PETROLOGICAL FEATURES OF SOME ALPUJARRIDE, MAFIC IGNEOUS BODIES FROM THE SIERRA DE ALMAGRO (BETIC CORDILLERAS, SPAIN)

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ABSTRACT

The mafic shallow-intrusive bodies in the Sierra de Almagro occur within a Permo-Triassic sequence as sill-like bodies with an ophitic/subophitic texture. The geochemical data, although sometimes rather ambiguous, indicate magmatism with sub-alkaline characteristics and (along with other geological evidence) a continental-crust emplacement. The considerable analytical similarity and positive anomalies of Zr and Hf in the incompatible element pattern indicate a model in which crustal contamination, probably in the lower crust, and limited fractionated crystallization in the upper crustal levels are the most important processes. Subsequently these rocks have been highly metamorphosed and/or altered by hydrothermalism. The P-T conditions of this metamorphism were about 4 kbar and 300°C. This pressure represents the minimum value from the blueschist-greenschist transition. The tectonic setting of this intermediate-gradient metamorphism may have been related to an underthrusting process, but several other settings are also conceivable.

Key words: Alpujárride Complex, metabasites, intracontinental magmatism, crustal contamination, intermediate metamorphic gradient.

RESUMEN

Los cuerpos intrusivos máficos de la Sierra de Almagro afloran como sills dentro de una secuencia permotriásica y presentan una textura ofítica o subofítica predominante. Los datos geoquímicos, aunque bastante ambiguos a veces, son indicativos del carácter subalcalino de este magmatismo y, junto con otras evidencias geológicas, reflejan su emplazamiento en un ambiente tectónico intracontinental. La gran similitud de los análisis químicos y las anomalías positivas de Zr y Hf en el diagrama de elementos incompatibles pueden ser indicativos de un modelo evolutivo con dos etapas. En la primera de ellas podría haberse producido cierta contaminación cortical en niveles bajos de la corteza, mientras que en la etapa posterior predominaría una cristalización fraccionada limitada, en niveles superiores de la corteza, aunque tampoco se puede descartar la asimilación de material cortical. Posteriormente estas rocas han sufrido una importante alteración secundaria debida a metamorfismo y/o hidrotermalismo. Las condiciones P, T del metamorfismo pueden ser establecidas aproximadamente a 4 kbar y 300°C, las cuales representan la mínima presión para la transición entre esquistos azules y esquistos verdes. El ambiente tectónico de este metamorfismo puede estar muy probablemente relacionado con una colisión continental, como ocurre en otras áreas del Complejo Alpujárride.

Palabras clave: Complejo Alpujárride, metabasitas, magmatismo intracontinental, contaminación cortical, metamorfismo de gradiente intermedio.

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1. INTRODUCTION

The Sierra de Almagro materials crop out in the eastern zone of the Betic Cordilleras (Fig. 1), in the eastern part of the Province of Almería. The structural position of the Sierra de Almagro in the general tectonic scheme of the Betic Cordilleras has been a subject of discussion for the last 60 years, due essentially to its lithostratigraphic and petrological peculiarities. Some of the first authors who worked in this area (Fallot, 1930; Blumenthal, 1950; Durand Delgá and Fontbôté, 1960) attributed the Sierra de Almagro materials to the Alpujárride Betic Complex, although Fallot *et al.* (1960) considered them as being part of the Betic of Málaga (Maláguide Complex at present). Some years later, a group of researchers from Amsterdam University described a new Betic Complex, which they called Ballabona-Cucharón (Simon, 1963; Egeler and Simon, 1969; Egeler *et al.*, 1971; Simon *et al.*, 1976). According to these authors, the setting of the new Complex could be between the Alpujárride and the Nevado-Filábride Complexes and would comprise most of the Sierra de Almagro, Sierra de Enmedio, Carrascoy, Orihuela and Callosa de Segura as well as the north of the Sierra de los Filabres. Aldaya *et al.* (1979) agree with the Dutch authors in the stratigraphic peculiarities of this series but nevertheless they do not consider them representative enough to define a new complex and therefore include them in the Lújar Nappe from the Alpujárride Complex. More recently, Simon and Visscher (1983) and Simon (1987) have defined the Almágride Complex, whose rocks, including the Sierra de Almagro ones, had been previously attributed to the Ballabona-Cucharón Complex. On the basis of the similarities between the Triassic series from this new Complex and those from the Subbetic Zone (External Zones of the Betic Cordilleras) these authors suggest that they are part of a single paleogeographic domain and the Almágride Complex may represent the southern continuation of the Subbetic below the Internal Zone Complexes.

This controversy has been based mainly on stratigraphic, magmatic and metamorphic differences which nowadays are not considered significant enough to justify the naming of a new complex. The stratigraphic differences (less developed Triassic series and more abundant gypsum) seem to be due exclusively to their paleogeographic position. In fact, very similar series to these crop out in areas which undoubtedly belong to the Alpujárride Complex (Aldaya *et al.* 1979; Martín and Braga, 1987). The supposed high-pressure, very low-temperature metamorphism affecting the basic rocks (Simon, 1963; Simon *et al.*, 1976) seems to have been produced at similar or lower P-T conditions than those recently reported (Goffé *et al.*, 1989) in the metapelites of the Alpujárride Complex. All these factors lead us to consider that the series of the Sierra de Almagro are part of the Alpujárride Complex.

In this paper we describe the mafic igneous rocks from the Sierra de Almagro and propose a hypothesis as to their origin, magmatic evolution and tectonic setting. We also discuss the supposed high-pressure, low-temperature conditions of the metamorphism.

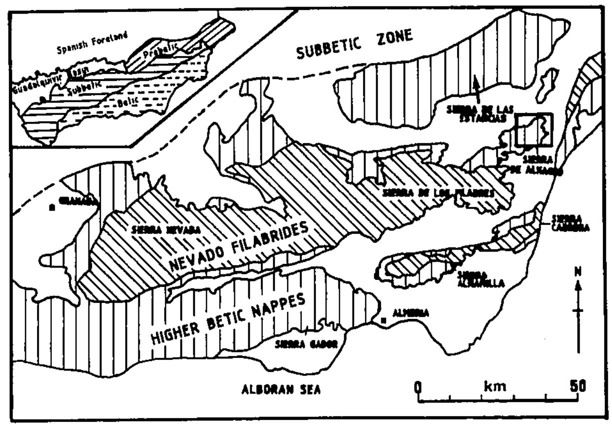

Fig. 1.-Geological location of the Sierra de Almagro in the tectonic sketch map of the eastern Betic Zone. "Higher Betic Nappes" include Alpujárride and Maláguide complexes. Taken from Platt and Behrmann (1986).

Fig. 1.-Localización geológica de la Sierra de Almagro en el mapa tectónico de la Zona Bética Oriental. Los mantos béticos superiores incluyen los complejos Alpujárride y Maláguide. Tomado de Platt y Behrmann (1986).

2. FIELD DESCRIPTION

Mafic igneous bodies, which are very abundant in this area, intrude at different levels of the stratigraphic sequence (Fig. 2). This sequence consists, from bottom to top, of phyllites, about 400 m thick, with frequent intercalated quartzites which generally are considered as continental (they show frequent channelized conglomerates and sandstones, Delgado *et al.*, 1981) or shallow-marine deposits. In the upper part of the phyllites evaporitic material appears. This metapelitic sequence is Permo-Triassic. The top of this sequence is constitute by a thick series of calcite-dolomite marbles usually associated with evaporitic material. In the south of the Sierra de Almagro they are comprised of more or less continuous levels of gympsum about 600 m thick (Simon, 1963). The marble member is usually attributed to the middle Triassic.

The Sierra de Almagro igneous rocks occur as sills which have been faulted and dismembered into several isolated bodies. The bodies are significantly more abundant and generally larger than those that appear in other Betic complexes. Their size ranges from only a few meters up to 300 to 700 m long and 30 to 100 m thick. Commonly the original intrusive relationships as well as the igneous mineralogy and texture have been preserved in spite of later metamorphic and/or metasomatic processes. In those cases where the bedding of the surrounding metasediments is visible it is clear that both the chilled margins and bedding are essentially parallel and, therefore, can be considered as sills. We have also observed that the host rocks, especially carbonatic ones, are baked a few centimeters around the contact with the mafic bodies. Deformation, which affects both the igneous and metasedimentary rocks, has had different effects on the igneous rocks compared to the metasediments. The latter developed a penetrative foliation, while the metabasites behaved much more rigidly, giving rise to penetrative faults, joints and brecciation. Synmetamorphic tensional veins are also frequent and in some cases they show characteristic antitaxial fibrous minerals. Only when the rocks are sheared does strong foliation texture appear at the rim of the igneous bodies and, consequently, the original mineralogy and textures are obliterated. Nevertheless, it does not occur frequently and is restricted to local tectonic accidents.

In all the mafic bodies, irrespective of size, the textures and mineralogy are very similar. Ophitic to subophitic textures are especially developed at the core of the bodies. The grain size, very coarse (up to 0.5 cm) in the central parts, decreases towards the margins, where the most common texture is porphyritic with a microcrystalline groundmass. The bodies are cross-cut by many hydrothermal veins of varying thicknesses (up to 1 m), filled with ores and bluish opal. This hydrothermal event also produced a pervasive alteration of the walls of the veins.

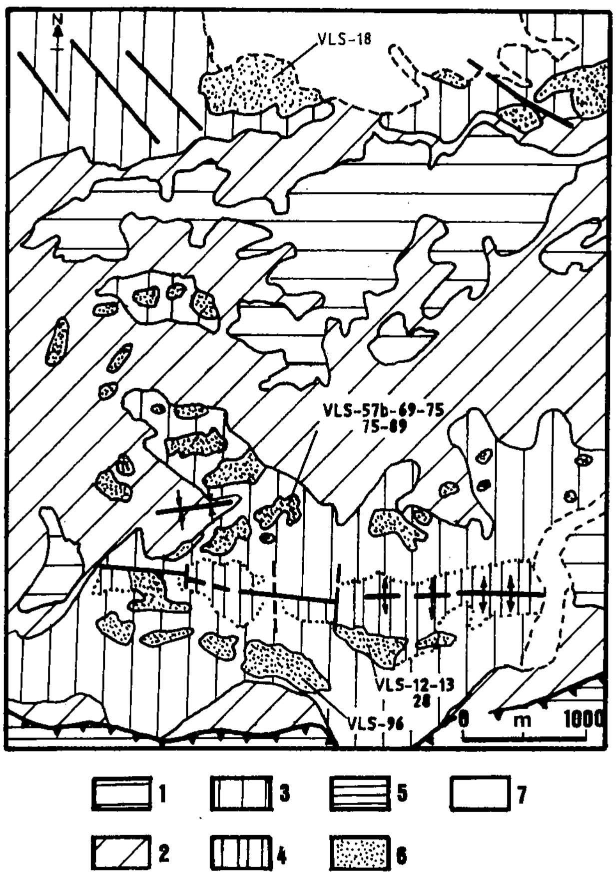

Fig. 2.-Geological sketch map of the Sierra de Almagro. 1. Upper-Triassic marbles; 2. Upper-Triassic (Carnian) gypsum, breccias, slates, phyllites, quartzites and marbles; 3. Middle-Triassic (Ladinian) marbles with gypsum; 4. Upper-Permian and Lower-Triassic quartzites and phyllites with gypsum; 5. Upper-Triassic phyllites, quartzites, marbles and gypsum; 6. Mafic rocks; 7. Quaternary materials.

Fig. 2.-Mapa geológico de la Sierra de Almagro. 1. Mármoles del Triásico superior; 2. Yesos, brechas, pizarras, filitas, cuarcitas y mármoles del Triásico superior (Carniense); 3. Mármoles con yeso del Triásico medio (Ladiniense); 4. Cuarcitas y filitas con yeso del Pérmico superior y Triásico inferior; 5. Filitas, cuarcitas, mármoles y yesos del Triásico superior; 6. Rocas máficas; 7. Cuaternario.

3. PETROGRAPHY

The mineralogy of these rocks is relatively complex as a consequence of the successive overprints upon the original igneous assemblages due to metamorphism, hydrothermalism and supergenic alteration. In this paper we will look at the primary mineralogy as well as the metamorphic modifications.

3.1. *Coarse and medium-grained facies*

Augitic clinopyroxene and *plagioclase* are the main igneous minerals which constitute the prevailing ophitic texture of these rocks. The clinopyroxene may also appear as very coarse-grained euhedral or subhedral phenocrysts. *Igneous amphibole* replaces clinopyroxene almost completely in most of the samples and also occurs as isolated subhedral grains. *Quartz* appears in these rocks with two different textural occurrences: as rounded crystals or as interstitial *granophyric intergrowths,* usually with plagioclase. Both occurrences are considered to have a secondary origin, as will be discussed later. Similar intergrowths of quartz with amphibole, clinopyroxene and ores have also been observed. *Biotite* occurs as rims around amphibole. The *ores* consist of Fe-Ti oxides, unstabilized into hematite or rutile ± titanite, with the typical cross-hatched structure. Minor apatite, rutile, zircon and titanite can also be found. Olivine and orthopyroxene (or their alteration products) are completely absent from all the studied samples, contrasting with the data reported by Puga and Torres-Roldán (1989) for very similar rocks from the Sierra de Enmedio and Sierra de Carrascoy.

The igneous minerals have been more or less transformed into secondary minerals which may be related to a metamorphic and/or to a hydrothermal event: Albite-rich end member replaces the large plagioclase crystals and the remaining relics are broken down into sericite and epidote. Pumpellyte has been reported in similar rocks by Puga and Torres-Roldan (1989), but we have not detected it in our samples either by petrographic methods or by microprobe analysis. Both the clinopyroxene and the amphibole relics are replaced by a pale-green amphibole, which in turn appears altered to a blue —or even lavender— coloured sodic amphibole. This latter mineral is especially abundant in the coarse-grained lithotypes.

3.2. *Porphyritic facies*

The only differences between these facies and the one described above, essentially concern to their texture. Plagioclase and clinopyroxene phenocrysts occur in a microcrystalline groundmass. Some of the clinopyroxene phenocrysts may be zoned, with colourless augite in the core and a pale-green variety at the rim. In these facies the effects of the metamorphic and/or metasomatic overprint are much more evident than in the coarse-grained facies. In fact, although the porphyritic texture is not obliterated, the grain size of the groundmass and its original texture (now granoblastic) were completely modified. Its mineralogy consists of epidote + actinolite + hematite, while the plagioclase phenocrysts are replaced by sericite and/or chlorite + epidote in the more altered rocks. The rare relics of plagioclase phenocrysts are albitized or transformed into a white-mica aggregate. In these rocks the clinopyroxene seems to be more resistant than plagioclase but may also be replaced by chlorite + epidote or only epidote.

Tensional veins filled by blue amphibole, epidote, chlorite, albite and quartz frequently occur in both the coarser-grained and the porphyritic facies. We interpret these minerals as being syntectonic due to their clear fibrous antitaxial growth, although in many cases this texture has been partially obliterated by later recrystallization.

4. MINERAL CHEMISTRY

Microprobe analyses of some igneous and metamorphic minerals were performed using an automatic (SX-50) Cameca microprobe at the University of Granada. Operating conditions were: 10 s counting time, c. 10 μA beam current and 15 kV accelerating voltage. Calibration was against Cameca standard minerals and a PAP correction procedure was used. Tables I, II and III show the representative analyses.

4.1. *Clinopyroxene*

The clinopyroxenes are augite or diopside (only number 2 in table I shows an abnormal composition) with a low TiO_2 content (ranging from 0.3% to 0.4%) and relatively high Al^{vi} = Fe^{3+} substitution (Fig. 3, Table I). In some of the porphyritic samples, zoned clinopyroxene phenocrysts occur with colourless augite in the core and a pale-green variety at the rim. In these cases the CaO and FeO contents decrease towards the rim while the MgO content increases. The acmite component is higher in the pale-green pyroxene. This variation of the chemical composition of clinopyroxene seems to be related to magmatic evolution and not to metamorphic recrystallization.

TABLE I

Microprobe analyses of clinopyroxenes from Sierra de Almagro

	1	2	3	4	5
SiO_2	51.57	42.50	49.29	52.54	53.21
TiO_2	0.41	0.33	0.37	0.30	0.31
Al_2O_3	2.84	9.89	2.49	2.10	2.00
Fe_2O_3	1.52	15.28	4.31	1.22	0.00
Cr_2O_3	0.97	0.34	0.69	0.64	0.67
FeO	5.17	1.62	3.90	5.81	6.94
MgO	17.66	16.94	13.64	18.14	18.36
MnO	0.16	0.33	0.26	0.19	0.24
CaO	18.93	11.98	19.55	18.64	17.73
Na_2O	0.21	0.77	1.24	0.19	0.18
Total	99.44	99.98	95.74	99.77	99.64
Si	1.899	1.583	1.906	1.927	1.950
Al^{IV}	0.101	0.417	0.094	0.073	0.050
Al^{VI}	0.023	0.017	0.019	0.018	0.360
Ti	0.011	0.009	0.011	0.008	0.009
Fe^{3+}	0.042	0.428	0.125	0.034	0.000
Cr^{3+}	0.028	0.010	0.021	0.019	0.019
Fe^{2+}	0.159	0.051	0.126	0.178	0.213
Mg	0.969	0.940	0.786	0.992	1.003
Mn	0.005	0.010	0.009	0.006	0.007
Ca	0.747	0.478	0.810	0.733	0.696
Na	0.015	0.056	0.093	0.014	0.013
En	51.7	64.0	45.6	52.1	52.5
Fs	8.5	3.5	7.3	9.4	11.1
Wo	39.8	32.5	47.0	38.5	36.4

Fe^{3+}/Fe^{2+} ratio calculated following Papike *et al.* (1979).

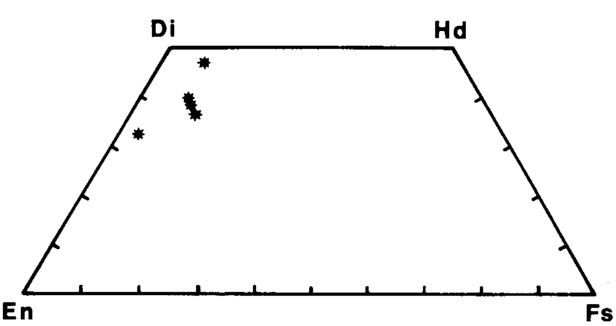

Fig. 3.-Nomenclature of igneous clinopyroxenes from Sierra de Almagro in the system Si-Ca-Fe-Mg (Poldervaart and Hess, 1951). Fs = ferrosilite, En = enstatite, Di = diopside, He = hedenbergite.

Fig. 3.-Nomenclatura de los clinopiroxenos ígneos de la Sierra de Almagro en el sistema Si-Ca-Fe-Mg (Poldervaart y Hess, 1951). Fs = ferrosilita, En = enstatita, Di = diópsido, He = hedenbergita.

4.2. *Plagioclase*

The extreme alteration of the igneous plagioclase is its most conspicuous feature and has prevented us from analysing most of the large crystals from either the coarse and medium-grained or the porphyritic facies. Due to this only three out of ten analyses of plagioclase were acceptable for this mineral. The results are shown in Table II. It can be observed that, except in sample 2, plagioclase crystals have an almost pure albitic composition as a consequence of secondary (metamorphic and/or hydrothermal) alteration.

TABLE II
Microprobe analyses of plagioclases from Sierra de Almagro.

Sample	1	2	3	4	5
SiO_2	66.82	64.66	67.81	69.75	68.47
Al_2O_3	20.33	23.23	19.51	20.76	20.39
Fe_2O_3*	0.61	1.73	0.52	0.00	0.36
MgO	0.00	0.93	0.02	0.02	0.00
CaO	0.03	0.15	0.51	0.15	0.81
Na_2O	12.23	7.09	11.20	11.74	10.59
K_2O	0.02	2.58	0.12	0.08	0.21
Total	100.04	100.37	99.69	102.50	100.83
Si	11.737	11.343	11.908	11.883	11.864
Al	4.210	4.804	4.039	4.170	4.165
Fe^{3+}	0.081	0.228	0.069	0.000	0.047
Mg	0.000	0.243	0.005	0.005	0.000
Ca	0.006	0.028	0.096	0.027	0.150
Na	4.165	2.412	3.814	3.878	3.558
K	0.004	0.577	0.027	0.017	0.046
Total	20.122	19.407	19.889	19.980	19.785
An	0.1	0.9	2.4	0.7	4.0
Ab	99.8	79.9	96.9	98.9	94.8
Or	0.1	19.1	0.7	0.4	1.2

(*) All Fe as Fe_2O_3

4.3. *Amphibole*

The amphiboles texturally interpreted as igneous are calcic amphiboles which can be classified as ferro-hornblende according to Leake (1978, see Figs. 4a and b). The probable secondary amphiboles show a much more distinct chemical composition. Some of them, pale-green in colour, plot into Leake's (1978) actinolite field, whereas many others, blue- or lavender-coloured, may be classified as sodic-calcic (ferri-winchite) or sodic (crossite or riebeckite) amphiboles. Nevertheless, no petrographic distinction can be made between the latter blue-lavender amphiboles, even when different chemical compositions appear. In fact, some of the sodic and sodic-calcic amphiboles listed in Table III have been analysed in different spots of a single small unzoned crystal. Obviously, the difference in the structural formulae within such a small area is not due to a real chemical variation but to the method for cation sites allocation in the mineral structure, and more precisely to the method used to estimate the Fe^{2+}/Fe^{3+} ratio. It is clear from Table III that the amphiboles in the studied samples are Fe^{3+}-rich members and in this case the error is larger than in the Fe^{3+}-poor amphiboles. In fact, sodic amphiboles may plot either in the riebeckite or in the crossite field (Al^{vi} = Fe^{3+} substitution), depending upon the method chosen to estimate Fe^{3+} concentration (see Fig. 3, and Table III). In this paper the Fe^{2+}/Fe^{3+} ratio calculations were made following the methods of Robinson *et al.* (1981) and Kimball and Spear (1984) who use for the above evaluation the crystal-chemical limits of cations substitution in the amphiboles structure (see also Essene, 1990). The most satisfactory formulae and Fe^{3+} content were obtained using the average between options of normalization: *13 cations excluding Ca, K and Na and all Fe as FeO.* Maximum Fe^{3+} content was estimated in these Al-rich amphiboles assuming Si + Al = 8 p.f.u. The Fe^{3+} number of cations per formula unit and the Fe^{3+} content obtained with this method are the same as those obtained with the Papike *et al.* (1974) method (average between all Fe as FeO and all Fe as Fe_2O_3). Sodic-calcic and calcic amphiboles are usually classified on the basis of the $(Ca + Na)_{M4}$ content, which is also controlled by the Al^{vi} = Fe^{3+} one, which produce the large dispersion of points among several compositional fields in the Leake (1978) diagrams. As a consequence of this, we conclude that these blue-lavender amphiboles are essentially sodic Fe^{3+}-rich member amphiboles but the exact range of the crossite and winchite component cannot be determined by microprobe.

5. BULK-ROCK CHEMISTRY

Ten bulk-rock analyses have been made on the mafic igneous rocks from the Sierra de Almagro (Table IV). Eight of the samples show a very similar composition for the major as well as the minor and trace elements, whereas the other two (VLS-18 and VLS-96) have very different values, especially the latter. They correspond respectively to a very coarse-grained sample and to a plagioclase-rich sample, which may have been intensely

TABLE III
Selected microprobe analyses of amphiboles from Sierra de Almagro.

	1	2	3	4	5	6	7	8
SiO_2	53.23	53.49	52.06	52.80	55.24	54.58	44.90	45.86
TiO_2	0.08	0.00	0.12	0.05	0.00	0.05	1.58	1.32
Al_2O_3	2.30	2.14	2.64	2.24	1.03	1.35	6.06	5.85
Fe_2O_3	7.98	9.65	5.32	6.78	1.80	1.20	1.20	4.15
FeO	20.22	20.35	22.28	20.35	13.10	13.02	25.74	23.30
MgO	6.30	5.68	6.72	6.59	15.25	14.75	6.81	5.89
MnO	0.14	0.09	0.20	0.17	0.20	0.24	0.26	0.35
CaO	2.44	1.45	5.30	3.91	11.53	11.30	10.01	8.69
Na_2O	6.24	6.91	4.50	5.05	0.98	0.88	1.93	2.67
K_2O	0.00	0.00	0.00	0.00	0.00	0.00	0.67	0.61
Total	98.93	99.76	99.14	97.94	99.13	97.37	99.17	98.70
Si	7.912	7.910	7.783	7.918	7.867	7.894	6.922	7.051
Al	0.088	0.087	0.217	0.081	0.132	0.106	1.077	0.949
Al	0.315	0.286	0.249	0.314	0.040	0.124	0.024	0.111
Ti	0.009	0.000	0.014	0.005	0.000	0.005	0.183	0.153
Fe^{3+}	0.893	1.075	0.599	0.765	0.193	0.131	0.140	0.481
Fe^{2+}	2.514	2.517	2.786	2.552	1.560	1.575	3.319	2.996
Mg	1.396	1.252	1.497	1.472	3.237	3.179	1.564	1.350
Mn	0.018	0.011	0.025	0.021	0.024	0.029	0.034	0.046
Oct	5.143	5.141	5.170	5.129	5.054	5.043	5.265	5.136
Ca	0.389	0.229	0.849	0.628	1.759	1.751	1.653	1.432
Na_{M4}	1.468	1.628	0.981	1.239	0.187	0.203	0.080	0.432
Na_A	0.330	0.354	0.323	0.229	0.085	0.043	0.496	0.364
K	0.000	0.000	0.000	0.000	0.000	0.000	0.131	0.120

(1) to (6) = metamorphic amphiboles; (7) to (8) = igneous amphiboles.

TABLE IV

Major and trace analysis of some mafic rocks from Sierra de Almagro

Sample	vls-12	vls-13	vls-18	vls-28	vls-57b	vls-62	vls-69	vls-75	vls-89	vls-96
SiO_2	51.40	51.40	53.90	51.50	49.30	52.20	52.30	51.70	50.60	55.30
TiO_2	1.49	1.19	2.12	1.10	1.21	1.26	1.35	1.41	1.23	1.93
Al_2O_3	13.60	14.40	13.30	14.00	14.30	14.90	13.60	13.80	14.70	13.20
Fe_2O_3(*)	12.10	11.20	11.70	12.00	11.60	8.95	12.10	12.00	11.50	11.60
MnO	0.17	0.18	0.20	0.21	0.17	0.11	0.18	0.13	0.18	0.08
MgO	5.86	5.80	3.91	6.05	6.01	7.34	5.70	5.65	5.58	2.89
CaO	6.16	9.93	7.08	9.90	11.20	5.09	8.34	7.25	8.78	4.62
Na_2O	4.56	2.71	5.50	2.16	2.64	5.25	2.79	3.65	3.08	7.58
K_2O	1.30	0.75	0.63	0.98	1.03	0.81	0.92	1.36	1.77	0.08
P_2O_5	0.17	0.14	0.24	0.13	0.16	0.15	0.16	0.17	0.16	0.43
L.O.I.	2.85	2.39	1.47	2.08	2.39	3.62	2.93	2.54	2.77	2.23
Total	99.70	100.10	100.10	100.20	100.10	99.70	100.40	99.70	100.40	100.00
Trace and REE elements (ppm)										
Sc	38.5	35.9	40.5	38.8	36.4	37.3	36.3	35.9	34	27.9
V	400	350	500	320	310	310	330	380	340	170
Cr	120	390	200	420	400	240	210	130	250	100
Co	26	23	30	31	33	25	28	30	24	16
Ni	52	65	42	75	62	66	60	56	65	12
Cu	26.6	118	318	138	143	5.4	112	23.5	95.6	87.5
Zn	87.9	80.6	91	90.5	93	104	98.4	93.5	101	48.9
Rb	40	26	24	35	36	26	34	42	49	6
Sr	208	223	215	233	631	410	390	424	330	94
Ba	134	235	225	168	131	154	152	202	246	81
Y	26	22	34	21	23	20	22	24	22	52
Zr	174	186	908	321	426	137	141	137	252	327
Nb	32	10			14	13	30	25	17	28
La	16	13	22.7	12.7	13.4	10.7	14	14.5	13.8	35.7
Ce	34.3	27.1	49.8	26.9	28.3	25.1	29.6	30.1	27.7	77.1
Pr	4.6	3.7	6.6	3.6	3.8	3.4	4	4.1	3.7	10.1
Nd	18.7	14.9	26.8	14.5	15.6	15.2	16.8	17.8	16.1	44
Sm	4.9	3.6	6.6	3.4	4	3.7	4	4.3	3.8	11
Eu	1.6	1.25	1.98	1.27	1.55	1.19	1.42	1.33	1.38	2.4
Gd	5.2	4.4	6.9	3.9	4.3	4	4.7	5	4.8	11.6
Tb	0.9	0.7	1.1	0.7	0.8	0.7	0.8	0.8	0.7	1.9
Dy	5.8	4.6	7.6	4.6	4.9	4.5	5.1	5.3	5.2	11.4
Ho	1.11	0.93	1.49	0.85	0.98	0.88	0.97	1.06	1.02	2.28
Er	2.9	2.4	3.8	2.2	2.5	2.2	2.6	2.7	2.5	6.4
Tm	0.3	0.3	0.5	0.3	0.3	0.3	0.3	0.4	0.3	0.8
Yb	2.2	2	2.8	1.7	1.9	1.8	2	2.3	2.1	4.9
Lu	0.34	0.26	0.33	0.25	0.23	0.22	0.23	0.28	0.27	0.63
Th	2.8	2.3	3.9	2.3	2.5	2	2.5	2.5	2.3	7.4
U	0.7	0.6	1.4	0.7	0.7	0.6	0.8	0.8	0.5	2.1

(*) Total Fe as Fe_2O_3

affected by hydrothermal alteration. The analyses have been made in the X-Ray Assay Laboratories (Ontario) using different methods for each group of elements: major and S, Zr, Rb, Nb, Ba, and Sr by **XRF**; V by **DCP-AES**; Sc, Co, Ni, Cu, Zr, Ga and Y by **ICP-AES**; REE by **ICP-MS**; Th, Hf and U by **NA**.

5.1 *Major elements*

Representative major element values range as follows: SiO_2 (49.30 - 52%) and MgO (5.58 - 7.84%). Values for Al_2O_3 (13.60 - 14.90%), CaO (5.09 - 11.20%), Na_2O (2.16 - 5.25%) and K_2O (0.81 - 1.77%)

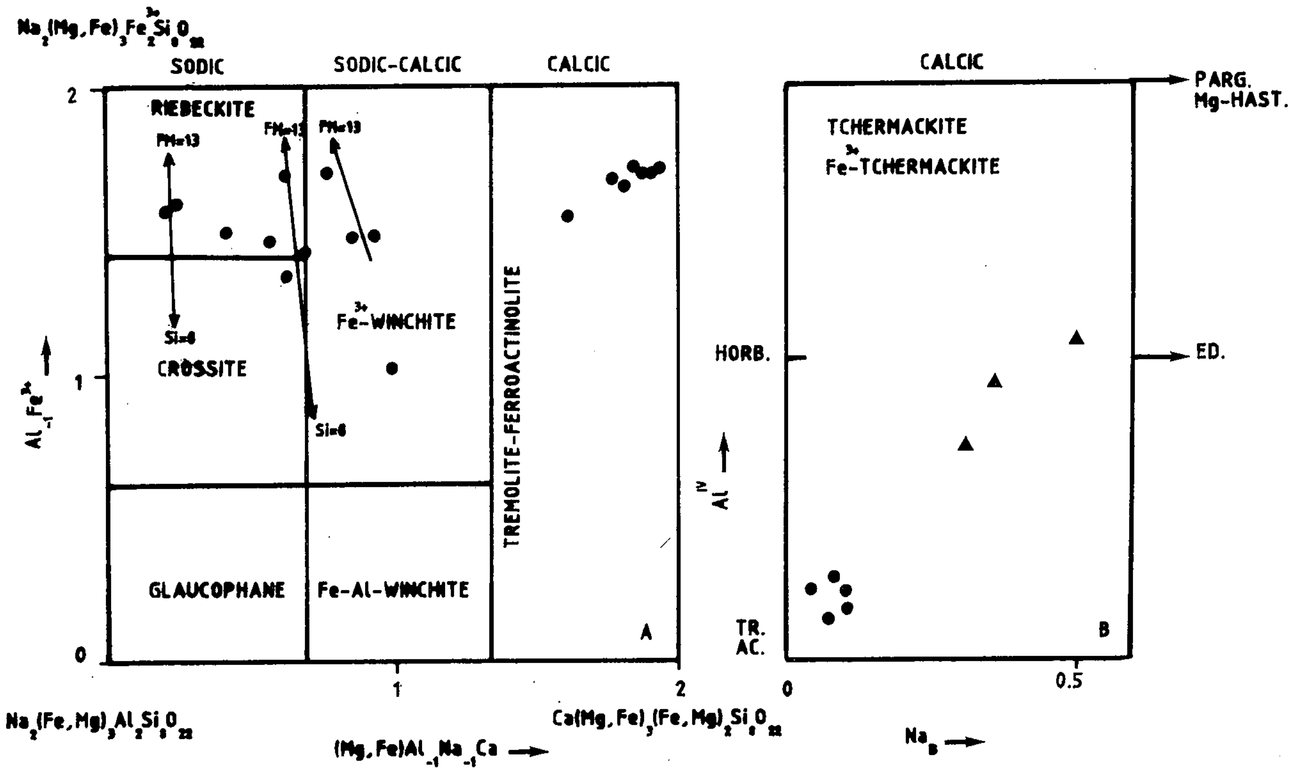

Fig. 4.-Chemical composition of igneous (triangles) and metamorphic (dots) amphiboles. A) The additive component is glaucophane and the two exchange components are (Mg,Fe)Al-1Na-1Ca and Al-1Fe^{3+}. The X_{Mg} value was fixed between 0.37 and 0.67 in order to obviate this representation and only the Ca-Na variation is taken into account in the ordinate axis. The arrays show the variation in the amphibole ploting with the different methods for calculating the Fe^{2+}/Fe^{3+} ratio. B) The calcic-amphiboles field was expanded in order to better differentiate between igneous and metamorphic amphiboles.

Fig. 4.-Composición química de los anfíboles ígneos (triángulos) y los metamórficos (puntos). A) El componente aditivo es la glaucofana y los dos componentes de intercambio son (Mg,Fe)Al-1Na-1Ca y Al-1Fe^{3+}. El valor de X_{Mg} se ha fijado entre 0.37 y 0.67 para poder obviar su representación, de modo que la única variación que se tiene en cuenta en el eje de abcisas es la de Ca-Na. Las flechas muestran la variación en la representación de los anfíboles con los diferentes métodos para calcular la razón Fe^{2+}/Fe^{3+}. B) El campo de los anfíboles cálcicos ha sido ampliado para poder distinguir mejor los anfíboles ígneos de los metamórficos.

are also quite homogeneous and do not show a good correlation. Samples VLS-18 and VLS-96 are SiO_2-richer (53.9 and 55.3%) and MgO-poorer (3.91 and 2.89%), with a considerable enrichment in Na_2O (5.50 and 7.59%), accompanied by a depletion in CaO (7.08 and 4.62%) and K_2O (0.81 and 1.77%). This very slight variation in major-element contents, as well as the lack of good correlations between them prevent us from obtaining any precise information with respect to the origin and evolution of the magmatism.

5.2. *Trace elements*

Trace elements also show very homogeneous values. They do not show a good correlation with the differentiation indices (D.I., SiO_2, Th) with the exception of some of the compatible elements. While Ni, Cu and Zn correlate negatively with hygromagmatophilic elements, considered as being differentiation indices, V, Rb and Y show a positive correlation. It is a key chemical feature, as is discussed later, that Zr and Hf correlate negatively with SiO_2 but not with La. The REE trend (Fig. 5) is very similar for all the samples and uniformly fractionated for both heavy and light REE. No Eu anomaly is present, indicating that plagioclase fractionation has not been a dominant process in the magmatic evolution.

The incompatible element pattern, normalized to chondrite composition, following Thompson *et al.* (1983), is quite similar for all the samples (Fig. 6). Its shape is more or less humped, with a progressive enrichment towards more incompatible elements. Its most notable feature is the Zr and Hf enrichment, which is related to the negative correlation of both elements with the SiO_2 content. The wide dispersion of Nb values, probably due to low analytical precision, is also noteworthy.

6. GEODYNAMIC CONTEXT

The mafic igneous rocks from the Sierra de Almagro can be classified as subalkaline as indicated by their alkali content and position in the SiO_2-Zr/TiO_2 diagram (Fig. 7, Winchester and Floyd, 1977) and by the location of points in the Ti/Y-Nb/Y plot (Fig. 8, Pearce, 1982), where most of the points plot in the alkalic

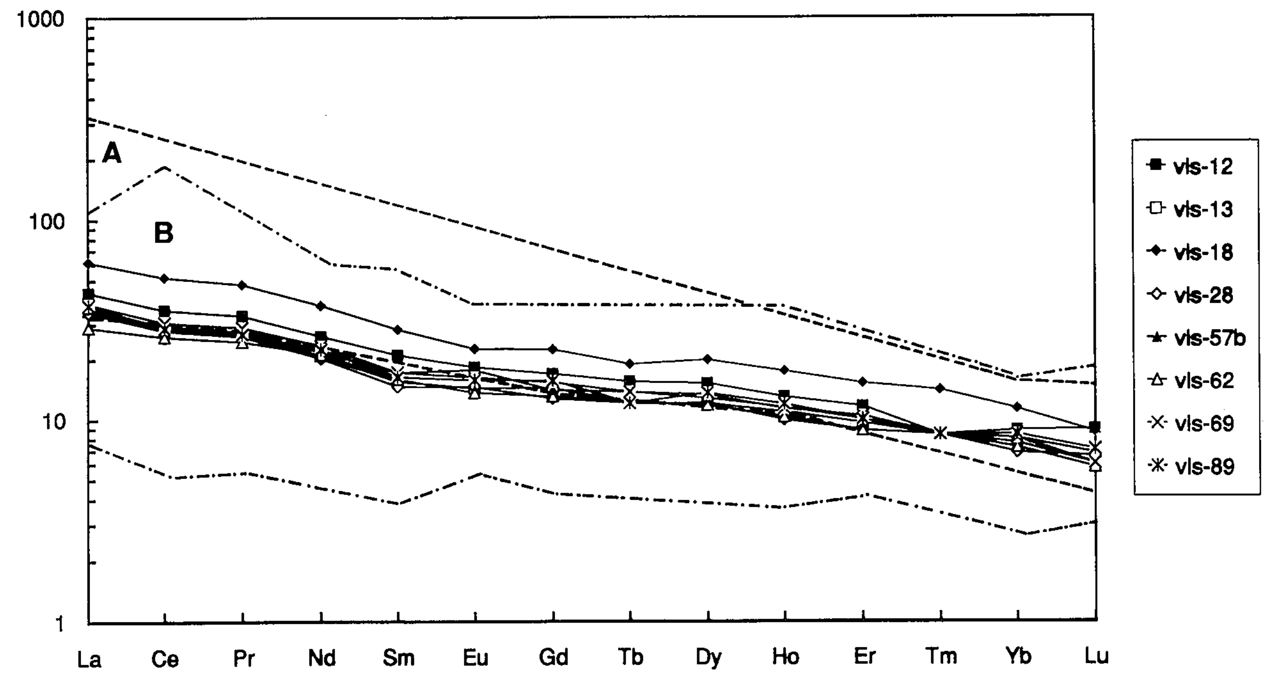

Fig. 5.-Chondrite normalized REE diagram. A. alkaline-basalts field; B. tholeitic- basalts field (Cullers and Graf, 1984).
Fig. 5.-Diagrama de abundancia de Tierras Raras normalizadas a la composición condrítica. A. campo de los basaltos alcalinos; B. campo de los basaltos toleíticos (Cullers y Graf, 1984).

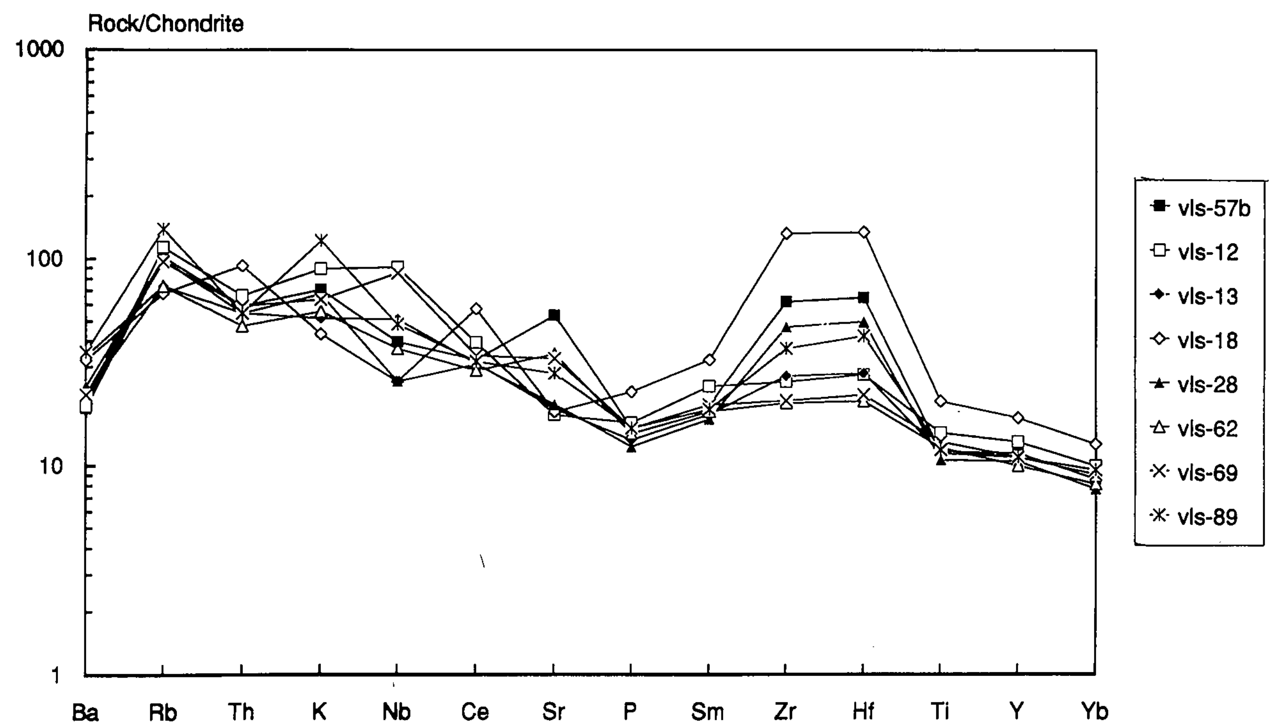

Fig. 6.-Chondrite normalized incompatible element diagram (spiderdiagram) from the Sierra de Almagro.
Fig. 6.-Diagrama de abundancia de elementos traza incompatibles de la Sierra de Almagro normalizados a la composición condrítica.

field or in the transition field between alkalic and tholeitic basalts. Within this series, the analysed rocks comprise differentiated basalts, compositionally close to basaltic andesites.

Although major and minor elements from the rocks generally plot within the range given by Marsch (1987) and Thompson *et al.* (1983) for intracontinental basalts, the specific tectonic environment cannot be conclusively established with the chemical data available, as a consequence of their great homogeneity. This in-

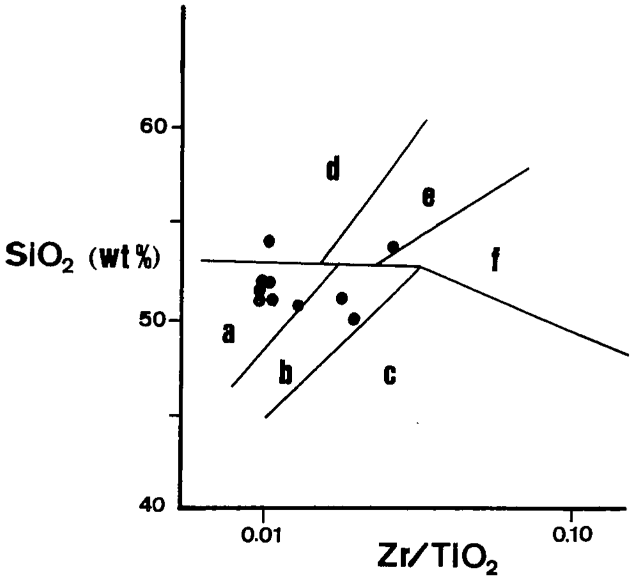

Fig. 7.-SiO_2 versus Zr/TiO_2 plot of the samples from the Sierra de Almagro. a. subalkali basalt; b. alkali basalt; c. basanite, trachybasanite and nephelinite; d. andesite; e. trachyandesite; f. phonolite (Winchester and Floyd, 1977).

Fig. 7.-Representación de las muestras de la Sierra de Almagro en el diagrama SiO_2-Zr/TiO_2. a. basalto subalcalino; b. basalto alcalino; c. basanita, traquibasanita y nefelinita; d. andesita; e. traquiandesita; f. fonolita (Winchester y Floyd, 1977).

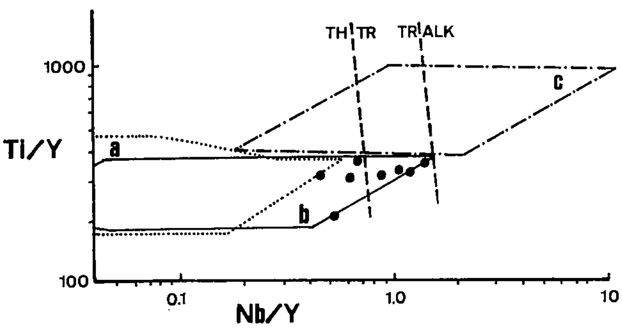

Fig. 8.-Ti/Y versus Nb/Y plot of the samples from the Sierra de Almagro. a. volcanic-arc-basalts compositional field; b. midocean-ridge-basalts compositional field; c. intraplate-basalts compositional field. TH: tholeitic; TR: transitional; ALK: alkaline (Pearce, 1982).

Fig. 8.-Diagrama Ti/Y-Nb/Y para las muestras de la Sierra de Almagro. a. campo composicional de los basaltos de arco volcánico; b. campo composicional de los basaltos de dorsal mediooceánica; c. campo composicional de los basaltos intraplaca. TH: toleítico; TR: transicional; ALK: alcalino (Pearce, 1982).

certitude, present in any tectonic environment basaltic magmatism, is even greater for continental settings (Arculus, 1987), such as this one. In fact, plots of the analyses in discrimination diagrams from Pearce (1982) show clear evidence of this ambiguity; whereas in the Ti/Y-Nb/Y diagram (Fig. 8) all the analyses plot in the mid-ocean-ridge-basalt field. 2Nb-Zr/4-Y discrimination diagram for basaltic rocks (Meschede, 1986, Fig. 9), on the contrary, shows a within-plate environment for the studied magmatism. These incongruent geochemical results can be attributed to the post-consolidation changes related with metamorphic and hydrothermal processes, and it is impossible to know at the present the role played by each alteration process in the migration of the minor and major elements. Nevertheless, the geological evidences about the tectonic-setting magmatism are very clear in this case (e.g. it is a gypsum-bearing stratigraphic sequence) indicating that the Sierra de Almagro magmatism intruded into an intracontinental crust environment, as evidenced also by the general trend of the incompatible element pattern (Fig. 6).

7. MAGMATIC EVOLUTION

As stated above, field relationships, together with some tectonomagmatic discrimination diagrams and REE and spider diagrams indicate a general intraplate continental environment for the Sierra de Almagro magmatism, but more conclusive data about the precise origin and evolution undergone by this magma is not available. Nevertheless, any model attempting to explain the geochemical and magmatic evolution of the Sierra de Almagro basic rocks must account for the following facts: (a) the rather restricted span of compositional variations —although certainly larger in some of the more mobile elements—, (b) the rather evolved nature of the basaltic magma, (c) the humped profile of the chondrite-normalized spidergram of incompatible elements (Fig. 6), a fact common to many other continental basaltic provinces, and (d) the remarkable Zr-Hf positive anomalies in these spidergrams, which are accompanied by a negative correlation between SiO_2 and Zr or Hf, but without zircon crystallization. A preliminary interpretation, which may explain the limited data avai-

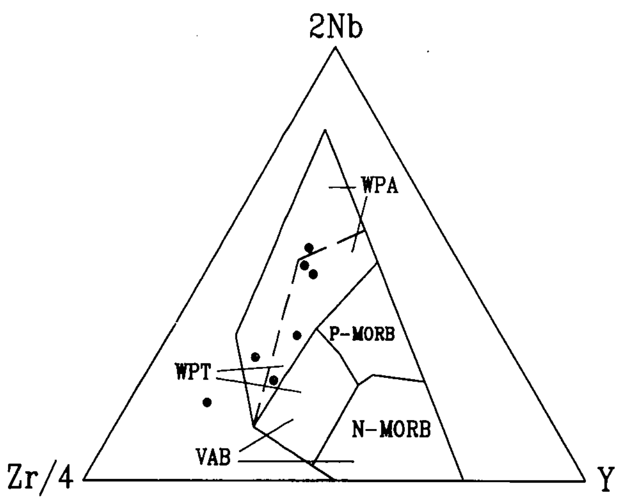

Fig. 9.-2Nb-Zr/4-Y discrimination plot of the metabasites of Sierra de Almagro. WPA within-plate alkaline basalts; WPT within-plate tholeitic basalts; VBA volcanic arc basalts; P-MORB Plume MORB; N-MORB normal MORB (Meschede, 1986).

Fig. 9.-Diagrama de discriminación tectonomagmática para las muestras de la Sierra de Almagro. WPA basaltos alcalinos de intraplaca; WPT basaltos toleíticos de intraplaca; VBA basaltos de arcos volcánicos; P-MORB plumas mantélicas; N-MORB composición MORB normal. (Meschede, 1986).

lable, suggests an evolution model which developed in two successive stages (described below) in which possible crustal contamination and fractional crystallization would have played different roles.

In the first stage, a poorly evolved (basaltic or picritic) magma would have been stored in magmatic chambers, perhaps at the lower crust or lower crust-mantle interface. There, more evolved magmas with a low compatible-element content were produced through extensive fractionation of olivine and pyroxene, as suggested by low Ni and Cr contents, and possibly a certain degree of contamination from surrounding crustal rocks, which justifies the relative enrichment in the most incompatible trace elements (humped profile; Fig. 6).

During a second stage, relatively homogeneous magma batches from these low-crust magma chambers would eventually rise to higher levels of the upper crust, where they were finally emplaced. During their ascent and emplacement a limited amount of fractional crystallization of clinopyroxene and plagioclase would prevail. This is supported by the plotting (although without clear tendencies) of normative values around the pyroxene + plagioclase low-pressure cotectic in the CMAS system (Thompson, 1982; Thompson *et al.*, 1983). We think, however, that fractionation was not too important in absolute terms at this stage.

One of the effects attributed to crustal contamination in these rocks is the observed enrichment in Zr and Hf, which clearly correlates negatively with SiO_2. We relate this negative correlation to the greater capacity of assimilation of the more refractory (crustal) Zr-Hf minerals (zircon) by the hotter, less evolved, SiO_2-poor magmas compared to the more differentiated rocks. Nevertheless, the data is not sufficient to conclude whether this effect occurred in the lower-crust magma chambers or during the ascent and emplacement to shallower levels.

As well, it must be taken into account that these rocks have undergone an important secondary alteration by metamorphism and/or hydrothermalism and their original igneous composition has been modified in the case of the more mobile elements. For this reason the present interpretation of the magmatic evolution must be considered to be tentative until new data are available.

8. METAMORPHIC FEATURES

One of the most important difficulties in the interpretation of the secondary mineralogy of these rocks is the correct attribution to metasomatic or metamorphic processes of some of the recrystallized minerals and also the pseudomorphism of the older ones. Thus, the origin of the described granophyric intergrowths is specially controversial. They have been assigned to a post-consolidation stage in basaltic rocks, although the granophyric quartz-plagioclase intergrowth may also be related to the crystallization of final differenciated basaltic melts (Augustithis, 1978). In the studied samples, the frequent occurrence of quartz intergrowths with amphibole, clinopyroxene or ores is, nevertheless, clearly indicative of a secondary origin, even for the quartz-plagioclase intergrowths; but they cannot be clearly related, either to the metamorphic or to the metasomatic stage, as no certain age relationships can be established with metamorphic minerals. The same ambiguity also exists in the interpretation of the plagioclase pseudomorphism into sericite or albite. Nevertheless, it must be stated that textural relations can be relevant enough in some samples and minerals (amphiboles), especially when metasomatism has not been too intense.

As to the metamorphic conditions, the presence of a blue-lavender amphibole was the basis for proposing a high-pressure metamorphic event in the Sierra de Almagro and similar series (Simon, 1963), which consequently would belong to an intermediate metamorphic complex located between the lower pressure Alpujárride Complex and the high-pressure Nevado-Filábride Complex (see Introduction). Nevertheless, the presence of this amphibole, which is not glaucophane, is not significant enough to support this metamorphic interpretation. Furthermore, its riebeckite-rich composition is not indicative of any definite P-T conditions as it has a large stability field (Brown, 1977b). In any case, the presence of such critical minerals as chlorite, actinolite, albite and iron oxide (hematite and magnetite), together with epidote, white mica and quartz, which complete the metamorphic assemblage, supply enough information about the P-T conditions of metamorphism.

In the NCMASH basalt system, blue-lavender amphiboles, normally glaucophane, indicate a high-pressure metamorphism (Maruyama *et al.*, 1986, Liou *et al.*, 1987), but in the Al-poor, Fe^{3+}-rich compositions, as in the cores of our samples, the total pressure may have been much lower, decreasing continuously with the gradual introduction of Fe^{3+} into the system (Maruyama *et al.*, 1986). The equilibrium conditions of the discontinuous reaction (Brown, 1977a) are:

actinolite + albite + iron oxide + H_2O *=*
epidote + riebeckite + chlorite + quartz,

and represent the minimum P-T conditions in our rocks, and also for the blueschist-greenschist transition, at about 4 kbar and 300°C for f_{O_2} values defined by the hematite-magnetite buffer (Maruyama *et al.*, 1986).

Complementary information can be obtained using the Al_2O3 wt% content in sodic amphiboles as a geobarometer (Marayuma *et al.*, 1986). This method has the advantage of avoiding the microprobe uncertainties of the Fe_2O_3 content analysis of amphiboles. In our samples, the Al_2O_3 wt% content from the sodic amphiboles versus X_{Fe} in chlorites (X_{Fe} ranges from 0.4 to 0.7), as a part of the buffer assemblage Ca-amphibole + epidote + chlorite + albite + quartz, plots arround 4 kbar (Liou *et al.*, 1987; Fig. 3-17), which agrees with the above results. Nevertheless, the Na_{M4} content of Ca-amphiboles (Brown, 1977b) in the buffer assemblage

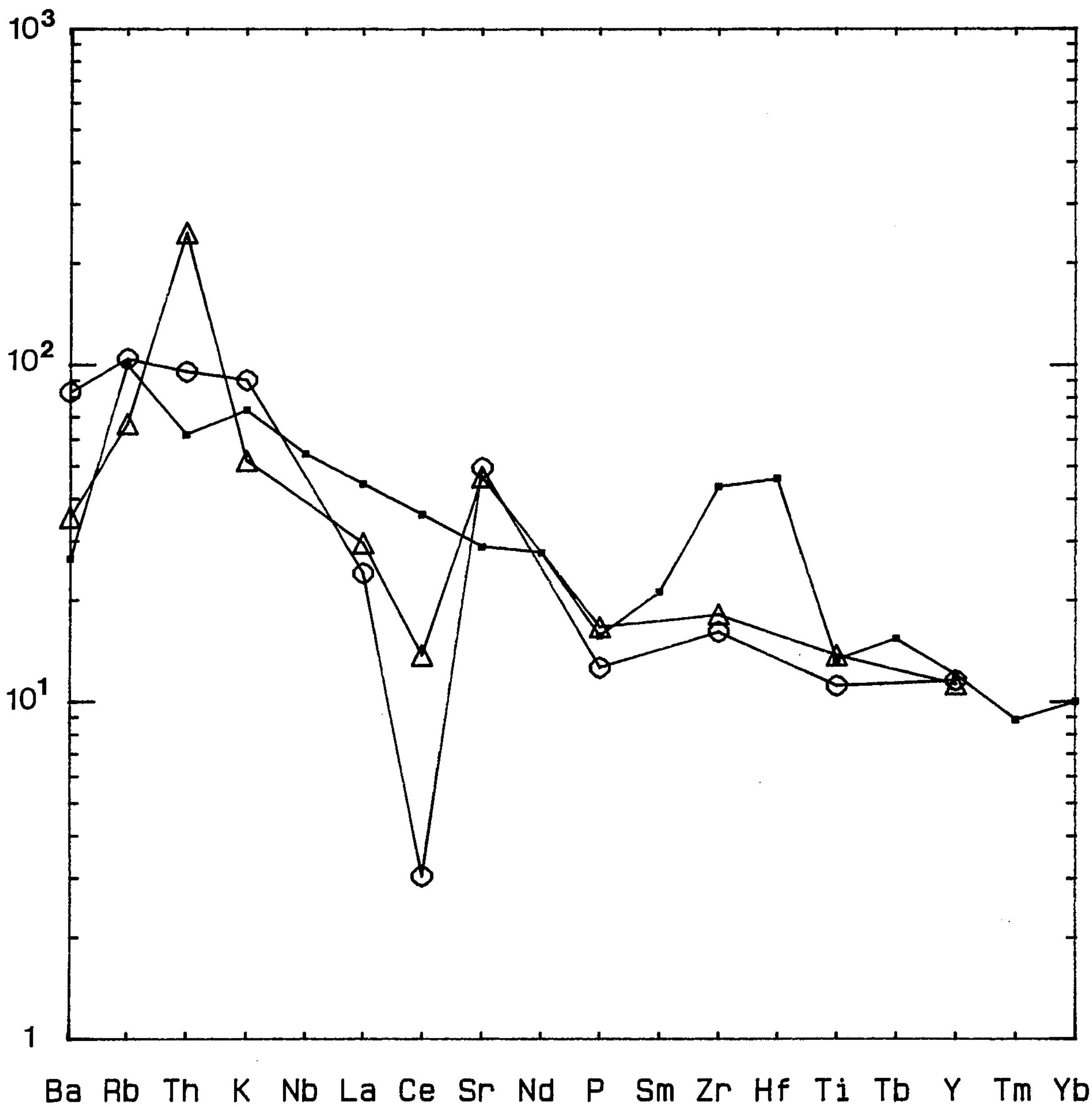

Fig. 10.- Normalized incompatible element patterns for representative analyses from the Sierra de Almagro (squares), Sierra de Enmedio (triangles) and Sierra de Carrascoy (open circles). For references and comments see text. Normalization factors according to Thompson *et al.* (1983).

Fig. 10.- Patrones normalizados de elementos incompatibles para análisis representativos de la Sierra de Almagro (cuadrados), Sierra de Enmedio (triángulos) y Sierra de Carrascoy (círculos abiertos). Ver el texto para referencias y comentarios. Factores de normalización según Thompson *et al.* (1983).

sodic amphibole + Fe oxide + albite + chlorite + epidote indicates a pressure range of between 2 and 4 kbar, which means slightly lower P conditions than those deduced for the blue amphiboles. The latter geobarometer is, moreover, very sensitive to temperature, which cannot be accurately gauged in our rocks, but it seems to be clear that the use of the Na_{M4} content as a geobarometer is better applied to rocks which have undergone temperatures higher than those deduced for the Sierra de Almagro samples.

9. DISCUSSION

The analytical data and the magmatic-tectonic interpretation presented here are very similar to those proposed by Puga and Torres-Roldán (1989) for the magmatism in the Sierra de Enmedio and Sierra de Carascoy (Fig. 10). The main differences are the higher Th content in some of the samples from the Sierra de Enmedio rocks and the lower Ce values in some samples from the Sierra de Carrascoy. In their patterns neither the

Zr nor the Hf anomalies appear. These discrepancies might be explained by the different analytical methods used.

Basic magmatism can also be found in other Betic regions, such as the Nevado-Filábride Complex and the Subbetic Zone. The correlation between the Alpujárride magmatism and the other two shows several affinities which can be interpreted as being due to their similar tectonic setting.

The incompatible element pattern from the Nevado-Filábride metabasites is very similar to the Sierra de Almagro one, except for the depletion in the more incompatible elements in some samples (Fig. 11), which, in any case, are not as low as in the ophiolitic basalts (Bodinier *et al.*, 1987). This depletion in some of the Nevado-Filábride rocks may nevertheless be simply local. In fact, the whole of the published chemical data (Puga *et al.*, 1989 a) reveal a large variation in the con-

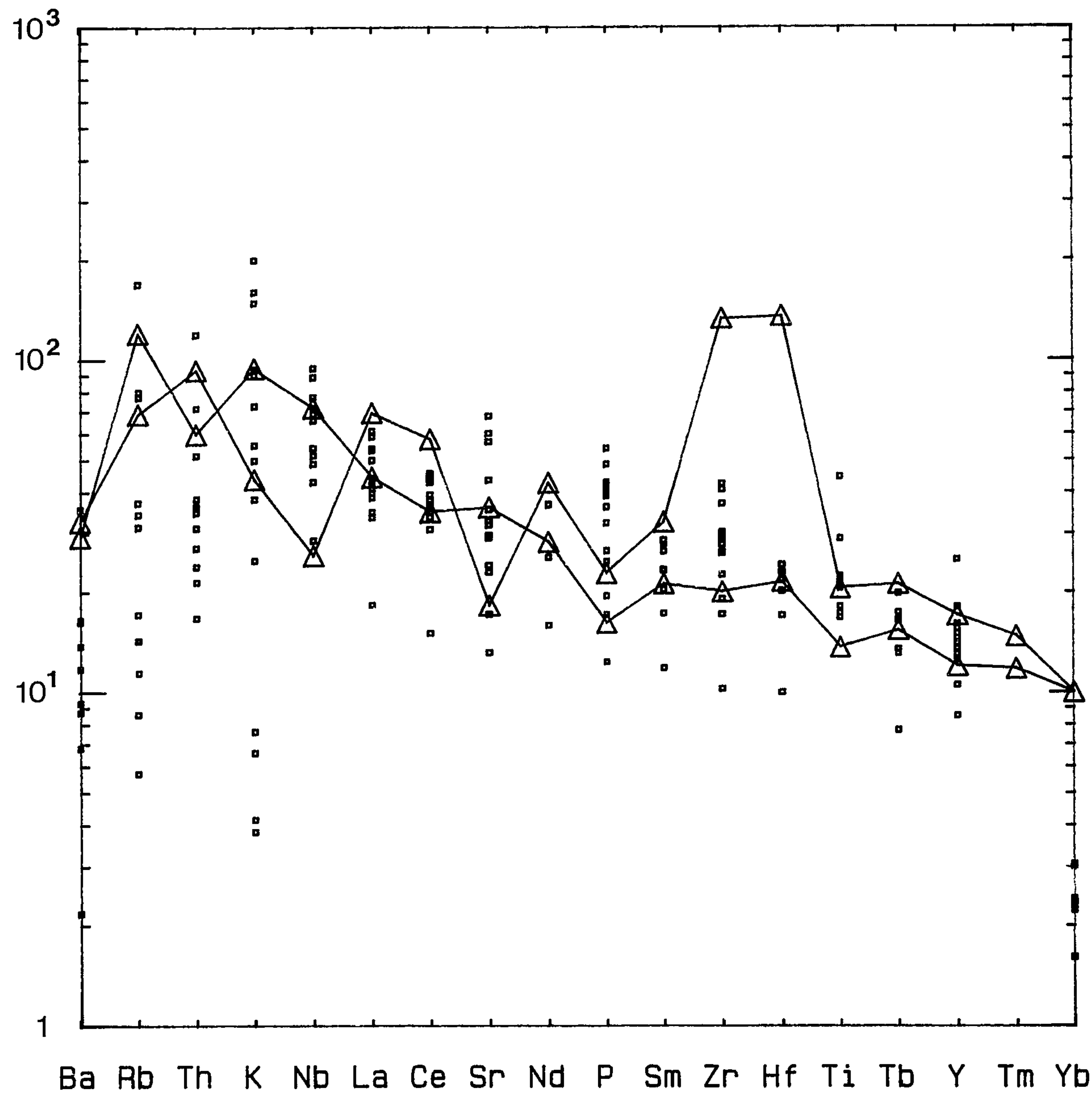

Fig. 11.- Normalized incompatible element patterns for the Sierra de Almagro extreme values (maximum and minimum contents, triangles). Squares represent the variation range for the incompatible element content from the Nevado-Filábride metabasites (our data and Bodinier *et al.*, 1988, Puga *et al.*, 1989 a). Note the large variation range in the most incompatible elements, specially Ba, Rb and K, as well as the higher or similar contents in Rb, Th and K, of some of the samples, with respect to the Sierra de Almagro metabasites. See text for additional comments. Normalization factors as in Fig. 9.

Fig. 11.- Patrones normalizados de elementos incompatibles para los valores extremos (contenidos máximo y mínimo) de la Sierra de Almagro (triángulos). Los cuadrados representan el rango de variación para el contenido en elementos incompatibles de las metabasitas del Nevado-Filábride (datos propios y Bodinier *et al.*, 1988, Puga *et al.*, 1989 a). Nótese el gran intervalo de variación de los elementos más incompatibles, especialmente Ba, Rb y K así como los contenidos más elevados o similares en Rb, Th y K, para algunas muestras, con respecto a las metabasitas de la Sierra de Almagro. Ver en el texto para comentarios adicionales. Factores de normalización como en la Fig. 9.

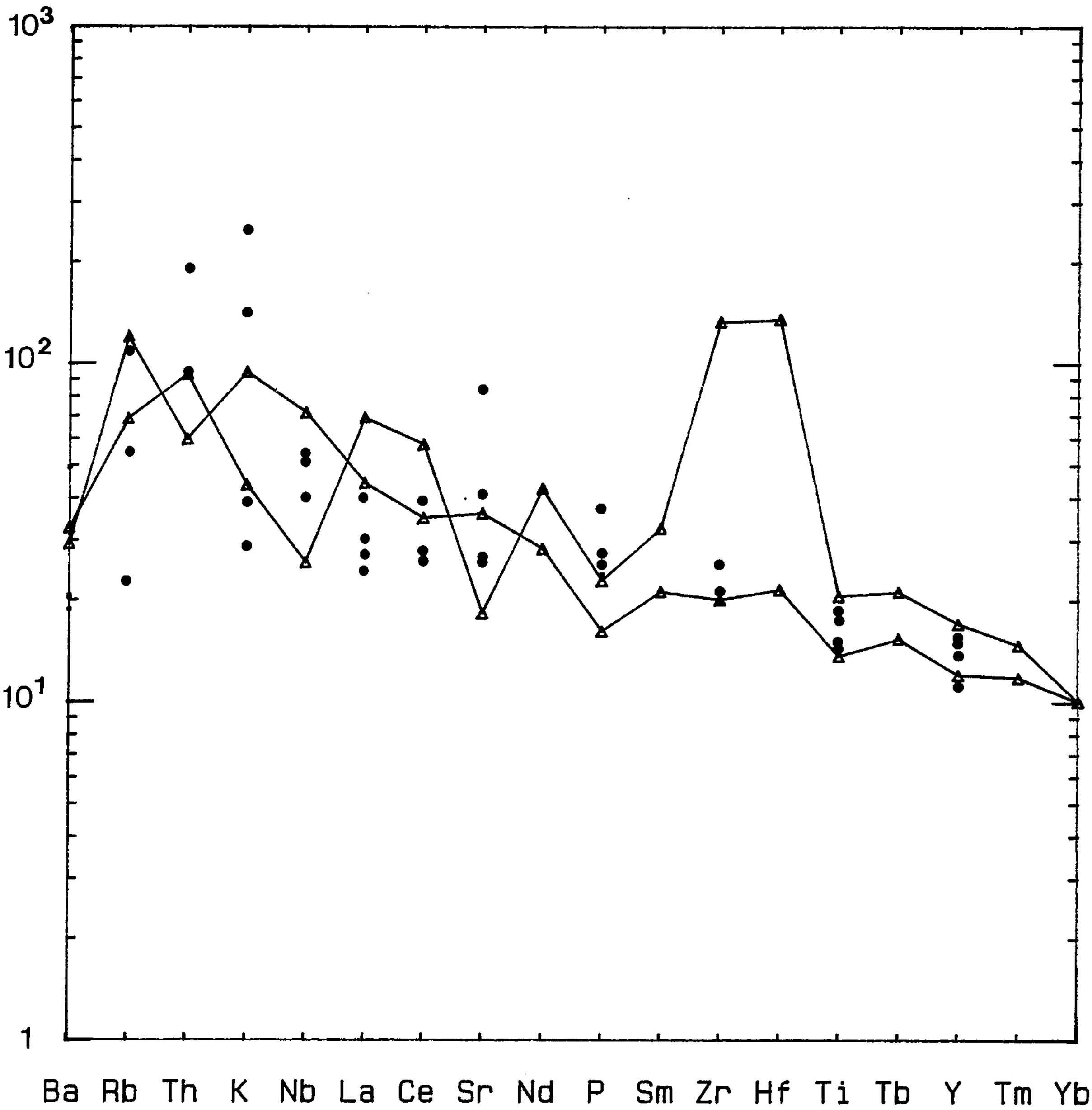

Fig. 12.- Normalized incompatible element patterns for the Sierra de Almagro extreme values (maximum and minimum contents, triangles). Squares represent the variation range for the incompatible elements from the Subbetic mafic rocks (Puga *et al.*, 1989 b). See text for comments. Normalization factors as in Fig. 9.

Fig. 12.- Patrones normalizados de elementos incompatiblespara los valores extremos (contenidos máximo y mínimo) de la Sierra de Almagro (triángulos). Los cuadrados representan el rango de variación de los elementos incompatibles de las rocas máficas del Subbético (Puga *et al.*, 1989 b). Ver el texto para los comentarios. Factores de normalización como en la Fig. 9.

tent of the more incompatible, more mobile, elements which may indicate secondary modification. On the other hand, Fig. 11 shows that a group of samples have contents of incompatible elements similar to those of the Sierra de Almagro rocks; the existence of crustal contamination is also evidenced by the Zr-spiked spidergrams of the same Nevado-Filábride rocks. Other evidence of crustal assimilation, such as the presence of continental crust xenoliths, has been described in some of the Nevado-Filábride metabasites (Gómez Pugnaire and Muñoz, 1990). This interpretation is congruent with its intracontinental origin (Gómez Pugnaire, 1981; Muñoz, 1986).

The Subbetic mafic rocks also show evidence of crustal assimilation and the general trend of the mean values in the incompatible-element diagram is very similar to that of the Sierra de Almagro (Puga *et al.*, 1989 b, Fig. 12). The similar or even lower content in some samples of the more incompatible elements compared to the Nevado-Filábride metabasites is noteworthy. Nevertheless, the lack of data concerning the geochemical variation between the rocks with Al-rich xenoliths and those without them in the Nevado-Filábride Complex prevents any comparison, at the present time, with the results obtained in the Subbetic Zone.

The geochemical peculiarities of the Alpujárride basic rocks compared to the other two areas of the Betic Cordilleras can be explained by their precise magmatic source, the range of crustal thinning during their emplacement and their peculiar magmatic evolution, but the general trend in all of them generally accords with a continental rifting environment.

As far as the geological setting of the metamorphism is concerned, a lack of experimental data concerning the mineral assemblages and also a scarcity of thermodynamic data sufficiently indicative to provide a thermobarometer have not allowed us to make a precise estimation of the metamorphic gradient. Nevertheless, the P/T-ratio deduced (about 25°C/km) is not a high-pressure gradient, requiring only 12-14 km of lithostatic load, which could be related to an underthrusting process. This metamorphism, nevertheless, may have been produced in several other tectonic settings. A high-pressure metamorphism has been inferred (16°C/km), however, in the Alpujárride metapelites to the south of Granada (Goffé *et al.*, 1989), which probably belong to the same sedimentary sequence as the Sierra de Almagro. These authors propose a lithostatic load of 20-25 Km, which would need a collisional event to attain these metamorphic conditions. A careful study of the Sierra de Almagro metapelites and more data about the metamorphic parageneses from the metabasites are required to understand the precise P-T regime of the metamorphism and, consequently, the tectonic setting.

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