THE STRUCTURE OF THE NE CAP DE CREUS PENINSULA. RELATIONSHIPS WITH METAMORPHISM AND MAGMATISM

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Estudi realitzat a la Unitat de Geotectònica, Departament de Geologia, de la Facultat de Ciències de la Universitat Autònoma de Barcelona, sota la direcció del Dr. Jordi Carreras Planells, per optar al grau de Doctora en Ciències Geològiques.

Signat: Elena Druguet Tantiñà

El director del treball: Jordi Carreras Planells

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Cover design: Jordi Carreras


Yo necesito un centro di gravità permanente
che non mi faccia mai cambiare idea sulle cose, sulle gente.
Over and over again.
(Franco Battiato)

AGRAÏMENTS

Vull manifestar el meu agraïment a totes aquelles persones i institucions que d'alguna manera han col.laborat en la realització d'aquest treball. Expressaré aquest agraïment segons els diferents aspectes en que s'han basat aquestes contribucions, amb la intenció de no oblidar-me de ningú. De totes maneres, voldria que aquells que per oblit no constin en aquesta llista em disculpin i rebin un doble agraïment.

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ABSTRACT

This work concentrates in the tectonics of the deepest-seated domains exposed in the northern Cap de Creus peninsula, and in the associated magmatism and metamorphism. The Cap de Creus peninsula forms the most easterly outcrop of Paleozoic basement along the Axial Zone of the Pyrenees, in which penetrative foliations, metamorphism and magmatism are Hercynian in age. Rocks outcropping in the study area correspond to a metasedimentary sequence with minor interlayered meta-igneous rocks.

The presence of a metamorphic gradient, where grade increases towards the north, reflects a prograde low pressure regional metamorphism, initiated during the early deformational events, and ranges from the chlorite - muscovite zone in the south to the sillimanite - K-feldspar zone in the north. Locally, in medium and high grade domains, small migmatite areas are present, together with a sequence of calc-alkaline granitoids, emplaced sequentially from the more basic magmas to the more acid ones. A swarm of pegmatite dykes extends over the anatectic and perianatectic domains up to the cordierite-andalusite zone. A retrograde metamorphism is heterogeneously distributed along late structures, especially along mylonitic bands, and appears superimposed on the prograde metamorphic pattern.

Polyphasic structures are interpreted as part of a progressive deformational history, with an evidenced continuity of events from prograde to retrograde metamorphic conditions. However, three main deformational events have been distinguished. The early event (D_1) developed a penetrative, originally shallow-dipping, schistosity (S_1). Afterwards, a sequence of regional deformation events caused steep structures. Each event was inhomogeneous in space and characterized by progressive non-coaxial deformation, leading to a complex structural pattern. The D_2 event produced NE-SW trending folds affecting the S_1 schistosity in prograde metamorphic conditions. Fold-related strain gradients across the area define a structural zonation, with domains of low and high strain and a broad shear zone-like geometry. High strain deformation took place preferentially in the north, and was associated to migmatization and granitoid emplacement. A transitional stage between D_2 and D_3 events (named $D_{2\text{-}3}$) is characterized by the development of sub-vertical E-W trending folds. This deformational stage took place around the time of peak metamorphism grading to high temperature retrogression in the north (where the pegmatite dyke swarm emplaced syntectonically), but under clear retrograde conditions in central and southern domains. Progressive deformation at retrograde conditions produced NW-SE-trending D_3 structures and gave rise to a second structural zonation, with a fold belt covering the southern part of the studied area, and a mylonite belt tracking the higher grade metamorphic zones.

The studied relationships between high temperature structures (D_2 and $D_{2\text{-}3}$) in the metasediments and the deformational features in the granitoids and pegmatites support the synchronicity of deformational processes and magmatism. In addition, strain and kinematic analysis of these structures reveals that, dispite the existence of complex relationships between geometry and kinematics, deformation took place in a broadly transpressive regime, involving subvertical extension and NNW-SSE subhorizontal bulk shortening with a dextral component.

RESUM

Aquest estudi es centra en la tectònica dels dominis més profunds que afloren a la península del Cap de Creus, així com en el magmatisme i metamorfisme associats. La península del Cap de Creus constitueix l'aflorament de sòcol paleozoic més oriental de la Zona Axial pirinenca, en la qual les deformacions penetratives, el metamorfisme i el magmatisme són d'edat herciniana. Les roques que afloren a l'àrea d'estudi corresponen a una sequència metasedimentària amb esporàdiques intercalacions de roques metaígnies.

La presència d'un gradient metamòrfic amb augment del grau cap al nord, reflexa un metamorfisme regional prògrad del tipus de baixa pressió, iniciat durant els primers estadis de deformació, i comprèn des de la zona de la clorita - moscovita al sud fins la zona de la sil.limanita - feldspat potàssic al nord. Localment, en dominis de grau mig i alt, hi ha unes reduïdes arees migmatítiques juntament amb uns granitoids calcoalcalins, emplaçats seqüencialment des dels magmes més bàsics fins als més àcids. Ocupant tot els dominis anatèctic i perianatèctic, fins la zona de la cordierita-andalusita, s'extén un eixam de dics pegmatítics. El metamorfisme retrògrad es distribueix de forma heterogènia al llarg de les estructures tardanes, especialment associat a bandes milonítiques, i es superposa sobre les zones anteriors de metamorfisme prògrad.

Les estructures tectòniques polifàsiques s'han interpretat com el resultat d'una història deformativa progressiva, amb una evident continuïtat d'episodis esdevinguts des de condicions metamòrfiques prògrades fins a retrògrades. Per tal d'exposar aquesta evolució tectònica, s`han diferenciat tres episodis principals. El primer episodi (D_1) donà lloc a una esquistositat penetrativa (S_1), que presumiblement tindria una disposició original sub-horitzontal. Posteriorment s'inicià una seqüència de deformacions caracteritzada pel desenvolupament d'estructures dretes. La deformació en cada fase fou heterogènia en l'espai, progressiva i de caràcter no-coaxial, donant lloc a una complexa configuració estructural. L'episodi D_2 va generar plecs d'orientació NE-SW que afectaren l'esquistositat S_1 en condicions de metamorfisme prògrad. La presència de gradients de deformació al llarg d'aquestes estructures de plegament defineix una zonació estructural, amb dominis d'alta i baixa deformació i amb una geometria anàloga a la de les zones de cisalla. Les zones de més deformació es situen a la part septentrional, associades a processos de migmatització i a l'emplaçament de granitoides. S'ha considerat un estadi de transició (D_{2-3}), entre els episodis D_2 i D_3, caracteritzat per la formació de plecs subverticals de direcció E-W. Al nord, aquest estadi de deformació es produí en condicions properes al clímax metamòrfic i sincrònic amb l'emplaçament de les pegmatites, mentre que a les zones central i meridional ho feu en condicions clàrament retrògrades. La progressió de la deformació en condicions retrògrades generà les estructures D_3, de direcció NW-SE, que en el sud conformen una banda de plecs i en el nord una faixa milonítica sobre les roques més cristal.lines. Aquest fet dona lloc a una segona zonació estructural.

L'anàlisi de les relacions entre les estructures d'alta temperatura (D_2 i D_{2-3}) presents als metasediments i els trets deformacionals als granitoides i pegmatites recolça el sincronisme entre els processos deformatius i el magmatisme. Per altre banda, l'anàlisi de la deformació i de la cinemàtica d'aquestes estructures mostra que, a pesar d'existir unes complexes relacions entre geometria i cinemàtica, la deformació es produí en un règim tectònic transpressiu, en el que hi hauria implicats una extensió subvertical i un escurçament general NNW-SSE amb un component direccional dextre.

ABBREVIATIONS AND SYMBOLS

CPL	crossed polarised light
D_1, D_2, D_{2-3}, D_3	sequential deformation events
ΔA	area change
F_1, F_2, F_{2-3}, F_3	folds related to D_1, D_2 and D_3
L_1, L_2, L_{2-3}, L_3	fold axes and lineations related to D_1, D_2 and D_3
L_m	mylonitic stretching lineation (sometimes included in L_3)
Infls	lines of no finite longitudinal strain
LP-HT	low pressure-high temperature
PPL	plane polarised light
P-T	pressure temperature
P-T-t	pressure temperature time
R	axial ratio of sectional ellipses of finite strain
S	stretch of a line
S_1, S_2	principal finite stretches
S_1, S_2, S_{2-3}, S_3	foliations related to D_1, D_2 and D_3
S_{cr}	crenulation cleavage
S_e	external foliation with respect to a porphyroblast with inclusions
S_i	internal foliation in a porphyroblast with inclusions
S_m	mylonitic foliation
S_s	bedding surface
$S_{s/1}$	bedding-parallel S_1 foliation
TRR	tourmaline-rich rim
W_k	kinematic vorticity number
ω	rotation of the principal stretches (S_1, S_2), rigid rotation component
X, Y, Z axes	principal axes of strain

Minerals

Ab	albite
Al	almandine
An	anortite
And	andalusite
Ann	annite
Bt	biotite
Cd or Crd	cordierite
Chl	chlorite
East	eastonite
Gr	grossular
Gt	garnet
Hbl	hornblende
Kfs or K-feldspar	potassium feldspar
Ky	kyanite
L	liquid phase
Ms	muscovite
Or	Ortose
Phl	phlogopite
Pl	plagioclase
Px	piroxene
Py	pyrope
Qtz	quartz
Sid	siderophyllite
Sil	sillimanite
Sp	spessartine
St	staurolite
Tourm	tourmaline

CONTENTS

1 INTRODUCTION

The space and time recurrent association of deformation, magmatism and metamorphism in mid to deep crustal levels in orogenic belts is well known since long time ago. However, only recent works have evidenced and interpreted such links on the basis of detailed analysis of structures, which record an often complex evolution. In such settings, an approach based exclusively on the distinction of different tectonic phases and interkinematic periods is often inadequate, because progressive deformation episodes are involved and, moreover, because magmatic episodes appear to be strongly controlled by the overall deformation rather than being independent events with solely a spatial coincidence.

Close looks at internal structures of igneous rocks as well as the structural relationships between igneous bodies and country rock have become an important tool for the understanding of the evolution of this sort of geological settings. Also recently, approaches involving detailed structural analysis on all scales combined with kinematical analysis have become habitual. Such kind of approach is a requirement when characterizing the geotectonic settings governing the structural transformations in high grade terrains. However, in some settings, simplistic links established between a determined shear kinematic indicator and an assumed crustal scale tectonic regime have often lead to questionable results, evidenced by presentation of controversial models. In this context, the Hercynian basement of the Pyrenees conforms a piece of crust with a huge accumulation of geological data and also literature, but where diverse interpretations have arisen, some of them highly contradictory. Most of these contradictions arise from different interpretations of the structural evolution, mainly in areas where deep-seated crustal levels are exposed.

The Cap de Creus peninsula is one of these areas where deep seated crustal levels are well exposed. In consequence, a detailed knowledge of its tectonic evolution will not only help to highlight the evolution of the Hercynian basement of the Pyrenees but also will provide some new ideas on the mid-lower crust tectonics and related phenomena in an orogenic belt.

The Cap de Creus peninsula forms the most easterly outcrop of Hercynian basement of the Axial Zone of the Pyrenees (Fig. 1).

The Axial Zone consist on an elongated area along the Pyrenean chain. In this Axial Zone, together with the North Pyrenean massifs, rocks from the Hercynian basement outcrop due to both Hercynian and Alpine exhumation. In outline, while along the central and western part of the Pyrenean Axial Zone, the Hercynian basement consists of predominantly upper crustal rocks, towards the eastern Axial Zone deep seated rocks become more abundant. Hercynian basement rocks can be classified in three groups:

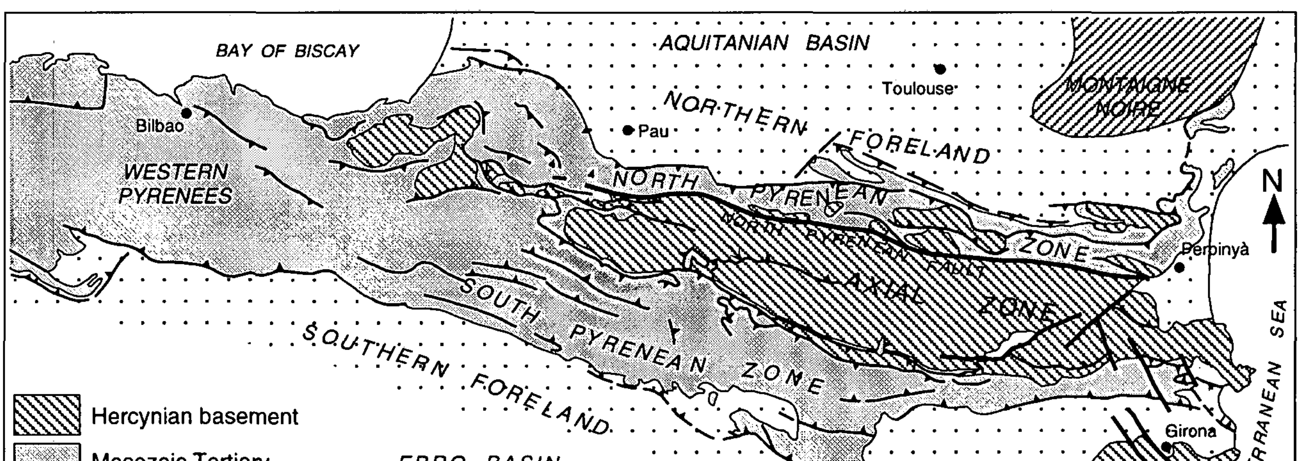
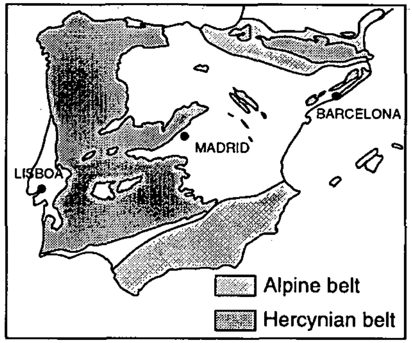


Fig. 1. Main structural units of the Pyrenean belt (After Teixell 1990).



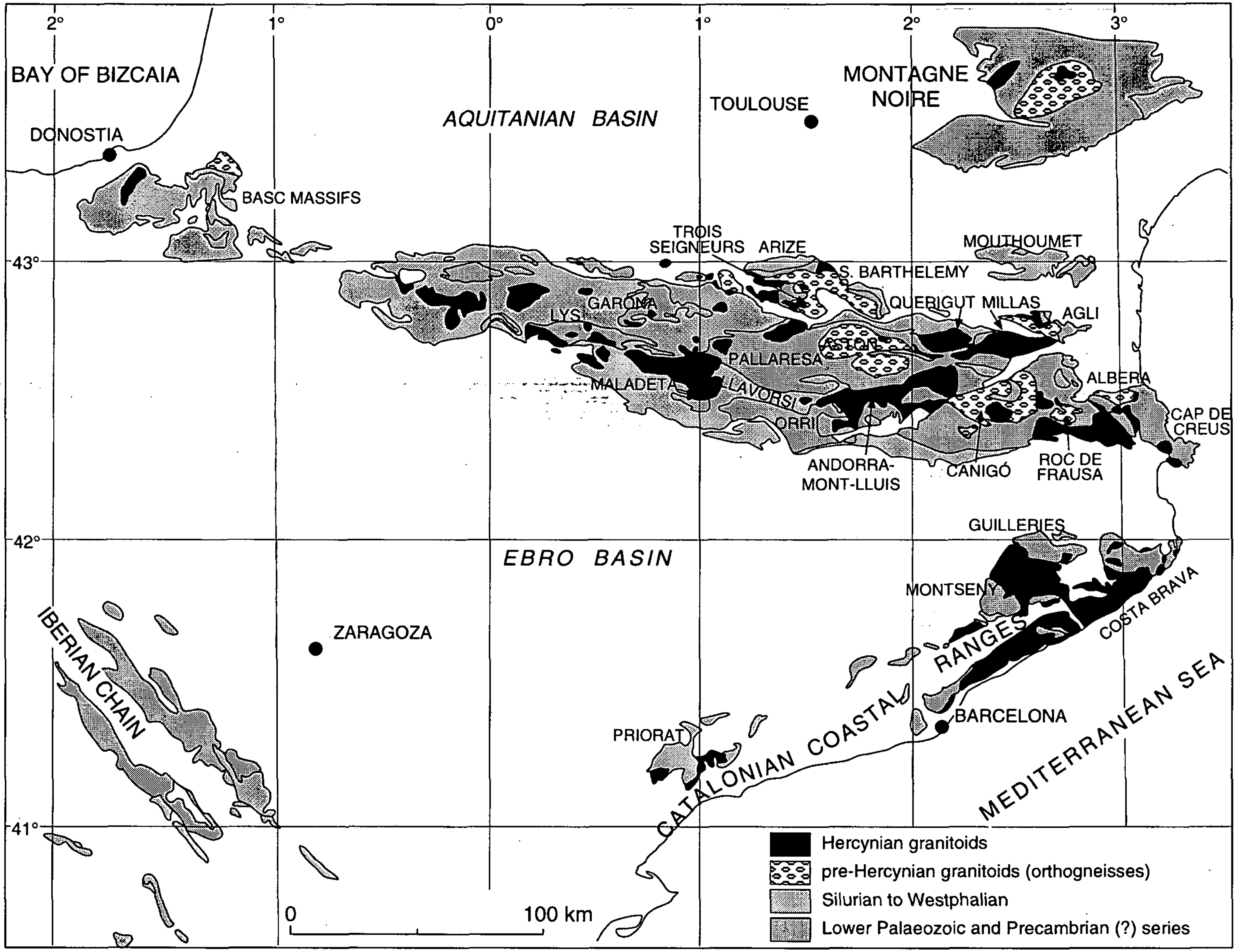


Fig. 2: Sketch map of the Hercynian outcrops in NE Spain (Carreras & Capellà 1994).

(i) Sedimentary rocks and metasedimentary equivalents (ii) gneiss series, mainly orthotypes, derived from pre-Hercynian granitoids and (iii) Hercynian granitoids. Penetrative alpine structures in this zone are generally poorly developed and the main internal deformation features can be attributed to the Hercynian events (Fig.2).

In this setting, the rocks in the Cap de Creus peninsula represent medium to deep-seated structural levels in the Mattauer (1973) sense, and are affected by low to high-grade Hercynian metamorphism. This thesis is concentrated in the study of the deepest domains exposed in the northern Cap de Creus (Fig. 3), from low grade (chlorite muscovite) metasediments to high grade metamorphic rocks and associated igneous rocks. This area is particularly suitable to the understanding of complex deformation processes, as well as the metamorphism and plutonism occurring in the middle crust during the Hercynian orogeny. This interest is due to several reasons: the presence of a good profile across the middle crust, available in only 5 kilometres horizontal distance, and the exceptional outcrop conditions for structural and petrological studies. Another reason that avail the singularity of this area is the a priori absence of significant alpine structural reworking, although this statement will be briefly discussed later by comparison with similar areas in the Pyrenees where alpine reworking has been assumed.

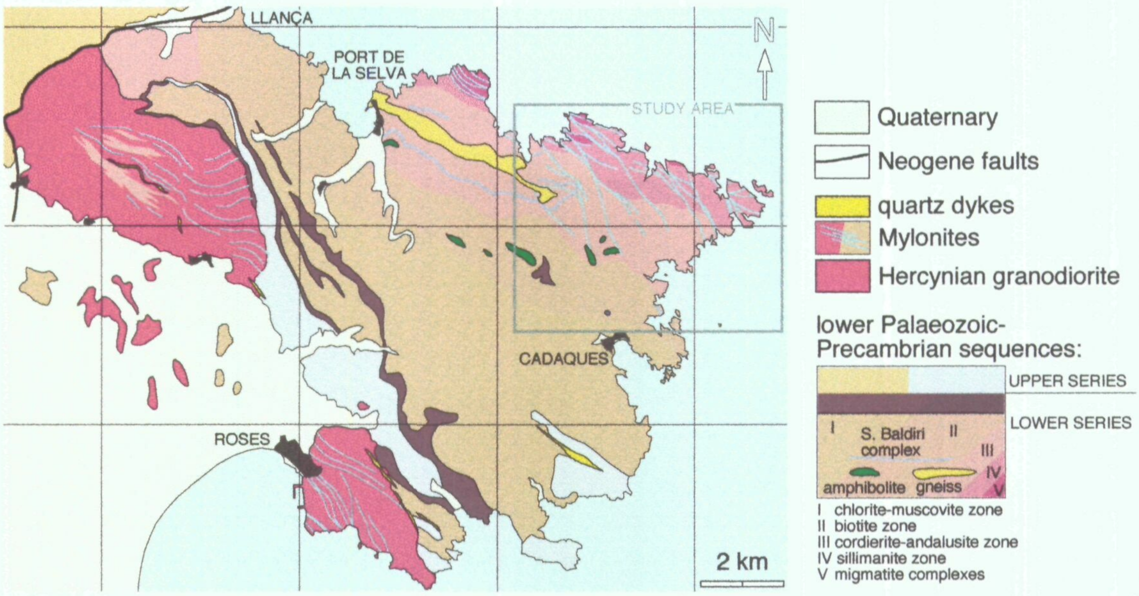


Fig. 3. Geological map of the Cap de Creus peninsula (modified from Carreras and Losantos, unpublished).

1.1. PREVIOUS WORK AND STATE OF THE ART

Objectives of this work were defined taking into account the state of the art in three different related fields: 1. The recent developments and achievements in structural geology of deep seated levels specially concerning two aspects: strain regime analysis and syn-magmatic tectonics. 2. The Pyrenean basement controversy arisen when extensional tectonics was introduced as a main event in the Hercynian evolution and 3. The slanted knowledge of the Cap de Creus geology, where although considerable literature existed, this was concentrated mainly on two aspects shear zones and petrology of magmatic rocks, while the early tectonic evolution remained poorly understood.

1.1.1. RECENT ADVANCES ON DEEP-SEATED TECTONICS

In last two decades there has been a growing interest in different aspects and scales of deep-seated deformation processes involving a prevalent ductile flow concentrated along deformation bands, specially shear zones. This was evidenced, for instance, in the conference Shear zones in rocks that took place in Barcelona in 1979, which included a field trip precisely in Cap de Creus. In the past recent years, this growing interest has been going on, embodying many more structural and tectonic aspects as well as embracing multiple new methodologies and techniques, which lead to more accurate reconstructions of structural processes. In this perspective, where one of the main objectives is to obtain tectonic models, some see large advantages, whereas others see many dangers in this urge to "modelling".

The characterization of deformation is a main objective in studies focused in deep seated structural levels, in order to reconstruct the tectonic regimes operating in the crust and to interpret associated processes like metamorphism and magma emplacement. Since the landmark publication by Ramsay (1967), much quantitative structural data have been collected and the combined use of both observational strain and kinematic analysis and numerical approaches (Talbot 1970, De Paor 1986, Passchier & Trouw 1996), have contributed to significant improvement. It is now commonly accepted that deformation in deep zones can depart from plane strain flow and consequently the correlation between structural and kinematic elements can be far more complex than assumed some years ago (e.g. no unique relationship exists between fold or boudin axes and principal stretching directions). Consequently, field and laboratory data, which drive to strain and kinematic determinations, need to be carefully evaluated in order to achieve a specific deformational regime. The transpressional-transtensional models, introduced by Harland (1971) and kinematically modelled by Sanderson & Marchini (1984) and Robin & Cruden (1994), have many applications to these geotectonic backgrounds, although the practical value of these approaches will require to deepen in the knowledge of how structures form in deformation settings other than pure and simple shear.

In addition, in the study of processes in orogenic belts, multidisciplinary approaches are required, and have been used by many workers and many times data is presented in terms of three binary relationships: deformation-plutonism, plutonism-metamorphism and metamorphism-deformation (Karlstrom & Williams 1995).

The metamorphic-deformational approach involves characterization of pressure-temperature-time history (P-T-t) in relation to deformational regimes and thus leads to reconstruction of the tectonometamorphic evolution. Established relations between successive metamorphic zones and deformation phases have been worked out with the aid of microstructures (Zwart 1963, 1979; Spry 1969). Interpretation of microfabrics suggests that peak metamorphism coincides with deformation in many orogenic belts (Bell et al. 1986).

Relationships between deformation and magmatism are typically investigated by comparing deformation fabrics and structures in igneous intrusions (from plutons to small veins) and in adjacent country rocks. A particular established analytic method is the measurement of the anisotropy of magnetic susceptibility (AMS) in igneous intrusions, which allows determination of weak magmatic fabrics (Borradaile 1988). In some cases, variations in shape and intensity of the susceptibility ellipsoid gives information on the kinematics of magma emplacement (Bouchez et al. 1990, Cruden and Launeau 1994). As deduced from many studies, granites may be fundamentally "syntectonic". Moreover, synkinematic intrusions are commonly associated to high-strain zones formed at deep crustal levels (Bossière 1980, Reavy 1989, Ingram & Hutton 1994, McCaffrey 1994, Carreras & Druguet 1994a, Karlstrom & Williams 1995), thus arising the question of what the precise relationship is between the magmatic processes and the deformational processes. It is now accepted by many authors that major faults and shear zones may control the localization of granitoid bodies (see Hutton 1988, 1997 for reviews), and that there is no a priori reason to believe in regional extension as the unique tectonic regime which permits granite emplacement (Paterson & Fowler 1993). This has been documented for dilational sites occurring in transcurrent (Castro 1986, Hutton & Reavy 1992) and extensional systems (Tobisch et al. 1986), as well as for contractional zones (Blumenfeld & Bouchez 1988, Ingram & Hutton 1994, Davidson et al. 1996). The idea of a siting control has led to models which link the genesis of granitoids to the large scale deformational thickening which occurs, for example, in transpressional zones (D'Lemos et al. 1992).

1.1.2. PRESENT KNOWLEDGE OF THE GEOLOGY OF THE HERCYNIAN BASEMENT OF THE PYRENEES

As stated above, the geology of the Hercynian basement of Pyrenees has been frequently used to conceive models for the architecture and geotectonic regime in orogenic belts. While earlier models concentrated on the spatial variations of style across different structural levels (Sitter & Zwart 1960, Zwart 1963) and the related metamorphic evolution, more recent interpretations emphasize the temporal changes of tectonic regime, with reference to the role of either extension (Eeckhout & Zwart 1988, Vissers 1992, Soula et al. 1986) or transpression in this orogenic setting (Carreras & Capellà 1994, Gleizes et al. 1997).

It is not the aim of this introduction to give a detail account of the main features of the Hercynian geology of the Pyrenees, neither to discuss in detail the present day problems. A deep treatment of these aspects is included in the Pyrenean synthesis treatise (BRGM-ITGE 1997). Only a short mention of some crucial questions to the Hercynian geology of the Pyrenees will be given, based on a succinct review of the main problems about the Hercynian basement geology of the Pyrenees presented by Carreras (1988). The problems mentioned in this summary (op. cit.) refer to following aspects. First, the significance of the orthogneiss sheets is not yet well established. These rocks have been interpreted either as reworked Cadomian basement (Guitard 1970, Lagarde 1978, Eeckhout 1986; Soliva et al. 1989), as intrusive granitic sheets (Zwart 1965, Liesa & Carreras 1989), or as diapiric mantled gneiss domes (Soula 1982). In close connection to this first point, the age of the lowermost series remains unknown. It should be younger to the age of the orthogneiss protolith if the boundary between both types was an unconformity. On the contrary, it should be older if the gneiss protolith was an intruded granite sheet. Second, specific structural interpretation discrepancies concern the correlation of penetrative structures across different structural levels. Although the existence of two differentiated structural domains was recognized long time ago in the central Pyrenees (Sitter & Zwart op. cit.), no consensus exists on the correlation of structures in different domains. However, the main controversy concerns the identification of geotectonic setting controlling the evolution of this crustal domain. A variety of models have been put forward which involve significant discrepancies (see Carreras & Capellà 1994 for review).

Finally, the age and significance of the mylonite belt is still under debate, being this problem directly linked to the alpine tectonics, because some interpretations consider these structures to be active during Mesozoic and/or Tertiary reactivation of the Hercynian basement (Lamouroux et al. 1980, Mc Caig & Miller 1986, Saint Blanquat 1993, Monié et. al. 1994). Other interpretations consider these structures Hercynian in age without alpine reactivation (Carreras et al. 1980, Guitard et al. 1980, Saillant 1982, Carreras & Cirés 1986). Mylonites affecting the Sant Llorenç-La Jonquera Hercynian granodiorite in the eastern Pyrenees have been dated at 50 Ma (Soliva et al. 1991). New geochronological data on the Saint Barthelemy massif indicate that main mylonitization events are Hercynian in age (Delaperrière et al. 1994).

Nearly ten years after the above mentioned review most of these major problems still remain unsolved. However, some advances have been made in specific subjects. Among these, significant to the author of this author is the recognition of the syntectonic character of most magmatic rocks and that their emplacement took place in a broadly transpressional regime (Gleizes et al. 1991; Evans et al. 1997; Gleizes et al. 1997). In close connection arguments have been put forward (Gleizes et al. 1991) indicating the existing continuity between early magmatic fabrics in rocks and later solid state mylonitic fabrics.

1.1.3. PREVIOUS WORK AND STATE OF THE ART ON THE CAP DE CREUS GEOLOGY

The dawn of the Cap de Creus geology can be placed in the early seventies. Previous works were rather scarce and lacked a global approach to the main geological features of the region. Some references on minerals and rocks from the Cap de Creus area appear in general treatises and compilations (Calderón 1910, San Miguel de la Cámara 1936). The most remarkable among these early works are Denaeyer (1947) and Denaeyer & San Miguel (1954) on the petrology of some rocks in the area; and Cañada (1964), a preliminary work on the geology of the area corresponding to the Roses 1:50000 sheet. A first petrological study on the pegmatites and enclosing metasediments in the Llançà area was published by Montoto (1968). Structural and petrological studies in the Cap de Creus area began systematically in the early seventies with Carreras (1973). This early work consists mainly of a lithological, structural and metamorphic preliminary description of the whole peninsula. The deformation history was presented as the result of three main deformation events, namely a syn-schistose, an intermediate and a late one including late folds and shear zones. During the seventies, specific works on the area were devoted mainly to the shear zones and mylonites. Among the works of this period, a detailed kinematic analysis of the northern belt shear zones was published in Carreras & Santanach (1973). The first detailed microstructural and microfabric study on mylonites appeared in Carreras (1974). In Carreras (1975), a first interpretation of the significance of Cap de Creus shear zones was given. Most significant of the interpretation presented in this work was the consideration that the shear zones were genetically related to the so-called Hercynian late deformation phases.

During this period, besides above mentioned works on mylonites, some progress was also done on the knowledge of the structure and its relation with metamorphism and magmatism. Orta (1973), Morales (1975), and Carreras et al. (1975) refer all of them to the geology of pegmatite-rich areas.

In the late seventies more detailed works were performed on shear zones and mylonites. The most remarkable of these is Carreras et al. (1977), where the kinematic significance of asymmetric fabrics was presented.

Most significant advance during the eighties decade was the revision of the map of the whole Cap de Creus peninsula performed by Carreras and Losantos, and later published in I.T.G.E. (1994a, b). The use of a detailed topographic base enabled an accurate lithological and structural mapping. A significant contribution of this survey was the recognition of different stratigraphic units in the metasedimentary series. Although the paper which included this lithological description remains unpublished, the terminology has been used herein after. Also, during the first half of this 80's decade, detailed mapping was performed in selected areas. These detailed maps insisted in presenting evidences of the relationships between late folding structures and shear zones. Although part of these maps remain unpublished, some of them were later included in geological guidebooks (Carreras 1989) or improved and used for latter publications. Another work focused on the Port de la Selva gneisses was developed by Ramírez (1983). In addition to the study of these orthogneisses, a new sequence of deformation events was presented, consisting of seven phases. Results concerning metamorphism and significance of the Port de la Selva gneisses are respectively published in Ramírez (1983b) and Carreras & Ramírez (1984). Several works on the Roses Granodiorite and associated shear zones also correspond to this early eighties period (Carreras & Losantos 1982, Simpson et al. 1982).

Specific studies on shear zones and microstructures and microfabrics of related mylonites proceeded during the eighties. Concerning shear zones, Carreras et al. (1980) insisted on the relationship between shear zones and late folding, extending the model to other massifs of the Eastern-Pyrenees. The publications by Carreras & García (1982) and García (1983) focused on quartz c-axis fabric studies in shear zones, and Norton (1982) presented a comprehensive and detailed analysis of shear zones and mylonites of the northern belt.

The most significant work of the late eighties is Carreras & Casas (1987), where the connections between shear zones an late folds is presented once more, but this time supported by abundant structural data and detail maps. Other works published during this period were mainly compilations of pre-existing data and occasionally new material, like that of Carreras (1989). Also in the late eighties, new data on the metamorphic petrology where obtained by Reche, although these results will be included in the BRGM-ITGE (1997) Pyrenees synthesis.

In the early nineties, the majority of works focused in petrologic aspects of different rock types. First results on geochemistry of pre-Hercynian magmatic rocks appeared in Navidad & Carreras (1992, 1995). A detailed study on the mineralogy of Cap de Creus pegmatites was developed by Corbella (1990) and Alfonso et al. (1995). These works consider, in opposition to other interpretations (e.g. Carreras et al. 1975), that pegmatite are late differentiates of a hidden deeper batholith. Nearly simultaneously, Damm et al. (1992) published stable isotope geochemical data of the pegmatites, including a fanciful geological map of the lighthouse area and a title with a misleading geographic location of the area. This work presents a succinct interpretation where the pegmatites are associated to anatectic melts.

Later studies on the petrogenesis of the pegmatites have been developed by Alfonso (1995). Pau (1995) presented REE analysis of the igneous and metamorphic rocks from Cap de Creus. A general petrogenetic approach where regional metamorphism is related to magmatism is given by Enrique (1995).

Some preliminary results of a collaborative work on the metamorphic petrology and PT conditions of mylonites are summarized in Bossière et al (1995). Results of a similar approach to the same topic are summarized in Ohtomo (1995).

In close connection with this thesis, some results have been recently published. These refer mainly to the Cap de Creus migmatites and to the structure of the northernmost Cap de Creus peninsula. Druguet (1992) and Druguet et al. (1995) refer to the migmatite complex mainly from a petrological point of view. Directly linked to this thesis are the recent results on the structural evolution of pegmatite and migmatite bearing zones: Carreras & Druguet (1994 a, b), Druguet et al. (1997) and Druguet & Hutton (1995 and submitted). As part of the present thesis, these works will be presented here in detail. Finally, in connection to this subject, Victor (1996) has also presented an analysis of structures related to pegmatite dykes in the lighthouse area.

As shown above, before the onset of the present work, there was abundant literature on the Cap de Creus geology, and thus a good geological background of the area was available. Regarding the structure, the main structural trends of the area had been established, and the polyphase deformation history was known. However, many fundamental structural problems remained unsolved, specially because most of the earlier efforts were concentrated either to shear zones and late structures or to the petrology of different rock types. In particular, little was known about the deformation events prior to shear zones development and about the relations between tectonic events and magmatism.

1.2. OBJECTIVES AND PROCEDURES

The primary and main purpose of this study is to deepen in the space and time characterization of different deformation episodes, in the relationship between deformational history, metamorphism and intrusions and, whenever possible, in the identification of tectonic regimes involved in the Hercynian evolution of this crustal domain. This involves inferences on the tectonic significance of these deformations in the Hercynian setting, and on orogenic processes occurring in the medium and deep crust. The coexistence of deformational processes along with regional metamorphism and plutonism, makes necessary a study approach embracing the relations and interactions between all three processes.

Taking into account the bold character of the project objectives and the complexity of the Cap de Creus geology, a working plan with some priority objectives and a selection of most adequate procedures was established beforehand. It was considered that the most adequate procedure should be essentially based on a very detailed mapping, in order to be able to correlate structures through different scales and across different structural domains. The application of this time-consuming procedure required to restrict the study to a selected area rather than pretending to cover the whole Cap de Creus peninsula. On the basis of the existing data, it was quite evident that this study should concentrate on the north-eastern part of the peninsula, where a complete section from low to high grade rocks is available (Fig. 3). The area for this study deliberately excludes vast areas with low and very low grade metasediments belonging to part of the lower series and to the whole set of the upper series. The granodiorite massifs of Roses and Rodes have also been excluded from the detailed structural analysis, as these are emplaced in shallower levels made up of low grade metasediments.

Additionally, different generations of structures in this north-eastern part are better depicted than in the north-western part, were they are closely parallel to each other. From the metamorphic point of view, the selected area comprises different metamorphic domains, from the onset of the biotite zone up to the migmatite zones.

Although for the purpose of the study it may be convenient to approach the problem simultaneously from a structural and petrological point of view, time constraints suggest that the most convenient procedure is to concentrate on a very detailed structural analysis, and include a restricted amount of additional petrological evidence.

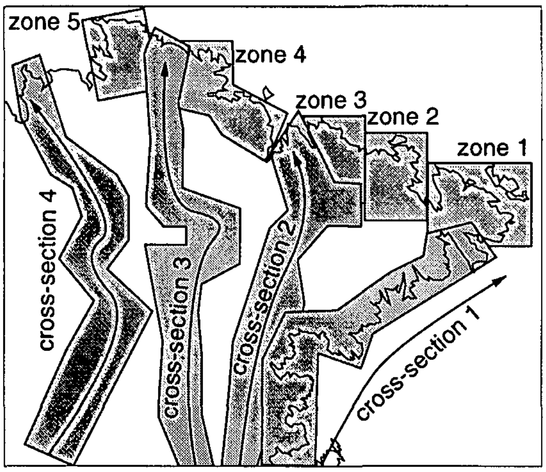


Fig. 4. Location of cross-sections and zones across the study area. Location of this sketch within the peninsula is shown in Fig. 3.

With this scheme in mind, a preliminary area demarcation was made. The procedure for the understanding and interpretation of the structure is based on the use of a continuous set of scales, in an attempt of avoid scale gaps resulting in the classic method where usually one skips from outcrop and microscope-scale observations to conventional 1:5000 or 1:25000 maps. Within the study area, four continuous S-N transects were selected (Fig. 4). Along each of these, a continuous mapping at scale 1:1000 was performed. In addition, some zones of special relevance were analyzed at scales ranging between 1:250 and 1:1000. Sampling of metamorphic and intrusive rocks has been carried out along all cross-sections and zones. In consequence, great part of this study was taken up by fieldwork and most of the employed techniques are standard procedures in structural geology: detailed mapping, geometric and stereographic analysis of structural elements and microscopical observations.

All mapping was performed, where available (i.e. in most of the studied area), on aerial photograph enlargements from originals ranging in scales 1:6000 to 1:3000. In areas not covered by detailed aerial photographs, enlarged 1:5000 topographic maps or orthophotomaps have been used.

In addition, survey was performed to cover the gaps between the mapped sections and zones. These gaps were covered mainly by stereoscopic observations of enlarged aerial photographs. In some instances compiling of structural data obtained by Carreras and co-workers prior to this work was incorporated. At the interpretation stage, all information was translated into 1:1000 orthoscopic maps which were subsequently digitized using a computer aided design (CAD) program. Synthesis structural maps (at scales 1:5000, 1:10000, 1:20000) have been ultimately drawn.

In addition to the above explained procedures, specific structural and petrologic analysis techniques were occasionally applied, exclusively when the expected results could be relevant for the purpose of the work. A systematic use of these analytic procedures has been deliberately avoided, in order to optimize the balance between time and results.

2 GEOLOGICAL SETTING

Rocks outcropping in the Cap de Creus peninsula belong to four main lithological categories: 1) the sedimentary sequence, 2) pre-Hercynian magmatic rocks emplaced in (1), 3) Hercynian deep seated intrusives emplaced in medium and high grade metasediments and 4) Hercynian granitoids emplaced in shallow low or very low grade metasediments. In the Cap de Creus peninsula, rocks corresponding to the deepest structural levels outcrop along the northern part of the peninsula and belong to categories 1, 2 and 3. (Fig. 3).

The sedimentary sequence and the pre-Hercynian magmatic rocks constitute two originally different sets of rocks, both affected by Hercynian deformations and metamorphism, giving rise to the metasedimentary series and the interlayered metaigneous rocks. These rocks form a schist belt with higher grade terms located along domains close to the northern seashore of the peninsula.

2.1. THE METASEDIMENTARY SEQUENCE AND OTHER LITHOLOGIES

The metasedimentary sequence

The metasedimentary sequence in the study area consists of a thick and rather monotonous succession of alternating metapsammites and metapelites rocks. The lower and thickest part of the succession is a monotonous alternance of predominant metagreywackes, minor metapelites and scarce lithological differentiable intercalations, which is named the Cadaqués Series (Carreras and Losantos, unpublished), also referred to as the Cadaqués-Cap de Creus Series (Carreras & Ramírez 1984). Towards upper stratigraphic levels, the metasediments become gradually darker and more pelitic, until they form a well distinguishable unit of black schists with minor marble lenses, which are known as the Montjoi Series, after a locality in the SE of the Cap de Creus peninsula. This Series is represented in the study area by pelitic black schists outcropping in Muntanya Negra (Fig. 5). The ensemble including Cadaqués and Montjoi Series forms the Lower Series in the Cap de Creus area.

In the Cap de Creus peninsula, these Lower Series are unconformably covered by a siliciclastic-carbonate series, known as the Upper or Norfeu Series, outcropping essentially in the south-eastern corner of the Peninsula and along a NW-SE trending band bounding the Roses and Rodes granodiorite massifs.

In the study area, the Cadaqués Series (Fig. 6a) consist of an alternance of metagreywackes (usually a few tens centimetres thick) and thinner metapelites. However, in some areas (e.g. eastern coast of Cala Culip, western coast of Cala Portaló, Puig de Cala Sardina) massive greywacke beds up to 10 meters thick with minor pelitic interlayers form the dominant lithology.

The colour of these rocks varies between ochre-grey (the most psammitic layers) and eaden grey (the most pelitic), although colour may change in function of the metamorphic grade. Occasionally, an original or mimetic graded bedding is recognizable (Fig. 6b). The discontinuous character of bedding and the monotony of the series hinder the use of greywacke beds as mapping tracers.

Most abundant interbedded layers in this metasedimentary sequence are plagioclase-amphibole rocks (Fig. 6c). These form discontinuous millimetric to decimetric layers, and are spatially related to greywacke-rich parts of the sequence. They are especially abundant and thick (up to 80 cm) in the Culip-Lighthouse area. They usually display lensoid and sub-concordant geometries with the enclosing metasediments, and sometimes graded layering with greywackes. Discontinuity of these lenses is in part the result of tectonic boudinage, but in a few places, lenses that apparently crosscut bedding have also been observed. These rocks bear strong analogies with intercalations in the Villalba series (Capdevila 1969, Bard et al. 1972) or with some amphibolites associated to the "Ollo de Sapo" gneisses (Navidad 1978), in the Central Iberian Zone.

Apart of these thin plagioclase-amphibole layers, two main intercalated units have been recognized in the Lower Series, namely a quartzite unit and a lithologically complex unit made of variable rock types, with black schists and calc-silicate rocks as the most representative (Fig. 5).

The quartzites form distinct layers whose thickness range between a few centimetres and a few meters. They are well banded and may appear either predominantly dark (named Rabassers quartzite) or predominantly light coloured (named Culip quartzite). Types with similar proportion of dark and light-coloured internal bands are also common. The best outcrops of the Rabassers quartzite are located close to Mas Rabassers de Dalt, where it is made of metric-scale beds of black and white striped fine grained quartzites. (Fig. 6d). The darker streaks are due to abundant carbonaceous material. The Culip quartzites (Fig. 6e), also called white quartzites in this work, are lighter and coarser grained than the Rabassers type.

The other mentioned lithological intercalation, appearing sporadically within the sequence, is heterogeneous in both thickness and composition. It has been called Sant Baldiri complex (Ramírez 1983a) and it is mainly made of black schists (carbon-rich metasediments), calc-silicate rocks, marbles, white quartzites, leucogneisses, and amphibolites (Fig. 6f). In the area this complex is best developed in La Birba zone, surrounding the Port de la Selva gneiss, described below. Rusty schists are usually present adjacent to the rocks of the Sant Baldiri complex.

The Rabassers and Culip quartzites, together with the Sant Baldiri complex, are the only traceable marker beds in the area. However, as it will be explained below, there is evidence against the Sant Baldiri complex being a primary intercalation in the sedimentary series.

The pre-Hercynian igneous intercalations

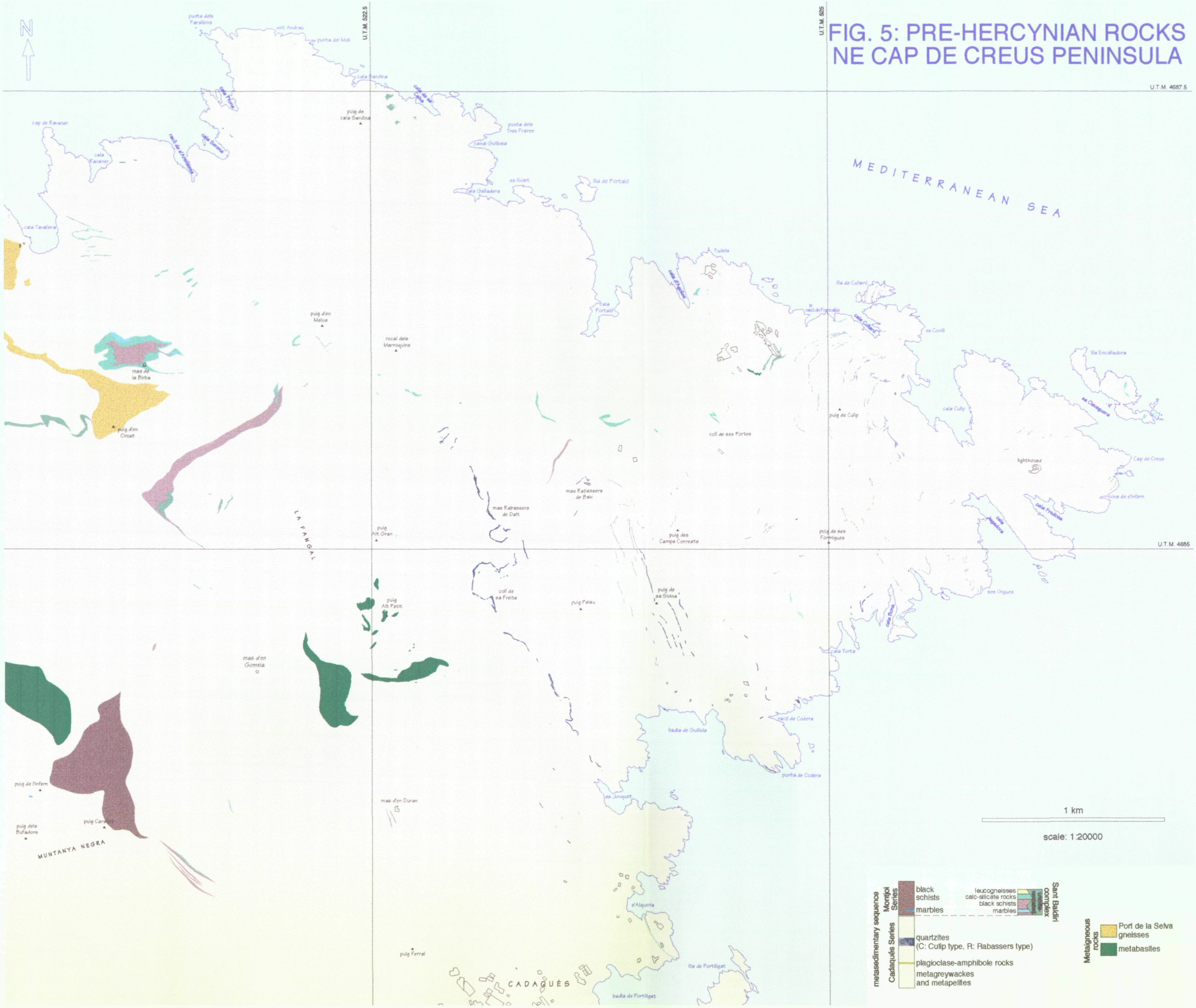
Two main types of pre-Hercynian igneous rocks are present in the area: gneisses and metabasites (Navidad & Carreras 1995). The gneisses correspond predominantly to the Port de la Selva gneiss and to some thin lenses of leucocratic gneisses included in the Sant Baldiri complex. The metabasites form discontinuous bodies located at different positions within the Cadaqués Series and they are also found as thin lenses within the Sant Baldiri complex.

The Port de la Selva gneisses form a continuous E-W trending sheet-like body, the eastern closure of which outcrops in the study area (Fig. 5). It is granitic to quartz-monzonitic in composition (Ramírez 1983a, Carreras and Ramírez 1984), with relict porphyric texture and sporadic feldspar phenocrysts. It has an intrusive character in the Cadaqués series.

Metabasic rocks form several bodies. The largest ones are those of the northern slopes of Muntanya Negra and at the Puig Alt Petit summit (Fig. 5) and have been named after these two localities. Other outcrops occur in the vicinity of the mentioned ones. They were originally gabbro-dolerite intrusions, now forming lens-shaped bodies which have been transformed into greenschists and amphibolites due to Hercynian metamorphism. In low-strained domains, metagabbros are texturally heterogeneous with pegmatoid differentiates, and display diablastic or lepido-nematoblastic textures with relict diabasic textures allowing to identify them as orthotype rocks (probably subvolcanics). In the western slopes of Muntanya Negra, outside of the study area, some metabasalts with identical geochemistry to the metagabbros have been identified (Navidad & Carreras 1995), indicating the comtemporaneity of this magmatic event and the sedimentation of the Cadaqués Series. In a similar way, the REE patterns of the plagioclase-amphibole intercalations and the metabasites are analogous, suggesting that all these rocks have a similar origin, the plagioclase-amphibole rocks bearing partly a sedimentary and partly an igneous character.

According to Navidad and Carreras (1995), basic and acid magmatic events, although overlapped in time, have no genetic connection, since the former have crustal origin and the latter derive from the mantle.

FIG. 5: PRE-HERCYNIAN ROCKS
NE CAP DE CREUS PENINSULA



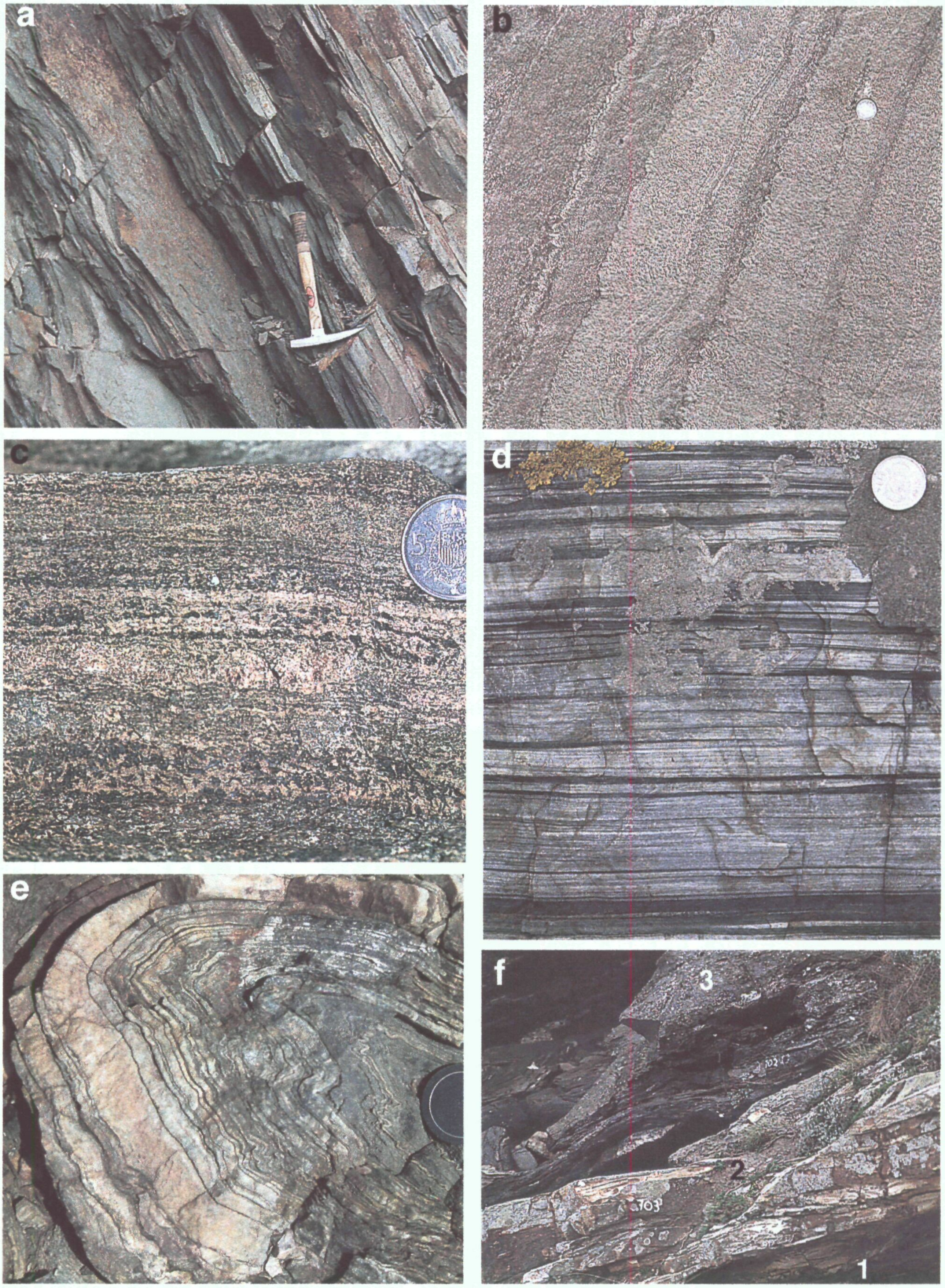


Fig. 6: Field photographs. (a) Metasediments of the Cadaqués Series, close to Cadaqués village. (b) Mimetic graded bedding in metasediments at Puig de Culip, showing younging direction to the right (East). (c) Plagioclase-amphibole rocks at Puig de Culip. (d) Black and white striped quartzites (Rabassers type) at Mas Rabassers de Dalt. (e) Light quartzites (Culip type) at Puig de Culip. (f) Rocks of the Sant Baldiri complex in S'Alqueria. 1: black schists, 2: leucogneisses, 3: marbles.

Interpretation, correlation and possible ages

In the Pyrenees, the basement stratigraphy is relatively well established for rocks of Upper Ordovician (Caradoc-Asghill) or younger ages, but little is known about the stratigraphy of lower series. These lower unfossiliferous series are habitually named "the Cambro-Ordovician". The origin of such naming is due to Cavet (1957), who considered, by analogy to the Montaigne Noire massif, that the series along the northern side of the Canigó massif, in spite of lack of fossils, could be correlatable with the well dated Cambrian and Ordovician rocks of the Montaigne Noire massif. Although conclusive dating is lacking, ages older than Cambrian were not considered, due to the interpretation that these series were unconformabily covering a Cadomian granite basement of 580±20 Ma age (Vitrac-Michard & Allegre 1975 a, b).

Because of the analogy of the Cap de Creus series with other series occupying similar positions in other Pyrenean areas, these have been generally included in the Cambro-Ordovician. However, the lack of conclusive evidence concerning their stratigraphic position is the reason why in some works the black slates (Montjoi Series) and the overlying calcareous-siliciclastic layers (Norfeu Series) have been tentatively attributed either to the upper Ordovician (Carreras, 1979) or to the Silurian-Devonian (Carreras 1979).

Nowadays, the age and position of the Series in the Cap de Creus peninsula is still an enigma, however, two tentative correlations have been proposed (Fig. 7). On one hand, in Laumonier's contributions to the Pyrenean synthesis and other works (Laumonier & Guitard 1978, Laumonier 1988 and BRGM-ITGE 1997). The Cadaqués Series are correlated with the Canavelles Series of Cavet (1957), while the Montjoi and Norfeu Series are considered to be equivalent to respectively the lower and Upper part of the Cabrils formation of Laumonier (1988).

An alternative correlation is defended by Carreras (1988 & pers. comm.), in which the Cap de Creus rocks are considered to occupy a lower stratigraphic position than the above mentioned, and even lower than the Canavelles type series. This idea is based on the assumption that the Pyrenean orthogneiss series do not represent the basement of the sedimentary series and hence the sequences which are now found overlying the gneisses might continue downwards. In such interpretation (Fig. 7), the Cadaqués Series could be correlatable to the greywacke series of Balaig in the Canigó massif and to the schists of the Roc de Frausa, while the Montjoi Series might be an equivalent of the dark pelitic series with interlayered marbles of Canavelles s. str. (i.e. the sequences close to Canavelles village). In this scheme, the Norfeu series could correlate with the Evol formation of Laumonier (1988) northof the Canigó. If these correlations and assumed Cambrian ages for the Canavelles formation (Laumonier 1988) were correct, the Cap de Creus series could be lower Cambrian or even upper Proterozoic in age.

Apart of the dating and correlation problems, there is an additional question of relevance to the Cap de Creus geology. This refers to the origin of the Sant Baldiri complex. There are strong arguments suggesting that this unit is rather a tectonic emplaced slice than a primary intercalation (see chapter 4, section 2.1). Although the age of the emplacement will be described later, one can put forward that mapping of the whole peninsula evidences the continuity between (i) the Norfeu and Montjoi Series in the SE, and (ii) the black series containing marbles, calc-silicate rocks and quartzites described by Morales (1975) in the NW (South of Llancà) (Fig. 8). The series at Llançà have significant analogies with the Sant Baldiri complex and, furthermore, they also appear pinched in between psammitic-pelitic alternances.

In the study area, such continuity can not be demostrated, but anyhow it is manifest that the black schists of Muntanya Negra (Montjoi Series), toward the SE closure of the outcrop, become pinched in between the Cadaqués series forming narrow stripes of black schists similar to those attributed to the Sant Baldiri complex further North. Thus, the black schists of the Sant Baldiri complex could match the Montjoi Series and the calc-silicate rocks and marbles could match the carbonate base of the upper series or the carbonates in the Monjoi Series. The unusual association of lithofacies of the Sant Baldiri complex, the irregularity with which each different lithology is present in each outcrop and the tectonic contacts with the adjacent metasediments, suggest also the proposed correlation.

A recent Rb/Sr datation of the Port de la Selva gneiss gives an age of 375 ± 51 ma (Navidad, pers. comm.). This age calls into question the possibility of the Port de la Selva magmatism being synchronous with sedimentation of the lower Palaeozoic sequences.

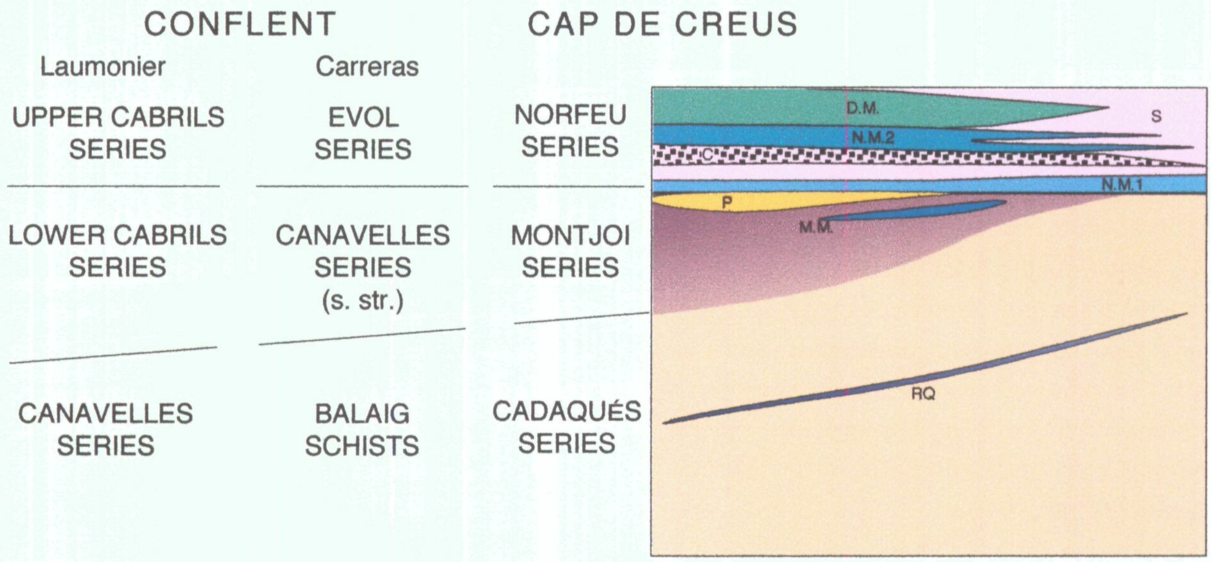


Fig. 7: Stratigraphic sketch of the Cap de Creus series and suggested correlations with the Conflent (E-Pyrenees) series. RQ: Rabassers quartzite; M.M.: Montjoi marbles; P: metaporphyres; N.M.1: lower Norfeu marbles; C: conglomerates; S: sandstones; N.M.2: upper Norfeu marbles; D.M.: dolomite marbles.

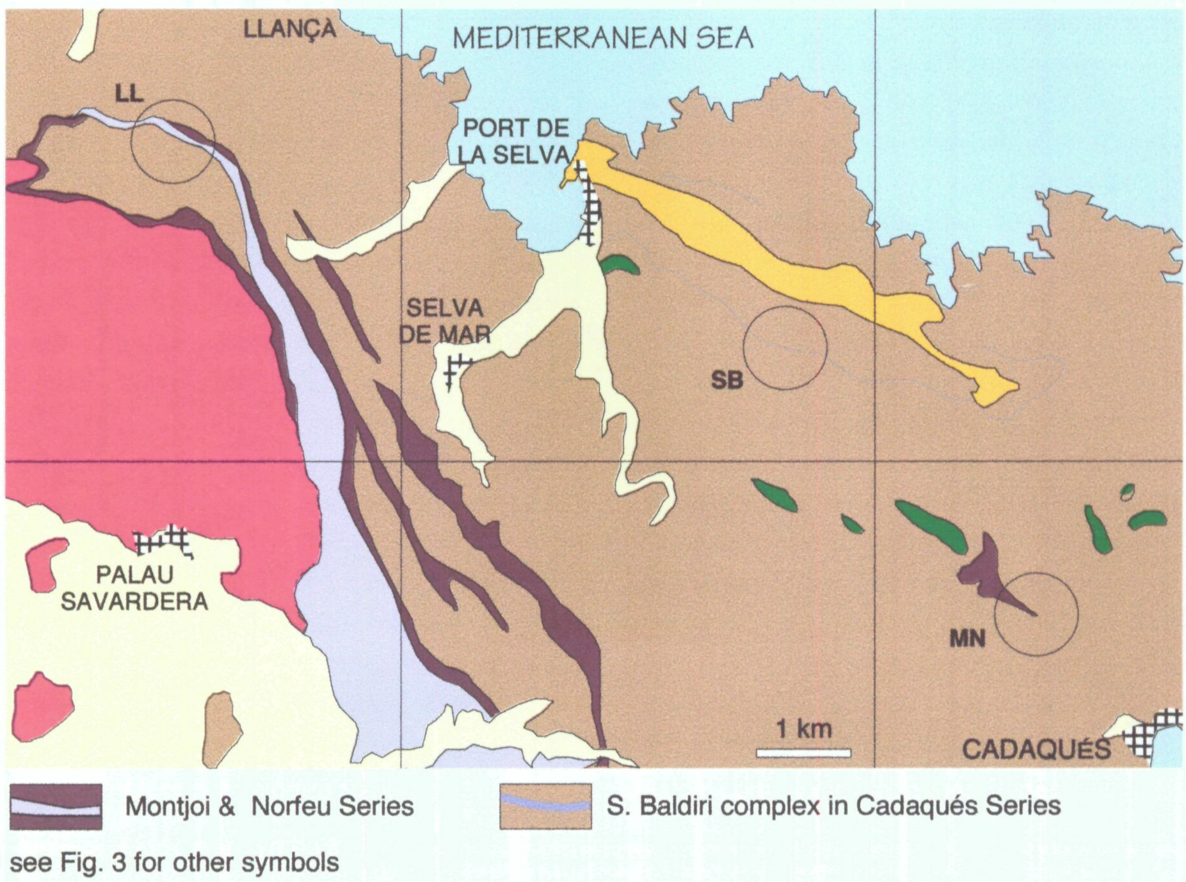


Fig. 8: Map showing three different settings of the slices of dark schists ± calc-silicate rocks. While in localities LL (S Llançà) and MN (Muntanya Negra) these slices belong to Montjoi series (and Norfeu series), in locality SB (Sant Baldiri), a slice with similar lithologies was considered as a primary intercalation. It is suggested that the Sant Baldiri complex represents also tectonic slices and thus cannot be used as a stratigraphic marker.

2.2. TECTONIC SETTING

The structure in the northern Cap de Creus area is complex and characterized by polyphase tectonics, with at least two main deformation events during the prograde metamorphic episode and late folding and shearing events in retrograde conditions. Although individual deformation phases are easily recognized in a given outcrop, their correlation from one domain to the other is a rather arduous task. Main difficulties arise from the following facts:

1) Each deformation phase produces structures that vary significantly in style and orientation from one domain to the other. These variations are due to strain inhomogeneities, changes in properties of the deforming rocks and differences in thermal conditions during deformation.

2) Most structures appear to have developed as a result of a progressive deformation, without a clear cut from one phase to the next.

3) There is a lack of manifest large scale structures correlatable with widespread minor structures. This is due to the absence of markers and to the dominating deformation style.

In outline, the following structural features are most characteristic to the Cap de Creus Massif. The overall structure in map view is characterized by a predominant trend of structures ranging between E-W to NW-SE (Fig. 9), although folds with variable axial traces exist. This structural orientation is essentially the result of folds affecting ubiquitous penetrative foliations, but also results from the effect of shear zone-related mylonite belts, which cut across the previous folded foliations and also across the Hercynian intrusives. These shear zones show similar orientations to the above mentioned folds. Folds affecting an early foliation have a south vergence, with axial planes being subhorizontal on the south-eastern part of the peninsula but becoming inclined towards the Northwest. In a NE-SW section of the peninsula, structures of the NE side show moderate to steep NE dips, while on the SW part of the section, moderate to subhorizontal SE dips of prevalent foliations and axial planes dominate. This change in attitude is caused by the existence of a gentle fold that caused the doming of all pre-existing structures. Axes of all mappable fold structures have predominantly SE plunges, although in the NE part of the peninsula they acquire gradually E, NE and even N orientations.

The above mentioned structural arrangement is considered to be the responsible for the distribution of different tectonic and lithostratigraphic levels of the Cap de Creus peninsula. Shallow levels consisting of Upper Series of very low metamorphic grade outcrop mainly on the SE corner of the peninsula and along a NW-SE trending zone bounding the Roses and Rodes granodiorites. On the other hand, deeper seated structural levels, consisting of the medium to high grade Cadaqués Series, are located along the northern side of the Peninsula. In Carreras (1975), a WNW-ESE synformal structure, located on the northern part of the Peninsula, was considered to be responsible for the distribution of the metamorphic zones, as metamorphism increased northwards across the steep limb of the synform (Fig. 10). In fact, as it will be presented later, this structure is far more complex than described in that work.

A remarkable structural feature is the variation in tectonic style through different domains, depending on the achieved metamorphic grade. While low grade metasediments deformed continuously in the same tectonic style, giving rise to folds with associated axial plane foliations, medium to high grade domains deformed in a highly ductility regime during episodes close to the metamorphic peak and developed anastomosed shear zones in later retrograde events (coarse grained schists, developed by previous recrystallization and grain growth, where unable to nucleate folds). These differences in tectonic style lead Carreras & Casas (1987) to distinguish in the northern part of the peninsula three zones: a northern shear belt, a southern fold belt and a transition zone in between where the folds and the shear zones coexisted. The existence of such changes in tectonic style through different domains is not exclusively the result of different behaviour of deforming rocks during late episodes. Moreover, differences in tectonic style arose also during earlier deformation events as result of strain inhomogeneities and differences in the thermal conditions.