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Paleozoic of the Tethys

Hercynian Metamorphism in the Catalonian Coastal Ranges

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ABSTRACT

Paleozoic rocks in the Catalonian Coastal Ranges are in their largest part affected by a low- to very-low grade Hercynian metamorphism. Amphibolite facies conditions are only found in restricted areas such as the southwestern part of the Guilleries massif where upper amphibolite facies conditions are reached.

Metamorphic grade increases from top to bottom of the Paleozoic stratigraphic sequence and the metamorphic peak is diachronous, being progressively older in the lower grade metamorphic zones. The isograd pattern, mineral assemblages, mineral chemistry and preserved reaction textures are consistent with a low pressure metamorphism possibly evolving from a previous Barrovian type event. The metamorphic climax in the high grade zone was reached after the second deformational phase. Calculated peak P-T conditions are 620-640 °C and around 3.5 Kb. A latter episode of decompression from the maximum conditions to 1-2 Kb, with an associated temperature decrease to 530-550 °C, is recognized.

The intrusion of late Hercynian granitoids produced contact metamorphic aureoles where the pyroxene-hornfels facies is locally reached.

Key words : Regional metamorphism. Contact metamorphism. Catalonian Coastal Ranges. Hercynian Chain.

RESUMEN

Los materiales prehercínicos de las cadenas Costero-Catalanas están en su mayor parte afectados por un metamorfismo regional Hercínico de bajo o muy bajo grado, alcanzándose en áreas mas restringidas la facies anfibolítica y al SO del macizo de Guilleries condiciones de alto grado. La intensidad del metamorfismo aumenta hacia los materiales más antiguos, teniendo lugar el clímax cada vez mas tarde en el tiempo a medida que aumenta el grado metamórfico. Las asociaciones minerales, composición mineralógica y reacciones observadas muestran para diferentes áreas un clímax metamórfico del tipo de baja presión, con una posible etapa anterior de presión intermedia. En las zonas de alto grado el clímax se alcanza posteriormente a la segunda fase de deformación Hercínica, cifrándose las condiciones máximas de P y T alrededor de 3.5 Kb a una temperatura entre 620-640 º C. produciéndose a continuación una descompresión hasta 1-2 Kb asociada a un pequeño descenso de la temperatura (530-550º C).

La posterior intrusión de granitoides tardihercínicos provoca aureolas de metamorfismo de contacto de hasta 2km de espesor, alcanzándose localmente la facies de las corneanas piroxénicas.

Palabras clave: Metamorfismo regional. Metamorfismo de contacto. Cadenas costero-catalanas. Cordillera Herciniana

INTRODUCTION

Paleozoic rocks which crop out in the Catalonian Coastal Ranges (Fig. 1), range in age from Carboniferous to probable early Cambrian (Julivert *et al.*, 1987). An important part of the pre-Hercynian Paleozoic sequence has been more or less affected by Hercynian regional metamorphism and, in some areas, has also been affected by a later contact metamorphism associ-

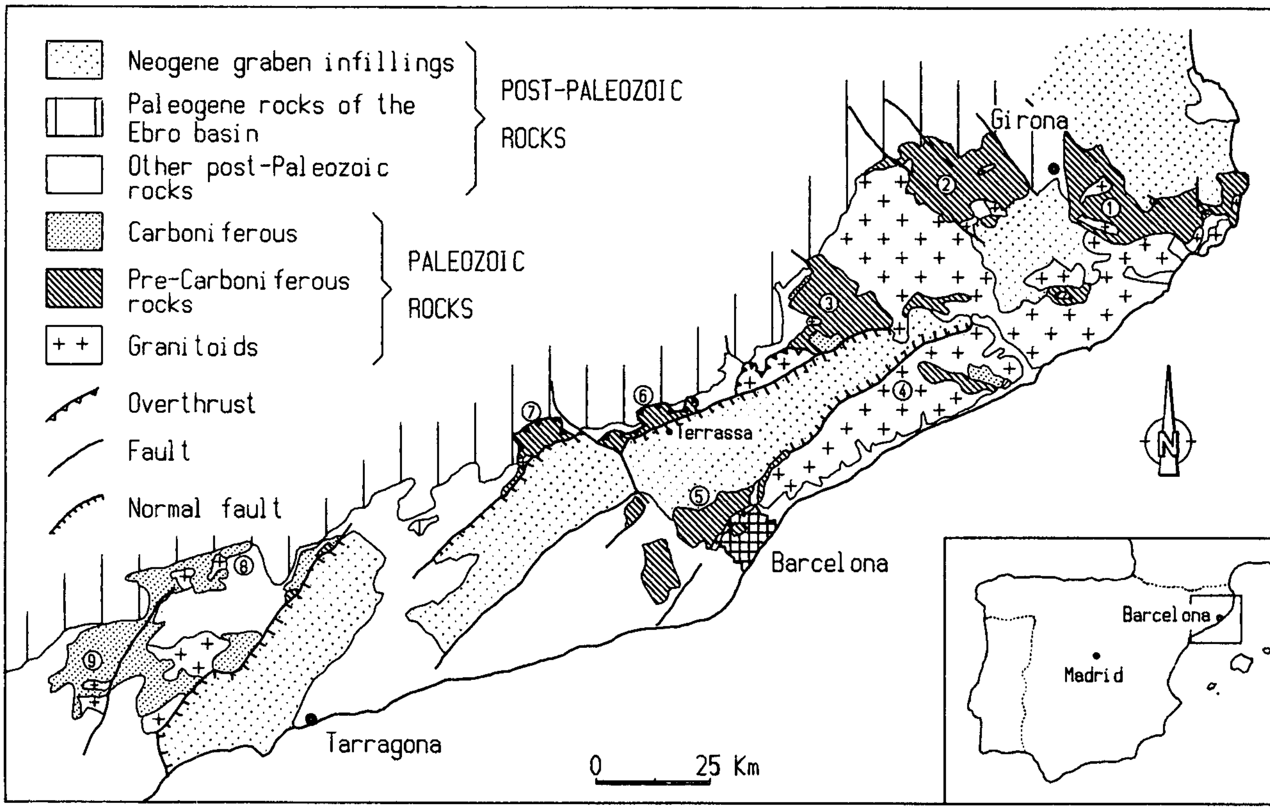

Figure 1.- Simplified geological map of the Catalonian Coastal Ranges. 1) Gavarres massif; 2) Guilleries massif; 3) Montseny massif; 4) Montnegre massif; 5) Tibidabo area; 6) Terrassa-Castellar del Vallès thrust-sheets; 7) Capellades-Bruc thrust-sheet; 8) Prades massif; 9) Priorat area.

ated with the intrusion of late-Hercynian granitoids. The metamorphic sequence involves mainly pelitic and psammitic materials; carbonate and basic rocks are also present in minor amounts. Carbonate rocks are predominantly of Silurian and Devonian age and are affected by very low-grade metamorphism. Marble layers occur in the lower Cambrian. Basic rocks are present in the Silurian and in the lowest levels of the stratigraphic sequence.

REGIONAL METAMORPHISM

Most pelitic rocks in the Catalonian Coastal Ranges record a low to very low-grade metamorphism reaching only the chlorite and biotite zones. The first sillimanite Isograd is reached in the thrust sheet near Castellar del Valles and to the southeast of the Montseny massif (Van der Sijp, 1951 Viladevall, 1978; Ubach, 1987), whereas high-grade assemblages have only been observed to the southwest of the Guilleries massif (Durán, 1985).

In general, metamorphic grade increases towards the oldest stratigraphic levels: Devonian and Carboniferous rocks are little affected whereas the high-grade metamorphic rocks only appear in probable lower Cambrian levels.

Low and medium-grade metamorphism

The following metamorphic zones have been found In pelitic rocks: chlorite, biotite, andalusite-cordierite, and sillimanite.

The characteristic assemblage in the chlorite zone is chlorite-muscovite and in the biotite zone, biotite-chlorite-muscovite, which gradually is replaced with increasing metamorphic grade by biotite-muscovite.

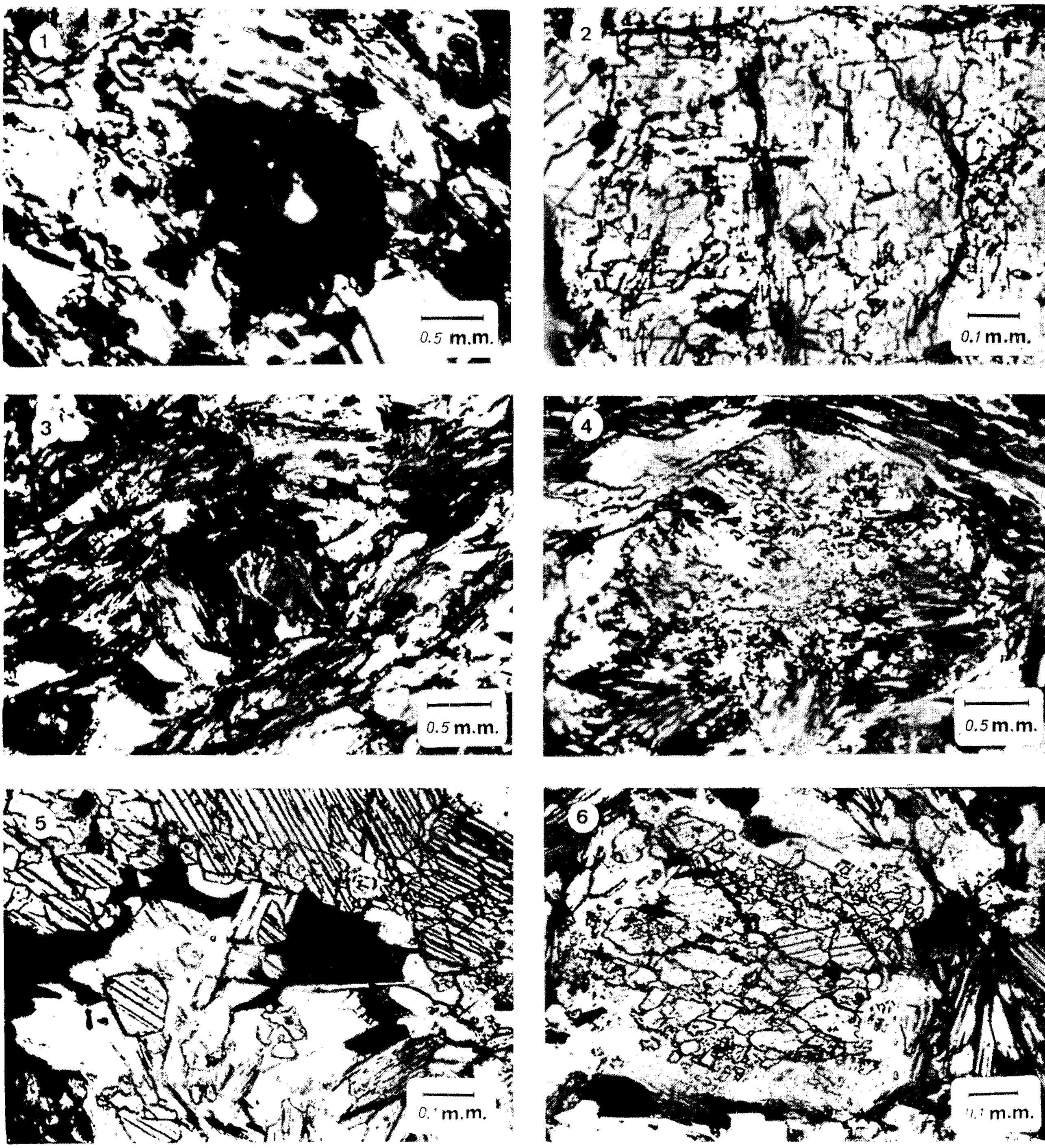

Plate I .- Microphotographs showing some reaction textures. 1: Cordierite corona sourrounding resorbed garnet. Amphibolitic rocks in Cd-Kf zone at the Guilleries area. 2: Relict staurolite in andalusite. 3 and 4: sillimanite (fibrolite) + biotite pseudomorphs after garnet. 5 and 6: Resorbed sillimanite + biotite in cordierite.

In low, and medium-grade metamorphic zones, rocks show a slaty cleavage defined by the parallel arrangement of muscovite, chlorite and biotite, although pretectonic chlorites and biotites as well as retrograde muscovite are also present. This slaty cleavage is the first and main foliation, S_1, in these metamorphic zones, although in some places a crenulation cleavage is developed that cross cuts S_1.

Medium-grade metamorphism is less widespread, being well developed only in the Guilleries massif, southeast of the Montseny massif and in the Terrassa and Castellar del Vallés thrust-sheets of Alpine age (Fig. 1).

The andalusite-cordierite zone is characterized by the following assemblages : andalusite-cordierite-muscovite, cordierite-biotite and andalusite-cordierite-biotite-muscovite. In more quartz-feldspatic compositions garnet occurs. This garnet is unstable and reactions to produce cordierite and biotite (Ubach, 1984, Huerta, 1986). Also in this zone (Huerta, 1986), and in the sillimanite zone (Durán, 1985) relict staurolite in andalusite along with matrix of muscovite and quartz has been described (Plate 1, photo 2). This fact suggests the reaction:

staurolite + muscovite + quartz = biotite + andalusite +H2O (1)

Rocks in the andalusite-cordierite zone show S_1 crenulated by a second deformation phase which often erases S_1 almost completely. They are also characterized by an important recrystallization and by the presence of andalusite and/or cordierite poikiloblasts which clearly grow after S_1. Almost all these poikiloblasts show rotational features that are syntectonic with respect to S_2.

The upper limit of medium-grade metamorphism is determined by the occurrence of sillimanite (fibrolite) in the presence of muscovite. The most common assemblages that can be observed in this zone are : sillimanite-muscovite-cordierite-biotite-andalusite and sillimanite-muscovite-biotite-andalusite, coexisting andalusite and sillimanite being restricted to the lower grade part of the zone. In the highest grade levels garnet is locally found. Garnet has normally a poikiloblastic core and is almost always rotational. Garnet is also usually resorbed by sillimanite and biotite aggregates, probably through the reaction:

garnet + muscovite = sillimanite + biotite + quartz (2)

Occasionally, reaction (2) products form recognizable garnet pseudomorphs (Platel, photos 3 and 4). The main foliation in sillimanite zone rocks is S_2, but its crenulation character is by no means clear due to intense mineral recrystallization that causes alignement of all micas and sillimanite parallel to the S_2 surfaces.

High grade metamorphism

The high grade metamorphism is restricted to the oldest rocks cropping out in the southwest part of the Guilleries massif. These lower stratigraphic levels are locally affected by partial melting. In pelitic rocks, the diagnostic mineralogical assemblage is cordierite + K-feldspar which is produced from breakdown of biotite + sillimanite. The following reaction has been proposed (Durán 1985):

biotite + sillimanite + quartz = cordierite +K-feldspar +H_2O (3)

Textural evidence of this reaction is shown in Plate 1 (photos 5 and 6), where corroded biotite and prismatic sillimanite are included in cordierite. Occasionally, in the matrix, metastable andalusite instead of sillimanite is also observed. Metastable corroded garnets resorbed by biotite and sillimanite as in the sillimanite zone, and relict staurolite in andalusite are also observed at the beginning of the cordierite-Kf zone.

The dominant fabric changes gradually from granolepidoblastic to granoblastic, partially overlapping the main foliation, S_2. Cordierite and K-feldspar, as well as prismatic sillimanite, statically overgrow S_2 Consequently, the metamorphic peak in the cordierite-Kfeldspar zone postdates S_2 fabric development.

P-T conditions of high grade metamorphism

The coexistence of garnet-biotite and garnet-cordierite ± biotite in pelitic and amphibolitic rocks, respectively, allows temperature conditions to be obtained using exchange geothermometry. The Ferry and Spear (1978); Hodges andSpear (1982); and Thompson (1976) , calibrations for garnet-biotite and Thompson (1976); Holdaway and Lee (1977) and Perchuk and Laurent' eva (1983) calibrations for garnet-cordierite were used to calculate temperatures.

Pressure conditions have been obtained through garnet-plagioclase-Al_2SiO_5-quartz (GPAQ) assemblages using expressions from Newton and Haselton (1981) and Koziol and Newton (1988), and from garnet-biotite-muscovite-plagioclase-quartz assemblages using expressions from Ghent and Stout (1984) and Hodges and Crowley (1985). These particular calibrations were selected since the analyzed phase compositions summarized in Table 1, fell within the author´s recomended limits.

Table I .- Representative microprobe analysis of minerals from the high grade metamorphic zone in the Guilleries massif. Abbreviations: G: garnet; B: biotite; Pl: plagioclase; C: cordierite; M: muscovite; N: mineral core; O: mineral rim; E: matrix; P: pelites; A: amphibolites. Structural formulas are calculated on the basis of: plagioclase (8), garnet (24), biotite (22), muscovite (11), cordierite (18) oxygens.

ANALYSIS	GNP75	GNP76	GNP77	GNA16	GOA38	PIOP9
SiO2	36.54	36.69	36.29	38.27	37.32	61.76
TiO2	0.03	0.01	0.03	0.02	0.08	0.00
Al2O3	20.77	20.49	20.61	21.36	21.52	24.03
Cr2O3	0.00	0.02	0.05	0.01	0.07	0.00
FeO	37.31	37.70	37.93	32.62	34.65	0.22
MnO	1.64	1.58	1.58	1.22	1.33	0.00
MgO	1.67	1.77	1.78	4.37	3.56	0.00
CaO	0.78	0.54	0.78	2.66	2.01	3.40
Na2O	0.01	0.03	0.04	0.00	0.00	9.04
Total	98.74	98.83	99.09	100.52	100.54	98.86
STRUCTURAL FORMULA						
Si	6.017	6.041	5.978	6.041	5.952	2.762
Ti	0.004	0.001	0.005	0.001	0.009	0.000
Al	4.030	3.975	4.001	3.974	4.046	1.266
Fe	5.138	5.190	5.224	4.307	4.622	0.008
Mn	0.228	0.221	0.220	0.163	0.179	0.000
Mg	0.409	0.438	0.437	1.029	0.846	0.000
Ca	0.137	0.095	0.138	0.449	0.344	0.162
Na	0.004	0.008	0.012	0.000	0.000	0.783

ANALYSIS	BEP55	BEP56	BEP60	BEA16	COA38	MEP20
SiO2	34.44	34.23	34.31	35.83	48.43	45.39
TiO2	2.31	2.08	2.26	2.16	0.01	0.78
Al2O3	20.30	20.47	20.27	17.07	32.89	35.37
Cr2O3	0.04	0.00	0.02	0.00	0.01	0.00
FeO	24.36	24.01	24.09	19.76	8.70	1.14
MnO	0.05	0.05	0.02	0.06	0.07	0.00
MgO	5.40	5.56	5.45	11.74	8.21	0.46
CaO	0.00	0.00	0.02	0.11	0.03	0.00
Na2O	0.44	0.37	0.38	0.20	0.23	0.69
K2O	8.96	8.81	8.99	7.74	0.01	10.56
Total	96.30	95.59	95.81	94.74	98.59	94.39
STRUCTURAL FORMULA						
Si	5.303	5.297	5.304	5.458	4.985	3.053
Ti	0.267	0.241	0.263	0.247	0.001	0.039
Al	3.683	3.733	3.694	3.064	3.990	2.803
Fe	3.137	3.107	3.115	2.517	0.748	0.064
Mn	0.006	0.006	0.002	0.007	0.006	0.000
Mg	1.239	1.283	1.257	2.666	1.259	0.046
Ca	0.000	0.000	0.004	0.017	0.003	0.000
Na	0.131	0.112	0.113	0.059	0.045	0.089
K	1.759	1.740	1.774	1.504	0.001	0.906

Metapelite mineral analyses were done in the CAMEBAX microprobe of the Laboratoire de Petrologie at Paris VI University, under the following analytical conditions: 15 Kv. accelerating potential with a sample current of 20 nA and 20 sec. counting rate. ZAF program was used to correct element concentrations. Amphibolite mineral analyses where carried out in a CAMECA microprobe at Harvard University under the conditions : 15 Kv. Accelerating potential, 15 nA sample current and 20 sec counting rate. Oxide standards were used, in addition to a standard garnet, for calibration.

Table II .- Metamorphic temperatures for the metapelites and amphibolites from the high grade zone in the Guilleries massif. (M=Peak temperature. R=Retrograde temperature). Abbreviations as in Table I. Garnet-biotite calibrations: FS: Ferry and Spear, (1978). HS: Hodges and Spear, (1982). T: Thompson, (1976). Garnet-cordierite: HL: Holdaway and Lee, (1977). PL: Perchuk and Lavrent´eva, (1983). T: Thompson, (1976).

GARNET-BIOTITE

Sample	P(Kb)	FS 7	FS 3	HS 7	HS 3	T 7	T 3
75/55P	(M)	631	616	640	624	625	598
74/55-59P	(M)	632	616	638	621	626	596
73/55-59P	(M)	634	616	643	627	629	600
77/60P	(M)	641	625	649	633	634	605
76/60P	(M)	644	626	651	635	632	605
77/55-59P	(M)	642	636	650	634	636	606
424/423A	(M)	647	638	650	634	657	627
461/502A	(M)	650	634	677	661	659	629
510/502A	(M)	645	629	657	641	655	625
186/185A	(M)	638	622	645	629	650	621

GARNET-CORDIERITE

Sample	P(Kb)	HL	PL 7	PL 3	T
459/445A	(M)	613	613	637	629
359/373A	(M)	615	616	639	632
388/385A	(M)	612	613	636	628
48/47A	(R)	549	545	566	554
474/473A	(R)	550	546	567	555
487/488A	(R)	513	507	527	512
31/13A	(R)	528	523	547	529

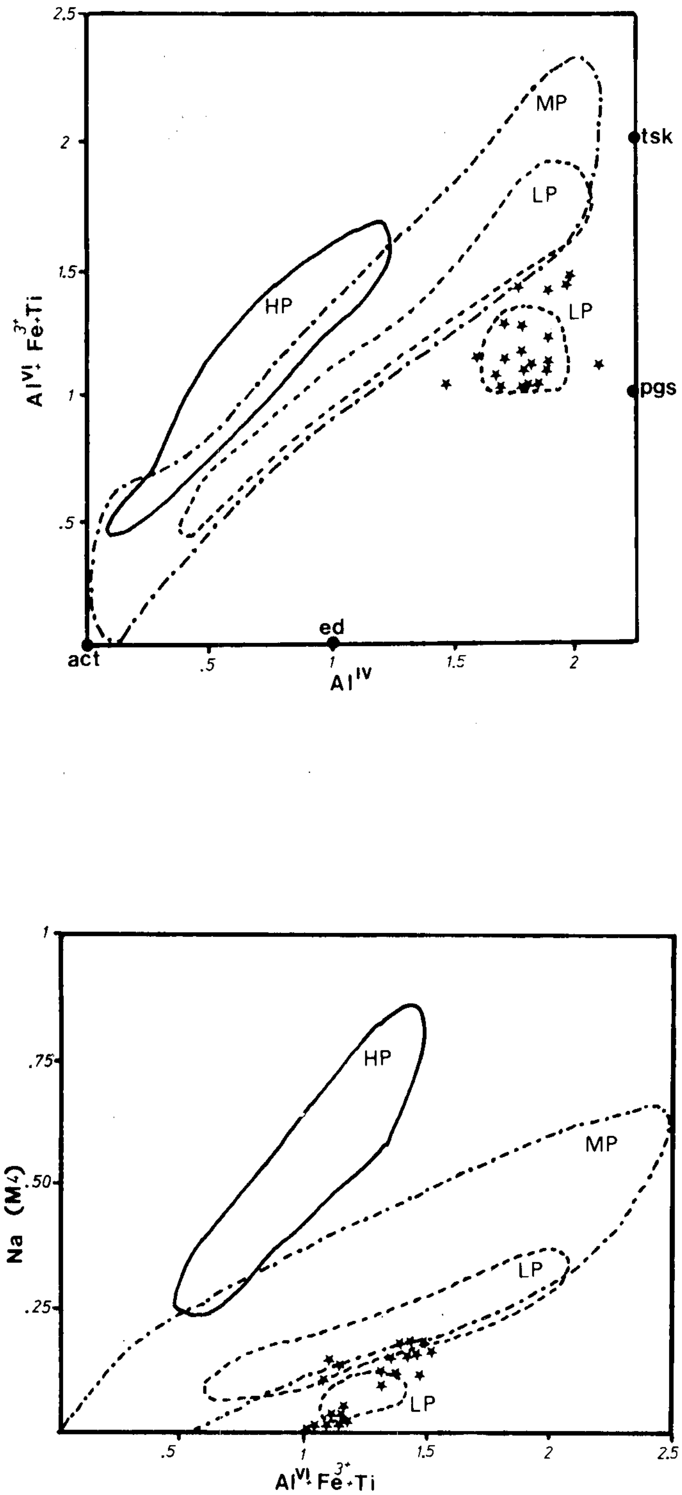

Figure 2.- Al^{VI}+Fe^{3+}+Ti vs. Al^{IV} and Na (M4) vs. Al^{VI}+Fe^{3+}+Ti plots for calcic amphiboles from high-grade metabasites of the Guilleries massif. The envelopes delimit high (HP), medium (MP) and low-pressure (LP) fields as defined by Laird and Albee, 1981.
act= actinolite; ed= edenite; pgs= pargasite; tsk= tschermakite.

The garnets used in thermometry show retrograde zoning at their rims, and smooth growth zoning or homogeneous composition in their cores. This type of garnet zoning allows peak temperature as well as retrograde temperature to be estimated. The coexistence of growth and diffusion zoning in garnet seems to indicate that only for a brief period of time, temperature conditions of zoning homogenization (around 650ºC. after Tracy,1982), were reached.

Peak temperatures have been calculated using compositions with a minimum Fe/Fe+Mg ratios in garnet and matrix biotite, assuming that matrix biotite compositions held nearly constant after the metamorphic climax. Temperature results are shown in Table 2. Note that the garnet-biotite calibration shows similar temperatures in pelitic and amphibolitic rocks. Results from the Ferry and Spear and Hodges and Spear calibrations are similar (5-10 °C higher for the latter). Results from Thompson are lower, although this is a common fact below 650-700ºC (see Hodges andSpear, 1982, for instance).

Garnet-cordierite results are very consistent with garnet-biotite determinations, although the former are slightly lower for the maximum temperatures obtained.

Pressure determinations for the peak temperature conditions show a range between 3.3-3.8 Kb. Presures calibrated from Koziol and Newton (1988) using films of plagioclase around garnet rims give 1-2 Kb between 550-580ºC. Amphibole compositions ploted on Laird and Albee (1981) Al^{VI}+Fe^{3+}+Ti - Al^{IV} diagram, Fig. 2, support these low-pressure metamorphic conditions obtained from plagioclase-garnet rims.

Conclusions about regional metamorphism

The pattern of metamorphic zones, mineral assemblages, mineral compositions, and thermobarometric determinations suggest that Hercynian regional metamorphism in the Catalonian Coastal Ranges was of a high-temperature low-pressure type. Nevertheless, relict staurolite in andalusite porphyroblasts, garnet-bearing assemblages, and reaction textures clearly indicate a volume increase (see for instance photo 1 in Plate 1), suggesting that low-pressure metamorphism was superimposed an earlier medium-pressure event. This medium-to low-P progression has also been proposed in other Hercynian areas in the Iberian Peninsula (Martínez, 1974; Gil Ibarguchi, 1982).

In the high grade areas the metamorphic peak was reached after the second deformation phase. Peak conditions are older in lower grade areas with respect to deformation phases. Whereas in the sillimanite and andalusite-cordierite zones the metamorphic climax is reached during S_2 development, in the biotite zone peak conditions are syn-S_1, and in the chlorite zone they are pre-syn-S_1.

CONTACT METAMORPHISM

After the second phase of Hercynian deformation, igneous rocks were intruded in the Catalonian Coastal Ranges, producing contact metamorphism in the country rocks. Most of these igneous rocks are granitoids which reach shallow crustal levels and were intruded after the development of crenulation cleavages (Enrique 1984, 1985). The country rocks are often affected by a previous regional metamorphism usually not exceeding greenschist facies. The shallow intrusives produced thermal aureoles, which range between ten meters up to two or three Km across.

In many areas affected by this contact metamorphism, the country rocks reach the hornblende-hornfels facies (Vaquer, 1972, Ubach, 1987) and in the shallowest levels, and near the contact with the most basic intrusions, the pyroxene-hornfels facies is reached (Huerta, 1986; Gil Ibarguchi and Julivert, 1988). Gil Ibarguchi and Julivert, estimated maximum temperatures of around 675-700ºC and pressure around 1 to 1.5 Kb for the Tibidabo area.

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