The high-pressure granulites of the Bacariza Formation: an earlier stage in the exhumation of other eclogite in the Cabo Ortegal Complex (Hercynian belt, NW Spain)

Gumer Galán[1] and Alberto Marcos[2]

[1] *Departamento de Geología. Universidad Autónoma de Barcelona. Edificio C (Sur).*
08193 Bellaterra. Barcelona. España.

[2] *Departamento de Geología. Universidad de Oviedo. c/ Arias de Velasco s/n. 33005 Oviedo. España.*

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Resumen: La formación Bacariza aflora en dos unidades tectónicas superpuestas del Complejo de Cabo Ortegal (NO del Macizo Ibérico) e incluye granulitas ultramáficas y máficas, anfibolitas granatíferas y gneisses trondhjemíticos con granate. La presencia en las granulitas de distena relicta en equilibrio con granate-clinopiroxeno y, de plagioclasa sólo en relación con texturas características de pérdida de jadeita en los piroxenos sugiere un primer estadio metamórfico en facies de las eclogitas para estas rocas. Los datos geotermobarométricos confirman este hecho e indican condiciones de mayor temperatura y presión para la unidad superior.

Palabra clave: granulitas, eclogites, petrología, mineralogía, termobarometría.

Summary: This paper deals with the metamorphic evolution of the Bacariza Fm that outcrops in the two uppermost structural units of the Cabo Ortegal Complex (NW Iberian Massif). This formation includes ultramafic and mafic granulites, garnet amphibolites and garnet trondhjemitic gneisses. Although mineral associations characteristic of high pressure granulites predominate in the least retrogressed of these rocks, the presence of relic kyanite along with the fact that plagioclase only appears in symplectitic textures resulting from de-jadeitization of pyroxenes point to an earlier eclogite facies metamorphism. Thermobarometric estimations indicate higher P-T conditions for the rocks in the uppermost structural unit.

Key words: granulites, eclogites, petrology, mineralogy, thermobarometry.

The Cabo Ortegal Complex (COC) (Fig. 1a, b) is situated in the Galicia-Tras-os-Montes Zone of the Iberian Massif (Farias et al. 1987) along with the complexes of Ordenes, Bragança, Morais and the Malpica-Tuy Band. All of them are formed of ultrabasic, basic rocks, orthogneisses and different metasediments that show a complex metamorphic evolution. At present, it is generelly accepted that these complexes represent allochthonous terrains (e.g., Ribeiro et al. 1964; Anthonioz 1970; Ries and Shackleton 1971; Bayer and Matte 1979; Iglesias et al. 1983; Bastida et al. 1984; Arenas et al. 1986; Matte 1986; Pérez Estaún et al. 1991) emplaced on the Gondwana edge during the Hercynian orogen. However, there is still much controversy over the origin and the metamorphic evolution of their lithological units. Two groups of hypotheses are highlighted:

(i) Poly-cyclic metamorphic models which support that the eclogite and granulite facies metamorphism of these rocks occurred during a Precambrian cycle (Vogel 1967; Anthonioz 1970; Engels 1972),

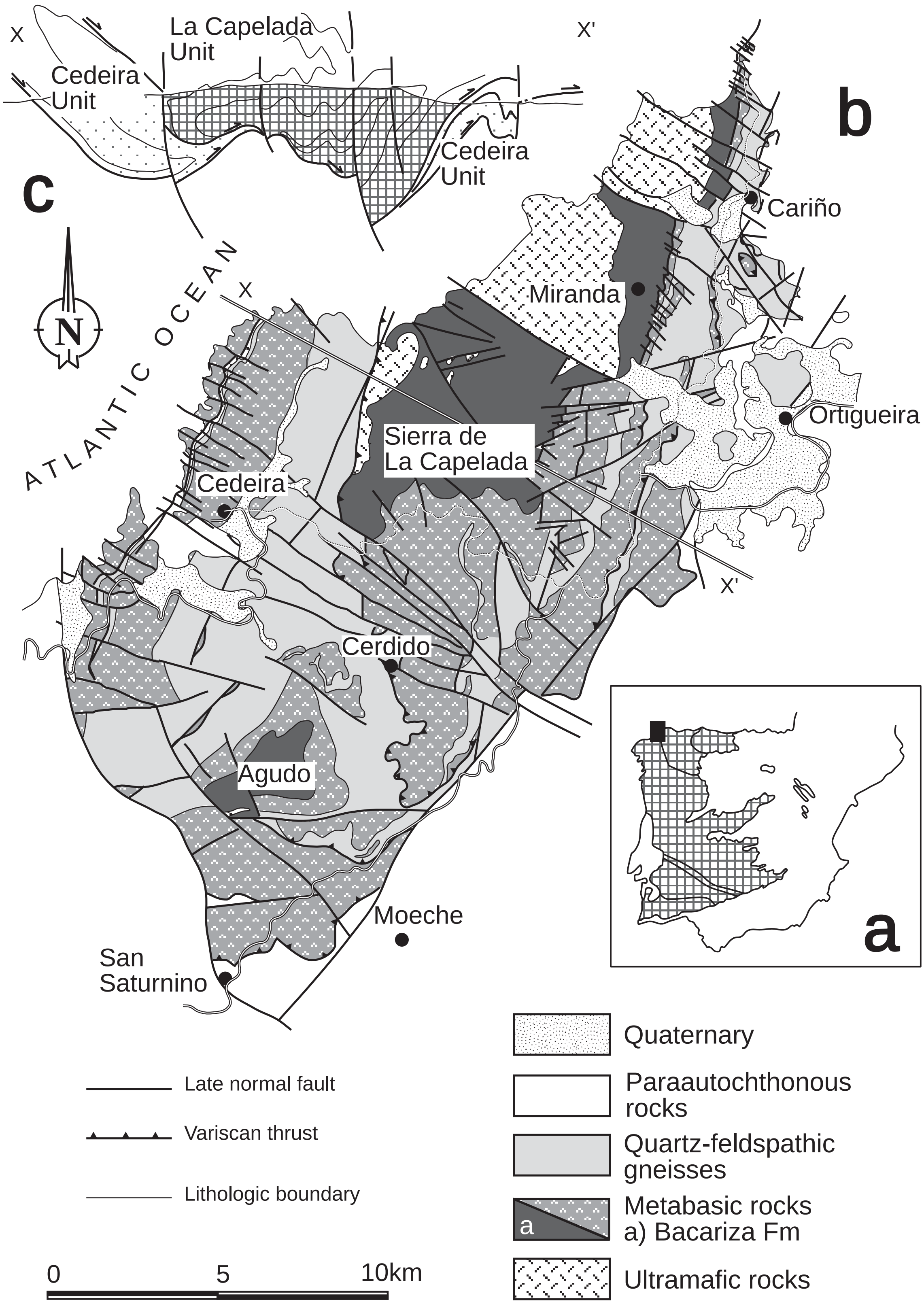

Figure 1. a) Different zones of the Iberian Massif. b) Geological map of the Cabo Ortegal Complex based on Marcos (unpublished). Metabasic rocks other than the Bacariza Fm include both the Candelaria amphibolites and the Concepenido eclogites. c) Cross-section of the COC showing La Capelada and Cedeira units (Bastida et al. 1984).

while a strong retrogression in amphibolite facies is related to pre- and Hercynian events. The "mantle plume" model (Keasberry et al. 1976; Van Calsteren 1978, 1981; Van Calsteren and Den Tex 1978; Kuijper and Arps 1983; Kuijper et al. 1985) can be included in this category but it supports that an eclogite facies Precambrian metamorphism was followed by Early-Middle Paleozoic granulite facies metamorphism related to the intrusion of ultrabasic and basic magmas into the lower crust. More recently, poly-cycled metamorphism is also defended by Marques et al. (1996), who support a Precambrian cycle (1.0-0.5 Ga) causing simultaneous eclogite and high pressure (HP) granulite facies metamorphism in a subduction zone. Then, the subduction would have been followed by continental collision and post-collision associated with the intrusion of ultrabasic and basic magmas into the lower crust. This would have led to the formation of younger granulites (ca. 620 Ma).

(ii) Single cycle metamorphic models which defend the subduction or underthrusting of both oceanic and fragments of continental crust and later obduction of them during the Hercynian orogen (Gil Ibarguchi et al., 1990; Peucat et al., 1990; Arenas 1991; Schäfer et al. 1993; Marcos and Galán 1994; Abalos et al. 1996; Santos Zalduegui et al. 1996). Eclogite and quasi-simultaneous granulite facies metamorphism is related either to the subduction or underthrusting process, while pre- and Hercynian up lift and exhumation would have caused retrogression in amphibolite and greenschist facies. However, some of these models consider that the subduction process would have started during the Ordovician (ca. 480 Ma) (Peucat et al. 1990) while others support an Eo-Hercynian subduction (ca. 395 Ma) (Schäfer et al. 1993; Santos Zalduegui et al. 1996) with rapid Hercynian exhumation (Marcos and Galán 1994).

In the COC, as in other similar Hercynian terrains elsewhere, HP-mafic granulites and eclogites appear straight related to each other (Smulikowsky 1968; Pin and Vielzeuf 1983, 1988; Carswell and Cuthbert 1986; O'Brien and Vrána 1995), and the relationships between them is crucial to evaluate the different geodynamic models. The most remarkable HP-mafic granulites from the COC are included within the Bacariza Fm and this study deals with the petrographic and some mineralogical characteristics of these granulites in order to assess their P-T metamorphic conditions and their relationships with neighbouring eclogites. Controversial hypothesis exist on this topic at present. Although it is true that most authors defend quasi-simultaneous metamorphism in eclogite and granulite facies (Vogel 1967; Engels 1972; Arenas and Peinado 1984; Gil Ibarguchi et al. 1990; Arenas 1991), they differ in the estimation of the P-T conditions. Vogel (1967) pointed to both higher P and T in the mafic granulites than in the eclogites (viz., Concepenido eclogites). Engels (1972) suggests that metamorphism was prograde from amphibolite through granulite to eclogite facies. For Gil Ibarguchi et al. (1990), the mafic granulites register the same temperature but lower pressure than the eclogites. Arenas (1991) suggests that the metamorphic path of the granulites corresponds to a higher metamorphic gradient than that of the eclogites so that they could be related to different geodynamic settings. Finally, Van Calsteren (1978) and Kuijper et al. (1985) consider that the granulite facies metamorphism was static and post-dated the eclogite facies metamophism; it would have been caused by increasing T and slight decrease in P related to the "mantle plume" effect.

Geological setting and field relationships

The COC is generally accepted to be a klippen (Fig. 1a) composed of different structural units mainly formed of ultramafic rocks, different metabasites and quartz-feldspathic metasediments. In earlier studies (Vogel 1967; Engels 1972; Vogel 1984), the Bacariza Fm and other metabasites from the Agudo Fm and from the Candelaria Fm were grouped in the Capelada Complex. However, later structural, geochemical and radiometric studies have led to other controversial subdivisions of the COC and the HP-mafic granulites of the Bacariza Fm were included in La Capelada Unit (Bastida et al., 1984), the Upper Catazonal Unit (Arenas et al. 1986) or the Concepenido-La Capelada Unit (Gil Ibarguchi et al. 1990). Despite the different nomenclature, all these subdivisions consider the Bacariza Fm within the upper structural unit of the COC. More recently, the outcropping area of the Bacariza

Fm was re-defined (Marcos and Galán 1994; Galán and Marcos 1997) with respect to other high grade metabasites from the COC (Fig. 1). According to this new mapping, some metabasites from the Bacariza Fm outcrop in the upper structural unit of the COC (Capelada unit) and others outcrop in the Agudo area, which is situated in the underlying Cedeira unit (nomenclature of units after Bastida et al, 1984) (Fig. 1c). Therefore, these HP granulites appear in the two upper tectonic slabs of the COC, limited by a Variscan thrust (Bastida et al. 1984). In both units, the Bacariza Fm is exposed in normal contact between structurally overlying ultramafic rocks, which include partly serpentinised spinel-pargasite peridotite, ±spinel pyroxenites, garnet pyroxenites, harzburgites and dunites (Vogel 1967; Maaskant 1970; Van Calsteren 1978; Ben Jamaa 1988; Girardeau et al. 1989; Gravestock 1992), and other underlying metabasites, which comprise retrogressed amphibolites and metagabbros of the Candelaria Fm. This sequence of rocks is interpreted as inverse since it is situated in ther reverse limb of a recumbent fold (Bastida et al., 1984; Marcos and Galán 1994).

Preliminary structural and metamorphic data on the evolution of the Bacariza Fm by Marcos and Galán (1994) pointed to an earlier eclogite P-T regime (M1) that was followed by the development of different structures related to up-lift, and sequentially equilibrated in HP-granulite (M2), amphibolite (M3) and greenschist facies (M4). The most conspicuous structure of the Bacariza Fm is a general mylonitic foliation mainly equilibrated in amphibolite facies that can be seen throughout the COC (Marcos et al. 1984) and that will be named ‘general foliation’ in this study. This foliation was then folded by isoclinal folds at different scales. These folds were also developed in amphibolite facies and evolved to East-facing Variscan thrusts, which account for the present stacking of the different units of the COC. Metamorphic conditions prevailing during the development of thrusts were transitional between amphibolite and greenschist facies.

Petrography

The Bacariza Fm is heterogeneous mainly due to the existence of a layering at centimetric to metric scale, which would have been inherited from a gabbro-type protolith (Galán and Marcos 1997). This protolith was formed of ultrabasic-basic, intermediate and acid rocks in this order of abundance. Ultrabasic-basic rocks are predominant at the lower part of the formation, and alternate with intermediate rocks at the upper part of it. Acid rocks are much more subordinated and alternated with the other types. All these rocks show low M number (M= 100*MgO/(MgO+FeOt= 31-72; oxides in moles) and the ultrabasic-basic terms are especially enriched in Ti for which they could be related to Fe-Ti gabbros (Galán and Marcos 1997). According to the previous authors, the initial heterogeneity seems to have determined not only the metamorphic mineral associations but also the behaviour of these rocks during their retrograde path. Accordingly, the less evolved are now exposed as ultramafic-mafic granulites, while the more evolved appear as garnet amphibolites and garnet trondhjemitic gneisses. Moreover, there are other minor rock types derived from the previous ones by tectonical processes.

A detailed petrographic description of all these rocks is given below taking into account their different geochemistry and the influence of the different tectonical processes on them.

The ultramafic-mafic granulites

They include the ±hornblende pyrigarnites (pl<5%) and ± hornblende plagiopyrigarnites (pl>5%) of Vogel (1967). In some of the former rocks, plagioclase is lacking in equilibrium with garnet and clinopyroxene, which supports an eclogite P-T regime (Smith 1982), named M1 in Figure 2. These rocks are eclogites s.l. and s.sr. characterized by coarse and very coarse granoblastic texture (Fig. 3a). No optical strain features are observed within the grains, which points to low deviatoric stress conditions (Rutter and Brodie 1992) and only the clinopyroxene displays a weak linear fabric (Engels 1972). The abundance of garnet crystals arranged in a honeycomb-like structure would account for this characteristic since this structure would enclose and preserve clinopyroxene from deformation. This honeycomb-like arrangement of garnets also characterizes the Concepenido eclogites (Vogel 1967) and others elsewhere (Godard 1988, Philippot and van Roermund 1995). Moreover, other typical minerals of eclogites facies exist in these rocks (Fig. 2), such as rutile, kyanite and zoisite (Fig. 4a, b). Rutile form either isolated crystals (ø up to 100 mm) or tiny crystals which appear as dusty clouds or sagenitic inclusions in garnet. These inclusions have been considered as a distinctive feature of eclogites or retrograde eclogites with respect to HP granulites from the COC (Vogel 1967). However, the results of this study show that they are also frequent in the garnet crystals from the Bacariza Fm. An origin as pseudomorphes after some titaniferous pre-eclogitic minerals (e.g., clinopyroxene) was envisaged for these rutile inclusions (Vogel 1967; Godard 1988), which would be in agreement with the Fe-Ti rich composition of the Bacariza rocks (Galán and Marcos 1997). However, a later origin related to exsolution of Ti from garnet (Bishop et al. 1978) during retrogression cannot be excluded since these inclusions are more common in corroded garnet crystals. The presence of kyanite, which is characteristic of eclogite facies metamorphism in metabasites, is remarked although it is much more scarce in these rocks than in the Concepenido eclogites (Mendia 1996). Vogel (1967) already noticed this difference and considered that kyanite in the Bacariza Fm was only present in pegmatoid veins and therefore, not to be related to an earlier eclogite facies stage. However, we have observed that the presence of kyanite in these metabasites is not only related to veins but it seems to have co-existed with garnet and clinopyroxene (Fig. 4a). Kyanite appears either as inclusions in garnet or as relic crystals mantled first by zoisite and later by clinozoisite-epidote (Fig. 3b). In both cases, kyanite can be transformed into plagioclase, following its cleavage systems, and then into sericite. Zoisite is also more scarce than in the Concepenido eclogites and appears as rims around kyanite or as isolated long primatic crystals orientated according to the general foliation (Fig. 4a). In both cases, it shows corroded borders and is rimmed by clinozoisite or saussurite. In more retrograde rocks, both kyanite and zoisite are completely pseudomorphosed by grouped clinozoisite-epidote crystals forming orientated nodules (up to 5 mm wide). Brown green amphibole also characterises the earlier eclogite facies stage since it is shown in rocks where plagioclase is lacking. Some of these rocks are mainly formed of garnet and amphibole and are named garnet hornblende schist. This amphibole crystallized later than clinopyroxene and garnet since these two phases are included by it.

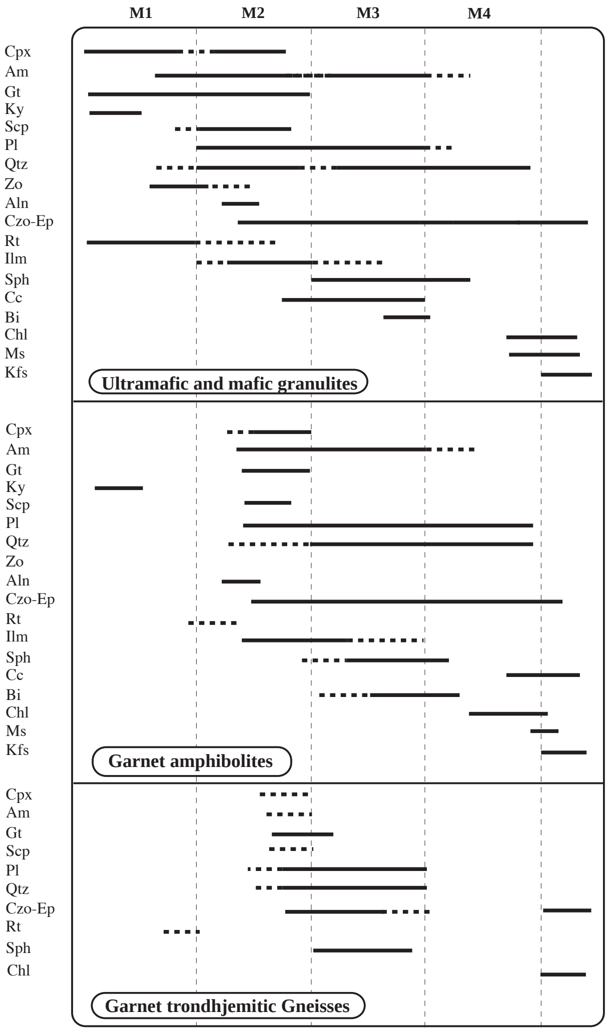

Figure 2. Relationships between blastesis and the four metamorphic stages for each of the three main rock types of the Bacariza Fm. The earlier phases are better preserved in the less evolved rocks. Mineral abbreviations after Kretz (1983).

The second metamorphic stage (M2 in Fig. 2) is related to the formation of plagioclase mainly from reaction of clinopyroxene (Fig. 2, 4c). Shear zones from few centimetres to several metres wide are associated with this metamorphic stage. Three main type of microtextures are related to it: (i) discrete microshear zones that caused drastic grain size reduction and dynamic recrystallisation of neo-

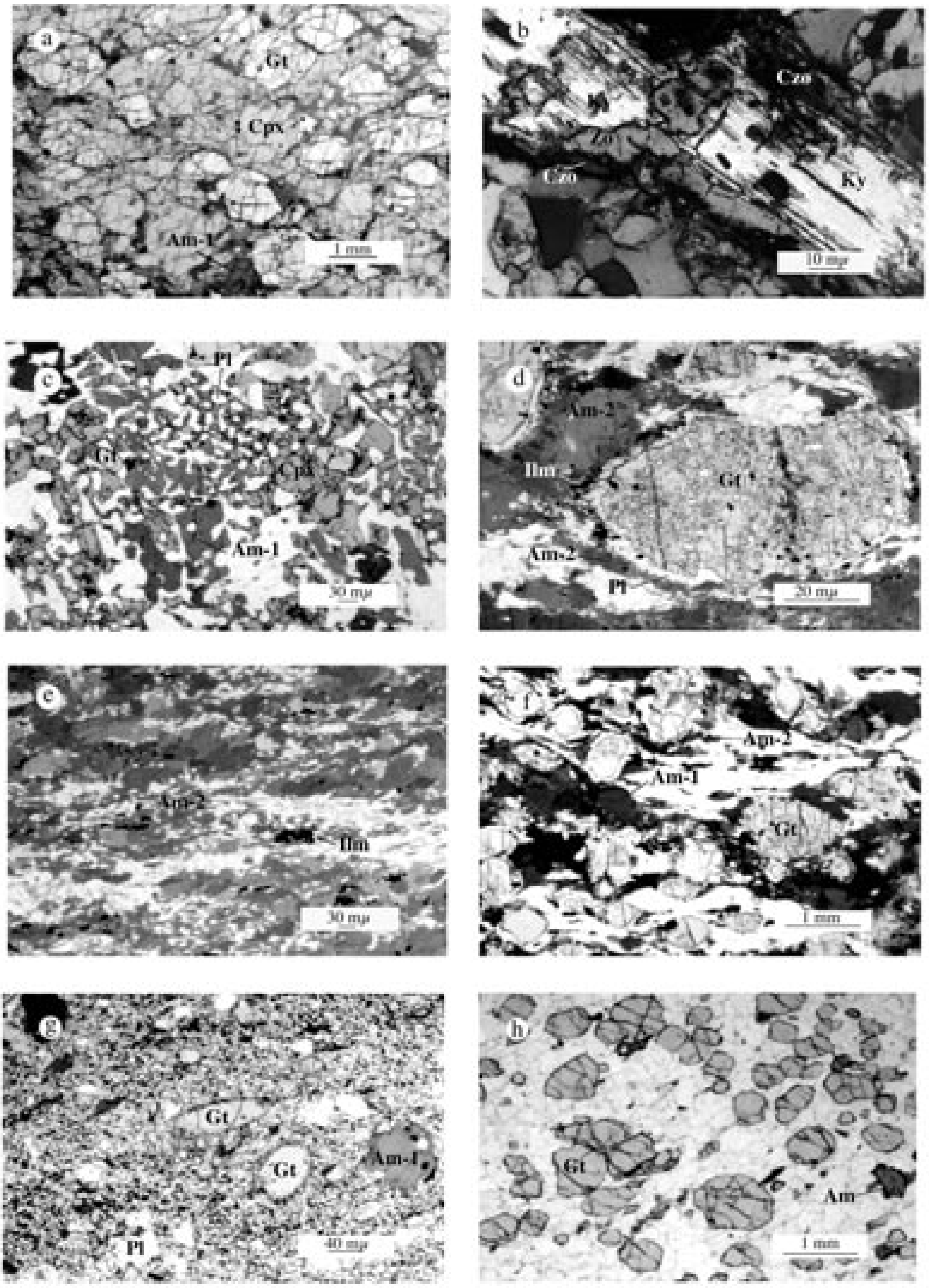

Figure 3. a) Granoblastic texture defined by garnet-clinopyroxene-Am-1 type amphibole in eclogites s.l. (also called pyrigarnites by Vogel 1967).The arrangement of the garnet crystals is of the honey-comb type. b) Relic prysmatic crystal of kyanite first mantled by zoisite and then by clinozoisite in a mafic granulite. c) Coarse grained clinopyroxene-plagioclase symplectites and amphibole-plagioclase symplectites in mafic granulites. d) Garnet porphyroclast with sieve and corona texture defined by an inner rim of plagioclase and an outer rim of Am-2 type amphibole and ilmenite. e) Blastomylonitic amphibolites formed by deformation of ultramafic granulites in shear zones. f) Typical mylonitic texture in garnet amphibolites showing porphyroclasts of garnet and Am-1 type amphibole in a matrix of plagioclase-quartz-Am-2 type amphibole. g) Blastomylonitic biotite gneisses with rounded porphyroclasts of garnet, Am-1 type amphibole and plagioclase. h) Granoblastic texture in a garnet trondhjemitic gneiss with garnet crystals defining a honey- comb like structure.

clinopyroxene, neo-amphibole along with plagioclase; (ii) clinopyroxene-plagioclase vermicular symplectites and (iii), coarse grained symplectites between clinopyroxene and plagioclase (Fig. 3c) and between amphibole and plagioclase. The clinopyroxene-plagioclase coarse grained symplectites, considered as reminiscent of de-jadeitized omphacites from the reaction omphacite + quartz = albite + diopside (Boland and van Roermund 1983; Dunn and Medaris 1989), are the most widespread. These three microtextures rarely coexist in the same sample but sometimes, they coexist in pairs (e.g., dynamic recrystallized clinopyroxene rimmed by clinopyroxene-plagioclase vermicular symplectites or coarse grained symplectites with finer vermicular borders) as it happens in other retrogressed eclogites elsewhere (Godard 1988; Dunn and Medaris 1989). Coarse grained symplectites are more common in the core of granulites which outcrop as tectonic inclusions within more retrogressed garnet amphibolites. Vermicular symplectites and drastic grain size reduction of neo-clinopyroxene and neo-amphibole are mainly related to the neighbouring of shear zones already associated with the onset of the 'general foliation', which points to both decreasing P and T related to higher degree of deformation (van Roermund and Boland 1983). The amount of amphibole increases during the M2 stage. It forms large brown green crystals (Ø up to 5 mm) usually following the 'general foliation'. These large crystals equilibrated either in eclogite or granulite facies (Fig. 2) will be named in this study Am-1 type. They are texturally different from the smaller neo-amphibole crystals (Am-2 type) related to the development of the conspicuous general mylonitic foliation (Marcos et al . 1984), the initial conditions of which seem to have been in granulite facies in the Bacariza Fm as in equivalent quartz feldspathic gneisses from the COC (Fernandez and Marcos 1996). Scapolite is particularly abundant (up to %25 modal amount) in some granulites (i.e., scapolite granulites) (Fig. 4d) where it is orientated following the general foliation. However, this mineral could have onset during the earlier M1 stage as it happens in high temperature eclogites elsewhere (Smith et al. 1982): in samples where scapolite is better preserved it only co-exists with garnet, clinopyroxene and amphibole. Zoisite still persits in the M2 stage often mantled by clinozoisite that is the main epidote group mineral in the granulite facies. Allanite also characterizes M2 and is often metamictic and rimmed by clinozoisite. Finally, Rutile persits during M2 especially as inclusions in major phases, although, it is transformed to ilmenite in some microshear bands with higher degree of deformation.

Ultramafic and mafic granulites are ocassionally cross-cut by trondhjemitic veins from few milimetres to several centimetres wide. Some of these veins include kyanite (Vogel 1967) and zoisite. Moreover, along the largest of them, a thin border of amphibole is observed in the host granulite. The injection of most of these veins pre-date the 'general mylonitic foliation' that affected them and is mainly associated with the M3 metamorphic stage. These veins acted as weaker zones favouring the localisation of shear bands in more rigid granulites (Galán and Marcos, 1997).

The generalization of the mylonitic foliation is associated with an increasing reaction of earlier phases and onset of others characteristic of amphibolite facies, M3 in Fig. 2. Thus, amphibole-plagioclase± ilmenite coronas are formed around garnet crystals. These coronas are rarely kelyphitic as it happens in the Concepenido eclogites (Vogel 1967). In the less deformed rocks, this reaction texture began with the formation of a thin rim of green amphibole (Am-2 type) between garnet and clinopyroxene and was followed by a second inner rim of polycrystaline plagioclase± ilmenite around garnet (Fig. 3d). Clinopyroxene is transformed to green amphibole (Am-2 type) and dynamically recrystallised neo-amphibole (Am-2 type) is also formed from deformed Am-1 type crystals. When the degree of deformation is very high, as it happens in shear bands in the Agudo area, the earlier phases can desappear completely, and the ultramafic-mafic granulite is transformed into a blastomylonitic amphibolite. These tectonical rocks show grain reduction with respect to the original ones; they are medium grained and show a granonematoblastic texture which is mainly defined by the orientation of type-2 amphibole crystals (Fig. 3e). Their characteristic mineral association is formed of type-2 amphibole-plagioclase-ilmenite-epidote± quartz. Scapolite reacts during the M3 stage and is mainly transformed into saussurite at its borders.

However, in some peculiar rocks where this mineral was important, it seems to have behaved as a "softer" mineral during deformation and is transfomed into plagioclase+ calcite. The resultant rocks are rich in calcite (calcite rich granulites of Galán and Marcos, 1997) and are considered to be of tectonical origin. These are peculiar rocks within the Bacariza Fm and are mainly located at its lower part, where they form discontinuous layers and enclose fragment of other granulites in a more ductile plagioclase-calcite rich matrix. They differ from other mafic granulites by their higher retrogression: clinopyroxene is in relic crystals, garnet crystals display a sieve texture and they are rimmed by scapolite against calcite. Scapolite also appears as tiny relic crystals in the plagioclase-calcite matrix, amphibole is less important than in other retrogressed granulites, and epidote and sphene are especially abundant. The last mineral is the main characteristic Ti mineral in the M3 stage, post-dating both ilmenite and rutile since they are included by sphene. Clinozoisite and epidote also characterize this stage and finally, small biotite crystals can appear in samples with higher degree of deformation. Other later retrogressive phases are illustrated in figure 2.

The garnet amphibolites

These are intermediate rocks, medium to coarse grained, streaky, with porphyroclastic or gneissic texture and protomylonitic to mylonitic matrix (Fig. 3f). They are remarked because the retrogression associated with the M3 metamorphic stage in amphibolite facies (Fig. 2) is more conspicuous than in ultrabasic-basic rocks. This is related to their more evolved composition that provides higher amount of "softer" minerals, such as quartz and plagioclase (Brodie and Rutter 1985), which enhanced later deformational processes and concomitant retrogression (Galán and Marcos 1997). As a result, minerals of eclogite and granulite facies only persist as relic phases. Thus, kyanite relics are very scarce and enclosed by clinozoisite nodules, clinopyroxene crystals always show corroded bordes and are mostly transformed into amphibole, Am-1 type amphibole appears mainly as porphyroclast with anomalous extintion (Fig. 3f), scapolite crystals always show corroded borders, rutile only persists as inclusions in other phases and finally, garnet is also a reactant mineral with coronas of amphibole-plagioclase and often with a sieved texture core. This peculiar texture of garnet crystals is due to the presence of quartz-plagioclase and less amphibole and epidote within garnet as a result of its transformation. In such a case, plagioclase and quartz show distinct angular shapes that differ from earlier rounded inclusions in garnet. This process occasionally ends in the formation atoll garnet crystals. Furthermore, the intermediate composition of these rocks was more susceptible of following partial melting during the eclogite or granulite facies metamorphism than that of the ultrabasic-basic granulites (Rushmer 1991). This partial melting would have resulted in the formation of the trondhjemitic veins that either were removed and cross-cut the ultramafic-mafic granulites or crystallized "in situ". These veins are predominant in the garnet amphibolites and are affected by the 'general mylonitic foliation'. Since the amount of "softer" minerals would have increased as a result of this partial melting, this process would have further enhanced later retrogression in these rocks. As a result, the mineral association related to the amphibolite facies (M3) (i.e., amphibole-plagioclase-quartz-clinozoisite-epidote-ilmenite-sphene) is the most characteristic of these rocks (Fig. 4e).

With increasing degree of deformation during late M3, garnet amphibolites are transformed into biotite blastomylonitic gneisses in shear bands from centimetric to decametric scale. At the outcrop scale, these tectonical gneisses locally enclose centimetric blocks of ultramafic-mafic granulites and garnet amphibolites in a chaotic arrangement. The texture of the bitote blastomylonitic gneisses includes porphyroclast of garnet, Am-1 type amphibole, plagioclase, scapolite and clinozoisite with allanite cores and epidote rims in a mylonitic matrix formed of biotite-plagioclase-quartz-ilmenite-sphene (Fig. 3g). These tectonical gneisses are locally affected by shear bands, equilibrated in greenschist facies, where biotite is transformed into chlorite, M4 in Figure 2, and ended in the formation of ultramylonites or pseudotachylites. In other less deformed rocks, the M4 retrograde stage is mainly

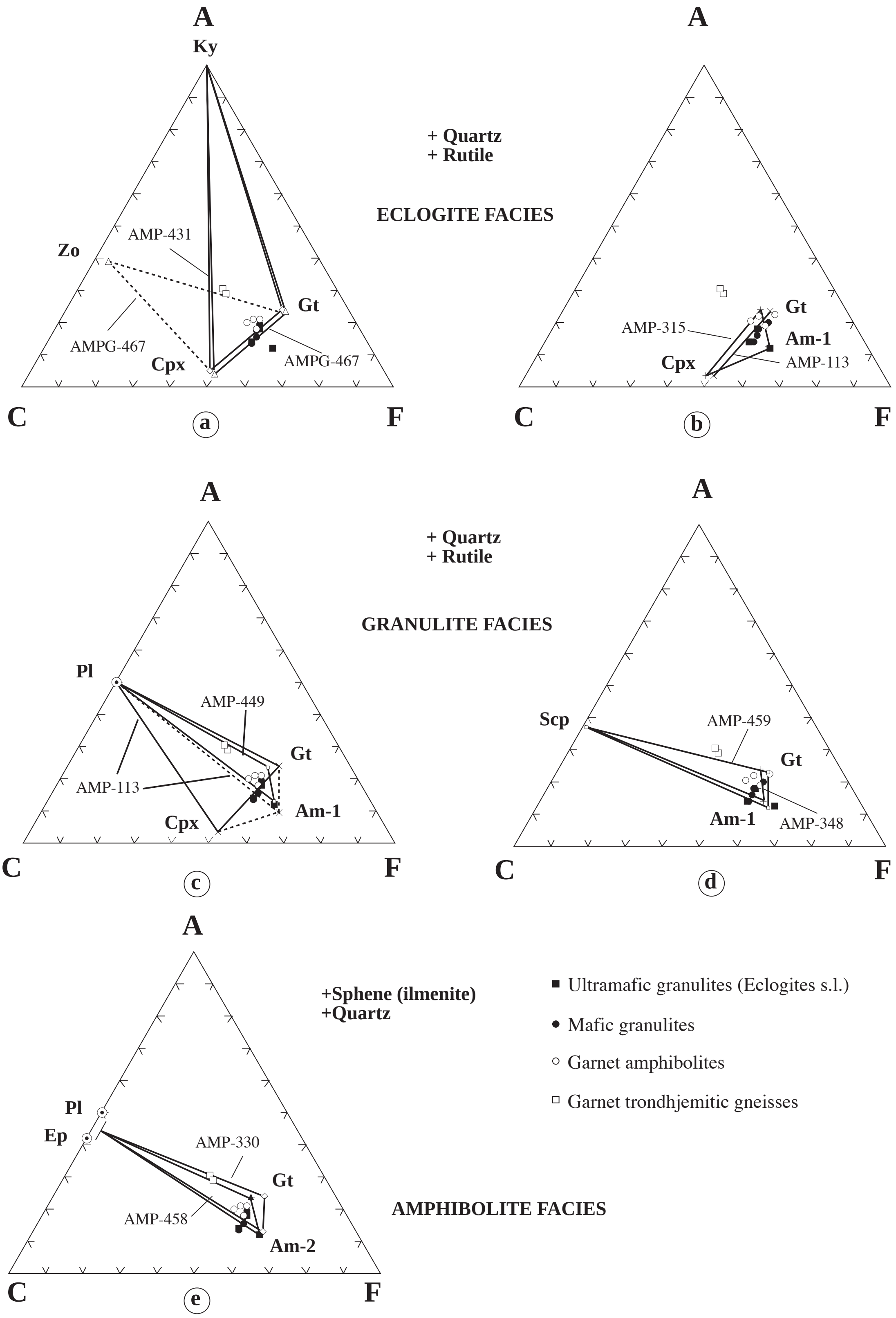

Figure 4. ACF diagrams for the mineral associations characteristic of the eclogite facies (a, b), the granulite facies (c, d) and the amphibolite facies (e). Whole rock chemical analyses of the different rock types are also plotted after data from Galán and Marcos (1997). All samples are granulites except AMP-330, 458 (garnet amphibolites) and AMP-449 (garnet trondhjemitic gneiss).

remarked by retrogression of garnet to chlorite and epidote along microfractures. Finally, cross-cutting veins filled with epidote, chlorite, adularia and white micas are also observed.

The garnet trondhjemitic gneisses

They represent the more differentiated rocks and form several centimetres to one metre wide bands always showing sharp borders. They are distinguished by their white or pink colour due to the abundance of garnet and show medium grain and granoblastic (Fig. 3h) to orientated granoblastic texture formed of garnet-plagioclase-quartz± amphibole-clinozoisite-epidote-sphene. This mineral association corresponds to the amphibolite facies (M3 in Fig. 2, Fig. 4e). Earlier minerals, such as rutile, clinopyroxene, scapolite, and type-1 amphibole only exist as relics. Minerals of the greenschist facies are mainly represented by chlorite and epidote from transformation of garnet. Deformational textures are less evident in these rocks than in the garnet amphibolites but garnet also shows corona textures only formed of polycrystaline plagioclase.

Mineral Chemistry

Only the composition of clinopyroxene and garnet is discussed below in order to estimate the P-T conditions of both eclogite and granulite facies stages. A futher description of the composition of these and others phases will be given elsewhere (Galán and Marcos, in prep.)

Clinopyroxene

The composition of the clinopyroxene straddles the Quad (viz., diopside) and omphacite domains (Morimoto et al. 1988; Fig. 5) and touches the aegirine-augite field regardless the rock type. X_{Jd} ,determined after Kushiro (1962), ranges from 0.4% to 33% with both maximum and minimum values measured in clinopyroxene from coarse grained and vermicular symplectites respectively. It is to note that X_{Jd} in clinopyroxene crystals not co-existing with plagioclase is not particularly important. X_{Ac} ranges from 0 to 15% with maximum values corresponding to earlier clinopyroxenes not co-existing with plagioclase and minimum values to vermicular symplectites. Since available whole rock geochemical data (Galán and Marcos 1997) indicate that these rocks show high CaO/Na_2O radio (6-9) and low M number, it is suggested that the low X_{Jd} in these earlier clinopyroxenes is not only constrained by metamorphic conditions but also by the composition of the protolith. Furthermore, decreasing X_{Ac} towards symplectites points to lower fO_2 with the retrogression.

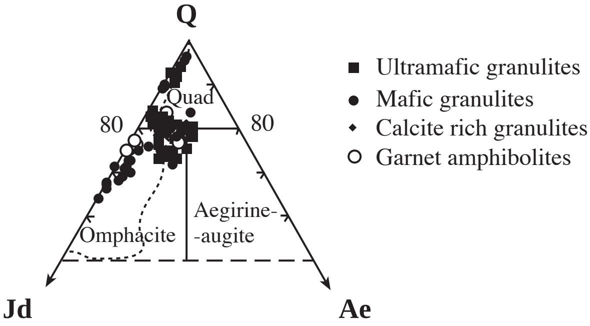

Figure 5. Q-Jd-Ae plot (Morimoto et al. 1988) for the clinopyroxenes of the Bacariza Fm. The dashed line defines the domain of the clinopyroxenes from the Concepenido eclogites (data from Mendia 1996).

The results of this study agreee with earlier ones on that clinopyroxenes from the Bacariza Fm show lower X_{Jd} and higher X_{Ac} than clinopyroxenes from the Concepenido eclogites in the COC (Vogel 1967; Arenas and Peinado 1984; Gil Ibarguchi et al. 1990, Mendia 1996) (Fig. 5). However, this difference is not necessarily to be related to different metamorphic conditions but it could be also constrained by difference in whole rock composition between the Concepenido eclogites and the granulites from the Bacariza Fm. Most eclogites in the Concepenido band show higher M number and low CaO/Na_2O radio than the metabasites here studied, according to data from Vogel (1967), Gravestock (1992) and Mendia (1996). This last author distinguishes different types of eclogites, among which those that are enriched in Fe-Ti show simillar M number to the Bacariza rocks but have much more lower CaO/Na_2O ratio. Thus, the higher CaO/Na_2O ratio observed in some Bacariza metabasites (e.g., in pyrigarnites or eclogites s.l.) would account for the lower X_{Jd} in earlier clinopyroxenes.

Garnet

Composition of garnet is heterogeneous (Alm_{34-57}, Adr_{0-15},Grs_{7-29}, Py_{9-39}, Sps_{0-5}). The most enriched compositions in Ca and the most depleted in Mg correspond to garnets from the retrogressed calcite rich granulites, while the highest pyrope content was mesured in mafic granulites with pseudomorphes of clinozoisite-epidote after kyanite. There is no important difference between garnet composition from one rock type to another (Fig. 6a, b, c). Zoning in most garnet crystals is generally weak and irregular and it is suggested that it could be mainly related to post-peak diffusion processes (Tracy 1982). Inclusions, different degree of corrosion and plausible rotation during the general mylonitic deformation could account for this irregular zoning.

Finally, our data agree with previous studies on that the composition of garnet from the Bacariza rocks is depleted in pyrope with respect to garnet from the neighbouring Concepenido eclogites (Vogel 1967; Arenas and Peinado 1984; Gil Ibarguchi et al. 1990, Mendia 1996) but they also differ by higher composition in grossular (Fig. 6d). That is to say, the different composition between these garnets is in a great deal determined by the main whole rock compositional differences between the Bacariza Fm and the Concepenido eclogites and not necessarily by different P-T conditions during metamorphism.

P-T conditions during eclogite and granulite facies metamorphism

An estimation of the conditions prevailing during the earlier metamorphic stages (viz., M1 and M2) is attempted by using geothermobarometric reactions based on the presence of both garnet and clinopyroxene which are the most characteristic minerals of these two stages. Available experimetal data on characteristic mineral associations are also considered for such a purpose. Samples from the uppermost tectonic unit (i.e., La Capelada) and from the Agudo area in the underlying tectonic unit (Fig. 1c) are dealt with separately in order to establish plausible differences between them. A more detailed study on the whole metamorphic path is in progress and will be given elsewhere (Galán and Marcos, in prep.)

The eclogite facies stage (M1). Only in few samples relic kyanite from the association garnet-clinopyroxene-kyanite exists or was inferred from the existence of epidote nodules. Since plagioclase was lacking, composition of garnet from these samples (AMP-437, AMP-475, AMP-431) was considered to estimate minimum pressures according to the geobarometer based on the reaction: 3 anorthite= 1 grossulaire + 2 kyanite + quartz (Newton and Haselton 1981 modified by Koziol and Newton 1988). Minimum pressures obtained from the geobarometer based on the reaction jadeite+ quartz= albite (Holland 1980, 1983) were discarded since they are lower than the previous ones. This is to be related to the fact that clinopyroxene non co-existing with plagioclase are among those which show low X_{jd}. Temperatures were estimated from the thermometer garnet-clinopyroxene using the calibration of Krogh (1988) as the most representative. These are maximum values since all Fe is considered as Fe^{2+} in the calculation. Other calibrations of this thermometer give similar (Powell 1985) or systematically higher temperatures (Ellis and Green 1979). The results for representative samples AMP-113, AMP-315 (Capelada) and AMP-431 (Agudo) (Fig. 1b, c) are shown in Figure 7a. These values were calculated using inclusions of clinopyroxene in garnet and the cores of garnet and of earlier clinopyroxenes crystals not in equilibrium with plagioclase. Several points are highlighted from Figure 7a: (i) estimated P and T are lower in the Agudo area, within the Cedeira unit, than in samples from the overlying La Capelada unit; (ii) clinopyroxene inclusions in both AMP-113 and AMP-315 give lower values than the cores of isolated crystals and similar to those of their rims, which suggests that the data from cores of isolated crystals are bound to represent the metamorphic peak temperature; and (iii), temperatures in AMP-113 are systematically higher (60°C) than in AMP-315 in spite of their similar position. This is to be related to the much higher amount of acmite molecule in clinopyroxenes from AMP-113 than in those from AMP-315, since Fe^{3+} is not considered in the temperature estimation. Taking AMP-315 as the most representative sample from La Capelada, the P-T range defined by the polygon shape for the M1 stage is 842-884° C for $P \geq 14$-16 Kb while in the Agudo area $P \geq 11.9$Kb and T is 754°C. Furt-

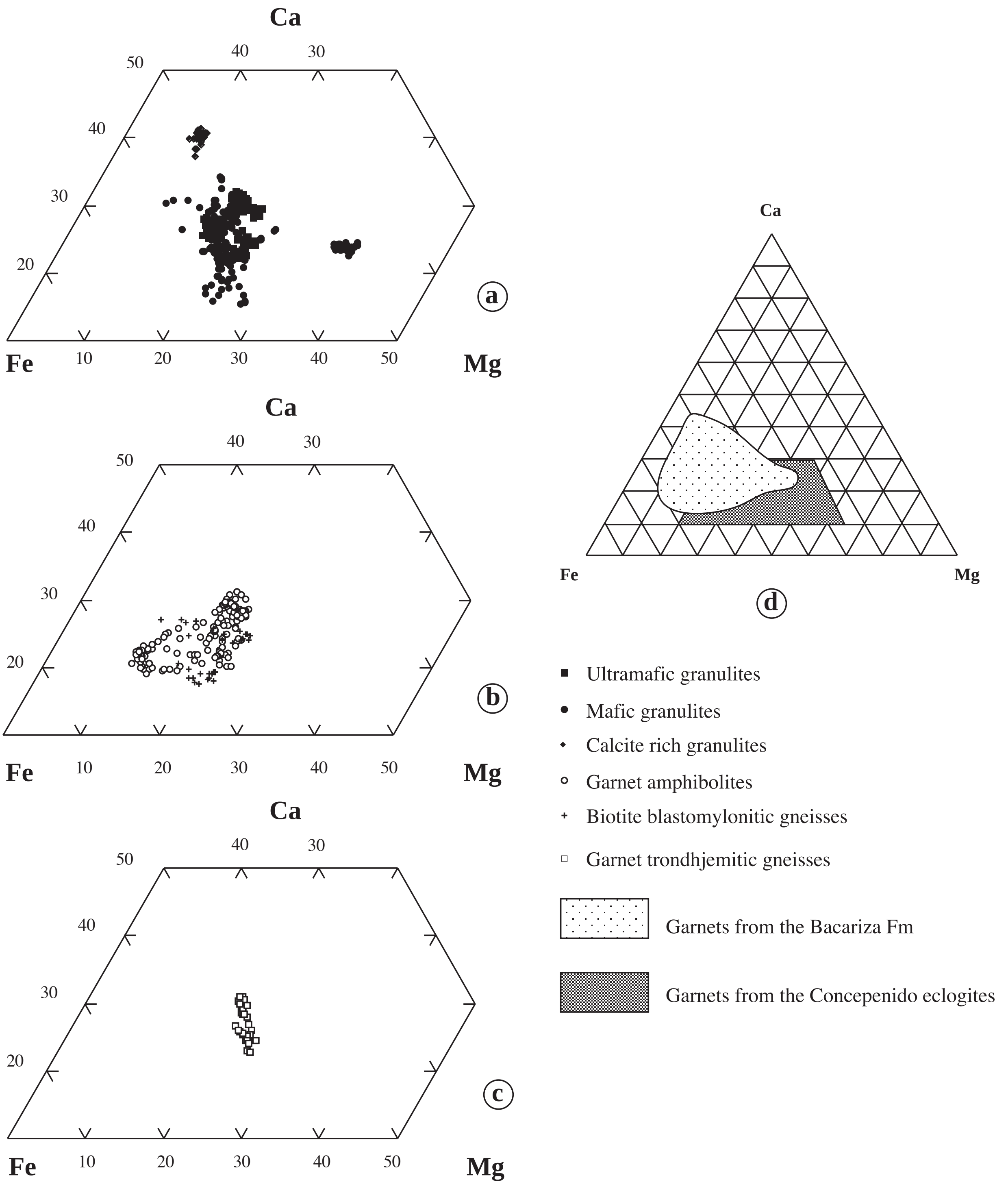

Figure 6. a, b, c, Compositions of garnets from the different rock types of the Bacariza Fm in the Ca-Fe-Mg triangular plot. 5d. Compositional domain of garnets from the Bacariza Fm compared to the domain of garnets from the Concepenido eclogites (data from Mendia 1996).

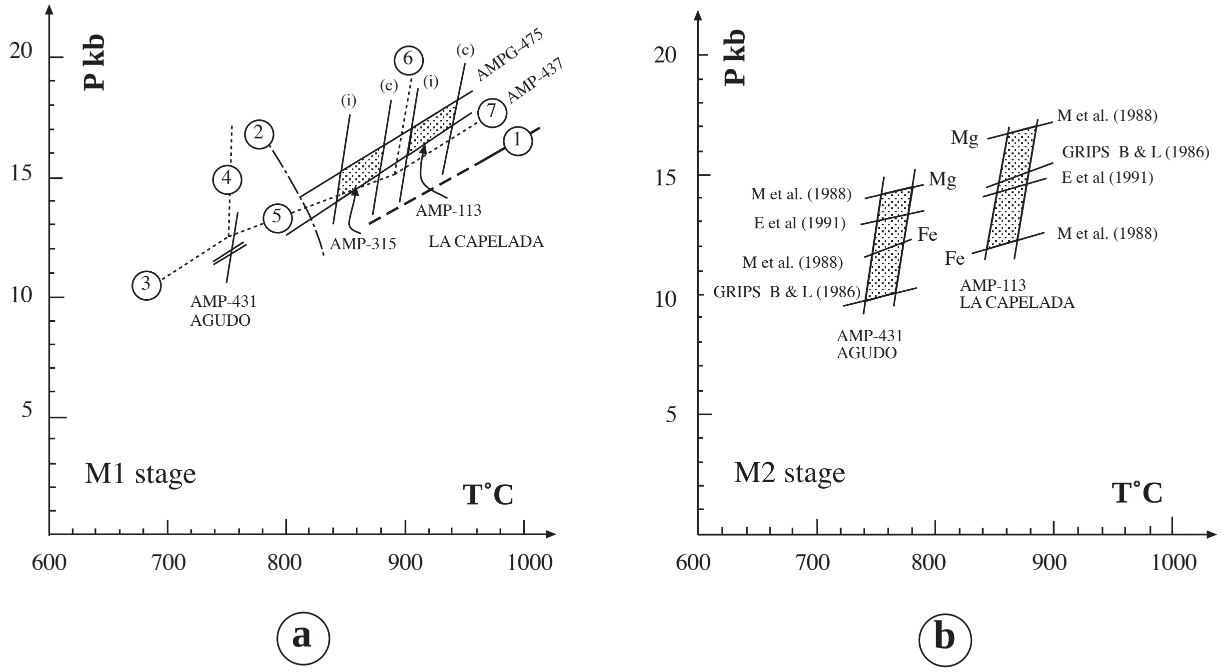

Figure 7. a) Pressures and temperatures estimated for the eclogite facies (M1 stage) for La Capelada and the Agudo rocks based on the garnet-clinopyroxene thermometer (Krogh 1988) and the anorthite-garnet-kyanite-quartz barometer (Koziol and Newton 1988). c, stands for the core of garnet and clinopyroxene isolated crystals, while (i) means clinopyroxene inclusion in garnet. Other boundaries are as follow: (1). Experimental limit between HP granulites and eclogites for quartz-tholeiites (Green and Ringwood 1967); (2). Dehydration melting of amphibole in oversaturated tholeiites according to the experimental data of Rushmer (1991); (3). An+ Vapour= Zo+ Ky+ Qtz; (4). Zo+ Ky+ Qtz+ Vapour= Liquid; (5). An+ Vapour= Zo+ Ky+ Liquid; (6). Zo+ Ky+ Vapour= Co+ Liquid; (7). An+ Co+ Liquid= Zo+ Ky. (3), (4), (5), (6) and (7) according to the experimental data for the system CaO-Al_2O_3-SiO_2-H_2O (Boettcher 1970). b) Pressures and temperatures estimated for the granulite facies (M2 Stage) based on the garnet-clinopyroxene thermometer as before, and on the barometers garnet-clinopyroxene-plagioclase-quartz (Moecher et al. 1988, Eckert et al. 1991) and garnet-rutile-ilmenite-plagioclase-quartz (GRIPS) (Bohlen and Liotta 1986). See text for further explanation.

hermore, temperatures indicated by the garnet-clinopyroxene thermometer in La Capelada are high enough for dehydration-melting of amphibole in oversaturated metabasites according to the experimental data of Rushmer (1991) (Fig. 7a). This dehydration-melting of amphibole would account for the conspicuous partial melting observed in more evolved layers from the Bacariza Fm (e.g., in garnet amphibolites). Subsequently, the resultant trodhjemitic veins would have followed the reverse crystallisation-hydration process during the retrogession, which would explain the formation of amphibole rich borders around these veins.

On the other hand, kyanite relics are often mantled by zoisite and both minerals characterize earlier trondhjemitic veins in these rocks (Vogel, 1967). Their co-existence and the presence of a partial melt would have been constrained by the presence of a vapour phase, according to the reactions for silica saturated and undersaturated rocks respectively (Boettcher 1970) (see Fig. 7a):

zoisite+ kyanite+ quartz+ vapour = liquid
anorthite + vapour = zoisite+ kyanite+ liquid

Estimated P-T conditions for La Capelada are in agreement with available experimental data for the co-existence of kyanite-zoisite-liquid or kyanite-zoisite-quartz. If a vapour phase was lacking, kyanite-zoisite domain is enlarged to higher temperatures and the reactions boundaries which determine the co-existance of these phases are still shifted to higher pressures (Boettcher 1970). However, the presence of kyanite-zoisite bearing veins points to vapour oversaturated conditions at least in some of these rocks during the eclogite facies stage.

The granulite facies stage (M2). The mineral association that characterizes this stage is suitable for using the garnet-clinopyroxene thermometre and the garnet-clinopyroxene-plagioclase-quartz barometre to constraint its P-T conditions. The calibrations of Moecher et al. (1988) and Eckert et al. (1991) were considered for the latter one. Also, the garnet-rutile-ilmenite-plagioclase-quartz (GRIPS) barometre of Bohlen and Liotta (1986) was taken into account since in some deformed granulites rutile and ilmenite co-exist. The estimated conditions are illustrated in Figure 7b for samples AMP-113 (La Capelada) and AMP-431 (Agudo). Several points are highlighted: (i) calculated temperatures with the garnet-clinopyroxene thermometer for AMP-113, using neo-clinopyroxene tiny crystals in microshear bands and crytal rims of garnet, are slightly lower with respect to those estimated for the M1 stage in the same sample; (ii) the two barometres with the different calibrations provide consistent data and the P-T range from the polygonal shape is 842-884˚C for 11.9-17.0 kb; (iii) other samples from La Capelada, where clinopyroxene is less rich in acmite molecule, give lower temperatures and show a large range: 740-874˚C for 10.0-18.8 kb with average values of 802˚C-14.5 kb for 5 samples; (iv) the values estimated for the Agudo sample always point to lower P-T conditions than in La Capelada: 740-780˚C for 9.5 -14.5 kb; finally (v), although temperature decreases slightly from the M1 to the M2 stage in both La Capelada and Agudo areas, the pressure range for the latter stage overlaps that estimated for the former. This supports the idea that pressures calculated for the eclogite facies are minimum.

Discussion

The following points are highlighted from previous results:

– An earlier eclogite facies metamorphism (M1) is inferred for the Bacariza metabasites from the mineral association kyanite-garnet-clinopyroxene. Kyanite is later on replaced by zoisite. This earlier eclogite facies stage is further supported by the fact that when plagioclase appears in equilibrium with garnet and clinopyroxene, the last mineral always show characteristic textures of de-jadeitized omphacites.

– Lower X_{Jd} in earlier clinopyroxenes not in equilibrium with plagioclase than in those of other eclogites in the COC (viz., Concepenido eclogite) is mainly to be related to the whole rock composition of some of these rocks which show high CaO/Na_2O ratio.

– The same compositional control is observed in garnets; they show lower pyrope and higher grossular than most garnets from the Concepenido eclogites. The lower M number and higher CaO/Na_2O radio of the Bacariza rocks with respect to most Concepenido eclogites would account for this difference.

– The P-T conditions estimated for the eclogite facies stage are above the transition between high-pressure granulites and eclogites for quartz-tholeiites (Fig. 7a), according to available experimental data (Green and Ringwood 1967).

– Temperatures calculated for the granulite facies stage (M2) are slightly lower than those of the eclogite facies while pressures overlap. This would point to the attainment of the peak temperature in eclogite rather than in granulite facies.

– P-T conditions during the eclogite and granulite facies stages are lower in rocks from the underlying Agudo area, in the Cedeira unit, than from the uppermost La Capelada unit, which is to be related to their different tectonical position.

- The estimated metamorphic peak conditions for La Capelada (842-884˚ C for P≥ 14-16) are higher in temperature and slightly lower in pressure than the metamorphic peak conditions calculated by equivalent geothermobarometric methods for the Concepenido eclogites (770-800˚C for 14.5-17.9 kb after Mendia 1996).

- P-T conditions for the already retrogressed granulite facies stage in La Capelada are comparable to the symplectitization of the Concepenido eclogites (600-800°C for 10-16 kb; data from Mendia 1996) but temperature is always higher in the Bacariza rocks (740-874˚C for 10.0- 18.8 kb).

Therefore, our results support the hypothesis that the granulite facies metamorphism in the Bacariza Fm is already retrograde and post-dates an earlier stage in eclogite facies. This is in contradiction either with poly-cyclic models such as the “mantle plume” (Keasberry et al. 1976; Van Calsteren 1978, 1981; Van Calsteren and Den Tex 1978;

Kuijper and Arps 1983; Kuijper et al. 1985), which considers the granulite facies as static and caused by increasing T after an earlier eclogite facies metamorphism, or with those that consider the granulite facies as a prograde stage towards the eclogite facies metamorphism (Engels 1972). The former hypothesis is constrained by (i), granulitic mineral associations giving lower temperatures than eclogitic mineral associations and (2), textures related to the granulite facies (viz., microshear bands, vermicular and coarse grained symplectites), which are associated with the initial development of the 'general mylonitic foliation'' caused by the up-lift of these rocks.

Although our results provide more evidence for a single cycle model, we differ from previous hypothesis of this type (Gil Ibarguchi et al. 1990; Peucat et al. 1990; Arenas 1991) because the granulite facies metamorphism is considered to be retrograde and post-dating the eclogite facies metamorphism while the others consider them quasi-simultaneous events .

Although estimated minimum P and maximum T for the eclogite facies are lower and higher respectively in the Bacariza rocks from La Capelada than in the neighbouring Concepenido eclogites, both parameters can be considered still comparable. Therefore, they do not provide enough support to justify different tectonic settings for these two metabasic formations. They are more likely to be constrained by whole rock geochemistry differences since the Bacariza rocks have both lower CaO/Na_2O ratio and M number than most Concepenido eclogites. This would account for lower X_{jd} in clinopyroxene and higher Fe^{3+} content in both clinopyroxene and garnet, which would lower minimum pressures and would increase maximun temperatures respectively.

Finally, one of the most remarkable features of the Bacariza Fm with respect to the Concepenido eclogites is that the former show a higher degree of retrogression. Vogel (1967) pointed to the major abundance of pegmatoid trondhjemitic veins in the Bacariza Fm as the main cause of this. We suggest that this abundance is also to be related to compositional differences in the protoliths: the Bacariza Fm shows higher amount of intermediate rocks than the Concepenido eclogites, whose composition is mainly basic (Gravestock 1992; Mendia 1996). These intermediate rocks would have followed a higher degree of melting during the catazonal metamorphism than the basic compositions, which would be mainly due to dehydration melting of amphibole. The resultant trondhjemitic veins would have enhanced deformational processes and concomitant retrogression.

Conclusions

The HP granulites of the Bacariza Fm outcrop in the two uppermost structural units of the COC. They are interpreted as a result of an ealier retrogression stage of eclogites during a single-cycled metamorphism.

These eclogites differ from others in the COC (viz., the Concepenido eclogites) by a higher degree of retrogression, which is mainly to be related to the more heterogeneous composition of their protolith that includes intermediate and acid rocks.

The presence of an important amount of intermediate rocks in th Bacariza Fm would account for a higher degree of partial melting during the catazonal metamorphism, causing the formation of abundant trondhjemitic veins. These represented weaker zones that favoured later deformational processes and concomitant retrogression.

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