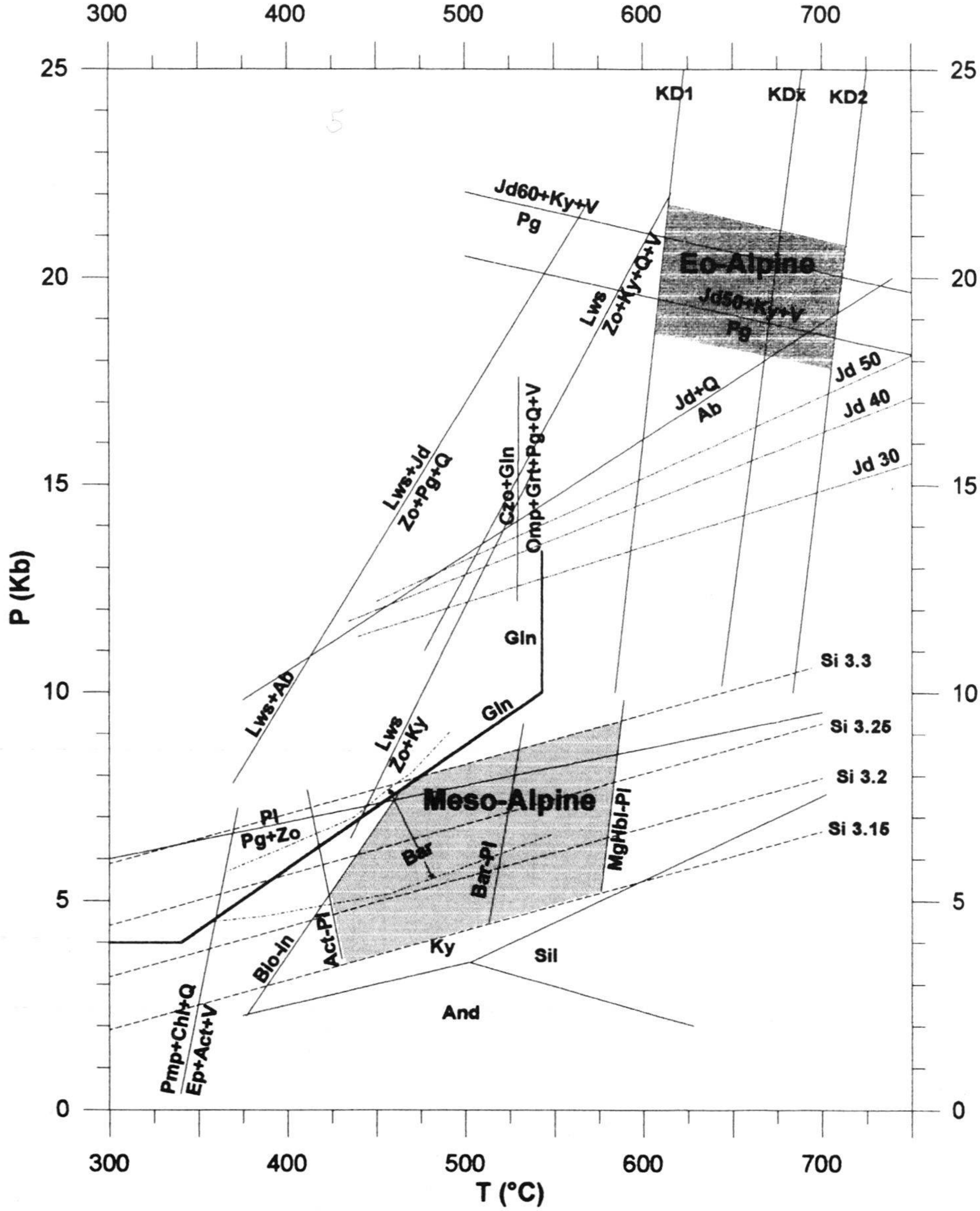


Fig. 15. P-T diagram showing the stability field of the different parageneses found in the rocks belonging to the SF (light-shaded area). A field of the Eo-Alpine paragenesis (dark-shaded area) from to the metabasites of the BOA is also plotted as a comparison. Reaction curves after Ellis & Green (1979), Gasparik & Lindsley (1980), Holdaway (1971), Holland (1979), Holland & Blundy (1994), Liou et al. (1985), Maresch (1977), Massone & Schreyer (1987), Ridley (1984) and Yardley (1989).

clearly lower than those attained in the same units during the eo-Alpine event. In figure 15 the physical conditions deduced for the eo-Alpine metamorphism of the BOA metabasites (Puga et al. 1995), which underlie the SF in some outcrops, have also been represented in the dark-grey shaded area for comparison.

Age of the metamorphism

The most probable age for the SF metamorphism is Oligocene, according to the K/Ar radiometric datings of amphibole, plagioclase and biotite separated from meta-andesites, collected from the Ohanes and Bastidas outcrops, the results of which are set out in table 3.

The metamorphic conditions registered in the Ohanes outcrop correspond to the lower P-T field within the range attributed to the meso-Alpine event in the SF (Fig. 15). The climax paragenesis in the Ohanes meta-andesites is: albite-actinolite-biotite-epidote-chlorite, to which correspond T formations lower than 450 °C (Fig. 15). Albite and actinolite, the main constituents of these rocks, have been dated by K/Ar as being 28 ± 4 M.a. and 28 ± 3 M.a. respectively (Tab. 3). Throughout the entire outcrop these metamorphic minerals directly replace the igneous minerals (plagioclase and pyroxene) preserving the volcanic textures of the protolith (Fig. 8 top), and were never found to have been recrystallized after any other preexisting metamorphic minerals, in contrast to the BOA metabasites, in which the amphibolite paragenesis mainly derives from the previous eo-Alpine eclogite paragenesis. Thus, we can deduce that the Oligocene age, radiometrically dated in these meta-andesites, corresponds to the first metamorphic event undergone by these rocks and, therefore also by their host rocks (conglomeratic marbles and gypsum-bearing phyllites), all very slightly deformed and recrystallized in greenschist facies conditions.

The metamorphism in the Bastidas outcrop, which reached higher temperatures than in the Ohanes outcrop, is represented in figure 15 by the Bar-Pl curve, corresponding to the stability conditions of its barroisite and other amphiboles (Fig. 14), all of them in equilibrium with albite, epidote and green biotite. The biotite of an amphibolite from this outcrop, similar to that in the Ohanes meta-andesites, has been dated by K/Ar to be 26 ± 0.5 M.a. The similarity between this age and those obtained for the Ohanes outcrop, which is separated from the Bastidas outcrop by several tens of kilometres (Fig. 1), supports the Oligocene age of the meso-Alpine metamorphism.

The whole-rock K/Ar age of 43 ± 0.5 M.a. of another meta-andesite from Bastidas (Tab. 3) could be interpreted as the climax age of the same metamorphic event, because this rock is formed by the barroisite-albite paragenesis, stable at higher T (Fig. 15) than the actinolite-albite from Ohanes. Nevertheless, the paragenetic association of the amphibole and albite in these rocks with the biotite dated at 26 ± 0.5 M.a., seems to indicate that the whole-rock age represents the metamorphic resetting of the age of an igneous paragenesis that may have been formed in the same way as the Ohanes meta-andesites in the distensive period dated as Paleocene for the western zone of the Tethys (Dewey et al. 1973; Savostin et al. 1986).

The radiometric ages of the SF meta-andesites fall within the range of datings corresponding to the meso-Alpine metamorphism of the BOA metabasites and other MC formations, in which minerals and parageneses corresponding to HP eo-Alpine metamorphism have also been dated (Portugal et al. 1988; Puga et al. 1989b; De Jong 1991; De Jong et al. 1992). The absence in all the SF outcrops of HP eo-Alpine minerals, or textures indicating their replacement, differs from the other MC formations, in which relics of parageneses and textures corresponding to the eo-Alpine eclogite facies are preserved, although partly obliterated by the meso-Alpine, higher-gradient metamorphism (Puga & Díaz de Federico 1978; Puga et al. 1989a, b, 1995). The more plausible explanation for this difference is that the SF originated later than the development of the eo-Alpine metamorphic event in the MC, which would agree with the Paleocene age indicated by the whole-rock radiometric dating of its meta-andesites (Tab. 3).

Discussion about the genesis, age and metamorphic conditions of the SF

The conglomeratic character of some carbonatic levels in the Soportújar Formation, which contain clasts of high-pressure metamorphic rocks and minerals from underlying units, was previously recognized by Brouwer & Zeylmans van Emmichoven (1924), who named these rocks "Konglomeratische Mergel" (conglomeratic marls). The pebbles and rock fragments present a more complicated metamorphic evolution than the matrix of their host rock, for which reason they were considered to derive from syn-orogenic sediments by Banting (1933) and from intra-orogenic sediments by Puga (1976), Puga & Díaz de Federico (1978) and Bourgois (1979) among others. Moreover, these carbonates, partly conglomeratic or tuffitic in origin, have often been brecciated, and locally mylonitized, during the thrusting of the overlying nappes, so that some of their outcrops were considered by Van Bemmelen (1927) and Zermatten (1929) as sedimentary breccias subsequently tectonized in some cases. Leine (1968), however, considered these rocks as tectonic breccias and classified them as polymict rauhwackes from the Nevado-Filabride Complex in comparison with the Alpine rauhwackes for which, similarly, both a sedimentary or tectonic origin and a Triassic or Neogene age have been put forward by different authors (cfr. Jeanbourquin 1986).

Some authors have considered that these Betic polymict rauhwackes, or conglomeratic marbles, more or less brecciated or mylonitized, together with other types of rocks (phyllites, gypsum and metavolcanites) associated with them in many outcrops, constitute an independent formation in the MC. This formation has received different names, some of which allude to its most characteristic types of rock: "conglomeratic marbles and metatuffs formation" (Díaz de Federico & Puga 1974); to its relative age with respect to the Alpine metamorphic events: "Intra-orogenic formation" (Puga & Díaz de Federico 1978); or to different localities in which this formation is well represented: "Huertecicas Formation" (Nijhuis 1964) and "Alboloduy Formation" (Martínez Martínez 1986) in Sierra de Filabres, "Los Lobos Formation" (Gómez-Pugnaire 1981) in Sierra de Baza and "Soportújar Formation" (Puga et al. 1984) in Sierra Nevada (Fig. 1).

Some outcrops of the Soportújar Formation between the Mulhacén and the Alpujárride complexes in Sierra Nevada and Sierra de Filabres were assigned by Egeler & Simon (1969) to the previously named Ballabona-Cucharón Complex, the components of which were later subdivided into the Almágride and the Alpujárride Complexes (Simon & Visscher 1983; Platt et al. 1983). In other outcrops intercalated between different MC tectonic units no distinction has been made between the Mesozoic metasediments making up the covers of these units and this formation, or have been considered as being brecciated or mylonitized levels, locally containing gypsum or scapolite, formed by the thrusting of these Mesozoic metasedimentary rocks (Nijhuis 1964; Voet 1967; Linthout & Vissers 1979; Vissers 1981; Torres Ruiz et al. 1982; Platt et al. 1983; De Jong & Bakker 1991; Gomez-Pugnaire et al. 1994). This confusion may be due to the fact that macroscopically some SF and MC Mesozoic cover lithologies look very similar when they are brecciated or mylonitized, although it is easy to distinguish them taking into account the petrologic and geochemical SF peculiarities.

The gypsum in the Soportújar Formation, better preserved in the outcrops placed on top of the uppermost Mulhacén unit, has been considered to be Triassic by analogy with series containing gypsum from the Betic External Zones and from the Almágride and Alpujárride Complexes, which have been dated as Triassic by palinology and microfauna (Simon & Kozur 1977; Simon & Visscher 1983; Platt et al. 1983). The carbonatic rocks of the Soportújar Formation, however, have not been dated by fossils, until now, and its possible algae remains only indicate a very shallow depositional environment (Puga 1976), also consistent with their mineralogy and isotopic signature. Therefore, this locally evaporitic formation could have been deposited during the Paleocene (as the radiometric dating of its meta-andesites indicates) on top of the Mulhacén Complex materials after their eo-Alpine metamorphism and exhumation, which must quickly have followed the eo-Alpine subduction as in other Alpine chains (Carpena et al. 1986; Winkler & Bernoulli 1986; Ernst 1988). This episode of continental sedimentation and calc-alkaline volcanism likely coincided with the Paleocene stage of relative distension between the African and Iberian plates, located between magnetic anomalies 33 and 24 (Dewey et al. 1973, 1989; Savostin et al. 1986). This extensional period that took place between the eo-Alpine and the meso-Alpine events in the Betic Cordilleras (Puga & Díaz de Federico 1978; Bourgois 1979; Durand-Delga & Fontboté 1980; De Jong 1991) and in the Alps (Trümpy 1973; Hunziker & Martinotti 1984; Deville 1990; Steck & Hunziker 1992; Ballèvre & Merle 1993; Froitzheim et al. 1995), would facilitate the ascent of magmatic fluids that originated during the eo-Alpine subduction.

The deposition of the continental SF during the Paleogene (instead of during the Triassic) would also be congruent with the abundance of continental deposits in this period throughout the Iberian Peninsula (de Ruig et al. 1991) and more specifically in the External Zones of the Betic Cordilleras, in which conglomeratic levels with a carbonate matrix are abundant and gypsum can be locally found (Jerez Mir 1973; Kenter et al. 1990). In the External Zones of the Morrocan Rif there are also volcanic and subvolcanic basic rocks, radiometrically and stratigraphically dated as Paleocene, which crop out together with gypsum levels (Hernandez et al. 1986). Furthermore, in the Alpine range there are some Paleogene volcanoclastic formations interlayered in sedimentary sequences with lithological characteristics which resemble that of the SF and which were affected, like this formation, by metamorphism during the Oligocene meso-Alpine event. This is the case of the basic meta-tuff level interlayered with chloritic marbles in the Grande Motte Unit of the western Alps, dated as Paleocene (Deville 1990), and that of the Taveyannaz greywacke formation in the Helvetic nappes. This latter formation (Upper Eocene – Lower Oligocene) is made up of several greywacke layers fed by abundant calc-alkaline andesitic material and scarce volcanogenic tuffs, alternating with marls, carbonates, conglomerates and breccias, containing polygenic clasts of metamorphic rocks of diverse provenance (Vuagnat 1958; Martini 1968; Vitally 1980; Pairis et al. 1992, Lapierre et al.

1992), which are remarkably similar to the SF lithology, despite the lower metamorphic grade of the Taveyannaz greywacke formation (Martini & Vuagnat 1965; Hunziker et al. 1986; Frey 1988; Rahn et al. 1994).

The awarding of a Triassic age to the Soportújar Formation, due to the existence of gypsum in it, has greatly constrained and complicated both the objective interpretation of the observational data to deduce its genesis (Leine 1968) and the attempts of the tectonostratigraphic subdivision of the Mulhacén Complex (De Jong & Bakker 1991). In contrast, the acceptance of the probable Paleogene age of this formation, suggested by the radiometric dating of its meta-andesites and the recognition of the conglomeratic character of some of its carbonate and pelitic metasediments, fed by Mesozoic polymetamorphic rocks from the different oceanic (ophiolitic) and continental MC units, in a monometamorphic matrix, lead us to interpret this formation as being intraorogenic and give it an important tectonic value as a guide level of separation among the thrust nappes related to the meso-Alpine metamorphic event (Puga & Díaz de Federico 1978; Puga 1980; Puga et al. 1984, 1992). A similar problem of awarding a Triassic age to Neogene continental sediments, made up by rauhwacken and gypsum, was described in the Alps by Grandjacquet & Haccard (1973, 1975).

With respect to the metamorphic conditions characterising the SF, a lower metamorphic grade compared to the remaining MC formations has generally been admitted (Egeler & Simon 1969; Puga & Díaz de Federico 1978; Torres Ruiz et al. 1982; Simon & Visscher 1983; Martínez Martínez 1984). This was the reason why previously some outcrops of this formation were included not in the Nevado-Filábride complex but in other overlying complexes, such as the Ballabona-Cucharón or the Alpujárride, characterised in the eastern part of the Betic Cordillera by their lower grade of metamorphism.

However, Gomez-Pugnaire et al. (1994) have put forward much higher metamorphic conditions for some components of the SF in the Sierra de Filabres. These authors deduced pressure conditions of about 18 Kb for the metamorphism affecting a scapolite-bearing phyllite outcrop in the Cóbdar region, based on a kyanite-talc-phengite paragenesis that appears, according to them, in small proportions in these rocks. After a careful sampling survey intended to check this statement, we did not identify this HP assemblage either in this outcrop or in others with the same type of phyllites with scapolite existing in several localities of the Sierra de Filabres (such as Chercos or Sierro, Fig. 1), or in any other outcrop of this formation throughout the extension of the MC. Nevertheless, in some phyllite levels, as in the marbles of this formation, there are detrital grains and monomineralic or polymineralic pebbles, proceeding from different MC unit rocks affected by the eo-Alpine HP metamorphism (such as those shown in Fig. 6), which might have been interpreted by Gomez-Pugnaire et al. (1994) as having been formed in situ, making part of the metamorphic assemblage of the scapolite-bearing phyllites in the Cóbdar outcrop. According to these authors, the HP paragenesis (cited by them) would represent the metamorphic climax conditions in the phyllites, while the other minerals making up the matrix of these rocks and the scapolite poeciloblasts, including these minerals, would represent retrograde phases formed after this climax. This interpretation is not supported by our mineralogical and textural data for the Cóbdar phyllites, according to which the climax paragenesis would be formed by biotite, phengite, albite, Na-Ca amphibole and minor elbaite, apatite, rutile and quartz, making up the matrix of the rocks, and by scapolite poeciloblasts (Fig. 7 top). These poeciloblasts, rich in marialite, are frequently zoned with a higher meionite content at the rims, indicating their development below increasing temperature conditions during the prograde path towards the metamorphic climax and not as a retrograde phase as suggested by Gomez-Pugnaire et al. (1994). The composition of the Na-Ca amphiboles of these phyllites, mainly Fe-pargasite and Mg-hornblende, which locally overgrow barroisite, and the Si content of their phengites (not paragenetic with kyanite and talc) comprised between 3.24 and 3.28 (analyses 9 to 13 in Tab. 4, and Fig. 14) indicate, according to the petrogenetic grid represented in figure 15, pressure conditions lower than 10 Kb and T of about 500 to 550 °C. This type of rock alternates in the same Cóbdar outcrop with other phyllite types rich in actinolitic hornblende, paragenetic with paragonite and talc (analyses 14 and 15, Tab. 4), which is locally recrystallized in veins (Fig. 7 bottom). This paragenesis, according to figures 14 and 15, might more probably have been formed under conditions below 500 °C and 5 Kb.

Finally, the HP metamorphism hypothesized by Gómez-Pugnaire et al. (1994) for the Cóbdar phyllites is in contradiction with the fact, generalized to all the SF outcrops, of the absence in any lithotype of this formation of glaucophane or omphacite, or some residual texture suggesting their preexistence. These HP minerals are, however, normally found in the BOA metabasites and micaschists underlying the Cóbdar phyllites and in the other MC units between which the SF outcrops are tectonically sandwiched.

Concluding remarks

The existence of a Paleocene intraorogenic formation in the MC with conglomerates fed by polymetamorphic xenoclasts of rocks dated as Triassic and Jurassic, which preserve relics of Upper Cretaceous eclogite facies paragenesis, partly obliterated by Oligocene Ab-Ep amphibolite paragenesis, in a matrix only affected by the latter metamorphism, confirms the polycyclic nature of the Alpine orogeny in the Betic Cordilleras. This polyciclic nature in the MC consists of two metamorphic events, eo-Alpine and meso-Alpine, separated by a partial or total exhumation process of rocks, which before reached a depth of up to 70 km during the eo-Alpine subduction (Puga et al. 1995), as opposed to one single compressive-distensive cycle suggested by other authors (Vissers 1981; Gómez-Pugnaire & Férnandez Soler 1987, among others) as the cause of the Alpine metamorphism in this complex.

The calc-alkaline character of the SF amphibolites deriving from basaltic andesites, which by geochemical affinity seem to have originated in a continental margin from magmas formed in a suprasubduction zone, suggests that the Jurassic oceanic slab, from which the materials forming the BOA proceeded, was subducted during the Upper Cretaceous, originating fluids by dehydration, which would have facilitated the melting of the overlying lithospheric material.

The time interval between the development of the eo-Alpine metamorphic climax in the BOA eclogites, dated as Late Cretaceous (Portugal et al. 1988; Puga et al. 1989b), and the deposition of the SF coetaneous with the calc-alkaline volcanism, dated as Paleocene, represents about 20 M.a. During this period, the calc-alkaline magmas must have originated in the suprasubduction zone and later extruded, partly as pyroclastites, favoured by the Paleocene distensive stage between the Iberian and African plates. This extensional situation would also have facilitated the exhumation of part of the materials previously subducted and eclogitized. The slab-breakoff model referred to by von

Blanckenburg & Davies (1995) as an explanation for the near-simultaneous development in the Alps of the uplift of the HP nappes and the onset of the Periadriatic magmatism, could also be applicable, together with the Paleocene distension, for explaining the exhumation of the MC eclogitized rocks and the development of the subsequent andesitic magmatism in the SF. However, the geodynamic environment in which these processes developed in the Betic, during Paleocene, was not post-collisional, but corresponded to an active intra-orogenic continental margin according to the geochemical affinity of the SF magmas.

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