

Progressive metamorphic evolution of eclogites containing kyanite veins in the Betic Cordilleras (SE Spain)

MARIA TERESA GOMEZ-PUGNAIRE

Departamento de Mineralogía y Petrología e Instituto Andaluz de Geología Mediterránea (CSIC).
Facultad de Ciencias, Fuentenueva S/u. 18002 Granada (Spain)

GERHARD FRANZ

Institut für Angewandte Geophysik, Petrologie und Lagerstättenforschung, Technische Universität,
1000 Berlin 12 (West Germany)

MERCEDES MUÑOZ

Departamento de Mineralogía y Petrología e Instituto Andaluz de Geología Mediterránea (CSIC).
Facultad de Ciencias, Fuentenueva S/u. 18002 Granada (Spain)

ABSTRACT. — Veins of kyanite + omphacite + zoisite + rutile sometimes occur within the kyanite-bearing eclogites of the Betic Cordilleras (Nevado-Filábride Complex).

They indicate the existence of water-rich fluid infiltration during eclogitization. The fluid were produced by devolatilization reactions in the surrounding metasediments and transported along fracture and vein systems. The phase relations in the veins and matrix point to three progressive metamorphic stages. The first was produced at high-pressure and relatively low temperature (about 12 Kbar and 500-575°C), while the second was almost certainly related to an isothermal decompression stage (about 7 Kbar at 575°C). The final stage involved heating accompanied by uplifting, the physical conditions being those of the peak of the Alpine metamorphism (about 6 Kbar and 600°C.) The textural relationships, chemical data concerning the most significant minerals and phase relations in the veins and matrix are also described.

Key words: Betic Cordilleras, Nevado-Filábride Complex, kyanite-bearing eclogites, veins of kyanite, fluid infiltration, high-pressure metamorphism.

RESUMEN. — Venas de distena + onfacita + zoisita + rutilo se encuentran en algunos cuerpos de eclogitas granoblasticas con distena de las Cordilleras Béticas (Complejo Nevado-Filábride). Estas venas indican infiltración de una fase fluida rica en agua durante la

eclogitización, procedente de los sedimentos encajantes y producida por reacciones de desvolatilización. Las relaciones de fases estudiadas en las venas y en la matrix nos han permitido deducir tres etapas progresivas de metamorfismo. La primera de ellas tuvo lugar en un régimen de altas presiones y relativamente baja temperatura (alrededor de 12 Kbar y 550-675°C); la segunda representa una etapa de descompresión isothermal (alrededor de 7 Kbar y 575°C) y, durante la última etapa, calentamiento y descompresión tienen lugar con respecto a las dos anteriores, de manera que la última paragenesis mineral se formó en condiciones próximas al climax termico del metamorfismo alpino. En este artículo se describen también las relaciones texturales, los datos quimicos de algunos de los minerales más significativos y las relaciones de fases en las venas y en la matrix.

Introduction

The presence or absence of a fluid phase, its composition and its interaction with the solid phase during metamorphism control many of the phase relations, textural development and mechanical behaviour of eclogites. While it was formerly assumed that eclogites generally crystallize under dry

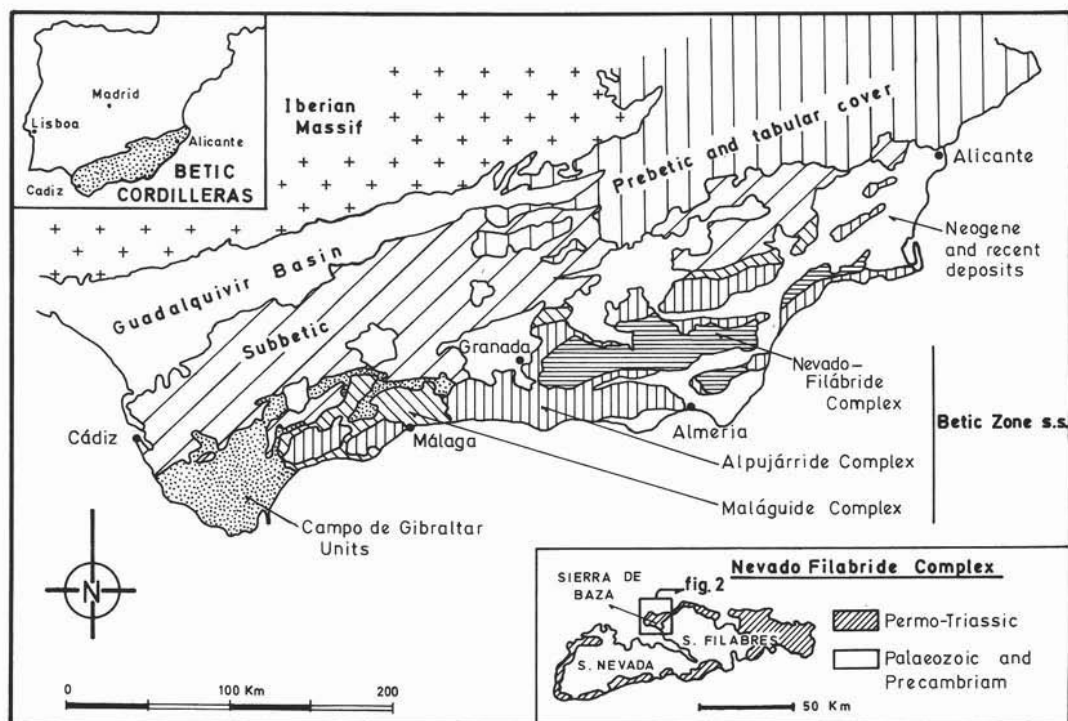


Fig. 1. — Tectonic sketch of Betic Cordilleras, SE Spain. Bottom right inset: Nevado-Filábride Complex shown as part of the Internal Zones, together with distribution of Permo-Triassic and the oldest rocks.

conditions, many cases are now known of crystallization taking place under obviously wet conditions, that is, in the presence of a certain quantity of a hydrous phase (e.g. HOLLAND, 1979a, OKAY *et al.*, 1985).

During the retrograde alteration of eclogites into amphibolites, the infiltration of a hydrous fluid phase is also a controlling factor. The sources of these fluids are either surrounding non-mafic schists or gneisses (HEINRICH, 1982), or the hydrous mineral phase of the eclogites themselves (FRANZ *et al.*, 1986).

Two factors have been proposed to explain the different types of eclogites: deformation and the water content of the protoliths. The fact that eclogites found in ductile shear zones are granoblastic in texture, while coronitic ones show non signs of deformation indicates the influence of deformation in mass transport as an important mechanism in the generation of the different types of eclogites (MORK, 1985; POGNANTE, 1985), increasing diffusion rates and also allowing access of fluids during

the metamorphic process (AUSTHEREIM, and GRIFFIN, 1985). Another important factor is the type of protolith (metabasalts or metadolerites), which influences the activity of the fluid phase and consequently determines the character of the eclogite (GOMEZ-PUGNAIRE and FERNANDEZ-SOLER, 1987).

The existence of kyanite veins, occasionally with omphacite, zoisite and rutile, as well as globular kyanite segregations, leads us to believe in the presence of a water-rich fluid phase during the metamorphism of the undeformed kyanite-bearing eclogites. The textures, phase relations and mineral equilibria, all reflecting the progressive mineralogical changes in the rocks, also indicate the pervasive infiltration of a fluid phase during recrystallization.

Field relations and geological setting

The rocks in question come from the Nevado-

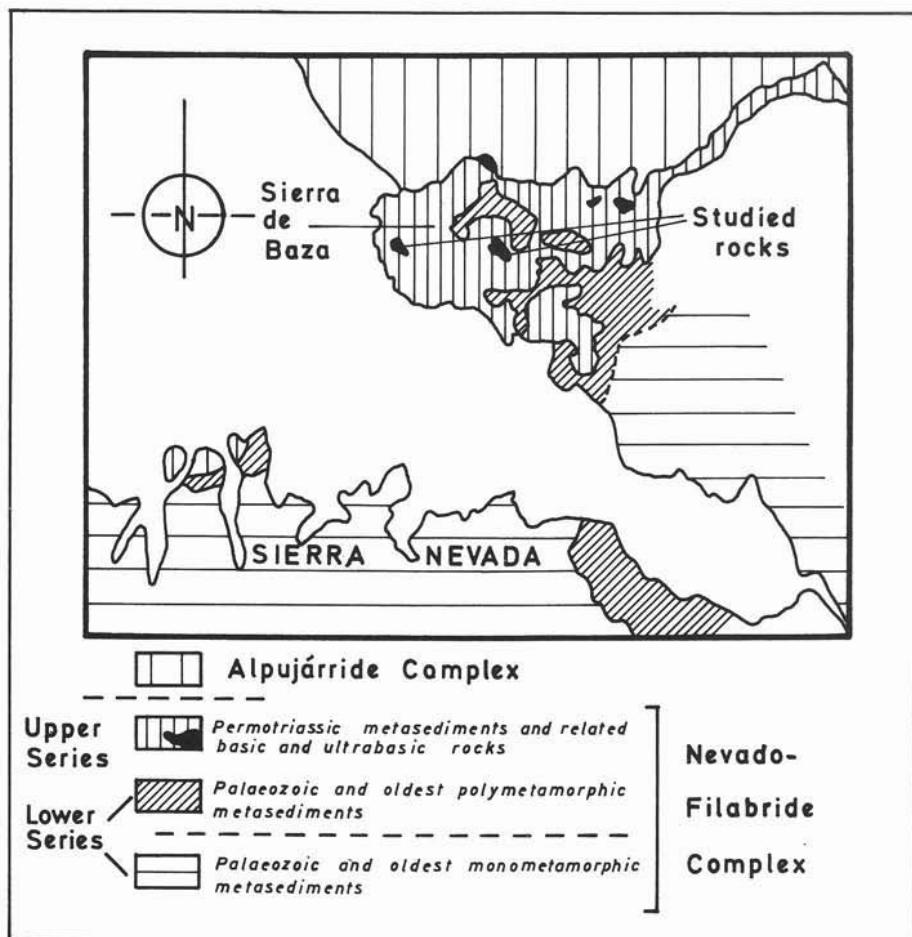


Fig. 2. — Provenance of samples of studied metabasites and associated metasediments. Tectonic subdivision in central part of the Nevado-Filábride Complex.

Filábride Complex of the Sierra de Baza, part of the Internal Zones of the Betic Cordilleras (SE Spain, Figs 1 and 2), and are to be found within two discordant, intrusive bodies of metabasic rocks (GOMEZ-PUGNAIRE, 1979).

Kyanite in metabasic rocks has so far only been described in the Nevado-Filábride Complex as part of pseudomorphs after lawsonite (GOMEZ-PUGNAIRE et al., 1985) or as rare isolated crystals partly replaced by white mica (GOMEZ-PUGNAIRE, 1979a). Nevertheless, rocks with kyanite veins, hitherto unknown in this complex, do in fact appear, generally occurring at the boundaries between metabasic bodies and pelitic and

carbonatic metasediments, though non regular distribution is discernible. The surrounding metapelites also contain kyanite-quartz veins, while the metacarbonates have kyanite + zoisite segregations, all related to the older metamorphic stage (GOMEZ-PUGNAIRE, 1979a).

The whole sequence of metasediments and metabasic rocks forms part of the Permo-Triassic Series of the Nevado-Filábride Complex (FALLOT et al., 1961). The rocks were affected by the two main stages of Alpine metamorphism: the first stage was a high P/intermediate T event ($P_{\min.} = 12,5$ Kbar, $T = 550^{\circ}\text{C}$) and evolved into a second stage at

TABLE 1
Microprobe analyses of pyroxenes

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
SiO ₂	55.65	54.94	56.07	55.86	56.55	56.17	56.26
TiO ₂	0.05	0.10	0.03	0.07	0.07	0.05	0.01
Al ₂ O ₃	12.28	12.44	11.05	9.69	10.25	10.51	11.03
Fe ₂ O ₃ (*)	0.54	2.08	2.67	2.87	2.73	2.37	2.26
FeO	3.79	2.44	1.83	2.11	1.97	2.26	2.49
MgO	8.07	7.61	7.40	8.36	8.09	7.83	7.57
MnO	0.02	—	0.02	0.03	—	0.03	0.04
CaO	12.43	12.02	11.55	12.89	12.44	12.22	11.75
Na ₂ O	7.00	7.41	7.78	7.06	7.35	7.35	7.59
TOTAL	99.83	99.04	98.40	98.94	99.45	98.79	99.00
Si	1.975	1.964	2.012	2.006	2.013	2.012	2.010
Al ^{iv}	0.025	0.036	—	—	—	—	—
Al ^{vi}	0.489	0.488	0.467	0.410	0.430	0.444	0.465
Ti	0.001	0.003	0.001	0.002	0.002	0.001	0.001
Fe ³⁺	0.014	0.073	0.072	0.078	0.073	0.064	0.061
Fe ²⁺	0.113	0.056	0.055	0.063	0.059	0.067	0.074
Mg	0.427	0.405	0.396	0.447	0.429	0.418	0.403
Mn	0.001	—	0.001	0.001	—	0.001	0.001
Ca	0.473	0.461	0.444	0.496	0.474	0.469	0.450
Na	0.482	0.514	0.541	0.492	0.507	0.511	0.526
Acm	—	—	7.4	8.6	7.7	6.7	6.1
Jad	48.2	51.4	46.7	41.0	43.0	44.4	46.5
Aug	51.8	48.6	45.9	50.8	49.3	48.9	47.4

(*) The ratio Fe³⁺/Fe²⁺ was calculated according PAPIKE et al. (1974).
Structural formulae calculated on the basis of 6 oxygens.

a lower pressure (about 6.5 Kbar) with a maximum temperature of 610°C (GOMEZ-PUGNAIRE 1979b, GOMEZ-PUGNAIRE and FERNANDEZ-SOLER, 1987).

This sequence rests on Paleozoic (FALLOT et al., 1961) and probably Precambrian (GOMEZ-PUGNAIRE et al., 1982) graphite-rich pelitic and psammitic metasediments. They show clear evidence of polymetamorphism (GOMEZ-PUGNAIRE and SASSI, 1983), but its regional distribution and significance are not yet completely understood (GOMEZ-PUGNAIRE, 1984; GOMEZ-PUGNAIRE and FRANZ, 1988).

Both the Permo-Triassic and Palaeozoic / Precambrian formations belong to the *Charches* tectonic unit in the Sierra de Baza (GOMEZ-PUGNAIRE, 1979a), which corresponds to part of the *Nevado-Lubrin* unit

in other parts of the Sierra de los Filabres (NIJHUIS, 1964) and to the *Mulhacén nappe* in the Sierra Nevada (PUGA et al., 1974).

Petrography

The eclogites containing kyanite veins are pale green, dense, massive rocks with preserved igneous doleritic, granular or, very rarely, porphyritic textures. Although all these various types do include kyanite veins, which locally bear omphacite, zoisite and rutile, only those displaying a granular texture show clear evidence that the kyanite crystallized in equilibrium with the omphacite and garnet in the matrix.

Veins are 1 to 5 cm thick and 0.5 to 3 m long. The contact with the matrix is straight

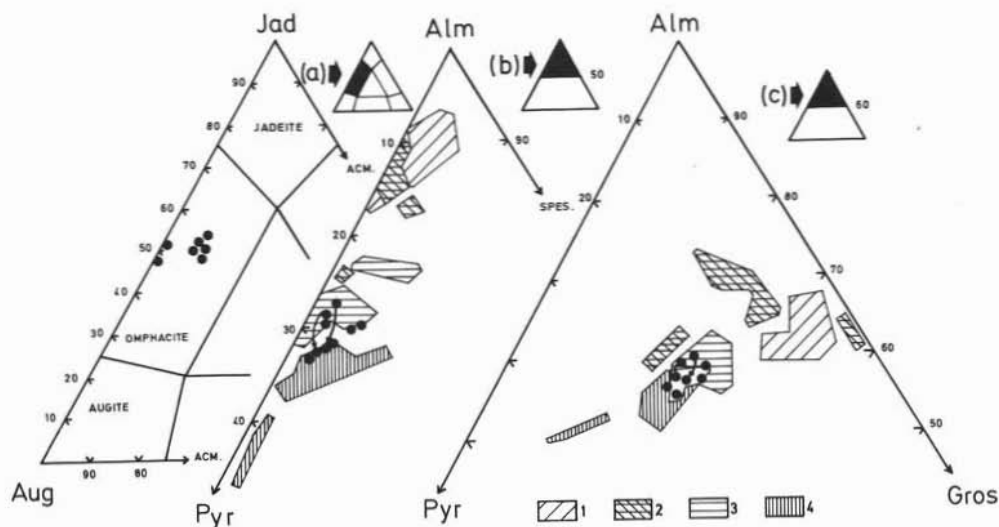


Fig. 3. — Composition of pyroxenes (a) and garnets (b, c) in terms of their end-members: a) jadeite - acmite - augite; b) almandine - pyroxene - grossularite and c) almandine - pyroxene - spessartine. For comparison, compositional fields of garnet from other metabasites from Sierra de Baza are also shown (from GOMEZ-PUGNAIRE and FERNANDEZ-SOLER, 1987): 1. carbonate-bearing granoblastic eclogites; 2. glaucophane-bearing granoblastic eclogites; 3. granoblastic eclogites; 4. coronitic eclogites.

and sharp. Small kyanite segregations of up to 1 cm are also frequent in the matrix. The kyanite crystals in the veins are radially orientated and their length ranges from a few millimeters to 18 cm. They are sometimes highly deformed and aligned parallel to the border of the wall rocks. Locally they are bent and/or fractured. The matrix shows no evidence of deformation except for some small fractures (late stage?) cutting across the eclogite mineral assemblage and the undulose extinction of the omphacite crystals.

Igneous relics are very rarely present, in contrast to other parts of the metabasite bodies, although occasional relics of clinopyroxene (augite) are preserved inside the omphacite and amphibole.

The size of the omphacite and garnet crystals increases gradually from 0.2-0.3 mm in the matrix to 3 mm towards the border of the kyanite veins. However, it is worth noting that the amphibolite-facies alteration involved not only the eclogites but also the kyanite-omphacite-bearing veins. This fact, and the above referred increase of mineral size towards the veins, are clear evidence that the

veins formed relatively early, probably close to the climax of the high-pressure conditions.

Description of minerals

The matrix minerals near the kyanite veins were analysed by microprobe (WDS Camebax, using K-feldspar and albite as standards for K, Na and Al, wollastonite for Ca and Si, synthetic TiO_2 for Ti, synthetic MgAl_2O_4 for Mg and metals for Fe and Mn). Their composition is essentially similar to that of the minerals in granoblastic eclogites described by GOMEZ-PUGNAIRE and FERNANDEZ-SOLER (1987).

Omphacite

This mineral has a jadeite content between 41 and 51 mol%, with a mean composition of $\text{Ac}_{51}\text{Jd}_{46}\text{Ag}_{49}$ (structural formulae were calculated according to PAPIKE et al., 1974, and end-members according to CAWTHORN and COLLERSON, 1974). The crystals are only slightly zoned, with a small increase in jadeite content towards the rim. The acmite content

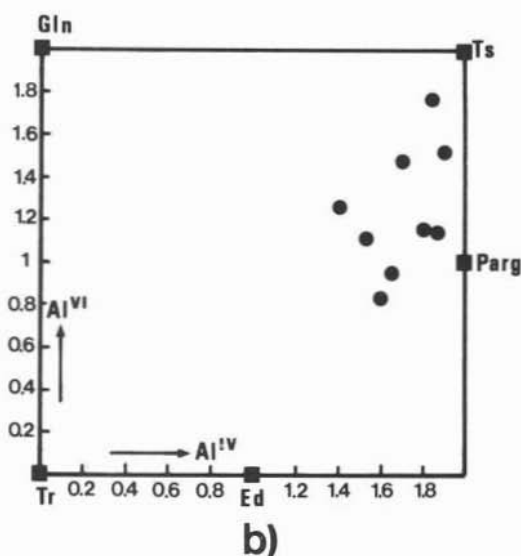
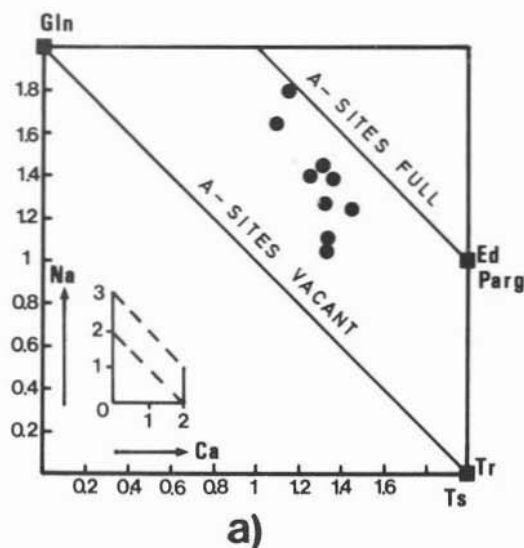


Fig. 4 (a, b). — Amphibole composition from different textural sites in terms of total sodium content versus calcium (a), and Al^{VI} versus Al^{IV} (b).

is generally lower than in the omphacite crystals occurring in other rocks of the same body but, despite this small chemical difference, no real composition difference exists between the omphacite crystals from the kyanite-free and kyanite-bearing rocks. The chemical composition of the omphacite is shown in Table 1 and Fig. 3a.

Both the omphacite crystals in the matrix

and those in the veins are texturally very similar, with very fine-grained symplectitic rims. The symplectite is sometimes recrystallized into coarse-grained amphibole and plagioclase intergrowths, which reveal a similar symplectitic texture. The inclusion-free omphacite crystals, which only rarely include garnet, are also altered into an aggregate of white mica, amphibole, epidote, quartz and, locally, plagioclase; this latter aggregate developed only at the contact with the kyanite and garnet crystals.

The augite relics are pseudomorphosed by omphacite which, at a later stage, was also altered into amphibole.

Garnet

Table 2 shows the chemical composition of the garnet. The garnet crystals are slightly zoned, with the pyrope content (from 18 to 22 mol%) increasing towards the rims and the spessartine content decreasing (from 4 to 1.5 mol%). The grossularite content is almost constant at approximately 20 mol%. These compositional data are compared in Fig. 3(b,c) to those of garnets from other metabasic rocks: they plot close to the compositional field of garnet belonging to kyanite-free eclogites.

The garnet occurs either as small, idioblastic or subrounded, isolated crystals of about 0.2 mm or, more frequently, as aggregates of 1 mm diameter. Amphibole, epidote and plagioclase are the decomposition products of the garnet + omphacite and appear where both minerals are in contact. No reaction rim generally occurs between the garnet and the kyanite, although locally both minerals are replaced by zoisite and amphibole. Inclusions are rare and only randomly orientated minute crystals of rutile occur.

Amphibole

This mineral is found in various different textural sites:

- within symplectitic aggregates surrounding omphacite crystals and/or included in their fractures;
- as small, randomly-orientated, acicular

TABLE 2
Microprobe analyses of garnets

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
SiO ₂	39.60	39.11	39.56	39.71	39.90	39.62	37.83	36.94	38.40
TiO ₂	0.11	0.13	0.01	0.06	0.09	0.15	—	—	0.01
Al ₂ O ₃	22.73	22.74	22.88	22.61	22.64	22.28	21.28	21.19	21.45
FeO(*)	26.40	25.95	26.03	25.90	26.62	25.81	26.66	27.75	26.38
MgO	5.80	4.88	6.29	6.40	5.96	5.15	5.77	5.88	5.14
MnO	1.25	1.95	0.80	0.74	1.08	1.63	0.67	0.69	0.69
CaO	7.63	7.86	7.37	7.61	7.42	8.33	7.79	7.61	7.64
TOTAL	103.52	102.62	102.94	103.03	103.71	102.97	100.00	100.06	99.70
Si	5.958	5.953	5.960	5.976	5.986	6.002	5.930	5.830	6.015
Al	4.031	4.080	4.063	4.011	4.003	3.978	4.002	3.943	3.961
Ti	0.012	0.015	0.001	0.007	0.010	0.017	—	—	0.001
Fe ²⁺	3.322	3.304	3.280	3.260	3.340	3.270	3.495	3.663	3.456
Mg	1.301	1.107	1.412	1.436	1.333	1.163	1.349	1.383	1.200
Mn	0.159	0.251	0.102	0.094	0.137	0.209	0.089	0.092	0.092
Ca	1.230	1.282	1.190	1.227	1.193	1.352	1.309	1.287	1.282
Oct	10.056	10.039	10.048	10.035	10.016	9.99	10.238	10.368	9.991
Alm	55.3	55.6	54.8	54.2	55.6	54.6	56.0	57.0	57.3
Pyr	21.6	18.6	23.6	23.9	22.2	19.4	21.6	21.6	19.9
Spes	2.6	4.2	1.7	1.6	2.3	3.5	1.4	1.4	1.5
Gross	20.5	21.6	19.9	20.4	19.9	22.6	21.0	20.0	21.3

(*) All Fe as FeO. Structural formulae calculated on 24 oxygens

- crystals at the grain boundaries between omphacite and garnet;
 iii) in interstitial aggregates together with epidote;
 iv) as larger crystals surrounding the omphacite, which in turn replaces igneous relics of augite;
 v) in polymineral aggregates consisting of amphibole, zoisite, white mica and plagioclase, produced by the breakdown of garnet + omphacite + kyanite.

Despite the various textural occurrences, the chemical composition of the amphiboles is relatively constant (Table 3, Fig. 4) and corresponds to that of the calcic (ferropargasitic) to sodic-calcic amphiboles (LEAKE, 1978). The increase in the Tschermak substitution towards the rim (analyses 5 to 7) from the glaucophane component in the core (analyses 3, 8 and 9) is accompanied by a more intense green colour. This feature is consistent with the conclusion that the eclogites were affected by a late alteration under lower

pressure and higher temperature, as described by GOMEZ-PUGNAIRE and FERNANDEZ-SOLER (1987).

Kyanite

As well as the already described occurrences, there are two further textural aspects to this mineral, which have special significance in the interpretation of phase relations.

- Kyanite both within the veins and in the matrix appears as idioblastic crystals altered into white micas (margarite and paragonite) and quartz. The crystals are similar to those described by GOMEZ-PUGNAIRE et al. (1985) but without the coronitic textures (Fig. 5). Zoisite is associated with kyanite, sometimes as minute inclusions (see reaction 5 in the following section).
- Zoned plagioclase corrodes margarite-bearing aggregates deriving from kyanite as well as the coexistent zoisite (see Fig.

TABLE 3
Microprobe analyses of amphiboles

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
SiO ₂	42.14	44.35	44.67	40.77	39.76	41.60	41.84	45.19	45.97
TiO ₂	0.06	0.19	0.39	—	0.13	0.15	0.28	0.25	0.17
Al ₂ O ₃	17.10	14.27	15.52	16.73	18.74	20.47	17.71	15.76	15.71
Fe ₂ O ₃ (*)	1.83	3.70	4.98	2.83	1.39	0.35	1.63	1.89	0.55
FeO	16.95	10.93	9.37	16.09	16.36	14.85	14.59	14.21	15.98
MgO	6.88	11.19	11.13	6.61	5.28	6.02	6.64	9.07	8.11
MnO	0.65	0.47	0.21	0.56	0.49	0.67	0.64	0.11	—
CaO	8.46	8.75	8.36	8.91	8.11	8.36	8.31	7.57	7.18
Na ₂ O	5.07	4.96	5.09	4.27	4.29	3.70	3.84	6.37	5.87
K ₂ O	0.51	0.45	0.43	0.38	0.54	0.44	0.12	0.11	1.02
TOTAL	99.65	99.26	100.15	97.15	95.09	96.60	95.60	100.53	100.55
T ₁ Si	2.215	2.412	2.352	2.168	2.114	2.181	2.306	1.472	2.605
Al ^{IV}	1.785	1.588	1.648	1.832	1.886	1.819	1.694	1.528	1.395
T ₂ Si	4.000	4.000	4.000	4.000	4.000	4.000	4.000	4.000	4.000
Al ^{VI}	1.187	0.844	0.953	1.151	1.510	1.766	1.452	1.132	1.266
Ti	0.007	0.021	0.042	—	0.015	0.017	0.032	0.027	0.018
M ₁ Fe ²⁺	0.203	0.403	0.533	0.323	0.161	0.039	0.185	0.204	0.059
Fe ²⁺	0.350	0.259	0.152	0.304	0.199	0.103	0.183	0.298	0.345
Mg	0.253	0.473	0.321	0.222	0.115	0.075	0.148	0.339	0.312
M ₂ Fe ²⁺	1.741	1.062	0.962	1.732	1.905	1.742	1.657	1.403	1.575
Mg	1.259	1.938	2.038	1.268	1.095	1.258	1.343	1.597	1.425
Mn	0.081	0.058	0.025	0.072	0.064	0.084	0.082	0.013	—
M ₃ Ca	1.337	1.356	1.274	1.444	1.336	1.331	1.342	1.162	1.105
Na	0.582	0.587	0.701	0.484	0.600	0.585	0.576	0.825	0.895
A Na	0.868	0.804	0.702	0.769	0.679	0.481	0.546	0.944	0.741
K	0.096	0.083	0.078	0.073	0.106	0.083	0.023	0.020	0.187
	0.036	0.113	0.220	0.158	0.215	0.435	0.431	0.036	0.072

(*) Structural formulae calculated on 23 oxygens and on the basis of Si + Ti + Fe²⁺ + Fe³⁺ + Mg = 13; Fe³⁺ calculated by difference with the theoretical 46 positive charges.

6). The substitution of the margarite + zoisite + quartz assemblage by plagioclase + vapour has a important petrologic significance within this chemical system because took place at univariant P-T conditions.

(about 85 mol% margarite) at the contact with the kyanite and Na-rich towards the matrix (nearly pure paragonite), just like that described by GOMEZ-PUGNAIRE et al. (1985, cf. type A pseudomorphs).

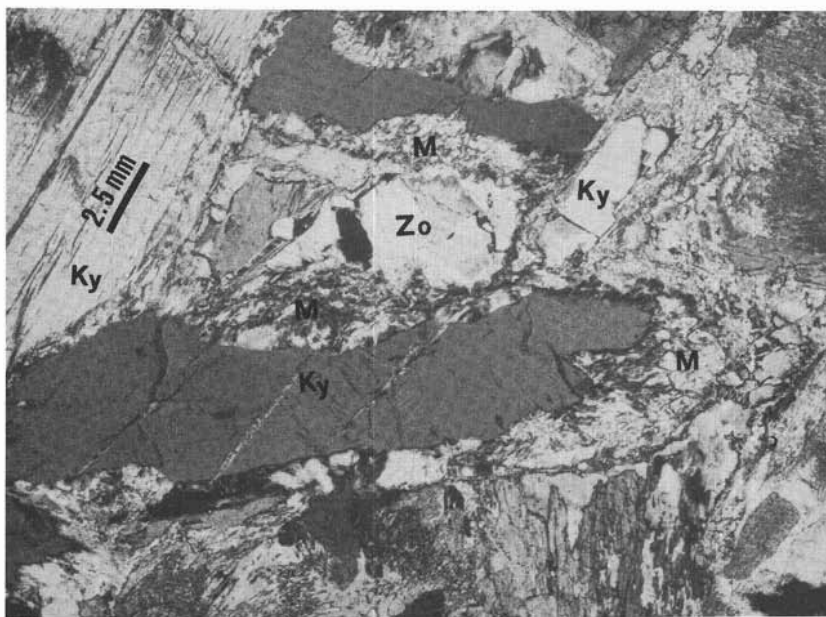
White mica

This phyllosilicate only occurs as a replacement product of kyanite crystals and sometimes coexists with zoisite, quartz or albite, according to the minerals in contact with the kyanite. It consists of a paragonite-margarite solid solution, which is Ca-rich

Other minerals

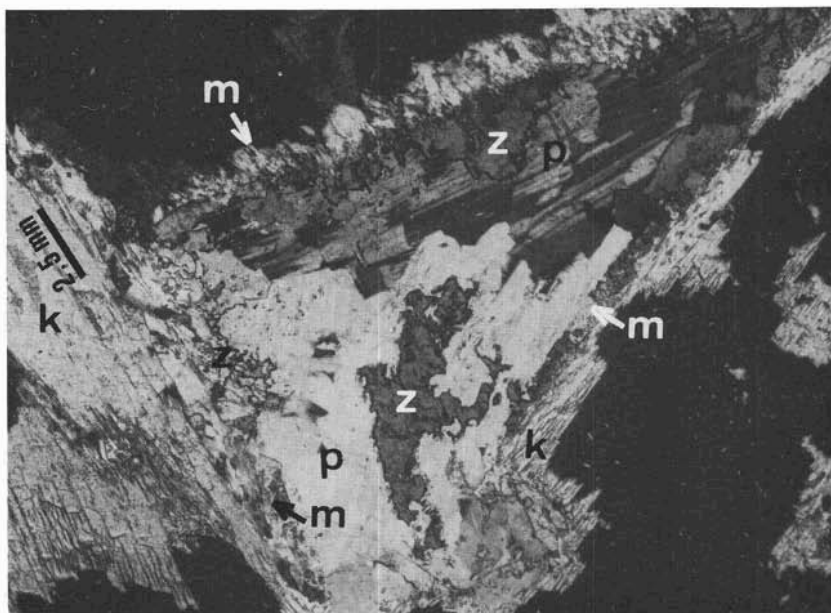
Rutile is present both in the veins, as large crystals rimmed by ilmenite, and in the matrix, as small crystals, sometimes outlining the shape of former Ti-bearing minerals such as amphibole, biotite, pyroxene and/or magnetite-ilmenite solid solutions.

Zoisite appears in the veins as crystals of



a)

Fig. 5. — Kyanite (ky) and zoisite (zo) replaced by margarite + quartz (M) aggregates in a kyanite vein.



b)

Fig. 6. — Margarite + quartz (m) aggregates replacing kyanite (k) and zoisite (z) are corroded by plagioclase (p) (see reaction (5) in Table 4 and text).

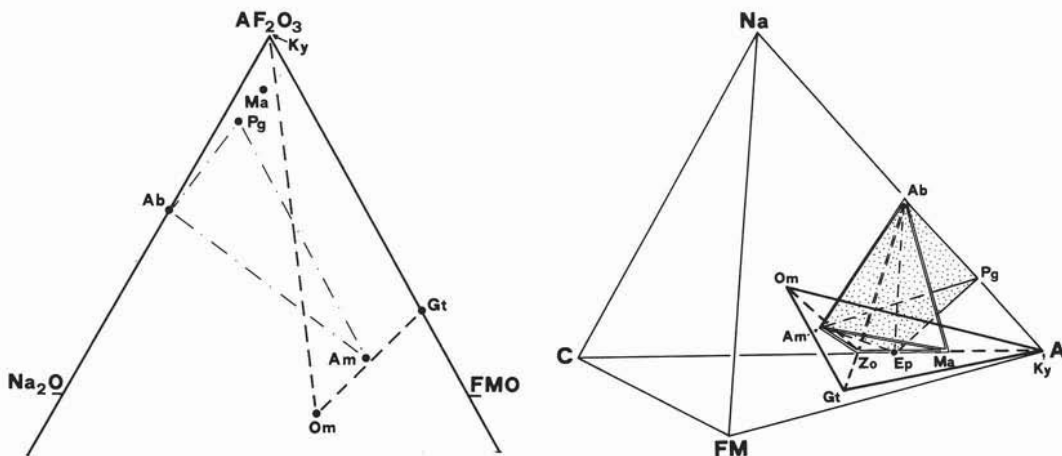


Fig. 7 a, b). — a) Phase relations of the mineral assemblage in granoblastic eclogites with kyanite veins projected from zoisite/epidote, quartz, and water onto plane AF_2O_3 ($Al_2O_3 + Fe_2O_3$) - Na_2O -FMO ($FeO + MgO$). Dashed heavy lines connect the eclogitic assemblage (M_1); dashed and dotted light lines connect the last stage of equilibration (M_3).

b) Phase relations in same rocks in $C(CaO)$ -FM($FeO + MgO$)-Na-A($Al_2O_3 + Fe_2O_3$) tetrahedron. Om-Gt-Ky-Zo subtetrahedron represents the eclogitic assemblage (M_1). The subtetrahedron in double lines represents the second mineral assemblage (M_2); the dotted subtetrahedron shows the youngest mineral assemblage (M_3). See text for additional information. The composition of plotted minerals is shown in Tables 1, 2 and 3.

up to 0.3 mm in length and also in the matrix as smaller crystals, sometimes surrounded by an epidote rim, which may be produced during the amphibolite-facies overprint. Hematitised magnetite and carbonate occur rarely as accessory minerals.

Phase relations

Omphacite, garnet, kyanite, zoisite and quartz represent the oldest mineral paragenesis in these rocks. The occurrence of some of them in both veins and matrix sites lead us to believe that they crystallized in equilibrium with a water-rich fluid phase. All the alteration products related to later stages may be explained by the decomposition of the above-mentioned mineral phases.

Textural observations suggest the phase relations shown in Fig. 7a, b, and the several possible reactions listed in Table 4, the latter being shown together with the chemical composition of the participating phases. The stoichiometry of these reactions was calculated according to SPEAR et al. (1982), but they are expressed in Table 4 in terms of oxygen units (THOMPSON et al., 1982), thus evidencing the

changes in modal abundance of the minerals during reactions.

Equilibria (1) and (2) may explain the textural occurrence of amphibole, that forms interstitial aggregates with quartz, either with (1) or without (2) epidote. The modal proportion of the kyanite involved in reaction (1) is small, and this equilibrium is therefore also possible in the kyanite-free domains with minor balancing-exchange substitution in the amphibole and/or a great modal proportion of omphacite (see reaction 2).

Symplectite aggregates from omphacite may have been produced by the hydrolysis of omphacite in the presence of quartz (3), in both veins and matrix. A reaction with garnet (3b) might also be assumed, but it does not agree with the petrographic evidence: the corresponding modal proportion of albite is too low, and quartz never occurs with the albite + amphibole symplectite aggregates. Figs. 7 (a, b) show graphically that the Ab-Am pair is not equivalent to the Om-Gr one, and that the Om-Ky pair may possibly be substituted by the Ab-Am one. In fact, (3a) might be a symplectite-forming reaction, but, petrographic evidence shows that the

TABLE 4

Proposed reactions deduced from the textural phase relations and chemical composition of the phases involved in the reactions

- (1) $0.69 \text{ Om} + 0.19 \text{ G} + 0.09 \text{ Ky} + 0.04 \text{ H}_2\text{O} = 0.73 \text{ Am} + 0.14 \text{ Ep} + 0.13 \text{ Q}$
 (2) $0.74 \text{ Om} + 0.27 \text{ G} + 0.04 \text{ H}_2\text{O} = 0.84 \text{ Am} + 0.16 \text{ Q}$
 (3) $0.59 \text{ Om} + 0.07 \text{ H}_2\text{O} + 0.41 \text{ Q} = 0.84 \text{ Ab} + 0.16 \text{ Am}$
 (3a) $0.59 \text{ Om} + 0.21 \text{ Ky} + 0.01 \text{ H}_2\text{O} + 0.21 \text{ Q} = 0.7 \text{ Ab} + 0.3 \text{ Am}$
 (3b) $0.62 \text{ Om} + 0.33 \text{ G} + 0.05 \text{ H}_2\text{O} = 0.091 \text{ Q} + 0.009 \text{ Ab} + 0.9 \text{ Am}$
 (4) $0.50 \text{ Ky} + 0.48 \text{ Zo} + 0.02 \text{ H}_2\text{O} = 0.81 \text{ Ma} + 0.19 \text{ Q}$
 (5) $2 \text{ Zo} + \text{Ma} + \text{Q} = 4 \text{ An} \text{ (in plagioclase)} + \text{H}_2\text{O}$
 (6) $0.29 \text{ Ab} + 0.70 \text{ Ma} + 0.1 \text{ H}_2\text{O} = 0.80 \text{ Pa} + 0.17 \text{ Ep} + 0.03 \text{ Q}$

Abbreviations: Ab = Albite, Am = Amphibole, An = Anorthite, Ep = epidote
 G = garnet, Ky = Kyanite, Ma = Margarite, Om = omphacite, Q = quartz
 Pa = paragonite, Zo = zoisite.

References: (1): OKAY et al. (1985); (2), (3) and (6): this paper
 (4) and (5): CHATTERJEE (1976)

Phases	Formulae
Albite	$\text{Si}_2\text{AlNaO}_6$
Amphibole	$\text{Si}_{1.2}\text{Al}_{0.8}\text{Fe}_{0.2}\text{Mg}_{1.5}\text{Ca}_{1.4}\text{Na}_{1.6}\text{O}_{22}(\text{OH})_2$
Anorthite	$\text{Si}_2\text{Al}_2\text{CaO}_8$
Epidote	$\text{Si}_2\text{Al}_2\text{FeCa}_2\text{O}_{12}(\text{OH})$
Kyanite	SiAl_2O_5
Garnet	$\text{Si}_{0.4}\text{Al}_{0.6}\text{Fe}_{0.4}\text{Mg}_{1.6}\text{Ca}_{1.2}\text{O}_{24}$
Margarite	$\text{Si}_2\text{Al}_2\text{CaO}_{10}\text{NaO}_2(\text{OH})_2$
Omphacite	$\text{Si}_2\text{Al}_{0.5}\text{Fe}_{0.5}\text{Mg}_{0.5}\text{Ca}_{0.5}\text{NaO}_6$
Paragonite	$\text{Si}_2\text{Al}_2\text{NaO}_{10}(\text{OH})_2$
Zoisite	$\text{Si}_2\text{Al}_2\text{Ca}_2\text{O}_{12}(\text{OH})$

omphacite is replaced by amphibole + plagioclase although in the domains (or rocks) in which kyanite is not present.

The alteration of kyanite into margarite + quartz occurred according to equilibrium (4), which is consistent with the textural observations (see Fig. 5 and the above petrographic description of kyanite). The zoisite + kyanite + quartz assemblage changes to zoisite + margarite + quartz at a given P-T, according to the experimental results of CHATTERJEE (1974, 1976) concerning the univariant point defined by the intersection of equilibria (4) and (5).

The instability of the margarite + zoisite assemblage and its replacement by plagioclase, according to reaction (5), may also be texturally identified, as shown in Fig. 6. A Fe^{3+} -rich epidote coexisted with a more calcic plagioclase during the last metamorphic stage, but was never in equilibrium with the

margarite; the only mica stable with the above minerals during the latest stage was paragonite, which replaced the older margarite. The fact that margarite and albite become incompatible is clear in Fig. 7b: the appearance of the Ep-Am-Pa plane separates the Ab from the Ma representative points and determines two subtetrahedra with either albite or paragonite as the fourth apex. Reaction (6) explains these textural and graphical relationships in the CASNH subsystem.

Phase compatibilities, based on textural analyses, suggest three successive mineral parageneses, and therefore three successive metamorphic stages. From oldest to youngest, they are:

- stage M₁*: omphacite + garnet + kyanite + zoisite + quartz;
- stage M₂*: amphibole + albite + zoisite/epidote + margarite + quartz;

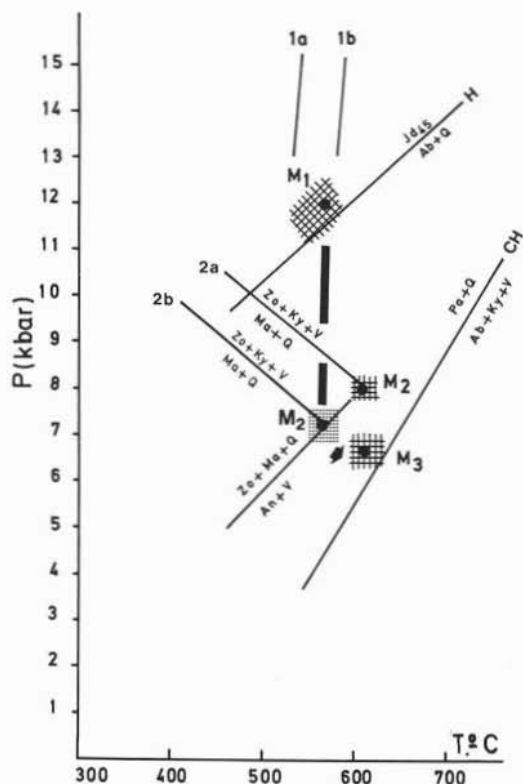


Fig. 8. — P-T paths for kyanite-bearing eclogites and Alpine metamorphism inferred from the three mineral assemblages. Lines 1 (a, b): K_D for Fe^{2+}/Mg partitioning between garnet and clinopyroxene. Dots: estimated P-T conditions at peak of three metamorphic stages (M_1 , M_2 , M_3). Two estimations of M_2 P-T conditions are possible: one according to PERKINS et al. (1980; equilibrium 2a, square area), and one according to CHATTERJEE (1976; equilibrium 2b, dotted area). H = HOLLAND (1979a); CH = CHATTERJEE (1972).

iii) stage M_3 : amphibole + albite + epidote + paragonite + quartz.

All these mineral assemblages crystallized in the presence of a water-rich fluid phase.

Metamorphic conditions

P-T conditions of the oldest mineral paragenesis (M_1 : eclogite facies)

Fe^{2+}/Mg partitioning between garnet and clinopyroxene was calculated according to ELLIS and GREEN (1979). Only the analyses of the rims of coexistent and unaltered crystals

of garnet and omphacite were taken into consideration for K_D calculations. The Fe^{2+} content in omphacite was obtained according to PAPIKE et al. (1974). Temperature values were 525–575°C at a nominal pressure of 10 Kbar (Fig. 8). These results are consistent with those of GOMEZ-PUGNAIRE and FERNANDEZ-SOLER (1987).

Pressure during the oldest metamorphic stage was estimated from the *albite* = *omphacite* (Jb_{45}) + *quartz* equilibrium (HOLLAND, 1979b). As albite occurs in these rocks only as an alteration product of omphacite, we cannot discover whether the omphacite was saturated with the jadeitic component. In this case, the calculated pressure (11–12 Kbar) represents the minimum pressure (Fig. 8).

Metamorphic conditions during the later mineral parageneses (M_2 and M_3)

Reactions related to margarite stability are the best indication of P-T conditions during these metamorphic stages. The change from the kyanite + zoisite + quartz assemblage to a margarite + zoisite + quartz one, according to equilibria (4) and (5), occurs at 575°C and about 7 Kbar (univariant point, see Fig. 8), according to the experimental results of CHATTERJEE (1976). The thermochemical calculations of PERKINS et al. (1980) and HOLLAND (1979a) on this univariant point (about 8 Kbar at 590°C) seem to be less consistent with experiments on the stability of plagioclase (FRANZ and ALTHAUS, 1977; GOLDSMITH, 1982).

According to FRANZ and ALTHAUS (1977), HOLLAND (1979a), PERKINS et al. (1980), among other authors, the possible maximum variation of the P values at the univariant point in these rocks should be 2 Kbar, due to the influence of the Na content in the margarite-producing reactions. Nevertheless the experimental data suggest an isothermal pressure decrease during the development of the second mineral paragenesis, which may be estimated at about 4 Kbars. The P-T conditions of this M_2 stage (7 Kbar at 570°C) fall between those of the early high-pressure event and those of the climax of the

whole metamorphism, calculated by GOMEZ-PUGNAIRE (1979b) at 6 Kbar and about 610°C.

The final mineral paragenesis (M_3) of these rocks involved a recrystallization at the peak of the Alpine metamorphism, as shown by the instability of margarite + zoisite + quartz and the change from a sodic plagioclase to a more calcic one (GOLDSMITH, 1982; see reaction (5) in Table 5 and textural relationships in Fig. 6). In addition, the formation of paragonite may also be related to stage M_3 . However the paragonite-producing reactions are not very clear in these rocks due to the occurrence of paragonite only as a rim around the margarite flakes. The instability of sodium plagioclase + margarite might also have been a possible origin for paragonite, according to reaction (6). A lack of thermochemical data for this reaction prevents to ascertain the P-T conditions of this equilibrium, but the reaction:

$4 \text{ anortite} + \text{albite} + 2 \text{ H}_2\text{O} = \text{paragonite} + 2 \text{ zoisite} + 3 \text{ quartz}$ (FRANZ et al., 1977) suggest a temperature of about 600°C, which is consistent with the results of GOMEZ-PUGNAIRE et al. (1985). Fig. 8 shows the P-T path followed by the amphibolitized, kyanite-bearing eclogites, inferred from the textural relationships and experimental and thermochemical data on this chemical system.

Discussion and conclusions

Three successive mineral parageneses may be distinguished in the kyanite-bearing eclogites. The oldest one occurred at high-pressure and a relatively low temperature (M_1), while progressive decompression and an increase in the thermal gradient resulted in a second and third mineral parageneses (M_2 and M_3).

The last stage (M_3) coincided with the thermal climax of the Alpine metamorphism and took place under conditions of lower pressure (about 6 Kbar) and increasing temperature (about 50°C), compared to the older M_1 metamorphic stage.

The rocks show an underformed fabric, and the eclogitic minerals grew as rather large idiomorphs near the kyanite (+ omphacite +

zoisite + rutile) veins. This fact, together with the obliteration of all previous fabrics and the lack of pseudomorphism or coronitic textures, suggest that diffusion and mass transfer were very high during M_1 , related to the presence of an externally controlled, water-rich fluid phase during the eclogitic metamorphism.

The presence of kyanite veins undoubtedly indicates the infiltration of a fluid phase transported along fracture and vein systems. The composition of the fluids was not, therefore, internally controlled by buffering of mineral equilibria. This hypothesis is consistent with the compositional homogeneity of the eclogitic minerals, in the same and in different samples, a feature which may be explained as the result of the homogeneous fluid composition produced by fluid infiltration during the M_1 eclogitic stage (RICE and FYFE, 1982).

The influence of local buffering, during the M_2 stage at the same time as fluid infiltration operated is, however, deduced from the observation that the phases (reactants and products) involved in a specific reaction may frequently be found all together, displaying textural equilibrium. Therefore, the fact that local buffering by mineral equilibria took place after the vein formation indicates that fluid composition was externally controlled during the eclogitization. This fact is consistent with the hypothesis that the eclogites developed almost at the same time as the veins opened.

The fluid-present metamorphic conditions (*sensu* THOMPSON, 1983) continued during the second and third metamorphic stages, as the mineral parageneses formed after the eclogitic ones show. They indicate high fluid activity, partly controlled by buffering and partly controlled by infiltration. In fact, the margarite + quartz assemblage requires very high fluid activity in a wide P-T range, while the paragonite stability indicates water activity greater than 0.8 under the P-T conditions estimated for the peak of the metamorphism (PERKINS et al., 1980).

As far as the origin of the fluids is concerned, they may be related at least partly to the surrounding metapelites, in which the occurrence of kyanite porphyroblasts and

kyanite + quartz veins produced during the M_1 stage (GOMEZ-PUGNAIRE, 1979a) is quite frequent. Fluids generated by devolatilization reactions in the metapelites may have run into the basic body by flowing along fractures, almost at the same time as they underwent eclogitization.

Acknowledgements. — We thank Prof. F.P. Sassi for his critical review of the manuscript and his very useful comments. We also thank Mr. Galbert for his help in the electron microprobe analyses, which were carried out in Zelmi (TU Berlin). Travel grants were provided by DFG to G.-P. and CSIC & CAICYT (Spain), Project PB87-0461-C02-02. Careful review of the English text by Dr. J. Trout is acknowledged.

REFERENCES

- AUSTHEIM H., GRIFFIN W.L. (1985) - *Shear deformation and eclogite formation within granulite-facies anorthosites of the Bergen Ares, western Norway*. In: Chemistry and Petrology of eclogites. (D.C. SMITH, G. FRANZ and D. GEBAUER, guest-eds.). Chem. Geol., 50, 267-281.
- CHATTERJEE N.D. (1972) - *The upper stability limit of the assemblage paragonite + quartz and its natural occurrence*. Contrib. Mineral. Petrol., 34, 288-303.
- CHATTERJEE N.D. (1974) - *Synthesis and upper thermal stability limit of 2M-margarite, $CaAl_2Si_2O_{10}(OH)_2$* . Schweiz. Mineral. Petrol. Mitt., 54, 753-767.
- CHATTERJEE N.D. (1976) - *Margarite stability and compatibility relations in the system $CaO-Al_2O_3-SiO_2-H_2O$ as a pressure-temperature indicator*. Am. Mineral., 61, 699-709.
- CAWTHORN R.G., COLLERSON K.D. (1974) - *The recalculation of the pyroxene end-member parameters and the estimation of ferrous and ferric iron content from electron microprobe analyses*. Am. Mineral., 59, 1203-1208.
- ELLIS D.J., GREEN D.H. (1979) - *An experimental study of the effect of Ca upon garnet-clinopyroxene Fe-Mg exchange equilibria*. Contrib. Mineral. Petrol., 71, 13-22.
- FALLOT P., FAURE-MURET A., FONTBOTE J.M., SOLE SABARIS L. (1961) - *Estudios sobre las series de Sierra Nevada y de la llamada Mischungszone*. Bol. Inst. Geol. Min. España, 71, 347-557.
- FRANZ G., ALTHAUS E. (1977) - *The stability relations of the paragenesis paragonite-zoisite-quartz*. N. Jb. Miner. Abh., 130, 159-167.
- FRANZ G., HINRICHSSEN T., WANNMACHER E. (1977) - *Determination of the miscibility gap on the solid solution series paragonite-margarite by means of the infrared spectroscopy*. Contrib. Mineral. Petrol., 59, 307-316.
- FRANZ G., THOMAS S., SMITH D.C. (1986) - *High-pressure phengite decomposition in the E. Weissenstein eclogite, Münchberger Gneiss Massif, Germany*. Contrib. Mineral. Petrol., 92, 71-85.
- GOLDSMITH J.R. (1982) - *Plagioclase stability at elevated temperatures and water pressure*. Am. Mineral., 67, 653-675.
- GOMEZ-PUGNAIRE M.T. (1979a) - *Evaluación del metamorfismo alpino en el complejo Nevado-Filábride de la Sierra de Baza (Cordilleras Béticas, España)*. Thesis Univ. Granada, 354 pp.
- GOMEZ-PUGNAIRE M.T. (1979b) - *Some considerations on the highest temperature reached in the outcropping rocks of the Nevado-Filábride Complex in the Sierra de Baza during the Alpine metamorphism*. N. Jb. Min. Abh., 135, 75-87.
- GOMEZ-PUGNAIRE M.T. (1984) - *The distribution and significance of pre-Mesozoic metamorphism in the Betic Cordilleras (SE Spain, Nevado-Filábride Complex): discussion of existence and intensity of the Alpine metamorphism*. Newsletter, 6 (F.P. SASSI and M. JULIVERT eds.), 5, 57-64.
- GOMEZ-PUGNAIRE M.T., CACHON J., MITROFANOV F., TIMMOFEEV V. (1982) - *First report on the pre-Cambrian rocks in the graphite-bearing series of the Nevado-Filábride rocks in the graphite-bearing series of the Nevado-Filábride Complex (Betic Cordilleras, Spain)*. N. Jb. Geol. Paläont. Mh., 3, 176-180.
- GOMEZ-PUGNAIRE M.T., SASSI F. (1983) - *Pre-Alpine metamorphism features and Alpine overprints in some parts of the Nevado-Filábride basement (Betic Cordilleras, Spain)*. Mem. Sci. Geol. (Padua), XXXVI, 49-172.
- GOMEZ-PUGNAIRE M.T., VISONA D., FRANZ G. (1985) - *Kyanite, margarite and paragonite in pseudomorphs in amphibolitized eclogites from the Betic Cordilleras, Spain*. In: Chemistry and Petrology of eclogites. (D.C. SMITH, G. FRANZ and D. GEBAUER, guest-eds.). Chem. Geol., 50, 129-141.
- GOMEZ-PUGNAIRE M.T., FERNANDEZ-SOLER J.M. (1987) - *High-pressure metamorphism in metabasites from the Betic Cordilleras (SE Spain) and its evolution during the Alpine orogeny*. Contrib. Mineral. Petrol., 95, 231-244.
- GOMEZ-PUGNAIRE M.T., FRANZ G. (1988) - *Metamorphic evolution of the paleozoic series of the Betic Cordilleras (Nevado-Filábride Complex, SE Spain) and its relationship with the alpine orogeny*. Geol. Rundschau, 77, 619-640.
- HEINRICH CH.A. (19827) - *Kyanite-eclogite to amphibolite facies evolution of hydrous mafic and pelitic rocks, Adula nappe, Central Alps*. Contrib. Min. Petrol., 81, 30-38.
- HOLLAND T.J.B. (1979a) - *High water activities in the generation of high pressure kyanite eclogites of the Tauern Window, Austria*. J. Geol., 87, 1-28.
- HOLLAND T.J.B. (1979b) - *Experimental determination of the reaction paragonite = jadeite + kyanite + H_2O , and internally consistent thermodynamic data for part of the system $Na_2O-Al_2O_3-SiO_2-H_2O$, with applications to the eclogites and blueschists*. Contrib. Mineral. Petrol., 68, 293-301.
- LEAKE B.E. (1978) - *Nomenclature of amphiboles*. Am. Mineral., 65, 1023-1052.

- MORK M.B.E. (1985) - *A gabbro to eclogite transition of flemsoy, Summore, western Norway*. In: Chemistry and Petrology of eclogites. (D.C. SMITH, G. FRANZ and D., GEBAUER, guest-eds.). Chem. Geol., 50, 283-310.
- NIJHUIS H.J. (1964) - *Plurifacial alpine metamorphism in the south-eastern Sierra de los Filábres south of Lubrín, SE Spain*. Thesis Univ. Amsterdam, 151 pp.
- OKAY A.I., ARMAN M.B., GÖNCÜOĞLU M.C. (1985) - *Petrology and phase relations of the kyanite-eclogites from eastern Turkey*. Contrib. Mineral., Petrol., 91, 196-204.
- PAPIKE J.J., CAMERON K.L., BALDWIN K. (1974) - *Amphiboles and pyroxenes: characterization of other than quadrilateral components and estimates of ferric iron from microprobe data*. Geol. Soc. Am. Abstr. Progr., 6, 1053-1054.
- PERKINS D. III, WESTRUM E.F. JR., ESSENE E.J. (1980) - *The thermodynamic properties and phase relations of some minerals on the system $\text{CaO-Al}_2\text{O}_3\text{-SiO}_2\text{-H}_2\text{O}$* . Geochim. Cosmochim. Acta, 44, 61-84.
- POGNANTE U. (1985) - *Coronitic reactions and ductile shear zone in eclogite metagabbro, Wester Alps, North Italy*. In: Chemistry and Petrology of eclogites. (D.C. SMITH, G. FRANZ and D. GEBAUER, guest-eds.). Chem. Geol., 50, 99-109.
- PUGA E., DIAZ DE FEDERICO A., FONTBONÉ J.M. (1974) - *Sobre la individualización y sistematización de las Unidades profundas de la Zona Bética*. Est. Geol., 30, 543-548.
- RICE J.M., FYFE J.M. (1982) - *Buffering, infiltration and the control of the intensive variables during metamorphism*. In: Characterization of metamorphism through mineral equilibria. (P.H. RIBBE, ed.). Reviews in Mineralogy of the Min. Soc. Am., 10, 263-324.
- SPEAR F.S., RUMBLE III D., FERRY J.M. (1982) - *Linear algebraic manipulation of N-dimensional composition space*. In: Characterization of metamorphism through mineral equilibria. (P.H. RIBBE ed.). Reviews in Mineralogy of the Min. Soc. Am., 10, 397p.
- THOMPSON A.B. (1983) - *Fluid-absent metamorphism*. J. Geol. Soc. London, 140, 533-547.
- THOMPSON J.B. JR., LAIRD J., THOMPSON A.B. (1982) - *Reactions in amphibolite, greenschist and blueschist*. J. Petrol., 23, 1-27.