LGV 75th anniversary Pyrenees Field Trip, June 11-17, 2008

Revisiting the past, Leiden back in the Pyrenees

Painting: "Marriage of Erill Castell with its geological past" by Peter Nagtegaal

Field guide assembled by Karel Roberti

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de Catalunya

On behalf of the Institut Geològic de Catalunya, we would like to acknowledge the organizers, Karel Roberti, Peter Nagtegaal, Peter Mey and especially Berend van Hoorn for their kindness in inviting us to participate in the celebration of the 75th anniversary of the Leidse Geologische Vereniging. We really appreciate this very much.

When the Leiden geological school lead by Professor De Sitter started their works on the Axial Zone of the Pyrenees in the decade of 1950's, most of the area was geologically *Terra Incognita*. The availability of geological information was limited to the results of very general maps by Spanish mining engineers made in the first decades of the XX century, the regional mapping by Dalloni, and by German geologists during the decade of 1930's, especially Peter Misch, who depicted the Triassic unconformity in Gerri de la Sal in 1934.

The excellent piece of work made by the Leiden Faculty teams lead by Professor De Sitter and co-workers resulted, among other important scientific contributions, in the publication of the first consistent geological maps of the Axial Zone of the Pyrenees at a detailed scale. This marked a milestone in the geological knowledge of the Pyrenees.

A geological map synthesizes the geological constitution of a given area and results from a lot of efforts and studies, each of them involving several interpretative steps. The data collected directly in the field are filtered through an extense corpus of geologic theory. The consequence is that a geological map represents not only a set of objective data put all together on a nice piece of paper, in a more or less artistic way, but also reflects the ideas of the geologist who built it, and the constraints posed by the actual environment and epoch. This is why its authorship is important.

As all the geological mappers know, the intrinsic quality of a geological map at a given scale is demonstrated by the consistency through time of cartographic units (i.e. lithostratigraphic formations), their internal geometries, and that of their respective boundaries. Even if the advances on the scientific, geological theoretical corpus and the availability of new data allowing new interpretations on the nature of the contacts between contiguous lithostratigraphic units _ and in-depth correlations, the general picture of the map – and its represented lithostratigraphic units - remains, at the same scale, constant. And, as it can be easily visualized on the recent maps of this area, this is exactly what happens with the ten sheets of the Geological Map of the Central Pyrenees made by the Leiden School. And this is their strength.

On the first chapter of this guidebook Karel Roberti writes that “the interpretations of these rocks and their geological history have evolved considerably since the 1:50,000 map series (Zwart, 1979) was published”. Let us say that we only partially agree with his statement. Despite the advances in the information, communication, geophysical and other technologies being used in the diverse fields of the geology, and in particular, for geological mapping, all the field geologists working on this part of the Pyrenees know that the basic, general geological knowledge of this area (i.e., lithostratigraphic units, their names and their cartographic representations) is found in a pale yellow box called the “Mapa dels Holandesos”. And so we do.

To finish, we wish you a fruitful and pleasant LGV 75th anniversary field trip and enjoy again, from a new point of view, the Pyrenean geology, landscapes, meat and … the wine produced by one of the most outstanding representatives of the Leiden geological school: Peter Nagtegaal.

Antoni Roca, Director and Xavier Berástegui, Head Geology

Institut Geològic de Catalunya

Preface

It was a tempting idea of the committee of the Leidse Geologische Vereniging to take the 75th anniversary of the association as excuse to plan an excursion to the Pyrenees, where in the past many of its members got acquainted with real geology. Since their mapping excercises carried out by Leiden students and staff, which resulted in good map coverage of the Axial Zone, impressive progress has been made by many others in forming a comprehensive picture of the development of the Pyrenees. Therefore the main point of this excursion with the theme “Revisiting the past, Leiden back in the Pyrenees” is to show the progress made in understanding the Pyrenees in the recent decades.

Such an excursion and its guidebook would never have been possible without the support of the Institut Geologic de Catalunya, and in particular by Xavi Berástegui and his collaborators, who facilitated the printing of this guide and who, together with professor Josep Muñoz of the University of Barcelona gave permission to copy so liberally from the field guide of the AAPG South Central Pyrenees Field Trip 2003. Their assistance is greatly appreciated.

In using the present guide readers should realize that I have left unchanged the original reference to and the numbers of the illustrations of the AAPG field guide. Where I have pasted other figures, new numbers are given where necessary, preceded by the section indication
The AAPG field guide contained an extensive list of references. This list has been omitted. The references in the text have been left intact. However, some important references follow below.

Karel Roberti

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Revisiting the Past, Leiden back in the Pyrenees

The 75th anniversary of the Leidse Geologische Vereniging (LGV) provide**s** an excellent reason to revisit the old stamping ground of many former students of the Geological Department of Leiden University. Thanks to the good help of the staff of the Institut Geologic de Catalunya (IGC) we can offer you an overview, though far from complete, on the progress of the geological interpretation since the days we used to roam around in this geologically exciting and beautiful mountain range.
Since the structural geology department of Leiden University started mapping in the Spanish Pyrenees in 1953, a lot has changed in the region: politically, accessibility, means of transport and communication, new exposures by road cuts, etc., but the rocks of the Pyrenees remain the same. However, the interpretation of these rocks and their geological history have evolved considerably since the 1:50,000 map series (Zwart, 1979) was published.

A bit recent history: Why Leiden in the Pyrenees

The geological mapping by Leiden concentrated on the Paleozoic and crystalline rocks. The reason to select these older rock sequences stems originally from an agreement with professor M. Casteras from Toulouse in 1948, who as “owner” of the French Pyrenees, allowed de Sitter and his group of students to study the Paleozoic and the crystalline rocks of the Arize Massif. Casteras himself was mainly interested in the Mesozoic and Cenozoic rocks and did not much care about the Paleozoic. So in the summer of 1948 De Sitter went with 25 undergraduate students to the Arize Massif for a first look into the Paleozoic. In the years that followed de Sitter extended the mapping exercise terrain to the west and into the Vall d’Aran in 1953. Each year the group of students consisted of 20 to 25 undergraduates. As all students were inexperienced their work had to be considered as preliminary. To get better and more reliable information graduate students working towards a M.Sc. degree were assigned to an area within the region already surveyed in the mapping course. This started in 1949 in the Arize and Saint Barthelémy (French Pyrenees). From then on many students spending two or three seasons in the field concluded their study with a M.Sc. thesis. Some of this work was published in the “Leidse Geologische Mededelingen”. Altogether about 100 students were involved in this project. Their names are mentioned in the legends of the map sheets. In addition some of these students went on for a Ph.D. degree which involved usually about two or three more field seasons.
After the first reconnaissance in the Valle d’Aran work continued in the southern part of the axial zone, in the Valira, Flamisell, Pallaresa, Ribagorzana and Esera valleys
In 1958, De Sitter decided to publish the results in a series of maps on a scale of 1:50.000 of the region between Ax-les-Thermes in the east and Bagnières de Luchon in the west. In total ten maps should cover the whole area and each sheet was to be named after a river. The first sheet, nr. 3 Ariège, was published in 1959, the last one, nr. 10, in 1969. For the color scheme De Sitter took his own way. He did not like the internationally accepted colors because for the Paleozoic he found those not bright enough and he proposed the now well known colors. The maps had to be rectangular and consequently

covered also post-Paleozoic terrains outside the axial zone. Mapping of these Mesozoic and Tertiary rocks had a lower priority and was in general done without further analysis.

Henk Zwart established in the sixties the relationships between polyphase deformation and the metamorphic history in the axial zone and the northern satellite massifs.

The emphasis of the structural mapping was the axial zone. When the lithostratigraphy of the Devonian was elucidated by Peter Mey in the area to the west of the Ribagorzana river, the basis was laid for the mapping of the axial zone from the Esera valley in the west to the Valiri valley in Andorra in the east.

Because of this emphasis on the axial zone the effects of the overprinted Alpine tectonics were not recognized or grossly underestimated. This excursion will try to show which important developments in the interpretation have been taken place since the geological map series has been published.

Whereas the emphasis of the Leiden Geological Insititute was dedicated preliminary towards geological mapping and structural geological interpretation of the Central Pyrenees, some detailed sedimentological and stratigraphic investigations were also carried out. Of note were the interpretations of the Devonian by Rien Habermehl and Kerst Boersma. Peter Nagtegaal elucidated in detail the post-Hercynian evolution of the mountain chain from the Stephanian till the Triassic. Subsequent investigations resulted in several M.Sc. thesis on the Cretaceous, partly summarized by Berend van Hoorn, with the last efforts being focused on understanding the relation between the synsedimentary evolution of the South-Central Pyrenean nappe and the Eocene deltaic wedge. This work was subsequently taken over by the Utrecht University and several publications on this theme can be found in their archives.

An important spin-off of the study geology in Leiden is the firm bonding between students and staff, strengthened beyond question by summer’s fieldwork together. It has led to a prosperous LGV, even after the moving of the faculty to Utrecht. Lasting interest in geology remained as testified by our anonymous geological bard in Dutch and English:

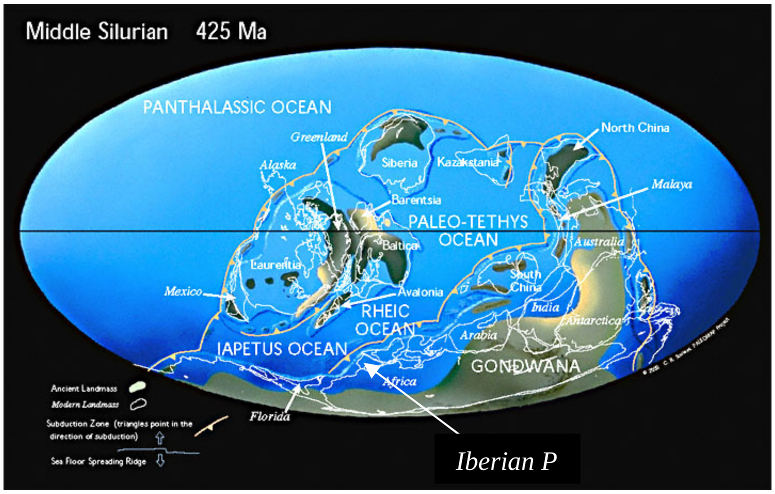
GEOLOGENVRIENDEN

het vak eren
samen het veld in
van fossielen en gesteenten leren
hoe het verhaal van de planeet
te reconstrueren
Pangea en Gondwanaland
hier reiken geologen, geofysici en dichters
elkaar de hand
één supercontinent één hecht verband
Alfred Wegener zag het openbreken,
de continenten ontstaan
John Joly reikte al veel eerder,
het mechanisme aan

zo begrijpen wij nu beter
hoe de deformatie van gesteenten,
hier in de Pyreneëen, is gegaan
terug in het dorp
gloeien we nog na van de zon
en het geologisch avontuur
wacht ons, tegen het avonduur,
een simpel maal, een goed glas wijn
en wie weet, wat filosoferen
klinken we weer
op het vreugdevolle feit
dat we indertijd
zo bevlogen waren
geologie te studeren

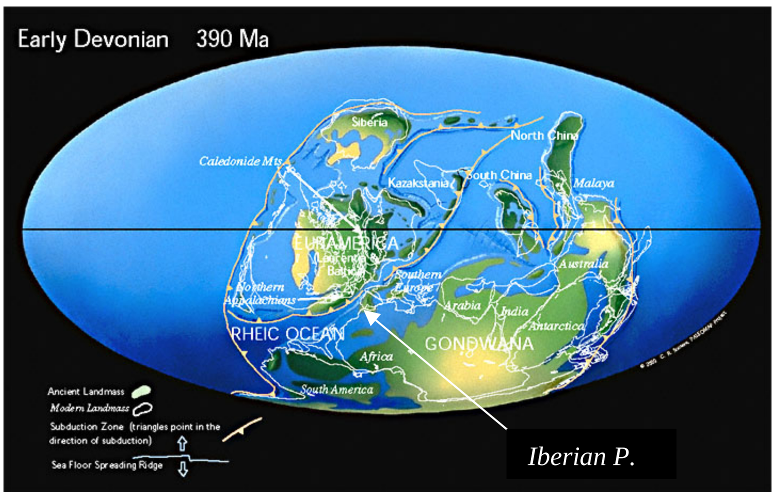
GEOLOGICAL FRIENDS

to honor the profession's glory
jointly into the field
to learn from fossils and rocks
how to reconstruct the planet's story
Pangea and Gondwanaland
where geologists, geophysicists and poets
go hand in hand
one closely knit supercontinent
Alfred Wegener saw it break open
the continents form and go
earlier still, John Joly
knew the reason why this should be so
thanks to them we now understand
how the deformation of the rocks
here in the Pyrenees went
back in the village
still glowing from the sun
and geological adventure
a simple meal, a good glass of wine
and maybe the fun
of some philosophizing
and a toast
to that we once have begun
full of inspiration
and with the innocence of the young
to study geology
the science linking gods and the universe
to the origin of life, and our own history



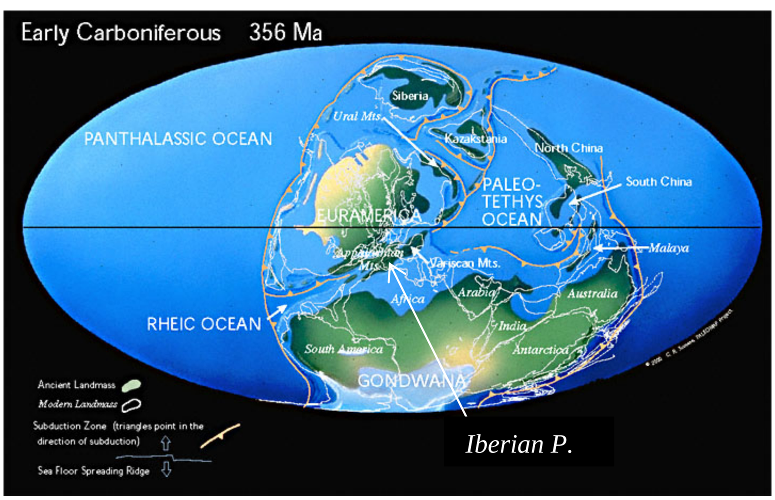
Silurian : Laurentia collides with Baltica closing the northen branch of the Iapetus Ocean and forming the "Old Red Sandstone" continent. Coral reefs expand and land plants begin to colonize the barren continents.

Outer shelf euxinic conditions with black shale-limestone deposition prevailed on the northeastern part of the Iberian plate. Iberia was part of the Gondwana continent.



By the Devonian the early Paleozoic oceans were closing, forming a "pre-Pangea". Freshwater fish were able to migrate from the southern hemisphere continents to North America and Europe. Forests grew for the first time in the equatorial regions of Artic Canada.

The Iberian plate was covered by a marine platform with widespread limestone deposition. Unstable conditions leading to influx of siliciclastic detritus occurred locally in the Middle Devonian.



During the Early Carboniferous the Paleozoic oceans between Euramerica and Gondwana began to close, forming the Appalachian and Variscan mountains. An ice cap grew at the South Pole as four-legged vertebrates evolved in the coal swamps near the Equator.
Pre-orogenic stage on Iberian plate is reflected by rather stable conditions with limestone/chert deposition, followed by formation of foredeeps and clastic influx (Culm facies in Pyrenees)

Global paleogeography with the position of the Iberian Peninsula during the Paleozoic (downloaded from www.scotese.com)

The Pyrenees: Two orogenic belts in one

The Pyrenean orogenic belt extends for about 400 km from the Bay of Biscay to the Mediterranean. It forms a doubly vergent collisional mountain range which resulted from Mesozoic –Cenozoic interaction between the Iberian microplate and the Eurasian plate. The range is flanked by two main foreland basins: the Aquitaine basin on the north and the Ebro basin on the south. (Part B, Fig 4) The Mz-Cz tectonic evolution of the Pyrenees is covered in part B of this guide.

The main body of the Pyrenees, called the Axial Zone, consists almost entirely of rocks folded, metamorphosed and intruded during the Variscan orogeny in Carboniferous times. They represent the relics of an older plate tectonic event: the collision and suturing of Gondwana of which Iberia was part and the Euro-American Plate (See Fig. 1). Post-Variscan were events responsible for localized deformation along thrust zones (brittle and ductile), general doming and tilting of the Variscan structures and for localized metamorphism along the North Pyrenean Fault. In Part A we will briefly try to outline the Paleozoic development.

Part A. The Axial Zone and the Variscan Orogeny

(Copied selectively from Vissers, 1992, and Zwart, 1978 for references see original article)

Pre- to Early Variscan Sedimentary Records

Four groups of rocks making up the pre-alpine basement of the Pyrenees are clearly involved in the Variscan orogeny. These are (1) a sequence of basal gneisses including amphibolite and granulitic facies metasediments and some charnockitic intrusives which possibly represent a pre-Cambrian basement, (2) a sequence of Paleozoic sediments generally in anchizone to low-greenschist facies but locally up to amfibolite facies grade and ranging in age from Cambro-Ordovician to Upper Carboniferous age, (3) pre-Variscan gneisses and (4) intrusive granodiorite plutons. Only the sequences relative to this field trip will be described in some detail

1. The basal gneisses are exlusively exposed in the North Pyrenean massifs, where they are observed to pass into Paleozoic metasediments.
2. The Paleozoic rocks occupy vast areas in the Axial Zone of the Pyrenees (Fig. A-1) and their lithology is summarized in Figure A-2

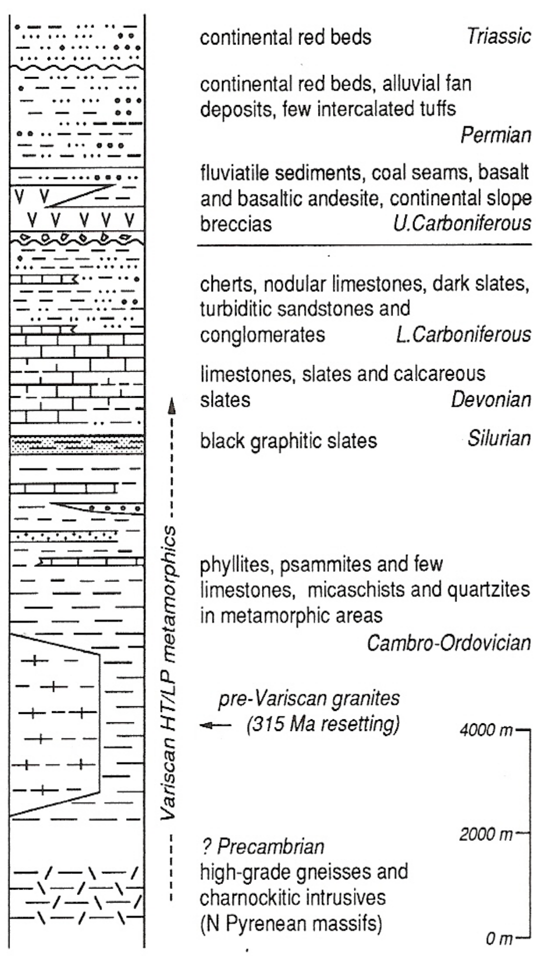


Fig A-2 Paleozoic and Mesozoic lithology of the Axial Zone

3. They comprise a monotonous sequence, up to several kilometers thick, of phylliets, psammites and few limestones referred to as Cambro-Ordovician followed by several hundred meters of Silurian black graphitic black slates. An overlying Devonian sequence of limestones, slates, calcareous slates constitutes a highly variable lithology with a thickness of up to 1500m. These rocks are overlain by Carboniferous cherts, nodular limestones and unconformably overlying dark slates and turbiditic sandstones, which, towards the eastern Axial Zone pass into coarser sandstones and conglomerates with several internal unconformities. The youngest rocks of this sequence have a lower Westphalian age. There is distinct evidence that the transition from calcareous to flysch-type deposits is diachronous, from Visean in the eastern Pyrenees to Namurian in the central and western Pyrenees, to Westphalian in the Cantabrian Mountains.
   The Cambro-Ordovian , Silurian and Devonian rocks commonly show anchizone to low-greenschist facies metamorphism, but locally they are metamorphosed into low pressure-high temperature (LP-HT) amphibolite facies rocks.
4. Pre-Variscan leucogratic augengneisses and granitic gneisses occur in a number of metamorphic massifs in the eastern part of the Axial Zone, like the Canigou massif
5. Granodioric plutons, up to 50 km across, intruded in the Axial Zone and North Pyrenean massifs (Fig.A-3) Their radiometric ages range from Westphalian to Permian and tend to cluster in the Early Permian. The Maladeta granite has an age of 277+/- 7 Ma. They may show a multiple intrusive history with variable composition and commonly are in contact with low-grade metasediments. Isotope studies indicate a dominantly crustal origin.

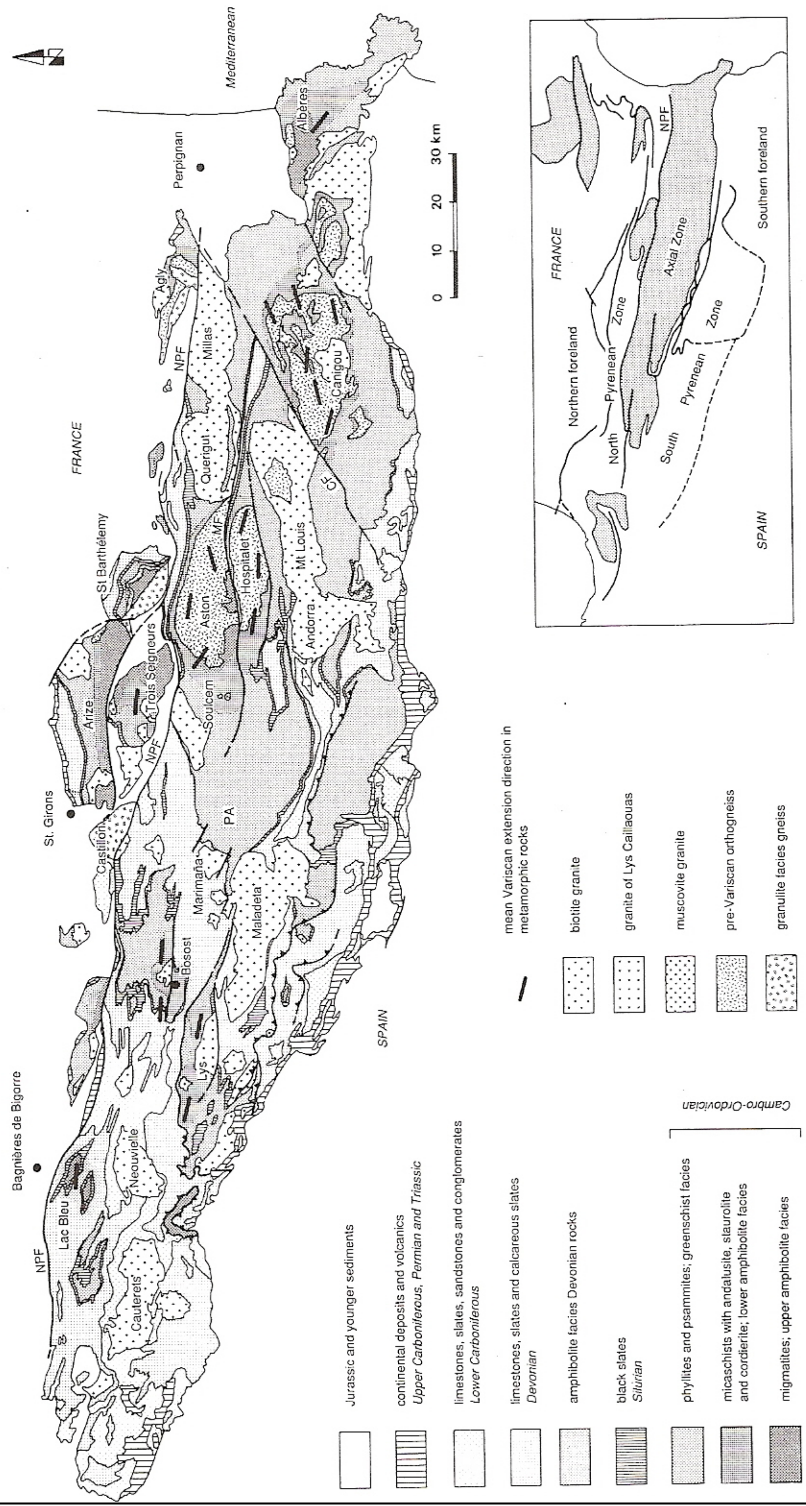


Fig. 1. Geological sketch map of the Axial Zone and North Pyrenean massifs, with mean Variscan stretching directions in metamorphic rocks. CF: Catalunya Fault, MF: Merens Fault, NPF: North Pyrenean Fault, PA: Pallaresa anticlinorium.

Fig. A-1 Late Paleozoic sedimentary record and compilation of geochronological data on met.infrastructure and granitic intrusions

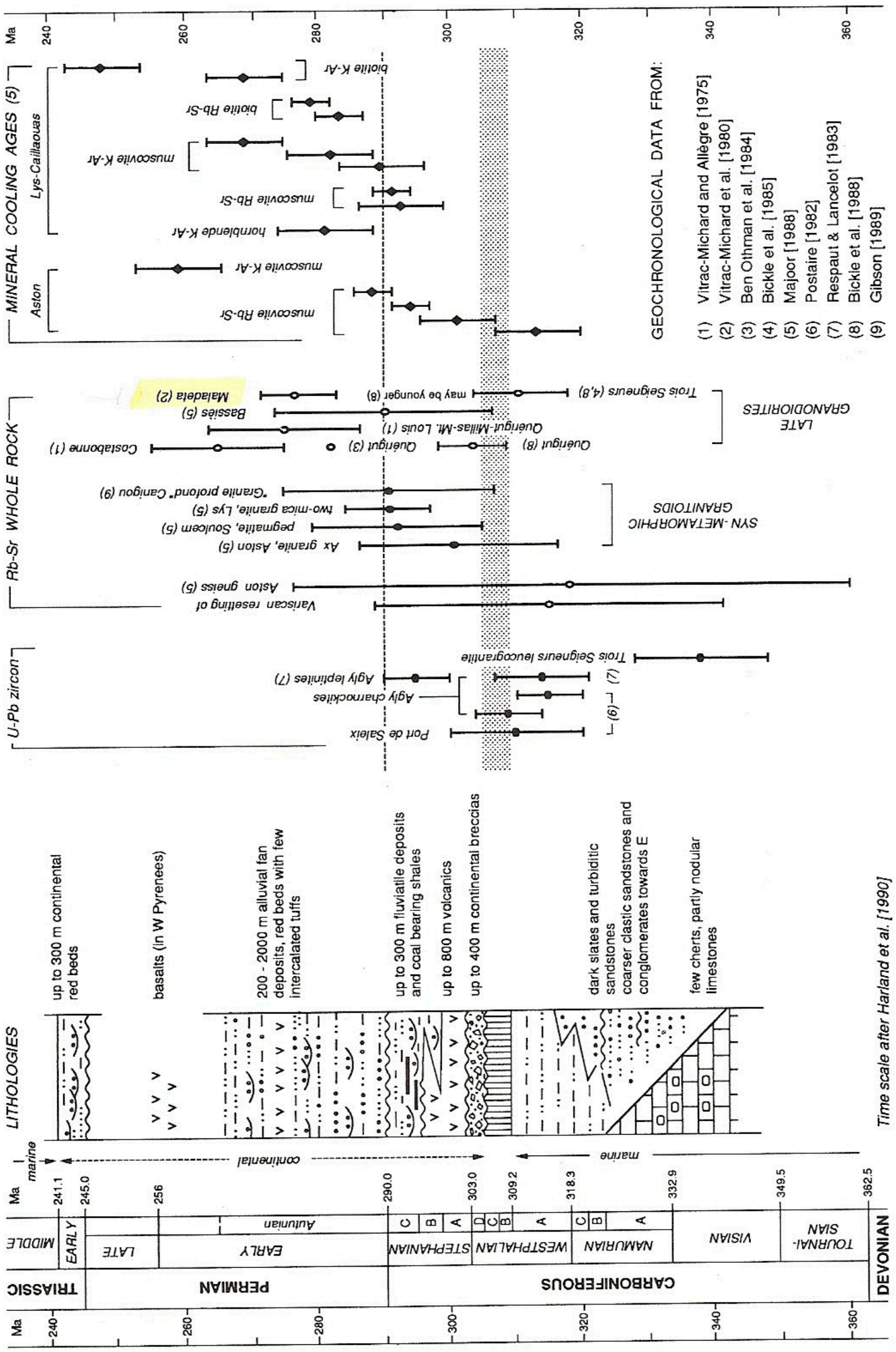


Fig. 3. Late Paleozoic sedimentary record, with a compilation of geochronological data on the metamorphic infrastructure and granitic intrusives. Shaded: time slice accentuating mid-Westphalian hiatus, stippled: Stephano-Permian boundary.

Fig. A-3 Geochronology

Late to Post-Variscan Sedimentary Record.
The Variscan basement rocks are unconformably overlain by up to 2500 m of non-metamorphic continental sediments with intercalated tuffs and basaltic andesite, ranging in age from the uppermost Westphalian to the Early Triassic (Fig. A-2 and A-3). These sediments, exposed mainly along the southern leading edge of the Axial Zone are characterized by highly variable thicknesses due to paleorelief and unconformities between and within units. The basal part consists of coarse-clastic breccias, sandstones, coalbearing mudstones and tuffs of Westphalian D age unconformably overlain by up to 800m of ignimbrite and basaltic andesite with intercalated slope breccia near the Segre valley. Up to 300 m of fluviatile sandstones, mudstones, and coal-bearing shales build an overlying sequence of Stephanian age in turn overlain by up to 1500 m of continental red beds and subordinate tuffs. These red bed deposits are commonly assigned to the Permian and are thought to have been deposited in E-W oriented tilted halfgrabens.

Variscan Structure
The Variscan rocks of the Pyrenees exhibit a polyphase structural evolution that in some domains is contemporaneous with magmatism and an associated LP-HT temperature metamorphism. The number of deformation phases recognized can vary considerably from place to place as well as from author to author. Thus, many interpretations remain and critical questions relating to the structural evolution and tectonic regimes involved in the Variscan Pyrenees are still under debate and controversial.

Structurally two domains can be distinguished in the Palaeozoic rocks: a low-grade suprastructure mainly with steep folds and cleavages, and a high-grade infrastructure with small-scale recumbent folds and low-dipping foliations.
The low-grade rocks form a typical slate belt, occupying a large part of the Axial Zone in which a number of major structural units can be distinguished. These are Cambro-Ordovician anticlinoria with in between synclinoria containing Devonian and Carboniferous rocks. A good example of a structure of this kind is the Llavorsi syncline, which can be followed over a large distance (Fig. A-1). Folds of dimensions varying in scale from hundreds of metres to centimetres are parasitic to the major structure. All these folds with E-W strike have an axial plane cleavage and are usually rather tight.

In the southern part of the Axial Zone a more complicated picture is present. From the geological maps the simple pattern of E-W folds is no longer present and instead structures with different directions are visible, as well as a typical “Schlingenbau”, sometimes with completely closed structures. The map pattern already suggests that this is due to the interference of fold generations. It proved to be the result of N-S to NE-SW terndring folds apparently predating the main cleavage phase as they are cut by a cleavage accompanied by small scale folds with an E--W orientation. These early folds are devoid of any cleavage, whereas the E-W trending cleavage has the same character as cleavages further north. Because its well developed lithostratigraphy this fold interference pattern is especially clear in Devonian rocks. There is some evidence, however, that also in the monotonous Cambro-Ordovician phyllites a similar succession of fold generations is present, which is not apparent from the maps, but can be deduced

from cleavage-bedding intersections, also varying in orientation instead of an E-W maximum (Speksnijder, 1986).
Folds postdating the main cleavage phase also occur at many places in the Axial Zone. They are seldom larger than a few meters, have no influence on the map pattern and are commonly accompanied by crenulation cleavages. Assignment of these cleavages to a certain folding phase is always based on overprinting criteria.

Variscan Events
The steep mainphase folds of the suprastructure clearly indicate ongoing crustal-scale shortening during the Westphalian, as rocks of that age are affected by folding. There is less evidence for contemporaneous crustal shortening at mid and lower crustal levels, but the relict early structures with steep enveloping surfaces suggest that the deeper portions of the Variscan crust also underwent thickening.
The structural data indicate that crustal-scale extension and development of flatlying infrastructure foliations and metamorphic domes postdate the steep mainphase folds affecting the Lower Westphalian. In the upper crust, Late Westphalian, Stephanian and Early Permian continental sediments of the extensional halfgrabens were deposited unconformably on Paleozoic rocks deformed by these steep structures. The majority of the geochronological data suggest metamorphic culmination between 300 and 290 Ma. The basaltic-andesitic volcanics intercalated in the Stephanian continental sediments of the extensional halfgrabens are evidently related to the extensional stage and suggest partial melting of the underlying mantle, while the Stephanian and Early Permian rhyolitic to andesitic tuffs are possibly related to the onset of the granodiorite intrusion. The huge volume of granodiorites in the Axial Zone are evidence of extensive lower crustal melting and a highly anomalous thermal structure, not only during but also after peak conditions in the metamorphic domes.
The late Hercynian suturing phases of the Pangea megacontinent led to modification of plate movements, which induced in Europe a phase of non-orogenic faulting. The associated magmatism was widespread and not so much related to the final phase of consolidation of the Variscan fold belts to the first phase of disintegration (Fig. A-4)

The above explanation for the Variscan events: compression followed by extension (Vissers) is contested by several authors (Carreras and Capella, 1994 and Abalos et al, 2006 in Gibbons and Moreno)

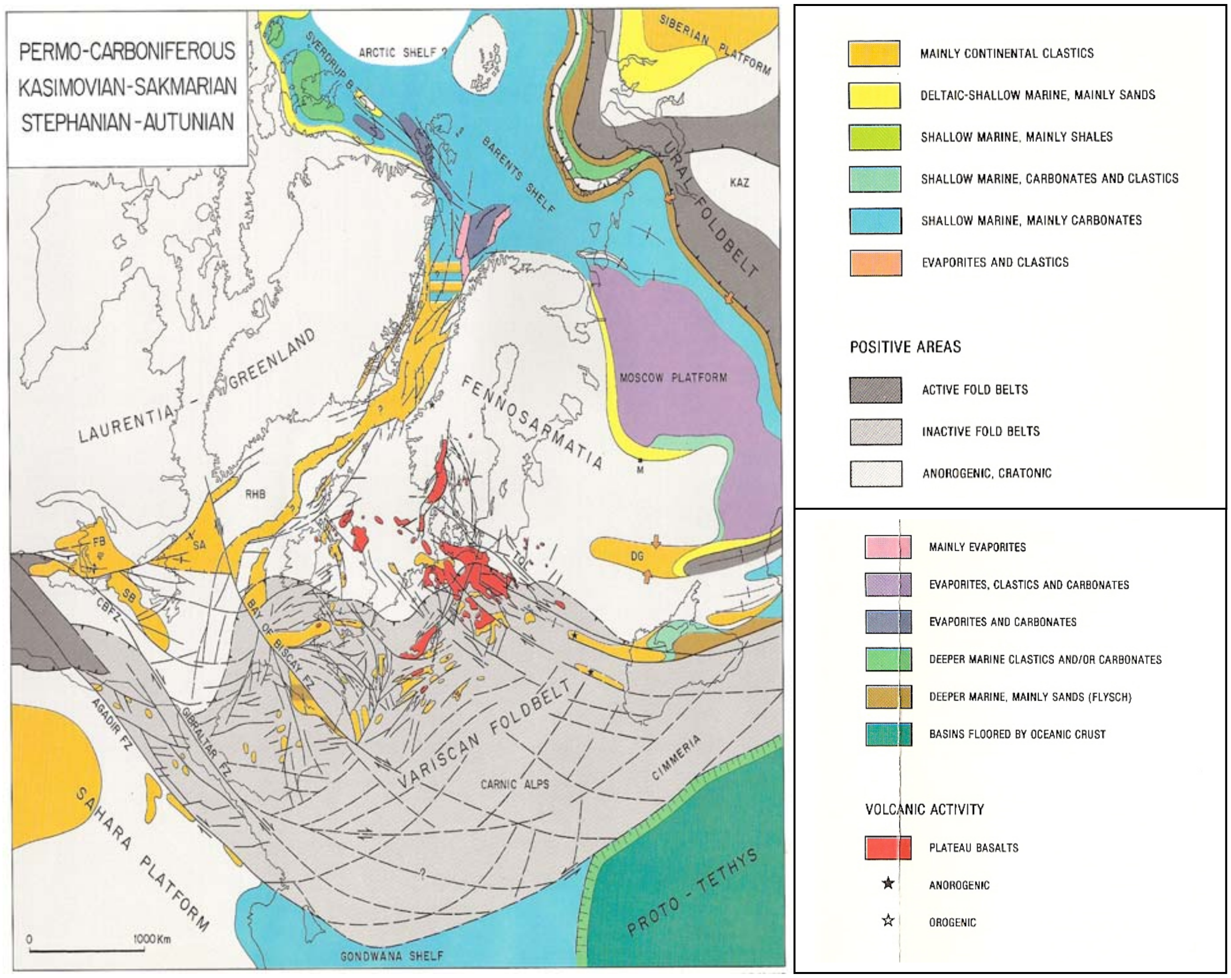


Fig.A-4 Permo-Stephanian Paleogeographic map: Consolidation of Pangea after the Hercynian Orogeny and initiation of desintegration features.

Alpine overprinting (after Muñoz,1992 and Saura and Teixell, 2006)

The Alpine overprinting in the Axial Zone is responsible for localized deformation along thrust zones (brittle and ductile), general doming and tilting of the Variscan structures, and for localized metamorphism along the North Pyrenean Fault. The effect of the thrusts was demonstrated by the ECORS deep seismic line shot in 1985-1986. This line provided many new ideas for interpreting the deeper crustal structure beneath the Pyrenees.

The structure of the Axial Zone is characterized by the stacking of several southward facing thrustsheets, which involve Variscan basement and an Upper Carboniferous to Triassic cover. These thrust sheets define a large antiformal stack that is built up by four main complex thrust sheets: Nogueres, Erta, Orri and Rialp (Fig. A-5). During progressive deformation, the location of new thrust ramps behind the overlying thrust sheet foretips resulted in forelandward rotation of previous thrust sheets. The uppermost thrust sheet (Nogueres thrust sheet is far-travelled and appears unrooted, now resting on a complex footwall flat on top of Triassic sediments. The outcrop area of this thrust sheet and the underlying Erta sheet is traditionally referred to as Nogueras Zone. Several distinct extensional basins of Stephanian–Permian age are involved, one of which is the Erill Castell basin in the Erta thrust.
The age of emplacement can be constrained by the Upper Eocene-Oligocene conglomerates. Based on contents of the debris, onlap relations and deformation, it is concluded that the emplacement of the Nogueres thrust sheet was dated as late Cretaceous to Middle Eocene as it preceded the sedimentation of the Sarocca calcareous conglomerate group attributed to the uppermost Eocene. The deepest and youngest thrust sheet is the Rialp thrust sheet, emplaced probably in the Oligocene.

1910 *E. Saura, A. Teixell / Journal of Structural Geology 28 (2006) 1909–1920*

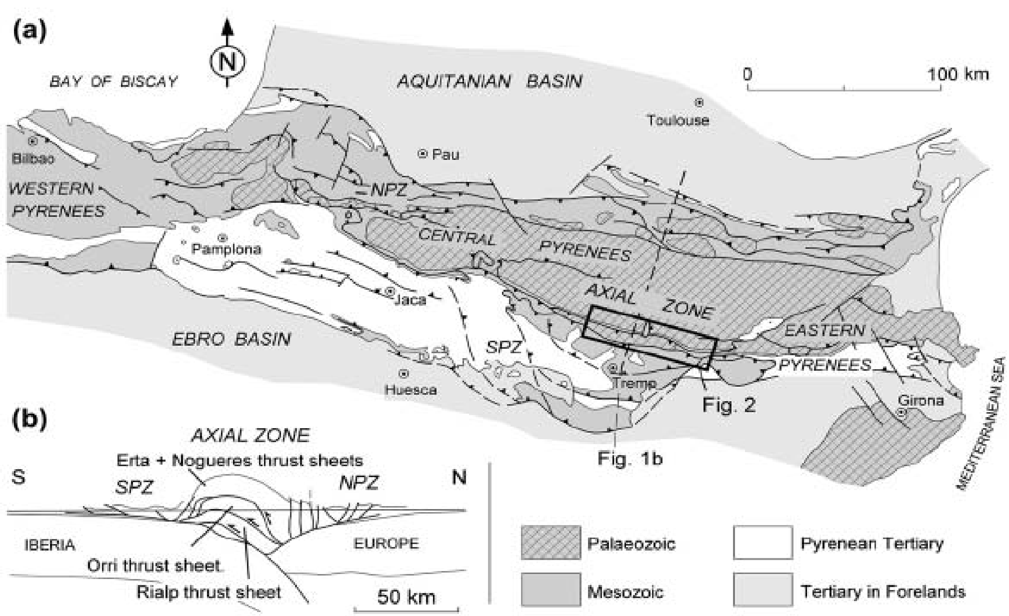


Fig. 1. a) Geologic sketch map of the Pyrenees showing the main longitudinal and transverse divisions of the chain and the location of the study area (after Teixell, 1992). b) Interpretation of the ECORS-Pyrenees deep seismic profile through the Pyrenean chain (after Muñoz, 1992), showing the main thrust sheets of the Axial Zone. SPZ: South Pyrenean Zone (cover thrust sheets); NPZ: North Pyrenean Zone.

Fig A-5

Part B Overview of the Tectonic Evolution of the Pyrenees

From: AAPG South Central Pyrenees Field trip compiled by J.A. Muñoz, J. Garcia-Sens, X. Berástegui and K. McClay

GEODYNAMIC SETTING OF INVERSION EVENTS

The Iberian Peninsula has a number of Cretaceous extensional basins which development was controlled by the opening of the North Atlantic and the Bay of Biscay as well as by the evolution of the Ligurian Tethys. These basins are not only present along the margins of the Iberian Peninsula but also in its interior. All these Cretaceous basins have been weakly to strongly inverted during the Alpine contractional events along the major orogenic belts surrouding the Peninsula as well as along intraplate ranges and uplifted areas (Fig. 1).

Extension in the Pyrenean domain began in the Upper Carboniferous-Triassic related to the post-Hercynian break-up of Pangea (Fig. 2). Most of the deposits are continental, including thick series of volcanics. This rift system played a role in the location of the E-W Cretaceous grabens. The Early and Middle Jurassic is a time of epicontinental seas in the North-Atlantic, with development of carbonate platforms. During the Late Jurassic-earliest Cretaceous times, rifting started in the North Atlantic related to the sea-floor-spreading system north of the Azores fracture zone. As a consequence, the North Atlantic area became domed up by thermal uplift (Ziegler, 1989). Thermal uplift around the J/K boundary caused an important drop in relative sea level and deep truncation of Jurassic rocks, giving place to a regionally correlative unconformity ("late Kimmerian" in the North Sea literature).

Early Cretaceous rifting lasted 45 Ma maximum in the northern basins of Iberia and Aquitaine and the postrift stage started around the Late Albian-Cenomanian boundary. Extension continued after the formation of the first oceanic crust in the Bay of Biscay. Hiscott et al.(1990) conclude that anomalous postbreakup subsidence may result from (1) gravitational adjustments of elevated continental blocks adjacent to warm, weak oceanic crust, (2) continued flow of salt at depth, or (3) tensional intraplate stress associated with oblique-slip faulting driven by the North Pyrenean fault. In our opinion, one clue that support the third is the odd factor of inversion events superimposed upon the general trend of crustal extension, and among these events, the Late Albian-base Cenomanian inversion was of special signifiance. On the one hand it involved the uplift of the Iberian craton with widespread occurrence of coarse clastics in the sedimentary basins (a fact sometimes referred as the "tectonic rejuvenation of Iberia") on the other –and this brings us to our objective- the high angle normal faults bounding the grabens were reactivated and the filling experienced low amplitude folding.

As thermal subsidence progressed along the Upper Cenomanian-Turonian, the sea submerged the lowlands occupied by inverted basins (Fig. 1). Rapid overstepping of the basin margins, rapid decrease in clastic influx and high sea levels are the main signals accompayning the transgression. The bottom of the open sea was covered by a drape of chalk-like calcareous facies with planktonic marine algae (calcispheres) and foraminifera and mass flows derived from the basin flanks.

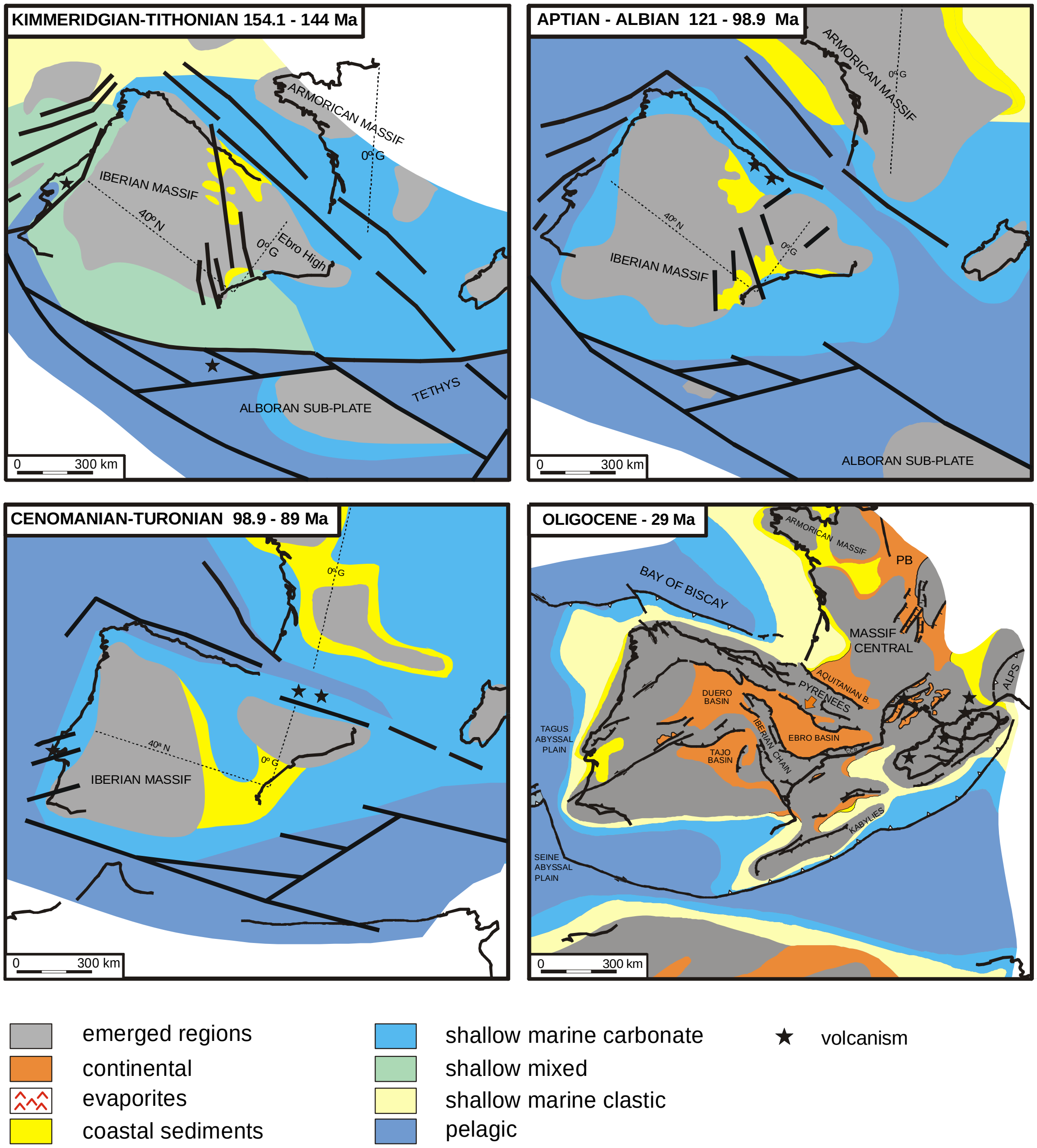


Figure 1.- Evolution of the Iberian plate during the pre-rift, syn-rift, post-rift and collisional stages. From Salas et al., 2000 (IGCP-369 project).

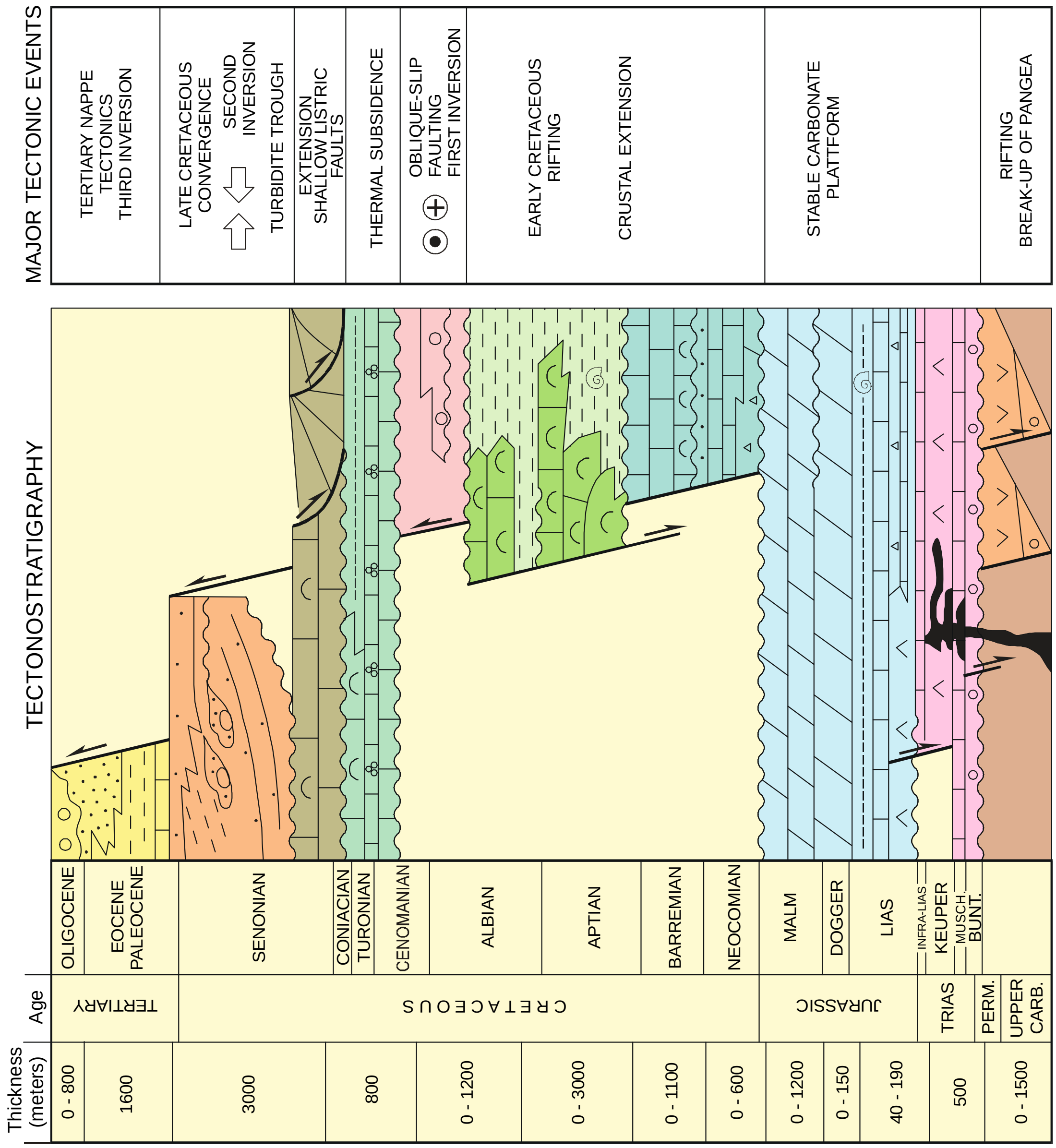


Figure 2.- *Chronostratigraphic diagram of the South-Central Pyrenees showing the main tectonic events which affected the Mesozoic basins.*

During the Senonian and Paleocene, northwest Europe was affected by intraplate compressional stresses that can be related to the Alpine collision of Africa and Europe (Ziegler, 1987). These stresses induced the inversion of Mesozoic basins in Central Europe (Fig. 1). One of the best places where the start of the collision has been studied and dated is the Southern Pyrenees. The Late Santonian-Maastrichtian compression is, however, of capital importance for the understanding of the inversion geometries because in this gap the basins underwent complete inversion.

MAIN GEOLOGICAL FEATURES OF THE PYRENEES

The Pyrenees is a doubly-vergent collisional orogen which resulted from the Mesozoic-Cenozoic interaction between the Afro-Iberian and European plates (Roest & Srivastava, 1991). It extends for some 1500 km from the eastern Alps, along the Mediterranean coast, to the Atlantic ocean northwest of the Iberian Peninsula. The range is flanked by two main foreland basins: the Aquitaine basin on the north and the Ebro basin on the south (Fig. 4).

The Pyrenees display different characteristics along strike. In the east, the Pyrenees were overprinted by the Neogene extensional features related with the opening of the Gulf of Lions and the drift of the Corso-Sardo block. The main part of the range between France and Spain corresponds with a continental collisional orogen. Here, the orogen developed over a previously thinned continental crust but without intervening oceanic crust between the two plates. Furthermore to the west, the oceanic crust of the Gulf of Biscay is involved in the Pyrenean orogen but, unlike most oceanic lithosphere, was only moderately subducted. Instead, deformation was mainly concentrated in the previously thinned continental crust south of the Gulf of Biscay oceanic zone.

The Pyrenees is a mountain range of tectonic inversion which is superposed on Triassic-Cretaceous extensional to transtensional rift systems. These are associated with the fragmentation of southern Hercynian Europe and western Tethys as a result of the break-up of Pangea, as well as the opening of the Central Atlantic Ocean and the Bay of Biscay, and the resulting rotation of Iberia (Roest & Srivastava, 1991). Convergence occurred from Campanian to Middle Miocene time as the Afro-Iberian plates moved generally northward against Europe. As a result, the earlier extensional structures were inverted, then incorporated into the thrust system.

The size of this orogen, the quality of the exposures, the unusually good preservation of the synorogenic strata and the knowledge of its lithospheric structure make of the Pyrenees a natural laboratory to investigate orogenic processes and foreland basin formation mechanisms.

The Pyrenees is characterized by a thrust system which displays an asymmetric double upper crustal wedge. In the central and eastern Pyrenees the southern wedge consists of an imbricate stack involving cover rocks (South Pyrenean thrust system) and an antiformal stack of basement rocks (Axial Zone). Both are southward directed. The northern wedge is formed by a northward directed imbricate stack (North-Pyrenean thrust system) involving basement and cover rocks (Fig. 5). The southern wedge is wider than the northern one. Correspondingly, displacement and cumulative shortening is also greater in the southern wedge. This asymmetry varies along strike, the greater being across the central Pyrenees.

In the southern Pyrenees the cover Upper Thrust Sheets (Muñoz et al., 1986) consist of Mesozoic and syntectonic Paleogene rocks which were initially detached from the basement over the Late Triassic evaporites. These thrust sheets were later on thrusted on top of authochtonous Paleogene rocks in continuation with the Ebro foreland basin (Fig. 5). They are the Central-South Pyrenean thrust sheets (Cotiella, Boixols, Montsec and Sierras Marginales) in the central Pyrenees and the Pedraforca thrust sheets in the eastern Pyrenees (Figs. 4 and 5). Mesozoic series is only tens of meters thick in the southernmost units and progressively thickens northwards up to 7km. This sedimentary wedge is the result of the progressive southwards thinning and pinch out of the Cretaceous stratigraphic units coupled with the geometry imposed by Cretaceous (mainly Early Cretaceous) extensional faults. The Upper Thrust Sheets show numerous oblique and lateral structures, probably related to the original Mesozoic basin configuration. From these structures an approximately N-S transport direction can be deduced. Location of thrusts is strongly controlled by previous extensional faults, mainly Lower Cretaceous in age. Inversion tectonics is a structural feature of the Upper Thrust Sheets.

Below the Upper Thrust Sheets the lower south-Pyrenean thrust sheets are characterized by an incomplete and reduced Mesozoic series overlain by Paleogene foreland basin platform and turbiditic sequences deposited forwards of the previously emplaced Upper Thrust Sheets. These cover series unconformably overlie upper Palaeozoic basement rocks. Mesozoic series is absent in the lower thrust sheets of the eastern Pyrenees (Cadí thrust sheet) and only represented by Upper Cretaceous sequences in the central Pyrenees (Gavarnie thrust sheet).

To the north and below the cover imbricate thrust sheets, basement rocks constitute an antiformal stack (Axial Zone). This antiformal stack only involves upper crustal rocks, its floor thrust being located at 15 km depth below the top of the basement. It is constituted by three main structural units: Nogueres, Orri and Rialp thrust sheets (Fig. 5, Muñoz, 1992). The Nogueres thrust sheet is the uppermost of the antiformal stack and its southern tip is the basement of the lower cover thrust sheets. In the central Pyrenees the contact between the cover Upper Thrust sheets and the basement antiformal stack corresponds to a passive-roof backthrust (Morreres backthrust). During the development and southwards displacement of the basement antiformal stack the cover units have been wedged northwards and up the top of the basement, similarly as described in other orogenic belts.

The basement antiformal stack is bounded to the north by the North Pyrenean fault (Figs. 4 and 5). This is a major strike-slip fault which developed during the sinistral displacement of Iberia during the Middle Cretaceous (Choukroune, 1976). The fault evolved from an initial Albo-Cenomanian transtensional regime with the formation of pull-apart basins and the development of a thermal metamorphism (Debroas, 1990; Goldberg and Maluski, 1988) to a later transpressional regime during the onset of convergence in Early Senonian time (Puigdefabregas and Souquet, 1986; Debroas, 1990). Lower crustal granulitic rocks as well as ultrabasic upper mantle rocks (lherzolites) are observed embedded between the Early Mesozoic metamorphic rocks along a narrow strip parallel to the North Pyrenean fault (Choukroune, 1976; Vielzeuf and Kornprobst, 1984). These rocks were carried to upper crustal levels during the strike-slip faulting. Apart from this narrow strip parallel to the North Pyrenean fault neither post-Hercynian metamorphic rocks nor lower crustal rocks are observed at surface in the Pyrenees.

North of the North Pyrenean fault, north-directed thrusts involve basement and cover rocks (Figs. 4 and 5). The Hercynian basement forms culminations, the so called North Pyrenean massifs. The non metamorphic and weakly deformed character of the Upper Cretaceous turbiditic series which unconformably overlie basement rocks of the North Pyrenean massifs (e.g. Trois Seigneurs) contrasts with the strongly deformed Jurassic and Lower Cretaceous metamorphic rocks outcropping in the North Pyrenean fault zone. The structural style of the north Pyrenean thrust sheets is strongly controlled by the inversion of the Early Cretaceous extensional faults. The north Pyrenean frontal thrust coincides

with a previous major extensional fault as evidenced by a several km thick Early Cretaceous synrift sequence in its hangingwall and the presence of several basement short cuts along the thrust.
Deformation of the Pyrenean double-wedge migrated outwards in a piggy-back manner, although synchronous hindwards internal deformation has been also documented. The forward propagation of the deformation in the southern Pyrenees was modified, in the last stage of the evolution of the thrust-belt, by a break-back reactivation of the older thrusts and by the development of new, minor out-of sequence thrusts affecting syntectonic deposits (Martínez et al., 1988, Vergés and Muñoz, 1990). Thrust transport direction was constantly N-S to NNE-SSW through most of the tectonic evolution as deduced by the map pattern of the structures, kinematic criteria along thrust planes and the absence of significant rotation around a vertical axis along the analyzed cross-section (Dinares et al., 1992). This implies a near normal convergence through the main orogenic phase.

FORELAND BASINS

Since the initial stages of the Pyrenean collision at Late Santonian-Campanian times two foreland basins developed, one in each side of the double-wedge (Figs. 4 and 5). The northern foreland basin, the Aquitaine basin, consists of a thick (few km) succession of Upper Cretaceous turbidites overlain by an up to 4km thick Paleogene series. Most of the latter are represented by continental deposits as only marine platform sediments of Early Ypresian age are observed (Buy & Rey, 1975). The Aquitaine basin mainly developed in the footwall of the north-Pyrenean frontal thrust and was not greatly involved in the north-Pyrenean thrust system.
The south-Pyrenean foreland basin is wider in planform and has a thicker composite succession than the Aquitaine basin. Its filling is characterized by an alternance of marine sediments (Late Cretaceous and Early-Middle Eocene) and continental deposits (Paleocene and Late Eocene-Miocene). The first synorogenic deposits consist of Upper Cretaceous turbidites and marls which grade upward into a Latest Cretaceous-Palaeocene shallow water and continental succession. The Eocene series above is characterized by thick, mainly marine sediments with strong lateral variations in facies and thickness as a result of basin partitioning and development of piggy-back basins (Tremp-Graus and Ager basins) during the southward displacement of the Upper Thrust Sheets (Puigdefrebregas et al., 1986, 1992). The piggy-back basins contain lower Eocene platform and continental terrigenous facies that grade in the footwall of the Upper Thrust Sheets into deeper marine turbidites and pro-delta marls (Mutti et al., 1988). These marine Eocene successions were incorporated into the south-Pyrenean thrust system and were overthrust on top of initially marginal facies, as a result new piggy-back basins developed below the previous ones (Jaca basin in the central Pyrenees and Ripoll basin in the eastern Pyrenees). The autochthonous part of the south-Pyrenean foreland basin, southward the south-Pyrenean frontal thrust, is known as Ebro basin. It is mainly filled by the last stage continental sediments of the foreland basin after the Early Priabonian evaporites. These evaporites represent the closing of the Ebro basin. Upper Eocene-Lower Miocene continental clastics filled the enclosed basin and progressively backfilled

and buried the south-Pyrenean thrust system during its late stages of development (Coney, et al., 1996).

GEOPHYSICAL DATA AND CRUSTAL STRUCTURE

The crustal and lithospheric structure of the Pyrenees has been constrained by different geophysical techniques (deep reflection and refraction seismic profiles, gravity, magnetotellurics, magnetic anomalies, tomography, heat flow. The data that best constrain the Pyrenean crustal structure are from the deep seismic reflection profiles, mainly the ECORS-Pyrenees profile (Choukroune et el., 1989). This profile has been interpreted to show the subduction of the Iberian plate below the European one and has been the basis for the construction of crustal balanced cross-sections (Roure et al., 1989, Muñoz, 1992).

Several different interpretations of the crustal structure of the Pyrenees have been given on the basis of the combined geological and geophysical data (Roure et al., 1989, Mattauer, 1990, Muñoz, 1992). We believe that an explanation in which the orogenic double-wedge involves only upper crustal rocks provides the best geometry in which to integrate all these data (Fig. 5). Apparently, the crust was decoupled and the lower crust, below the upper crustal double-wedge, was subducted together with the lithospheric mantle into the mantle. This inferred crustal subduction is compatible with other geophysical data as well as the absence of post-Hercynian metamorphic rocks or lower crustal rocks in the Pyrenean orogenic double wedge. Subduction of the lower crust has also recently corroborated by a tomographic analysis (Souriau & Granet, 1995) and by a magnetotelluric profile across the central Pyrenees (Pous et al., 1995). In this profile the presence of a very high conductive zone at lower crustal and mantle depths below the basement antiformal stack is interpreted as the subducted lower crustal slab partially melted during the post-orogenic thermal reequilibration (Pous et al., 1995). The deformation style of orogens involving crustal subduction has also been reproduced by numerical models (Beaumont & Quinlan, 1994). These authors concluded from an initial test for the Pyrenees that simple models involving lower crustal subduction best explain the observed features. Their initial models have been recently refined and integrated with the geodynamic evolution as deduced from the geological record (Beaumont et al., 2000).

Balanced and restored cross-sections

Balanced and restored cross-sections were constructed not only to integrate geophysical and geological data but also to estimate the amount of orogenic contraction (Fig. 7). A geometrical solution of a crustal cross-section of the central Pyrenees along the ECORS profile gave a total shortening of 147km (Muñoz, 1992). However, this value increases up to 160km if the internal deformation of the crust below the sole thrust of the Pyrenean thrust system is restored (Beaumont et al., 2000, Muñoz, 2002). Other cross-section restorations of the central Pyrenees have estimated shortening values over 100 Km (Deramond et al.,1985; Roure et al.,1989). A shortening calculation for a crustal cross-section in the eastern Pyrenees yielded a shortening estimate of about 125km (Vergés et al., 1995).

These shortening calculations are compatible with the estimated separation of the Iberian and European plates as deduced by reconstruction of the past motion of Iberia after paleomagnetic data (Roest & Srivastava, 1991, Olivet, 1996). These paleomagnetic data, as well as cross-sections west of the ECORS one, show that shortening decreases westwards. Shortening values of the order of 80km are reached to the west of the ECORS cross-section (Grandejan, 1992, Teixell, 1996, 1998).
The estimated duration of convergence in the central Pyrenees is about 60 Ma , which gives a mean shortening rate of 2.5 mm/yr. A similar shortening rate has also been deduced in the eastern Pyrenees during a shorter period of convergence (Vergés et al., 1995). The latest deformation migrated westwards. It stopped during Middle Oligocene time in the eastern Pyrenees and continued to the Middle Miocene in the westernmost Pyrenees (Vergés, 1993). In the central Pyrenees, along the ECORS cross-section, deformation ended by Early Miocene times.
The restored cross-section gives an estimate of the geometry of the crust before the Pyrenean collision (Fig. 7). The geometry of the inherited structures (Hercynian cleavage and thrusts, Late-Hercynian extensional faults and Early Cretaceous extensional system) display a listric geometry over the lower layered crust. Most of these structures dip to the north. This geometry has been observed in the undeformed part of the ECORS-Pyrenees profile, deduced after the restoration or by comparison with other areas. The restored crustal geometry is consistent with the areas in the vicinity of the Pyrenean domain that were affected by the Mesozoic extensional events but were not subsequently deformed by contractional structures, e.g. those areas located in the Aquitaine foreland (Le Pichon & Barbier, 1987, Pinet et al., 1987, Boillot & Malod, 1988, Marillier et al., 1988). A similar geometry is observed in most of the BIRPS deep reflection profiles across the Mesozoic extensional basins of north-western Europe where the lower layered crust is not penetrated by the upper crustal extensional faults (Cheadle et al., 1987). The location of these discontinuities favoured the delamination of the crust, the upper part forming an orogenic double wedge. The crust below this intracrustal detachment was subducted beneath the European crust.

GEODYNAMIC EVOLUTION

In the Pyrenees the geometry of the thrust structures as well as their ages are constrained by the exceptionally well preserved synorogenic strata. This allow us to estimate the variation of the crustal structure through time and to construct partially restored cross-sections between the restored cross-section before the collision and the present state (Fig. 7). Partial restored cross-sections have been made using an area mass balance and taken into account the shortening partitioning between the two sides of the orogenic double-wedge, the planform extent and depth of the foreland basins and paleotopography where preserved (Muñoz, 1992, Vergés et al., 1995). These partial restored cross-sections integrate the crustal structure deduced from geophysical data and summarize the available information on the geodynamic evolution of the Pyrenees from geology. They are being the basis for comparison with numerical models with the idea to gain insight into the fundamental processes of orogenic growth and foreland basin development (Millan et al., 1995, Beaumont et al., 2000, Muñoz, 2002).

The restored cross-section shows an Early Cretaceous extensional system which evolved, in Late Albian-Early Cenomanian, to a combined sinistral strike-slip and extensional dip-slip fault system, driven by the North Pyrenean fault. This fault penetrated the crust and probably the whole lithosphere.

After a period of transpression along the North Pyrenean fault between the Cenomanian and the Santonian (Puigdefabregas & Souquet, 1986), the first stage of N-S convergence (Late Santonian-Maastrichtian) inverted the previous Early Cretaceous main extensional faults. The geometry of this system as well as the location of the intracrustal weak detachment zones not only determined the structure at surface but also at a crustal scale. Inversion tectonic features, dominant in the northern Pyrenees, occur in the Upper thrust sheets of the southern Pyrenees. They are also spectacular in the westernmost Pyrenees where the reactivation of the Early Cretaceous extensional faults was coeval with diapiric flow of thick Triassic evaporites. Numerical geodynamical modelling corroborates the idea that the tectonic style of the Pyrenees and partitioning of the deformation between both sides of the orogenic double-wedge is strongly influentiated by the inversion of previous extensional features (Beaumont et al., 2000). This conclusion can also be inferred from the structural pattern variations along the strike of the chain. Strongly subsident troughs filled by turbidites developed in the footwall of the inverted faults. These deep marine foreland basins of the initial stages were superimposed on previous marine post rift basins developed during a thermal subsidence phase (Brunet, 1986).

The Palaeocene was a time with relatively low plate convergence between Europe and Africa (Roest & Srivastava, 1991). In the eastern and central Pyrenees, the Lower Cretaceous extensional faults were completely inverted; thus the stretched upper crust recovered its initial pre-Cretaceous length, and probably the whole crustal also attained its pre-Cretaceous crustal thickness. The eastern and central parts of the foreland basins changed from marine to continental as topography developed and the amount of eroded material was sufficient to fill the basins. In the western Pyrenees the crust would have recovered its initial thickness later than in the central and eastern Pyrenees as a result of a greater extension of the Pyrenean crust during Early Cretaceous times coupled with a younger and lesser amount of convergence. In this area Palaeocene rocks are represented by deep-water carbonate and siliciclastic sediments deposited in continuity with the Upper Cretaceous turbidites (Pujalte et al., 1989).

During the Early-Middle Eocene the thrusting rate increased. Both foreland basins experienced a deepening which resulted into the widest extension of marine deposits in the Pyrenean foreland basins (Puigdefabregas et al., 1992, Burbank et al., 1992). The thrust front in the southern side of the central Pyrenees strongly advanced because deformation of the Mesozoic wedge on top of a weak detachment level (Triassic evaporites). Shallow marine deposits were deposited in the foreland as well as in the piggy-back basins which demonstrate a subhorizontal mean topography over the southern frontal wedge. Strongly subsident troughs filled by turbiditic sequences were developed southward the uplifted basement in the footwall of the Upper thrust sheets. Some relief existed hindwards as evidenced by the N-S river systems supplying basement clastics and by the geometry and location of proximal alluvial fans. A maximum topography of 1-2

km has been calculated based on paleotopographic reconstructions and flexural modelling (Vergés et al., 1995, Millan et al., 1995). Flexure of the Iberian and European plates was produce by a combination of topographic loading and subduction loading (Millan et al., 1995, Beaumont et al., 2000). The northern frontal thrust was mainly pinned and no piggy back basins developed in the Aquitaine basin.
The last stage (Late Eocene-Middle Miocene) of the Pyrenean orogenic growth is characterized by a change of deformational style (Fig. 7). Iberian upper crustal units were underthrusted below the previously southwards displaced basement and cover units. A basement antiformal stack developed in the middle of the chain synchronously with further southwards overthrusting of the southern lower cover thrust sheets on top of the foreland. The geometry of the emergent thrust front as well as the foreland structure of the southern Pyrenees were strongly controlled by evaporitc horizons deposited in the foreland basin succession (Vergés et al., 1992, Sans et al., 1996). In the northern Pyrenees frontal thrust migrated 6km into the foreland. At this time both foreland basins were filled by continental deposits. Relief and erosion rates increased. The Ebro basin became closed and separated from the Atlantic because the tectonic relief growth during the inversion of the Early Cretaceous basins in the western Pyrenees. Erosional debris of the Pyrenees and other surrounding chains of the Ebro basin (Iberian and Catalan Coastal Ranges) progressively filled the basin and then backfilled, to bury the flanking thrust belts on its margins (Coney et al., 1996). This progressive backfilling forced deformation to migrate hindwards and as a consequence reactivation of previously developed thrust structures and break-back thrust sequences occurred (Vergés & Muñoz, 1990, Burbank et al., 1992b). The southern Pyrenees were almost completely buried by Early-Middle Miocene times.
The present fluvial system developed as a consequence of the abrupt and subsequent Miocene-Pliocene re-excavation of the southern Pyrenees and subsidence of the Ebro basin in combination with the Miocene rifting of the western Mediterranean and the Messinian desiccation crisis. River incision has also been favoured by the ongoing post-orogenic isostatic rebound during the thermal re-equilibration of the lithospheric root and the subducted lower crust (Pous et al., 1995).

THE LATE TECTONIC EVOLUTION OF THE PYRENEES

The southern Pyrenees is an exceptionally well preserved example of the interaction between foreland sedimentation and thrust kinematics as well as the post tectonic evolution and exhumation of an orogenic belt (Coney et al., 1996, Muñoz et al., 1997). At Early Priabonian times the south Pyrenean foreland basin was cut-off from the Atlantic ocean by uplift of the western Pyreanean thrust sheets. As a result, the Ebro basin became a closed basin, its relative base level started to rise and the southern Pyrenees as well as other surrounding orogens started to be buried by their own erosional detritus (Fig. 8). What is relevant and well supported by excellent exposures is that the progressive burial of the frontal parts of the orogens changed their thrust kinematics. Tectonic activity migrated hindwards back to the maximum extent of the burying syntectonic conglomerates. As a result break-back thrust sequences developed and older thrust structures were reactivated (Vergés & Muñoz 1990; Meigs, 1997). This change in thrust kinematics is well recorded in the central and eastern Pyrenees, because probably in these areas the syntectonic conglomerates buried the orogen relatively further toward the hinterland than in other areas. There is evidence of hindward migration of thrust activity during conglomeratic burial around all the orogens surrounding the Ebro basin: Sierras Exteriores in the western central Pyrenees (Millan et al. 1995, Millan 1996, Hogan & Burbank 1996), Catalan Coastal Ranges (Lopez-Blanco 1994, 1996) and Iberian Ranges (Guimera 1988).

In spite of the hindward migration of the thrust activity during the sytectonic burial, the thrust front remained active as the mountain ranges were continously contracted and overthrust on to the Ebro foreland (Vergés & Muñoz 1990, Burbank et al 1992, Coney et al. 1996).

The tectono-sedimentation relationships at the thrust fronts surrounding the Ebro basin, such as the tectonic uplift and the amount of local sediment supply, vary along strike and depend on the structural style (Sans et al 1996). In the eastern Pyrenees the foreland Oligocene continental sediments were detached on top of the Priabonian salts and the present thrust front is located further forwards of the emergent sole thrust of the south-Pyrenean thrust sheets. In the western part of the central Pyrenees, the foreland was not detached and the thrust front was strongly emergent and pinned at the southern pinch out of the Triassic detachment level (Fig. 8). In this area the thrust front (Sierras Exteriores) was progressively buried by Early Oligocene conglomerates (Campodarbe Group) as demonstrated by the onlap geometry of these conglomerates above the San Felices thrust sheet (Millan 1996). A similar thrust front geometry involving equivalent tecono-sedimentary relationships during conglomeratic burial is observed along the Catalan Coastal Ranges thrust front (Guimera 1988, Lopez-Blanco 1996), always demostrating thrust kinematics modified by the burial of the frontal parts of the mountain range. In the central Pyrenees, in the area described by Coney et al. (1996), the emergence of the south-Pyrenean thrust sheets at the thrust front also controlled local sediment supply to the conglomerates. In contrast to the late evolution of the thrust front of Sierras Exteriores and Catalan Coastal Ranges above explained, the emergence of the central Pyrenean thrust front and the hindwards migration of deformation during conglomeratic burial was coeval with extensive overthrusting of the south-Pyrenean thrust sheets on top of Late Eocene-Early Oligocene sediments of the Ebro basin (Figs. 4 and 8). We have to emphasize that migration of the thrust front towards the foreland Ebro basin is not in contradiction with the burial of the surrounding mountain ranges, because the conglomeratic burial was syntectonic and the thrust front was always active. The amount of thrust front migration was controlled by the existence of suitable detachment horizons in the foreland succession. The different geometries of the thrust front results in different tectono-sedimentation relationships during the conglomeratic burial of the mountain ranges around the Ebro basin.

The extent of the conglomeratic burial towards the hinterland of the mountain ranges as well as the provenance of conglomerates depend on the tectonic style of the orogens and mainly on the geometry of the thrust system involving basement rocks. These relationships are very well illustrated by the longitudinal variations of the tectonic style in the southern Pyrenees (Figs. 4 and 8). In the central and eastern Pyrenees, basement thrust sheets are piled one on top of the other forming a huge antiformal stack in the midde of the chain (Axial Zone). Uplift and exhumation is mainly located in this central part of the chain and sediment supply during the late continental foreland basin stage was mainly derived from the basement units. The pile of basement units flexed down the Iberian lithosphere and the late synorogenic conglomerates buried the south-Pyrenean cover thrust sheets south of the basement antiformal satck and even overlaped their eroded frontal basement units (Fig. 8, Coney et al. 1996). Towards the west, in the Jaca basin transect, the basement thrust sheets are not piled one on top of the other, instead they constitute a piggy-back imbricate stack underthrusted below the cover units (Fig. 8, Camara & Klimowitz 1985, Teixell 1996). As a result, uplift was not concentrated in the centre of the chain during its late tectonic evolution but distributed in a wider area as younger basement thrust sheets were underthrust towards the foreland. The Late Eocene-Early Oligocene synorogenic continental deposits (Campodarbe Group) covered most of the south-Pyrenean cover thrust. Similarly with the eastern areas, these conglomerates unconformably overlie older structures and forced the hindwards migration of the deformation into the thrust wedge while the front was active.

The younger conglomerates in the central Pyrenees contain pebbles derived from both the basement units of the Axial Zone and local sources related with the emergence of the thrust front and reactivated structures into the thrust wedge.

REFERENCES:

References in the original AAPG South Central Pyrenees Field Trip Guide covered more than 7 pages and have been deleted in the present guide, but can be obtained from Berend or Karel

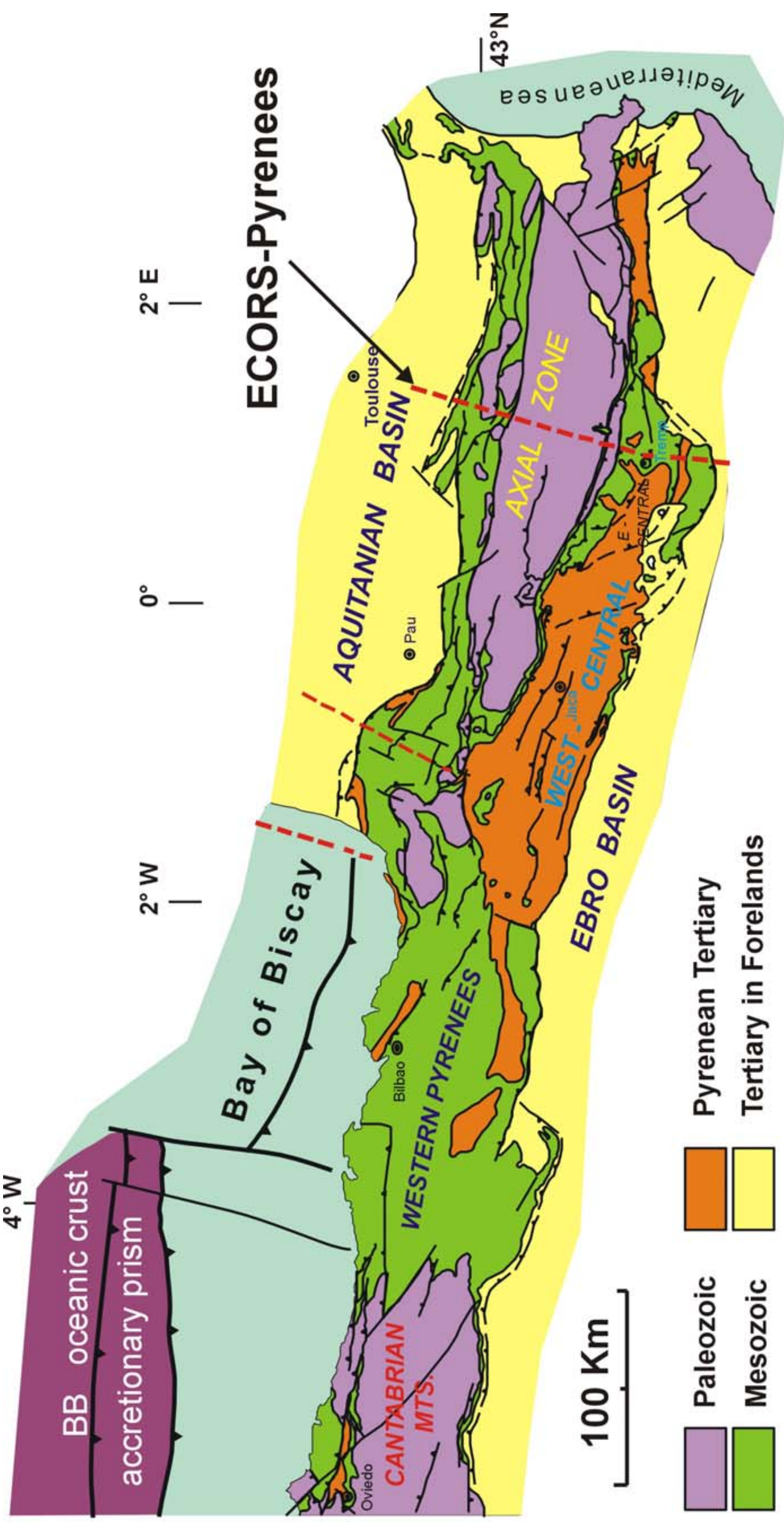


Figure 4.- Structural map of the Pyrenees.

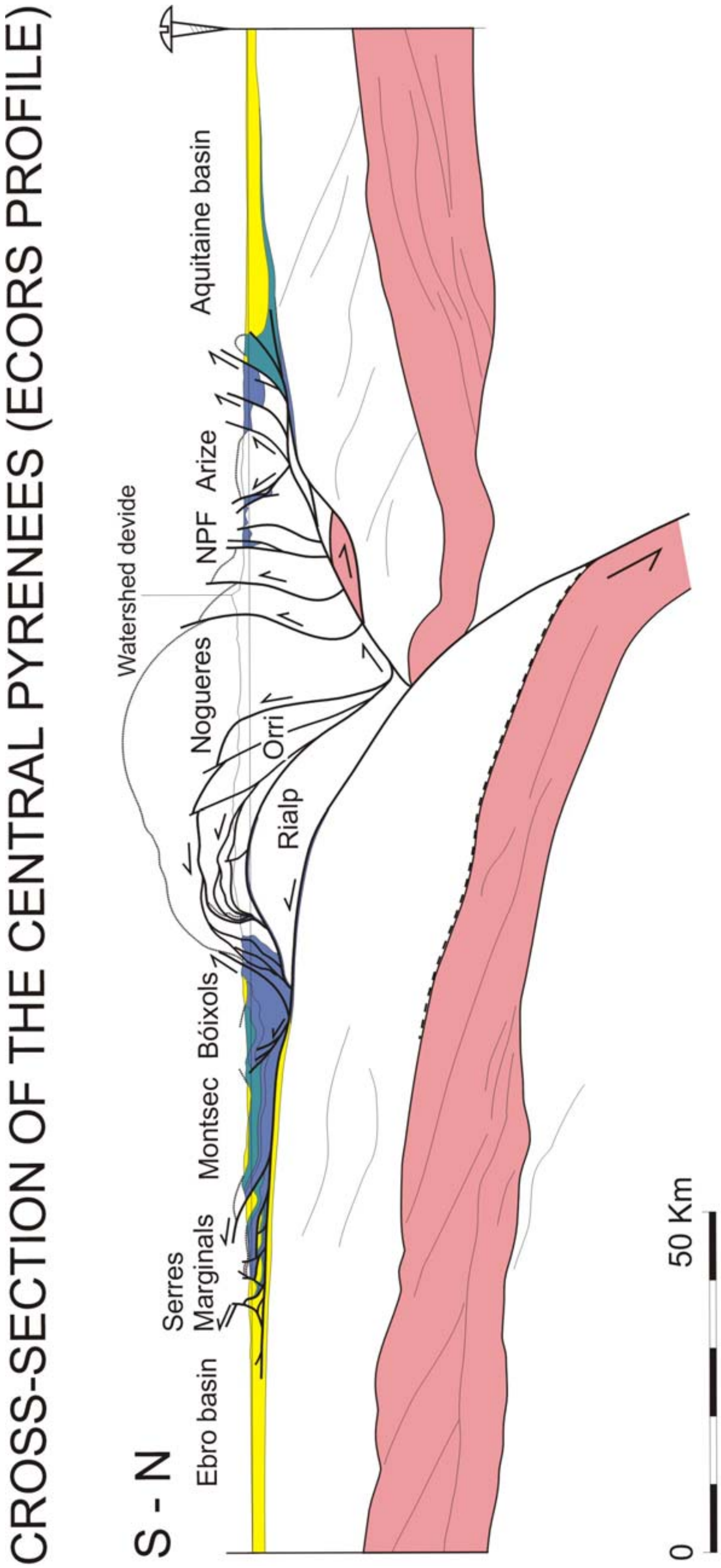


Figure 5.- *Crustal scale cross-section through the central Pyrenees. See Fig. 4 for location*

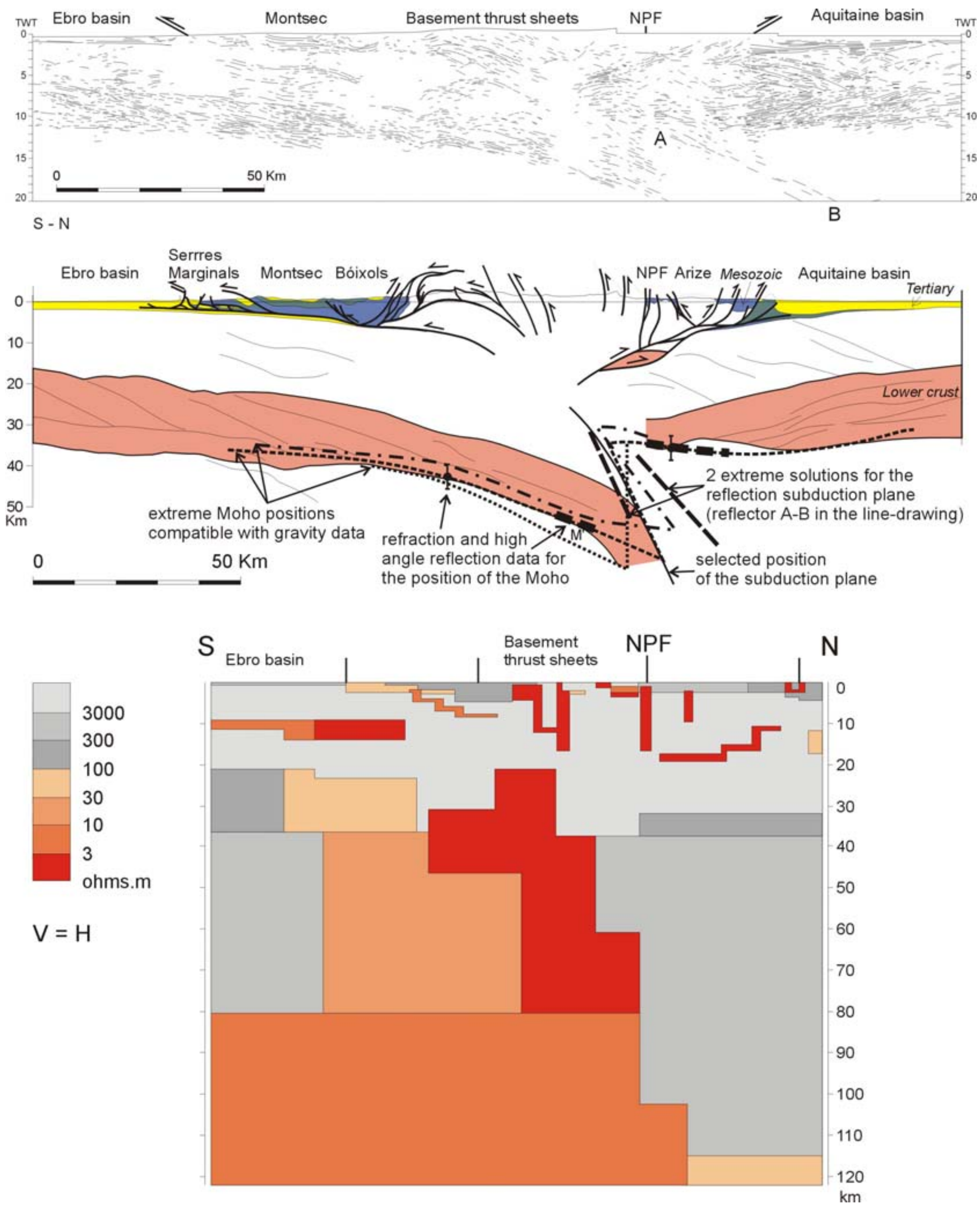


Figure 3 *Geophysical data of the Central Pyrenees along the ECORS transect. Reflection time section of the ECORS section of the ECORS profile (top). Interpreted cristal structure based on geophysical and geological data (centre): gravity constraints from Torné et al (1989): high angle reflection and refraction data from Daigniéres et al. (1989); geological data from Muñoz (1992). Main reflectors of the ECORS seismic profile have been depth converteed, taking into account gravity and reflection data, and then incorporated into the cristal geological cross-section.*

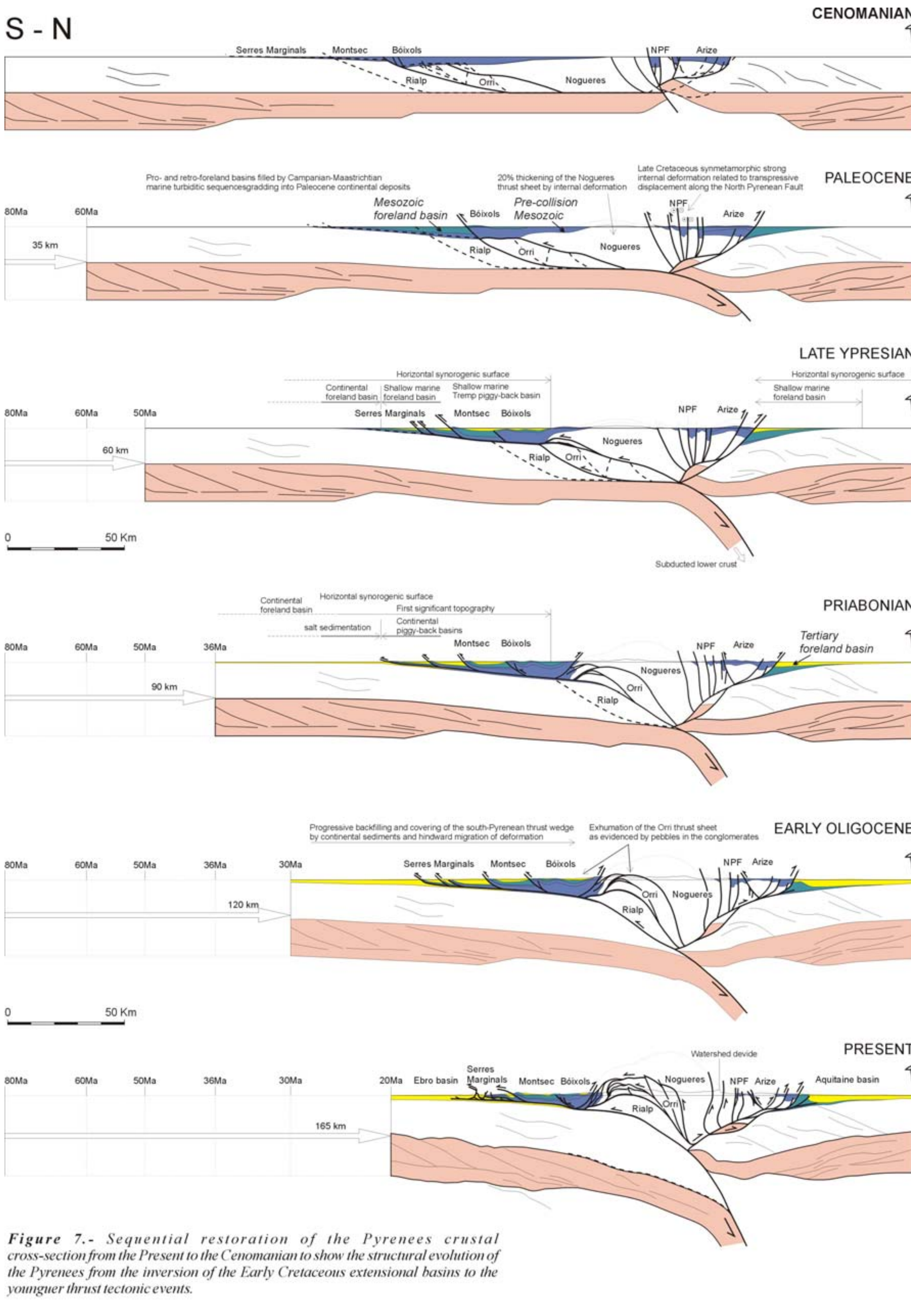


***Figure 7.-** Sequential restoration of the Pyrenees crustal cross-section from the Present to the Cenomanian to show the structural evolution of the Pyrenees from the inversion of the Early Cretaceous extensional basins to the younguer thrust tectonic events.*

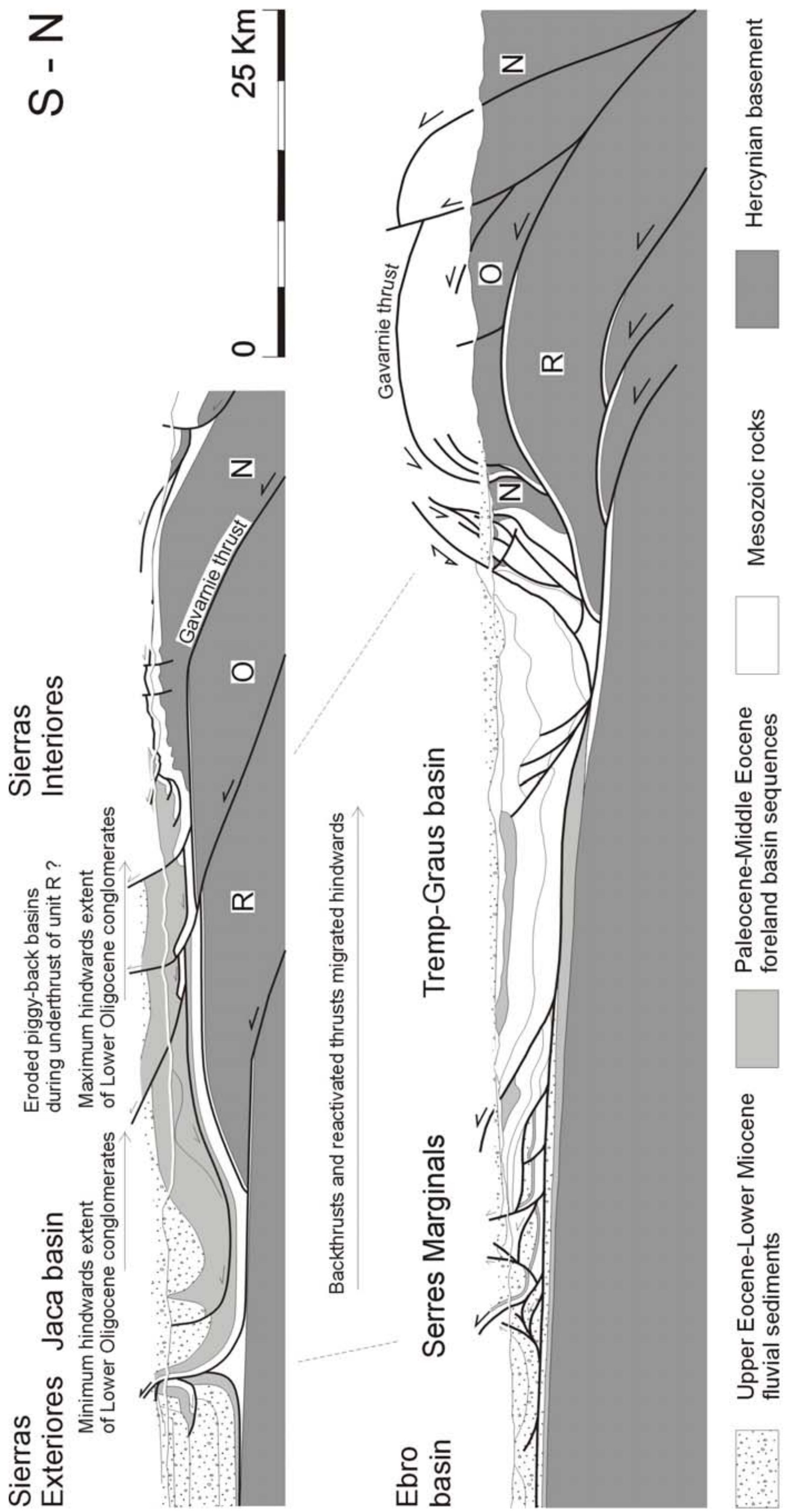


Figure 8.- *Cross-sections of the South-Central Pyrenees showing the position of the Late Eocene-Lower Miocene conglomerates.*

Part C Itinerary

Summary

Date	Day	Subject	Location	Leader
10/06	1	Meeting participants	Tremp	
11/06	2	Geological Introduction Variscan Orogenesis	Gerri de la Sal Llavorsi Syncline, Cardos valley	Xavi Berastegui Peter Mey Karel Roberti
12/06	3	Late stage Variscan Orogenesis	Perves Pass Erill Castell	Peter Nagtegaal
13/06	4	Alpine deformation in Axial Zone	Pallaresa valley	Peter Mey Karel Roberti
14/06	5	Pre-Pyrenean Phase	Tremp Basin Orcau	Peter Nagtegaal Orcauvins
15/06	6	First Pyrenean Closing Phase	Ribagorzana valley Isabena valley	Berend van Hoorn
16/06	7	Early Pyrenean movements	Esera valley	Berend van Hoorn
17/06	8	Departure		

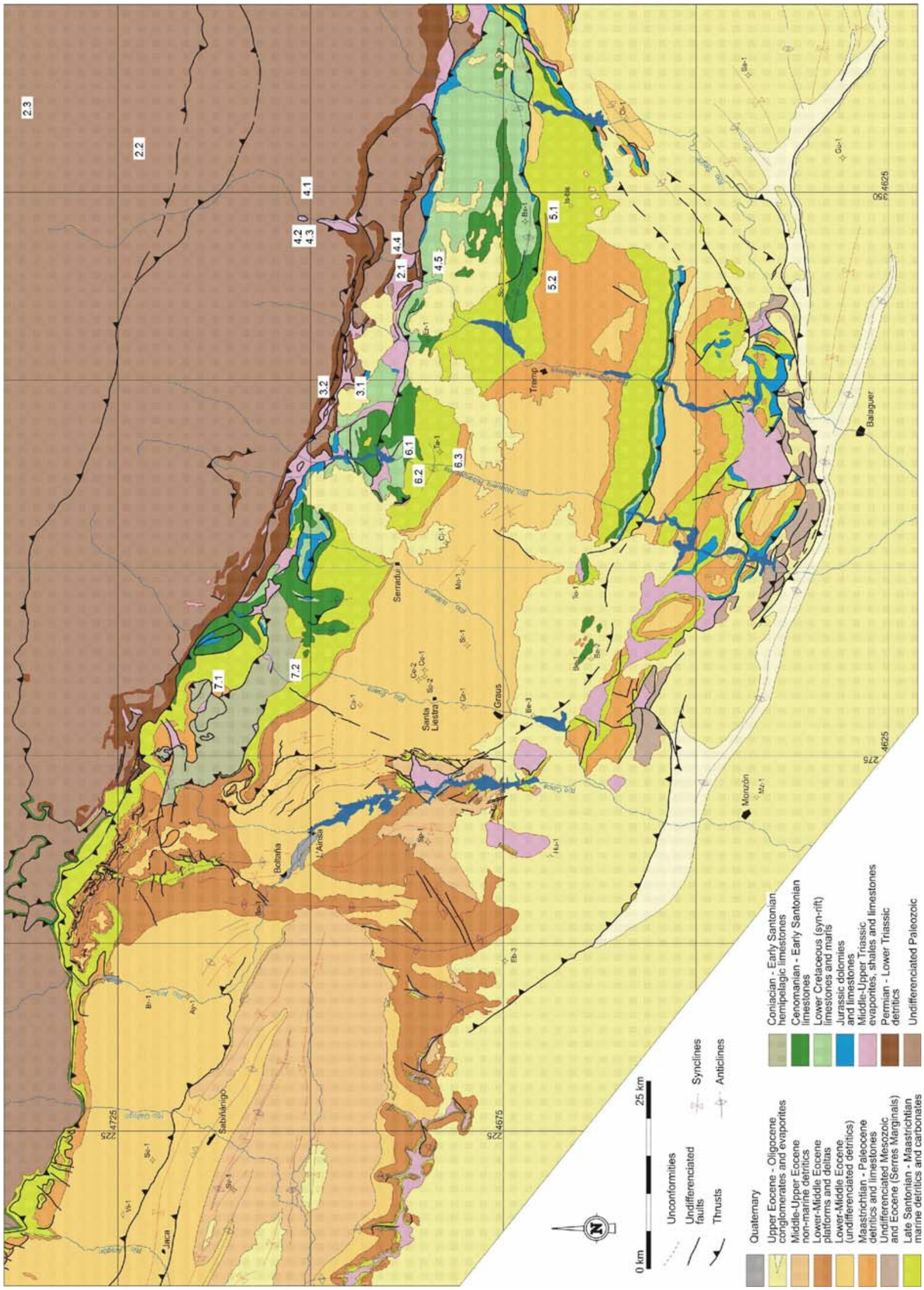


Fig. C-1 Geological map. Numbers refer to excursion stops

Day 2 11 June

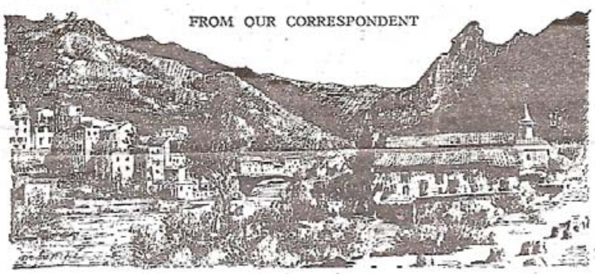
Stop 2.1 Gerri de la Sal

Introduction to the Geology of the Pyrenees by Xavi Berástegui of the Institut Geologic de Catalunya.

Gerri de la Sal was known by its local salt-making industry. The picture painted by the article of the Economist in 1962 belongs unfortunately to bygone ages. The salt pans have all but disappeared. The Benedictine monastery of Santa Maria founded in 807 is located on the eastern side of the Pallaresa River. The present 12th-century structure, with its huge and dilapidated bell-wall, faces the village on the far side of a beautiful bridge. (Source: *Marc Dubin, 2001.The Rough Guide to the Pyrenees*)

Pyrenean Paradise

FROM OUR CORRESPONDENT



SPANIARDS generally work so hard, for such appalling hours, that it is a relief to find a community whose way of life accords with our lazy northern myth about Spain. At Gerri, in the central Pyrenees, siesting and sitting in the shade really are major occupations. The sun does most of the work. The population lends a hand from time to time—but only for a few hours a day, and only in summer.

The shortest way to Gerri from the north is over the Col de la Bonaigua (6,000 feet). Beyond the col, the rough road winds first across a hillside as bleak as Dartmoor, then down through fragrant pinewoods that flash and quiver with cascading streams, finally along a valley lined with meadows and orchards. Briefly the valley becomes a gorge, then widens to form a basin luxuriant with both northern and Mediterranean vegetation. Here, glowing brightly in the sun on the right bank of the river, is Gerri.

"Gerri is a foretaste of paradise," said an old man who was sitting on the slender single-arch bridge that spans the river here. "If you want a fruit, you simply reach out your hand." He plucked a fig from the tree that grows happily from a crack in the stonework in the middle of the bridge. "Whenever you want trout for supper you just take them from the river. The climate is good and life is easy. Few people need to work more than three or four hours a day."

"Ours was the first Pyrenean valley to get rid of the Moors," another man explained. "This is our reward. Immediately the last Moor left, the spring began to flow."

The spring is a saline stream which gushes out of the mountain side on the edge of the village. Hollowed-out tree trunks distribute its waters to some 600 *salinas*—rectangular salt-pans whose average surface is about 30 square yards. Within three or four days the water has evaporated, the crystallised salt has been swept into dazzling little pyramids and removed, and the *salinas* can be refilled. In an average summer Gerri produces in this carefree way 2,000 tons of salt.

The *salinas* are privately owned—by about half the village's sixty families—but their output must be delivered at once to an ancient co-operative whose seat is the *Almacén de la Sal*, a beautiful salt-encrusted building, reputedly 800 years old, in the main square. The *Almacén* houses modern grinding and packing machinery (the salt is marketed in neat polythene bags), and a cinema, and most families have at least one wage-earner employed there.

There are storms, even in paradise. On the river bank opposite Gerri slumbers a tiny monastery, a jewel of Catalan Romanesque. "During the civil war it was damaged by the Reds," a villager said. He looked around and added: "Of course, the monks let the Nationalists store arms in several of these monasteries, in preparation for the uprising, so . . . ." He shrugged.

And now, though as yet no bigger than a Dutchman's hand, another storm is on the horizon. Booming Barcelona, 130 miles away, is ravenous for electric power. One way to increase the supply would be to build a dam across the Collegats gorge, one of the loveliest in the Pyrenees, a few miles south of Gerri, and flood the whole valley. Four charming Dutch geologists are now encamped in the gorge, chipping at the red and brown rock and asking one another whether it could stand the strain.

The people of Gerri are not alarmed. With the usual innocence of the over-privileged they assume that whatever corner of Spain they are evacuated to will provide them with as easy a living as Gerri—though one man, who has seen something of the outside world, said: "Surely they won't expect us to work on the land." His wife was more concerned about the salt. "You will never persuade me that they intend to let all this good salt run to waste," she said. "It's the purest salt in Spain—*es natural*. . . ." Her goitre quivered with pride.

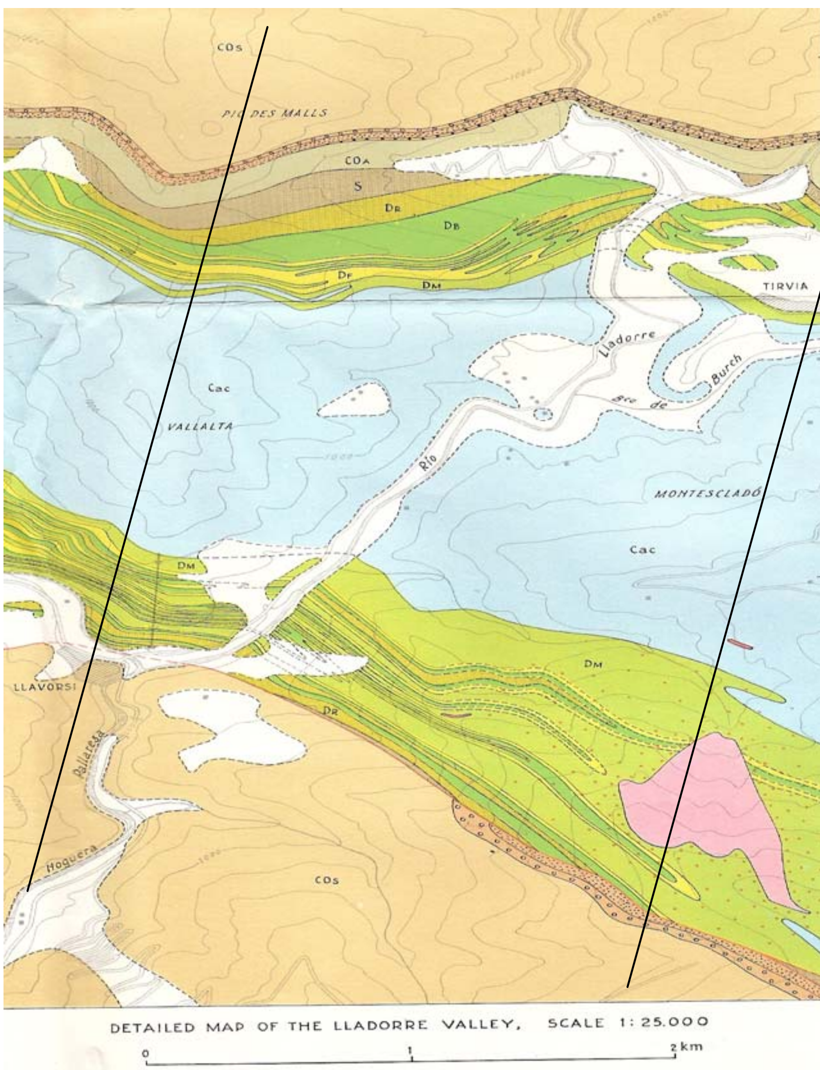
678 THE WORLD OVERSEAS THE ECONOMIST NOVEMBER 17, 1962

Stop 2.2 Variscan Orogenesis: Llavorsi Syncline

Location
Heliport Tirvia.

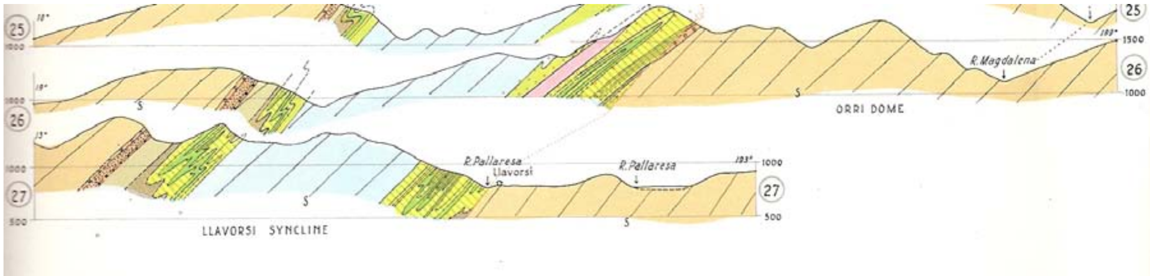
Objectives
Cleavage-bedding relationship on the northern limb of the Llavorsi Syncline

The Llavorsi syncline is a Variscan structure made up of Silurian, Devonian and pre-Varsican Carboniferous (Civis Fm) rocks. A Lower to Middle Devonian age is currently assigned to the Civis Fm. There are several folding phases associated with the formation of the Llavorsi syncline. The main folding phase, also responsible for the large map structure, is characterized by isoclinal folds overturned and developed on several scales. They are related to an ESE-WSW trending axial plane cleavage.



Part of sheet 10, Segre-Valiri (Jaap Hartevelt) , Section lines 27(W) and 26 (E)

For Legend , see p.



Cross sections 26 and 27 through Llavorsi Syncline

Stop 2.3 Llavorsi Syncline

Location

Pont de les Contioles, near junction road to Esterri de Cardos

Objectives

Multiple folding phases and crenulation cleavage.
Inspection of the corroded Leiden commemorative plate.

DAY 3 12 JUNE

Late stage Variscan Orogeny

Stop 3.1 Corrunco structure

Location
Perves Pass

Objectives
Pre-main phase folds in the Axial Zone

Corrunco: Anticlinal synform of Rueda Fm (dark colored rocks on crest) and synclinal antiform Basibé Fm (light colored) .

Stop 3.2 Erill Castell

Location

Village of Malpas, by foot to Erill Castell

Objectives

The Stephanian-Permian half-graben fill of Erill Castell

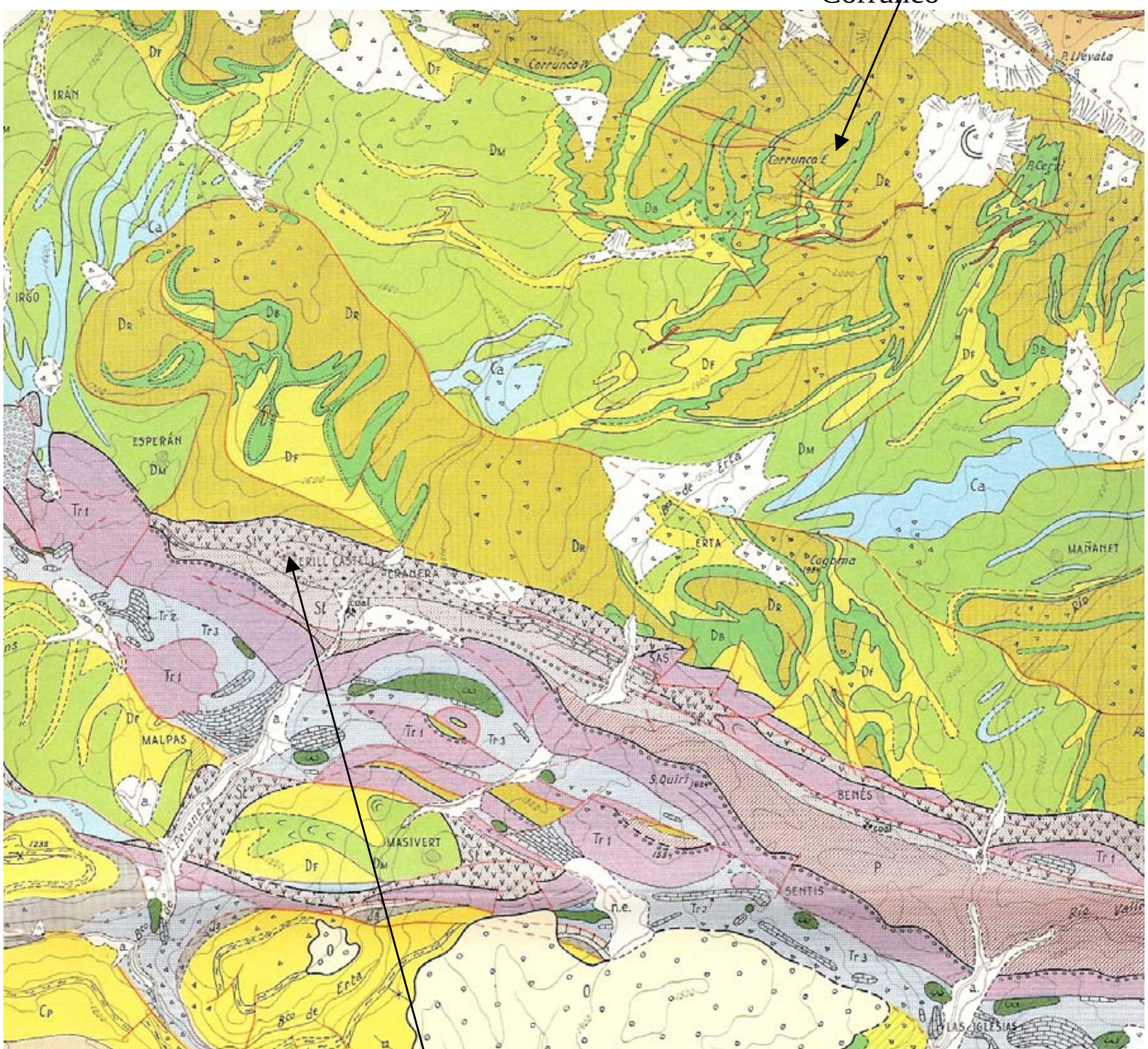
The Erill Castell half-graben fill has been seen and referred to by many and has been the subject of two more in-depth studies: by Nagtegaal (1969) and by Saura and Teixell (2006).
Nagtegaal focussed on sedimentary sequence and detailed sedimentary petrography while Saura and Teixell presented a convincing structural analysis of the southern edge of the Axial Zone including the structural setting and the inversion history of the small Erill Castell basin and two similar other small basins in the so-called 'Nogueras Zone'. These other two are the Estac and Gramós basins to the East, transsected by the Pallaresa and the Segre rivers, resp. (the Gramós basin fill was mapped and studied by Jaap Hartevelt). The sequence we will visit was tilted to the south prior to the deposition of the Triassic Buntsandstein and finally to a vertical position during the Pyrenean orogenesis in such a way that at surface we are actually looking at a cross section of the entire basin. We will walk, from bottom to top, through Stephanian volcanics (Erill Castell Volcanics, tuffs and andesitic lavas) and coal basin deposits (Malpas Formation). These are, at the location of the section, unconformably overlain by the Triassic (Bunter red beds). The unconformity has locally cut out the entire Permian section (Peranera Formation, red beds too, richly interbedded with volcanics). However, down in the valley on the east side a slice of the Peranera Formation can just be seen. The Permian red beds can be fairly easily differentiated from the Triassic ones as their sandstones are immature and dominated by rock fragments while the Triassic ones are mature and are rich in quartz and micas.
We will see a fascinating series of deposits ranging from fossil slope scree, richly textured tuffs and volcanic bombs, andesites, coal beds with plant imprints, siderite nodule horizons, volcanic sandstones and more.

If nowadays we stand in silence for 1 minute to honour our deceased, we should, at seeing the Permian section, spend at least the rest of the day standing here to commemorate the huge mass extinction of life that occurred at the time.

We all know too well that in geology things hang together. The Permian and the underlying Stephanian were deposited in a half-graben, very much like in many other extensional basins of this age in Europe (see Fig A-4). Many authors agree that this was a period of widespread extension although with local orogenic shortening. There is the volcanism in the sequence we study, the Axial Zone granodiorites are Permian, of the same age as the enormous Siberian traps, recording regional, up to 4 km thick sequences of basaltic lava flows. All this heralded the break-up of Pangea and Gondwanaland, and mainly from this peak of volcanic activity originated the global climatic change which brought about the Permian mass extinction with the loss of the largest percentages of life forms ever. The direct reasons for the disaster were an oxygen content in the air of only 16 – 12 %, an exceedingly strong greenhouse effect (CO2, CH4 and SO2) helped by an increased absorbtion of heat of the landsurface through the melting of the great glaciers of the Antarctic and Gondwanaland. The drama we see in the section has been really a planetary event of first order magnitude.

Once again, a clear picture of the structural evolution of the three extensional basins of Stephanian – Permian age you will find in Saura and Teixell’s paper. These basins may have been small, but they did accumulate considerable thicknesses of sediment: the Erill Castell basin close to some 1000 m and the Gramós basin, the biggest of the three, some 2000 m.

Corrunco

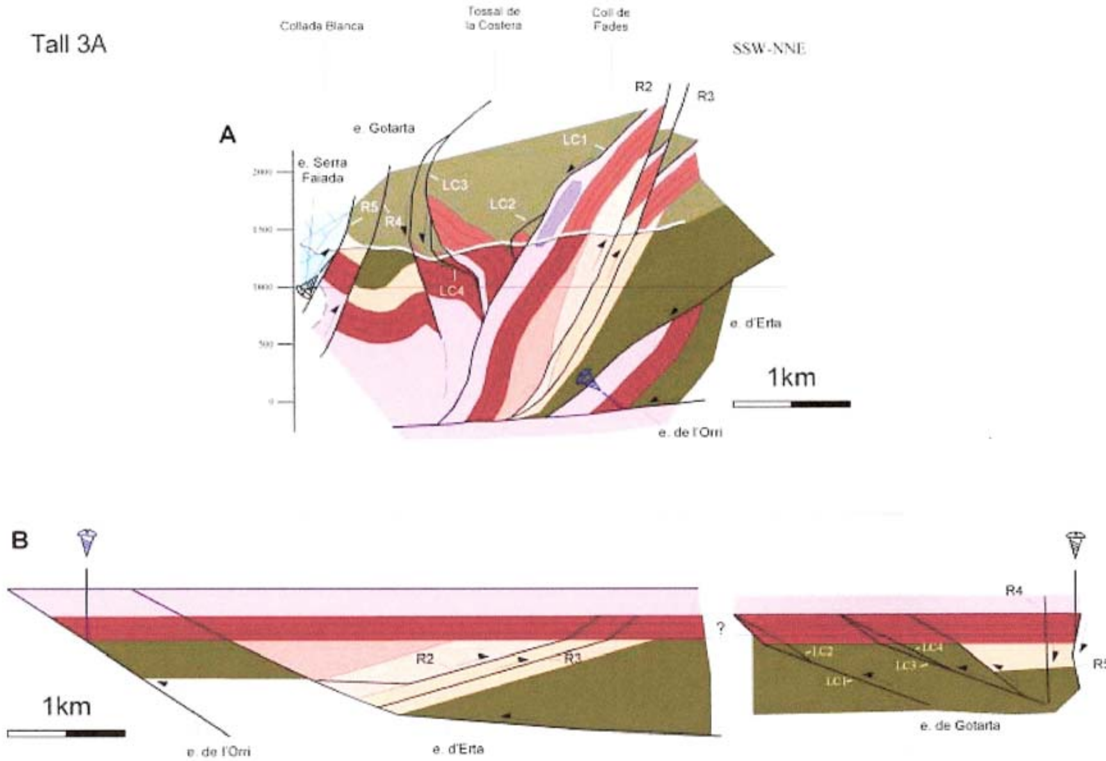


Erill Castell

Geological map (Sheet 8, Ribagorzana-Tor) of the Erta valley with location of Corrunco and erill Castell.

TERTIARY	Oligocene Upper Eocene	O	Collegats Conglomerates	coarse conglomerate
			Pyrenean folding phase	
CRETACEOUS	Senonian	Cv	Vallcarga Formation	marl, calcarenite and sandy lst.
	Turonian	CSF	Santa Fé Limestone	light-coloured, micritic lst. with slumps
	Cenomanian	CS	Sopeira Marls	sandy marl and nodular argill. lst.
		CAO	Aulet Orbitolina-Lst.	sandy, Orbitolina-bearing lst.
	Albian	CSM	San Martín Formation	sandstone and conglomerate
		CL	Llusa Marls	marl and argillaceous limestone
	Urgo-Aptian	CP	Prada Limestone	dark, micritic lst. with marl horizon
JURASSIC	Malm, Dogger	J2	Bonansa Formation	dark-grey, massive dolomite
	Liassic	J1		very fossiliferous, bituminous marl
		J1		platy, dolomitic limestone
TRIASSIC	Upper	Tr3 ω	Pont de Suert Formation	gypsum & dol. marl, with ophite bodies
		Tr3		scapolitized dol. marl and mudstone
	Middle	Tr2		micritic limestone and dolomite
	Lower	Tr1	Bunter	red silt-, sand-, and mudst., conglomerates
PERMIAN ?		P	Peranera Formation	red mudstone, breccia and dol. marl
CARBONIFEROUS	Stephanian	St	Malpas Formation	grey & brown mud- & sandst., coal seams
		St	Erill Castell Volcanics	tuff and lava
	U.Westphalian	W	Aguiró Formation	coarse conglomerate
			Hercynian folding phase	
	Middle? & Lower Carboniferous	Ca		micaceous shale, locally sandy
DEVONIAN	Undifferenti-ated	Du		badly exposed lst., argill. lst., shale
	Upper	DM	Mañanet Griotte	nodular limestone and calc-schist
		DF	Fonchanina Formation	slate with rare limestone beds
	Middle	DB	Basibé Formation	lst. & nod. lst., in the central and western part with quartzite & dol. intercalations
	Lower	DG	Gelada Fm. } Rueda Formation (DR)	quartzwacke, sandy sh. and argill. lst.
		DA	Aneto Fm. } Rueda Formation (DR)	slate with rare limestone beds
		DS		in the Durro-triangle: non-div. lowermost Dev. (lst. & slate) and Silurian black slate
SILURIAN		S		pyrite-bearing bl. sl. with thin-bed. lst. at the top
CAMBRO-ORDOVICIAN		CO		slate, sandy slate and thin quartzites thick quartzite impure limestone

Legend used for Sheet 8 (Ribagorzana- Tor).



Saura, 2000

A) SSW-NNE geological section over Coll de Fades – Massivert, just East of Erill Castell.
B) Restored section, question mark indicates uncertainty about the original distance between the Erta thrust sheet and the front of the Nogueres thrust sheet to the north.

Structure of the Erill Castell basin (from Saura and Teixell, 2006)
The present-day structure of the Erill Castell basin and adjoining areas and its restoration are shown above. The cross-section shows a south-dipping system of foreland-directed thrusts and backthrusts. The uppermost thrusts have experienced strong rotation and overturning (Nogueres thrust sheet) whereas the lower Erta and Orri thrusts show progressive less rotation. The Erill Castell basin is incorporated in the Erta thrust sheet, and is internally deformed by an imbricate fan of backthrusts. Restoration indicates that this basin formed initially as a halfgraben with its basin-bordering fault, named the Erta fault, located to the south. The Stephanian-Permian layers, with a maximum thickness of about 1000 m in the depocentre of the basin, were tilted to the south up to 30°. The basin was covered by tabular unconformable Triassic.

DAY 4 13 JUNE

Alpine deformation in Axial Zone

Stop 4.1 Rialp tectonic window

Location

Rialp, petrol station south of the village

Objectives

Tectonic window of Triassic rocks in the footwall of the Orri thrust.

Between Rialp and Sort, Triassic rocks outcrop below the Cambro-Ordovician and Silurian-Devonian rocks of the Orri dome. This tectonic window represents one of the most striking structural features of the southern Pyrenees, as the allocthony of lower Paleozoic rocks together with the antiformal stack geometry of the basement thrust sheets can be demonstrated (Muñoz et al., 1984). Triassic rocks constitute in detail three tectonic windows. The southern one, 6 kilometers long, is constituted by Upper Triassic rocks (Keuper facies). In the northern ones, of hectometric-scale, only Lower Triassic (Buntsandstein) and Middle Triassic (Muschelkalk) rocks outcrop (Figs. 27).

Stop 4.2 Rialp tectonic window

Location

Rialp, across bridge to the west, road Rialp to Llesui

Objectives

Triassic rocks in the footwall of the Orri thrust

Examples of cleavage development in the Lower Triassic Buntsandstain (Fig 29)

Stop 4.3 Rialp tectonic window

Location

Road Sort to Llesui, near junction road to Rialp.

Objectives

Contact thrusted Paleozoic rocks over the Middle Triassic (Muschelkalk) rocks (see picture below). Pedro (Pequeño) Mey acting as scale.

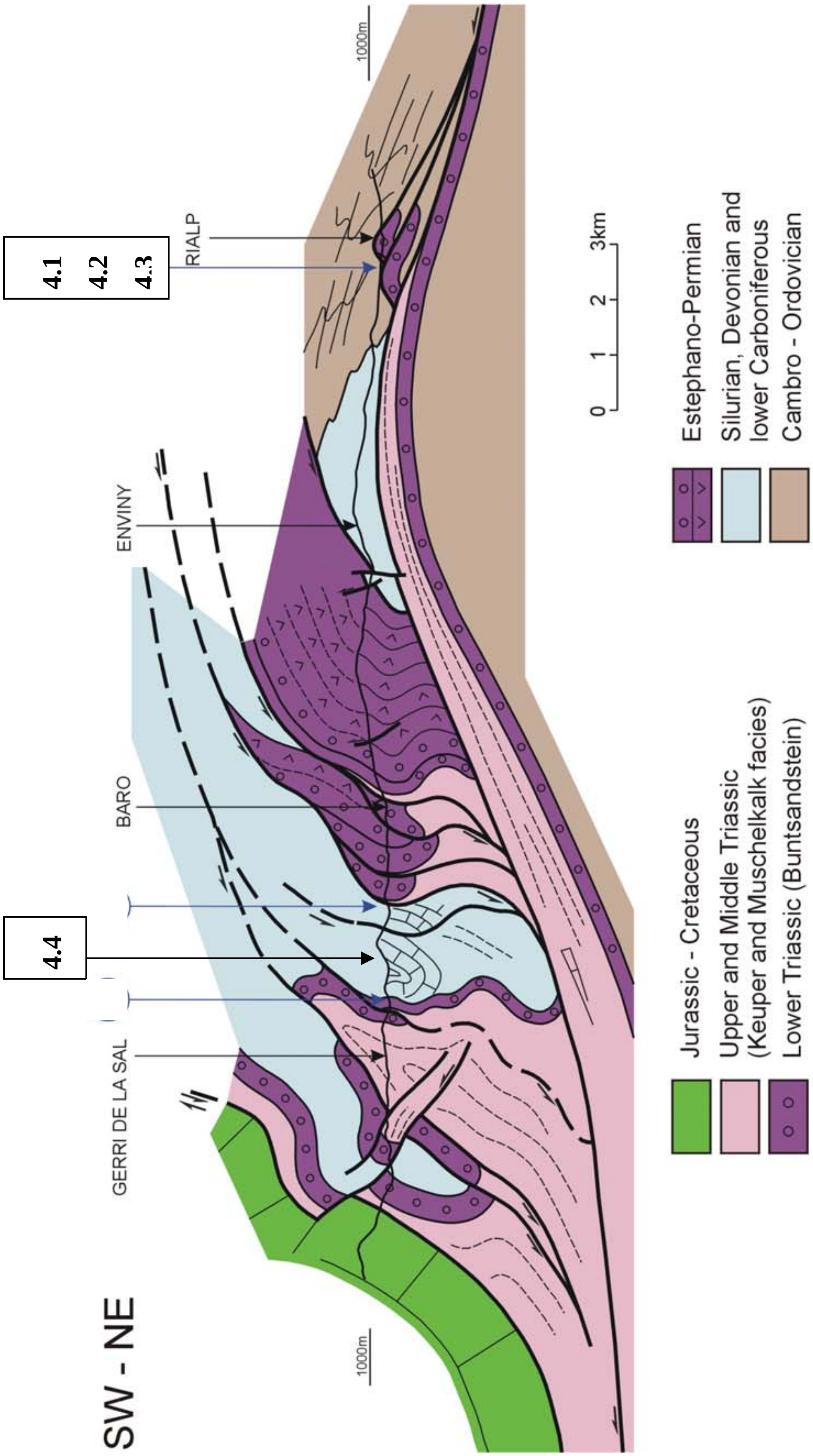


Figure 27.- *Geological cross-section of the southern Axial Zone along the Pallaresa valley (Muñoz, 1988). Location of the 3 last stops of day 2.*

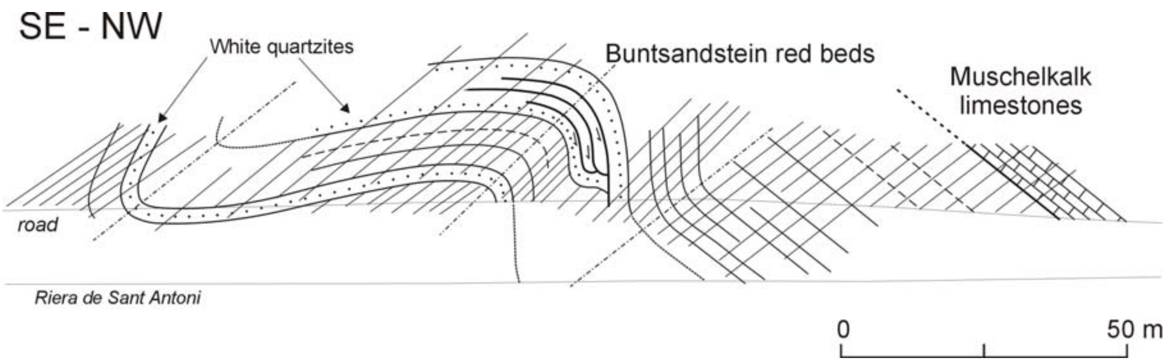


Figure 29.- *Detailed geological cross-section of the Triassic beds outcropping in the Rialp tectonic window.*

Stop 4.4 Nogueres

Location

El Comte, north of Gerri de la Sal. The able ones amongst the partipants should go up to the chapel of Sra Madre de Deu d’Arbolo for a great overview.

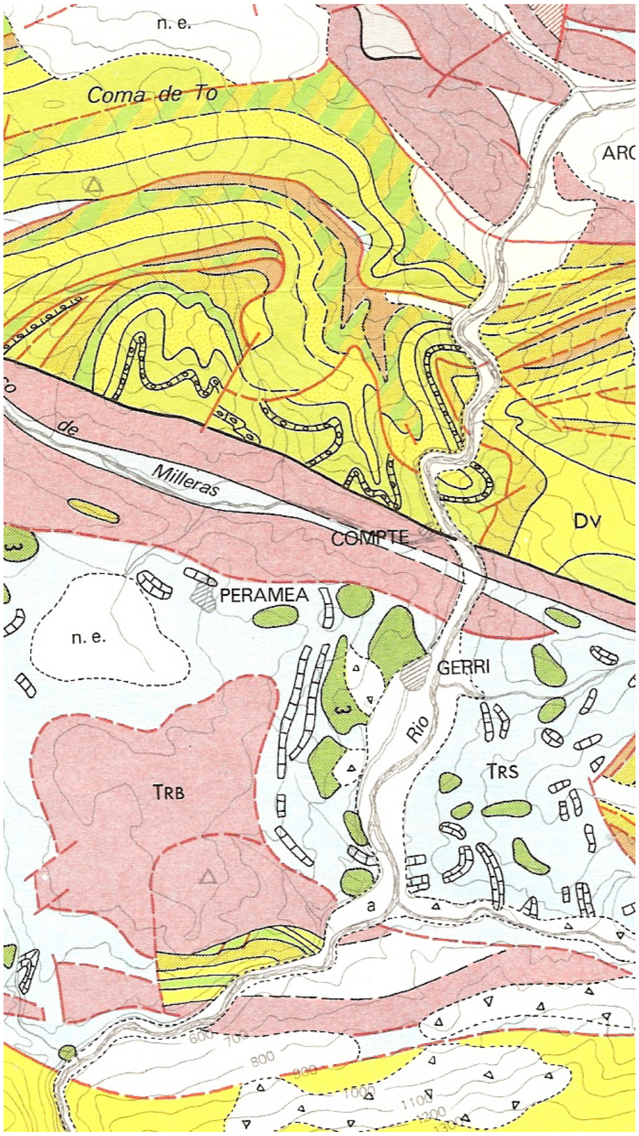
Objectives

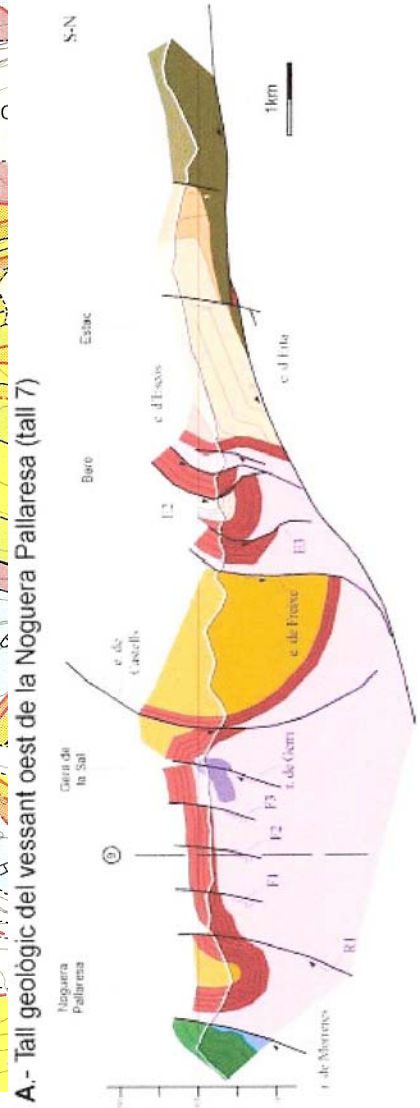
Internal structure of the Nogueres thrust sheet. Post-Hercynian unconformity.

The frontal part of the Nogueres thrust sheet is characterized by steepened thrust structures to vertical or even overturned. As a result, hangingwall anticlines display a downward facing geometry which puzzled Pyrenean geologists for decades (Dalloni, 1930, Mey, 1968, Seguret, 1972).

Silurian, Devonian and Lower Carboniferous rocks involved in the Nogueres thrust sheets display an internal Hercynian structure characterized by thrusts and related folds. Post-Hercynian Permian and Triassic rocks unconformably overlie the Hercynian structures (Figs. 26).

Figure 26.- *Photograph from bridge in Gerri de la Sal looking north at the Triassic red beds unconformably overlying folded and thrust Hercynian units.*





Geological Map of the Compte Block, part of the Nogueres thrust (sheet 9 Flamisell-Pallaresa) showing the folds and thrust of Variscan age.

Next to it a copy of a geological section from the thesis of Eduard Saura (2000) over the western side of the Pallaresa River showing the plunging front (tête plongeant of Seguret) of the Nogueres Thrust sheet.

Photograph an anticlinal synform in the Nogueres Thrust Sheet with on the foreground the chapel Sra de Madre d'Arbolo.

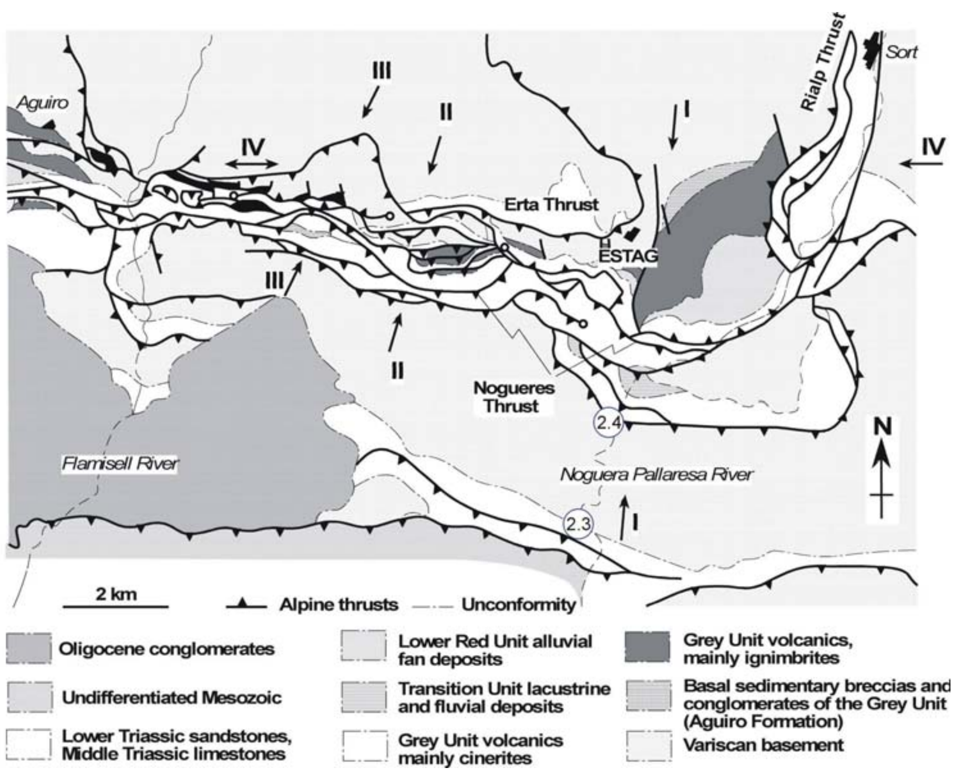


Figure 28.- *Geological map of the Nogueres thrust system and Ancs duplex (After Soriano et al., 1996).*

Stop 4.5 Collegats

Location

Starrt on parking place north of the Collegats gorge, south of Gerri de la Sal.

Objectives

Structure of the Bóixols thrust sheets. Lower Cretaceous synrift sediments of the Organyà basin and unconformity below the postrift sequence. Unconformity and paleorelief related with La Pobla de Segur conglomerates. Travertinee deposit in the Barremian Limestones

We walk from N to S through the northern outcrop of the Bóixols thrust sheet.
Its northern boundary corresponds to a backthrust. In the Pallaresa valley this backthrust is located in between the Lower Cretaceous rocks of the Bólxols thrust sheet and the Triassic beds of the Les Nogueres thrust sheet (Fig. 23).

Along the road cut, Triassic basaltic rocks (ofites) outcrop. Along the road to the north, marls, probably Triassic in age can be observed and immediately to the south, the first limestones and breccias are Lower Cretaceous in age. All the Jurassic succession, almost 1000m thick, is omitted. This substractive contact is the result of the truncation of previously developed folds by the Morreres backthrust. In detail, a conjugated set of shear zones deforming a layer parallel cleavage can be observed. Cleavage developed once the beds acquired a vertical dip (by folding) and the consecutive formation of the shear zones represent a recording of the progressive deformation of the Bóixols thrust sheet in front and over the Nogueres units, from the early folding stages to the final development of the passive roof Morreres backthrust during the Axial Zone antiformal stack development.

The cross-section along the Collegats gorge allow us to observe the structure of the northern Bóixols thrust sheet and two major unconformities: the end rifting unconformity and the unconformity at the unconformity at the base of the Eocene-Oligocene La Pobla de Segur conglomerates.

The relationships between the progressive backfilling of the south Pyrenean thrust sheets by the late syntectonic conglomerates, the thrust kinematics and the geomorphic features are prominent in this area. La Pobla de Segur conglomerates (Rosell & Riba, 1966) or Collegats Formation (Mey et al., 1968) consists of an alluvial fan complex comprosing more than 20 interfingering alluvial fan lobes that prograded into floodbasin and shallow lacustrine environments (Mellere, 1992). The total stratigraphic thickness is 3.500m obtained by adding the thickness of each alluvial fan lobe, from the lowest in the La Pobla basin to the highest in the Senterada basin.

Mammal fauna from lacustrine deposits located in the lower part of the section (Casanovas, 1975; Sudre et al., 1992) and recent magnetostratigraphic data (Beamud et al., 2003) indicate they are Late Lutetian to Middle Oligocene in age.

To the north of the Upper Cenomanian limestones of the Santa Fé Formation and below the La Pobla de Segur conglomerates a thick succession of lower cretaceous sediments outcrop. They are folded and tilted to the south.

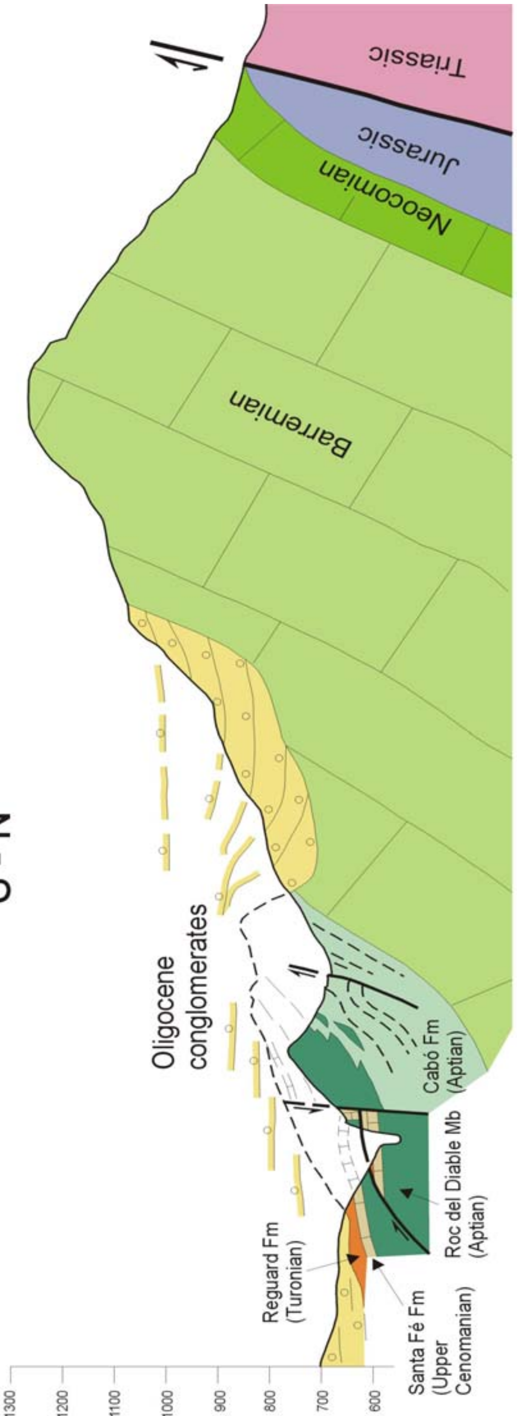


Figure 23.- *Cross-section along the Collegats gorge. The limestones of the Santa Fé Fm lie unconformably overlying the Aptian limestones of the Roc del Diable Mb. (Aptian). Albian sediments have been truncated and eroded. From Garcia-Senz, 2002. See Fig. 18 for location.*

Figure 24.- *Two main Pyrenean unconformities are exposed in the Collegats gorge: The unconformity at the base of the Eocene-Oligocene La Pobla de Segur conglomerates and the end rifting unconformity below the Upper Cenomanian limestones (distinct upper bed of limestones above the cliff). North to the left.*

Figure 25.- *Paleorelief at the base of the Eocene-Oligocene La Pobla de Segur conglomerates. NW to the left*

DAY 5 14 JUNE

THE PRE-PYRENEAN PHASE

Stop 5.1 Sant Corneli anticline

Location
Road Isona to Coll de Nargo

Objectives
General view of the Tremp basin and the Sant Corneli anticline.

Looking northwards, the highest mountains correspond to the hinge area of the Sant Corneli anticline. This anticline displays a high angle plunge as demonstrated by the disposition of the beds which are upper Cretaceous limestones and marls. The Sant Corneli anticline represents a hanging wall anticline of the Bóixols thrust sheet. The Sant Corneli anticline and the thrust located below are unconformably overlapped by the uppermost Cretaceous Arén sandstones of the northern part of the Tremp basin (Fig. 19)

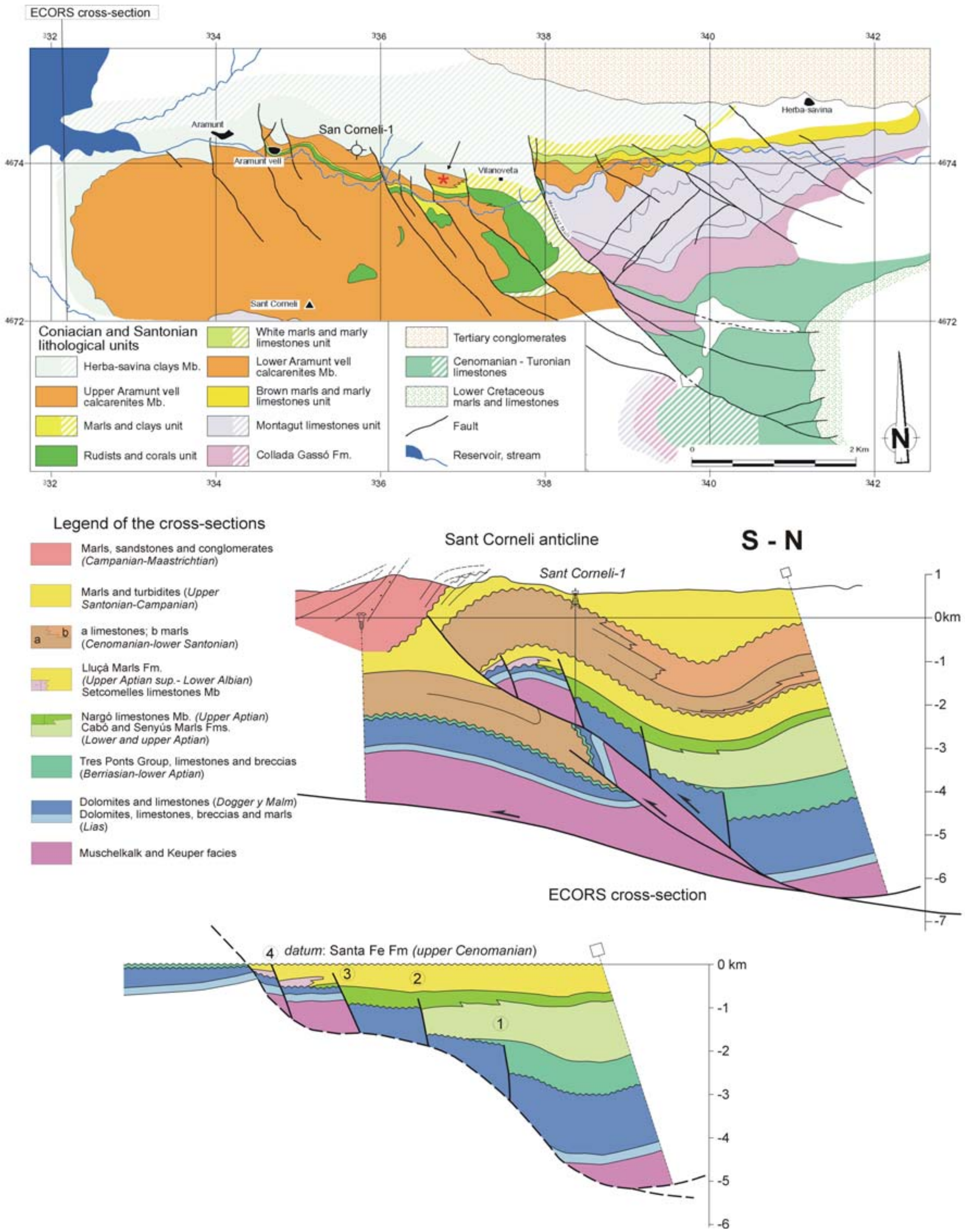


Figure 19.- Geological map of the Sant Corneli anticline and the portion of the ECORS cross-section through it. A restored cross-section is included to show the geometry of the extensional faults of the Organyà basin before its inversion during Late Santonian-Maastrichtian times. From García-Senz, 2002

Stop 5.2 Arén sandstone

Location
The village of Orcau and its castle

Objectives
Sedimentology of the Arén sandstone

The Conca of Tremp and Isona has been said to contain some of the most intensively studied sections in the world. The list of contributing authors is long and we suggest, for this short text, not to even make a start mentioning them.
The exposed stratigraphy runs from Upper Cretaceous to Oligocene. We will mainly focus on the lower part of this sequence, the Maastrichtian Arén Sandstone. This sandstone sequence, which varies from just a few meters to some 400 in thickness would in the past have been described as the ‘regressive top of the Cretaceous’ but in the terminology of the present, still our times, it is a prime example of an ‘offlap sequence’ typically formed during a relative sea level high. The sequence youngs from East to West which is also clear from large coastal foresets running in this direction as we can observe from our panoramic stop at the castle of Orcau.
The Arén Sandstone overlies shallow marine marls and limestones and is in turn is overlain first by thin lagoonal and then by much thicker coastal plain fluvial and lacustrine deposits (the Tremp Formation). The sandstones, largely calcarenites and ever-present mature, well rounded quartz, testify to a wide variety of sedimentary environments. These range from estuarine, foreshore, beach and barrier island to tidal inlet and many more typical littoral facies.
Although so far no isopach maps of the Arén Sandstone have been drawn up, field observations show an evident thickness decrease toward, and a probable onlap onto, the Sant Corneli anticline. This is seen as evidence that the Sant Corneli thrust was already active in Upper Cretaceous time which in turn dates the early onset of the Pyrenean orogenesis.
Since many years the Arén Sandstone has drawn the interest of the oil industry as it represents a well developed example of a potential oil and gas reservoir open to detailed study because of the almost complete exposure.
We will see all of the mentioned aspects in just three large stops. The first is a wide panoramic view close to the Faidella Pass, the second is a detailed inspection of a fully exposed section and the last stop is another wide overview from the location of the well known 'Castell d’Orcau'. The view from here became widely known since it appeared on the cover of the AAPG Bulletin (april 2002).

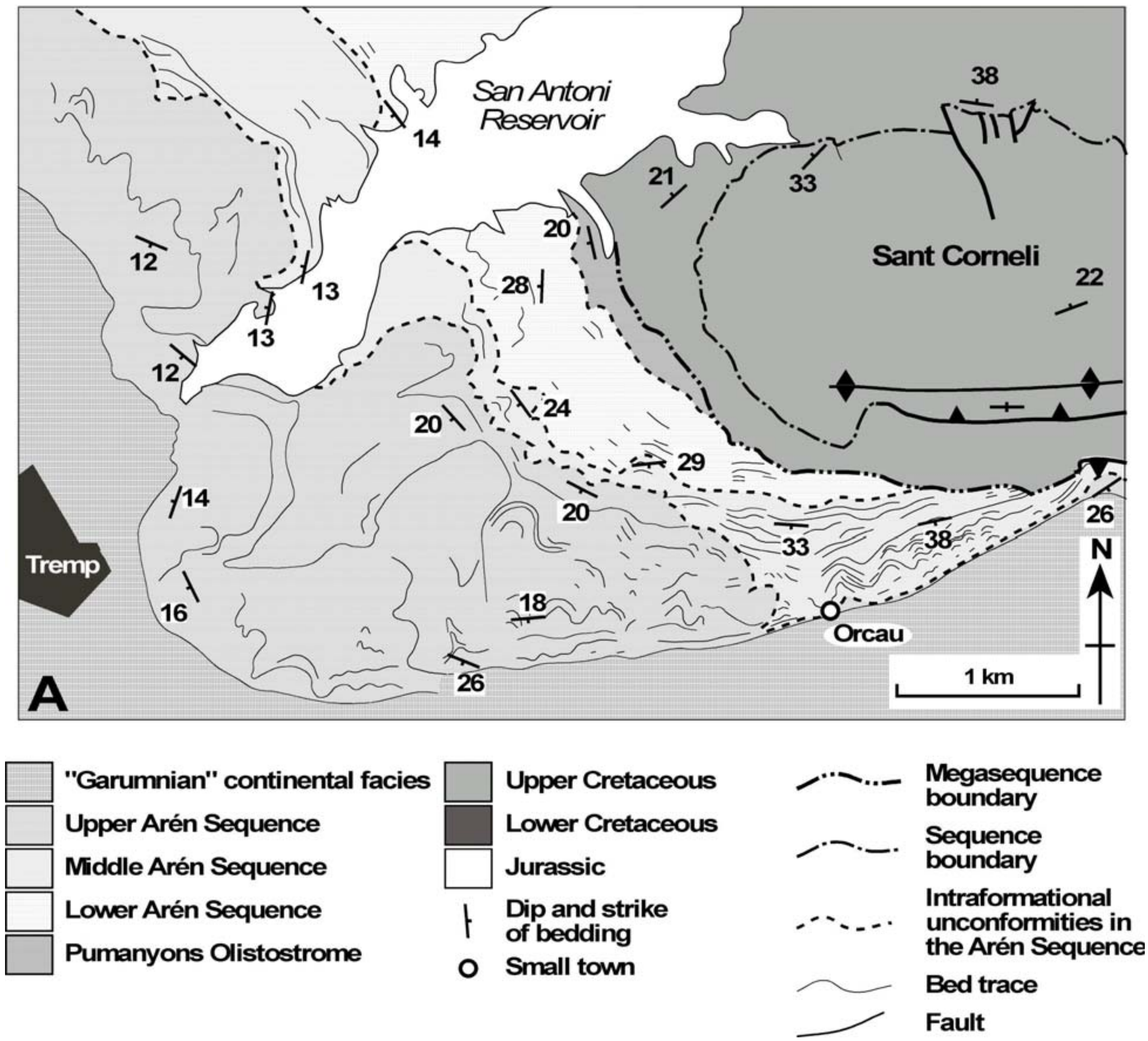


Figure 20.- *Detailed map of the western nose of the San Corneli anticline showing the onlap of the syntectonic Aren sandstone sequence (after Bond & McClay, 1995).*

Stop 5.3 Tremp basin wines

Location
The village of Orcau

Objectives
To sample the goodies of the Orcauvins vineyard

DAY 6 15 JUNE

FIRST PYRENEAN CLOSING PHASE

THE RIBAGORÇANA CROSS-SECTION

The Ribagorçana cross-section across the Bóixols thrust sheet is a key section to understand the inversion of the Early Cretaceous basins. In this area there are some geological units exposed and geometric relationhips which are unique and not visible at surface in any other section of the southern Pyrenees. The sedimentary succession of the Aulet basin, its structure, the unconformity at the base of the Upper Santonian-Campanian turbidites and the inversion geometries outstand. However, some fault geometries are difficult to understand, particularly the substractive fault contacts observed in the area. These have been recently interpreted as the result of the inversion of salt structures related with the Early Cretaceous extensional fault system.

Stop 6.1 Sopeira

Location
Road N-230, Sopeira village.

Objectives
General view of the Serra de Sant Gervàs. Aulet basin. Cenomanian succession and unconformities, Sopeira Marls and Santa Fé Formations.

Stop 6.2 Unconformity at the base of the Upper Santonian turbidites

Location
Sopeira dam.

Objectives
Geometric relationship between the Upper Santonian-Campanian turbidites and the older Upper Formations.

The postrift succession, Cenomanian-Early Santonian in age comprises several stratigraphic units with a general deepening upwards trend from the limestones and breccias of the Santa Fé Formation (Upper Cenomanian) to the marls and marly limestones with slumps of the Aguas Salenz Formation (Coniacian-Lower Santonian). This succession is truncated by an unconformity at the base of the Upper Santonian-Campanian turbidites. This unconformity represents the onset of the Pyrenean convergence and the inversion of the previous Early Cretaceous extensional basins. Before this inversion event a previous one, Cenomanian in age, partially inverted the Aulet basin.

Stop 6.3 Areny

Location

Aren village.

Objectives

General view of the Upper Cretaceous, Paleocene and Lower Eocene successions of the Montsec thrust sheet. Areny Sandstones Formation. Synthesis of the Tamurcia structure and the integration of surface geological data with subsurface data (seismics and Tamurcia well).Location

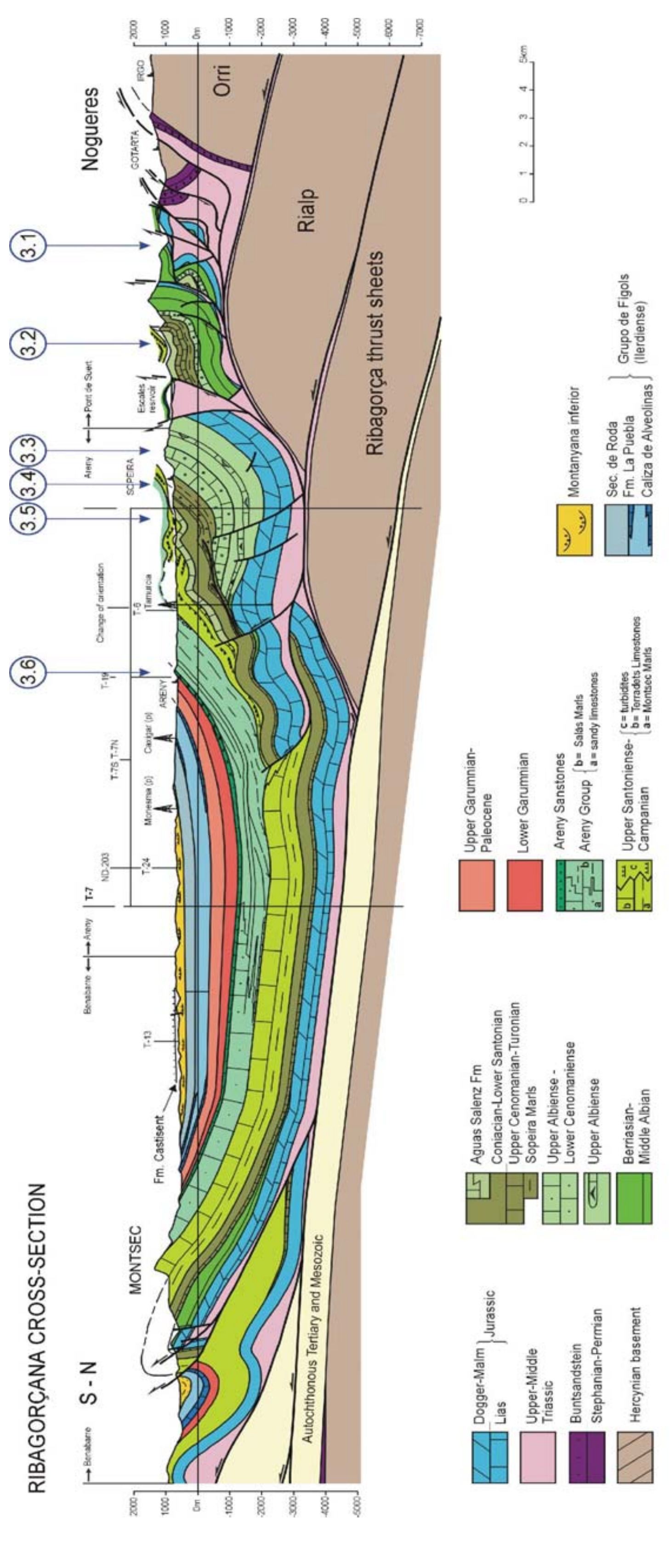


Figure 30.- *Geological cross-section along the Ribagorçana valley. This cross-section is based on geological surface data as well as on seismic and well data. Location of the stops of the third day.*

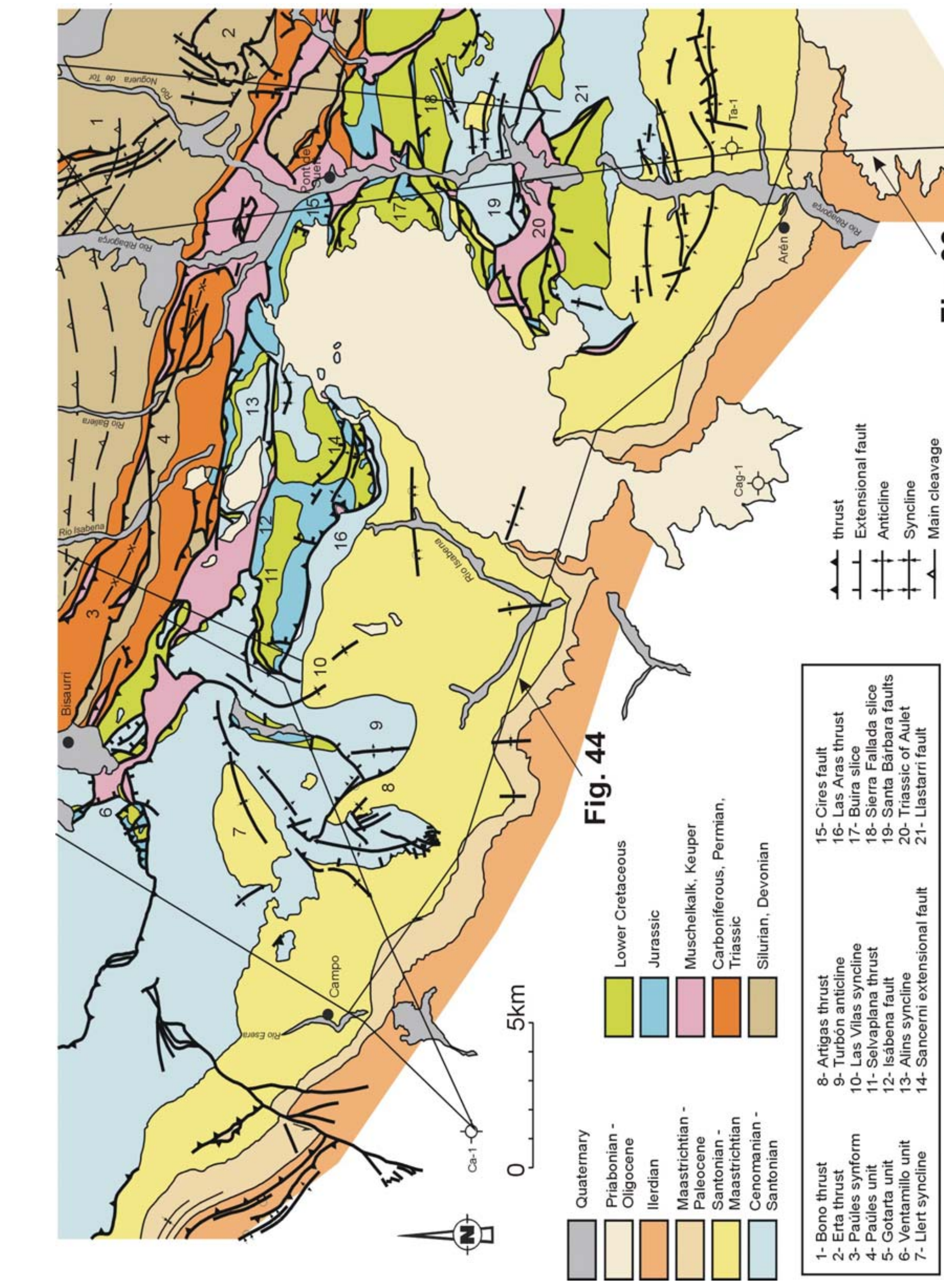


***Figure 31.-** Geological map of the western part of the Bóixols thrust sheet. From García-Senz, 2002.*

Stop 6.4 Obarra

Location
Obarra gorge.

Objectives
Syn-inversion turbidites. Las Aras thrust and inversion structure.

The geological cross-section of Las Aras thrust sheet at the Obarra gorge shows an inversion structure (Figs. 40-44). A north verging Mesozoic synclinal formed by the inversion of an Albian extensional fault lies over the Nogueres basement units. Towards the south a big south vergent anticline is cut by Las Aras thrust. In its hanging wall an Albian extensional basin and a thick Jurassic sequence are preserved. In the frontal limb of the anticline Cretaceous syn-compressive turbidites outcrop uncomformably over the inverted Upper Cretaceous limestones.
Restoring Cenomanian bottom to horizontal, Las Aras fault can be interpreted as an extensional listric fault (Figs. 40 and 41). It is inverted and contains an Albian rollover anticline and a graben in its hangingwall. The unconformity under the Upper Albian calcarenites (Pegà Formation) is interpreted as a consequence of the contraction of the extensional faults during the Upper Albian.

Stop 6.5 Turbón anticline

Location
Egea. Road from Isábena valley to Campo.

Objectives
Panoramic view of the Turbón anticline from Villacarlí, a detatchment fold in the footwall of Las Aras thrust.
Excellent view of the Turbón anticline showing their east limb and the abrupt plunging to the south. From this point we can visualize how the anticlinal relief, up to 1000 m, is fossilized by thick sequences of marls and the Arén Formation hogback. Discussion will focus on the interrelations of fold growth, subsidence and depocenter migration as main controls of the basin fill, ranging from deep-water turbidites, prodelta marls and finally coastal sands and redbeds (Fig. 45).

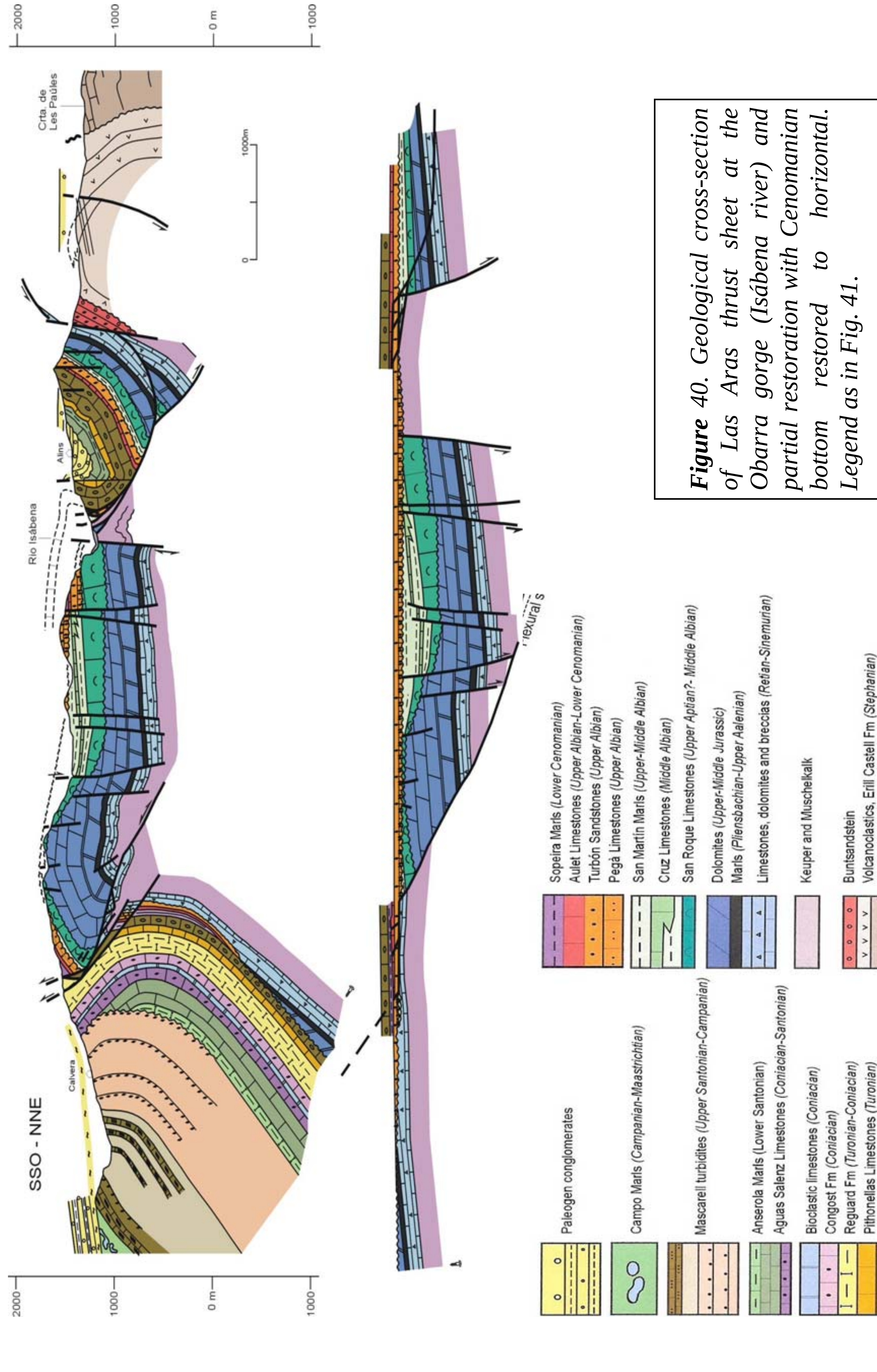


***Figure** 40. Geological cross-section of Las Aras thrust sheet at the Obarra gorge (Isábena river) and partial restoration with Cenomanian bottom restored to horizontal. Legend as in Fig. 41.*

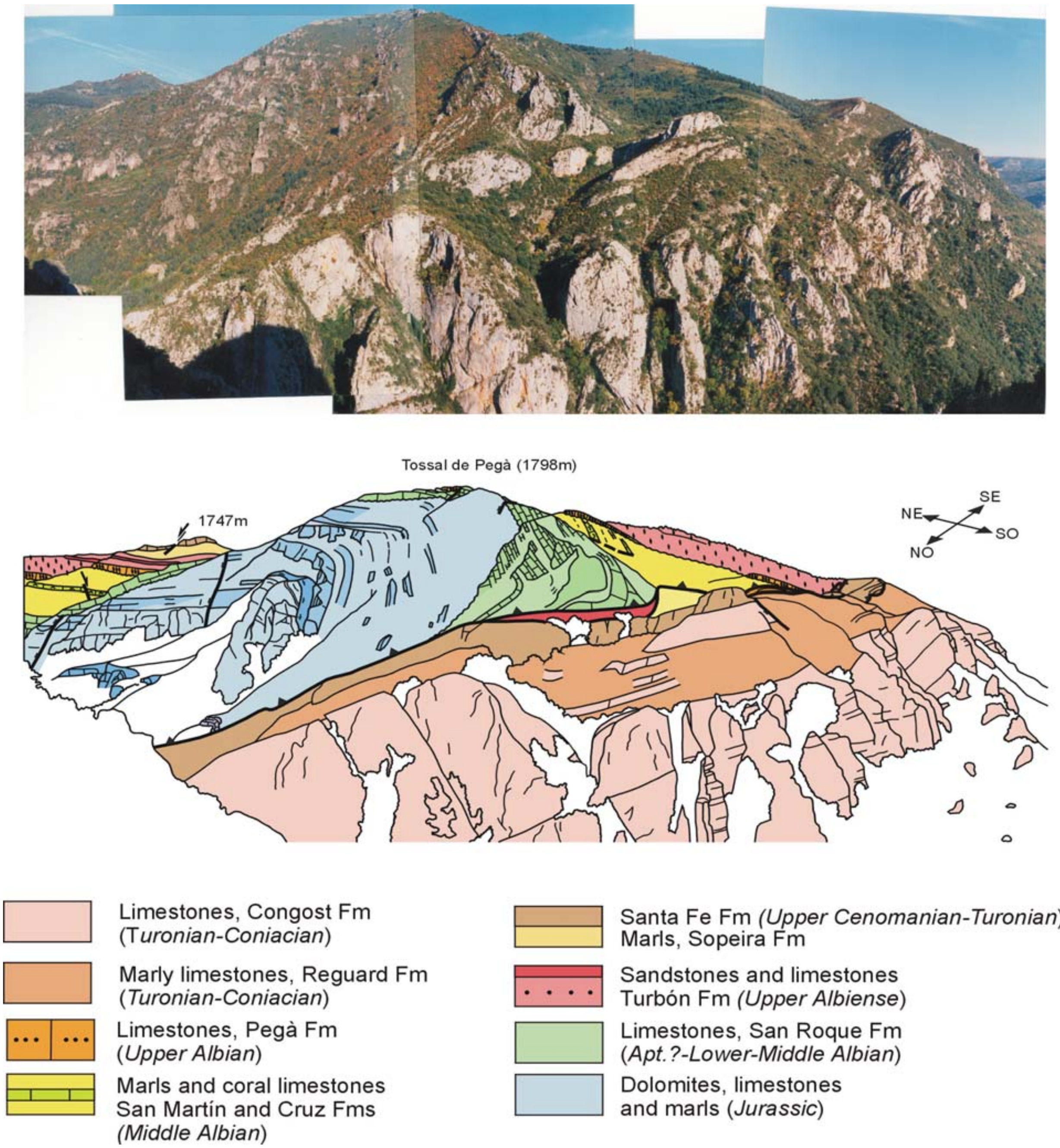


Figure 43.- *Panoramic view of the eastern margin of the Isàbena valley in the Obarra gorge.*

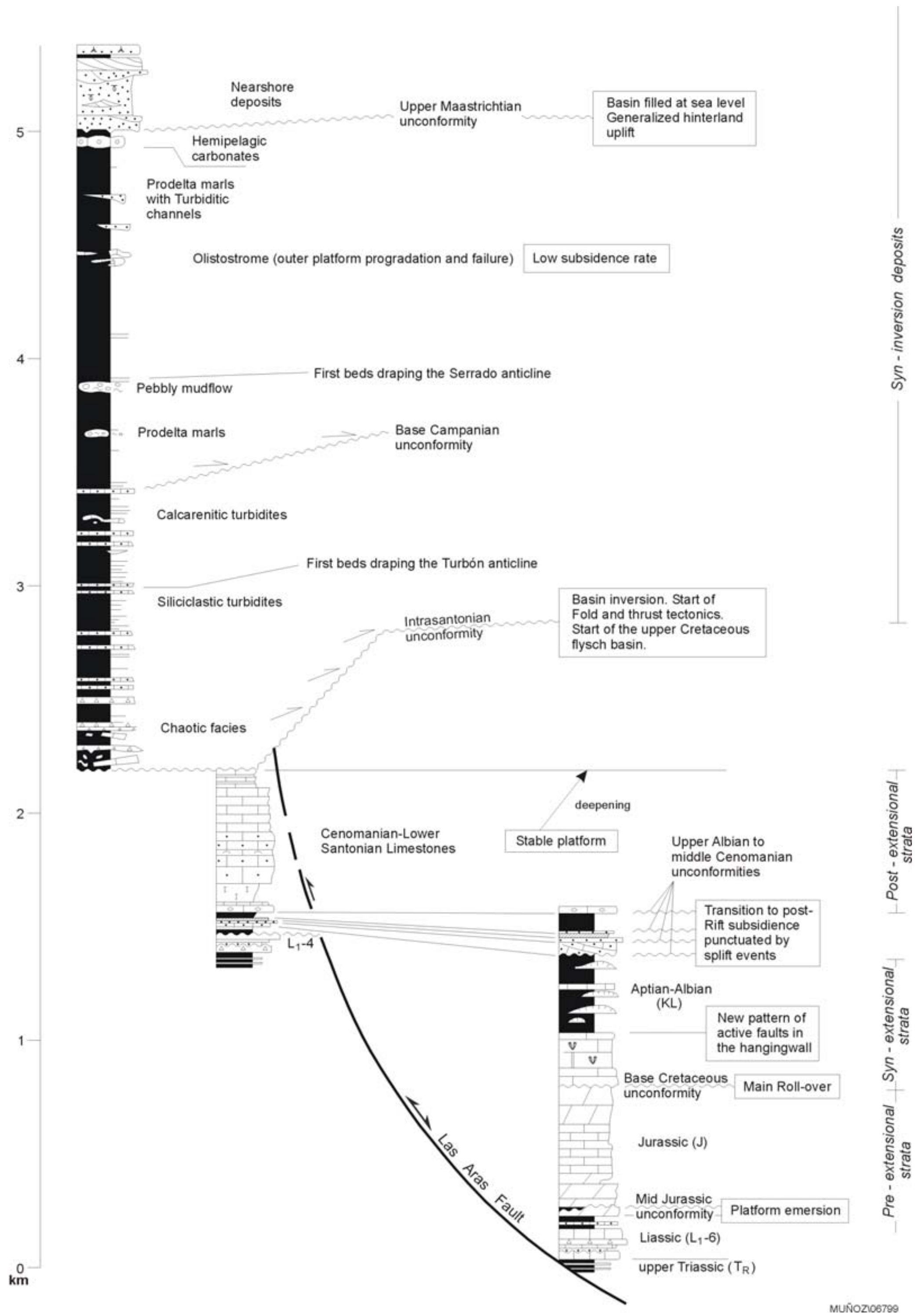


Figure 44.- *Synthetic column of Las Aras-Turbón area integrating the sedimentary filling with basin formation processes and the main tectonic events.*

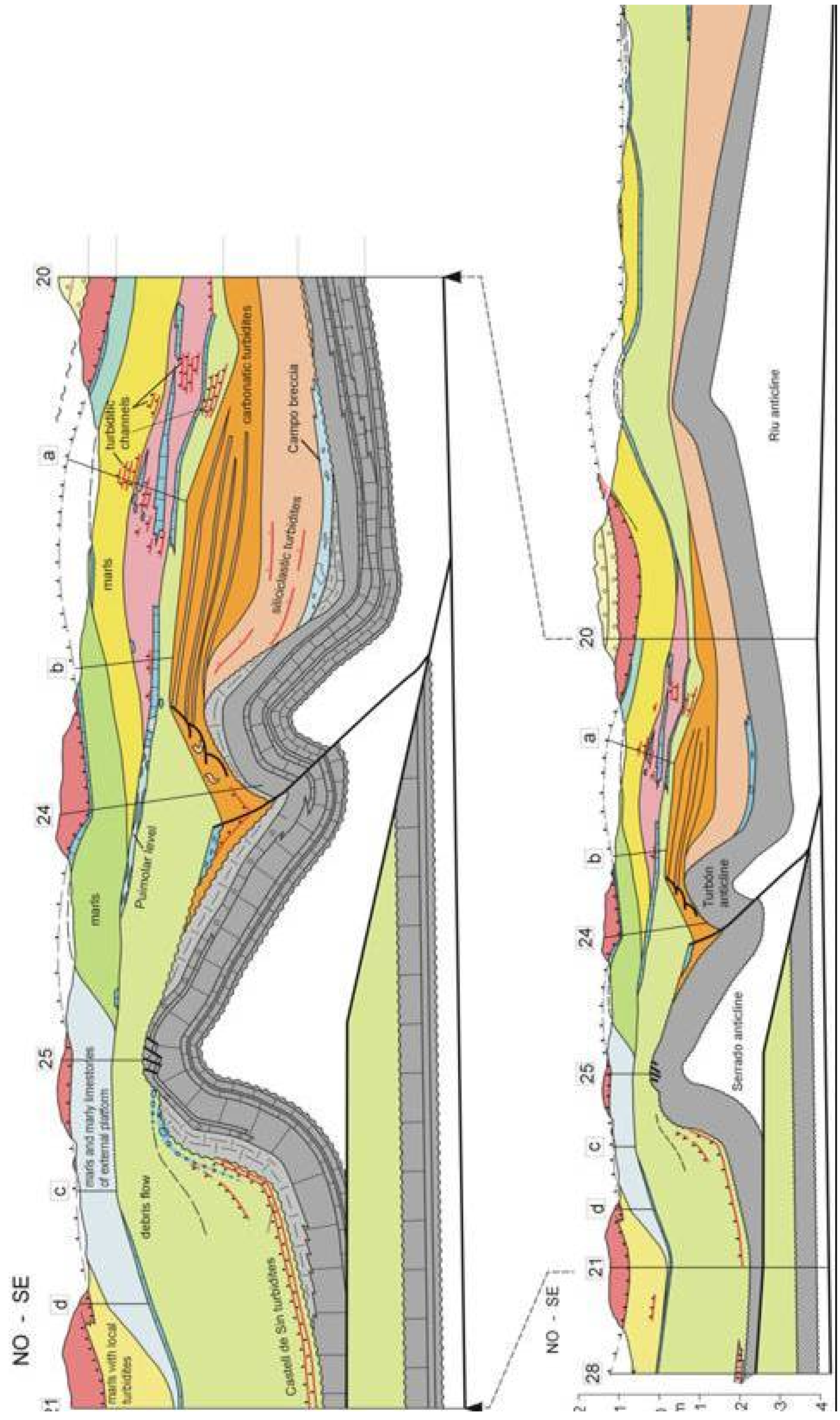


Fig. 45 See next page for description and legend

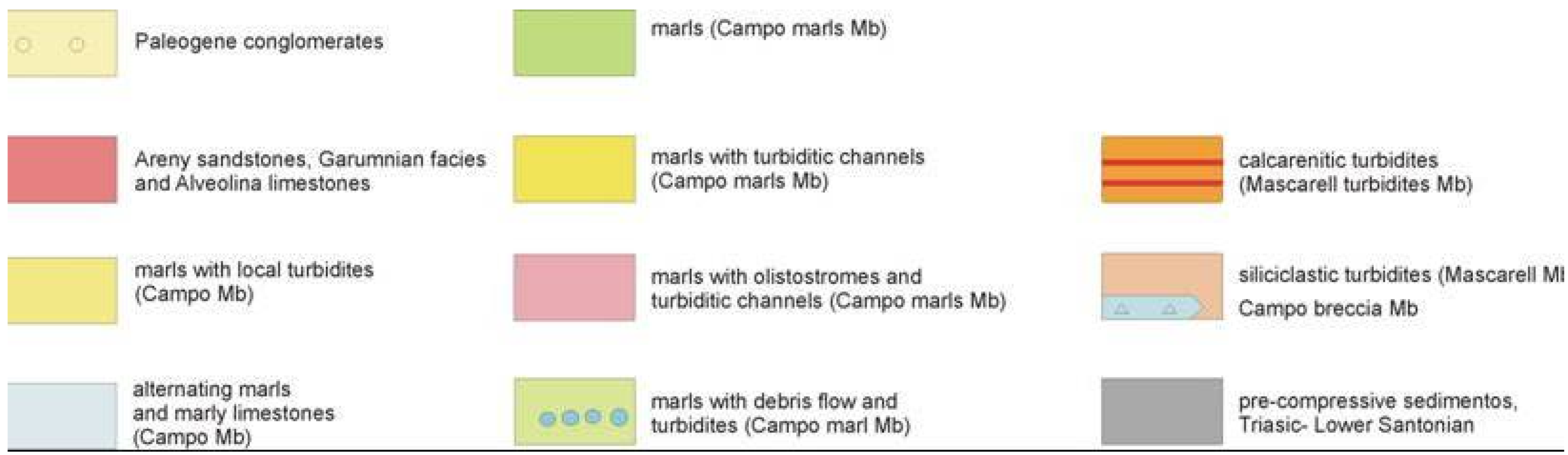


Figure 45. *Geological cross-section through Turbón oblique folds. The section shows some basement duplex below two cover sheets separated by the Cotiella Eocene thrust.*

DAY 7 16 JUNE

THE COTIELLA THRUST SHEET

Introduction to the Geology of the Cotiella Thrust Sheet

The Cotiella thrust sheet contains a Mid-Triassic through Lower Eocene succession thrust over Lower Eocene platformal and turbiditic sequences of the Ainsa basin (Fig. 46) (Séguret,1972; Garrido and Ríos, 1972; Munoz et al., 1994). The NE sector of the thrust sheet is characterized by inverted Early Cretaceous rift basin extensional faults (Figs. 46 and 48). The S and SW sectors of the thrust sheet consist dominantly of a thick (up to 4 km) succession of Upper Cenomanian – Lower Santonian post-rift units detached on pre-rift Triassic evaporites (Séguret, 1972; Garrido and Ríos, 1972). These strata are dominantly shallow water limestones and sandstones (Maciños del Cotiella Fm) interfingering with pelagic carbonates (Aguas Salenz Fm) (Garrido and Ríos, 1972 and Souquet, 1967). This post-rift succession unconformably overlies the pre-rift Triassic evaporites (Figs. 47 and 48). Here Jurassic strata were probably eroded from the rift margin and from the footwalls of the Early Cretaceous extensional faults.

The end-rifting unconformity is very well expressed not only in the rift margins but also in the hangingwalls of the Early Cretaceous extensional faults. It is marked by an unconformity at the base of the Upper Cenomanian limestones (Figs. 47 and 48).

The internal structure of the Cotiella thrust sheet is dominated by kilometer-scale folds and shallow-dipping faults that have previously simply been interpreted as thrusts (Séguret, 1972; Martínez-Peña, 1991).

Within the Cotiella thrust sheet we have identified three, kilometer-scale, listric extensional growth faults within the upper post-rift, Coniacian-Early Santonian section (Fig. 46). They dip northwards and detach on pre-rift Triassic evaporites (Figs. 49 and 50). Their hanging walls show spectacular continuous fanning of growth strata, from sub-horizontal and shallow southwards-dipping units to vertical and northwards-dipping overturned beds (Fig. 50). The cumulative thicknesses of the syn-extensional growth wedges varies from a minimum of several hundreds of meters for the northernmost unit and most highly eroded Peña de las Once fault system to more than 3 km for the Armeña fault system in the middle of the cross-section (Fig. 50). Cumulative growth wedge thicknesses of more than 5.5km occur in the southern Cotiella fault system which is the best preserved and areally the most extensive (Figs. 46 and 48). In the footwall of the Cotiella thrust fault the equivalent post-rift section is only 300m thick (Fig. 48). The listric nature of these fault systems is directly observed in the outcrops of the major faults and of the minor synthetic faults. The continuous curvatures of the hangingwall growth strata also indicate the listric nature of the bounding fault systems (Figs. 49 and 50).

The immediate hanging wall of the Armeña growth fault contains shallow-water red, sandy limestones and quartz sandstones (Maciños del Cotiella Fm) and these grade basinwards into the cherty limestones and marls of the Aguas Salenz Formation (Figs. 49 and 50). The hanging wall of the Peña de las Once fault system to the north is dominated by sandy limestones (Maciños del Cotiella Fm) whereas the hanging wall of the Cotiella fault system to the south mainly consists of Aguas Salenz Fm., with the siliciclastics of the Maciños del Cotiella Fm. being restricted to the base of the succession. This facies distribution across the three listric growth fault systems indicates progressive subsidence and northward tilting of the rift margin together with probable southward propagation of successive growth faults into the footwall of the rift margin.

Even though these listric growth faults have been inverted, which folded their hanging walls (giving rise to over-steepened beds) (Fig. 50), and were then transported in excess of 20 km southwards, the original thin-skinned extensional character is preserved (Fig. 50). Mapped relationships as well as line-length restoration of the hangingwall architectures reveals the original raft geometries as well as indicating a minimum down-slope (northward) extension of at least 9km (Fig. 50). The timing of the onset of inversion and folding is recorded by onlap of the syn-inversion, Late Santonian – Maastrichtian age Campo breccias and related turbidites onto the inverted hangingwalls (Fig. 52). Syn-inversion sedimentary wedging indicates continued folding and southward steepening of hangingwall strata that were already highly rotated by the earlier listric raft faulting.

The western continuation of the Cotiella thrust sheet along the leading edge of the Bóixols thrust is buried beneath syncompressional flysch deposits, although subsurface exploration reveals that describe an oblique trajectory joining the Turbón folded area. Folds in the Turbón area display either N-S and E-W orientations.

Interpretation and structural evolution of the Cotiella fault system

The kilometer-scale, listric-fault systems in the Cotiella thrust sheet are uniquely exposed outcrop examples of rift-margin raft tectonics. They represent a previously unrecognized postrift tectono-stratigraphic event in the central Pyrenees. They show striking geometric similarities to postrift, thin-skinned listric growth faults formed by raft tectonics on passive margins such as offshore Angola (Duval et al., 1992; Lundin, 1992; Spathopoulos, 1996; Cramez and Jackson, 2000; Marton et al., 2000; Valle et al., 2001), offshore Equatorial Guinea (Turner, 1999), offshore Brazil (Cobbold et al., 1995), and the Gulf of Mexico Basin (cf. Diegel et al., 1995; Schuster, 1995). The Cotiella listric-growth-fault systems have dimensions and involve stratigraphic thicknesses similar to those observed in seismic sections across these passive margins (e.g., Cramez and Jackson, 2000; Marton et al., 2000). They also occur in a similar postrift tectonic setting; however, they detach on prerift evaporites on the rift margin (in contrast to the detachments on postrift evaporites along most of the South Atlantic margins) and slide down into a thermally subsiding basin. Our inferred sequence of footwall propagation contrasts with that observed on the South Atlantic margins where progradational sediment loading produces successively younger raft faults basinward (e.g., Cramez and Jackson, 2000; Marton et al., 2000).

Our model for the evolution of these spectacular thin-skinned growth faults is that of gravity-driven detachment of the postrift strata above the Triassic evaporites (Fig. 51). This action produced northward displacement with the development of strongly listric extensional growth faults that formed sequentially, stepping back into the rift-margin platform during postrift thermal subsidence (Fig. 51). Rapid sedimentation produced thick growth wedges (>5 km cumulative wedge thicknesses) in Coniacian-lower Santonian strata. Subsequent Late Cretaceous to early Eocene contraction reactivated both the rift faults (to the north and east of the outcrops described here) and the postrift raft faults (Figs. 50). Upper Cretaceous synbasin-inversion Campo breccias and turbidites onlapped the growing hanging-wall anticlines, recording the progressive uplift of the inverted Early Cretaceous rift basins in the axial zone of the Pyrenean orogen. This preservation of listric extensional raft faults onshore in a mountain belt is unusual. Thus the Cotiella system provides an exceptional field analogue for similar raft structures found offshore in passive margins. In addition, raft tectonics may help to explain structural complexities found elsewhere in the Spanish and French Pyrenees as well as being considered in other mountain belts formed by contraction of passive-margin sequences.

Stop 7.1 Armeña

Location

Trail to Armeña hut from Barbaruens

Objectives

Inverted extensional growth faults developed in the postrift sequence of the Cotiella thrust sheet.

This is a magnificient view point for the inverted raft extensional collapse growth faults of the Armeña unit in the Cotiella thrust sheet. The Coniacian – Early Santonian listric raft faulting is a new tectonostratigraphic event in the Spanish Pyrenees (Fig. 47). The uniquely exposed extensional growth fault systems of the Cotiella thrust sheet show spectacular fanning growth wedges in their hanging walls. These raft faults were inverted during Alpine contraction and now inverted form large, hangingwall antiforms. These raft systems generate significant thickness changes in the post-rift succession in the Spanish Pyrenees and also explain the along-strike changes in structural styles within the thrust sheets. Post-rift raft tectonics may possibly help to explain complex thrust structures elsewhere in the Pyrenees and should also be considered for other mountain belts formed by contraction of passive margins. The down to the basin, listric growth faults are interpreted to have formed by gravity-driven extension of the late Cretaceous post-rift sequence, detached on evaporites, in a similar manner to the raft terranes found on the South Atlantic passive margins.

Stop 7.2 Campo Breccia

Location

Road N-260, north of Campo

Objectives

Syn-basin inversion uncorfomity. Campo breccias

The onset of the Pyrenean contractional deformation during the inversion of the previous extensional basins is well visible in this locality. The first synorogenic deposits consist of breccias and turbidites which onlap on top of hanging-wall anticlines.

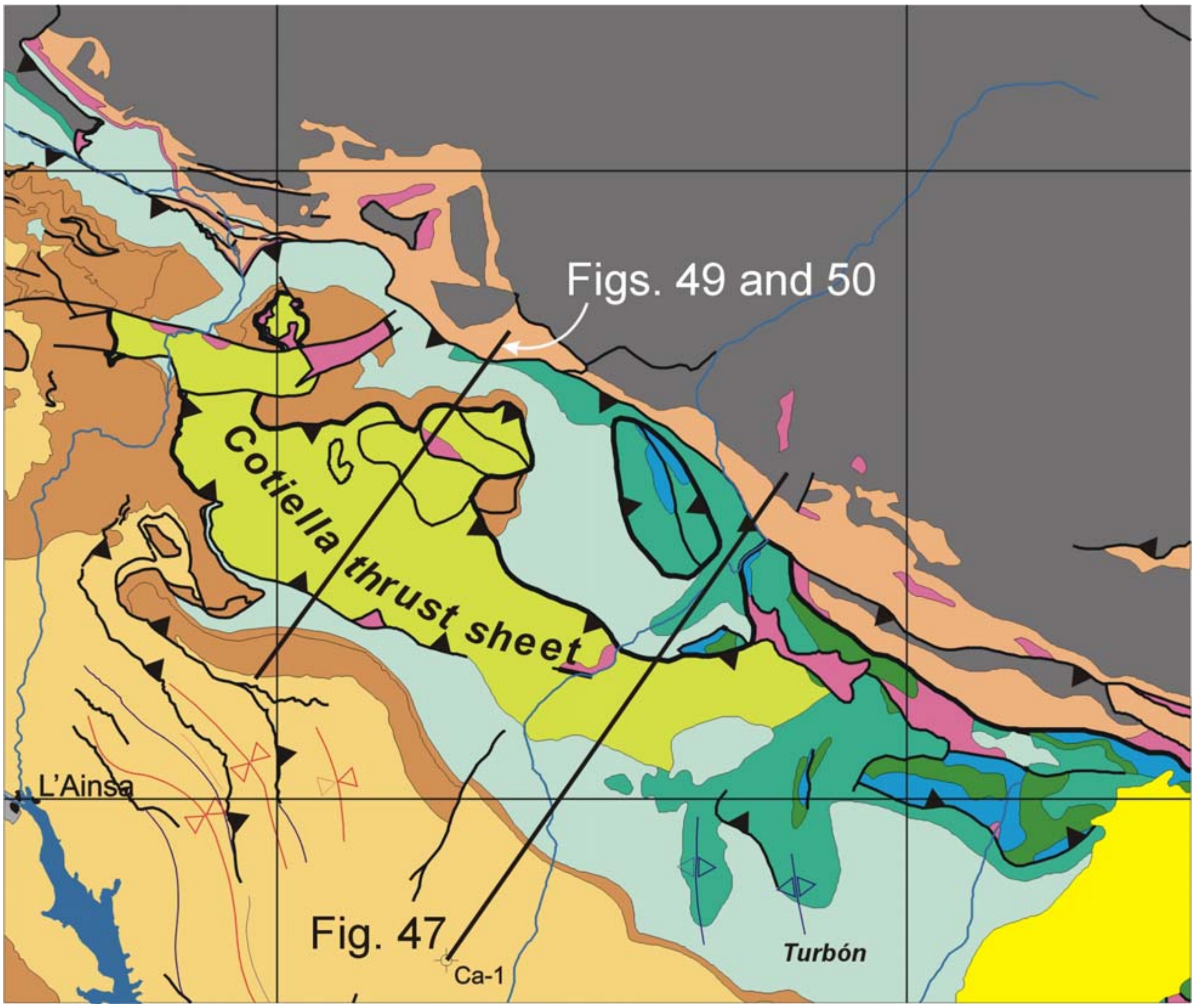


Figure 46.- *Geological map of the Cotiella thrust sheet. See Fig. C-1 for location and Fig. 47 for the legend.*

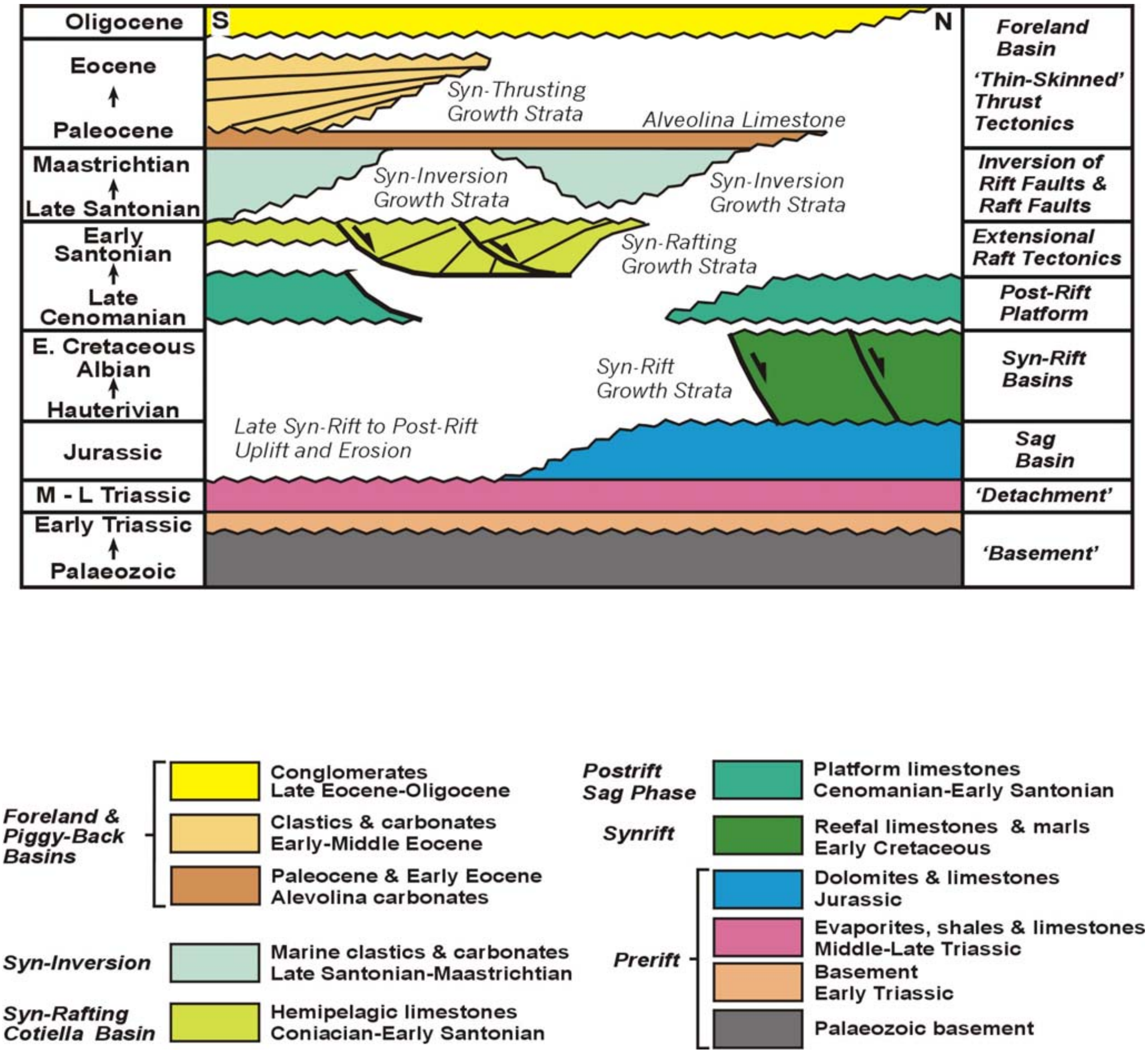


Figure 47.- *Chronostratigraphic diagram of the South-Central Pyrenees (Montsec-Cotiella and Boixols thrust sheets).*

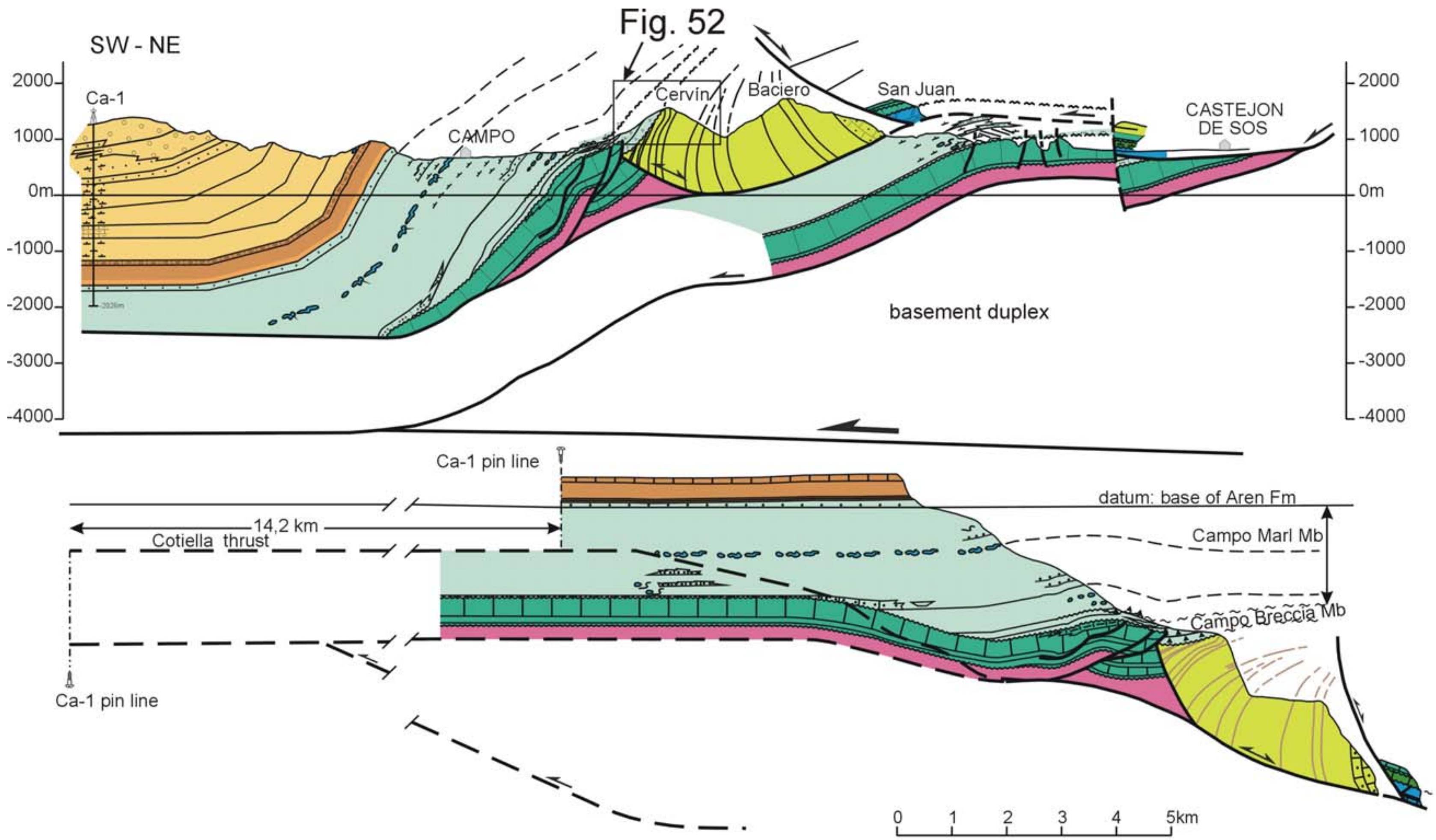
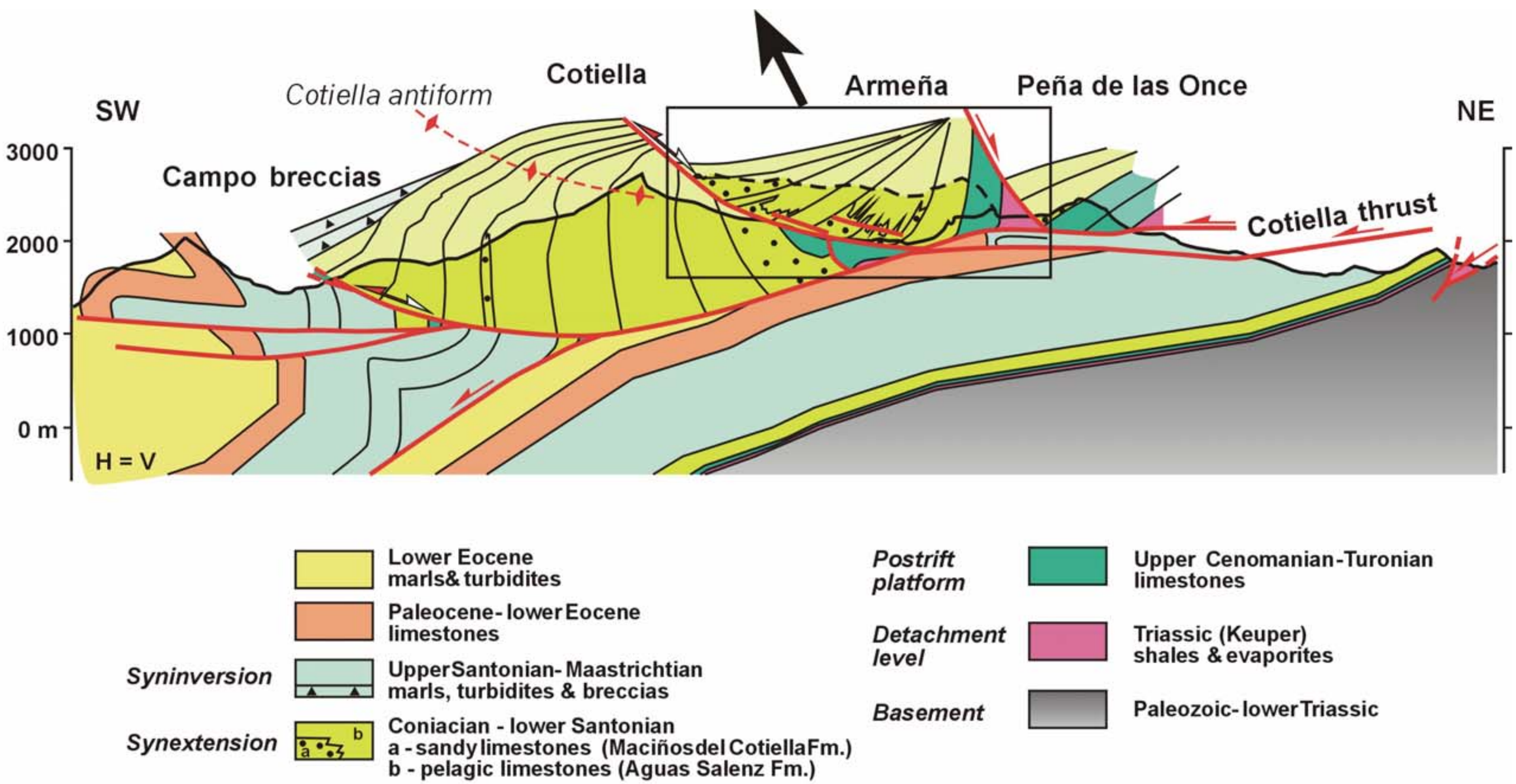


Figure 48.- *Cervín-Baciero cross-section showing a basement-cored duplex beneath two foreland dipping cover thrust-sheets. The uppermost thrust sheet contains a Coniacian-Santonian extensional basin which has been transported southwards over 14km. See a field shot of the southern boundary of this basin (Fig. 52). Cervín-Baciero restored cross-section showing the Coniacian-Santonian extensional structure, its inversion during Santonian-Maastrichtian time, and the future position of Tertiary thrusts. Notice the growth sequence and marked roll-over anticline over the shallow listric fault. Syn-inversion turbidites overlay the inverted structures. See Fig. 46 for location and Fig. 47 for the legend. From García-Senz, 2002.*



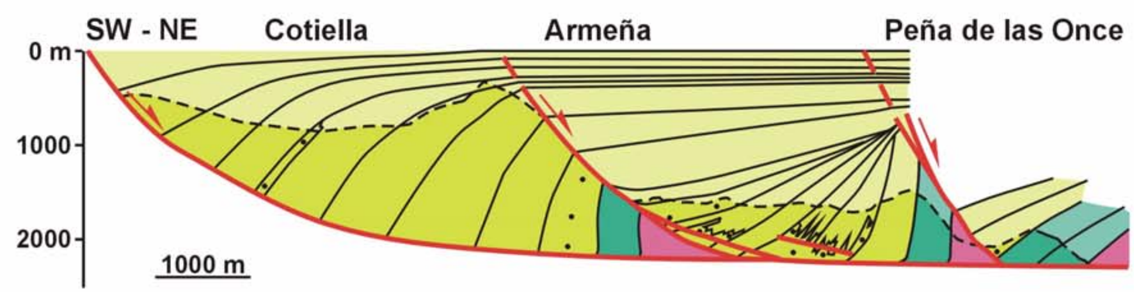


Figure 50.- *Cross-section through the Cotiella thrust sheet showing the inverted Santionian listric growth faults. The rectangle correspond with the field photo above. See Fig. 46 for location. Restored section through the Cotiella thrust sheet showing the extensional fault system before inversion.*

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LGV 75th anniversary Pyrenees Field Trip, June 11-17, 2008

http://web.mac.com/lgvweb/LGV/Welkom.html

http://www.yearofplanetearth.org/

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