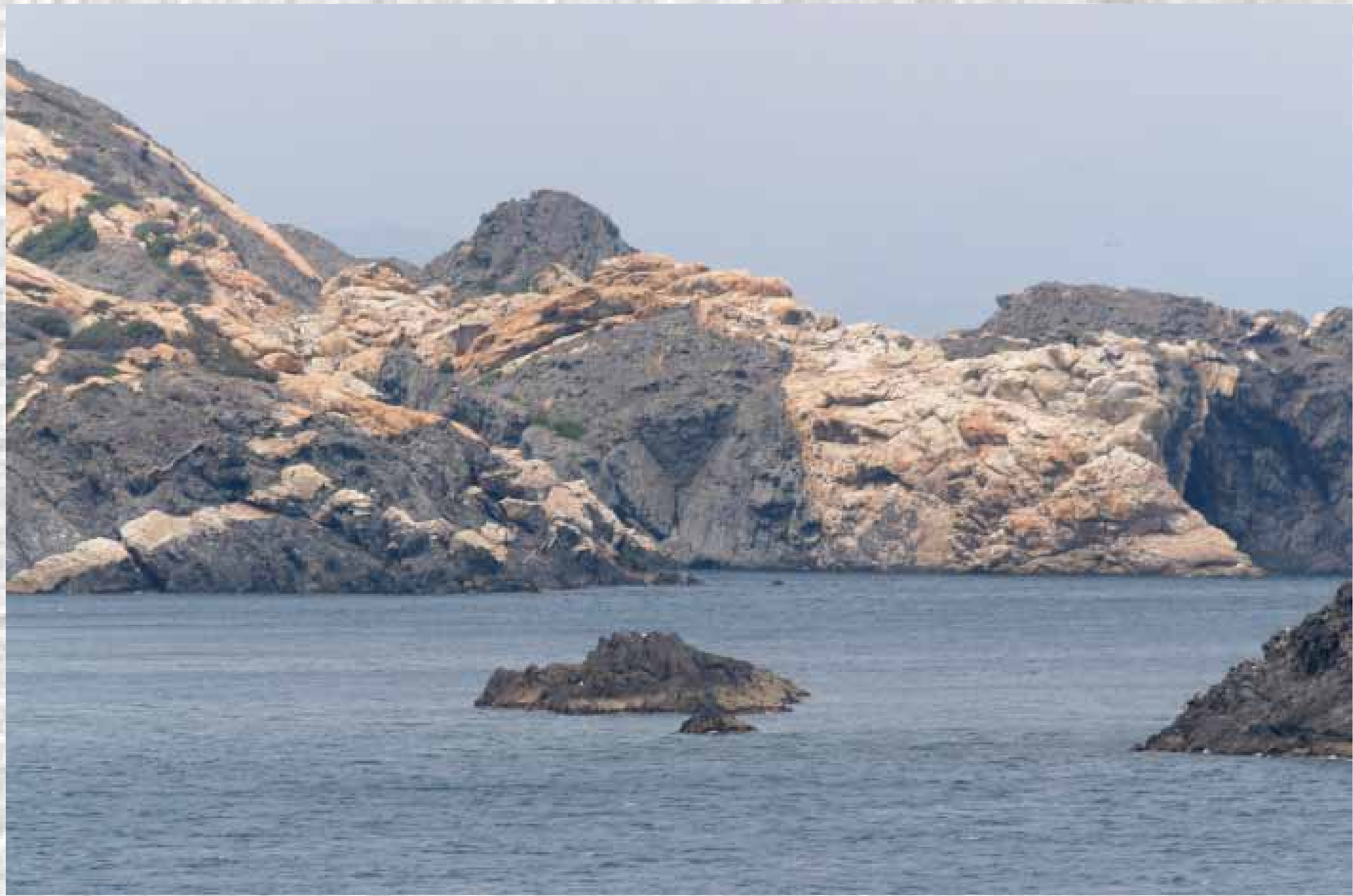
ILLUSTRATED FIELD GUIDE TO
THE GEOLOGY OF CAP DE CREUS

Jordi Carreras and Elena Druguet



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PREFACE

Cap de Creus is a paradigm of Geological Heritage. Located in the NE part of the Iberian peninsula, it represents the easternmost outcrops of the Pyrenees. The Cap de Creus forms a peninsula in the Mediterranean and contains the most singular landscapes of the Costa Brava. Geological, biological and historical-cultural elements converge on the Cap de Creus peninsula to shape a site of great scientific and landscape value. The outstanding character of this site is mostly achieved from its geological configuration and from the Mediterranean clime, which is here extremely windy (tramuntana), giving rise to many spectacular landforms and beautiful rocky coasts. Moreover, the main heritage value of this area concerns the quality and quantity of geological outcrops that enable the understanding of geological processes far beyond their regional interest.

The dawn of the Cap de Creus geological research 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) and later specific works on a transformist interpretation of the origin of pegmatites and Port gneisses (Denaeyer, 1947 and Denaeyer and San Miguel, 1954) and on the basic geology of the area (Cañada, 1964).

In the early seventies, Jordi Carreras thesis on the general structural and metamorphic trends of the area and his later M.Sc. research on shear zones and mylonites can be regarded as a milestone for the Cap de Creus geology. Nowadays, and after 40 years of research, this area has become a worldwide reference place for structural geology. The main reason for this is the exceptional quality of outcrops and structures exposed. This fact, together with that in the nineties the Cap de Creus stood as one of the unique landscapes preserved in the Catalan coast, lead the Catalan Government to protect vast areas of the Cap de Creus Peninsula, designating the Cap de Creus Natural Park. This has been essential to avoid the landscape and outcrop destruction due to the rampant urbanization that took place since the sixties elsewhere along the eastern Spanish coast. However, some spectacular geological outcrops are located in areas that suffered from uncontrolled touristic development. This is the case of the Roses lighthouse area, which, to make matters worse, was not later included in the Cap de Creus Natural Park because of its closeness to urban areas.

The geological value of the Cap de Creus area lies on the fact that it displays a great variety of key structures. Most of the exposed structures are "self-explanatory" and there is no need for speculation or extrapolations.

The relevance of the Geology of the Cap de Creus was first disseminated internationally in 1979 with the International Conference on Shear Zones in Rocks (the 3rd precursor of the present-day DRT meetings). From Catalan universities, Pere Santanach, Vicente Morales, Joan Manel Orta, Mariona Losantos, Joan (Ramírez) Palau, Josep Maria Casas, Amparo García-Celma and Felip Ortuño joined the research in Cap de Creus. In the early nineties Elena Druguet started her research in the area that continues nowadays. Albert Griera also did his Ph.D. thesis in this area. Many foreign researchers have visited the region, some of them being involved in research. Among them, Stan White and Carol Simpson were the first to collaborate with Jordi. Later, Gerard Bossière, Donny Hutton, Cees Passchier, Pia Victor, Paul Bons, Ian Alsop, Peter Hudleston, Dyanna Czeck and Isadora Mariani have collaborated with the MIET research group. Others, like Sandra Piazolo and Florian Fusseis, impressed by the suitability of the structures, also performed their investigations here.

Pere Enrique, K.W. Damm, Joan Carles Melgarejo, Mercè Corbella, Pura Alfonso, Montserrat Liesa and Marina Navidad have also done research in Cap de Creus from the petrological, mineralogical or geochronological perspectives, particularly devoted to the study of the pegmatite dyke swarm and the pre-Variscan igneous rocks.

An outstanding quality of the area is that it allows conclusions to be drawn that are beyond the regional interest, it is simply full of textbook examples of structures. Most of the thematic subjects are related to shear zones. One of the first papers relating folds in a shear zone with shear sense came out in 1973 using examples from the Cala Prona - el Llimac shear zone. Later, accurate studies on sheath fold evolution were presented using examples from here. The first published example of shear bands was taken from the Cala Sardina shear zone. A better understanding of the peculiarities of shear zones in foliated rocks was also based on Cap the Creus examples. In 1977, the relationship between fabric asymmetries and shear sense was first reported at the Leiden Conference (DRT precursor), using quartz-mylonite fabrics from this area. The subsequent discussion on c-axis quartz fabric rotations versus constant orientation with regard to the shear plane was based on published data from Cap de Creus. The present-day ongoing discussion of shear zones nucleating as buckling instabilities or evolving from brittle precursors is based, among others, on Cap de Creus examples.

More recently, Cap de Creus has furnished many examples of the problems associated with relating local strain regime with regional strain, and the complex relations between rock symmetries and asymmetries and kinematics. It has also provided important insights into the relationships between deformation, metamorphism, anatexis and magmatism, and the significance of some magmatic structures, such as the apparent boudinage of dykes and anatectic leucosomes. Another aspect that transcends the regional interest of the area is the well documented LP/HT metamorphism and granitoid emplacement in a transpressive regime.

The area is well suited to educational and research purposes. Each year many Universities visit Cap de Creus, where teaching and research will likely continue and increase in the coming years. As Win Means stated when he visited the area, a detail study of an appropriate square meter can furnish enough information to develop a whole Ph.D. thesis. The authors of this guide are ready to continue their research in Cap de Creus and are open to collaborate with researchers that share the same enthusiasm and dedication.

Compilation of comments by some of the structural geologists who have visited Cap de Creus include:

The Geology of Cap de Creus is unique. The exceptional exposures display the best exposed and most accessible examples of ductile shear zones that I have encountered in my nearly 30 years of field research and excursions. (…) Simply stated, Cap de Creus ranks with the "top 20" of all geologically significant (sites) (…)

Darrel S. Cowan
University of Washington, Seattle (USA)

I have carried out geological field research in many areas in the world, but the area around Cap de Creus is, to my knowledge, the region with the most spectacular shear zones in Europe and one of the best areas in the world to study structures. As an area to train students it is of exceptional significance in Europe because of good outcrop, a unique lithology and complex but clear structures. (…)

Cees W. Passchier
Johanes Gutenberg University, Mainz (Germany)

I have visited many of the world famous localities for basement deformation and shear zones. The rocks of Cap de Creus are the best I have seen for the geometry of basement deformation. (…) The shear zones of Cap de Creus are unsurpassed and will provide a continuing base for the scientific study of deformation in the crust.

David Prior
Liverpool University (UK), now at University of Otago (NewZealand)

(…) I have visited and worked in many areas around the world (…) Cap de Creus is in my opinion one of the most superb geological localities in the world. It is unparalleled for the variety and quality of the geological structures and rock types found there. (…) This area should be preserved and protected for international science.

Donald Hutton
Durham University, now at the University of Birmingham (UK)

It took great pleasure in seeing the world famous shear zones of Cap de Creus (…) The concepts of shear zone geometry have made a great impact in Earth Science, and have developed from such classic outcrops as these. (…) The smaller but equally elegant outcrops at Roses provide a contrast. (…) they show more features idealised in "textbook" shear zones than any others. (…)

John Wheeler
Liverpool University (UK)

It does not seem necessary to be a geologist to see and appreciate the beauty of the Cap de Creus rocks:

"Aquesta part compresa entre el Camell i l'Àguila que tu coneixes i estimes tant com jo mateix és i ha de continuar per sempre essent geologia pura, sense res que pugui mixtificar-ho; en faig qüestió de principi. És un paratge mitològic que és fet per a déus més que per a homes i cal que continuï tal com està."

(This part between the Camel and the Eagle, that you know and love as much as I do, is and should continue to be pure geology forever, without anything that can cause damage to it; I do state it. It is a mythological place made for the gods more than for men and it should continue as is.)

Salvador Dalí, artist, 1961

CONTENTS:

1 GEOLOGICAL SETTING

1.1 THE PYRENEES

In NE Iberia, Alpine tectonics gave rise to the Pyrenees, the Catalonian Coastal Ranges and the Iberian chain, due to the collision of Iberia with the European plate. The Pyrenees is a chain of Paleogene age which extends from the Mediterranean on the east to the Bay of Biscay on the west. The chain is part of a larger structure, developed along the boundary between the Iberian and the European plates, which extends westwards from the Alps to the northwestern corner of the Iberian Peninsula. The Pyrenees arose from crustal shortening between the European and Iberian continental crust and structures formed involve the Mesozoic and Tertiary sedimentary cover and the Variscan basement. Pyrenean structures consist of a fold and thrust belt with neither widespread metamorphism nor penetrative cleavages of alpine age.

From north to south the following WNW-ESE trending structural units have been distinguished (Figs. 1.1 and 1.2):

1. The foreland Aquitania basin.
2. The North Pyrenean zone, which includes cover sequences and basement rocks, is thrust to the north over the Aquitania foreland and bounded to the south by the vertical North Pyrenean Fault (NPF), a sinistral strike slip fault developed during the Cretaceous (≈100 Ma) associated with the anticlockwise rotation of Iberia.
3. The Axial zone, made up of Variscan basement consisting of Precambrian and Paleozoic rocks, forms the highest part of the chain.
4. The South Pyrenean zone is a south vergent fold and thrust belt involving cover and basement rocks.
5. The foreland Ebro basin.

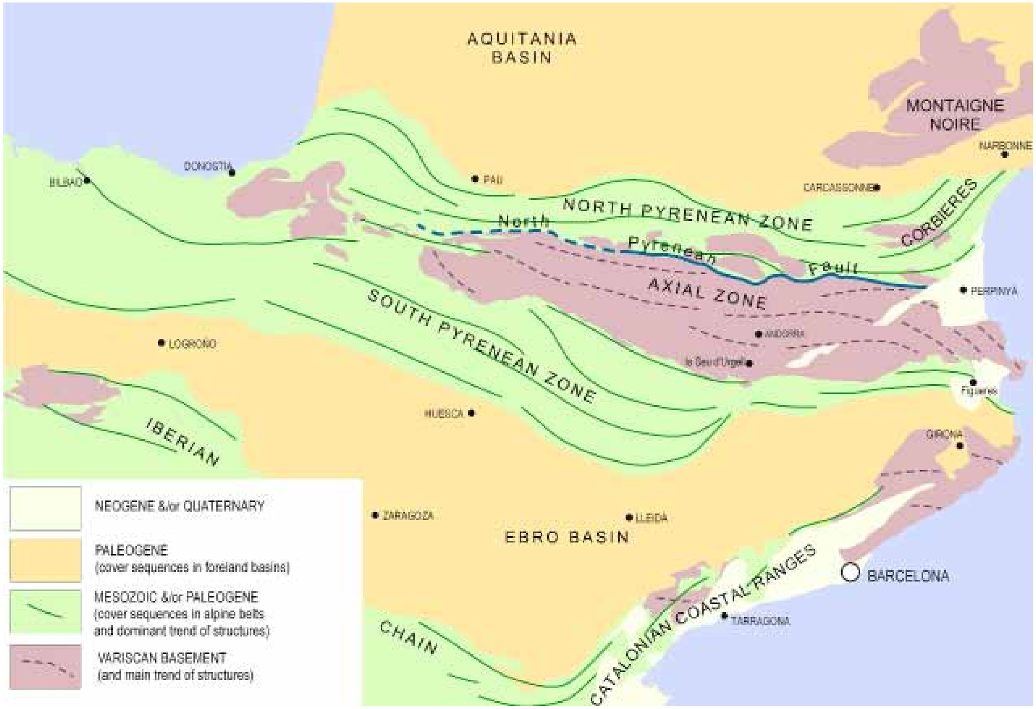


Fig. 1.1 Main geological units in NE Iberia and the Pyrenees.

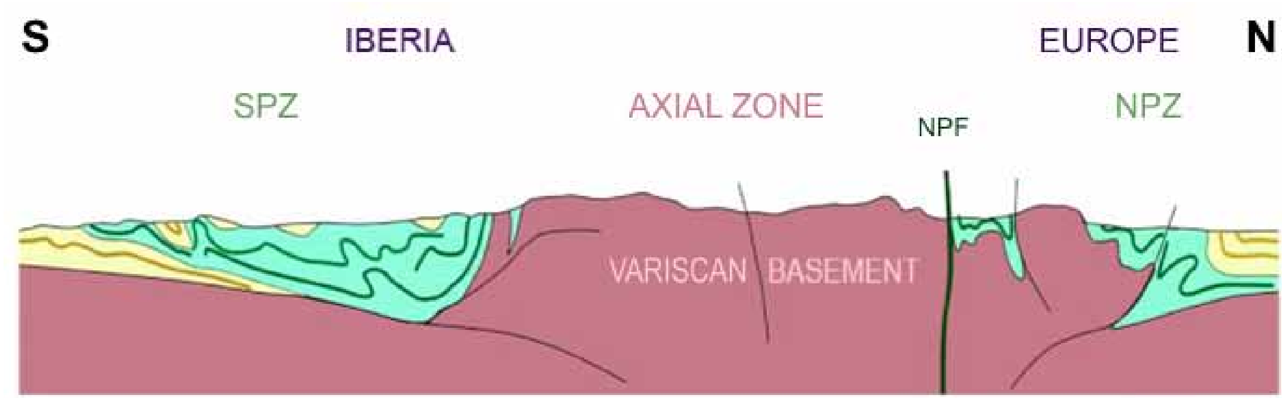


Fig. 1.2 Simplified cross-section of the Pyrenees. (Colours according to legend in Fig. 1.1; NPZ: North Pyrenean Zone, SPZ: South Pyrenean Zone, NPF: North Pyrenean Fault).

The Pyrenees show a fan-like geometry, defined by northward thrusting in the north and southward thrusting in the south, the North Pyrenean Fault zone being the axis of the fan (Fig. 1.2). This fan is asymmetric, with the south-directed thrusts more developed than the north-directed ones. The Axial zone belongs to the south-facing domain of the fan.

There are different interpretations regarding the effects of Alpine deformation on the basement rocks. However, there is a broad acceptance that penetrative ductile structures, metamorphism and igneous activity pertain to the Variscan orogeny. The assumed effects of Alpine thrusting on the Variscan basement would be: (i) the horizontal translation (and related rotations) of basement rock units without involving internal Alpine deformation, (ii) the tilting of Paleozoic units involved in the thrusting, and (iii) the development of fault zones with formation of mainly brittle fault rocks affecting the Variscan basement (Carreras *et al*., 1997).

Neogene tectonics is responsible for the development of extensional tectonics, with the formation of predominantly NE-SW trending faults and tectonic grabens due to the western European extension (Fig. 1.1). These grabens represent the southern prolongation of the Rhein-Graben and French Massif Central rift. Along the eastern coast of Iberia, it is locally associated with basaltic volcanism and hydrothermal activity. These grabens, mainly filled with Miocene sediments, are broadly parallel to the Catalonian Coastal Ranges and cut obliquely across the Pyrenees (e.g. the Cerdanya graben).

In spite of Alpine-Pyrenean and Neogene tectonics, the main structures of the NE Iberia segment of the Variscan belt can be reconstructed. This reconstruction involves the restoration of Iberia to post-Variscan pre-Alpine times and enables a broad zoning to be distinguished with external structures located towards the south and more internal structures towards the north (Fig. 1.3), in a similar way to the zonation in Sardinia.

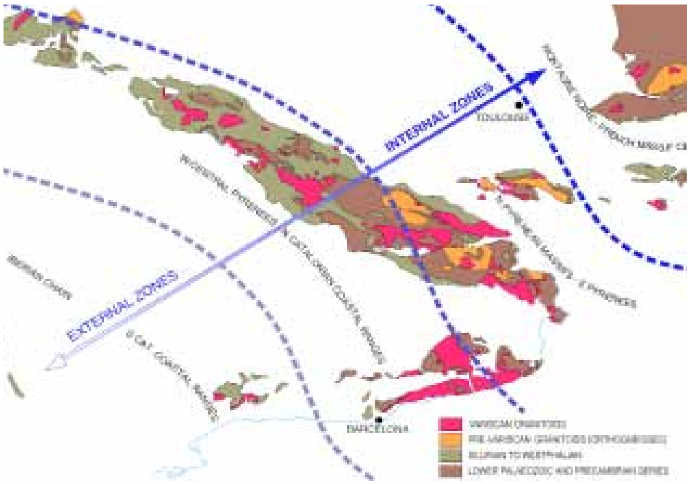


Fig. 1.3 Reconstruction of the Variscan rocks and units of the NE Iberia to their original relative position.

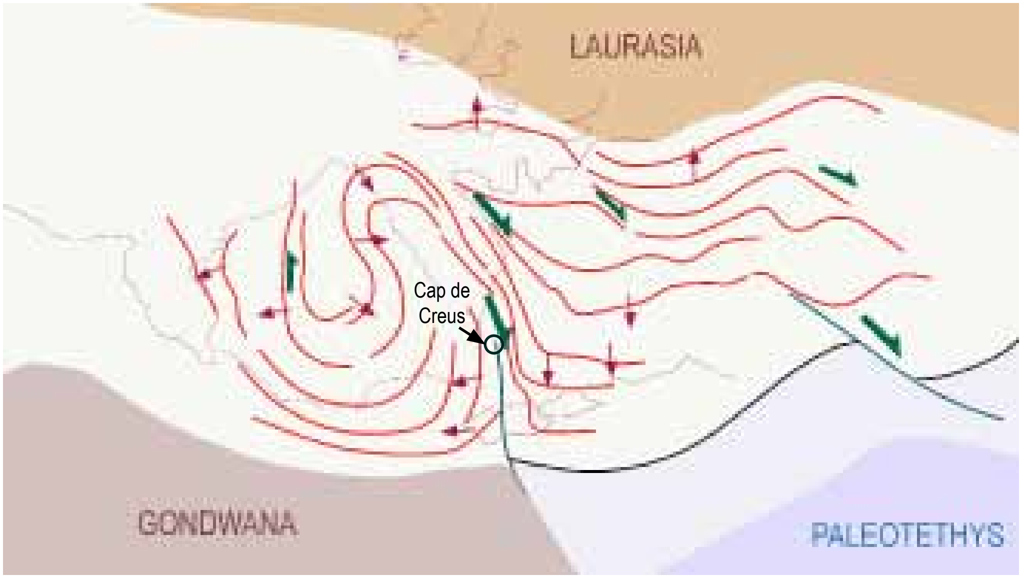


Fig. 1.4 Sketch of the structural trends of the Variscan belt (red lines: trends of main Variscan structures, green lines and arrows: late Variscan transpressive to wrench-dominated shear zones, purple arrows: facing of Variscan structures).

1.2 THE VARISCAN BASEMENT OF NE IBERIA

The main lithological units of the Variscan basement of the NE Iberia are:

1. The sedimentary pile and their metamorphic derivates resulting from Variscan transformations.
2. Pre-Variscan intrusives, appearing as interlayered bodies ein the former sequence and also tranformed into metamorphic rocks.
3. The Variscan intrusives, mainly granitoids

1.2.1 The sedimentary pile

Can be divided into two parts: the upper one comprises sedimentary rocks from Upper Ordovician to Westfalian (Carboniferous) which is relatively well known from a chronostratigraphic point of view. The lower part consists of a rather monotonous detritial sequences of unknown age. An unconformity between the Upper Ordovician and the underlying series has been reported (Santanach 1970; Casas and Fernández, 2007). Usually these the lower sequence is referred in the literature as Cambro-Ordovician, but recent data (Castiñeiras *et al.*, 2008) indicate that this series, besides Ordovician and Cambrian rocks, also comprises Neoproterozic sequences.

The sedimentary pile is affected by Variscan polyphase tectonics and metamorphism. Medium to high grade regional metasedimentary rocks are for the most part restricted to the lower part of the sedimentary pile.

1.2.2 Pre-variscan igneous rocks

Igneous rocks (intrusive and volcanic) appear interlayered in the sedimentary piles and record the same tectonic and metamorphic events. Magmatism is bimodal with predominance of acidic compositions. Concerning the ages of igneous rocks, both Neoproterozoic-Early Cambrian (580-540 Ma) and Ordovician (475-460 Ma) events have been recognized (Castiñeiras *et al.*, 2008). The Ordovician event is responsible for the emplacement of sheet-like bodies of granitoids transformed into orthogneisses during the Variscan orogeny. These gneiss bodies were formerly interpreted by Guitard (1970) and coworkers as derived from a Cadomian (Panafrican) granitic basement.

1.2.3 Variscan intrusions

These are mainly granitoids emplaced as sheet-like batholiths intruded into the metasedimentary pile. The composition of intrusives range from gabbros to leucogranites, with granodiorites the prevalent composition. Their ages range from 280 to 310 Ma (Cocherie, 1984; Guitard *et al*., 1996; Paquette *et al*., 1997; Roberts *et al*., 2000; Vilà *et al*., 2005; Olivier *et al*. 2008), depending on radiometric method and massifs. In general, the rocks of basic to intermediate composition are the oldest, while shallow leucogranites located in the upper part of the batholiths give younger ages. Batholiths are mainly located in low metamorphic grade shallow levels with development of a contact metamorphic aureole. At deeper levels migmatites appear in association with minor bodies of granitoids (from tonalites to granites) and often a widespread swarm of leucogranites and pegmatites.

1.3 VARISCAN EVOLUTION OF NE IBERIA

Variscan events comprise: (i) polyphase tectonics with widespread development of penetrative foliations, (ii) a LP/HT polyphase metamorphism and (iii) mainly syn-tectonic igneous activity.

1.3.1 Variscan tectonics

It is polyphasic, with tectonic style varying in space and time (Carreras and Capellà, 1994). Early tectonic events are responsible for thrusting in shallow levels and low dipping penetrative foliations in deeper levels. Main Variscan tectonic events are related to folding and associated penetrative foliations with variable attitudes (from low to steep dipping). In deeper tectonic levels foliations associated to the main phase appear as crenulation and/transposition foliations and occur close to the thermal peak of metamorphism. In shallow levels structures associated to the main phase appear as axial plane slaty cleavages or penetrative crenulation foliations. Late tectonic phases, developed under metamorphic retrograde conditions, give rise to shear zones, in highly crystalline rocks (i.e. granitoids, orthogneisses or high grade schists) and to crenulation foliations in lower grade rocks.

1.3.2 Variscan metamorphism

Variscan metamorphism in the Pyrenees is a classic example of low pressure, high temperature metamorphism. A widespread feature in different massifs is the distribution of prograde metamorphic zones, with large areas of low or very low grade metasediments bounding amphibolite to granulite facies metamorphic and migmatite cores. Most of these zones are concentric and dome-shaped, thus called thermal domes. These thermal domes often display an orthogneissic core, as in the Aston, St. Barthélemy, Canigó and Albera massifs. it was suggested that this gneissic cores acted as channels which caused and controlled the metamorphic gradient (Guitard, 1969; Fonteilles and Guitard, 1977). However, other massifs are cored by migmatitic schists, as in the Trois-Seigneurs and Cap de Creus massifs.

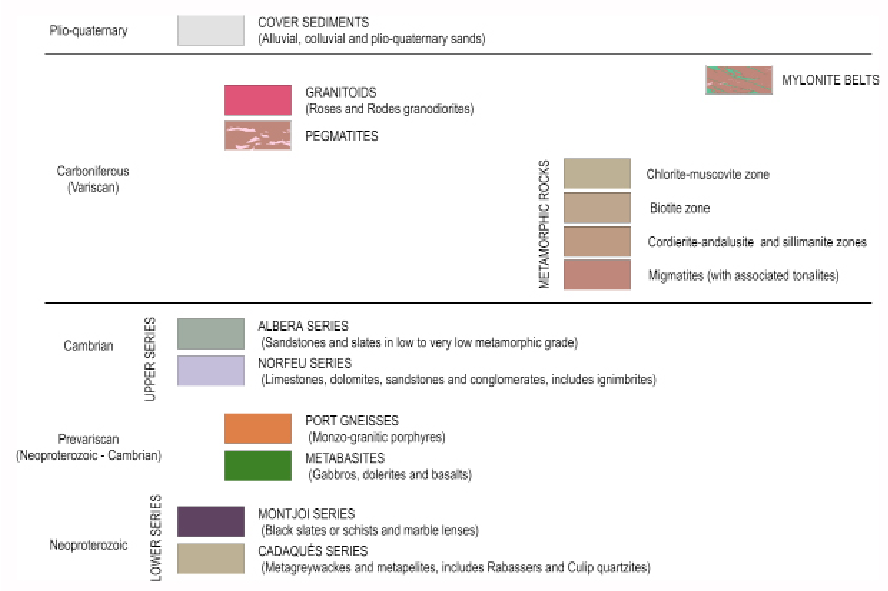
In these cases, the migmatite cores are usually associated with small funned-shaped intrusions of mantle-derived magmas.

A high thermal gradient metamorphism is found in the interval between the beginning of the amphibolite facies and the beginning of anatexis. A metamorphic gradient of between 65 and 75ºC/km is inferred from regional studies for the entire Variscan massifs (Zwart,1979; Guitard *et al*. 1996; Druguet, 2001).

1.3.3 Variscan igneous activity

This consist on a widespread emplacement of batholiths and stocks. Most plutons are sheet-shaped and emplaced in relative shallow levels. Granite to granodiorite compositions dominate although in many intrusions the composition range from minor gabbros to leucogranites. The gabbros, diorites and tonalites are the earlier and deeper seated intrusions, while leucogranites are the latest and occupy the apical parts of the intrusions. In deep seated levels, where medium to high metamorphic grade prevails, migmatites and associated granitoids appear as rather exiguous spots, commonly referred to as migmatite complexes. There, swarms of anatectic peraluminous leucogranites and pegmatites abound (referred to as peri-anatectic leucogranites by Autran *et al*., 1970). They are different from those occupying the apical parts of the large batholiths, which represent the ultimate differentiates. A comprehensive description of granitoids in the Eastern Pyrenean segment of the Variscides is given by Autran *et al*. (1970).

Field and AMS studies of these granitoid plutons have lead to conclude that their emplacement was contemporaneous with the main Variscan transpressive event (Evans *et al*., 1997; Gleizes *et al*., 1997; Auréjac *et al*., 2004). Migmatites and crustal anatexis granitoids are also syntectonic with transpression (Druguet and Hutton, 1998; Druguet 2001).


Plio-quaternary
COVER SEDIMENTS
(Alluvial, colluvial and plio-quaternary sands)
MYLONITE BELTS
GRANITOIDS
(Roses and Rodes granodiorites)
PEGMATITES
Carboniferous
(Variscan)
METAMORPHIC ROCKS
Chlorite-muscovite zone
Biotite zone
Cordierite-andalusite and sillimanite zones
Migmatites (with associated tonalites)
Cambrian
UPPER SERIES
ALBERA SERIES
(Sandstones and slates in low to very low metamorphic grade)
NORFEU SERIES
(Limestones, dolomites, sandstones and conglomerates, includes ignimbrites)
Prevariscan
(Neoproterozoic - Cambrian)
PORT GNEISSES
(Monzo-granitic porphyres)
METABASITES
(Gabbros, dolerites and basalts)
Neoproterozoic
LOWER SERIES
MONTJOI SERIES
(Black slates or schists and marble lenses)
CADAQUÉS SERIES
(Metagreywackes and metapelites, includes Rabassers and Culip quartzites)

2 CAP DE CREUS

The Cap de Creus peninsula forms the most easterly outcrop of the Variscan basement exposed along the Axial Zone of the Pyrenees.

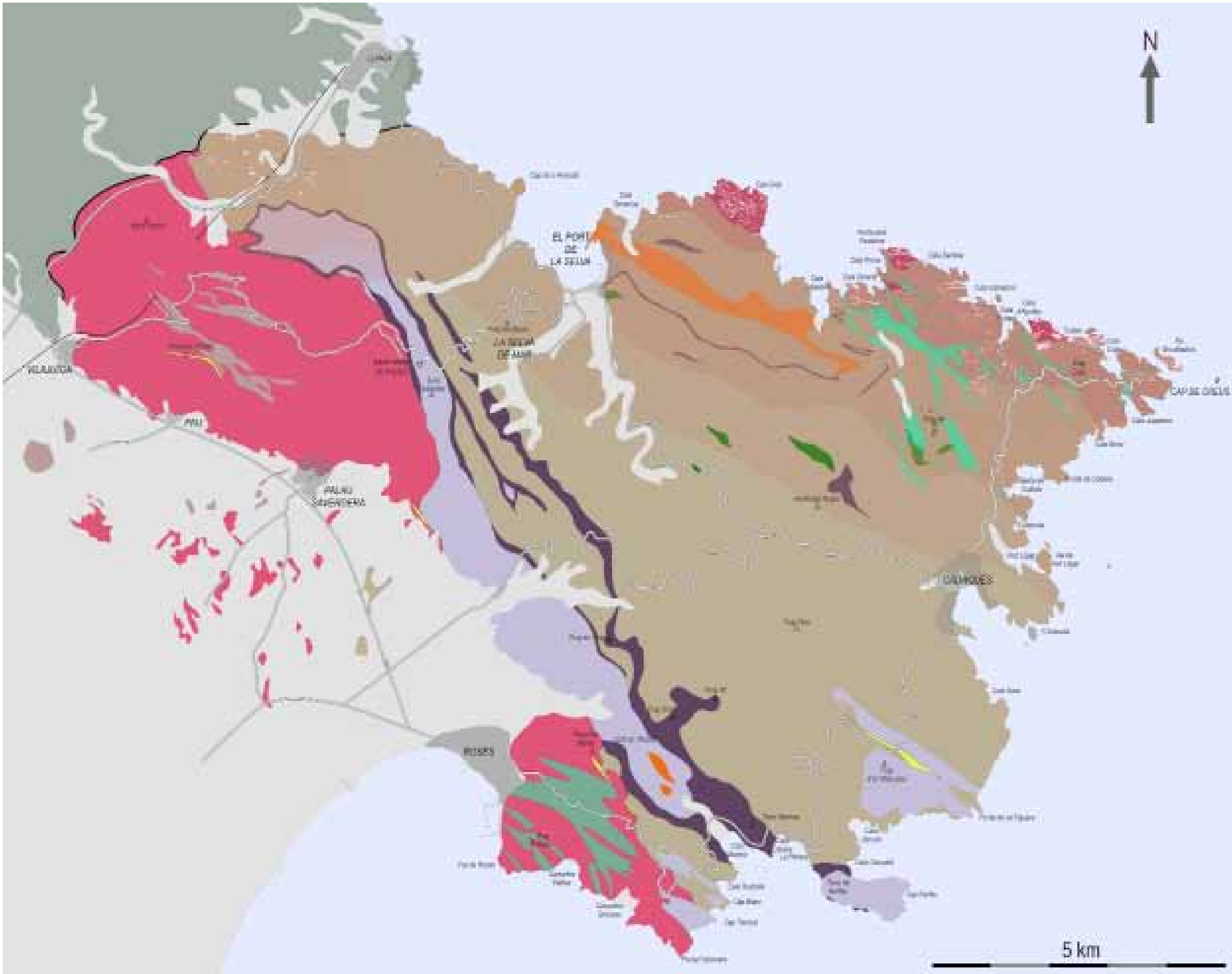


Fig. 2.1 Geological map and of the Cap de Creus peninsula (legend on the left).

2.1 LITHOLOGICAL UNITS

In the Cap de Creus peninsula two main lithological units can be delimited (Fig. 2.1):

I) An essentially psammitic-pelitic monotonous metasedimentary sequence of uncertain age, but probably Neoproterozoic to lower Cambrian, that includes pre-Variscan igneous intercalations, and

II) Two small stocks of granitoids (mainly granodiorites) which form the Rodes and the Roses Massifs.

2.1.1 The metasedimentary sequence

The lowermost metasedimentary sequence (Cadaqués Series) consists of a thick and rather monotonous succession of alternating metapsammites (metagreywackes) and minor metapelites (Fig. 2.3) and scarce intercalations of quartzites (Fig. 2.4) and abundant thin layers of plagioclase-amphibole rocks (Fig. 2.5). The quartzites form distinct layers whose thickness range between a few centimetres and a few meters. They are well banded (Fig. 2.4) and may appear either predominantly dark (named Rabassers quartzite) or light coloured (named Culip quartzite).

A Neoproterozoic age (Ediacaran) is assumed on the basis of the age of intrusive porphyries dated as 580-540 Ma age, Castiñeiras *et al.*, 2008.

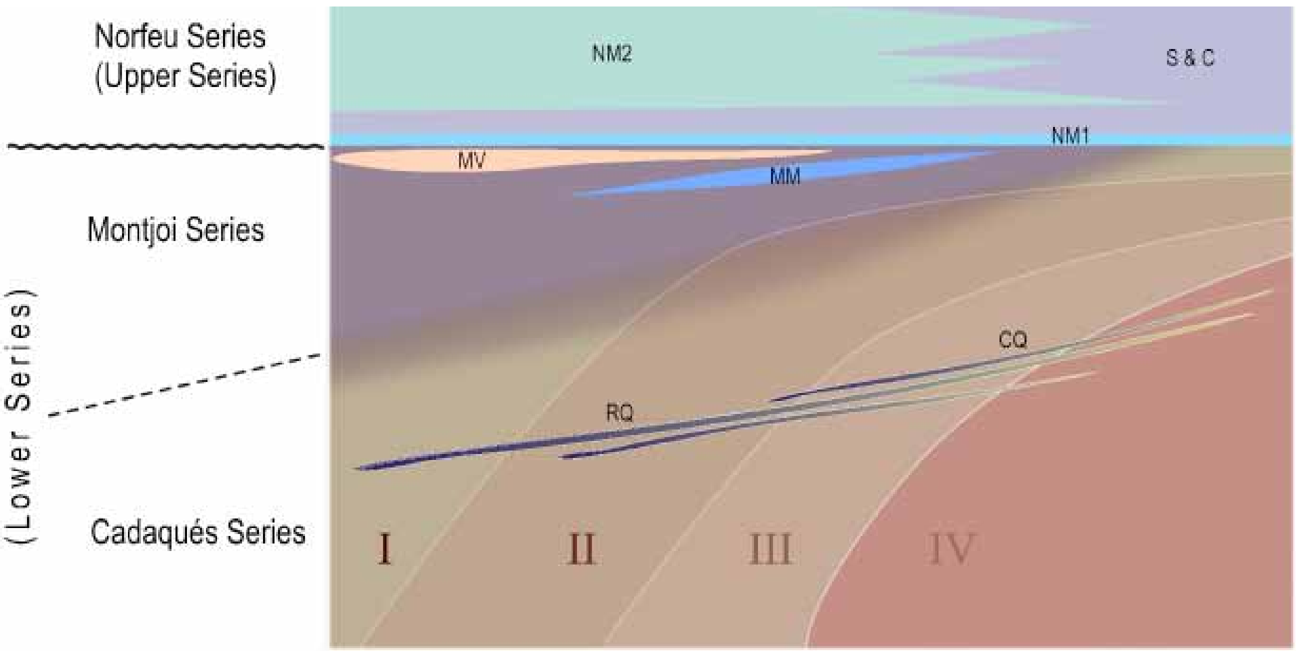


Fig. 2.2 The Cap de Creus Series and Metamorphic zones. RQ: Rabassers quartzite, CQ: Culip quartzite, MM: Montjoi marbles, MV: Montjoi volcanics, NM1: Norfeu marbles (basal layer) NM2 Norfeu marbles (upper marbles and dolomitic marbles), S & C: Norfeu sandstones and conglomerates. I: Chlorite-muscovite zone, II: biotite zone, III: Andalusite-cordierite zone, IV: Sillimanite zone.

Fig. 2.3 The Cadaqués Series at Barranc de Jònculs.

Fig. 2.4 The Rabassers (left) and the Culip (right) quartzites.

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. The ensemble including Cadaqués and Montjoi Series forms the Lower Series in the Cap de Creus area (Fig. 2.2).

Fig. 2.5 Plagioclase-amphibole rocks (S'Alqueria).

Fig. 2.6 Black slates of the Montjoi Series (Punta de la Ferrera).

The 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. These series lie unconformably over the lower series and include calcareous and dolomitic marbles (Fig. 2.7 left) and conglomerates (Fig. 2.7 right). On the basis of correlation with similar rocks from near areas, a lower Cambrian age is assumed for these series.