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Relations of Hercynian metamorphism with magmatism and deformation in the Eastern Pyrenees. Implications for Hercynian evolution

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Abstract

The Hercynian metamorphic evolution at different crustal levels of the Roc de Frausa Massif has been constrained relative to the deformation and intrusion of igneous rocks. The main deformation phase is considered to have been synchronous throughout the whole crustal section exposed. Intrusion of igneous bodies took place subsequently to deformation and overprinted the previously foliated texture of the country rocks. At shallow levels two metamorphic peaks are distinguished, viz. a regional one, synchronous with the main deformation, and a contact-metamorphic peak. At deeper levels and away from the intrusives the regional metamorphic climax is post-kinematic. Near the intrusives, the contact-metamorphic episode constituted the latest and highest temperature stage of a continuous prograde metamorphic evolution. The crustal evolution is characterized by a first compressive event at intermediate-pressure metamorphic conditions, followed by a post-tectonic event characterized by low-pressure – high-temperature metamorphism and ubiquitous magmatism. The first event is registered at shallow levels of the crust, whilst the second event is only recorded in exposures representing deeper crustal levels. The high-temperature metamorphism and magmatism could be a result of either the incorporation of mantle material into the lower crust subsequent to a thickening episode, or a subcrustal collapse of a previously thickened lithosphere.

Introduction

The relationships between metamorphism, magmatism and deformation, the major features of orogenic activity, allow us to reconstruct the succession of events in an orogenic belt. These relationships are reasonably well constrained in medium to high-pressure belts, where metamorphism is the consequence of tectonic activity and where magmatism postdates this evolution (England & Thompson 1984). For low-pressure – high-temperature belts there seems no clear sequence of events established: clockwise and anticlockwise paths have been described (Thompson 1989; Collins & Vernon 1991) such that uncertainty remains on whether or not metamorphism is a consequence of tectonic activity (Bohlen 1987; Clarke et al. 1987). Neither is it clear how these parameters are related to magmatism. Is magmatism a consequence of metamorphism (Zwart 1967, Thompson & Ridley 1987), or does metamorphism occur as a consequence of magmatism (Oxburgh & Turcotte 1970; England & Thomson 1986)?

The Paleozoic rocks exposed in the Pyrenees form part of the Western Europe Hercynian belt, a low-pressure fold belt which has been interpreted by some authors as a collisional belt (Julivert & Martínez 1987, Matte & Mattauer 1987). Nevertheless, on the basis of the time relations between deformation, metamorphism and magmatism a varie-

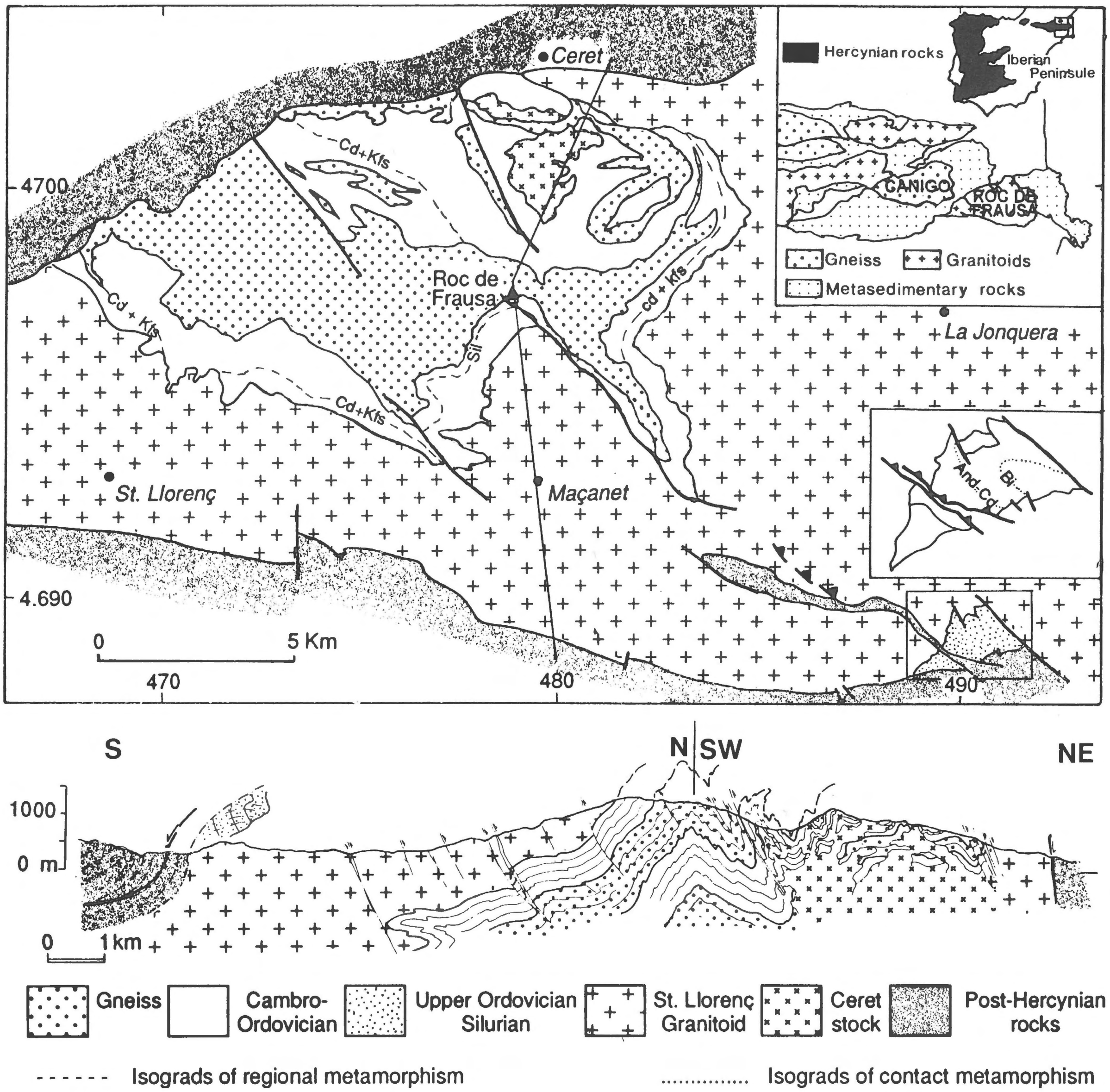


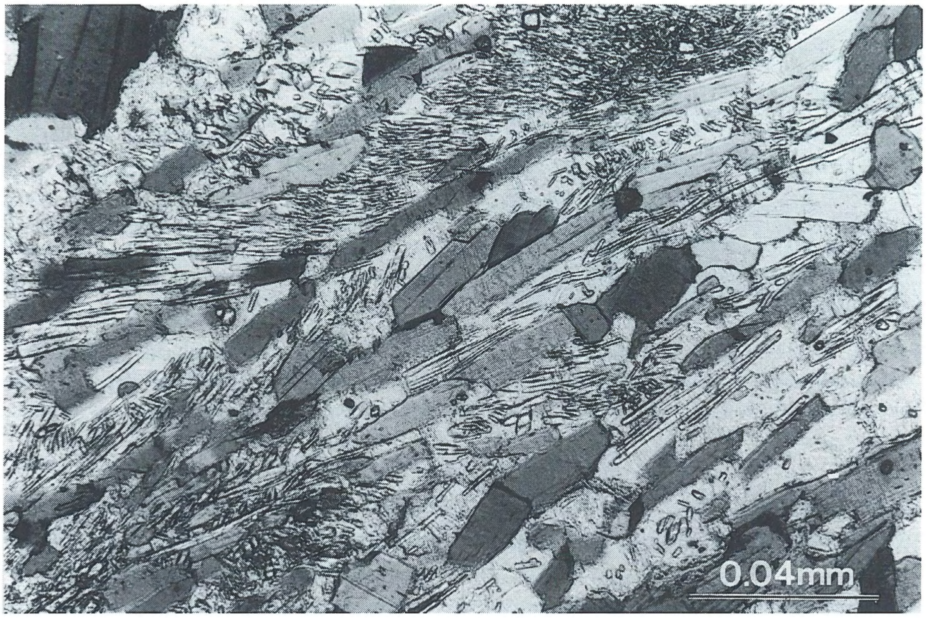
Fig. 1. Geological sketch-map and cross-section through the Roc de Frausa Massif.

ty of interpretations have been put forward on the geodynamic context of the Pyrenees during Hercynian times.

This paper analyses the relationships between deformation, metamorphism and magmatism in a wide section of the Hercynian crust exposed in the Eastern Pyrenees. On the basis of this analysis a sequence of events is established and evaluated against current models for the Hercynian evolution of the Pyrenees.

Geological setting

The Roc de Frausa Massif is located in the Eastern Pyrenees. Late Hercynian and Alpine tectonics have provided its uplift through thrusts and folds which account for the present antiformal structure of the area (Fig. 1). The southern limb of this antiform shows a succession from gneisses and Cambro-Ordovician metasediments exposed in the core of the antiform, to Upper Ordovician and Silurian



Photograph 1. Intensely folded S1 planes defined by polygonized sillimanite in a schist. S2 minerals (biotite and sillimanite) show parallel arrangement and tend to follow the axial-plane direction of the folds. Both biotite and sillimanite are included in a large cordierite porphyroblast.

rocks to the south. These rocks are unconformably overlain by Uppermost Cretaceous sediments.

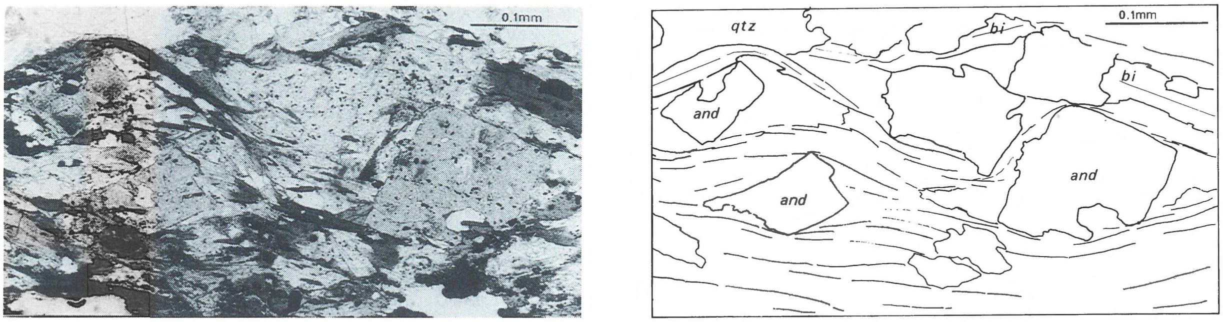
The Paleozoic rocks are intruded by a basic igneous body known as the Ceret stock, and by a composite granitoid, the Sant Llorenç – La Jonquera intrusive sheet (Fig. 1). Isotopic dating of this granitoid, including some cumulates of the Ceret stock, has yielded ages of about 282 ± 5 Ma (Rb-Sr whole-rock, Cocherie 1992).

Hercynian structures and regional metamorphism

A Hercynian main foliation is developed in the whole massif. In the Upper Ordovician and Silurian levels this foliation commonly makes a high angle with the bedding, whilst in the Cambro-Ordovician rocks the two planar features tend to be parallel. Minor and medium-scale folds related to the development of this foliation have been distinguished, but neither a consistent vergence nor a constant trend of the folds was found. Autran & Guitard (1969) describe tight major folds, related to the development of the main foliation, which face to the north. Nevertheless, other authors working in the Eastern Pyrenees agree on a south vergence of the main phase (Carreras 1973, Santanach 1974, Casas 1978, Muñoz 1992).

At structurally deeper levels in the Cambro-Ordovician rocks, the main foliation folds an earlier fabric, and both are clearly formed under metamorphic conditions (Photograph 1). No folded foliation has been observed in the Upper Ordovician and Silurian rocks, so uncertainty remains whether the only foliation observed in these latter rocks is related to the first or to the second foliation formed in the Cambro-Ordovician rocks.

Information supplied by microstructures in Upper Ordovician and Silurian metapelites shows that the crystallization of chlorite and muscovite is parallel to the main foliation planes. This paragenesis records the maximum intensity of metamorphism for these rocks. In the Cambro-Ordovician metapelites, the first foliation is preserved as folded relicts formed synchronously with the second foliation. It is defined by oriented biotite and muscovite in the upper levels and by oriented biotite and fibrolitic sillimanite at greater dephts (Photograph 1). The metamorphic climax is post-tectonic as is shown by the lack of preferred orientation of cor-



Photograph 2. Warped S2 foliation flattened by late folding phases around post-kinematic andalusite porphyroblasts. Andalusite is idioblastic and includes small ilmenite crystals parallel to the foliation. Note the asymmetry of the flattening, the pressure-shadows and the andalusite porphyroblasts, which are broken at the contacts with unprotected areas. Pressure-shadows are filled by plagioclase, quartz and biotite.

dierite porphyroblasts and by their inclusions of randomly oriented biotite and sillimanite from the matrix.

Two deformation phases post-dating the thermal peak have affected the main foliation. The map pattern in the massif is principally the result of fold interference of these two phases, the earlier of which had NE-SW trending folds, whereas the younger folds show NW-SE trends (Liesa & Carreras 1989). Flattenning of the main foliation and the mineral zones is associated with the late folding phases (Photograph 2). Related microstructures show a clear phase of retrogression, presumably due to deformation after cooling.

In the Upper Ordovician and Silurian rocks, only a chlorite-muscovite zone has been mapped, whilst at deeper levels, in the Cambro-Ordovician rocks, three metamorphic zones are recognized: a narrow andalusite zone, a sillimanite zone, and a wide cordierite – K-feldspar zone (Fig. 1). Partial fusion is observed in the cordierite – K-feldspar zone as millimetre-scale quartz-feldspatic layers parallel to the foliation. Two continuous reactions taking place in metapelitic rocks of the cordierite – K-feldspar zone allow the reconstruction of a short part of the metamorphic P-T path (Fig. 2):

– K-richer compositions in the outer rims of zoned K-feldspars in contact with muscovite indicate that the muscovite breakdown reaction: Muscovite + Quartz = Sillimanite + K-feldspar + H_2O (Evans 1965) progressed towards the high-temperature side.

– A continuous reaction involving sillimanite and biotite gave place to cordierite coexisting with K-feldspar: Biotite + Sillimanite + Quartz = Cordierite + K-feldspar + H_2O (Holdaway & Lee 1977).

The more ferroan compositions of the outer rims of cordierite coexisting with biotite indicate an evolution of the reaction towards the high-temperature side. Peak metamorphic conditions determined from Fe/Mg partitioning indicate values of about

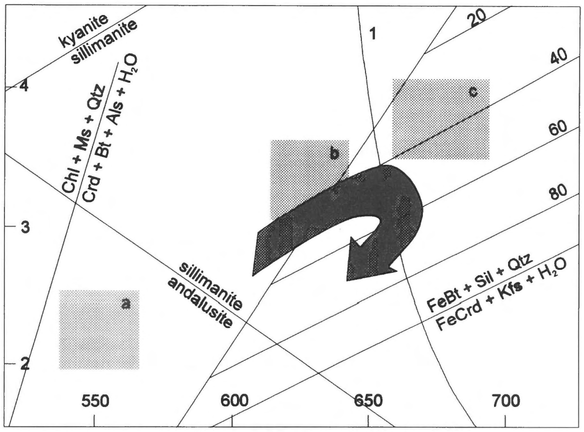


Fig. 2. P-T path reconstructed for regional metamorphism, and approximate temperature and pressure of contact metamorphism in the upper (a) and lower (b) part of the Sant Llorenç – La Jonquera intrusive sheet and around the Ceret stock (c). Reaction Bt + Sil + Qtz = Crd + Kfs + H_2O at $P_{H2O} = P_{Tot}$ from Holdaway & Lee (1977). Numbers (40, 60, 80) refer to mole fraction (Fe/Fe + Mg) of cordierite stable with the reaction products. Reactions above the minimum melting of granite are hypothetical. (1) Minimum melting of granite (X_{H2O} = 1) based on Kerrick (1972). Muscovite dehydration reaction after Chatterjee & Johannes (1974). Aluminosilicate reactions from Holdaway (1971). Reaction Chl + Ms + Qtz = Crd + Bt + Als + H_2O from Hirschberg & Winkler (1968).

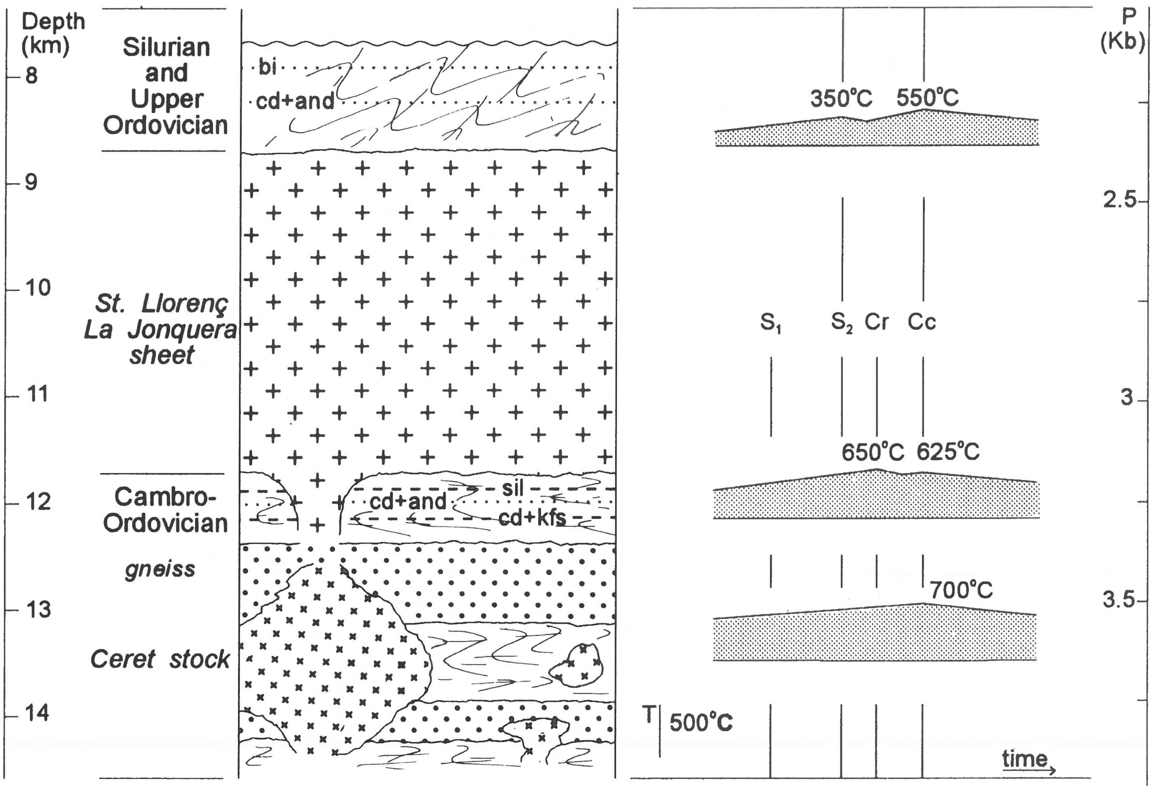


Fig. 3. Diagrammatic scale section through the Roc de Frausa Massif and timing of the tectono-metamorphic events and igneous intrusions. Legend as in Fig. 1. S: foliation; Cr: Climax of regional metamorphism; Cc: Climax of contact metamorphism.

650° C and 3–3.5 Kbar at $P_{H_2O} = P_{Tot}$ according to the Holdaway & Lee (1977) petrogenetic grid (Liesa & Carreras 1989).

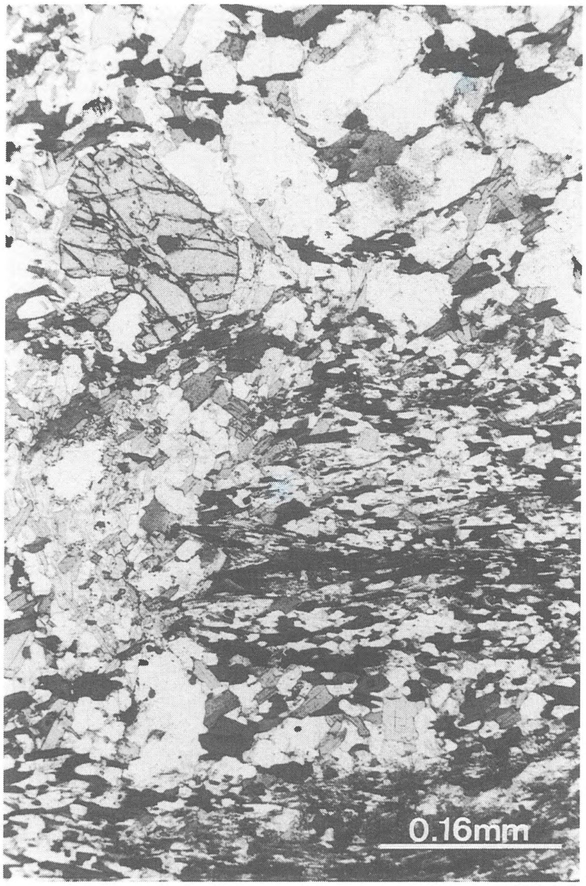
Hercynian intrusive rocks and contact metamorphism

Contact metamorphism is observed around the two main intrusive bodies, i.e. the Sant Llorenç – La Jonquera pluton and the Ceret stock.

The Sant Llorenç – La Jonquera pluton is made up of tonalites, granodiorites and granites and occurs in between the underlying Cambro-Ordovician metasediments and the overlying Upper Ordovician and Silurian rocks. It constitutes a stratoid intrusion with sharp boundaries, broadly parallel to the lithological contacts and to the regional foliation. The calculated thickness of the intrusive sheet is about 3 km and the exposure covers some 150 km^2 (Figs 1, 3).

The Ceret stock is formed by diorites and gabbros (Fe-gabbro-norites) emplaced at the deepest exposed levels. It is formed by a main mass and many small satellites, spread near its border. The small scale of the satellites, from metre down to centimetre scale, makes it difficult to define precisely the boundaries of the stock. Xenoliths of the country rocks are common inside the igneous body. The overall mass presents an approximately spherical body with a surface exposure of about 3 km^2. The contacts of the body with the country rock are clearly intrusive, diffuse, and show steep dips.

As no significant tectonic event occurred between the climax of regional metamorphism and the intrusion of the igneous bodies, the pressure conditions calculated for the regional metamorphism probably place a maximum to the depth of the intrusion of the two main igneous bodies. For this calculation an average crustal density of 2.75 gr/cm^3 has been assumed. It has also been considered that post-metamorphic deformational ef-



Photograph 3. Migmatization of pelitic layers by thermal effect of Ceret stock. Unorientated coarse-grained neosome formed by garnet, plagioclase, quartz and biotite in contact with orientated and finer-grained mesosome domains formed by biotite, sillimanite, quartz and plagioclase.

fects are not large enough to have modified the thickness of the column. However, considerable uncertainty about the depth remains. If the confining pressure at the base of the intrusive sheet of Sant Llorenç – La Jonquera was about 3 kbar, this body was emplaced at about 11 km depth; intrusion of the Ceret stock would then have taken place at 14 km depth.

Strontium and oxygen isotopes indicate a relatively homogeneous crustal origin for the Sant Llorenç – La Jonquera instrusive sheet (Cocherie 1985). The major suite is differentiated by fractional crystallization, giving rise to the small Fe-gabbronorite cumulates of the Ceret stock and to the tonalitic to granitic rocks of the Sant Llorenç – La Jonquera intrusive sheet. According to the isotopic relations, some diorites from the Ceret stock are not cogenetic with the granitoids, and possibly derive from the mantle (Cocherie 1985).

The contact aureoles of the Sant Llorenç – La Jonquera granitoid in the underlying and the overlying metasediments differ in width and metamorphic peak temperature. The aureole in the overlying Upper Paleozoic rocks is about 650 metres wide and is made up of a narrow inner zone showing incipient andalusite and cordierite and a wide outer zone with muscovite and biotite (Fig. 1). Contact-granoblastic textures are well developed because they overprint poorly recrystallized regional textures. The aureole in the underlying Cambro-Ordovician rocks cannot be defined accurately because contact metamorphism affects rocks showing the previous medium to high-grade regional event. In the outer part of the aureole, unoriented laths of muscovite partially changed the pre-existing regional parageneses of the andalusite and sillimanite zone. In the inner part of the aureole, complete recrystallization obliterated the old foliation and produced cordierite-andalusite hornfelses. Locally, the assemblage sillimanite + cordierite + K-feldspar occurs. Although this paragenesis certainly pertains to the regional metamorphism, the lack of any retrograde alteration demonstrates that it was also stable during contact metamorphism. This implies that the maximum temperature conditions attained during contact metamorphism underneath the Sant Llorenç – La Jonquera granitoid were similar to or only slightly lower than those achieved during regional metamorphism. Temperature values of about 625° C are obtained from compositions of coexisting cordierites and biotites (Liesa & Carreras 1989) in the equilibrium: Biotite + Sillimanite + Quartz = Cordierite + K-feldspar + H_2O (Holdaway & Lee 1977).

The thermal effect of the Ceret stock is recognized in the xenoliths and in the metasediments next to the igneous body, though no clear contact aureole is developed around the intrusive body. Microstructurally, these rocks are characterized by granoblastesis superimposed on a foliated texture, and by a widespread migmatization of the metapelitic layers. The leucosomes are generally coarser-grained than the mesosomes. They develop in thin layers parallel to the regional foliation or, at higher melt percentages, as irregular masses separating randomly orientated domains of mesosome (Photograph 3). The leucosomes are formed by garnet porphyroblasts, plagioclase, quartz and minor K-feldspar. The mesosome domains have preserved the mineralogy and the orientated mineral fabric formed synchronously with the main deformation event. In these rocks, only a contact-metamorphic climax is distinguished, and no previous post-tectonic regional metamorphic climax is recognized. This is interpreted as being essentially the result of contact metamorphism at deep levels, constituting the latest and highest temperature stage of the Hercynian metamorphic evolution. Garnet from the leucosome is subsequently corroded by biotite in equilibrium with sillimanite and K-feldspar, or by plagioclase. Thermometry for the compositions of coexisting garnet and retrograde biotite indicates equilibration at about 650–700± C (Liesa 1988).

Discussion and conclusions

Metamorphism, magmatism and deformation show different relative age relationships along the exposed section in the Roc de Frausa Massif (Fig. 3). Integration of these age relationships, together with the geological characteristics of each process, will allow a better understanding of the evolution of the Hercynian crust in this area.

Emplacement of the two igneous bodies has been considered as synchronous, in view of the Rb-Sr whole-rock dating (282 ± 5 Ma, Cocherie 1985) of different granitoid facies from the Sant Llorenç – La Jonquera sheet and cumulate rocks of the Ceret stock. The age of this sheet is very similar to the ages obtained for other granitoids in the Pyrenees, such as those of La Maladeta (277 ± 7 Ma, Michard-Vitrac et al. 1980, and the Querigut (282 ± 5 Ma, Fourcade 1981). A slightly younger age has been attributed to these high-level granitoids (Autran et al. 1970, Michard-Vitrac et al. 1980) than to possibly related deeper basic intrusives, though isotopic ages obtained so far for the Sant Llorenç – related basic intrusives have not confirmed this hypothesis. Isotopic dating of the Batera stock, exposed west of the Sant Llorenç granitoid in the neighbouring Canigó Massif, has yielded an isotopic age of 291 ± 16 Ma (Rb-Sr whole-rock, Gibson 1989). Further dating would clarify whether part of the basic intrusives were emplaced at a different stage.

The Sant Llorenç – La Jonquera granitoid was emplaced between the deeper high-grade metamorphic levels and the upper low-grade ones. As a geometrical consequence there is no evidence of any structural relationship between the schistosity in the metamorphic rocks and the cleavage at higher crustal levels. However, in the southern part of the Canigó Massif, the westward continuation of the Roc de Frausa Massif (Autran & Guitard 1969; Geyssant et al. 1978), the foliation has been described as being continuous throughout the entire Cambro-Ordovician sequence, from the low-grade to the high-grade rocks (Muñoz 1985; Ayora & Casas 1986). In the studied area, the foliation of the low-grade rocks has to be correlated with one of the two foliations observed at depth. Although the one or the other choice does basically not affect the relationships between the deformation and the metamorphism, observed to be post-tectonic at deep levels anyway, the main foliation has been considered to be synchronous throughout the exposed section as this interpretation seems to fit in better with the geological data elsewhere in the Eastern Pyrenees. If the second foliation in the deeper levels were formed after the main foliation at upper levels, as recently proposed by other authors working in the Hercynian of the Central Pyrenees (Verhoef et al. 1984; Gibson 1989, 1991, Van den Eeckhout & Zwart 1988), the age difference between the regional metamorphic climax at upper and lower levels would become greater.

At deep structural levels the climaxes of regional and contact metamorphism are almost indistinguishable. At shallow levels, both metamorphic histories are clearly distinguished and separated in time, whilst at deep levels they seem to constitute different stages of the Hercynian metamorphic evolution. On the other hand, the temperature attained by the contact metamorphism becomes higher with increasing depth of intrusion.

These two facts can be interpreted, according to other workers in the Pyrenees (Autran et al. 1970) and to thermal modelling of plutonic intrusions (Jaeger 1968), as indicating that the country rocks at deeper levels had higher ambient temperatures during the intrusion. This fact implies a spatial and temporal relationship between deeper intrusions and metamorphic development and has been designated as plutono-metamorphism by different authors working in the Pyrenees (Zwart 1962, Soula 1970, 1982, Fonteilles 1981) as well as in other areas, such as the northwestern Iberian Peninsula (Oen 1970).

According to the relationships between deformation and metamorphism, rocks from shallow crustal levels register earlier regional metamorphic histories, synchronous with the main deformation phase. Rocks from deeper levels provide longer metamorphic histories with a post-tectonic metamorphic climax and a high metamorphic gradient. The low-pressure – high-temperature metamorphic arrays observed in the middle and lower levels of the Roc de Frausa massif and their post-tectonic character, are a common feature in other areas of the Hercynian belt, both in the Pyrenees (Guitard 1970, Zwart 1979) and in neighbouring areas such as the Iberian Massif (Martínez et al. 1988, Martínez & Rolet 1988), the Armorican Massif (Martínez & Rolet 1988) and the Montagne Noire (Thompson & Bard 1981). These low-pressure – high-temperature series distinctly suggest high thermal gradients. In the upper crustal levels exposed in the area studied, diagnostic syn-tectonic parageneses, which allow to estimate ambient thermal gradients during metamorphism, have not been found. Nevertheless, in upper crustal rocks from the southern part of the Canigó Massif, a low-thermal gradient of 25° C/km has been calculated for the syn-tectonic episode of metamorphism (Ayora et al. 1993). In medium-grade metamorphic rocks from the Central Pyrenees (Pouget 1991, Alías & Liesa 1992) and from the Armorican and Iberian Massifs (Martínez & Rolet 1988), staurolite and garnet relicts in andalusite and cordierite indicate a low-thermal-gradient episode synchronous with the main deformation event, giving way to higher post-tectonic gradients. The diachronism of peak metamorphic conditions and its correlation with the structural level and metamorphic grade has been documented by isotopic dating of peak temperatures at different regional metamorphic zones in the Central Pyrenees (Majoor 1988). These datings indicate that the lower-grade zones attained their peak of metamorphism within a time span of 21 Ma before the higher-grade ones (313–292 Ma).

On the basis of the inferred high thermal gradients, Hercynian metamorphism of the Pyrenees has recently been interpreted as being due to a rifting stage (Wickham 1985, Wickham & Oxburgh 1987) or to an extensional event following a compressional stage (Van den Eeckhout & Zwart 1988, Gibson 1989, 1991, Vissers 1992). For the latter authors, the extensional event is linked to a subhorizontal schistosity synchronous with the peak of metamorphism. These two hypotheses contrast with the view of the Hercynian fold belt as a typical collisional belt, characterized by strong shortening with no evidence of late crustal-scale extensional collapse (Bard et al. 1980, Matte & Mattauer 1987, Julivert & Martínez 1987). It also contrasts with the opinion of scientists working on deeper levels of the crust (Vielzeuf 1984) who are of the opinion that the existence of high gradients in the middle crust does not necessarily imply that the crust was abnormally thinned, as the thermal gradient is not linear and diminishes at depth. In the studied area, the high metamorphic gradients observed in the middle and lower levels indicate an overheated crust at the end of Hercynian times. Nevertheless, the relation of the main schistosity with tight folds, the post-tectonic metamorphic peak, and the lack of widespread extensional faults in the upper crustal levels do not allow to attribute the high metamorphic gradients and the main schistosity to a stretching event. Though processes of extensional collapse have been invoked in other orogens, more information on the metamorphic, magmatic and structural features at different crustal levels in the Pyrenees must be integrated in order to find a satisfactory model.

In conclusion, the relationships among metamorphism, magmatism and deformation observed in the Roc de Frausa Massif, coupled with the information from the neighbouring Canigó Massif and other areas in the Hercynian belt, fit in with a crustal evolution characterized by two events: a first compressive event linked to intermediate-pressure metamorphism, followed by a thermal event characterized by high-temperature metamorphism and ubiquitous magmatism at different levels of the crust. The anomalous high temperatures could be the result of either a delamination process with the concomittant rise of hot asthenosphere and incorporation of mantle material into a thickened lower crust (Vielzeuf 1984, Platt & Vissers 1989, Vielzeuf et al. 1990), or a subcrustal collapse of a previously thickened lithosphere as proposed in other orogens (Platt & Vissers 1989).

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