Freistaat Bayern

RegioneEmilia-Romagna

Catalunya

8th EUREGEO

Barcelona | Catalonia | Spain | june 15th - 17th 2015

EUropean Congress on REgional GEOscientific Cartography and Information Systems

Geological 3D Modelling

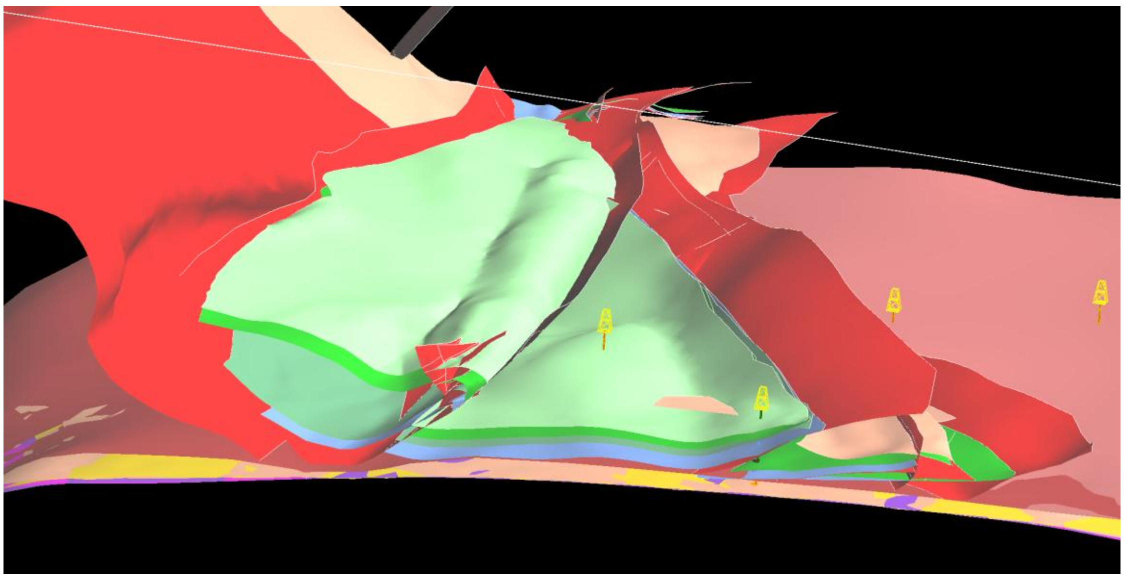
and

Soils: functions and threats

2015 International Year of Soils

Field Guide: The Montsec and Bóixols thrust sheets along the ECORS cross-section (South Central Pyrenees): from field data to 3D models

Field Guide: The Montsec and Bóixols thrust sheets along the ECORS cross-section (South Central Pyrenees): from field data to 3D models.



Josep Anton Muñoz, Núria Carrera, Gonzalo Rivas, Joana Mencos, Oscar Gratacós and Xavier Berástegui.

geomodels
institut de recerca

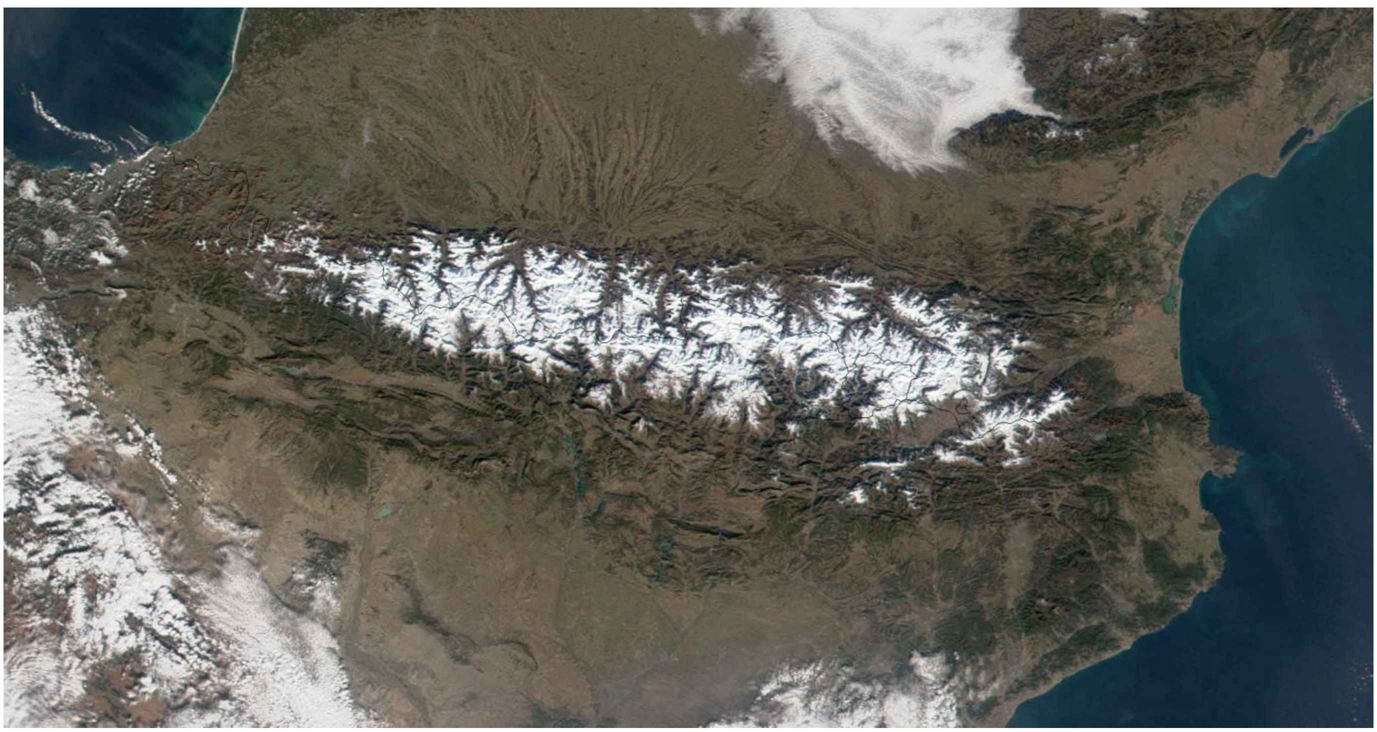
Universitat de Barcelona

ICGC
Institut Cartogràfic i Geològic de Catalunya

SUMMARY OF THE ITINERARY

1st stop	Montsec Thrust. Stratigraphic successions and geometric relationships of the Jurassic (prerift), Lower Cretaceous (synrift), Upper Cretaceous 1 (postrift) and Upper Cretaceous 2 (synorogenic). *Terradets* gorge.
2nd stop	Stratigraphy and structure of the eastern part of the Tremp Basin, Montsec Thrust. *Santa Helena de Claret*
3rd stop	Frontal structure of the Bóixols thrust sheet. *Faidella pass.*
4rt stop	Abella de la Conca Thrust. *Abella de la Conca.*
5th stop	Frontal structure of the Bóixols thrust sheet. The *Sant Corneli* anticlinal and the tectonic inversion of the Lower Cretaceous extensional basin. *Salàs de Pallars.*
6th stop	Hanging wall ramp of the Bóixols-Sant Corneli Thrust and the evolution of carbonate platforms in active margin. *Aramunt Vell*.
7th stop	Stratigraphy and structure of the Cretaceous units in the *Bóixols* thrust sheet. The paleorelief of the Paleogene conglomerates. *Collegats gorge*.
8th stop	Boundary between the basement-involved units of the Nogueres and the *Bóixols* thrust sheet, the Morreres backthrust. *Collegats gorge.*

OVERVIEW OF THE TECTONIC EVOLUTION OF THE PYRENEES



GEODYNAMIC SETTING

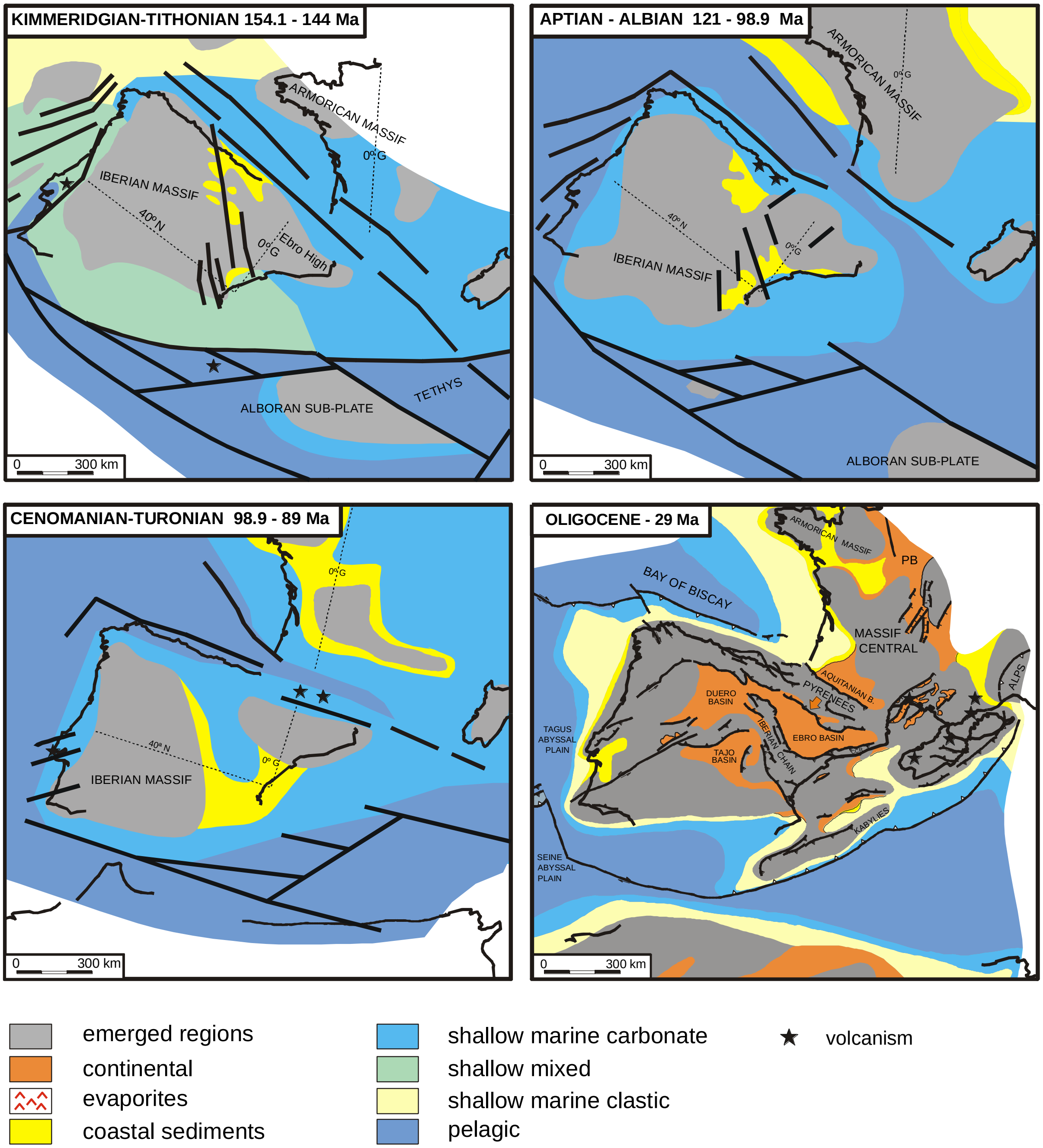
The Iberian Peninsula has a number of Cretaceous extensional basins which development was controlled by the opening of the North Atlantic and the Bay of Biscay as well as by the evolution of the Ligurian Tethys. These basins are not only present along the margins of the Iberian Peninsula but also in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

A first extension event in the Pyrenean domain occurred during the Upper Carboniferous-Triassic related to the post-Hercynian break-up of Pangea (Fig. 2). Most of these deposits are continental, including thick series of volcanics. The main rifting event started at Late Jurassic-Early Cretaceous times as a result of the opening of the North Atlantic related to the sea-floor-spreading system north of the Azores fracture zone (Fig. 2). As a consequence, the North Atlantic area became domed up by thermal uplift (*Ziegler, 1988*). 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 (Fig. 2). Extension continued after the formation of the first oceanic crust in the Bay of Biscay. As thermal subsidence progressed along the Upper Cenomanian-Turonian, the sea submerged the lowlands occupied by extensional basins (Fig. 1). Rapid overstepping of the basin margins, rapid decrease in clastic influx and high sea levels are the main signals accompanying the transgression.

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.

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).*



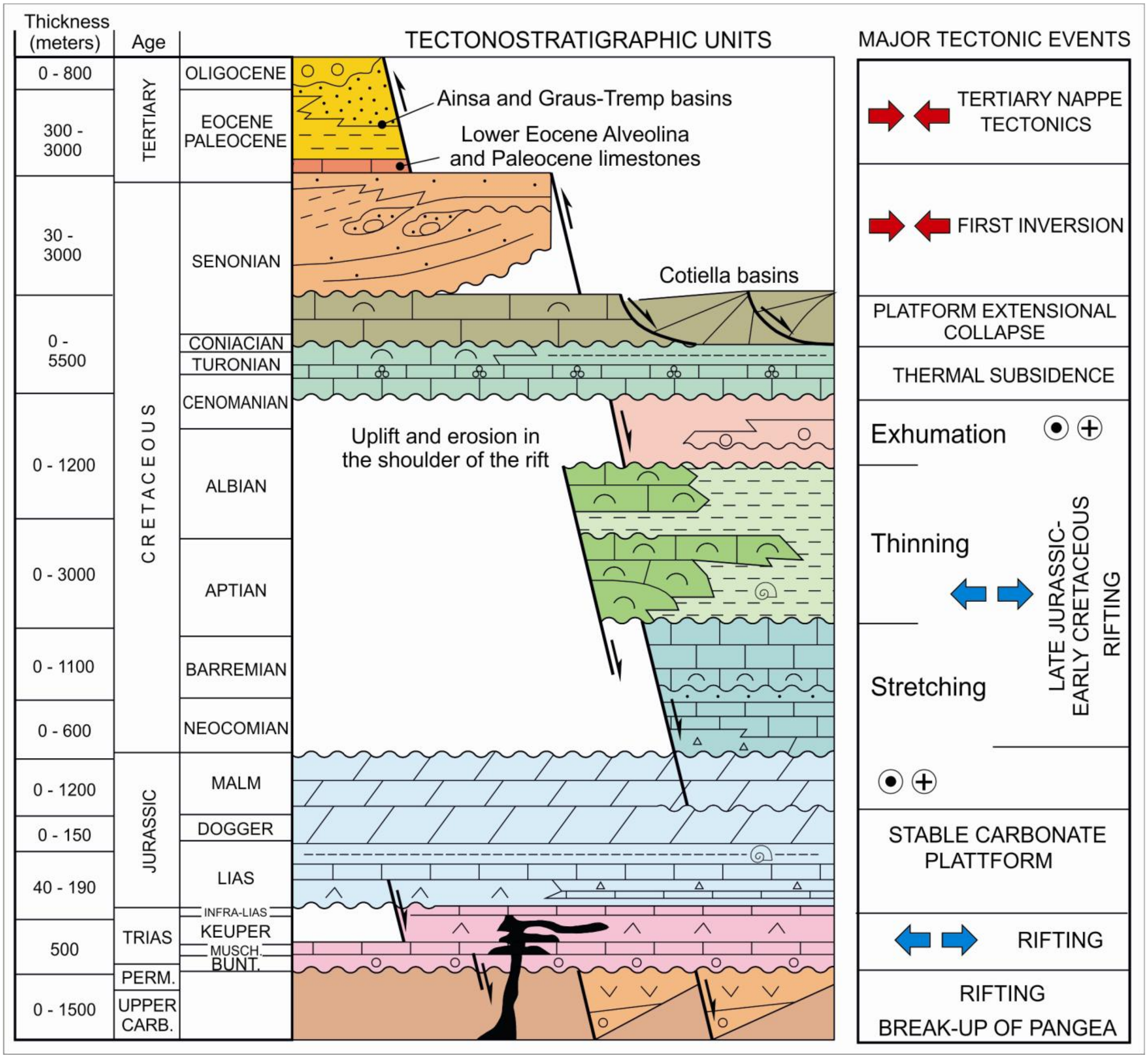


Figure 2. - *Chronostratigraphic diagram of the South-Central Pyrenees showing the main tectonic events, which affected the Mesozoic basins.*

MAIN GEOLOGICAL FEATURES OF THE PYRENEES

The Pyrenees is a doubly-verging 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. Two main foreland basins flank the range: the Aquitaine basin on the north and the Ebro basin on the south (Fig. 3).

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 where the oceanic lithosphere was moderately subducted.

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, and then incorporated into the thrust system.

The Pyrenees is characterized by a thrust system that 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. 4). 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.

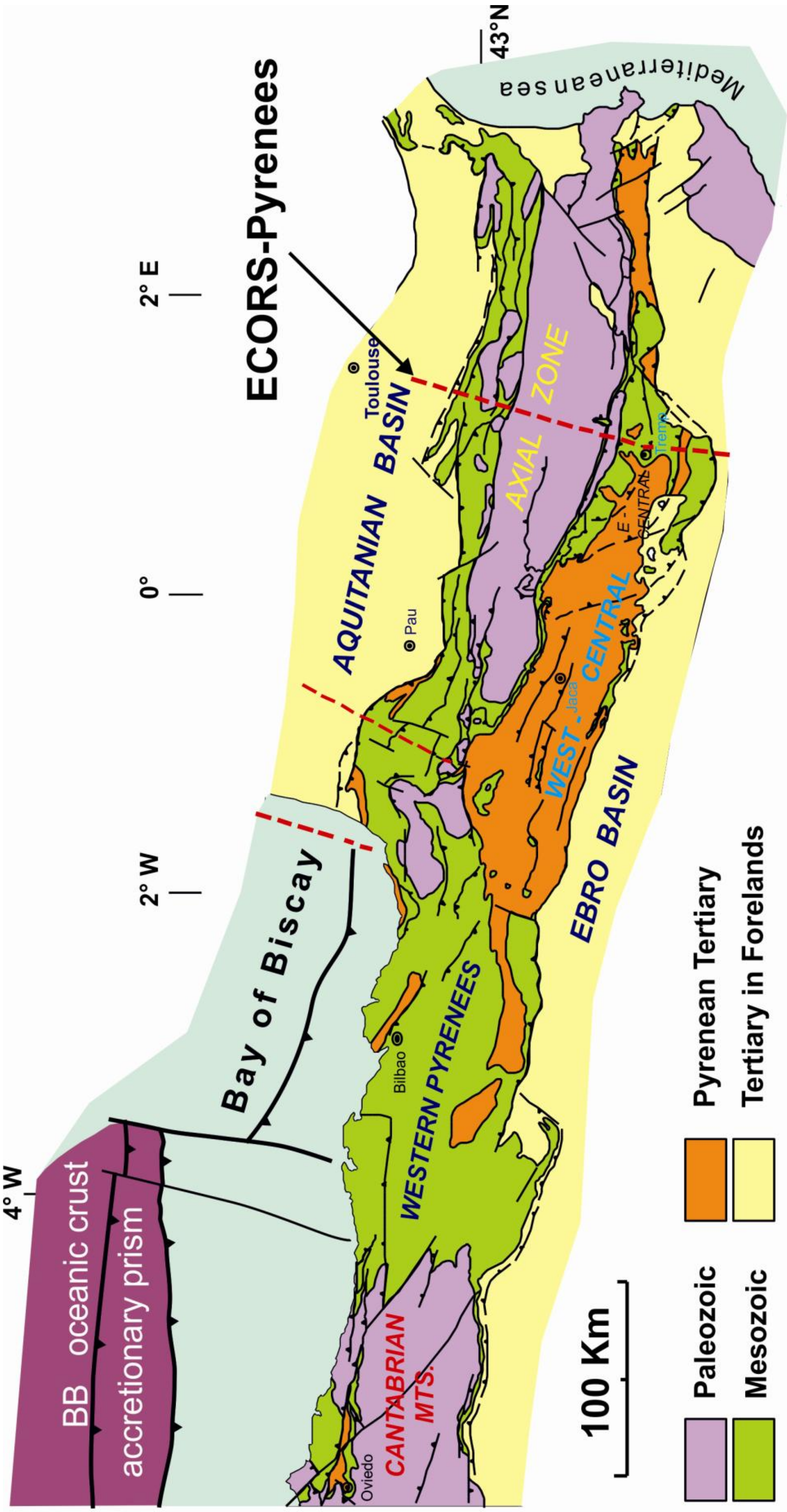


Figure 3.- Structural map of the Pyrenees.

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 autochthonous Paleogene rocks in continuation with the Ebro foreland basin (Fig. 4). They are the Central-South Pyrenean thrust sheets (Bóixols, Montsec and Sierras Marginales) in the central Pyrenees and the Pedraforca thrust sheets in the eastern Pyrenees (Figs. 3 and 4). 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 and the distribution of the detachment salt horizons. 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.

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. 4, *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.

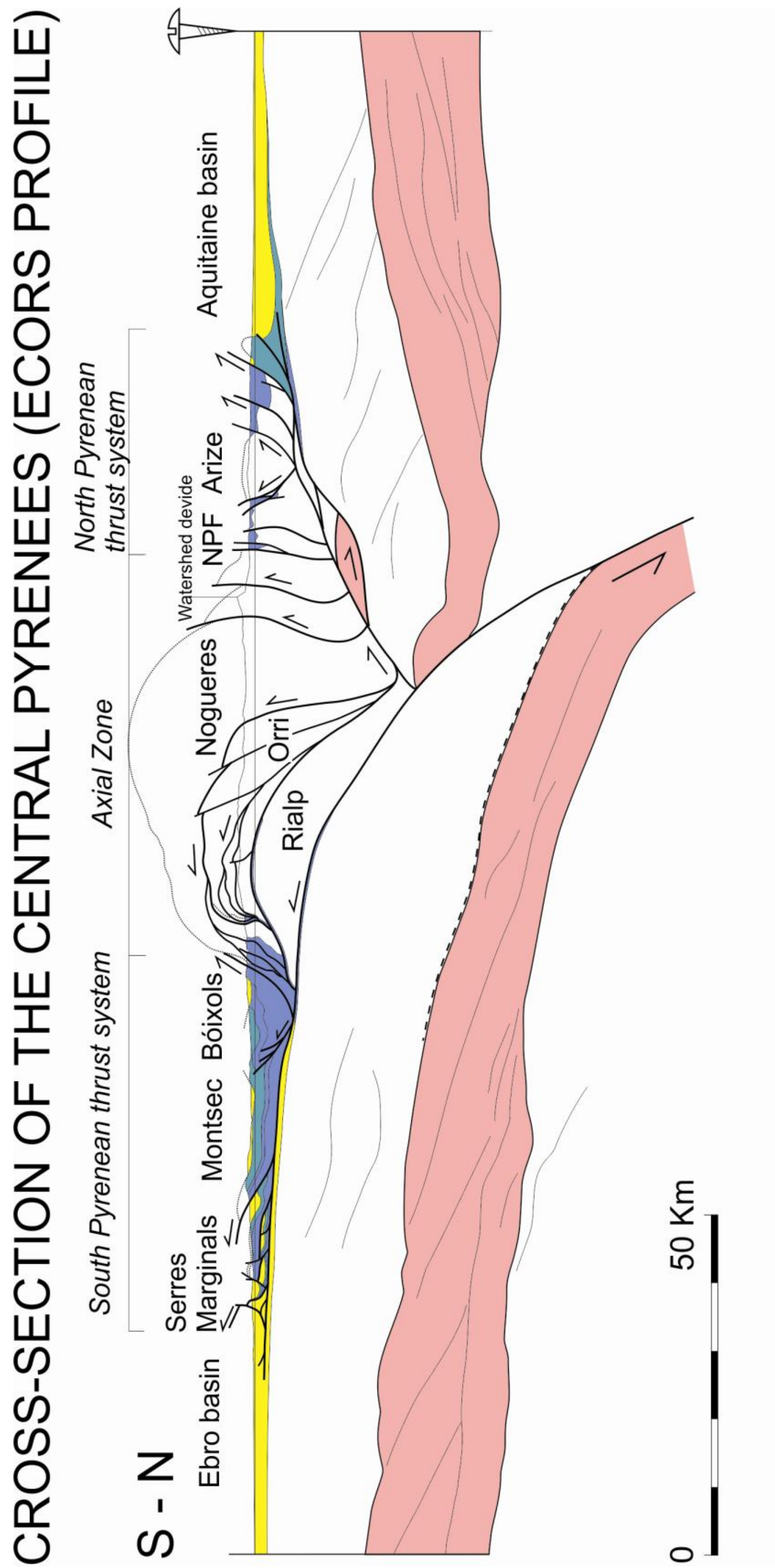


Figure 4.- *Crustal scale cross-section through the central Pyrenees. See Fig. 3 for location*

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. 3 and 4). 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 (*Buis & 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 basing 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*).

THE BALANCED AND RESTORED ECORS CROSS-SECTIONS

The crustal and lithospheric structure along the ECORS cross-section across the Central Pyrenees has been constrained by different geophysical techniques (deep reflection and refraction seismic profiles, gravity, magnetotellurics, magnetic anomalies, tomography, and heat flow. See Fig. 5 for a summary). 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*).

Balanced and restored cross-sections were constructed not only to integrate geophysical and geological data but also to estimate the amount of orogenic contraction (Figs. 5 and 6). 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*).

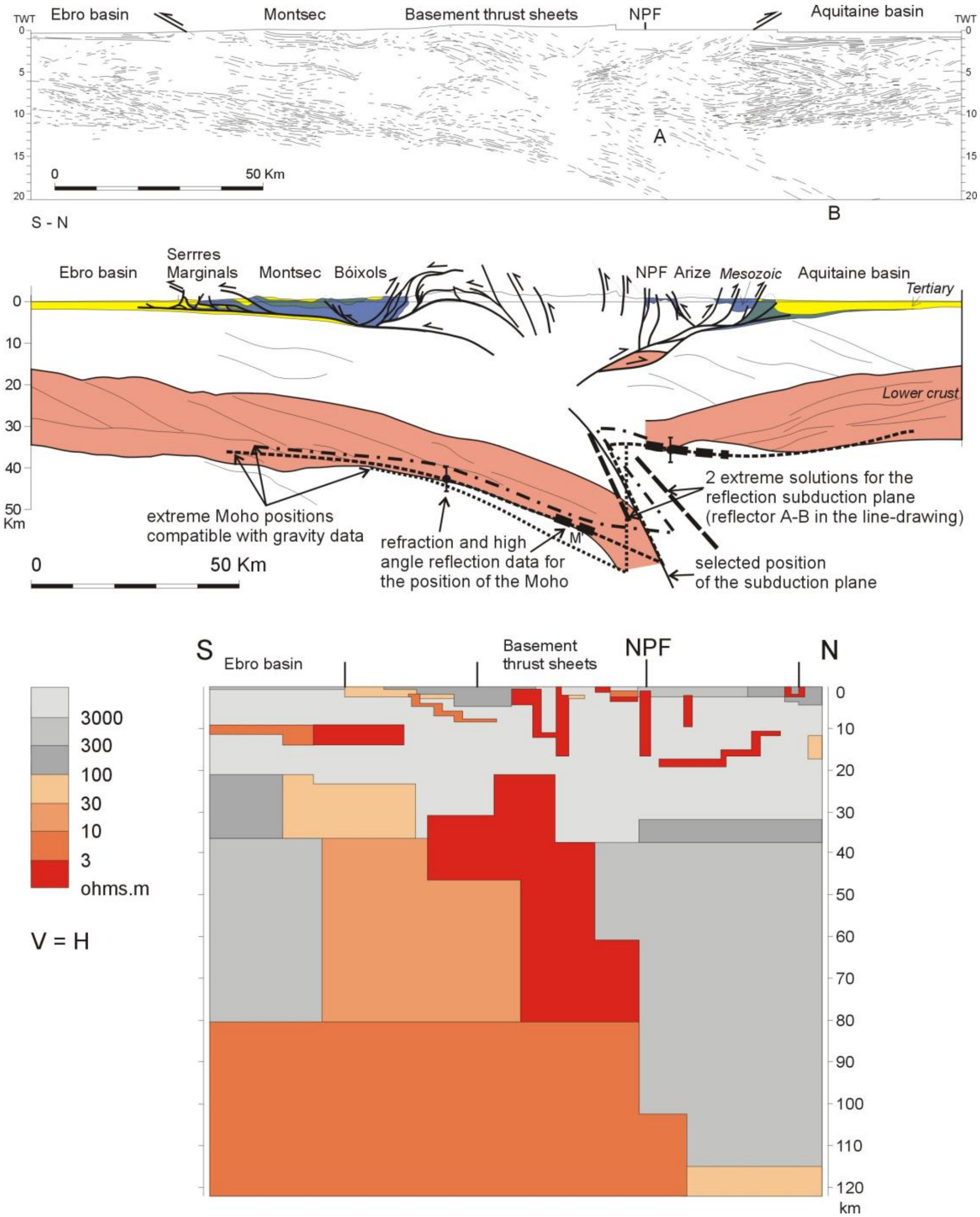


__Figure 5.-__ Geophysical data of the central Pyrenees along the ECORS transect. Reflection seismic time section of the ECORS profile (top). Interpreted crustal structure based on geophysical and geological data (centre); gravity constraints from Torné et al. (1989); high angle reflection and refraction data from Daigniéres et al., (1989);

geological data from Muñoz (1992). Main reflectors of the ECORS seismic profile have been depth converted, taking into account gravity and reflection data, and then incorporated into the crustal geological cross-section. Two dimensional electrical resistivity model from a magnetotelluric survey from Pous et al. (1995) located a few kilometers east of the ECORS profile (bottom).

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 restored cross-section gives an estimate of the geometry of the crust before the Pyrenean collision (Fig. 6). The geometry of the inherited structures (Hercynian cleavage and thrusts, Late-Hercynian extensional faults and Early Cretaceous extensional system) displays 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*).

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 allows 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. 6). 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 (*Millán et al., 1995, Beaumont et al., 2000, Muñoz, 2002*).

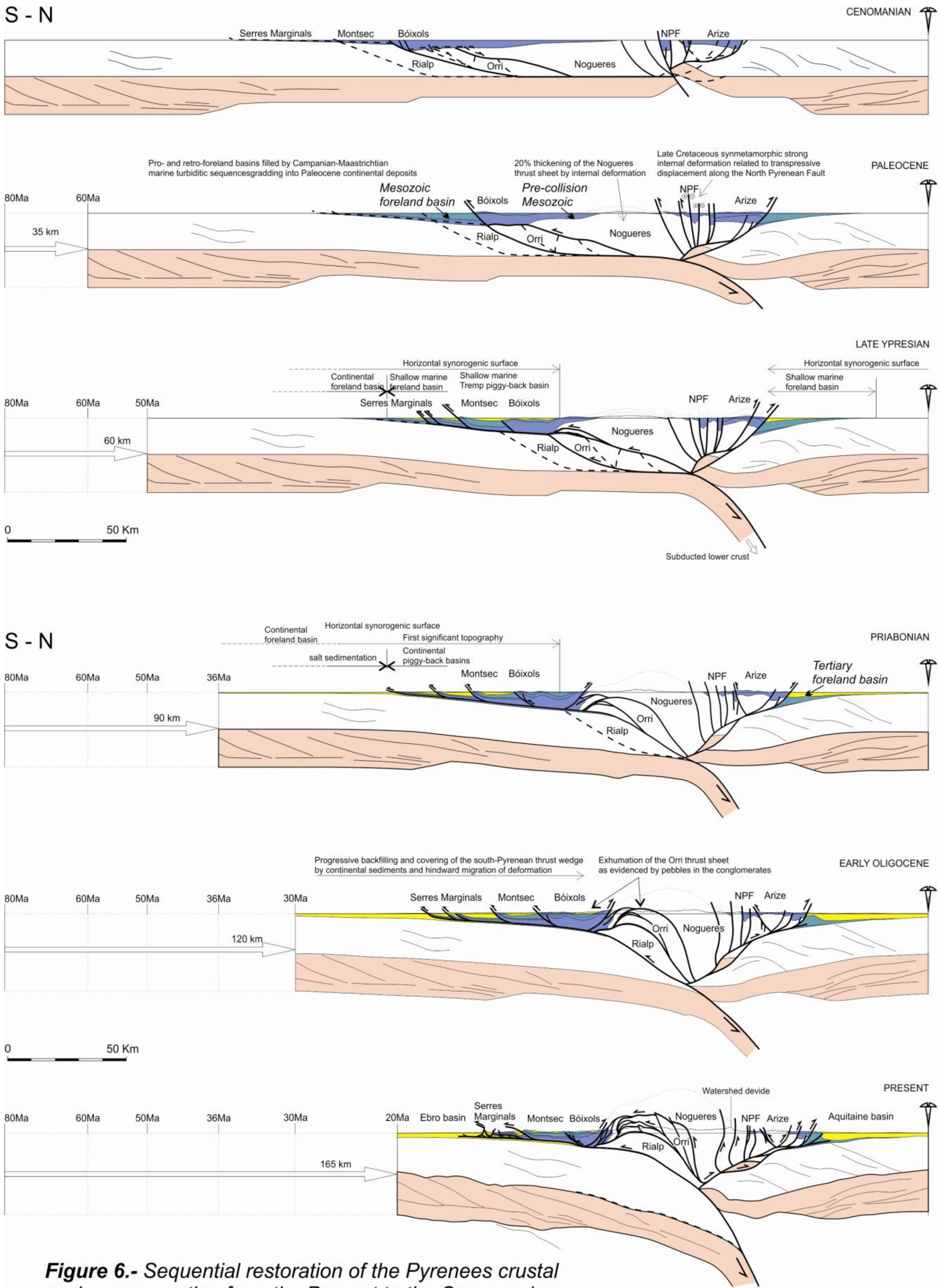


Figure 6.- *Sequential restoration of the Pyrenees crustal scale cross-section from the Present to the Cenomanian.*

The restored ECORS cross-section shows an Early Cretaceous extensional system, which was inverted during the first stage of N-S convergence (Late Santonian-Maastrichtian) (Fig. 6). 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 are dominant in the northern Pyrenees and 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 where coeval with diapiric flow of thick Triassic evaporites (*Ferrer et al. 2008, Roca et al. 2011*). 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 subsiding 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 (Fig. 6). 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.

During the Early-Middle Eocene 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., 1992a*). 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, Millán et al., 1995*). Flexure of the Iberian and European plates was produce by a combination of topographic loading and subduction loading (*Millán 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. 6). 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, Muñoz et al., 1997, Fillon et al. 2013*). The southern Pyrenees was almost completely buried by Early-Middle Miocene times.

The abrupt and subsequent Miocene-Pliocene re-excavation of the southern Pyrenees and the Ebro basin to develop the present fluvial system was some combination of 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 3D GEOLOGICAL MODEL OF CATALUNYA

INTRODUCTION

The geological community in the last years has been engaged in developing new technologies and workflows for acquiring, processing, analysing and visualising geological and geophysical data. This is closely linked to advances occurred both in computers (both hardware and software) and the availability of digital data, which have opened a new era with increasing possibilities to work with huge amount of data and different formats. These advances allow us to integrate more hard data with geological knowledge or constraints derived from the analysis of raw data. To do that, a valid 3D approximation and workflow must be used to minimize errors and to obtain valid 3D geological models.

Being aware of this, the Geomodels Research Institute and the Geological Institute of Catalonia (ICGC), worked to obtain (in 2013) a first version of the 3D geological model of Catalunya at 1:250.000 in order to take an important step in the geology disclosure as well as the type and quality of the geological product generated (Fig. 7).

METHODOLOGY FOR THE RECONSTRUCTION OF THE 3D GEOLOGICAL MODEL OF CATALUNYA

The workflow developed and followed for the 3D reconstruction of the 3D geological model of Catalunya is based on the explicit reconstruction methodology that implies: establishing 3D geometric relationships between initial hard data by means of defining a 3D vector field from the structural analysis of data, thus with geological criteria (*Langenberg et al.*, *1987*, *De Paor, 1988; Fernández, 2004*, *Groshong, 2006, Carrera et al., 2009, Mencos, 2011*)**.** This method is based on the basic concepts for geological cross-section construction but taking into account all the available data and their absolute position, avoiding unnecessary steps of section construction and preventing the introduction of additional errors during the interpolation between sections (*Fernández et al. 2003, Carrera et al. 2009*).

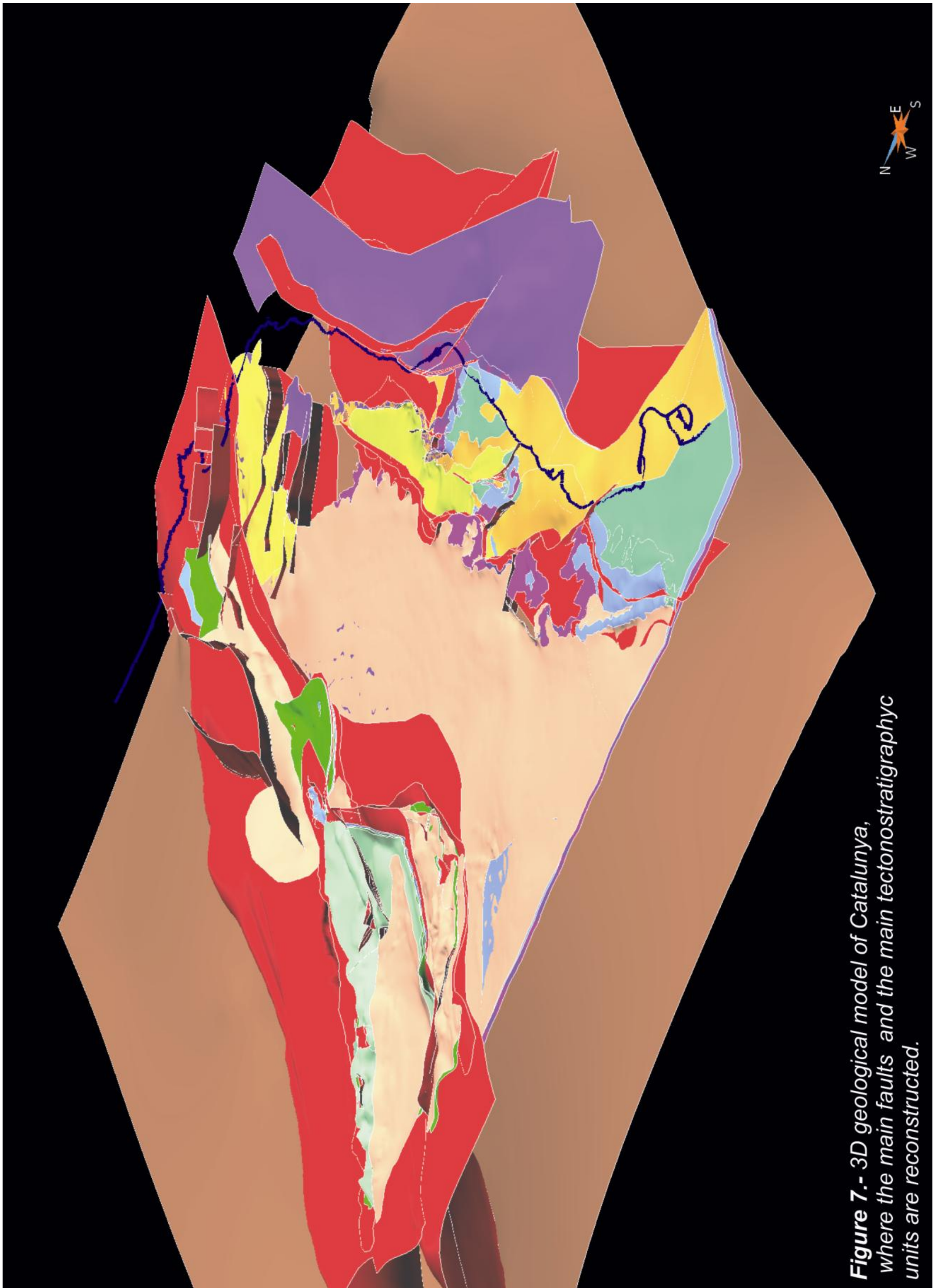


Figure 7.- *3D geological model of Catalunya, where the main faults and the main tectonostratigraphyc units are reconstructed.*

This method can deal with any sort of data such as horizons interpreted on 2D seismic lines, wells and associated data, geological map data and field observations (i.e. attitudes of planes and lines).

Taking into account these 3D reconstruction assumptions, the methodology used to generate the 3D geological model of Catalonia honours all available data and incorporates geological constrains derived from structural analysis (cilindricity, dip domains, plunge lines, etc.) where data is absent or scarce.

The hard data used to reconstruct this 3D geological model can be grouped into:

Surface data: digital geological map of Catalunya at 1:250.000 and all the available digital geological maps (mainly at 1:50.000 and 1:25.000) and digital terrain model of 200 x 200 m and 30 x 30 m.

Subsurface data: well data and seismic data (in SEG-Y; TIFF or JPG; and analogic format).

Derived data: combination of surface and subsurface data to obtain new geological data like cross-sections or contour maps (isopachs or isobaths).

THE MAIN STRUCTURAL UNITS OF THE SOUTH CENTRAL PYRENEES

Introduction

The main structural units of the South Central Pyrenees have been represented in the 3D geological model of Catalunya. The geometry of the main thrusts bounding these structural units, as well as the surfaces representing the main tectonostratigraphic events have been constrained by surface and subsurface data (Fig. 7). The main structural units form three main imbricated thrust sheets, which from south to north are: Serres Marginals, Montsec and Bóixols (Figs. 4, 8, 9 and 10). These units presently lie on top of autochthonous Paleogene rocks of the Ebro foreland basin. To the north and below the cover imbricate thrust sheets, basement rocks constitute an antiformal stack (Fig. 9). The wider structural units are the once involving the most complete stratigraphic record are the Montsec and Bóixols thrust sheets and they will be the objective for this field trip (See Figs. 8, 9 and 10 for location of stops).

Serres Marginals thrust sheets

The Serres Marginals thrusts sheets are located between the frontal thrust to the south and the Montsec thrust to the north (*Pocoví, 1978; Martínez Peña & Pocovi, 1988*). They consist of several small imbricate units characterized by a reduced Mesozoic sequence, which becomes thicker and more complete to the north (*Pocovi, 1978*), overlain by a Lower Eocene succession. The Upper Cretaceous carbonatic sequence is significantly thicker (1500 m) in the Montsec thrust sheet than in the northernmost outcrops of the Serres Marginals thrust sheets, below the Ager basin (*Martínez Peña & Pocoví, 1988*).

Upper Eocene-Lower Oligocene conglomerates, sandstones and gypsums were sedimented synchronously with thrust development resulting into espectacular tectono-sedimentary relationships. For instance, a break-back thrust sequence is clearly demonstrated more to the east of the section in equivalent structural units (Oliana-Peramola area), where a break-back thrust system is superimposed on a previous piggy back imbricate fan (*Vergés and Muñoz, 1990*).

Montsec thrust sheet

This thrust sheet includes a Mesozoic sequence of about 3000m thick, mainly of Upper Cretaceous limestones and a Cenozoic sequence represented by Paleocene and Lower and Middle Eocene clastic sediments (Tremp-Graus basin). lt shows a simple structure mainly consisting of a broad syncline, which supports the piggy back Tremp-Graus basin (Fig. 9). The Montsec thrust sheet is bounded to the south by the Montsec thrust, which displays cartographic arc geometry, much the same as the floor thrust of the Serres Marginals (Figs. 3 and 8). The age of the Montsec thrust is Ypresian as recorded by the syntectonic sediments at both sides of the thrust, especially to the south, in the Ager basin. A minimum displacement of about 10 km along the Montsec thrust is well constrained from the Comiols oil well data and from the cutoff points in its hangingwall and footwall (Fig. 9).

Bóixols thrust sheet

The Bóixols thrust sheet is located between the Tremp basin and the Nogueres Thrust sheet (Figs. 3, 8 and 9). This thrust sheet consists of a thick (over 5000 m) Mesozoic sequence, mainly Lower Cretaceous in age. The thickness of the Lower Cretaceous marls and limestones represents the main stratigraphic difference with respect to the Montsec thrust sheet. The southern boundary of the Bóixols thrust sheet corresponds along most of its cartographic expression to a non-exposed thrust, which is overlapped by the Maastrichtian Aren sandstone formation (*Souquet, 1967; Garrido-Megías and Rios, 1972*). The syntectonic character of the Aren sequence is clearly demonstrated by the fan attitude of the sandstone beds and by their onlap disposition over the southern limb of the Bóixols-Sant Corneli anticline (*Puigdefábregas and Simó, 1986*). The frontal part of the Bóixols thrust sheet presents a complicated structure as a result of the inversion of previous Lower Cretaceous extensional faults (*Berastegui et al. 1990*). The contact between the cover imbricated stack and the basement antiformal stack corresponds to a passive-roof backthrust (Morreres backthrust). During the development and southward displacement of the basement antiformal stack the cover units were wedged northwards and up over the basement.

Hercynian basement thrust sheets

North of the cover Upper Thrust Sheets (South Pyrenean Central Unit), Alpine thrusting has involved the Hercynian basement rocks. Basement rocks constitute thrust sheets, which are piled on top of each other forming the Axial Zone antiformal stack (Figs. 4, 9 and 10). The uppermost of these thrust sheets is the Nogueres unit (*Dalloni, 1910, 1930*) where thrusts affect basement and Triassic cover rocks. In the Nogueres unit, thrusts are steepened, and as a result, the hangingwall anticlines display downward facing fold geometry. In the Nogueres thrust sheet two units can be differentiated: the Upper Nogueres units, where lower Triassic red beds unconformably overlie Devonian rocks and Lower Nogueres units where thick Stephano-Permian sequences occur between the Triassic and the Devonian rocks. The Upper Nogueres units are rooted in the northern flank of the Axial Zone antiformal stack and have been displaced to the south a minimum of 10-15km. The Lower Nogueres units are constituted by several small thrust sheets with a hectometric to kilometric displacement to the south. Below the Nogueres thrust sheet, Cambro-Ordovician and Devonian rocks constitute the lower outcropping thrust sheets of the Axial Zone antiformal stack (Orri and Rialp), the lowermost one outcropping in the Rialp tectonic window (Figs. 9).

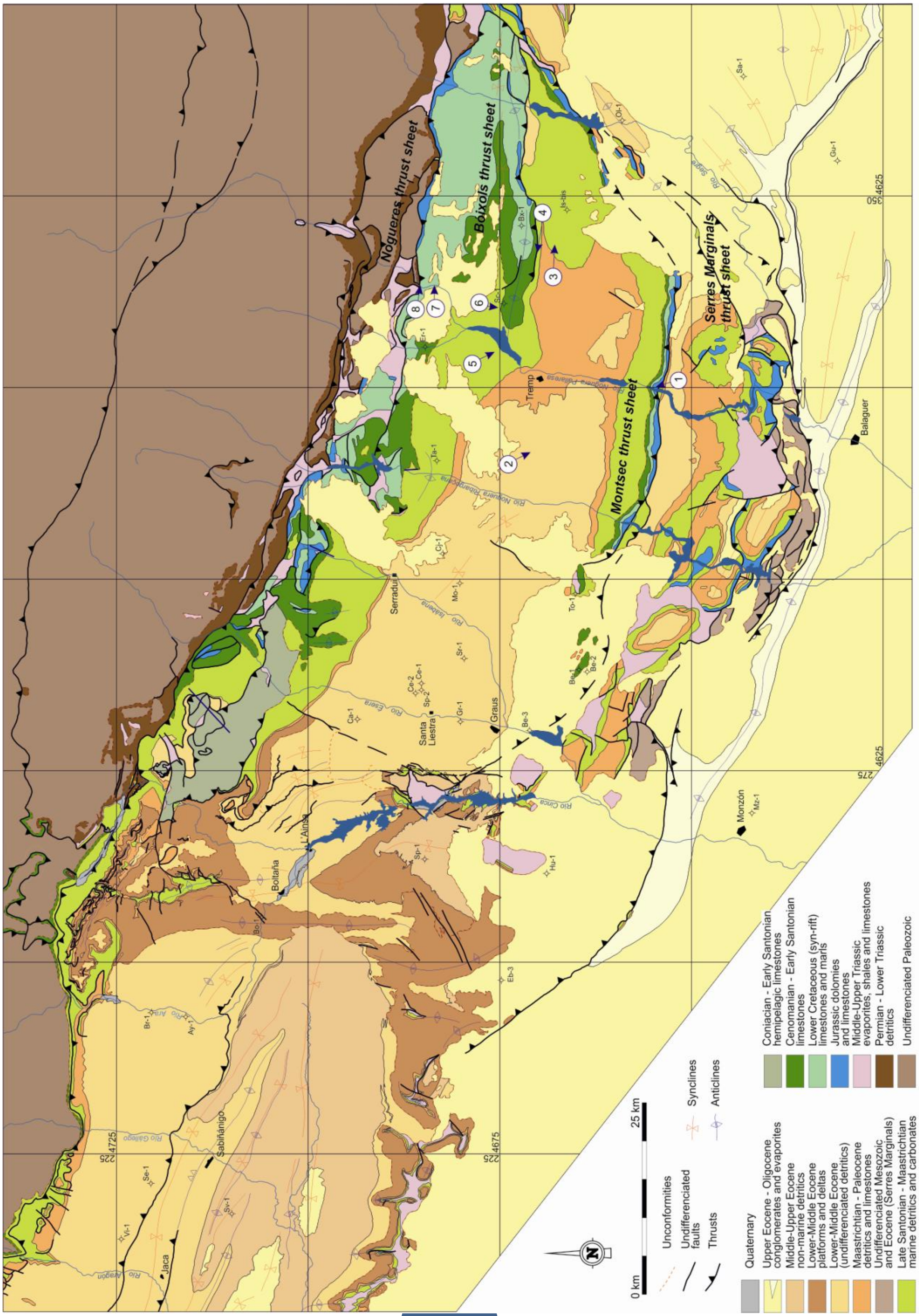


Figure 8.- Structural map of the South Central Pyrenees with a detailed location of the stops.

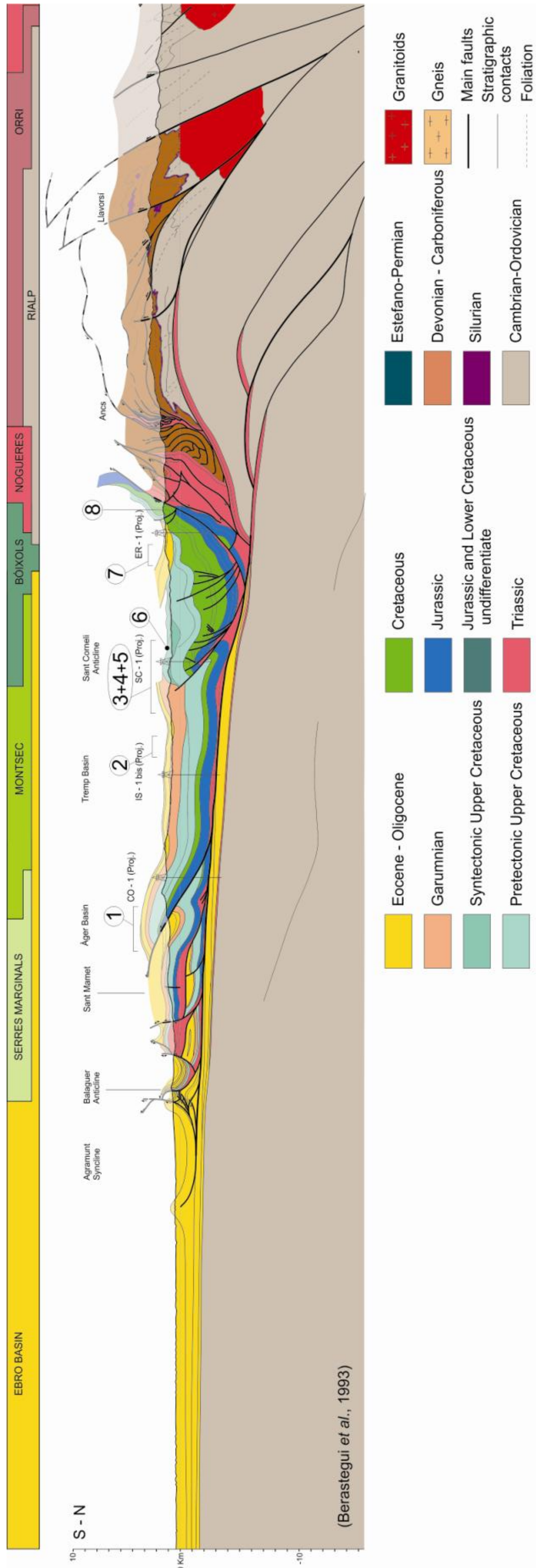


***Figure 9.-** Cross-section along the Pallaresa valley and location of the stops*

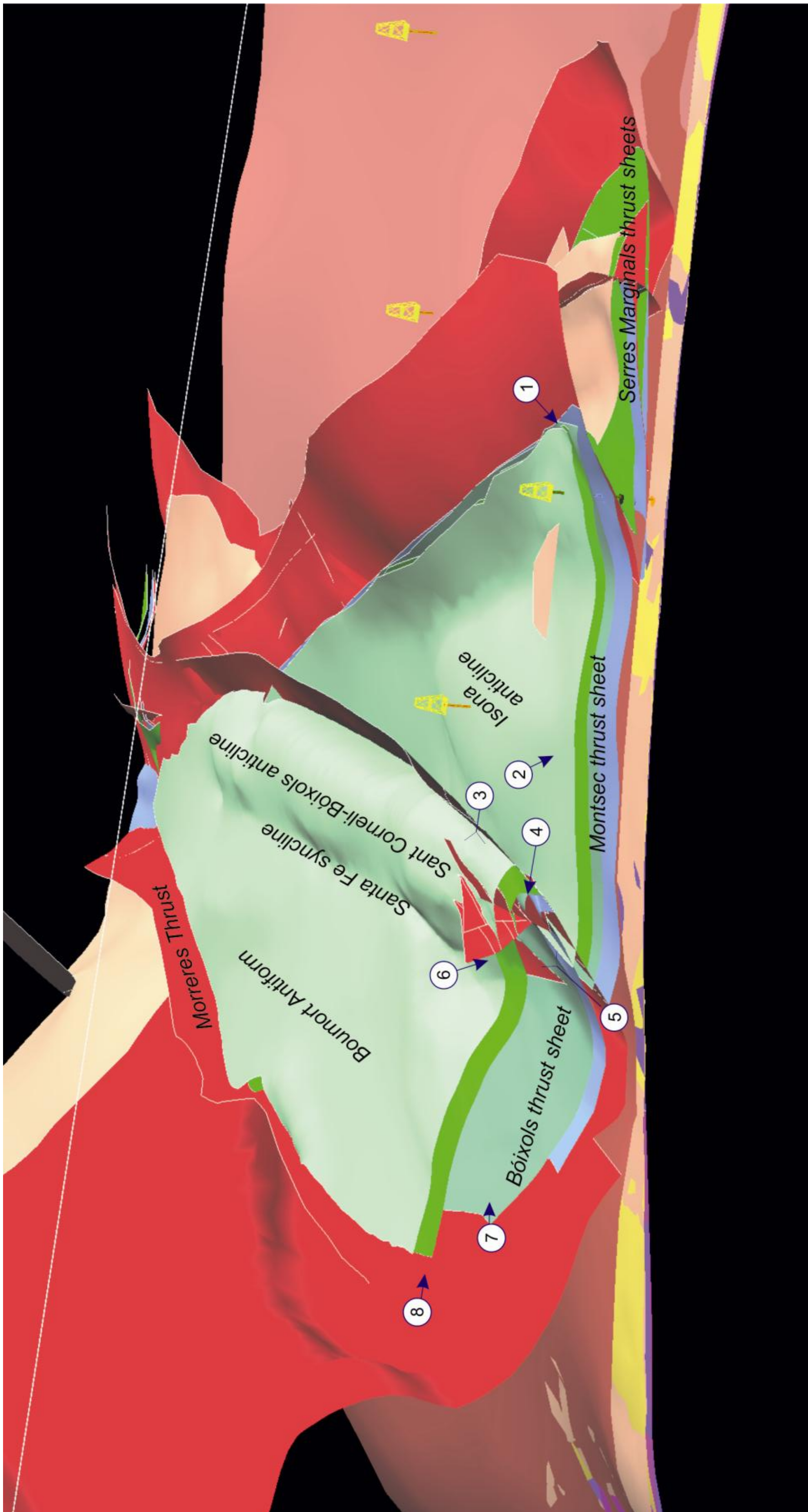


Figure 10.- *Section of the 3D model of Catalunya along the Noguera Pallaresa River and location of stops on it.*

PART B:

ITINERARY

STOP 1: MONTSEC THRUST

Terradets, intersection of the road to Ager

***Objectives**: General view of the Montsec thrust sheet, its structure and stratigraphy. The Montsec thrust and its relationships with the Lower Eocene rocks in its footwall.*

The aim of this stop is to obtain a general view of the Montsec thrust sheet and its footwall, the Ager basin (Figs. 1.1 and 1.2).

Looking northwards, the E-W elongated mountains, which correspond to the Montsec range, are made up of a Mesozoic succession, mainly of limestones (Figs. 9, 1.3 and 1.4). The highest ridges are formed by Upper Cretaceous limestones, up to l500m thick. A Lower Cretaceous succession, only 200m thick, is pointed out by an alignment of cliffs over the dark-grey coloured Dogger dolomies, which are very characteristic in the landscape. The depressed area at the bottom of the Montsec range is formed by the Lower Jurassic marls and limestones. The whole Mesozoic succession dips regularly, about 30º to the north and constitutes the Montsec thrust sheet. The bottom of the valley, around the lake, as well as the road cuts, is made by the Lower Eocene clastic sediments of the Ager basin (Figs. 1.3 and 1.4).

These Eocene rocks are located in the footwall of the Montsec thrust and display a kilometric-scale footwall syncline (Figs. 9 and 1.4). In the northern limb of this syncline progressive unconformities occur and close to the Montsec thrust, the lowermost part of the Eocene succession has been eroded below upper Lower Eocene sequences. The Montsec thrust is not a simple structure. Along the Pallaresa valley, small slices of Upper Cretaceous limestones and Lower Eocene sandstones outcrop in between the Montsec thrust sheet and the Eocene beds of the Ager basin (Fig. 1.3). Thrusts constitute a triangle zone in which the Montsec thrust (the northernmost one) has reactivated as an out-of-sequence thrust. The strong omission of stratigraphy by erosion (upper Lower Eocene sequences over lower Upper Cretaceous) in the slices of the triangle zone corroborates this hypothesis.

The Comiols-1 well drilled the complete Montsec thrust sheet succession, the Serres Marginals unit in its footwall, and finally the autochthonous Eocene rocks on top of the Paleozoic basement. It is interesting to emphasize the different thickness of the Lower Cretaceous rocks in these different structural units, being 450 m in the Montsec thrust sheet, and absent in the Serres Marginals and Autochthonous units (Fig. 1.5). The original Comiols-1 well described a thin Lower Cretaceous sandstone unit in the Serres Marginals (Fig. 1.5), which has been reinterpreted as Upper Santonian in age.

Figure 1.1*: Aerial view of, from North to South, the Tremp basin, the Montsec Range and the Ager basin (Photo by Jeroen Peters).*

Figure 1.2: *Panoramic view of the Montsec thrust sheet and the Montsec thrust in the Noguera Pallaresa Valley.*

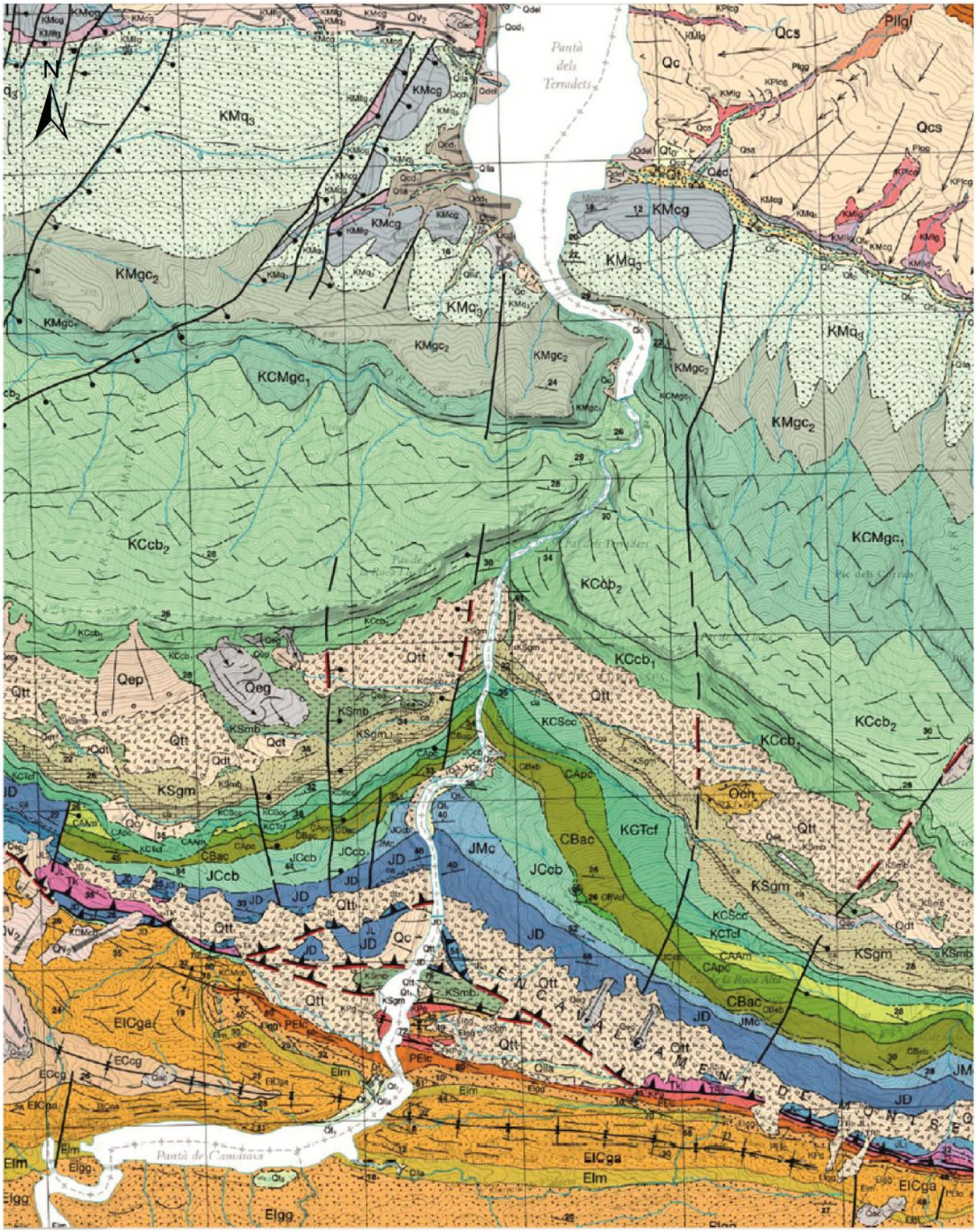


Figure 1.3: *Geological map of the Montsec Thrust Sheet along the Noguera Pallaresa Valley. From Pi et al 2003.*

Extrat of Geological map of Llimiana (65-24), scale 1:25 000. www.icgc.cat

Kilometers
0 0,5 1

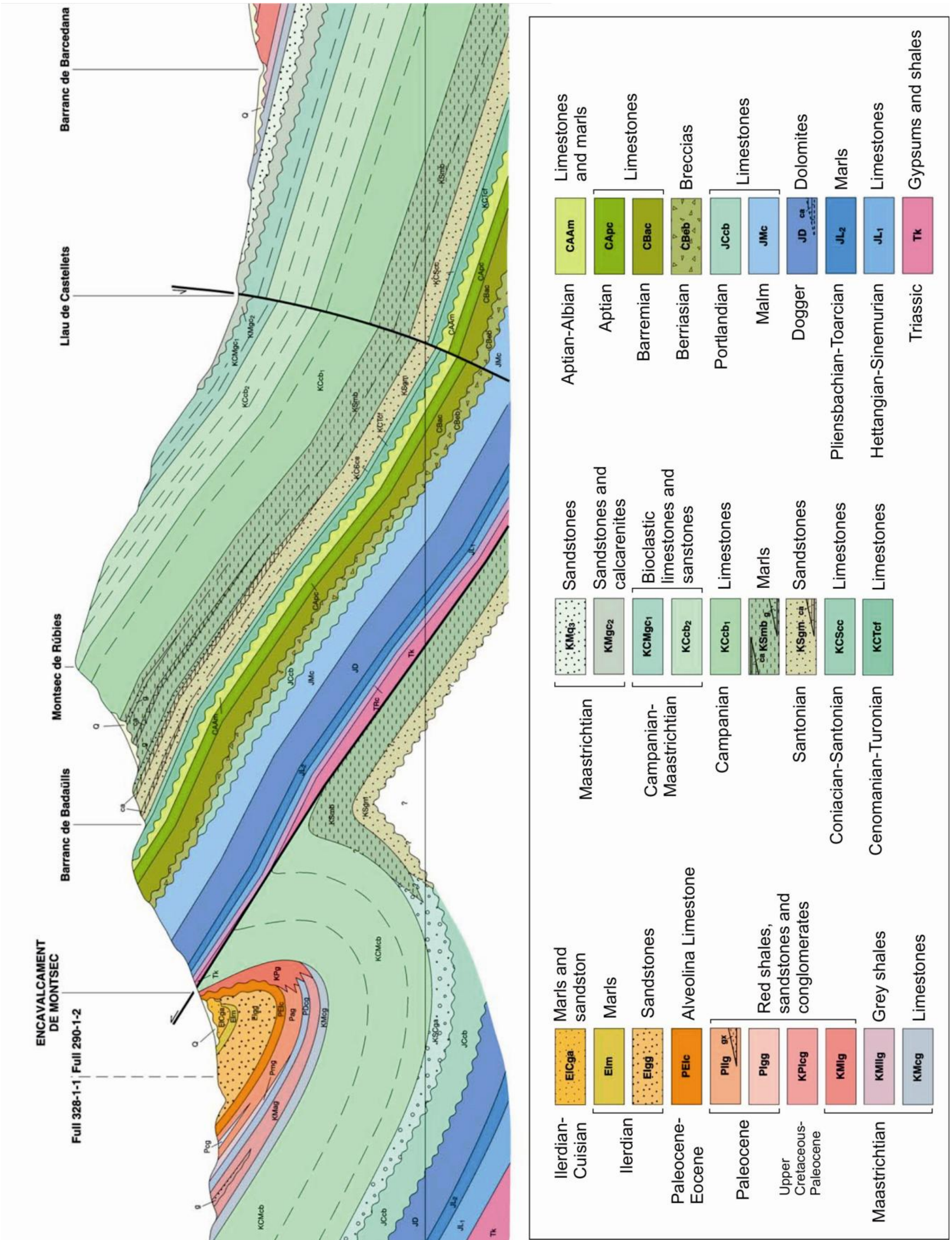


Figure 1.4: *Cross-section across the frontal part of the Montsec thrust sheet. From Pi et al. 2003*

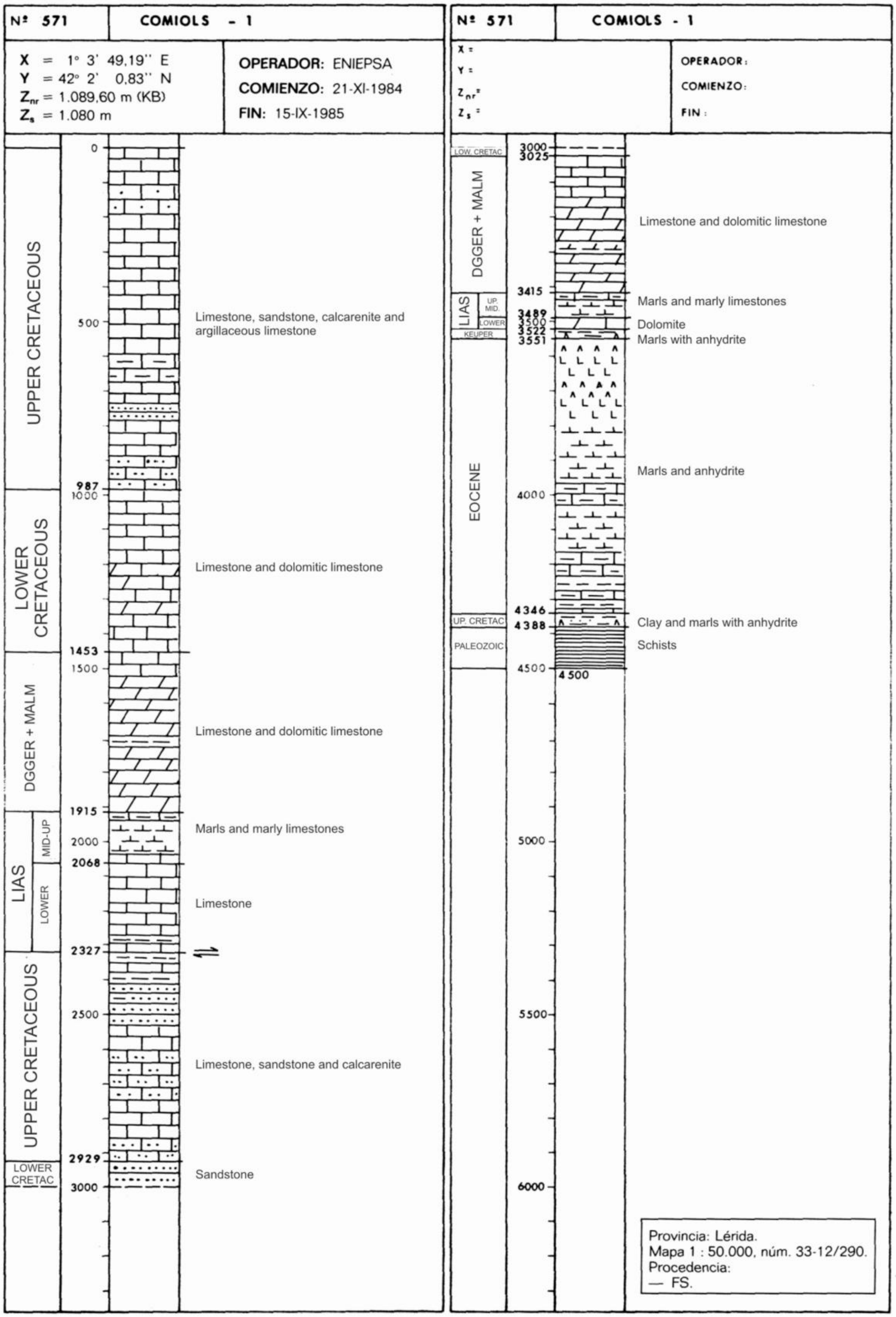


Figure 1.5: *Stratigraphic log from the Comiols-1 well. See Figure 3.4 for location. From Lanaja, 1987.*

STOP 2: TREMP BASIN

Santa Helena de Claret view point, chapel over Claret village

***Objectives**: General view of the eastern Tremp basin and the identification of the main lithostratigraphic units*

From this view point there is an excellent overview of the eastern part of the Montsec thrust sheet. It shows a simple structure mainly consisting of a broad syncline which represents the hanging wall of the Montsec thrust on which the Tremp basin is located.

Looking southwards, we observe the southern border of the Tremp basin formed by an E-W prominent range which corresponds to the northern flank of the Montsec thrust sheet. The top of the first ridges of the Montsec area are formed by Upper Cretaceous limestones, up to 1.500 m in thickness. The top of this bioclastic limestones succession is formed by a progressive unconformity of the Areny sandstone Formation (Mey et al., 1968; Nagtegaal, 1972). This unit, Campanian-Maastrichtian in age, comprises a syntectonic overall coarsening sequence of calcarenites which marks a strong tectonic control of the Boixols thrust sheet. This strong influence developed slumps and olistholits in a gravity flow sedimentation run into a slope and basin plain environment. On top, this sediments prograded westwards along the basin within a progradation pattern from a stuarine to fluvio-deltaic system. This unit appear in both flanks N, where the dam of Sant Antoni lake is located, and S of the Tremp basin with a clear opposite dip directions (Figure 2.1 and 2.2).

The top of the Areny sanstone Formation is an angular unconformity which marks an upward change into terrestrial Tremp Formation (Mey et al., 1968) also known as the Garumnian facies. These reddish facies stand out over landscape coinciding with the main arable area of the basin. This formation comprises a thick sequence, up to 400 m thick, of continental red beds composed by coastal-plain mudstones with intercalation of fluvial channels and lacustrine limestones. Within this unit is the K/Pg boundary. These sediments are overlain by transgressive shallow-marine carbonates (*Alveolina* limestone), which marks the base of the Ilerdian, Lower Eocene in this basin (Luterbacher, 1992). These sediments, grey-blue in color, was chosen as a study model because of its rich and varied faunal content and record the time when the sea invaded the Tremp region from the west through the Cantabric and Jaca troughs.

Looking northwards, the range at the back of the dam with an orane-red colouring, correspond to La Pobla de Segur conglomerates, Middle Eocene-Oligocene in age (Beamud et al., 2003; 2006) which unconformably overlies the Upper Cretaceous beds of the northern limb of the Sant Corneli anticline and also at eastern border of the basin in the Benavent-Comiols area. The stratigraphic thickness of these conglomerates is about 800m in that area (Robles, 1983) but, the complete sequence, reaches up to 2.600m, (Rosell and Riba, 1966) and these ones are interpreted as the result of alluvial fans progradation in relation to the steepened gradients which characterize the third stage in the development of the foreland basin.

Figure 2.1: *Panoramic view of the Tremp Basin from the Santa Helena de Claret.*

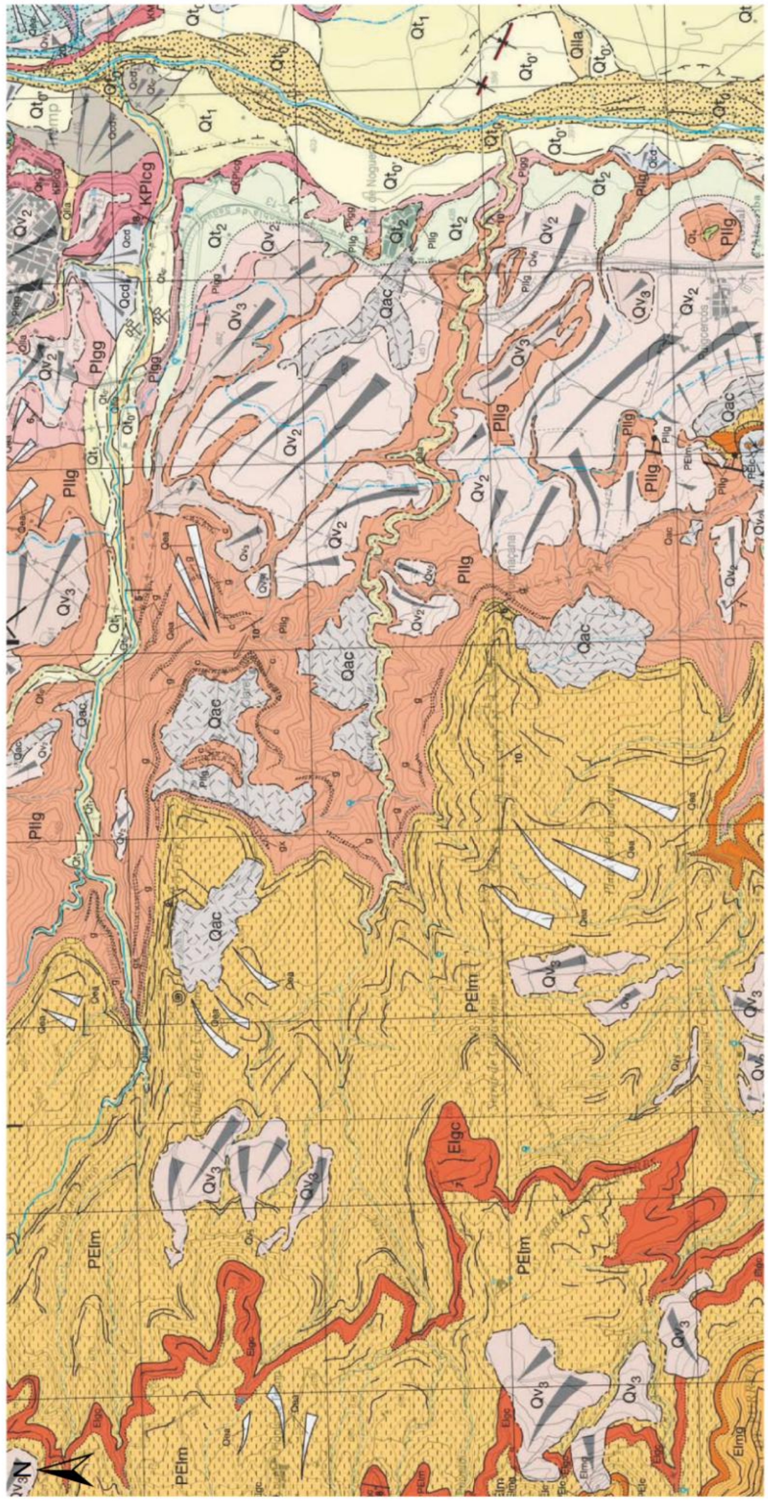


Figure 2.2: *Geological map of Tremp basin, West sector. From Pi et all 2004. Extract of Geological map of Vilamitjana (65-23). Scale 1:25.000.* *www.icgc.cat*

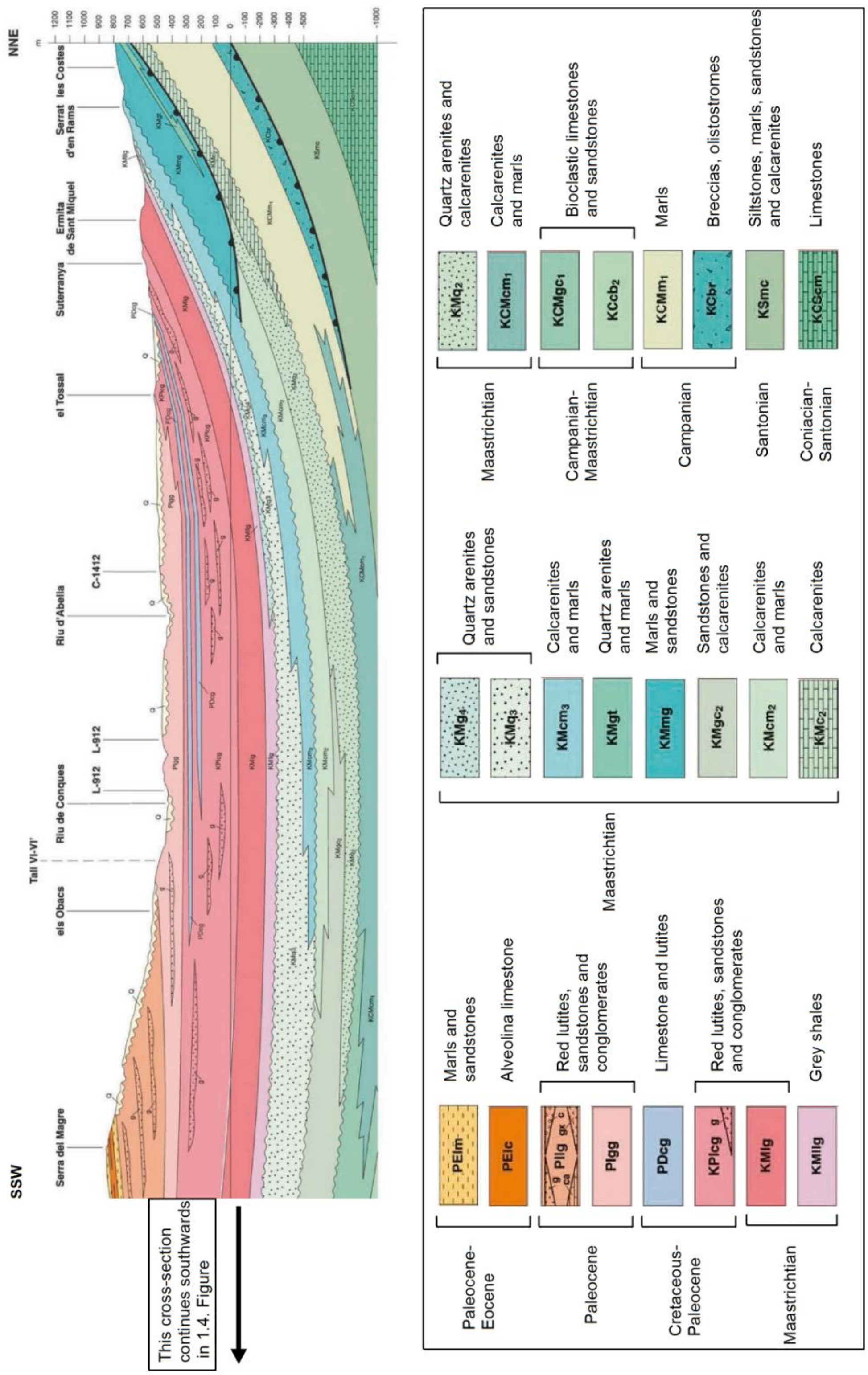


***Figure 2.3:** Cross-section across the Tremp basin*

STOP 3: BÓIXOLS ANTICLINE

Faidella, viewpoint from the road to Bóixols village.

***Objectives**: General view of the northern Tremp basin and the Bóixols anticline.*

From the road Isona to Coll de Nargó, near Faidella Pass, there are spectacular views of the Bóixols anticline (Figs 3.1 and 3.2). In the background, the cliffs (Serra de Carreu) correspond to the lower part of the Upper Cretaceous succession (upper Cenomanian to Coniacian limestones), which dip moderately to the north (Fig. 3.2). The same succession is involved in the forelimb of the Bóixols anticline where beds are close to vertical (Figs. 3.2). The anticline is cored by a thick succession of Lower Cretaceous carbonates, which were drilled by the Bóixols well (Figs. 3.2, 3.3, 3.4 and 3.5).

Maastrichtian sandstones of the Aren Group unconformably overlie the lower Santonian marls and limestones of the southern limb of the anticline. These sandstones are folded into a syncline south of the Bóixols anticline, the Faidella syncline (Figs. 3.4 and 3.5). This syncline is cored by the Garumnian (uppermost Cretaceous-Paleocene) red beds and located between the Bóixols anticline and the Isona anticline (Figs. 3.4 and 3.5). The latter belongs to the Montsec thrust sheet and was drilled by an exploratory well (Isona-1 well, figure 3.6).

The stratigraphic differences between the Montsec and Bóixols thrust sheets are highlighted by the stratigraphic succession drilled by the Boixols-1 and the Isona-1 wells. The first one drilled more than 2000 m of Lower Cretaceous rocks while the second one drilled less than 100 m of these rocks (Figs. 3.3 and 3.6). These significant differences resulted form the tectonic inversion of a previous Lower Cretaceous extensional basin (Fig. 3.5).

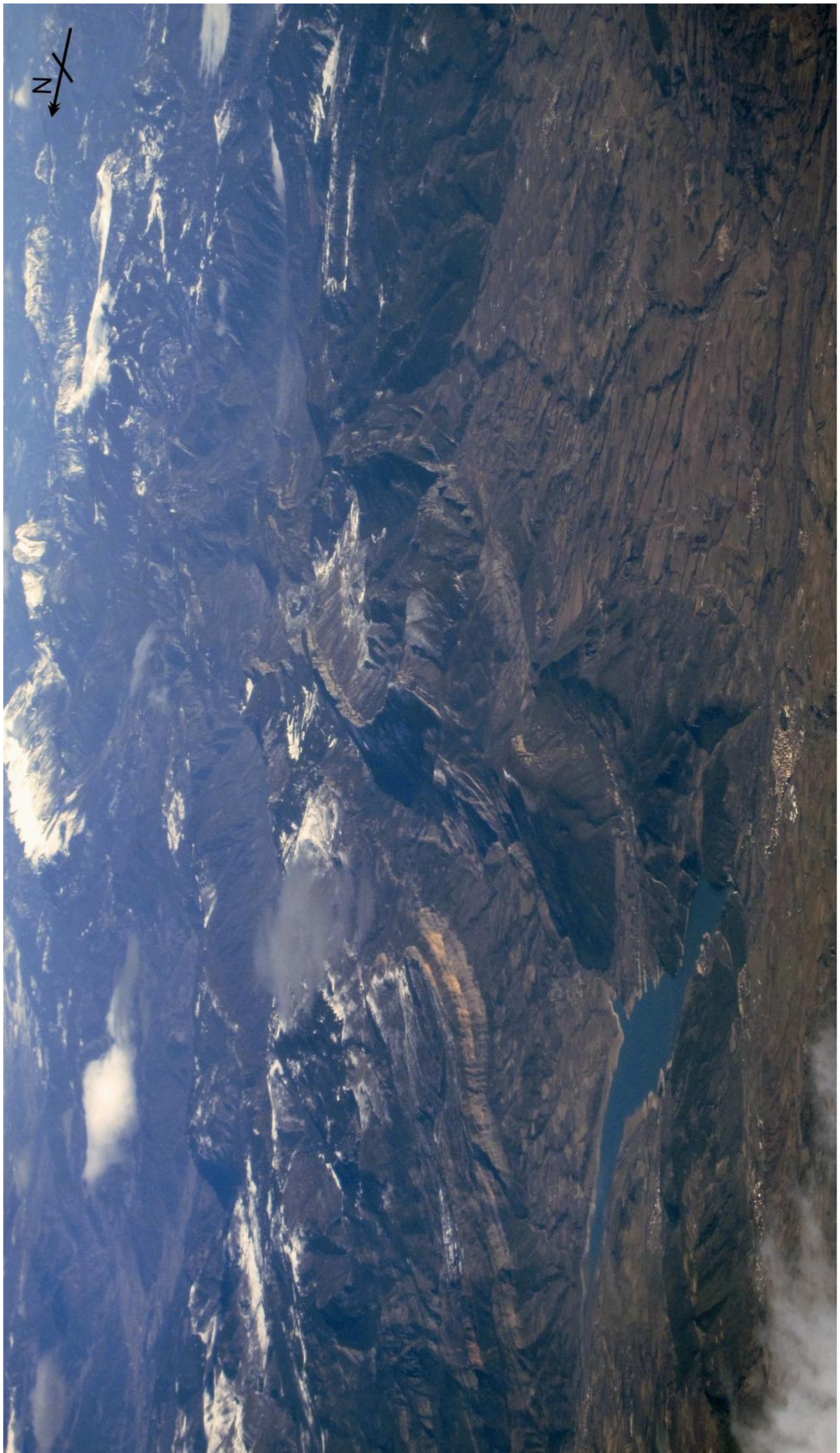


Figura 3.1: *Aerial view of the Sant Corneli-Bòixols anticline and the Tremp basin towards the south (Photo by Jeroen Peters).*

Figure 3.2: *Panoramic view of the Bóixols Anticline from the road of the Faidella pass.*

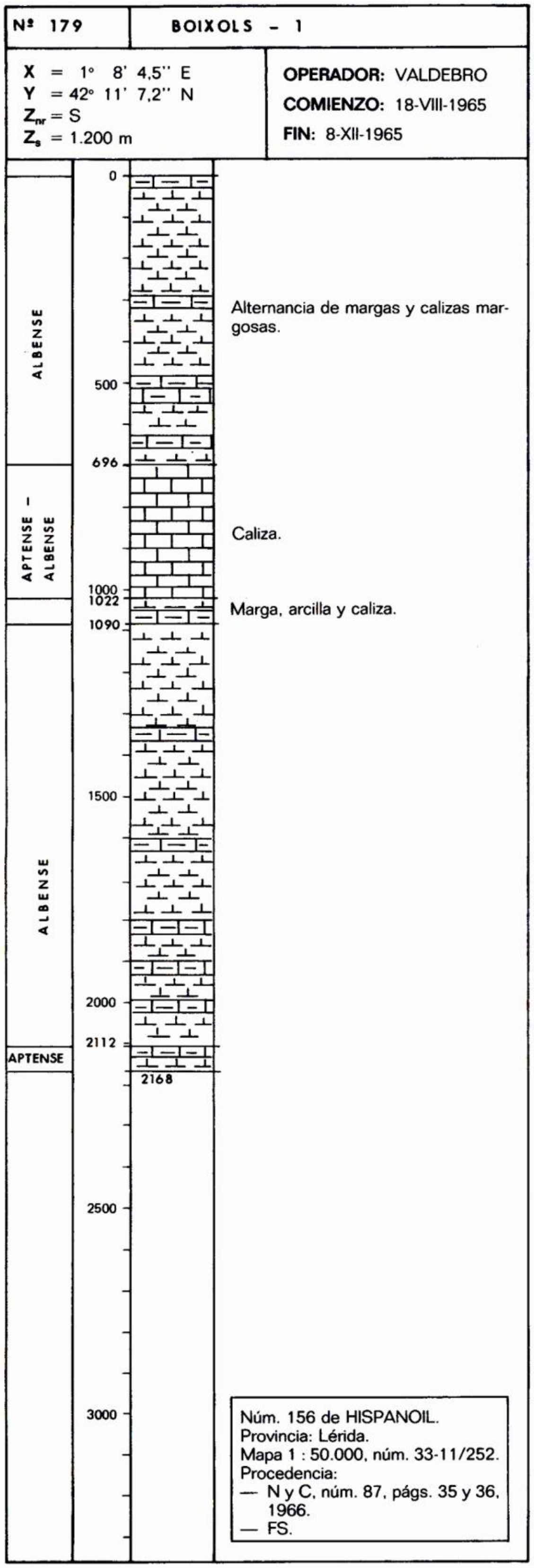


***Figure 3.3**: Stratigraphic log of the Bóixols-1 well. See Figure 3.4 for location. From Lanaja 1987.*

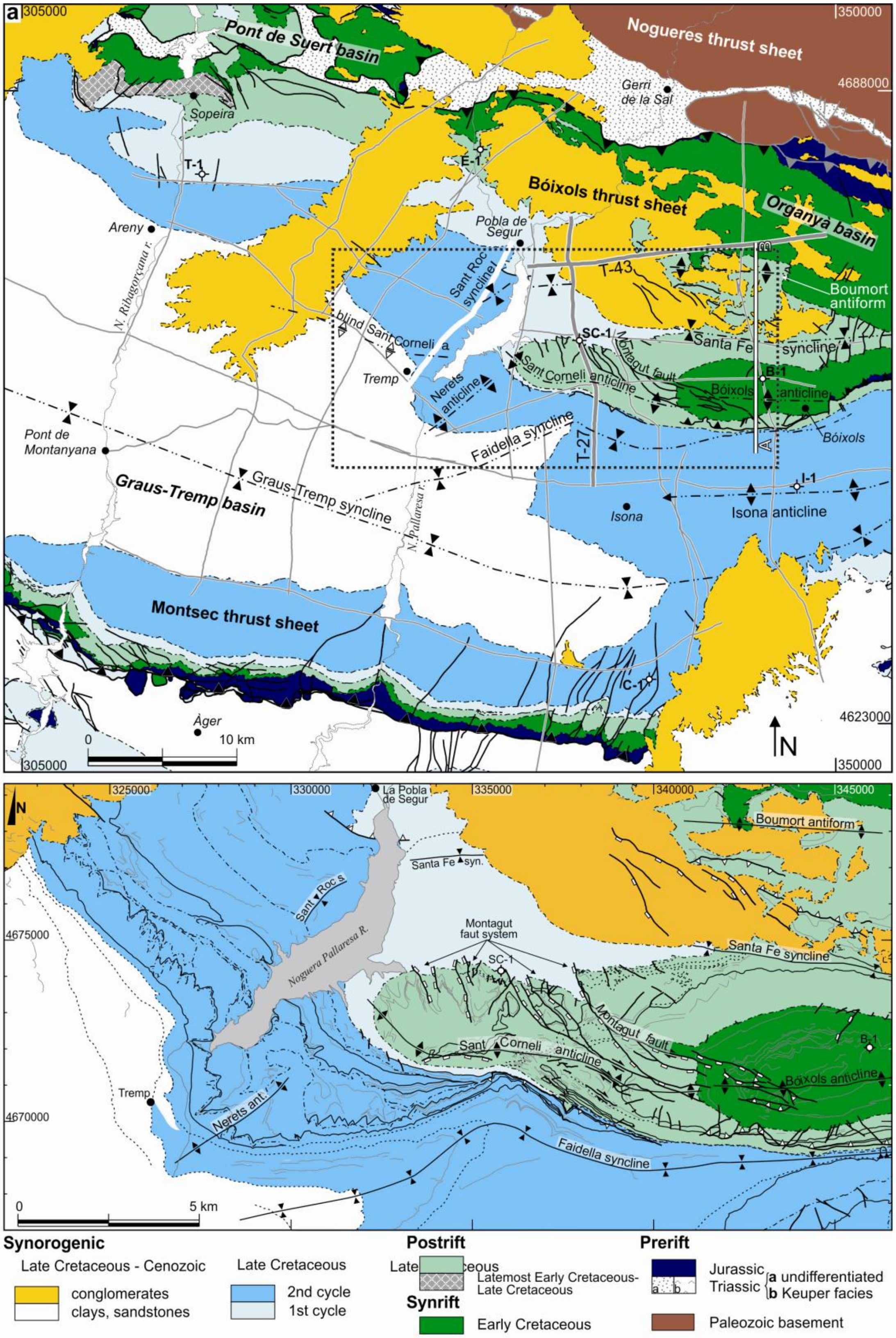


***Fig. 3.4.**-Geological map of the Montsec and the Bóixols thrust sheets around the Noguera Pallaresa River, with the main stratigraphic and structural units. The trace of the seismic lines included in this guide and the ones used for the 3D reconstruction of the area as well as the location of the exploratory wells Isona-1 (I-1), Sant Corneli-1 (SC-1), Bóixols-1 (B-1), and Comiols-1 (C-1) are shown. (From Mencos et al. 2015).*

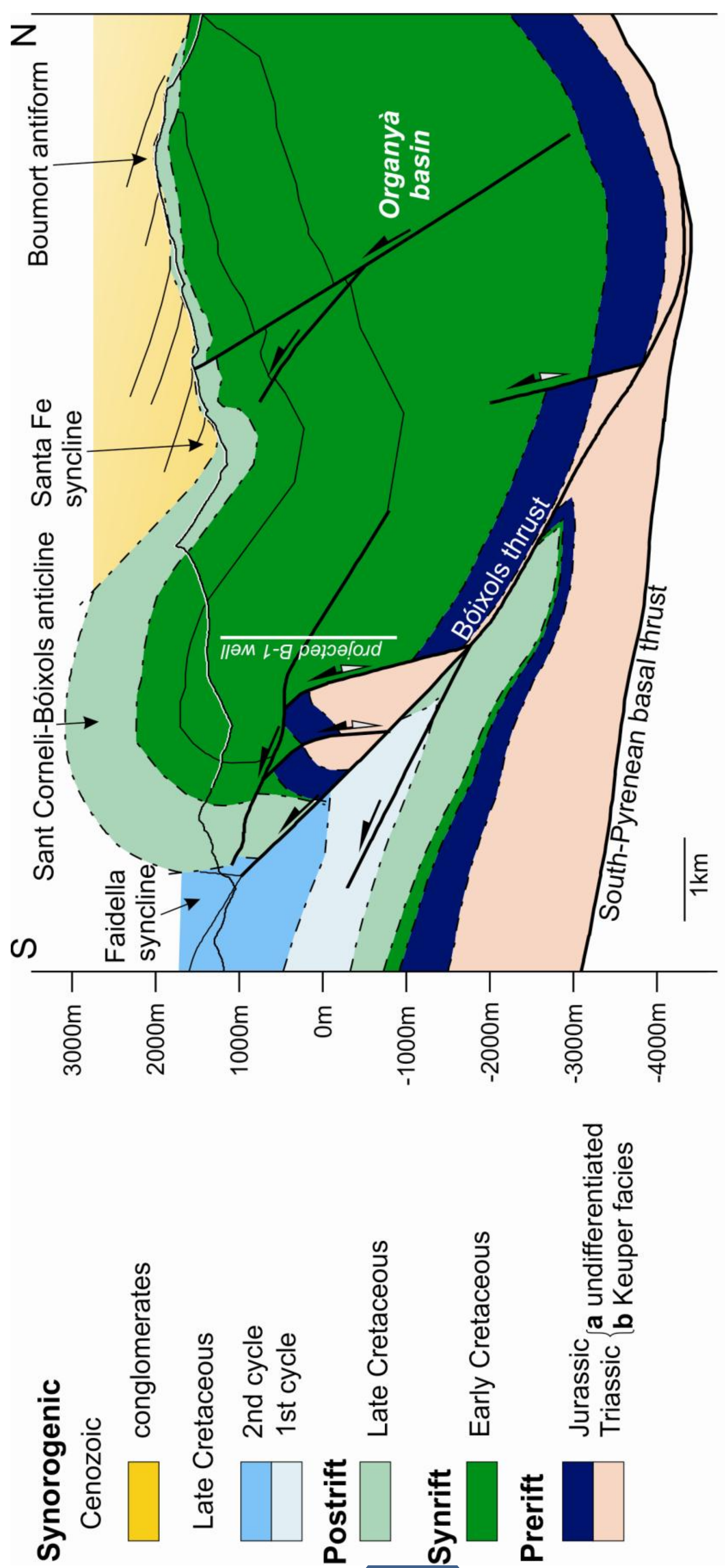


***Figure 3.5**.- N-S Geological cross-section of the Bóixols anticline where inversion of the Lower Cretaceous Organyà Basin may be observed. Bóixols-1 well has been projected onto this section. Modified from Mencos et al. 2015. See Figure 3.4 for location*

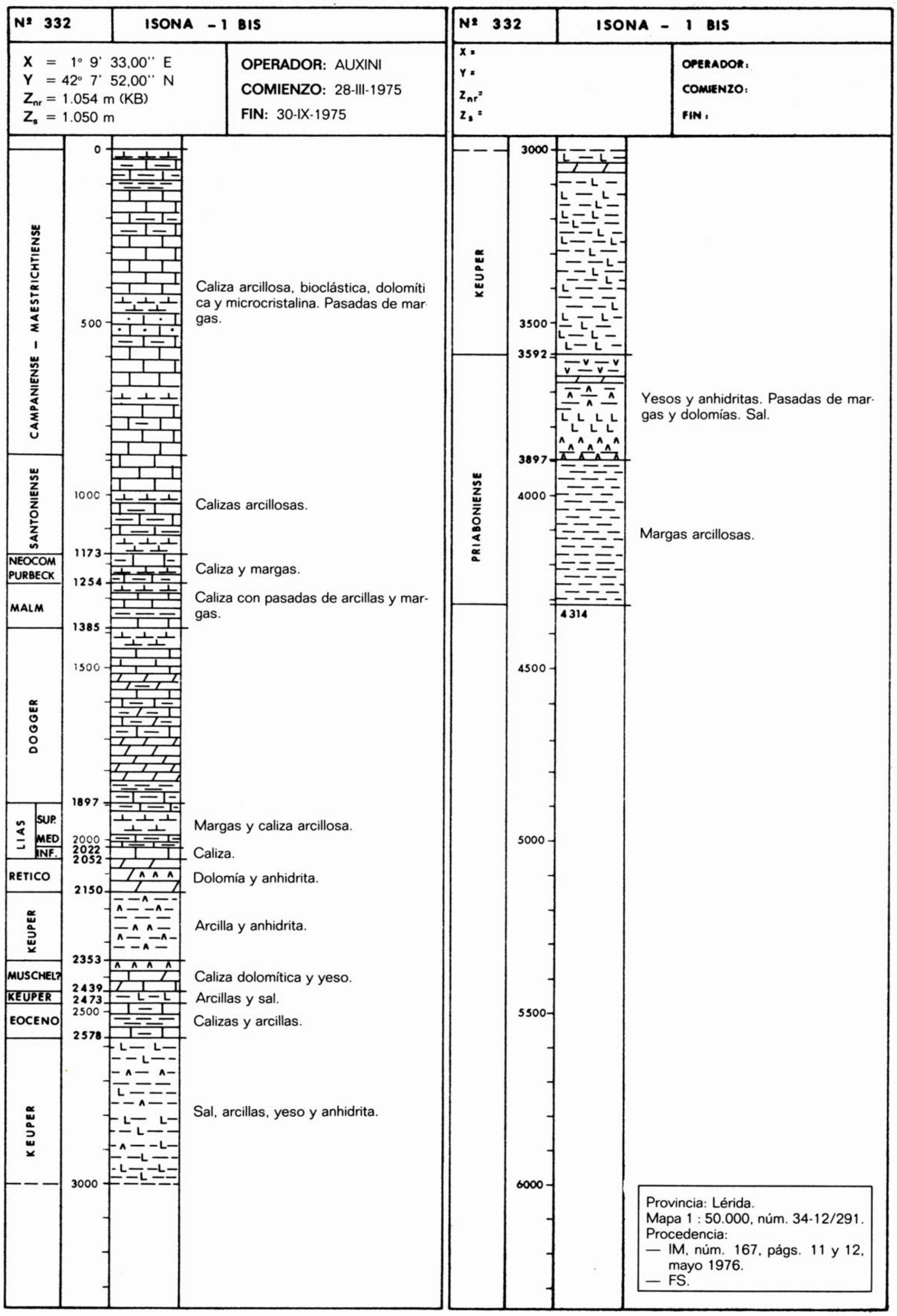


Figure 3.6: *Stratigraphic log of the Isona-1 Bis well. See Figure 3.4 for location. From Lanaja 1987.*

STOP 4: ABELLA DE LA CONCA THRUST

Abella de la Conca village.

Objectives*: Thrust structures in the forelimb of the Bóixols anticline. Damage zone and mesostructures related with a thrust.*

In the Abella de la Conca village, the near vertical forelimb of the Bóixols anticline is formed by from north to south: Lower Cretaceous synrift sediments and Cenomanian, Turonian, Coniacian and Lower Santonian postrift rocks (Figs. 3.4, 3.5 and 4.1).

In this area, minor thrusts truncating the forelimb of the Bóixols anticline are nicely outcropping (Figs. 3.4 and 4.1). The most prominent one corresponds to the Abella de la Conca thrust, which slightly dips towards the north, present a metric-thick damage zone characterized by sheared marls with a S-C structure and about 100-200m of displacement (Fig. 4.2).

Sigmoidal attitude of the cleavage as well as extensional shears reveals that the main sense of displacement of the Abella de la Conca thrust is towards the south (Fig. 3.4 and 4.3). However, an opposite sense of movement (hangingwall down) is also revealed by mesostructures in the damage zone, demonstrating a younger reactivation of the thrust as a normal fault.

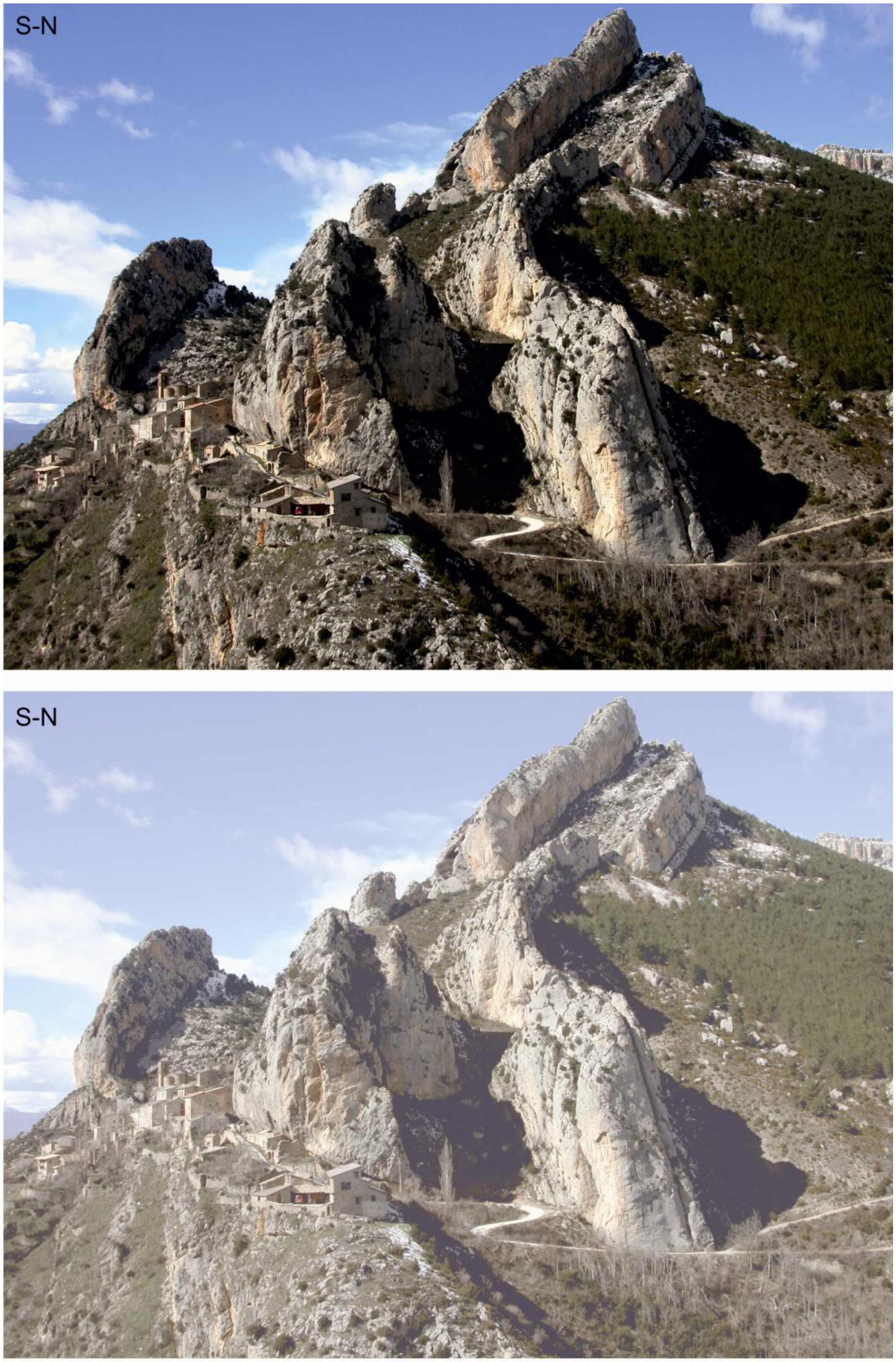


Figura 4.1*: Panoramic view of the forelimb of the Bóixols anticline affected by the Abella de la Conca thrust in Abella de la Conca village.*

Figure 4.2.- *Abella de la Conca thrust and related damage zone. S-C structures may be observed.*

Figure 4.3- *The forelimb of the Bóixols anticline and related thrust structures in the village of Abella de la Conca.*

STOP 5: SANT CORNELI ANTICLINE

Salas de Pallars village, viewpoint in the road between the main road and the village.

Objectives*: General view of the northern Tremp basin and the Sant Corneli anticline. Unconformity below the La Pobla de Segur conglomerates.*

Looking eastwards, the southern highest mountains correspond to the crestal area of the Sant Corneli anticline (Figs. 3.4 and 5.1). 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 hangingwall anticline of the Bóixols thrust sheet. Both structures, the Bóixols thrust and the Sant Corneli anticline, are unconformably overlapped by the Uppermost Cretaceous Aren sandstones of the northern part of the Tremp basin. This disposition can be observed in the landscape as the Aren sandstones are less affected by the Sant Corneli anticline. Moreover, each of the distinct Aren depositional sequences successively onlap the previously tilted ones on the southern limb of the anticline (Figs. 3.4).

The Sant Corneli anticline and the area located north of it, correspond to the Bóixols thrust sheet (Fig. 9). Looking northwards, the Middle-Upper Eocene Collegats conglomerates, which unconformably overlie the Upper Cretaceous beds, can be observed at the Pessonada range (Fig. 5.1).

The Sant Corneli-1 well, located in the northern limb of the Sant Corneli anticline, drilled about 1000 m of Lower Cretaceous rocks and an extensional fault (Figs. 5.2 and 5.3).

Stratigraphic and thickness variations between the two wells drilled in the Bóixols-Sant Corneli anticline reveal the 3D geometry of the Lower Cretaceous rift margin. Thus, the differences between the Sant Corneli-1 and the Boixols-1 wells, in a direction subparallel to the main rift-bounding extensional fault, are the result of an oblique transfer zone between right-lateral en echelon extensional basins (the Organyà basin eastward and the Pont de Suert basin norhtwestward the Sant

Corneli anticline) (Figs. 3.3, 3.4, 5.2 and 5.4). The structure of this transfer zone consists of a breached relay ramp characterized by an intial eastward tilted panel connecting the footwall of the Pont de Suert extensional fault with the hangingwall of the Organyà fault and affected by NW-SE to NNW-SSE trending extensional faults. These faults have been interpreted at subsurface in seismic sections (Fig. 5.4) and correspond with the Montagut faults cropping out in the northern limb of the Sant Corneli anticline (Fig. 5.5).

The plunge of the Sant Corneli anticline westward is related with the initial geometry of the relay ramp and its subsequent tectonic inversion and southward displacement in the hangingwall of the Bóixols thrust.

The present along strike variations of the Sant Corneli anticline and the oblique faults at surface are inherited from a complex 3D geometry of the lower Cretaceous extensional basins. The understanding of this structure has been the result of a 3D reconstruction of the main stratigraphic and structural surfaces from 3D digital mapping, well data analysis and seismic interpretation and demonstrates the power of the application of 3D geological reconstruction methodologies (Figs. 5.5 and 5.6).

Figure 5.1.- *Panoramic view of the Sant Corneli anticline and the Pessonada range*

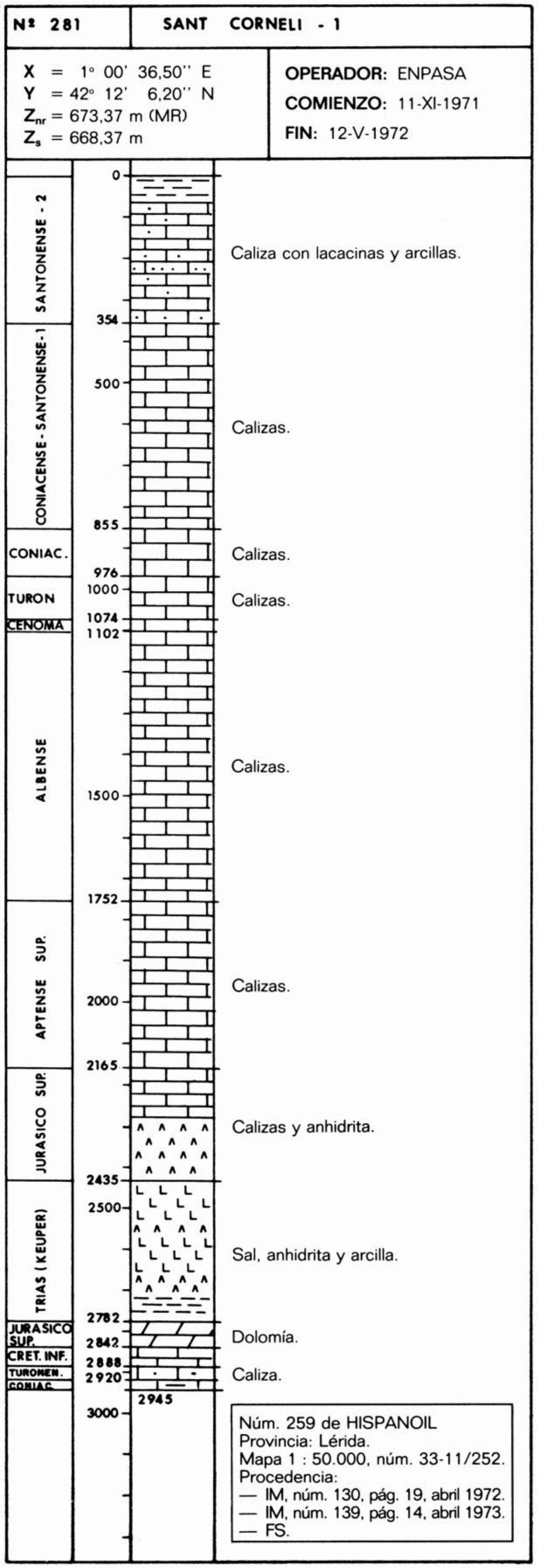


Figure 5.2: *Stratigraphic log of the Sant Corneli-1 well. See Figure 3.4 for location. From Lanaja, 1987*

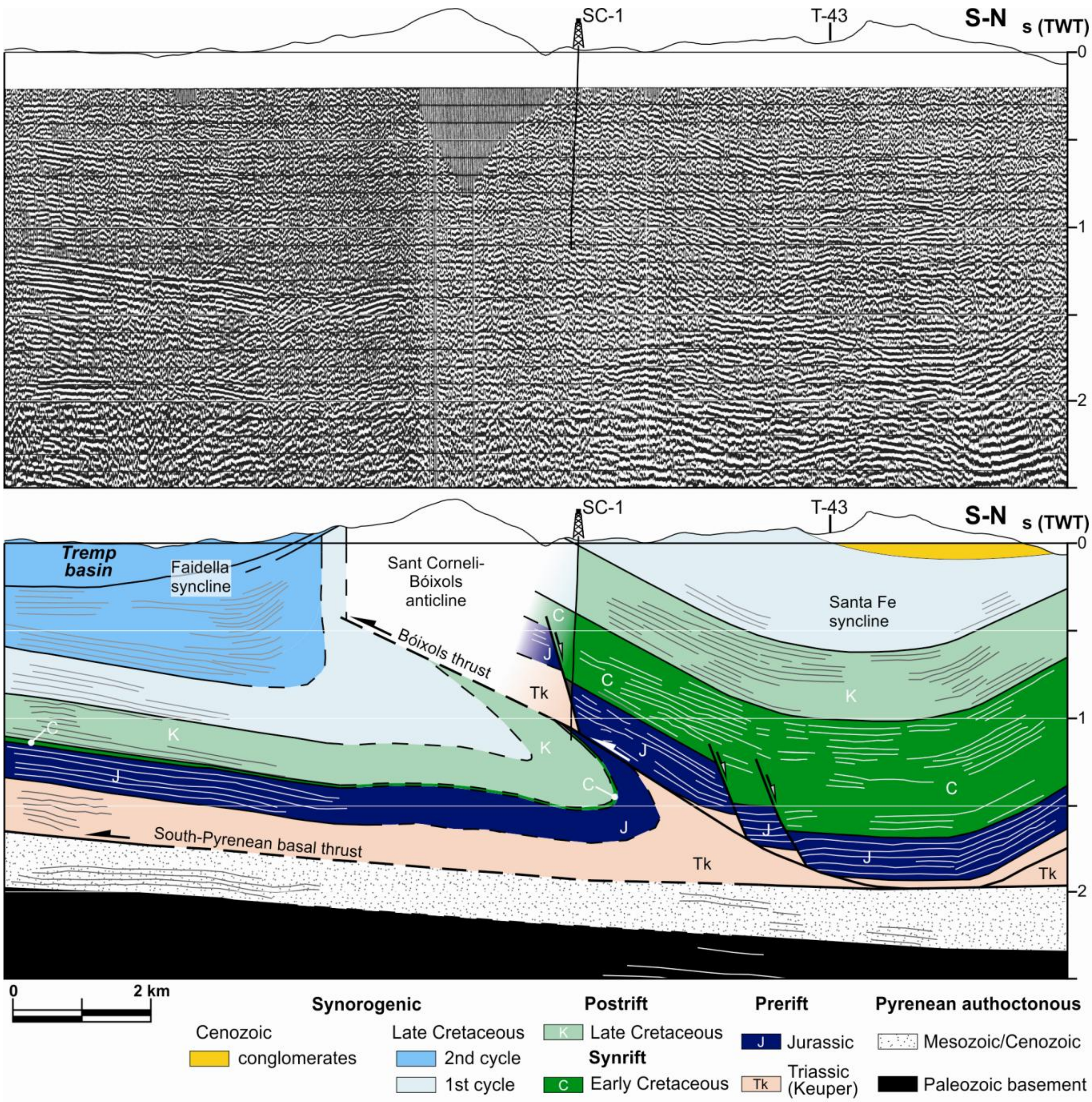


***Figure 5.3.-** T-27 seismic line and interpretation. The interpretation is supported by the surface data and the SC-1 well, which reaches the footwall of the Bóixols thrust. See Figure 3.4 for location. Modified from Mencos et al. 2015.*

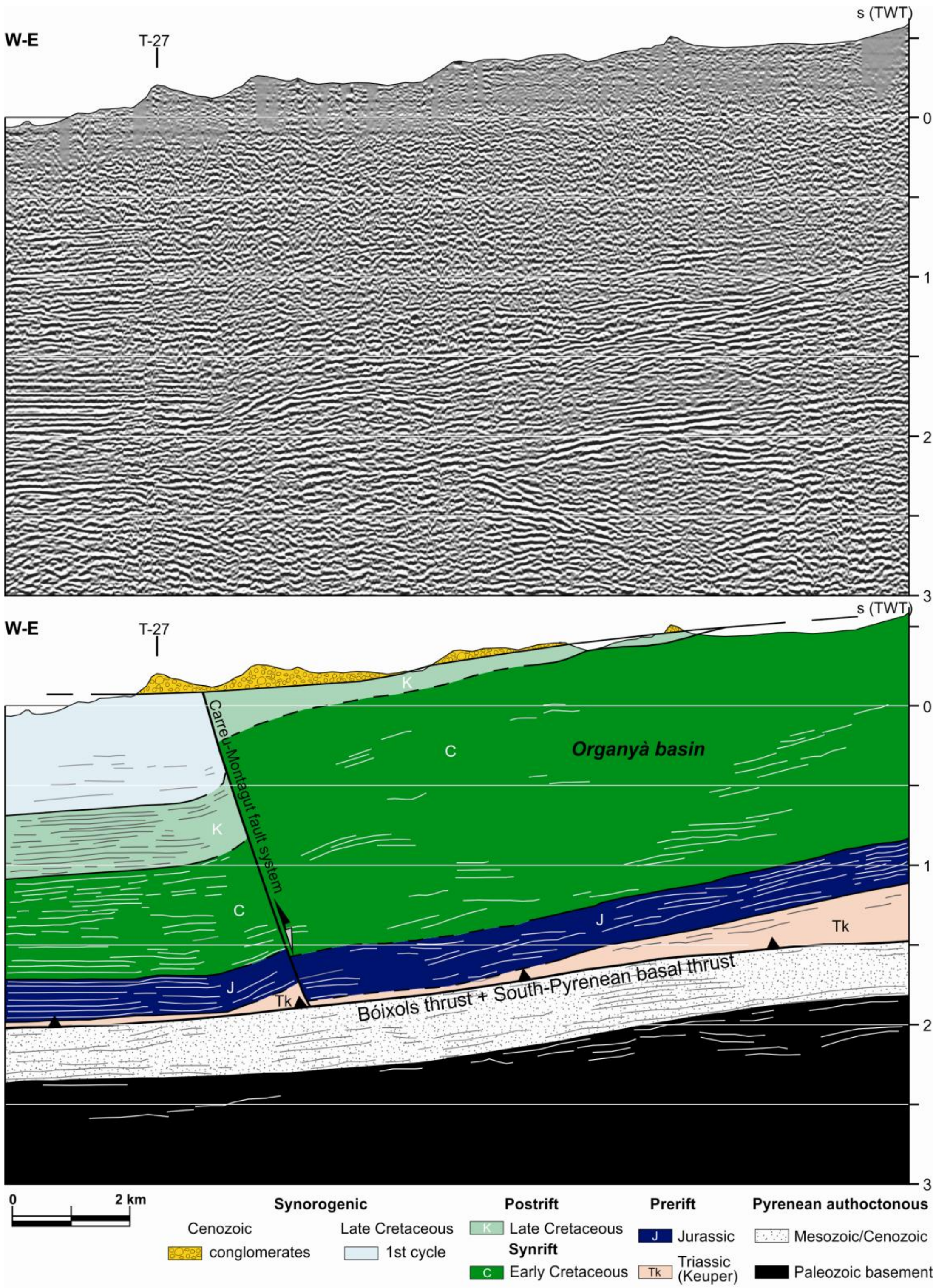


Figure 5.4.- *T-43 seismic line and interpretation. Longitudinal seismic line located north of the Santa Fe syncline, along the Boumort antiform. See Figure 3.4 for location. (Modified from Mencos et al. 2015).*

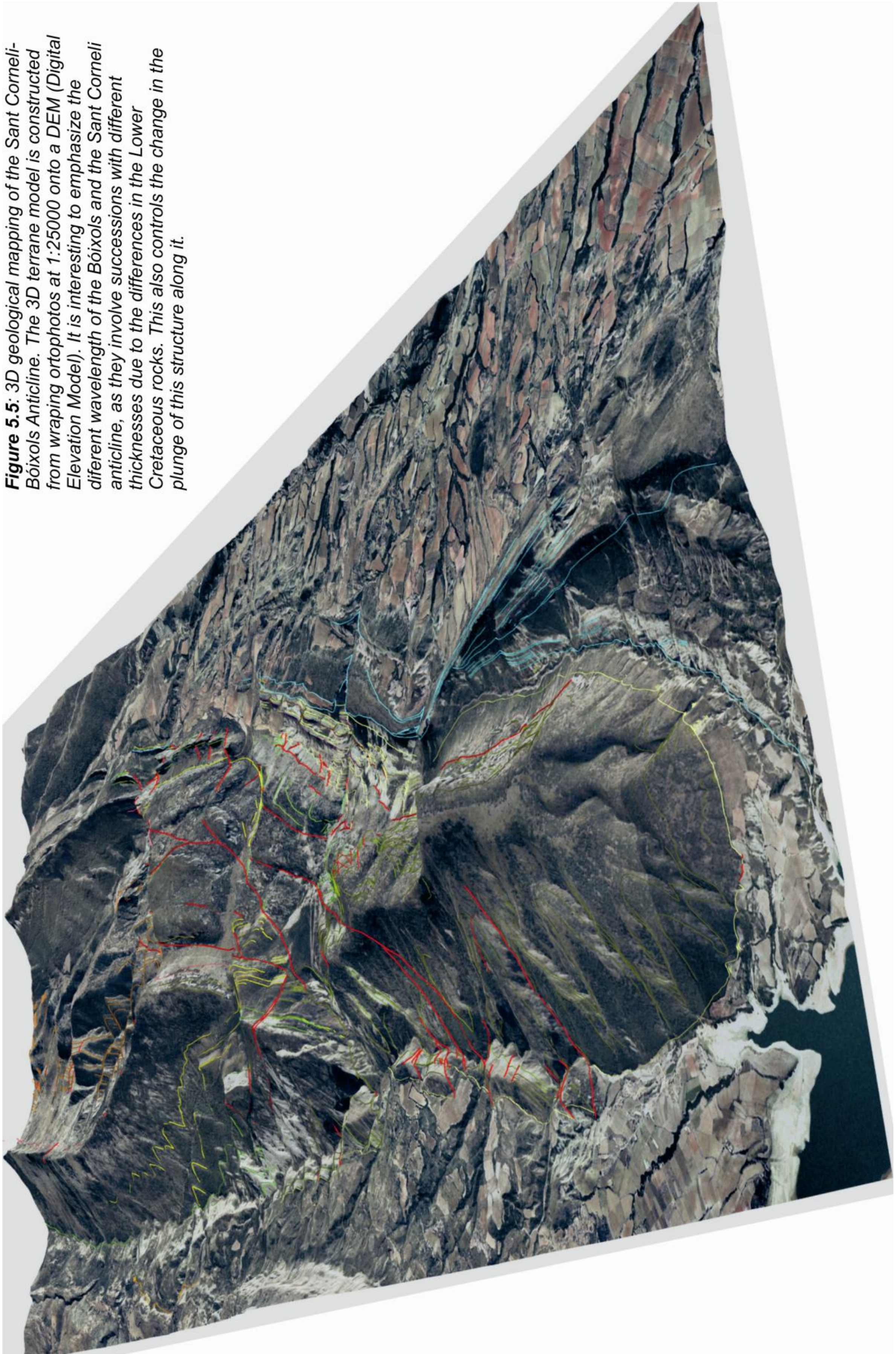


***Figure 5.5**: 3D geological mapping of the Sant Corneli-Bóixols Anticline. The 3D terrane model is constructed from wraping ortophotos at 1:25000 onto a DEM (Digital Elevation Model). It is interesting to emphasize the diferent wavelength of the Bóixols and the Sant Corneli anticline, as they involve successions with different thicknessses due to the differences in the Lower Cretaceous rocks. This also controls the change in the plunge of this structure along it.*

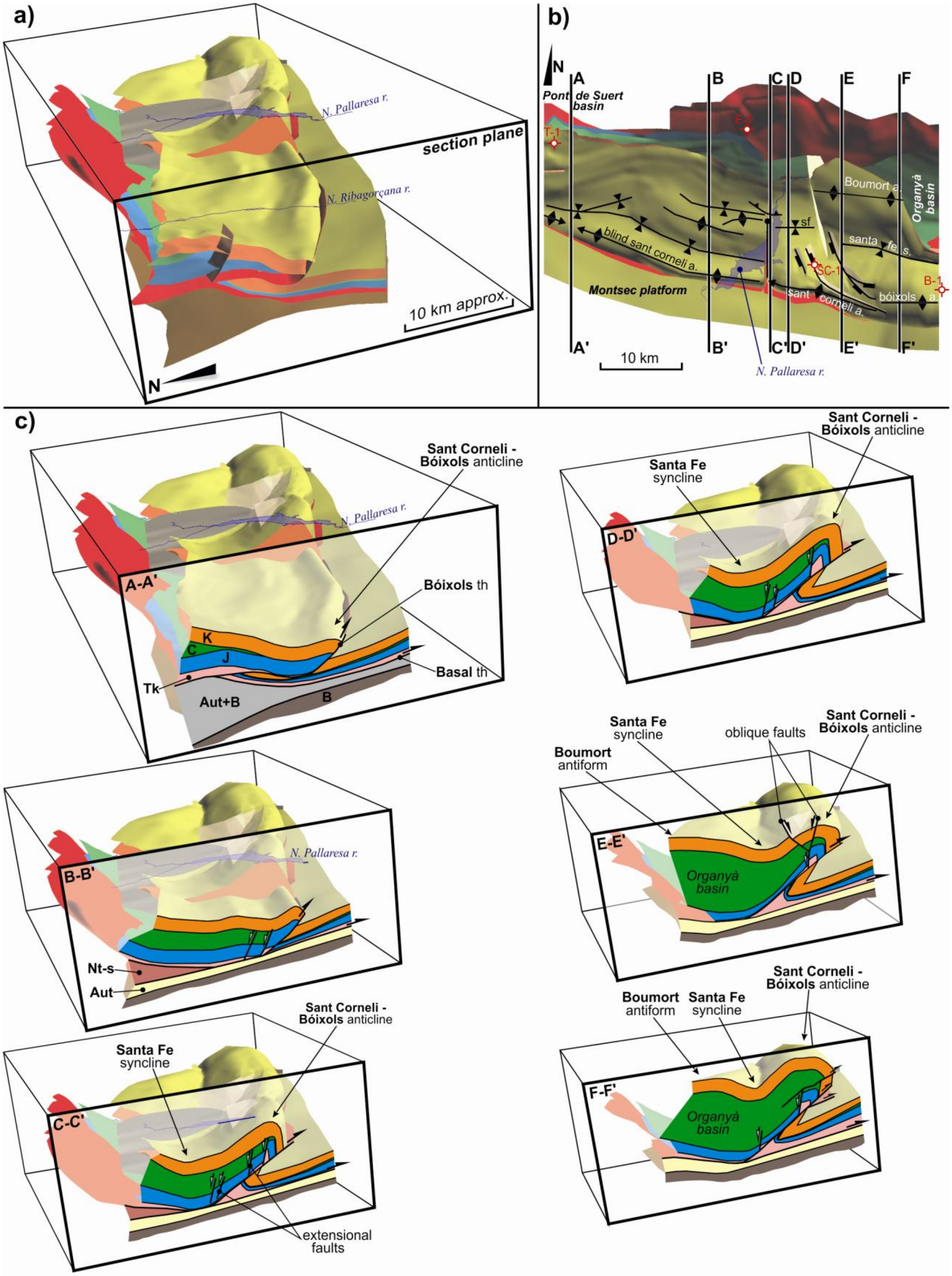


Figure 5.6: *3D model of the Boixols thrust sheet around the Noguera Pallaresa River and cross-sections of it.This 3D model has been constructed from the integration of surface and subsurface data.From Mencos et al., 2015.*

STOP 6: NORTHERN FLANK OF THE SANT CORNELI ANTICLINE

Aramunt Vell village, overview of the Carreu gorge

***Objectives**: The contact between the basement involved Nogueres thrust sheet and the Mesozoic succession of the Bóixols thrust sheet. Example of the evolution of the carbonate platforms in a active margin.*

We are located in Aramunt Vell a village now abandoned. Just looking southwards, we observe the highest mountains which correspond to the hinge area of the Sant Corneli anticline (see stop 5) that represents a hanging wall anticline of the Bóixols thrust. This thrust sheet consist of a thick (over 5.000 m) of Mesozoic sequence, mainly Lower Cretaceous in age. The thickness of the Lower Cretaceous marls and limestones represents the main stratigraphic difference respect to the Montsec thrust sheet located further to the South (see Comiols-1 well, figure 1.5 and Sant Corneli-1 well, figure 5.2).

From a frontal view, we observe the Carreu Valley where there are an excellent exposures of Upper Cretaceous succession which are unconformably overlie by the Upper Eocene Collegats conglomerates, a prominent relief further to the northern view.

On this northern flank of the Sant Corneli-Abella de la Conca anticlines were deposited carbonate platforms during relative tectonic quiescence period, from middle Cenomanian to middle-late Santonian times. In a front view, following the Carreu Valley we can observe an Upper Cretaceous (Santonian) carbonate platforms which are overlaying by the slope to basinal deposits of Herba-savina clays and marls indicating a deepening deposition.

The formation of the Santonian carbonate platforms registred two main types of carbonate shelves (Pomar et al., 2004) both coral-rudist buildups and calcarenite wedges. Two platforms types entail alternation on bedding patterns, internal facies architecture and skeletal composition, marked by a strong tectonic control. A syntectonic major extensional faults (Figure 6.2 and 5.5) represented changes in accommodation space and derived facies distribution.

The Santonian carbonate platforms ended by rapid subsidence and the generation of a NW-SE confined turbidite trough, related to the first inversion structures of the Late Cretaceous (Figure 2).

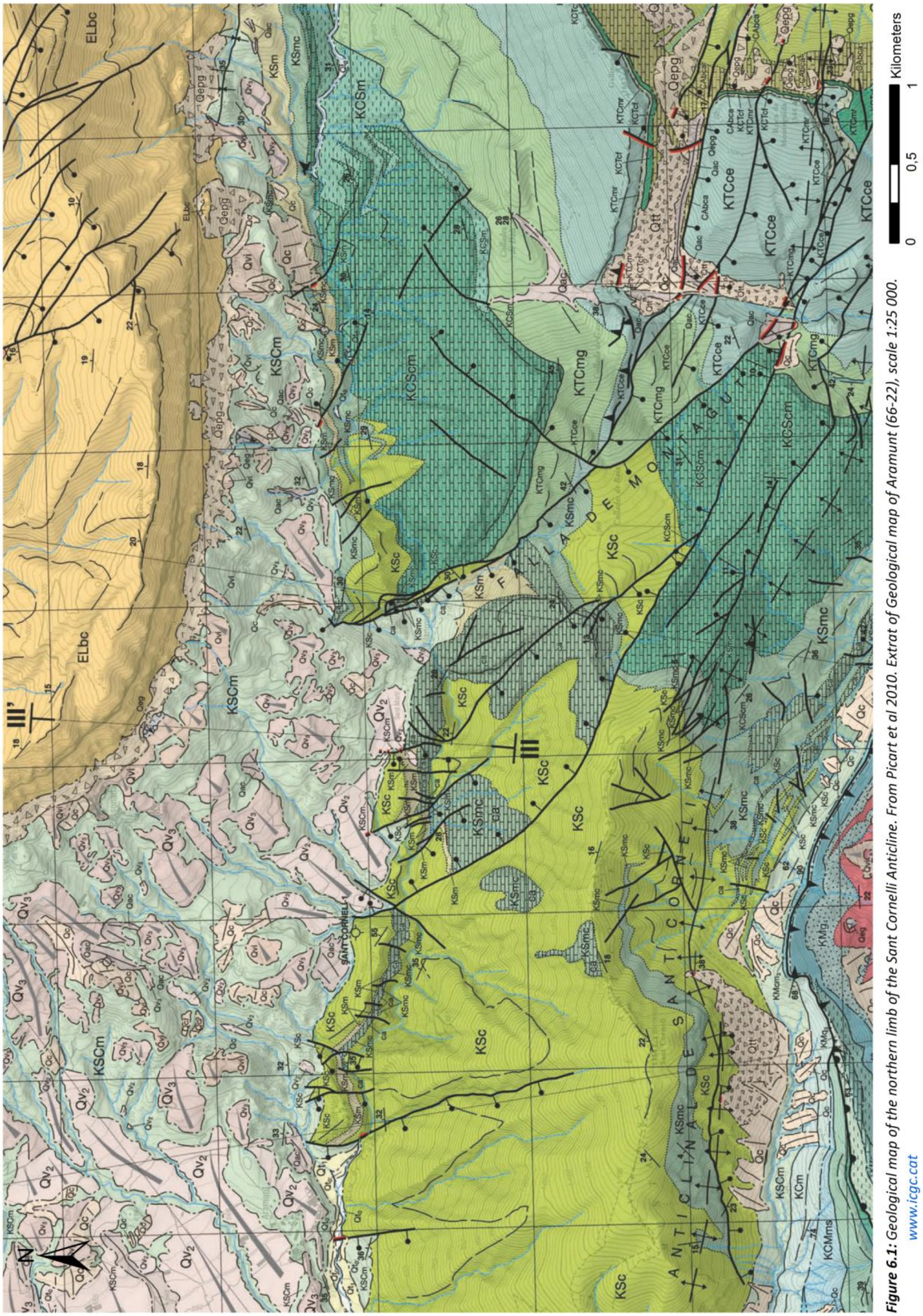


Figure 6.1: *Geological map of the northern limb of the Sant Cornelli Anticline. From Picart et al 2010. Extrat of Geological map of Aramunt (66-22), scale 1:25 000.*
www.icgc.cat

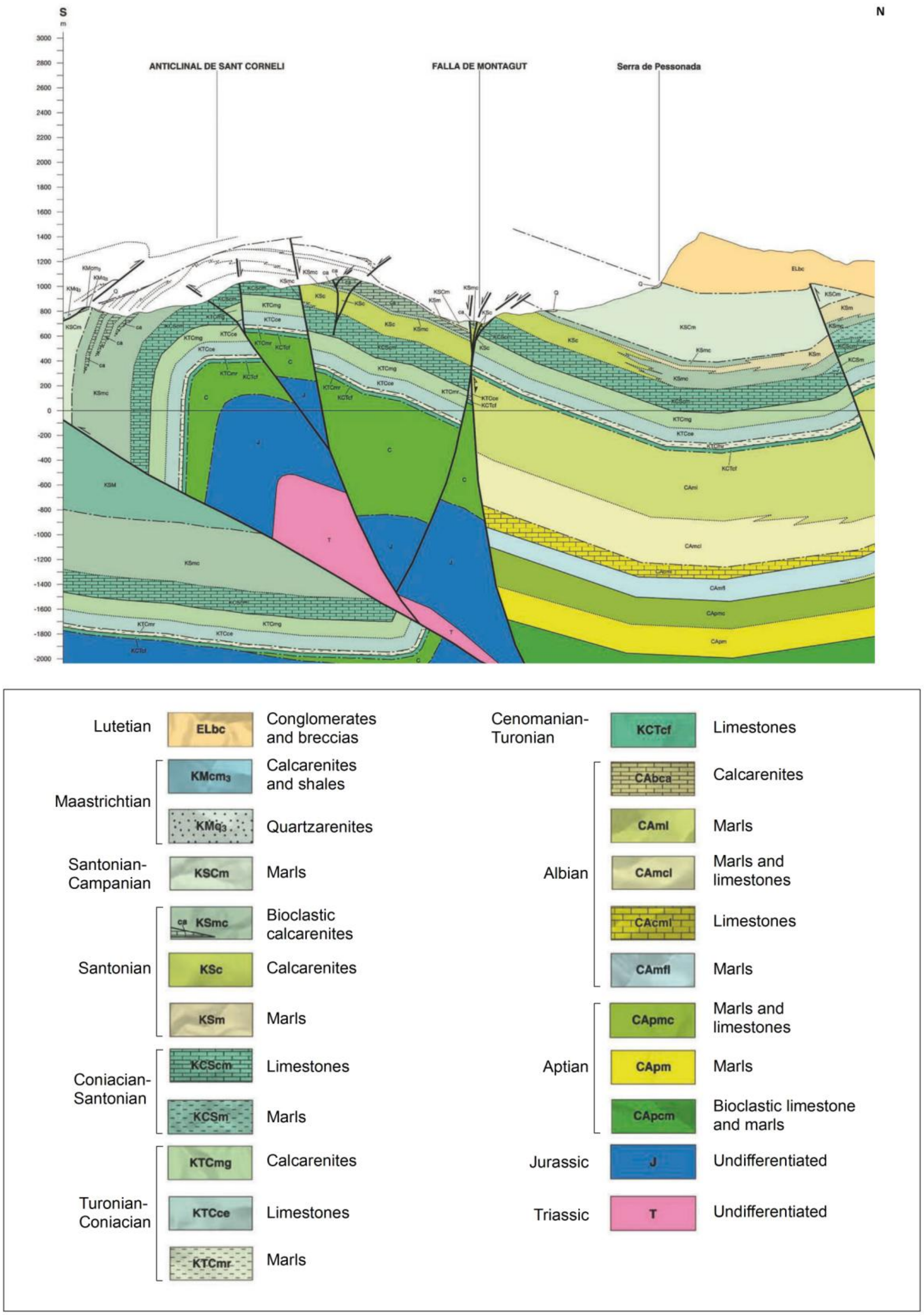


Figure 6.2: *Cross-section across the northern limb of the Sant Corneli Anticline. From Picart et al 2010.*

STOP 7: COLLEGATS

Collegats gorge, north of La Pobla de Segur.

***Objectives**: Structure of the Bóixols thrust sheet. Lower Cretaceous synrift sediments of the Organyà basin and unconformity below the postrift sequence. Unconformity and paleorelief related with La Pobla de Segur Paleogene conglomerates.*

A cross-section along the Collegats gorge allows us to observe the structure of the northern Bóixols thrust sheet and two major unconformities: the end rifting unconformity and the unconformity at base of the Eocene-Oligocene La Pobla de Segur conglomerates (Figs. 7.1, 7.2 and 7.3).

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 (Fig. 7.1). La Pobla de Segur conglomerates (*Rosell & Riba, 1969*) or Collegats Formation (*Mey et al., 1968*) consists of an alluvial fan complex composing more than 20 interfingering alluvial fan lobes that prograded into floodbasin and shallow lacustrine environments (*Mellere and Marzo, 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 Fe Formation and below the La Pobla de Segur conglomerates, a thick succession of lower Cretaceous sediments outcrops. They are folded and tilted to the south.

The Collegats Conglomerates filled a pronounced paleorelief with source areas mostly localized on the Nogueres and Bóixols units. These deposits are organised into a series of stacked, wedge shaped bodies which form repeated coarsening and thickening up sequences resulting from progradation of alluvial fans in relation to the steepened gradients which characterize the third stage in the development of the foreland basin (Fig. 7.1).

Figure 7.1.- *Paleorelief incised on top of Lower Cretaceous limestones and filled by the Upper Eocene-Lower Oligocene Collegats conglomerates (Collegats gorge).*

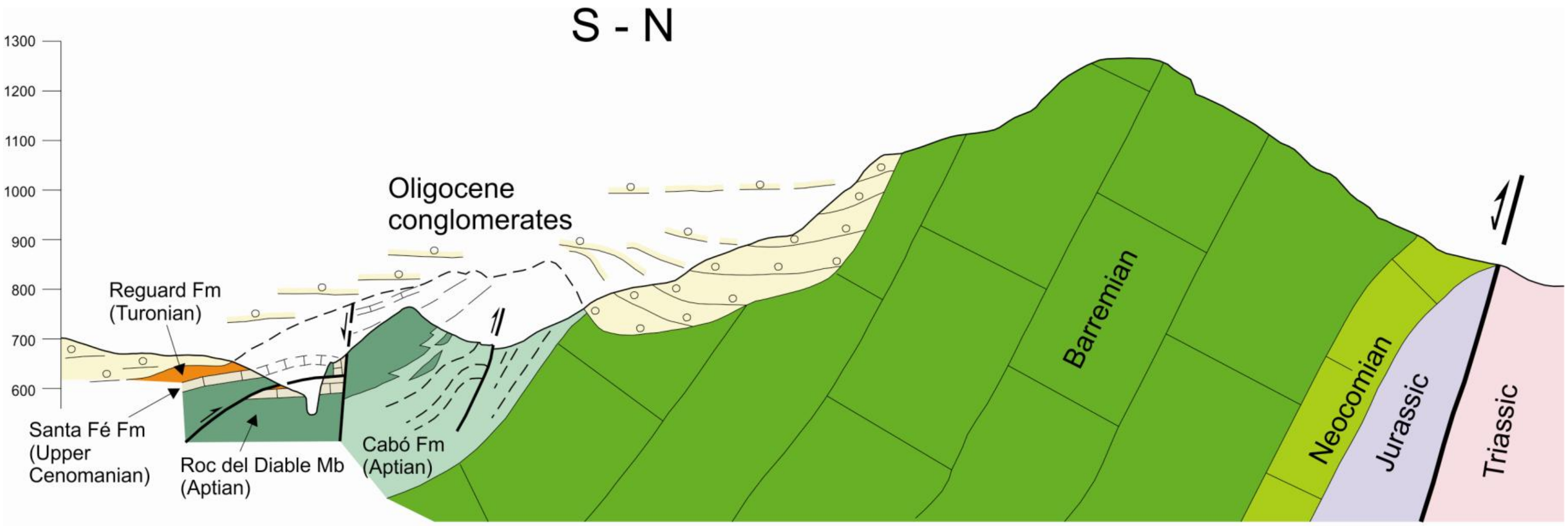


Figure 7.2.- *Cross-section along the Collegats gorge. The limestones of the Santa Fe Fm lie unconformably overlying the Aptian limestones of the Roc del Diable Mb. (Aptian). Albian sediments have been truncated and eroded. From García-Senz, 2002.*

Figure 7.3.- *Unconformity at the bottom of the Cenomanian limestones and at the bottom of the Pobla de Segur conglomerates in the Collegats Gorge..*

Stop 8: THE MORRERES BACKTHRUST AND THE NOGUERES ZONE

Morreres, south of Gerri de la Sal

Objectives*: The contact between the basement involved Nogueres thrust sheet and the Mesozoic succession of the Bóixols thrust sheet.*

The northern boundary of the central south Pyrenean units corresponds to the Morreres backthrust. In the Pallaresa valley this backthrust is located in between the Mesozoic rocks of the Bóixols thrust sheed and the Triassic beds of the Les Nogueres thrust sheets (Figs. 9 and 8.1). Along the road cut, Triassic basaltic rocks (ofites) outcrop. To the south, marls, probably Triassic in age, can be observed and immediately more to the south, the first limestones and breccias are Lower Cretaceous in age. All the Jurassic succession, almost 1000 m thick, is omitted. This substractive contact is the result of the truncation of previously developed folds by the Morreres backthrust (Figs. 8.1 and 8.2). In detail, a conjugated set of shear zones deforming a layer parallel cleavage can be observed (Fig. 6). Cleavage development 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 age of the Morreres backthrust is Early Oligocene as constrained by growth geometries of the syntectonic conglomerates in the Senterada basin (*Beamud et al., 2010*, Fig. 8.2). Nevertheless, older movements cannot be ruled out.

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 puzzle Pyrenean geologists for decades (*Dalloni, 1930; Mey, 1968; Seguret, 1972; Saura, 2004*).

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 (Fig. 8.1).

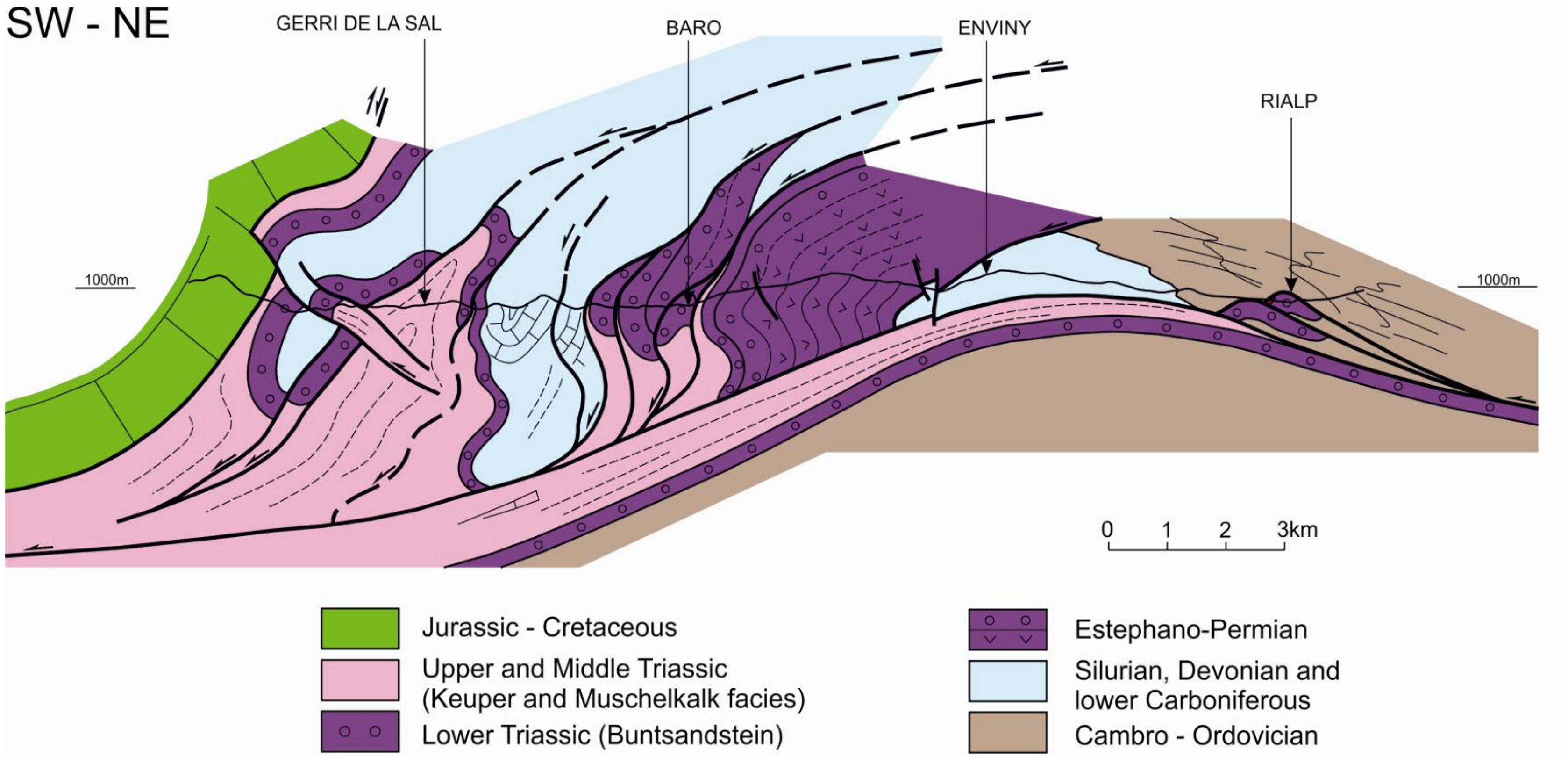


Figure 8.1: *Geological cross-section of the boundary between the Bóixols thrust sheet and the Nogueres unit (Axiall Zone) along the Noguera Pallaresa valley (Muñoz, 1988).*

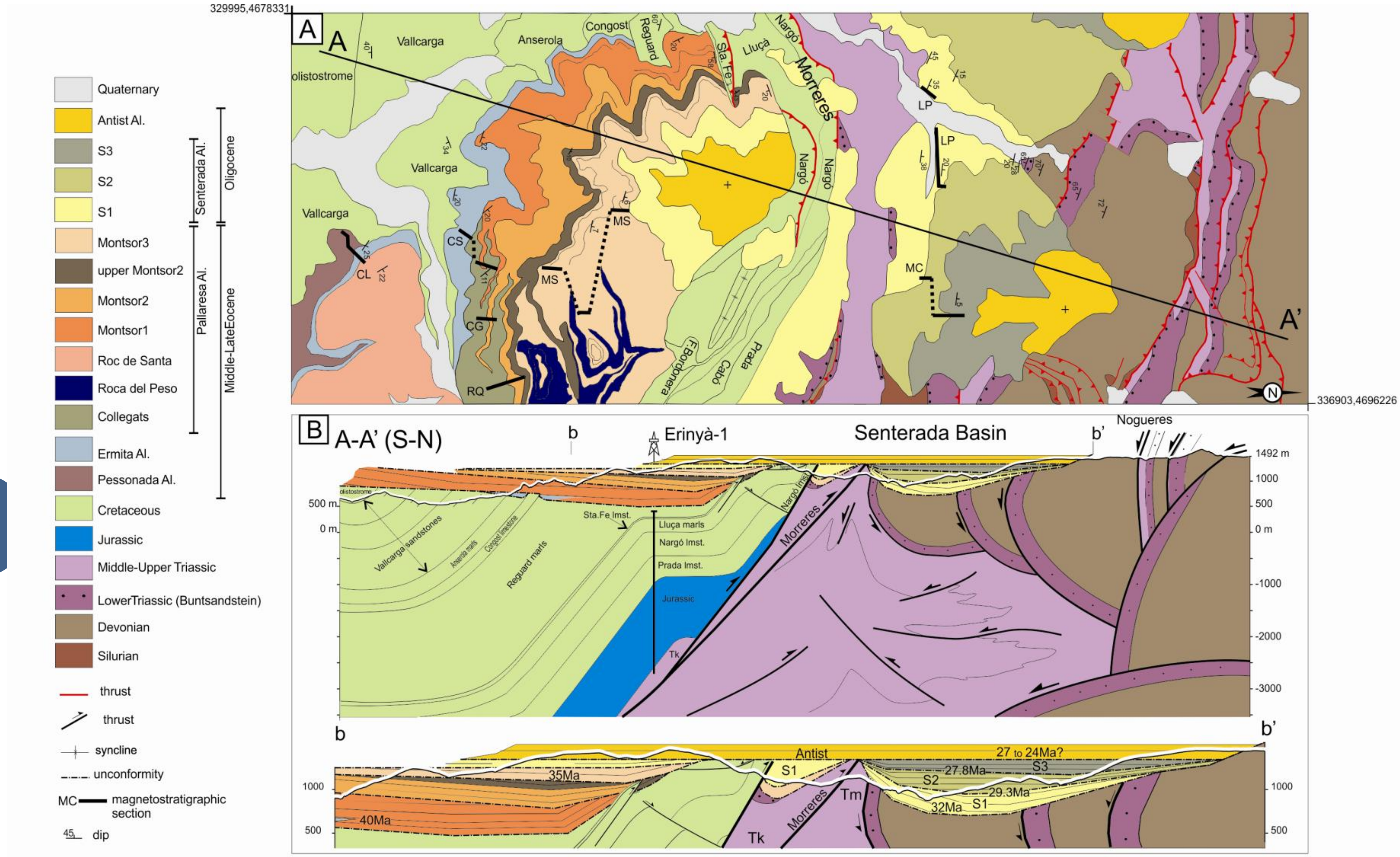


Figure 8.2.- *A) Detailed geological map of the La Pobla de Segur and Senterada basins.The position of the cross-section A-A' is shown. B) Cross-section A-A' across the La Pobla de Segur and Senterada basins showing the main structural features of the syntectonic conglomerates. b-b' corresponds to an enlargement of the central area of cross-section A-A'. From Beamud et al., 2010.*

REFERENCES

BEAUMONT, C., MUÑOZ, J.A., HAMILTON, J. & FULLSACK, P. 2000. Factors controlling the Alpine Evolution of the Central Pyrenees inferred from a comparison of observations and geodynamic models. *Journal of Geophysical Research*, **105**, 8121-8145.

BEAMUD, B., GARCÉS, M., CABRERA, L., MUÑOZ, J.A. & ALMAR, Y. 2003. A new middle to late Eocene continental chronostratigraphy from NE Spain. *Earth and Planetary Science Letters*, **216**, 501-514.

BEAMUD, B., MUÑOZ, J.A., FITZGERALD, P., BALDWIN, S., GARCÉS, M., CABRERA, L., & METCALF, J. 2010. Magnetostratigraphy and detrital apatite fission track thermochronology in syntectonic conglomerates: constraints on the exhumation of the South-Central Pyrenees. *Basin Research*, **216**, 501-514.

BERÁSTEGUI, X., GARCÍA, J.M. & LOSANTOS, M. 1990. Structure and sedimentary evolution of the Organyà basin (Central South Pyrenean Unit, Spain) during the Lower Cretaceous. *Bulletin de la Société Géologique de France*, **8**, 251-264.

BERÁSTEGUI, X., LOSANTOS, M., MUÑOZ, J.A. & PUIGDEFÀBREGAS, C., 1993. Tall geològic del Pirineu Central 1/200.000: *Publ. Geol. Catalunya Inst. Cartografic de Catalunya*, Barcelona, 62 p.

BOILLOT, G. & MALOD, J. 1988. The north and north-west Spanish continental margin: a review. *Revista Sociedad Geológica, España*, **1(3-4)**, 295-316.

BRUNET, M.F. 1986. The influence of the evolution of the Pyrenees on adjacent basins. *Tectonophysics*, 129: 343-354.

BUIS, M.G. & REY, J. 1975. Une évolution sédimentaire de type deltaique: le passage du Tertiaire marin au Tertiaire continental entre l'Ariège et le Douctouyre (Pyrénées Ariégeoises) *Bull. Soc. Hist. Nat. Toulouse,* **111**, 80-95.

BURBANK, D., PUIGDEFABREGAS, C. & MUÑOZ, J.A. 1992a. The chronology of the Eocene tectonic and stratigraphic development of the eastern Pyrenean foreland basin, northeast Spain. *Geological Society of America Bulletin,* **104**, 1101-1120.

BURBANK, D.; VERGÉS, J.; MUÑOZ, J.A. & BENTHAM, P. 1992b. Coeval hindward- and forward-imbricating thrusting in the central southern Pyrenees, Spain: timing and rates of shortening. *Geological Society of America Bulletin,* **104**, 3-17

CARRERA, N., MUÑOZ, J.A., & ROCA, E. 2009. 3D reconstruction of geological surfaces by the equivalent dip-domain method: an example from field data of the Cerro Bayo Anticline (Cordillera Oriental, NW Argentine Andes). *Journal of Structural Geology*, **31**, 1573-1585.

CASANOVAS-CLADELLAS, L. 1975. Estatigrafia y paleontologia del yacimiento Ludiense de Roc de Santa (area del Noguera-Pallaresa). *Paleontologia y Evolucion*, **10**, 158.

CHOUKROUNE, P., ECORS TEAM. 1989. The ECORS Pyrenean deep seismic profile reflection data and the overall structure of an orogenic belt. *Tectonics*, **8**, 23-39.

CONEY, P.; MUÑOZ, J.A., MCCLAY, K. & EVENCHICK, C. 1996. Syntectonic burial and post-tectonic exhumation of the southern Pyrenees foreland fold-thrust belt. *Journal of the Geological Society, London*, **153**, 9-16.

DAIGNIERES, M., DE CABISSOLE, B., GALLART, J., HIRN, A., SURINACH, E., & TORNE, M. 1989. Geophysical constraints on the deep structure along the ecors pyrenees line. *Tectonics*, **8(5)**, 1051-1058. doi:http://dx.doi.org/10.1029/TC008i005p01051

DALLONI, M. 1910 Étude géologique des Pyrénées de l'Aragon. *Annales de la Faculté des Sciences de Marseille*, **t. XIX**, 436 p.

DALLONI, M. 1930. Étude géologique des Pyrénées Catalanes. *Annales Faculte Sciences Marseille*, **XXVI**, 373pp.

DE PAOR, D.G., 1998. Balanced section in thrust belts. Part I : Construction. AAPG Bulletin **72**, 73-90.

DERAMOND, J., GRAHAM, R.H. HOSSACK, J.R. BABY, P. & CROUZET, G. 1985. Nouveau modéle de la chaîne des Pyrénées. *Comptes Rendus de l'Académie des Sciences, Paris*, **301**, 1213-1216.

DINARÉS, J., MCCLELLAND, E. & SANTANACH, P. 1992. Contrasting rotations within thrust sheets and kinematics of thrust-tectonics as derived from palaeomagnetic data: an example from the southern Pyrenees. *In*: MCCLAY, K. (ed) *Thrust Tectonics.* Chapman & Hall. 265-275.

FERNÁNDEZ, O., MUÑOZ, J.A., ARBUÉS, P., 2003. Quantifying and correcting errors derived from apparent dip in the construction of dip-domain cross-sections. *Journal of Structural Geology **25**(1), 35-42.*

FERNÁNDEZ, O. 2004. *Reconstruction of geological structures in 3D. An example from the southern Pyrenees.* PhD thesis, Universitat de Barcelona.

FERRER, O., E. ROCA, B. BENJUMEA, J. A. MUÑOZ AND N. ELLOUZ 2008 The deep seismic reflection MARCONI-3 profile: Role of extensional Mesozoic structure during the Pyrenean contractional deformation at the eastern part of the Bay of Biscay, *Mar. Petrol. Geol.*, **25(8)**, 714-730, doi: http://dx.doi.org/10.1016/j.marpetgeo.2008.06.002

Fillon, C., Huismans, R. S., Beek, P., & Munoz, J. A. 2013 Syntectonic sedimentation controls on the evolution of the southern pyrenean fold-and-thrust belt; inferences from coupled tectonic-surface processes models. Journal of Geophysical Research: *Solid Earth*, **118(10)**, 5665-5680. doi:http://dx.doi.org/10.1002/jgrb.50368

GARCÍA-SENZ, J. 2002. Cuencas extensivas del Cretácico inferior en los Pirineos centrales, formación y subsecuente inversión. Tesis doctoral, Universitat de Barcelona.

GARRIDO-MEJIAS, A. & RÍOS, L.M. 1972. Síntesis geológica del Terciario y Secundario entre los ríos Cinca y Segre (Pirineo central de la vertiente surpirenaica, provincias de Huesca y Lérida). *Boletín Geológico y Minero*, **83**, 1-47.

GRANDJEAN, G. 1992. *Mise en evidence des structures crustales dans une portion de chaine et de leur relation avec les bassins sedimentaires. Application au Pyrenees occidentales au travers du projet ECORS-Arzacq Pyrenees*. PhD thesis, Université de Montpellier II. 291pp.

GROSHONG, R.H., 2006. 3D structural Geology: A practical guide to Quantitative Surface and Subsurface Map Interpretation, *Springer-Verlag*, Berlin, Heudelberg.

LANAJA, J. M. 1987, Contribución de la exploración petrolífera al conocimiento de la geología de España, 465 pp., Instituto Geológico y Minero de España (IGME), Madrid.

LANGENBERG, W., CHARLESWORTH, H., LA RIVIERE, A., 1987. Computer-constructed cross-sections of the Morcles nappe. *Eclogae Geol. Helv*. **80**(3), 655-667.

LE PICHON, X. & BARBIER, F. 1987. Passive margin formation by low-angle faulting within the upper crust, the Northern Bay of Biscay margin. *Tectonics*, **6**, 133-150.

MARILLIER, F. TOMASSINO, A., PATRIAT, PH. & PINET, B. 1988. Deep structure of the Aquitaine Shelf: constraints from expanding spread profiles on the ECORS Bay of Biscay transect. *Marine and Petroleoum Geology*, **5**, 65-74.

MARTÍNEZ, A.; VERGÉS, J. & MUÑOZ, J.A. 1988. Secuencias de propagación del sistema de cabalgamientos de la terminación oriental del manto del Pedraforca y relación con los conglomerados sinorogénicos. *Acta Geológica Hispánica*, **23**, 119-127.

MARTÍNEZ-PEÑA, M.B. & POCOVÍ, A. 1988. El amortiguamiento frontal de la estructura de la cobertera surpirenaica y su relación con el anticlinal de Barbastro-Balaguer. *Acta Geológica Hispánica*, **23**, 81-94.

MENCOS, J. 2011, Metodologies de reconstrucció i modetització 3D d'estructures geològiques : anticlinal de Sant Corneli – Bóixols (Pirineus centrals), PhD thesis, 277 pp., University of Barcelona, Barcelona.

MENCOS, J., CARRERA, N., MUÑOZ, J. A. 2015 Influence of rift basin geometry on the subsequent postrift sedimentation and basin inversion: the Organyà basin and the Bóixols thrust sheet (South-Central Pyrenees), *Tectonics* (in press)

MEY, P. H. W. 1968 The geology of the upper ribagorzana and baliera valleys, central pyrenees, spain. Geologie En Mijnbouw.Netherlands *Journal of Geosciences*, **47(1)**, 71.

MEY, P. H. W. A. AND NAGTEGAAL, P. J. C. AND ROBERTI, K. J. AND HARTEVELT, J. J. A. 1968, Lithostratigraphic subdivision of post-hercynian deposits in the south-central Pyrenees, Spain, *Leidse Geologische Mededelingen*, **41**, pp. 221-228,

MELLERE, D. AND M. MARZO 1992 Los depósitos aluviales sintectónicos de la Pobla de Segur: alogrupos y su significado tectonoestratigráfico, *Acta Geol. Hisp*., **27**, 145-159.

MILLÁN, H. 1996. *Estructura y cinemática del frente de cabalgamiento surpirenaico en las Sierras Exteriores Aragonesas*. PhD Thesis, University of Zaragoza, 330pp.

MILLÁN, H., POCOVÍ, A. & CASAS, A. 1995. El frente de cabalgamiento surpirenaico en el extremo occidental de las Sierras Exteriores: sistemas imbricados y pliegues de despegue. *Revista de la Sociedad Geológica de España*, **8**, 73-90.

MILLÁN, H., DEN BEZEMER, T., VERGÉS, J., MARZO, M., MUÑOZ, J.A., ROCA, E., CIRES, J., ZOETEMEIJER, R., CLOETINGH, S. & PUIGDEFABREGAS, C. 1995. Palaeo-elevation and effective elastic thickness evolution at mountain ranges: inferences from flexural modelling in the Eastern Pyrenees and Ebro Basin. *Marine and Petroleum Geology*, **12(8)**, 917-928.

MUÑOZ, J.A. 1992. Evolution of a continental collision belt: ECORS-Pyrenees crustal balanced cross-section. *In*: MCCLAY, K. (ed) *Thrust Tectonics.* Chapman & Hall. 235-246.

MUÑOZ, J.A., MARTÍNEZ, A. & VERGÉS, J. 1986. Thrust sequences in the eastern Spanish Pyrenees. *Journal of Structural Geol*ogy, **8**, 399-405.

MUÑOZ, J.A., CONEY, P.; MCCLAY, K. & EVENCHICK, C. 1997. Discussion on syntectonic burial and post-tectonic exhumation of the southern Pyrenees foreland fold-thrust belt. *Journal of the Geological Society, London*, **154**, 361-365.

MUÑOZ, J.A. 2002. Alpine Tectonics I, The Pyrenees. In: *The Geology of Spain* (eds.: Gibbons, W. & Moreno, T.) Geological Society London, 370-385.

MUTTI, E. SÉGURET, M. & SGAVETTI, M. 1988. *Sedimentation and Deformation in the Tertiary sequences in the Southern Pyrenees*. AAPG Mediterranean Basins Conference, Nice, Field Guide 7. Inst. Geol. Univ. Parma, Italy.

OLIVET, J.-L. 1996. La cinématique de la plaque Ibérique, *Bull. Centres Rech. Explor.-Prod. Elf Aquitaine*, **20**, 131-195.

PI, E., M. COLOMER, J.M. SAMSÓ, E. CAUS, P. ARBUÉS, J.L. CUEVAS, L. MERCADÉ, X. BARBERÀ, J. CORREGIDOR, J. ESCUER, J. SOLÀ, J. MONTANER AND X. BERÁSTEGUI 2003, Mapa geològic de Catalunya, scale 1:25000, 290-1-2 (65-24), Llimiana, Institut Cartogràfic de Catalunya (ICC), Servei Geològic de Catalunya (IGC), Barcelona.

PINET, B., MONTARDET, L. & ECORS SCIENTIFIC PARTY 1987. Deep seismic reflection and refraction profiling along the Aquitaine shelf (Bay of Biscay). *Geophys. J. R. Astr. Soc.*, **89**, 305-312.

POCOVÍ, A. 1978. *Estudio geológico de las Sierras Marginales Catalanas (Prepirineo de Lérida).* PhD thesis, University of Barcelona, 218pp.

POUS, J., MUÑOZ. J.A., LEDO, J., LIESA , M. 1995. Partial melting of the subducted continental lower crust in the Pyrenees. *Journal of the Geological Society, London*, **152**, 217-220.

PUIGDEFÀBREGAS, C., MUÑOZ, J.A. & MARZO, M. 1986. Thrust belt development in the Eastern Pyrenees and related depositional sequences in the southern foreland basin. *In*: ALLEN P.A. & HOMEWOOD P. (ed) *Foreland basins*, Special Publication International Association Sedimentologists, **8**, 229-246.

Puigdefabregas, C., & Simo, A. 1986. Evolution and cyclicity in a tectonically controlled shelf; aren sandstone, maestrichtian, tremp, south-central pyrenees. *Memoir - Canadian Society of Petroleum Geologists,* **11**, 332.

in the Southern Pyrenees. *In*: MCCLAY, K. (ed) *Thrust Tectonics.* Chapman & Hall. 247-254.

ROCA, E., J. A. MUÑOZ, O. FERRER, AND N. ELLOUZ 2011 The role of the Bay of Biscay Mesozoic extensional structure in the configuration of the Pyrenean orogen: Constraints from the MARCONI deep seismic reflection survey, *Tectonics*, **30**, TC2001, doi:10.1029/2010TC002735

ROEST, W.R. & SRIVASTAVA, S.P. 1991. Kinematics of the plate boundaries between Eurasia, Iberia and Africa in the North Atlantic from the Late Cretaceous to the present. *Geology*, **19**, 613-616.

Rosell, J., & Riba, O. 1969. Nota sobre la disposicion sedimentaria de los conglomerados de pobla de segur (provincia de lerida). *Pirineos*, **22(81-82)**, 61-74.

ROURE, F., CHOUKROUNE, P., BERÁSTEGUI, X., MUÑOZ, J.A., VILLIEN, A., MATHERON, P., BAREYT, M., SÉGURET, M., CÁMARA, P. & DERAMOND, J. 1989. ECORS Deep Seismic data and balanced cross-sections, geometric constraints to trace the evolution of the Pyrenees. *Tectonics*, **8**, 41-50.

SALAS, R., GUIMERÀ, J., MAS, R., MARTÍN-CLOSAS, C., MELÉNDEZ, A. & ALONSO, A. (2000). Evolution of the Mesozoic Central Iberian Rift System and its Cenozoic inversion (Iberian Chain). In: Perytethyan

Rift/Wrench Basins and Passive Margins. W. Cavarazza, A:H:F: Roberston and P.A. Ziegler (eds.) Paris.

SANS, M., MUÑOZ, J.A. & VERGÉS, J. 1996. Triangle zone and thrust wedge geometries related to evaporitic horizons (southern Pyrenees). *Bulletin of Canadian and Petroleum Geology*, **44**, 375-384.

SAURA, E. 2004. *Analisi estructural de la zona de la Nogueres (Pirineus Centrals).* PhD thesis, Universitat Autònoma de Barcelona.

SÉGURET, M. 1972. *Étude tectonique des nappes et séries décollées de la partie centrale du versant sud des Pyrénées*. Pub. USTELA, sér. Geol. Struct. n.2, Montpellier; 1-155.

SOUQUET, P. 1967. *Le Cretacé superieur sud-pyrénéenne en Catalogne, Aragon et Navarre.* PhD thesis, University of Toulouse, 529pp.

Sudre, J., De Bonis, L., Brunet, M., Crochet, J. Y., Duranthon, F., Godinot, M., Vianey-liaud, M. 1992 La biochronologie mammalienne du paleogene au nord et au sud des pyrenees; etat de la question. *Comptes Rendus De l'Academie Des Sciences, Serie 2, Mecanique, Physique, Chimie, Sciences De l'Univers, Sciences De La Terre*, **314(6)**, 631-636.

TEIXELL, A. 1996. The Ansó transect of the southern Pyrenees: basement and cover thrust geometries. *Journal of the Geological Society, London*, **153**, 301-310.

TEIXELL, A. 1998. Crustal structure and orogenic material budget in the West-Central Pyrenees. *Tectonics*, **17**, 395-406.

TORNE, M., DE CABISSOLE, B., BAYER, R., CASAS, A., DAIGNIERES, M., & RIVERO, A. 1989 Gravity constraints on the deep structure of the pyrenean belt along the ECORS profile. *Tectonophysics*, **165(1-4)**, 105-116.

VERGÉS, J. 1993. *Estudi tectònic del vessant sud del Pirineu central i oriental: evolució en 3D*. PhD thesis, University of Barcelona, 203pp.

VERGÉS, J. & MUÑOZ, J.A. 1990. Thrust sequences in the Southern Central Pyrenees. *Bulletin de la Société Géologique de France*, **8, VI(2)**, 265-271.

VERGÉS, J., MUÑOZ, J.A. & MARTÍNEZ, A., 1992. South Pyrenean fold and thrust belt: The role of foreland evaporitic levels in thrust geometry. In: K.R. McClay (ed.) *Thrust Tectonics, London Chapman and Hall,* 255-264.

VERGÉS, J., MILLÁN, H., ROCA, E., MUÑOZ, J.A., MARZO, M., CIRÉS, J., DEN BEZEMER, T., ZOETEMEIJER, R. & CLOETINGH, S. 1995. Eastern Pyrenees and related foreland basins: pre-, syn- and post-collisional crustal-scale cross-sections. *Marine and Petroleum Geology*. **12**, 893-915.

VIELZEUF, D. & KORNPROBST, J. 1984. Crustal splitting and the emplacement of Pyrenean lherzolites and granulites. *Earth and Planetary Science Letters*, **67**, 383-386.

ZIEGLER, P. A. 1987 Evolution of the arctic-north atlantic borderlands Graham & Trotman, London.

ZIEGLER, P. A. 1988. Evolution of the arctic-north-atlantic and the western tethys. *AAPG Memoir*, **43**, 198 pp.